NON-ELECTRIC APPLICATIONS OF NUCLEAR POWER: SEAWATER DESALINATION, HYDROGEN PRODUCTION AND OTHER INDUSTRIAL APPLICATIONS

PROCEEDINGS SERIES

NON-ELECTRIC APPLICATIONS OF NUCLEAR POWER: SEAWATER DESALINATION, HYDROGEN PRODUCTION AND OTHER INDUSTRIAL APPLICATIONS

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FOREWORD

Today, nuclear power plants contribute about 16% to the world's electricity generation. Because electricity represents less than one third of the primary energy uses, nuclear energy provides only about 6% of total energy consumption in the world. If nuclear energy were used for purposes other than electricity generation, it could play a more significant role in global energy supply. This could have also a significant impact on global goals for reduced greenhouse gas emissions for a cleaner environment.

Nuclear power is the only large-scale carbon-free energy source that, in the near and medium term, has the potential to significantly displace limited and uncertain fossil fuels. To do this, however, nuclear power must move beyond its historical role as solely a producer of electricity to other non-electric applications. These applications include seawater desalination, district heating, heat for industrial processes, and electricity and heat for hydrogen production among others. These applications have tremendous potential in ensuring future worldwide energy and water security for sustainable development.

In recent years, various agencies involved in nuclear energy development programmes have carried out studies on non-electric applications of nuclear power and useful reports have been published. The IAEA launched a programme on co-generation applications in the 1990's in which a number of Member States have been and continue to be actively involved. This programme, however is primarily concerned with seawater desalination, and district and process heating, utilizing the existing reactors as a source of heat and electricity. In recent years the scope of the Agency's programme has been widened to include other more promising applications such as nuclear hydrogen production and higher temperature process heat applications. OECD/NEA (OECD Nuclear Energy Agency), Euroatom (European Atomic Energy Community) and GIF (Generation IV International Forum) have also evinced interest in the non-electric applications of nuclear power based on future generation advanced and innovative nuclear reactors.

The IAEA organized a Symposium on Nuclear Desalination of Seawater hosted by Korean Atomic Energy Research Institute in Taejon, South Korea in 1997. IAEA cooperated with World Council of Nuclear Workers (WONUC) and the Moroccon Association of Nuclear Engineers (AIGAM) on an International Conference on Nuclear Desalination held at Marrakesh in 2002. In view of the widened scope of the Agency's programme, it was proposed to hold the next International Conference in 2007 on Non-electric Applications of Nuclear Power. The objective of the conference was to share the experiences of Member States already engaged in the development programme in this area with those having interest and considering research studies.

This conference, held April 16–19, 2007 at JAEA, Oarai, Japan, covered various aspects of non-electric applications of nuclear power utilizing combined heat and power (CHP). The major focus was on desalination, hydrogen production or other fuel production as a complement to CO_2-free energy sources and many newer industrial applications. This publication contains the text of all the contributory papers, summary of the sessions and the panel discussion at the conference. The proceeding will be useful to the scientists and engineers interested in research and development of the non-electric applications of nuclear power worldwide.

The IAEA officer responsible for this conference was I. Khamis. The local coordination was by T. Nishihara of JAEA. The cooperation of OECD/NEA and IDA and the contribution of the steering committee members and of the participants of the conference is also acknowledged.

EDITORIAL NOTE

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Summary

The IAEA organized the International Conference on "Non-electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications" at Oarai, Japan on April 16-19, 2007, in cooperation with OECD Nuclear Energy Agency (OECD/NEA) and International Desalination Association (IDA) and hosted by the Government of Japan through the Japan Atomic Energy Agency (JAEA).

There were one hundred and twenty six participants from twenty four countries and five international organizations and the host organization. Sixty papers were presented at the conference and six poster presentations were displayed.

The programme of the conference was designed to cover the wider aspects of outlook of nuclear power and process heat applications as well as technology, safety and economics of non-electric applications. The current trends in nuclear desalination and research and development in the field of high temperature process applications including nuclear hydrogen production were particularly highlighted during the conference.

The global energy scenario and nuclear energy out look

All forecasts project increases in world energy demand, especially as population and economic productivity grow. There appears however no ideal or magic solutions to avoid the unclean, uncertain and expensive energy based on fossil fuels in the coming years, as the present trends indicate. Wind power, though growing, provides only a modest amount of electricity worldwide and cannot generate the heat required for alternative applications. Solar furnaces can provide high-temperature heat and electricity, but are still under development. Both of these renewable energy options require vast land resources and favorable climate conditions and would be incompatible with the large-scale applications. Nuclear energy on the other hand has the potential for large-scale deployment in future.

All energy technologies will be therefore needed in the years to come. As far nuclear is concerned, uranium resources are available for exploitation of nuclear energy and advanced nuclear technologies are developed/ are under development. From a sustainable development perspective, nuclear energy has a major role to play in terms of reduction of CO2 emissions, security of energy supply and diversification of supply and price stability.

As a proven technology, today nuclear power provides more than 16% of world electricity supply in over than 30 countries. The net nuclear power capacity in operation in developing countries alone is close to 14% of the total worldwide. More than ten thousand reactor-years of operating experience have been accumulated over the past 5 decades. In recent years, a growing interest in harnessing nuclear power in non electric applications has been shown by many countries all over the world. However, non electric applications of nuclear power may be foreseen for a wide range of applications such as hydrogen production, nuclear seawater desalination, district heating, oil recovery, coal conversion, and other industrial applications for the petrochemical and refinery process, paper and textile …etc. It is evident that the specific temperature requirements for such non electric applications vary greatly from low (less than 100 C in case of heating) to very high (more than 1000 C in Iron and steel industry).

The most prominent and economically seem competitive of nuclear power in the non electric applications are nuclear seawater desalination and hydrogen production. Currently, a great focus will be made on the latest activities on H-production economy and technology presented during the Japan conference which was held in Oarai during the period of 16-19 April 2007. Other major topic to be addressed thoroughly during the conference will be nuclear desalination. Overall, scientists of more than 170 persons are expected to attend coming from over than 40 Member states of the IAEA. The conference will constitute a large forum to exchange information on the status of process heat applications of nuclear power including high-temperature as well as low temperatures applications.

Various presentations on ongoing interest in Member States in the development and application of small and medium sized reactors will also be presented. Many innovative designs for nuclear reactors within the small-to-medium size range will be addressed. Such reactors are expected to play a positive role in the fulfilment for the need of non-electric applications of nuclear power. Recently, more than 50 concepts and designs of such innovative SMRs were developed in Argentina, Brazil, China, France, India, Japan, the Republic of Korea, Russian Federation, South Africa, and the USA.

In order for nuclear energy to contribute effectively to future global energy supplies and sustainable development, its applications should be extended beyond electricity, particularly in the transport sector where oil now supplies 95% of transport demand. The most promising way that nuclear energy might provide energy for transportation is through the production of hydrogen, either for direct use in fuel-cell vehicles or to produce synfuels.

Hydrogen research is currently on the rise. Major automobile manufacturers have set ambitious targets for putting affordable fuel cell cars on the road, and significant governmental initiatives have been launched in the EU, the USA and Japan. Nuclear energy is part of these initiatives, but for nuclear energy to become a major future hydrogen supplier will require significant efforts in both reactor technology development and installing new infrastructures. Both challenges are best addressed through a global approach. Nuclear energy can also make a substantial contribution to a critical non-energy ambition – universal access to plentiful fresh water.

Currently about 2.3 billion people live in water-stressed areas and among them 1.7 billion live in water-scarce areas, where the water availability per person is less than 1000 m 3/year. By 2025 the number of people suffering from water stress or scarcity could swell to 3.5 billion, with 2.4 billion expected to live in water-scarce regions. Water scarcity is a global issue, and every year new countries are affected by growing water problems. The desalination of seawater using nuclear energy (either low temperature heat or electricity) is a demonstrated option. Over 200 reactor-years of operating experience with nuclear desalination have been accumulated worldwide. Several demonstration programs are underway, with technical co-ordination support from the IAEA, to confirm its technical and economical viability under country-specific conditions.

Nuclear desalination is most attractive in countries that both lack water and have the ability to use nuclear energy such as China, India and Pakistan. These three countries alone account for about 40% of the world's population, and thus represent a potential long-term market for nuclear desalination. The market will expand as other regions with high projected water needs, such as the Middle East and North Africa, increase their nuclear expertise and capabilities. In industrialized countries, where most of the world's installed nuclear capacity is today, well run existing NPPs can be quite profitable. New NPPs, however, are most attractive in countries where energy demand " Nuclear energy can also make a substantial contribution to a critical non-energy ambition – universal access to plentiful fresh water.

Advocates of nuclear energy for sustainable development argue that it is a well- established non-carbon technology, as demonstrated by its 16% share of the world's electricity supply and even higher share in specific countries – 78% in France for example. Moreover, it has huge growth potential. Its resource base – uranium and thorium – is substantial and has no competing application. Nuclear energy increases the world's stock of technological and human capital. It is ahead of other energy technologies in internalizing external costs. From safety to waste disposal to decommissioning – the costs of all of these are in most countries already included in the price of nuclear electricity. It avoids GHG emissions.

The complete nuclear power chain, from resource extraction to waste disposal and including reactor and facility construction, emits only 2-6 grams of carbon per kilowatt-hour, about the same as wind and solar power and two orders of magnitude below coal, oil and even natural gas. If we were to extend our consideration beyond nuclear fission to nuclear fusion, which is largely outside the scope of this article, some of these arguments would be even stronger. The resource base for nuclear fusion, for example, is huge. However, fusion is still at an experimental stage. It is unlikely to provide a substantial share of electricity to the grid before 2050, although it is a possible contributor to global energy supplies in the second half of the century.

Non-electric applications of nuclear power

About one-fifth of the world's energy consumption is used for electricity generation. Most of the world's energy consumption is for heat and transportation. Nuclear energy has considerable potential to penetrate these energy sectors now served by fossil fuels that are characterized by price volatility and finite supply. The newer applications using combined heat and power from nuclear reactors include seawater desalination, district heating, heat for industrial processes, and electricity and heat for hydrogen production.

Non-electric applications of nuclear energy have been considered since the very beginning of nuclear energy development. These have for various reasons not been deployed so far to a significant industrial scale. With the dramatic increase in oil and gas prices in the last few years and also due to rising concerns of the green house gas emissions and its impact on climate change, there is renewed worldwide interest in considering nuclear energy sources for the above applications for the energy and water security in a sustainable manner.

Recent statistics show that currently 2.3 billion people live in water stressed areas and among them 1.7 billion live in water scarce areas. The situation is going to worsen further in the coming years. Better water conservation, water management, pollution control and water reclamation are all part of the solution to projected water stress. So too are new sources of fresh water, including seawater desalination. Desalination technologies have been now well established and the contracted capacity of the desalination plants worldwide is about 37 million m3/d. Interest in nuclear desalination is driven by the expanding global demand for fresh water, by concern about GHG emissions and pollutions from fossil fuels and in developments in small and medium sized reactors that might be more suitable than large power reactors.

Nuclear energy is a clean, safe, and powerful greenhouse gas emission-free option to help meet the world's demand for energy. It has a still unexploited potential of producing, in the Combined Heat and Power (CHP) mode, process heat and steam in a broad temperature range. There is experience with nuclear in the heat and steam market in the low temperature range such as desalination, district heating, industrial heat and extension in short term is possible in the tertiary oil recovery. In the higher temperature heat/steam range, a significant potential for nuclear exists for hydrogen production and in the petro-chemical industries including the production of liquid fuels for the transportation sector. It still needs, however, a broader deployment of respective nuclear heat sources.

Experiences in last decades

Desalination has decisively proven during last 30 years its reliability to deliver large quantities of fresh water from the sea. Unlike oil, fresh water has no viable substitute. The sea is the unlimited source to create new fresh water through desalination. The future requires effective integration of energy resources to produce power and desalinated water economically with proper consideration for the environment. Since nuclear energy is nearly carbon free generation and is long-term sustainable solution and potentially competitive with fossil fuels, it is necessary to consider it as a choice for desalination projects.

The desalination of seawater using nuclear energy is a feasible and demonstrated option to meet the growing demand for potable water. There have been successful experiences in nuclear desalination at several plants in Japan (12 reactors since 1977) and Kazakhstan (1 reactor since 1973). Over 200 reactor-years of operating experience on nuclear desalination have been accumulated worldwide. Few demonstration projects for nuclear desalination are also in progress to confirm its technical and economical viability in India, Pakistan and Russian Federation. Many countries are showing interest in or going forward with nuclear desalination projects, for domestic use or for international cooperation, including Argentina, Canada, China, Egypt, France, India, Indonesia, Korea, Morocco, Pakistan, Russia and Tunisia.

Most countries suffering from scarcity of water are, however, generally, not the holders of nuclear technology, do not generally have nuclear power plants, and do not have a nuclear power infrastructure. The utilization of nuclear energy in those countries will require infrastructure building and institutional arrangements for such things as financing, liability, safeguards, safety, and security and will also require addressing the acquisition of fresh fuel and the management of spent fuel.

District heating has been widely used for decades in many countries, such as central and northern European countries and countries in transition economies. District heating accounts for 11% of total final energy consumption in Central Europe and Ukraine and over 30% in Russia and Belarus. District heating accounts for almost half of the heat market in Iceland, Estonia, Poland, Denmark, Finland and Sweden.

There is already 1000 reactor years of experience accumulated on district heating using nuclear energy in Russian Federation, Ukraine, Switzerland and central European countries. Economic studies generally indicate that district heating costs from nuclear power are in the same range as costs associated with fossil-fuelled plants. In the past, the low prices of fossil fuels have stunted the introduction of single-purpose nuclear district heating plants. However, as environmental concerns mount over the use of fossil fuels, nuclear-based district heating systems have potential.

There have been some experiences in providing process heat for industrial purposes with nuclear energy in Canada, Germany, India, Norway and Switzerland. In Canada, CANDU reactors supplied steam for industries such as food processing and industrial alcohol production until their closure in 1998. In Germany, the Stade PWR has supplied steam for a salt refinery located 1.5 km from the plant from December 1983 until its shutdown in November 2003. In Norway, the Halden Reactor has supplied steam to a nearby factory for many years. In Switzerland, since 1979, the Gösgen PWR has been delivering process steam to a cardboard factory located 2 km from the plant. In India, the RAPS PHWR at Kota has been supplying heat to the nearby heavy water plant.

Of potential future applications of nuclear process heat, one is the use of nuclear energy for oil sand open-pit mining and deep-deposit extraction in Canada. Alberta's oil sand deposits are the second largest oil reserves in the world, and have emerged as the fastest growing, soon to be dominant, source of crude oil in Canada. Coal gasification/liquefactions as a relatively cleaner fossil fuel source is an area of active interest. Production of synfuels and other hydrocarbons using nuclear heat is another area of greater promise.

Future prospects of nuclear energy applications

As an alternative path to the current fossil fuel economy, a hydrogen economy is envisaged in which hydrogen would play a major role in energy systems and serve all sectors of the economy, substituting for fossil fuels. Hydrogen as an energy carrier can be stored in large quantities, unlike electricity, and converted into electricity in fuel cells, with only heat and water as by-products. It is also compatible with combustion turbines and reciprocating engines to produce power with near-zero emission of pollutants.

Nuclear-generated hydrogen has important potential advantages over other sources that will be considered for a growing hydrogen economy. Nuclear hydrogen requires no fossil fuels, results in lower greenhouse-gas emissions and other pollutants, and lends itself to large-scale production. The current worldwide hydrogen production is roughly 50 million tonnes per year. Although current use of hydrogen in energy systems is very limited, its future use could become enormous, especially if fuel-cell vehicles would be deployed on a large commercial scale.

As a greenhouse-gas-free alternative, the U.S., Japan, and other nations are exploring ways to produce hydrogen from water by means of electrolytic, thermochemical, and hybrid processes. Most of the work has concentrated on high-temperature processes such as high temperature steam electrolysis (HTE) and the sulphur–iodine (SI) and calcium-bromine cycles. There are many ongoing national programmes aiming at the development of a hydrogen economy such as the Hydrogen Initiative of the United States, the European Hydrogen and Fuel Cell Technology Platform, and fuel cell/hydrogen programmes in Japan and Korea. There are also various international efforts for the realization of a hydrogen economy.

In recent years, various agencies involved in nuclear energy development programmes worldwide have carried out studies on advanced applications of nuclear power.

- The IAEA launched a programme on co-generation applications and has published two TECDOCs (923 and 1184) and a Guidebook on Introduction of Nuclear Desalination (TRS-400) in 2000. IAEA also published a report in 2002 on the Market Potential for Non-electric Applications of Nuclear Energy (TRS-410).

- The Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency carried out a comprehensive survey of published literature on the non-electric applications, including reports from international organizations, national institutes and other parts of NEA and published a report summarizing the findings and recommendations.

- The Generation IV International Forum (GIF) project aims at development of innovative reactors with temperatures up to 1000^{o}C. The GIF road map recommends necessary R&D.

- The Michelangelo Network (MICANET) started within the 5th EUROATOM has been examining the role of nuclear energy in near and medium term missions; i.e. the transition phase from the present fossil era to CO_2 emission-free technologies in the future. The programme results were reported in November 2005 as a work package on “Non-electric application of nuclear energy”.

Nuclear heat applications have been considered for long time, but not much has succeeded. Effective and practical measures to gain the advantages of aspects of climate change / green house gas reduction need to be taken now. Nuclear technology and its related institutions should advance and address to the real world as other technologies and environmental institutions do. Practical application would be possible based on exchange of experiences and further international collaboration.

In considering the deployment of nuclear energy into newer potential applications, challenges and difficulties should not be overlooked. Moving from their potential to realities is undoubtedly feasible, but will need time, investments, and policy measures to address a wide range of techno-economic and socio-political challenges. Public acceptance is a major issue for nuclear energy. Non-electric applications of nuclear energy can play an important role in enhancing public acceptance.

IAEA’s roles and programmes and likely future direction

Various utilization of non-electrical applications of nuclear energy i.e. high and low temperatures of nuclear produced steam such as seawater desalination; hydrogen production; district heating; and other industrial applications, has been drawing broad interest in IAEA Member States. The IAEA has an active programme for supporting these activities. For example, the IAEA supports the demonstration of nuclear seawater desalination in the Member States through various activities including the optimization of the coupling of nuclear reactors with desalination systems, economic research and assessment of nuclear desalination projects, development of software for the economic evaluation of nuclear desalination plants as well as fossil fuel based plants (DEEP). It also provides training to interested Member States in the above areas. It cooperates with various international organizations involved in promoting major activities such as seawater desalination and hydrogen production.

As nuclear desalination is a very rapidly evolving field, more and more countries are opting for dual purpose integrated nuclear desalination systems, the need for R&D efforts to improve the hard technology on the one hand and the calculation methods on the other hand would also evolve asymptotically. The need for advances in technologies leading to more efficient and economic systems is obvious. What is still not commonly perceived is the need for advanced calculation methods for nuclear desalination systems. These, like in any other technology, are a pre-requisite to the conception of advanced systems. Yet another, more important requirement for more precise methods of calculations is the need by decision makers in many countries to access reliable and accurate information regarding the performances and economics of the proposed systems. Therefore, the IAEA is launching a new CRP on some specific advances in the field of nuclear desalination technologies which will be implemented in the forthcoming cycle (2008-2011). This new CRP will focus on integrating further activities on DEEP.

The IAEA's DEEP computer code has been widely used by engineers and researchers for preliminary economic evaluation of desalination (by a wide range of fossil and nuclear energy sources, coupled to selected desalination technologies). Various development stages, drawbacks, and achievement were presented and analyzed. Rational for the current activity and expected outcomes were discussed.

The IAEA has already started a CRP on Advances in nuclear power process heat Applications. The objective of the CRP is to evaluate the potential of all advanced reactor designs in process heat applications. Indeed, global concern over growing populations, peaking reserves of fossil fuels and greenhouse emissions associated with them, is driving the increased interest in nuclear power process heat applications, such as hydrogen production and seawater desalination. High Temperature Gas Cooled Reactors (HTGRs) are poised to play a potential role due to their high temperature output of 850-950 ºC, which improves hydrogen production efficiency and their available and free waste heat, which lowers the cost of thermal desalination. In parallel, there has been increasing interest and new research aiming at overcoming efficiency limitations at lower process temperatures, which would improve the potential of other reactor designs of lower temperature capacity, in process heat applications. Therefore, the challenges to be addressed by this CRP are related to process technologies, coupling safety, high temperature material technology and the economic merits of centralized or distributed production units.

The International Atomic Energy Agency (IAEA) is developing software to perform economic analysis and scoping studies related to hydrogen production. The software is expected to be based on few of the most promising processes for hydrogen production such as: high and low temperature electrolysis, thermochemical processes including S-I process, and typical conventional methods applicable for high and low temperature processes of hydrogen production. In addition, HEEP is expected to include conventional electrolysis and steam reforming for comparison purposes with nuclear hydrogen production. Furthermore, the HEEP software is expected to be building on other many activities on hydrogen production and cost assessments within the hydrogen economy.

HEEP is expected to be similar to the IAEA software DEEP which is being used to perform economic analysis and feasibility studies related to nuclear desalination in the IAEA and other Member States. It is expected that HEEP will have similar architecture to DEEP but with the possibility of easy update and future expansion. This HEEP development was initiated following a technical advisory meeting in September 2007. The meeting has helped catalyze the activities in many countries towards the development and testing of the HEEP software. The meeting covered:

- Design aspects of high temperature nuclear reactors suitable for hydrogen production;
- Most promising hydrogen production processes;
- Allocation of cost of hydrogen production using high temperature reactors;
- Available models for the production and delivery of hydrogen;
- Assessment of hydrogen economy

Among other future direction of the IAEA activities on non electric application of nuclear power will include: support to demonstrate nuclear desalination projects, enhance safety aspects of integrated nuclear desalination systems as well as nuclear hydrogen facilities, addressing the socio and environmental impacts of non electric applications of nuclear power, and continuing the validation/development of software for the economic evaluation of desalination technologies and hydrogen production. This will be achieved through technical meetings on non electric applications of nuclear energy in major areas such as desalination and hydrogen production, information exchange on advances in nuclear desalination technologies, addressing status of nuclear desalination; hydrogen production processes; district heating; as well as other industrial applications, and safety issues. The results of such activities will be published as technical reports.

OUTLOOK FOR NUCLEAR POWER AND THE FUTURE OF PROCESS HEAT APPLICATIONS

(SESSION 1) (Plenary)

Chairpersons

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Nuclear energy outlook

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Abstract. The paper presents the world energy outlook and discusses the prospects of nuclear power. The global energy demand for the next 25 years has been presented for OECD countries, developing countries and the transition economies. Two scenarios; the reference scenario with the current trends and the alternative policy scenario have been discussed. The latter takes in to the account the likely policy changes as a result of climate change and initiatives to be undertaken by the countries to address it. The paper also describes the NEA activities on nuclear energy and its non-electric applications. The economics of power production using nuclear and fossil fuels are compared.

1. Introduction

The World Energy Outlook 2006 (IEA) is discussed in this paper from present to the year 2030. Oil, coal and gas remain the major energy sources. However the contributions of biomass, nuclear and renewables are likely to increase. In the reference scenario, global demand will grow by more than half over the next quarter of a century, with coal use rising most in absolute terms. World oil demand will grow by just over half between 2004 and 2030. Oil remains by far the most heavily traded fuel, but trade in natural gas will expand faster. World electricity demand will double between 2004 and 2030. Most of the additional demand for electricity is expected to be met by coal, which remains the world's largest source of electricity up to 2030.

Alternative Policy Scenario (APS) envisages global savings in energy-related CO_2 emissions. Improved end-use efficiency of electricity & fossil fuels accounts for two-thirds of avoided emissions in 2030. More favourable policies on nuclear could significantly accelerate the growth in global capacity especially in OECD countries. Electricity supply investments are lower than in Reference Scenario, but renewables and nuclear investments are higher. Over a quarter of global electricity comes from renewable energy sources in 2030 in APS. A dozen policies in the US, EU & China account for around 40% of the global emissions reduction in 2030 in the Alternative Policy Scenario. The share of nuclear power drops much less than in the Reference Scenario (RS), helping to curb emissions growth

2. Energy outlook scenarios

In the reference scenario, global demand will grow by more than half over the next quarter of a century, with coal use rising most in absolute terms. World oil demand will grow by just over half between 2004 and 2030 (Fig 1).

Reference Scenario:
Primary energy demands

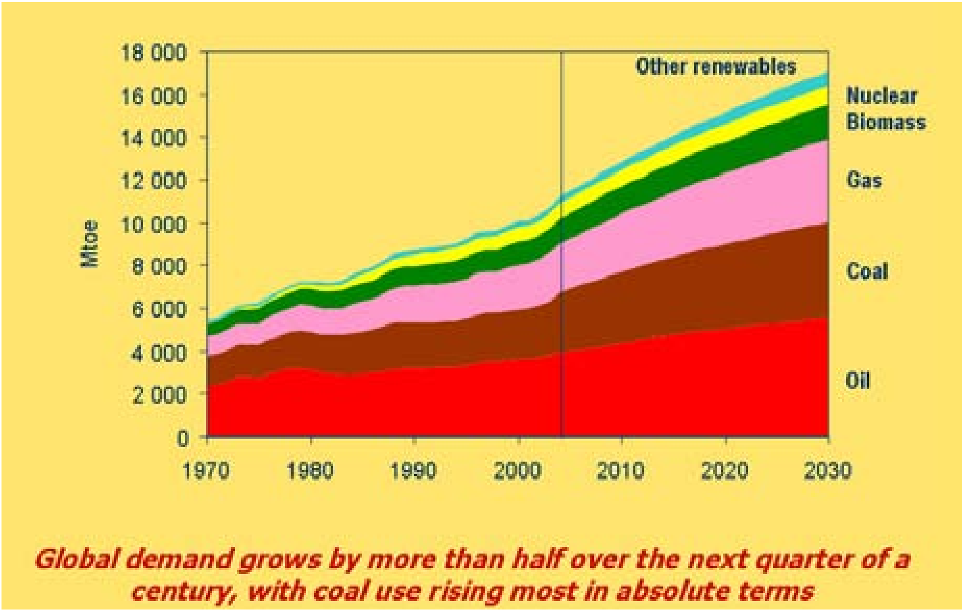

FIG. 1. World primary energy demand.

As shown in Fig. 2, most of the primary energy demand will come from developing countries.

Reference Scenario:
Primary Energy Demand by Region

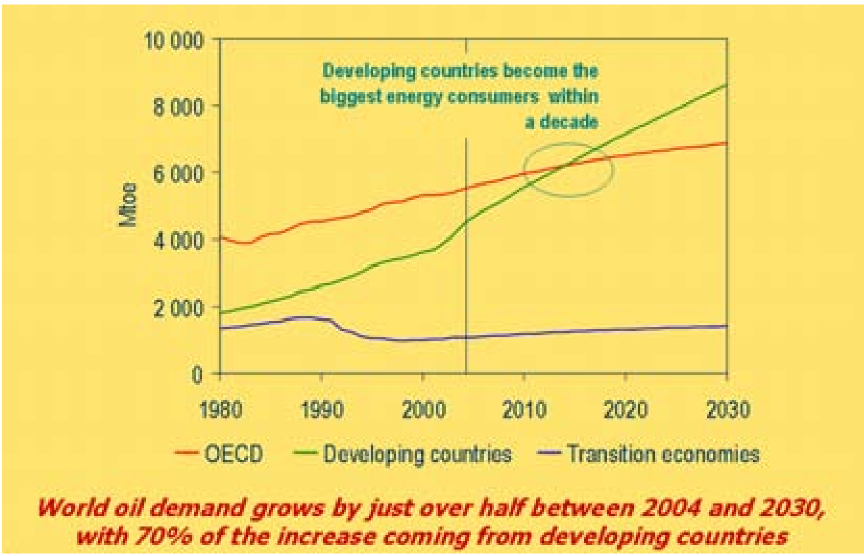

FIG. 2. Primary energy demand by region.

The world electricity demand by region is shown in Fig. 3. World electricity demand will double between 2004 and 2030. As can be seen, the demand in the developing countries triples during the period. Most of the additional demand for electricity is expected to be met by coal, which remains the world's largest source of electricity up to 2030.

Reference Scenario:
World electricity demand

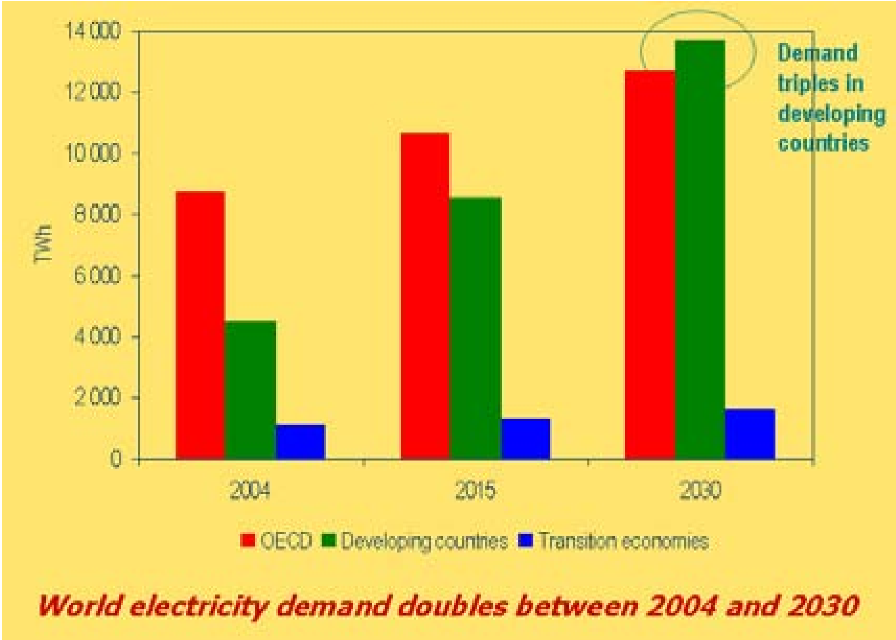

FIG. 3. World electricity demand by region.

With the increasing use of energy, there is consequent increase in CO_2 emission as shown in Fig. 4 for different regions. US and rest of OECD emissions increase gradually but the rest of non OECD emissions grow rapidly. China overtakes the US as the world's biggest emitter before 2010, though its per capita emissions reach just 60% of those of the OECD in 2030.
Reference Scenario:
Energy-Related CO_2 emissions by Region

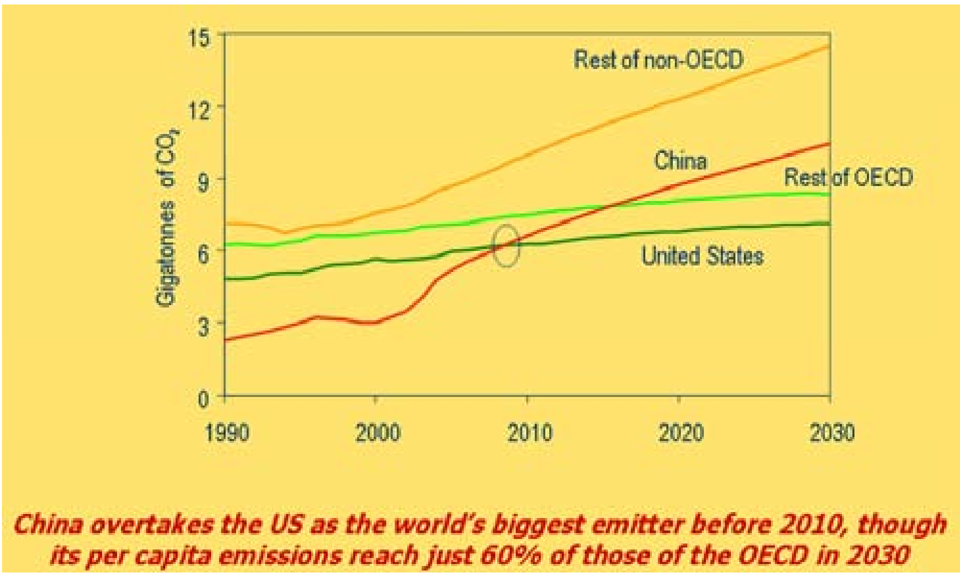

FIG. 4. CO_2 emission of the three regions along with the United States of America.

3. Prospects for nuclear power

Nuclear power with installed capacity of 370 GWe contributes 16% of worldwide power. The times are changing however due to concerns on rising of fossil fuels prices, security of energy supply (and diversity) and climate change. More favourable policies on nuclear could significantly accelerate the growth in global capacity especially in OECD countries

3.1. Nuclear in the energy world scene

The following were the major events
- World Energy Council – Sydney (9/04)
- "Keep all energy options open"
- No technology should be idolised or demonised
- IAEA Ministerial Conference – Paris (3/05) with OECD & NEA
- Greenpeace Co-Founder calls Nuclear Power "Environmentally Safe and Sound" (4/05) US Senate Energy and Natural Resources Committee
- Recent developmnts in Finland, France, USA, China, India, EC
- Role of GIF, INPRO, GNEP,

Figure 5 shows world nuclear capacity in the reference and alternative policy scenarios from 2005 to 2030 for OECD, transition economies and developing countries.

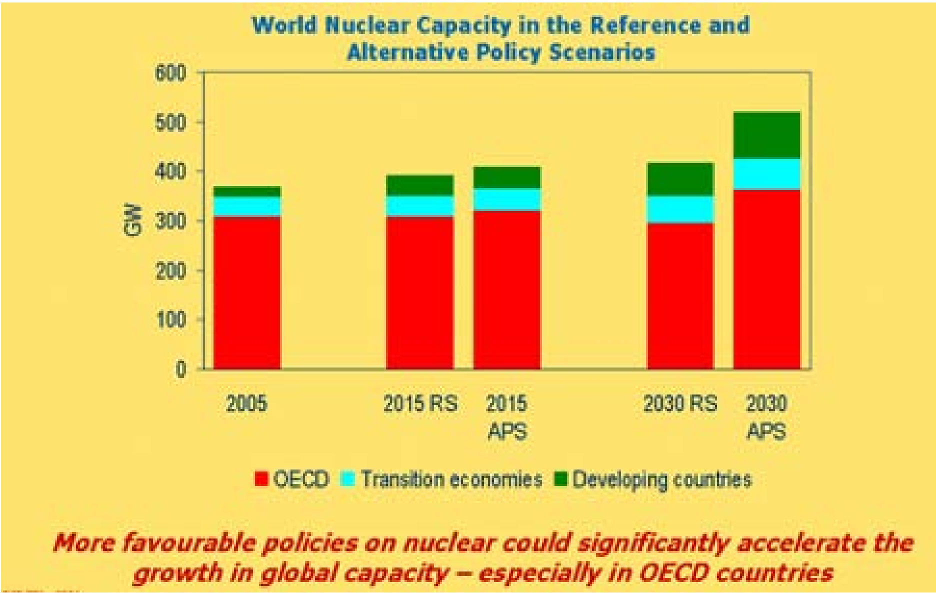

FIG. 5. World nuclear capacity in the reference and alternative policy scenarios.

3.2. Nuclear energy main features

Nuclear energy main features are: mature technology, nearly carbon-free electricity generation source, stable cost and low marginal cost, geopolitical distribution of uranium resources and domestic source of energy. Currently, 16% of world electricity is generated by nuclear power plants. There are 442 nuclear reactors operating in 33 countries. The existing power plants are very competitive; their load factors have remained very high. Upgrading of plant capacities in many cases have also taken place. A number of older reactors are scheduled for life- time extension as it is found economical. Nuclear power production is now a mature technology. Gas-fired electricity is no longer the cheapest form of generation; gas prices assumed to remain between 6 and $9 per Mbtu and even more.

As is known, the most significant aspect of nuclear power is its lesser sensitivity to the uranium fuel cost compared to fossil fuel based power. Fig 6 shows the cost of electricity due to doubling of both types of fuel cost. The cost of nuclear power increases only 5% compared to 75% for gas fired plant.

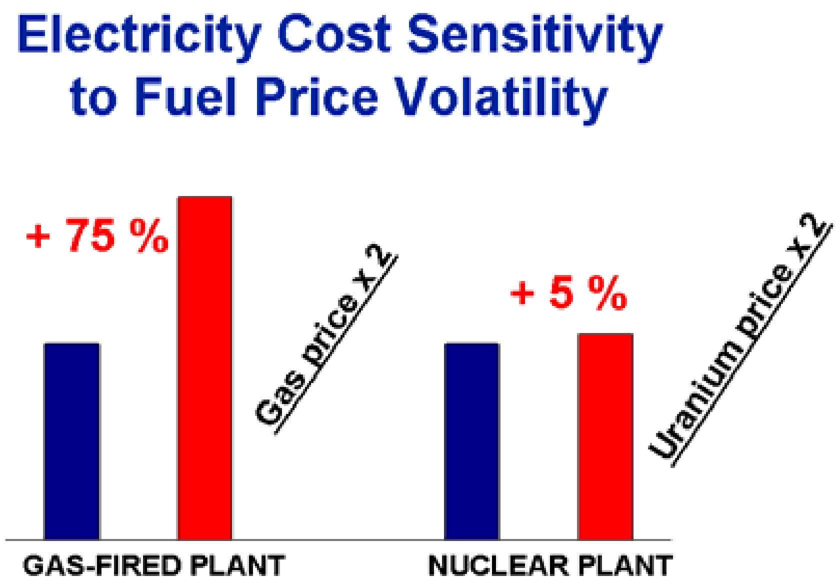

FIG. 6. Electricity cost sensitivity for gas fired and nuclear plant

Figure 7 shows the power generation cost using different fuel sources. While nuclear and gas based plant produce power at nearly similar cost, the coal base plants are the cheapest source of power production.

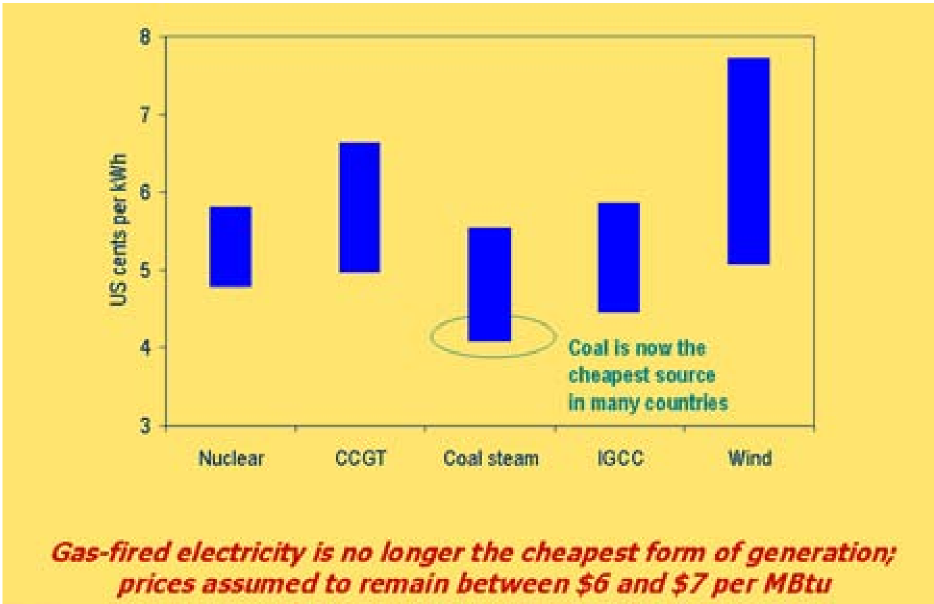

FIG. 7. Gas-fired electricity is no longer the cheapest form of generation; prices assumed to remain between $6 and $7 per Mbtu.

3.3. Generation-IV International Forum (GIF)

NEA acts as technical secretariat for GIF. The salient aspects of NEA's programme on non-electric applications, particularly hydrogen are as follows:

- Hydrogen production:
  - R&D activities and exchange of information are performed with the VHTR system project
  - Processes applicable to systems other than VHTR are also included
  - 6 (and possibly 7) organisations participate in the project

- Hydrogen production objectives:
  - developing and optimising the thermochemical water splitting processes of the sulphur family
  - advancing the high-temperature electrolysis process
  - evaluating alternative processes
  - defining and validating technologies for coupling reactors to process plants

Conclusions

There are no ideal or magic solution to avoid the unclean, uncertain and expensive energy in near future as the present trends indicate. All energy technologies will be therefore needed in the years to come. As far nuclear is concerned, uranium resources are available for exploitation of nuclear energy and advanced nuclear technologies are developed/ are under development. From a sustainable development perspective, nuclear energy has a major role to play in terms of reduction of CO_2 emissions, security of energy supply and diversification of supply and price stability.

IAEA activities in support of rising expectation for the role of nuclear power and its non-electric applications

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Abstract. The paper describes the IAEA activities supporting the Member State's programme on development of nuclear power. The ongoing trends in nuclear power worldwide and near term planned expansion in many countries are highlighted. With the rising expectations of strong growth in nuclear power in the coming years worldwide, the Agency's role in providing assistance to those countries, which are planning to introduce nuclear power or intend to extend their nuclear fleet, has been discussed. These include support to infrastructure building, technical cooperation for new projects on specific request from interested MSs, workshops and conferences. The Agency's increased scope of interest including activities on non-electric applications of nuclear power has been indicated.

1. Introduction

Worldwide there are 435 nuclear power plants in operation, which have shown excellent technical, economic and safety performance records during the last decades. The growing awareness of the need for environmental protection together with a recognition of energy supply security that nuclear power is offering has lead in many parts of the world to renewed discussion about the nuclear power option to meet increasing energy and electricity demands, particularly in developing countries. The IAEA has reflected this new trend of rising expectation in its programme by putting emphasis on assistance to those countries, which are planning to introduce nuclear power or intend to extend its capacity. More recently the Department of Nuclear Energy has increased its scope of interest and included activities on Non-electric Applications of Nuclear Power. This conference is the first major event within this new scope.

The mission of the Nuclear Energy Department of the IAEA is to catalyze innovation for sustainable development, to support existing nuclear power programmes, to achieve excellence, to assist new countries in their introduction of nuclear power through build up of necessary infrastructure, and to improve national capability in nuclear power development, deployment and operation. The IAEA programme is based on three pillars: Science and Technology; Safety and Security; and Verification. IAEA and the nuclear community would have three priorities: First to ensure protection when nuclear energy is used to produce electricity, for district heating, desalination or hydrogen production, it is used safely, securely, and with minimal proliferation risk. Second, to ensure continued technological innovation for improved economic viability, enhanced safety, security and proliferation resistance. Third, to ensure that the needs of developing countries are taken into account.

2. On-going trends in nuclear power

2.1. Current worldwide nuclear generating capacity

(a) Commercial NPPs in operation 435 (~ 370 GWe)
(b) Share of nuclear electricity 16%

2.2 Observed slowdown of capacity addition since late 80's

(a) Electricity market deregulation
(b) Slow growth of electricity demand in advanced countries
(c) Public perception
(d) Economic reforms in Russia and East European countries

2.3. Current expansion in Asia/East Europe

Table I presents the near term ambitious deployment plans in Asia and Eastern Europe.

Table I. Ambitious near-term expansion plans

Current	Near-Term Expansion Plan
(Asia)	
China 7.6 GWe (2.0%)	40 GWe (4%) by 2020 × 5
…2x 1000 MWe plant/year	
India 3.5 GWe (2.8%)	29.5 GWe (10%) by 2022 × 8
ROK 16.8 GWe (44.7%)	26.6 GWe by 2015 × 1.6
Pakistan 0.4 GWe (2.8%)	8.5 GWe by 2030 × 20
(Eastern Europe)	
Russia 21.7 GWe (15.8%)	40 GWe (25%) by 2020 × 2
Ukraine: 13.1 GWe (48.5%)	20-22 GWe by 2030 × 1.5

2.4. Rising expectation

Figure 1 shows the countries having nuclear power (NPs) and most importantly those considering NPs and planning massive expansion of their capacities.

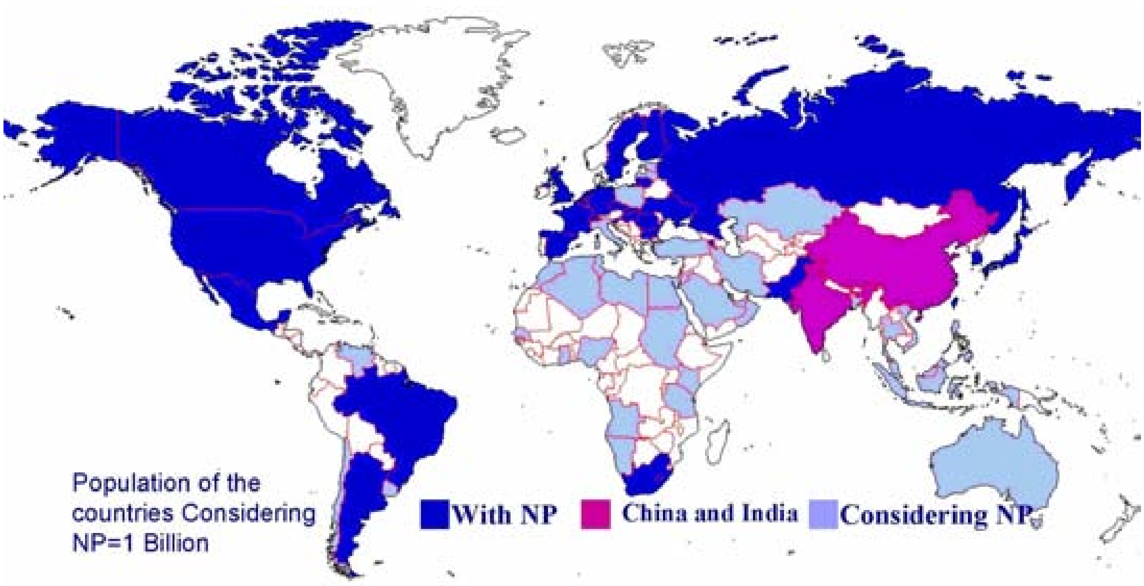

FIG. 1. Increasing number of countries thinking of introduction of nuclear power.

IAEA's role

The IAEA has put emphasis in recent years in providing assistance to those countries, which are planning to introduce nuclear power or intend to extend their nuclear fleet. The activities include various subjects, such as methodology development, information sharing through documents, databases and meetings and the fostering of coordinated research.
These also include support to infrastructure building, technical cooperation for new projects on specific request from interested MSs, workshops and conferences. The Agency has recently increased scope of interest including activities on non-electric applications of nuclear power. Specific support are also directed on the following activities.

3.1. Support to infrastructure building
The required infrastructure includes legal and regulatory frameworks, human resources development, physical facilities and equipments associated with delivery of electricity and so on. Since these topics are addressed by different departments within the IAEA, it has established inter-departmental coordination group to assure coordinated response.

3.2. Guidance for the introduction of nuclear power and for development of infrastructure

— Numerous guidance documents
— Filling in gaps & updating guidelines

3.3. Institutional issues

Assurance of supply, Financing, Licensing

4. Relevant ongoing/planned activities
Some of the current relevant ongoing/ planned activities are;

4.1. Technical cooperation project for new build in response to specific request from Member States
— Current : 6 TCP including coupling with desalination
— 2007-08 : 12 countries plus regional projects
— IAEA team visits (Nuclear Power, Energy Planning, Legal, Safety, TC) to establish coordinated work plan

4.2. Workshops and conferences
(a) "Issues for the Introduction of Nuclear Power" (Dec2006)
(b) Relevant workshops being planned, including;
  (i) Design evaluation: October 2007
  (ii) Milestone document: November 2007
  (iii) Financing: 2007-08 2^{nd} Ministerial Conference on Nuclear Power in the 21^{st} Century: 2009 in China

4.3. *Support to INPRO programme of the MSs*

IAEA has been the nodal Agency for INPRO and facilitates information exchange between the Member States who have undertaken development of future generation innovative reactors. 24 MSs are presently participating in this programme. Figure 2 shows the salient features of the INPRO activities. This programme is extra budgetary and has the support of many MSs offering cost free experts for implementation of the programme activities.

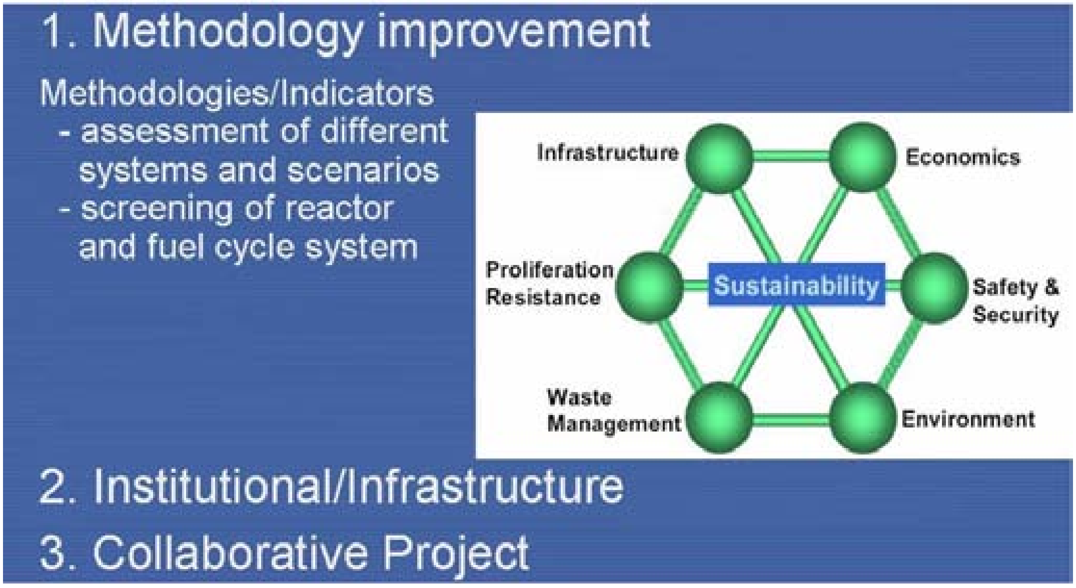

FIG. 2. INPRO (International project on Innovative Nuclear Reactors and Fuel Cycles) activities.

5. Non-electric applications

The linkage between climate change and human activities is increasingly considered as more probable. Use of nuclear energy has so far been almost entirely limited to electricity production. However due to prospect of production of oil tapering out in the next 20 years, increasing global demand for potable water and concerns for climate change due to excessive GHG emissions from fossil fuels, interest in non-electric applications of nuclear energy has grown worldwide. The nuclear power plants can provide in addition to electricity, hydrogen, process heat and desalinated water. Nuclear energy can also help in chemical energy production, recovery of oil from tar sand, sweetening by adding hydrogen, coal liquefaction with nuclear hydrogen

More recently the Department of Nuclear Energy of IAEA has increased its scope of interest and included new activities on Non-electric Application of Nuclear Energy. Some key development issues and planned programme changes for 2008-09 in the IAEA's programme A (Nuclear Power) are as follows:

(a) Focus more on key developing issues:
- — Plant life management
- — Response to rising expectation
- — Technology innovation

(b) Programme changes (planned for 2008-09)
- — A3 : Support to infrastructure building in Member States

— A6 : Non-electric applications

(State-of-the-Art Report on technology, economic evaluation, issues of coupling with nuclear systems, CRP)

(c) Dual use: also in other sub-programmes (ex. SMR)

6. Summary

The following are the highlights of this paper.

(a) Globally growing interest to the role of nuclear power

(b) Growing interest from countries without NPPSupport to developing country's infrastructure building, under inter-departmental coordination,

(d) Agency's programme for non-electric applications. Driven by global trends and needs

Non-electric applications of nuclear energy — Possible scenarios and their effects: The case of Japan

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Abstract. Utilization of nuclear energy in non-power application is rational desire to prevent further environmental distortion by massive use of fossil fuels. There have been a lot of efforts toward related developments in Japan as well as the other countries such as nuclear propelled ships, nuclear heat utilization in hydrogen production, etc. Brief related history and accomplishments in Japan are summarized in this paper. Recent analysis on possible applications of high temperature gas cooled reactor for non-power usage is described. One of the possible applications is hydrogen production by thermochemical water decomposition process for transportation market with fuel cell vehicles. Application in the industrial parks as heat and power source was surveyed to replace old existing units. Possible introduction to local hydrogen energy park concepts is discussed. Finally possible scenarios and its effects by non-power application of nuclear power are discussed.

1. Introduction

JAIF Committees on Nuclear Heat Application were established as early as in 1969. A number of useful publications were made covering the subject of industrial uses of nuclear heat, uses of LWR and HTR heat and contribution towards global environment protection. These cover the following areas;

- "Industrial Uses of Nuclear Heat"
  (Steel, Chemicals, Desalination)
- "The Uses of LWR and HTR Nuclear Heat"
  (Coal liquefaction and gasification, Hydrogen production, etc.)
- "The Contribution toward Global Environment Protection"
  (Hydrogen production and CO_2 recycle / application to steel industry, Cogeneration, Clean energy from fossil fuels)
- Interim Report: "The Study on HTR Future Perspective"

Figure 1 shows the temperature range of required heat for various industries based on a survey conducted in 1970's.The district heating and desalination required low temperature heat easily available from present day reactors and hence these have been demonstrated in many countries. The rest of applications would require high temperature reactors, which are still under development.

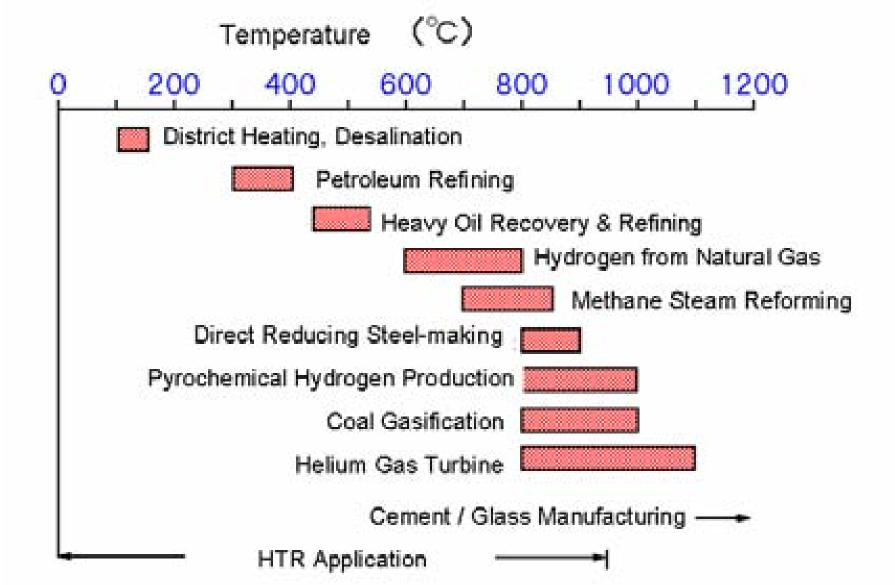

FIG. 1. Temperature range of required heat for various industries (based on survey in 1970's).

2. Industrial use of nuclear heat

Figure 2 shows photographs of the desalination plants at some of the Japanese reactors and also their capacities. These plants are successfully operating since 80's and meeting the water needs of the reactors and also for in house use.

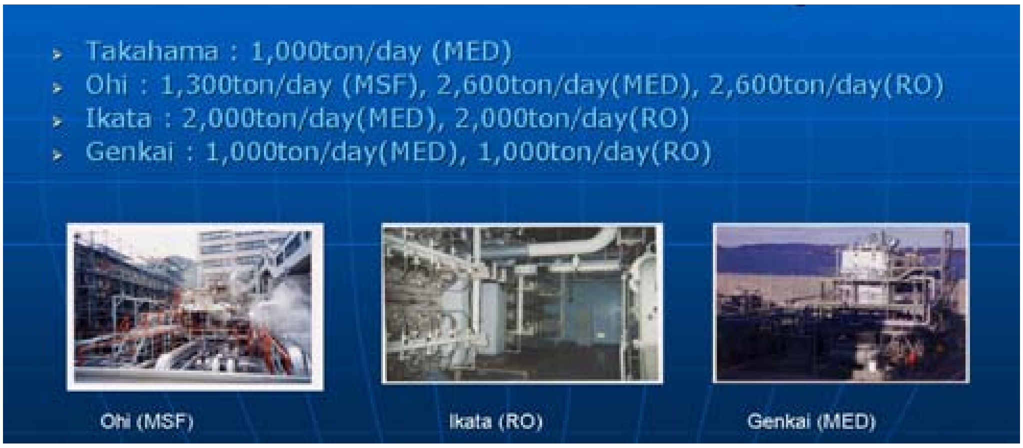

FIG. 2. Operating desalination systems in Nuclear Power Plants in Japan.

3. High temperature reactors

The global development of high temperature gas cooled reactors beginning since 60s and plans up to 2020s and beyond is shown in Fig. 3 The figure also shows the Japanese programme on HTTR and the future Gen-IV type reactors.

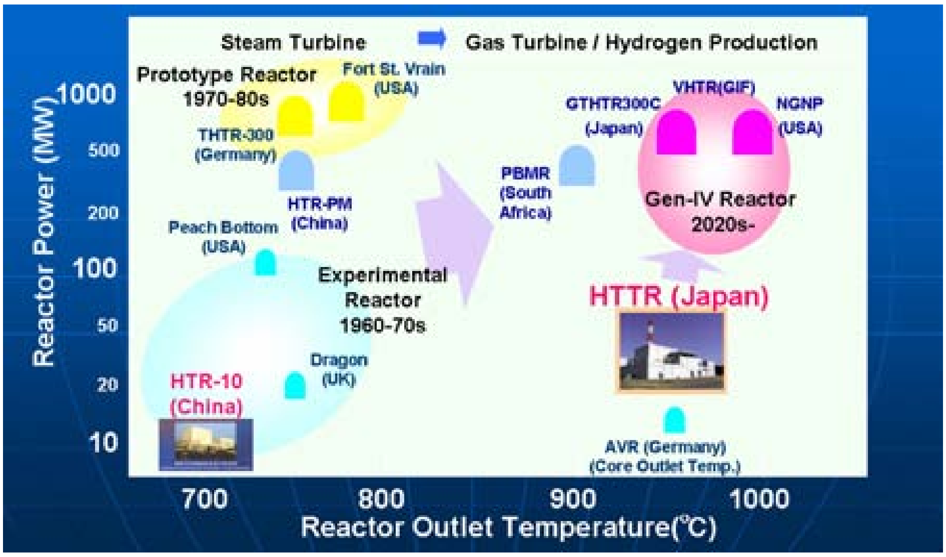

FIG. 3. High temperature gas-cooled reactor development.

3.1. VHTR deployment scenarios and R&D roadmap in Japan

Objectives

- Propose promising VHTR applications and utilization systems
- Estimate possible fossil energy savings and CO_2 reduction
- Identify technological gaps for practical use

– Promote governmental support and potential users
– Cogeneration System of VHTR hydrogen production system

Outline of VHTR Deployment Scenarios:

600 MWt, Outlet Temperature. 950 deg C, Cogeneration, Operation starts 2040
Salient economy, Inherent safety, Broad use of nuclear heat
No emission of CO_2

An artist view of the VHTR hydrogen production system is presented in Fig 4 The reactor power plant and the Iodine-Sulphur (I-S) hydrogen plant with various facilities are shown in separate buildings.

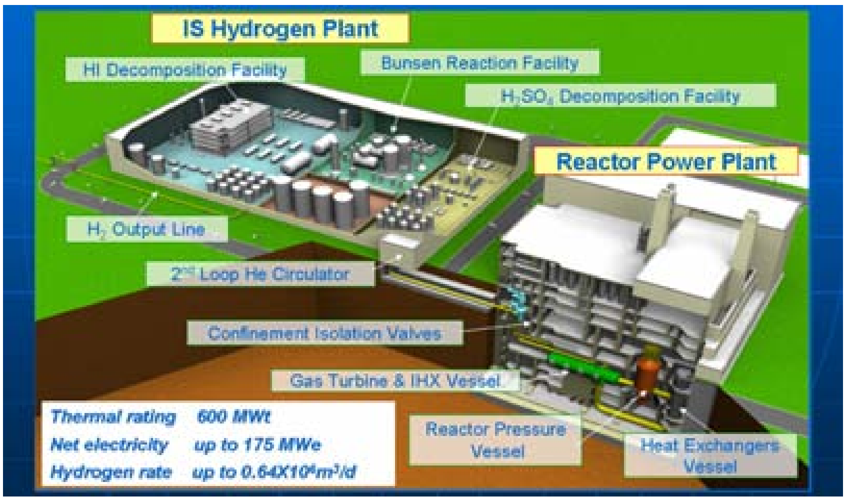

FIG. 4. Cogeneration system of VHTR hydrogen production system.

3.2. *Scenario for FCVs*

The vision for the Fuel Cell Vehicles (FCVs) scenario in Japan is shown in Fig.5 In the figure, the deployment schedule aims to deliver a demonstration plant by 2030 and commercial plants ten years later by 2040. It forecasts the building of one unit for every two years of construction, leading to about 30 units by the year 2100. It is further forecasted that the VHTR can supply hydrogen at the rate of 400 Mm^3 per unit per year, leading to 400,000 FCVs in 30 units which is 27% of total FCVs by 2100 in Japan. This is a very ambitious target of 15 million FCVs by the year 2030.

Use of VHTR in the transportation sector can contribute greatly to environmental protection and energy security.

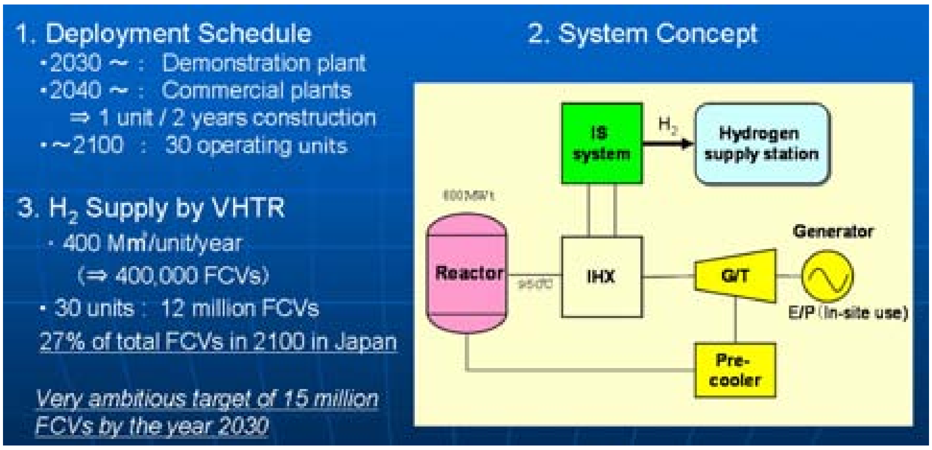

FIG. 5. The scenario for FCV (1/2).

3.3. *Scenario of hydrogen town*

Aomori Prefecture has a strategic plan to promote local use of hydrogen. By 2030 VHTR demonstration plant for hydrogen production 30 VHTRs do not affect future Japanese uranium demand much. This plan presents no deviation from the official fuel cycle policy of Japan.Technological subjects necessary to realize the VHTR deployment scenarios have been submitted from the industry. JAEA should take an initiative for steady promotion of VHTR research and development.

Figure 6 depicts the scenario of hydrogen town and the possible target date.

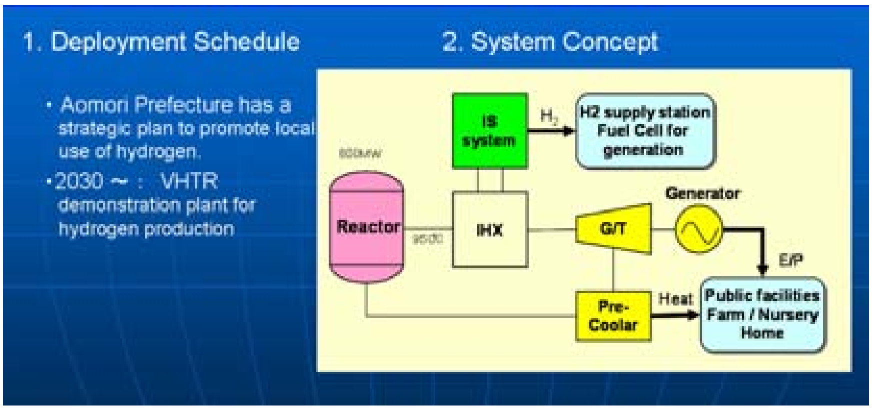

FIG. 6. The scenario for "hydrogen town".

Use of VHTR in the industrial sector, to be a “Nuclear Boiler”, can contribute greatly to environmental protection and energy security.

4. Remarks

In author’s opinion, nuclear heat applications have been considered for long time, but not much has succeeded. Effective and practical measures to gain the advantages of aspects of climate change/green house gas reduction need to be taken now. Nuclear technology and its related institutions should advance and address to the real world as other technologies and environmental institutions do. Practical application would be possible based on exchange of experiences and further international collaboration.

I have a dream. Someday we can develop fully nuclear capacity for human survival on this planet.

Potential for nuclear process heat application

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Abstract. Since more than five decades, nuclear power is being used for commercial electricity generation. There is, however, also a large potential in the non-electric market, where nuclear energy has currently only little penetration. Many industrial sectors have a high demand for process heat and steam at various levels of temperature and pressure to be provided for different industrial processes. All Gen-IV concepts proposed are designed for coolant temperatures above 500°C, which principally allow applications in the low and medium temperature range. Most industries need to rely on a secure and economic supply with energy to guarantee continuous and reliable operation of their process units. A modular arrangement of several units will be necessary for redundancy, reliability and reserve capacity reasons which again reduce power size per modular unit. For nuclear process heat plants in close vicinity to the site of application, conceivable event scenarios characterized by interacting influences must be taken into account. The main challenge at present is to include nuclear CHP applications into the general strategies. In the low temperature heat market, typical examples of nuclear applications are district heating or seawater desalination, both with some experience, but still lacking the large-scale demonstartion. In the area of high temperature heat demand, the chemical and petrochemical industries offer ideal chances of CHP market penetration by nuclear power with near-term prospects.

1. Introduction

Despite energy saving efforts and improved efficiency of energy production, projections of the World Energy Council indicate a significant increase in global energy consumption in the mid and long term due to a further growing world population and rising prosperity, particularly in the developing countries where a further increase by 50 % in the next two decades is predicted. Among the non-fossil energy alternatives, whose use must be enhanced to curb the trend of man-made global warming, nuclear energy may emerge as one of the most significant carbon-free sources and contribute to a more secure energy world.

Nuclear energy has demonstrated already over many years a high level of safety and reliability. The next, fourth generation of nuclear reactors (Gen-IV) is expected to lead to innovative systems with more inherent and passive safety features. It may offer socially acceptable, environmentally benign and competitive solutions of the world's energy problems by addressing the areas of safety and reliability, proliferation resistance and physical protection, economics, sustainability [1]. At present, nuclear power is almost exclusively used for electricity generation and accounts for 16% of the world's (~370 GW as of 2006), or 25% of the OECD countries' demand. On the other hand, electricity represents less than a third of the final energy which is dominated by the heat and transportation market. The heat market has a variety of aspects to be taken into account such as type of (fossil) fuel, power size, temperature level, load factor, handling, storability, distance to customer, or environmental friendliness. By far most of the final energy consumption is in the low temperature range. The industrial demand for heat above 400°C is significant in the chemical industries, the steel and iron industries, as well as for the treatment of non-metallic minerals (ceramics, glass).

2. Nuclear energy for power and process heat production

2.1. *The next generation of nuclear reactor*

It is more than 50 years ago that in 1954 the first commercial nuclear power station, Obninsk in the former USSR, started its operation. Since then nuclear power has developed to an industrially mature and reliable source of energy and to a key component in the world's energy economy. Although from the beginning, nuclear was also used in multi-purpose reactors for cogeneration of heat, its principal use is presently as base load power plants for electricity production. Future nuclear power plant (NPP) designs will have to be much more flexible to be adjustable to multiple needs in terms of both size (including small and medium) and application, i.e., the expansion of the market potential to the wide fields of cogeneration of electricity and heat (CHP) and of non-electric applications like process heat provision for chemical processes (synfuel production), desalination, district heating, etc., but also destruction of existing Pu stockpiles and transmutation of radiotoxic waste.

A new, perhaps revolutionary nuclear reactor concept of the next generation will offer the chance to deliver besides the classical electricity also non-electrical products such as hydrogen or other fuels [1]. In a future energy economy, hydrogen as a storable medium could adjust a variable demand for electricity by means of fuel cell power plants ("hydricity") and also serve as spinning reserve. Both together offer much more flexibility in optimizing energy structures. Prerequisites for such systems, however, would be competitive nuclear hydrogen production, a large-scale (underground) storage at low cost as well as economic fuel cell plants [2].

There are many industrial sectors such as paper and pulp, food industry, automobile industry, textile manufacturing etc., which have a high demand for electricity and heat/steam at various levels of temperature and pressure, where nuclear energy specifically from HTGRs could play a major role in future [3, 4, 5]. The data elaborated for different CHP applications in EU clearly show that unit sizes of some hundred MW are sufficient. The main challenge at present is to include nuclear combined heat and power applications into the general strategies and to establish transition technologies from present industrial practice or emerging new resources ("dirty fuels") in order to stabilize energy cost.

2.2. Requirements

In principle, any type and size of nuclear reactor can be used as heat source for various processes. Different types of nuclear reactors provide a different range of coolant temperatures. The higher the temperature, the larger is the range of applications and products, respectively. Light Water Reactors (LWR) because of their lower temperature level of < 320°C, allow steam production at a lower quality only; therefore they are principally used for electricity generation with occasional steam extraction. Coolants of Fast Reactors (FBR) reach higher temperature levels at around 500°C, while High Temperature Gas-Cooled Reactors (HTGR) are able to provide heat at a level of 950°C.

Gen-IV concepts are designed for higher coolant temperatures than most of the today's nuclear reactors. It enables the future reactors to generate electricity at a higher efficiency as well as heat or steam which can be transferred to various processes depending on the temperature level provided. All proposed Gen-IV systems are able to supply heat for the lower temperature processes, e.g., the desalination of seawater.

In expectation of a future significantly increased demand for hydrogen, mass production of H_2 is a major goal for Gen-IV systems. Due to the need of high-temperature heat, it will be basically the helium-cooled reactors GFR and VHTR, the MSR and also one of the LFR designs appropriate to be linked with a H_2 production system. One of the most promising "Gen-IV" nuclear reactor concepts is the VHTR representing the nearest-term option of all reference plants selected and might be ready for deployment much sooner than 2030. The characteristic features of the VHTR are a helium-cooled, graphite moderated, thermal neutron spectrum reactor core with a reference thermal power production of 600 MW. The coolant outlet temperatures of 900-1000°C or higher is ideally suited for a whole spectrum of high temperature process heat applications. The employment of a direct cycle gas turbine promises a high efficiency of > 50%.

The connection between nuclear and heat application plant is principally independent of the method of hydrogen production. The hot coolant transfers its heat to the chemical process via an intermediate heat exchanger (IHX). Main purpose of the intermediate circuit is to clearly separate the nuclear from the chemical island. In this way, the direct access of primary coolant to the chemical plant and, in the reverse direction, of product gases to the reactor building can be prevented. Thus it is possible to design the chemical side as a purely conventional facility and to have possible repair works being conducted under non-nuclear conditions.

In industrial processes, energy supply security is essential demanding a very high degree of reliability and availability of continuous operation of their process units approaching 100%. The temperatures required are covering a wide spectrum. With respect to the size of the power plant, 99 % of the industrial users need a thermal power less than 300 MW, which accounts for about 80 % of the total energy consumed. Half of the industrial users even demand thermal power in the range less than 10 MW. Ensuring supply security by diversification of the primary energy carriers and, at the same time, limit the effects of energy consumption on the environment will become more important goals in future.

Future nuclear power will require a further enhancement of the safety standards. A safer operation of nuclear reactors can be obtained by designs with a very low probability and degree of core damage, minimal consequences even after severe accidents and limitation of the consequences to the plant site such that the public will not be affected. It can be achieved by a robust design, a high level of inherent safety, and transparent safety features. In order to be competitive, also reliability and performance must be at a very high level achievable by considering both technical improvements and human performance. A modular arrangement (2–6 units) will be necessary for redundancy, reliability and reserve capacity reasons which again reduce power size per modular unit. Smaller power size allows for simplicity and robustness by higher safety margins even at higher operational temperatures, and also for shorter distances of heat/steam transportation to the customer.

Of particular significance is the consideration of a qualitatively new class of conceivable accident scenarios typical for such combined nuclear and chemical facilities characterized by interacting influences. Arising problems to be covered by a decent overall safety concept are the cases of thermo-dynamic feedback in case of a loss of heat source (nuclear) or heat sink (chemical), respectively. Other safety aspects to be treated are associated with a fire and explosion hazard, when flammable gases are present like in a nuclear hydrogen production plant. The safety of the nuclear plant in case of an explosion of a flammable gas cloud on the chemical side or, hypothetically, inside the nuclear containment must be guaranteed. An approach to a safety analysis for the HTTR connected with a steam reformer unit has been conducted in a joint German/ Japanese effort [6]. But also the question of what influence an accident-induced release of radioactivity will have on the continuation of operation of the chemical plant needs to be answered.

3. Potential deployment areas for and experience with nuclear process heat

Since the beginning of the development of nuclear power, the direct use of the generated heat for district heating or in industrial processes has been considered convenient and practiced in many countries. Still, it is less than 1% of the nuclear heat worldwide which is presently used for non-electric applications, but there are signs of increasing interest.

The experience up to now gained with nuclear process heat/steam extraction is from 60 reactors and about 600 reactor-years, respectively [4]. Most present nuclear non-electric applications are found in the lower process temperature range with experience obtained, e.g., from district heating (most in Eastern Europe), desalination of seawater (most in Japan) or D_2O production (Canada). Cheap off-peak electricity from LWRs for electrolytical hydrogen production could be another low-temperature application. There are, as well, numerous concepts suggested for the use of nuclear in the high temperature range like the production of hydrogen by means of high temperature electrolysis and thermochemical cycles, or synfuels through hydrocarbons reforming.

3.1. District heating

District heating is predominantly applied in climate zones with relatively long and cold winters. It is usually provided in form of hot water (commonly used in Europe) or steam (e.g., USA, also Germany) at 80-150°C and at low pressures. Depending on local heat demand, it requires decentralized units, since heat transport over long distances is not efficient. With the improvement of hot water transportation, however, larger CHP grids could be realized, whereas steam transport is limited to a maximum of about 5 km. Typical district heating networks are in the range of 600-1200 MW(th) in large cities down to 10-50 MW(th) in smaller communities.

If NPP are used as primary energy source, heat is extracted from the low-pressure turbine. An intermediate heat transfer loop is employed to avoid a transition of radioactivity into the heat/steam circuit. Major drawback of nuclear systems is their usually insufficient economy. As of 1998, 46 commercial NPP in 12 countries are being used or have been used for heating purposes with a heat output between 5-240 MW demonstrating a safe and reliable operation. Among these plants were two dedicated plants in Russia (Obninsk) and China (NHR-5) [7].
One example is the NPP Beznau in Switzerland, which supplies since 1983 heat in form of 85°C hot water to over 2300 clients. The main heating network has a length of 31 km, from which the heat is transferred to local secondary networks with a total length of 99 km. Most recent example of nuclear district heating is the operation of the Chinese HTR-10 research reactor at the Tsinghua University in Beijing to contribute to local heating in winter time. It is actually the first high temperature reactor used for the purpose of "process heat" supply.

3.2. Water desalination

Another important example for the potential use of nuclear energy in the low temperature range is seawater desalination, a process with increasing importance due to growing drinking water shortage in many arid areas in the world. It is a fully developed, large scale commercial process providing an estimated 32 million m^3/d (as of 2005) of fresh water in about 120 countries.

The principal desalination processes are based either on distillation or on membrane separation. The first group includes the widely applied commercial methods of "Multi-Stage Flash Distillation" (MSF) and "Multiple Effect Distillation" (MED). Still under development is the "Thermal Vapor Compression" distillation (TVC) promising a higher conversion ratio. Major energy is in form of thermal energy in the range of 100-130°C required to heat the feed water. Since low-temperature heat input is sufficient, an economic and preferable constellation is the operation in a heat and power cogeneration plant which takes benefit from the added value of electricity sales.

In the second group, the "Reverse Osmosis" (RO) process employs a pressure-driven separation technique where water is forced under high pressure through a water-permeable membrane. No heating or phase change takes place. Main energy is electricity required for the initial pressurization of the feed water, 5-7 MPa for seawater or 2-3 MPa for brackish water. The advantages are a simple processing and low installation and maintenance cost. Drawbacks are the necessary pre-treatment of the feed water, the short lifetime of the membranes and the comparatively high contents (1-2%) of salt passing the membrane.

There is – limited – experience with nuclear desalination since the 1960s from nine nuclear units in Japan and one in Kazakhstan. The latter one was a BN-350 fast reactor which produced 135 MW(e) and 80,000 m^3/d of fresh water by MED over 27 years before taken out of operation in 1999. The Japanese plants are being used for on-site supply of cooling water with capacities of 1000-3000 m^3/d. In India, a combined MSF and RO hybrid system connected to a twin 170 MW(e) pressurized heavy water reactor has been constructed and is presently in the commissioning phase. With capacities of 1800 m^3/d by RO and 4500 m^3/d by MSF, it will become the largest nuclear based desalination plant in the world. The nuclear driven process is technically and economically feasible (EURODESAL project [8]), but is yet to be demonstrated on a larger industrial scale. Projects studies are currently being conducted in several countries.

Small and medium-sized nuclear reactors appear suitable for seawater desalination in the capacity range of 80-100,000 m^3/d and 200-500,000 m^3/d, respectively [9]. Nuclear power will penetrate the market, if desalination starts to compete with the alternative means of fresh water supply, which may become more limited and more expensive in future. Regional differences of fresh water supply could enhance this tendency. Besides nuclear desalination plants do not need to be close to the consumer, since water can be easily transported over longer distances.

3.3. Oil recovery

One example with near-term prospects is the provision of high temperature heat/steam and electricity in the tertiary oil recovery process increasingly applied with decreasing recovery of conventional oil resources. Particularly in this sector, massive amounts of H_2 will be required in future for the conversion of heavy oils, tar sands, and other low-grade hydrocarbons [10]. Due to the increasing share of "dirty fuels" such as heavy oils, oil shale, tar sands entering the market, the need for both process heat and hydrogen will also increase significantly. Figure 1 shows a schematic of the so-called "Steam-Assisted Gravity Drainage" process where a bituminous ground is flooded with steam at 200-340°C and 10-15 MPa, and the oil produced is retrievd through a separate well.

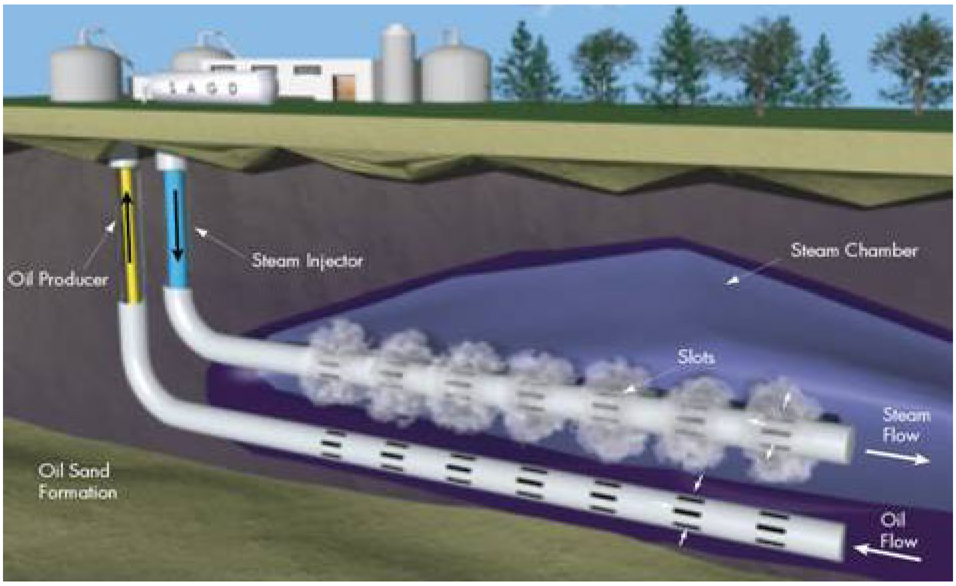

FIG. 1. Steam-assisted gravity drainage for enhanced oil recovery

For larger resources, nuclear could represent a large centralized steam source to be injected at several locations. Fluctuations in oil production could be compensated by cogeneration of electricity. Canada appears to be an ideal candidate for such a combined system due to its vast amounts of oil sands and its established CANDU nuclear plants.

3.4. High temperature process heat in the chemical industries

In the high temperature process heat range, CHP market penetration by nuclear power could be seen, e.g., in the chemical and petrochemical industries. The processes of splitting hydrocarbons are presently widely applied production methods for synthesis gas and hydrogen. The most important ones established on an industrial scale are steam reforming of natural gas, the extraction from heavy oils, and the gasification of coal. Biomass gasification is currently being tested on pilot plant scale.

The worldwide throughput of crude oil of $3*10^9$ t/yr requires a total energy of approximately 200 GW(th) or 8% of its energy contents. A refinery with a throughput of 6-7 million t/yr of crude oil consists of a large number of individual plants which need a steady supply of typically about 400 MW(th). Due to the complex interaction of the different chemical processes optimized to a very high degree, the potential supply of energy by nuclear power may not be dedicated to a specific process, but rather cover the overall cogeneration of process steam, process heat, and electricity. An additional approach will be the important H_2 generation. Process heat must be transmitted using an intermediate heat transfer loop.

Steam reforming of natural gas covering worldwide about half of the hydrogen demand, is one of the essential processes in the petrochemical and refining industries. The coupling with nuclear as process heat source may be an ideal starting point for nuclear power to penetrate this market in the near and medium term saving up to 35% of the methane feedstock, and a reasonable transition step towards a fossil-free H_2 production in the long term.

Nuclear steam reforming was subjected to a long-term R&D program in Germany and Japan with the aim to utilize the required process heat from an HTGR. The Research Center Juelich has developed in cooperation with the respective industries the design of a nuclear process heat plant as well as the necessary heat exchanging components which according to their dimensions belong to the 125 MW power class. A particular 10 MW(th) component test loop was constructed and successfully operated over a total of 18,400 hours with about 7000 hours at temperatures above 900°C. The components tested in terms of reliability and availability included two designs of an IHX, steam generator, decay heat removal cooler, hot gas ducts, and hot gas valves [11].

Within the frame of the project "Prototype Nuclear Process Heat", PNP, also the coal gasification processes for hydrogen production were investigated in Germany. These activities eventually resulted in the construction and operation of pilot plants for coal gasification under nuclear conditions. Catalytic and non-catalytic steam-coal gasification of hard coal was verified in a 1.2 MW facility using 950°C helium as energy source. The process of hydro-gasification of brown coal (lignite) was realized in a 1.5 MW plant operated for ~ 27,000 h with a total amount of 1800 t of lignite gasified.

3.5. Large-scale hydrogen production

Hydrogen is already a significant chemical product. The main fraction of the hydrogen (70%) is consumed in the fertilizer and petroleum industries as well as in the iron and steel industries, used as chemical raw material and intermediate product or directly as fuel, e.g., for process heat production. As a clean fuel of the future, it may also increase its demand in the transportation sector. Nuclear production of H_2 at a large scale has the potential to contribute significantly to the global energy supply in the 21st century in a sustainable, competitive and environmentally friendly manner.

The raw materials for hydrogen production in the future will be water and biomass. The major candidate processes for water splitting in future are high temperature electrolysis (HTE) and thermochemical cycles. Both methods are currently investigated in different countries, but are still at R&D level. A coupling to high temperature heat sources from HTGRs or solar energy is considered, but has not been realized up to now.

The electrochemical decomposition of steam at higher temperatures, 800-1000°C, offers the advantages of a reduction of electricity demand (minus 30% compared to the conventional electrolysis at room temperature) and a lowering of the activation barriers at the electrolyte surfaces resulting in efficiency improvement. In Germany, the high temperature electrolysis process became known in the 1990s under "HOT ELLY" demonstrated in tubular electrolysis cells in a 2 kW pilot plant. Japan's approach based on planar cells achieved hydrogen production rates of 3–6 NL/h per m^2 of cell surface at a temperature of 850°C. The INL in the USA is presently conducting an experimental program to test solid oxide electrolysis cell stacks combined with materials research and detailed CFD modeling [12]. R&D efforts in various countries are concentrating on the development and optimization of electrolysis cells, composition of cell stacks, and selection of appropriate materials.

In thermochemical cycles, the process of water splitting is subdivided into several partial reactions. The thermal energy required for the high temperature step is in the range of 800-900°C. In thermochemical-electric hybrid cycles, the low temperature reactions run on electricity. Numerous potential cycles were tested and checked in terms of reaction kinetics, thermodynamics, reactant separation, material stability, flow sheeting, and cost analysis. Those of the sulfur family like the iodine-sulfur (I-S) process (see Fig. 2) appear to be highly promising. Major problems arise by the large material flows, the introduction of impurities, the potential formation of toxic substances, and, last but not least, the still unsatisfactorily low overall energy efficiency of around 40%. Other processes considered worth of further investigation are the so-called Westinghouse process, a sulfuric acid hybrid (HyS) cycle where the low-temperature step runs in an electrolysis cell to produce the hydrogen, or the so-called UT-3 process based on a four-step cycle with calcium and bromine.

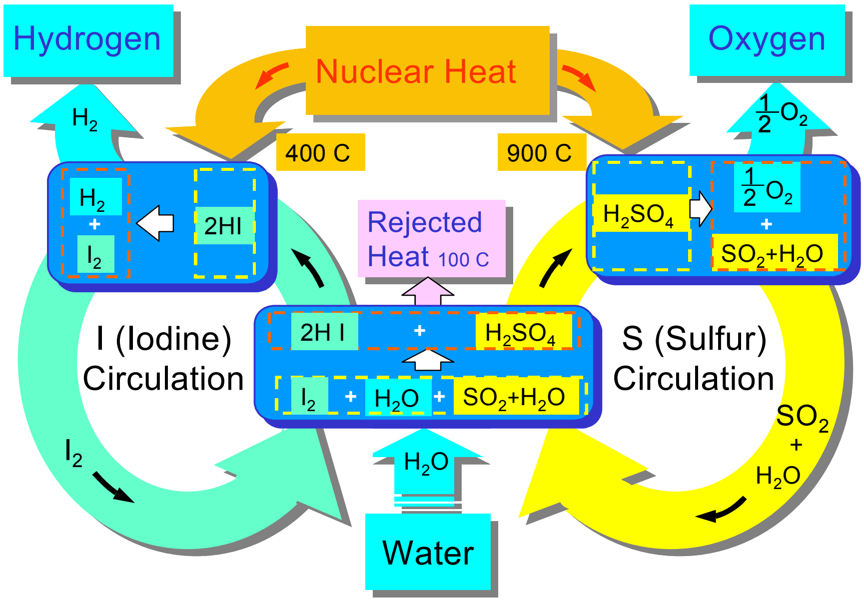

FIG. 2. Schematic of the sulfur-iodine (S-I) thermochemical cycle

As an alternative option, nuclear process heat from an HTGR can also be utilized for the production of energy alcohols from biomass, representing a CO_2-neutral production process by means of a CO_2-free primary energy input. For the generation of methanol (H/C ratio = 4) from biomass, e.g., wood (H/C ratio = 1.5), additional H atoms are needed, which means additional energy. The process could also be used for synthetic natural gas (SNG) production; however, energy alcohol has the advantage to be created in the user-friendly liquid state.

4. Conclusions

Conclusions can be drawn as follows:

1. Nuclear power is a safe, reliable, clean, and economic energy source. The experience achieved and lessons learned from five decades of commercial nuclear power plant operation have resulted in a status of minimal risk of severe occurrences, thus representing a powerful option within the existing mix of energy sources. The next, fourth generation of nuclear plants will be even safer, more reliable, more economic, and more proliferation-resistant, and will supply more than just electricity.
2. It is strongly recommended to investigate in more detail nuclear CHP options and its market requirements. Products others than electricity could significantly enlarge the energy market for nuclear CHP offering at the same time a considerable potential for fuel resource saving due to high overall efficiencies, improved economics and reduction of CO_2 emissions. There is already experience to couple nuclear energy to low temperature processes like district heating or desalination, but it still is lacking the demonstration on a larger scale. The petrochemical and refining industries represent another huge potential with their growing demand for hydrogen and process steam due to the increasing share of “dirty fuels” such as heavy oils, oil shale, tar sands entering the market.
3. In the high temperature heat market, nuclear is also applicable to the production processes of liquid fuels or of hydrogen by steam reforming or water splitting,

compatible with the needs of the transportation sector. The feasibility of steam reforming of methane or coal gasification under nuclear conditions was already successfully demonstrated. Technical and economical feasibility, however, remains to be demonstrated at a larger scale.

4. Many of the suggested designs of innovative nuclear reactors of the fourth generation are of small or medium power size (< 700 MW(e)), some even less than 300 MW(e). Among those, the VHTR, which is flexible in design, siting, fuel cycle and size, represents a promising concept. It clearly shows the features of a catastrophe-free reactor and is most advanced in terms of R&D works. It will provide coolant exit temperatures of up to 1000°C, which can be utilized in the cogeneration mode for a broad range of process heat applications.

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Integration of desalination, power, environment and security

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Past President and Chairman of IDA Technical Programs

Your Excellencies, Ladies and Gentlemen

It is great opportunity to take part in discussions on new challenges facing world needs for water and for seawater desalination particularly in the context of developing new solutions and potential use of nuclear energy to balance the significant increases in fossil energy and material cost which has a dramatic impact on capital and operational cost of desalination and power plants. Impact of US$ 60-75 per barrel oil and high demand for raw materials, steel, copper, nickel and concrete has dramatically increased pressure to develop novel solutions which can minimize energy consumption and reduce volume and weight of desalination plants.

The integration of energy –power and water becomes of even more important today in coping with the increased costs. The desalination technology has to adapt to the new conditions and find solutions to produce plants with higher efficiency, performance ratios and minimizing the use of materials.

Desalination is an energy and capital intensive process. All seawater desalting processes, multi-stage flash (MSF), multi-effect distillation (MED), and seawater reverse osmosis (SWRO) consume significant amounts of energy and materials. In view of the rising fuel costs, the amount and cost of fuel consumed to desalinate seawater becomes one of the main factors determining the operational cost of desalted water cost. Similarly the materials selected and the increased cost of materials for desalination has significant impact on capital cost. These raising costs in turn become a major factor in choosing the method and technology to be used.

The future of water demands creative solutions. It requires effective innovations and integration of energy resources to generate power and to economically create and store desalinated water. Confronting the water challenge is essential to a country’s sustainable development and to the security of its communities. Desalination is the only realistic hope to create new water resources in the midst of water crisis and water pollution

We need to innovate and integrate energy, power, and water. We have to look for new ideas on hybridization, energy recovery, and more effective materials and chemicals. We have to learn how to extend the life of existing plants and upgrade existing desalination facilities. The integration and innovation approach is of critical interests to the water and power sector in the world community. In an era of high energy and material cost, technology an integrated use can compensate the impact on rising cost. As desalination and water reuse expansion in the Middle East and the world continues at a rapid pace, these innovations must be integrated into the next generation of water facilities.

Global perspective

“If you have energy you can have power; if you have power you can have water; and if you have water you can have security.” Water supplies and the integration of desalination projects with power plants are particularly important issues. The 19th IDA Worldwide Desalting Plants Inventory states that worldwide desalination capacity amounts to 47 million cubic metre/d (over 10 billion of imperial gallons per day) of water, and of this 25.6 million cubic metre/d is in the Middle East. Because of the relative scarcity of potable water and the abundance of energy resources in the Middle East, the region is the largest user of integrated water/power schemes.

The global desalination industry is energy intensive, and is being hit by recent increases in energy prices. "The total water costs of desalination plants is consistently able to produce desalinated water from the sea at cost 0.70-0.80 $/m^3$. The trend now that prices of energy are high, in the range of $60/barrel for crude oil, is to optimise energy consumption. At the same time desalination has been hit, like all industries, by the recent increases in material costs. Desalination projects now under way have to balance these two factors and make further technological advances, in order to minimize the costs of desalination."

Despite these constraints, the Middle East demand for desalination is expected to increase rapidly. For instance, the Gulf region is expected to see water demand continue to increase at a rate of 10% a year, and countries including UAE, Kuwait, Oman, Qatar and Saudi Arabia are all planning major new capacity developments. "Global water demand growth is expected to require an investment of $40-50 billion on desalination projects over the next 10 years. The expansion rate will be particularly large in the Middle East, where governments are increasingly seeking private investment through independent water and power projects (IWPPs)." Abu Dhabi, for example, is undertaking the seventh IWPP projects by ADWEA at Fujairah. In each IWPP, ADWEA retains a 60 per cent share holding while the remaining 40 per cent share holding is owned by overseas private investors. All these IWPPs sell water and electricity from their production plant to the single buyer of the sector, ADWEC, under long-term Power and Water Purchase Agreements (PWPAs). Abu Dhabi has raised US$10.8 billion (Dh40 billion) from the sell-out of its electricity and water infrastructure. Abu Dhabi 7000 megawatt of electric power and 500 million gallon per day water is being produced by the vibrant private sector. In Saudi Arabia, the government is pursuing IWPPs with a 40% government stake and 60% from private investors.

Rising demand and the pressure to reduce costs provide a tremendous motivation for the desalination industry to improve its technology, "New processes are continually being developed. The industry now produces water a cost of 70-80 cents/m^3, but to sustain or reduce this given current market conditions is the challenge. We are looking at new technologies and at scaling up existing technologies. There is also tremendous benefit to be gained from upgrading existing plants, especially through privatization programs. Among the key technical trends is hybridization – many of the new projects may best be approached with a mix of distillation processes and membrane processes, such as reverse osmosis and nanofiltration. The balance between the water and power elements in integrated projects is also a critical issue for the Middle East, and hybrid technologies offer the ability to match better a particular water/power requirement."

We see hybrid technologies as offering part of the solution to another regional problem – water storage. "Most countries only have enough water storage to meet one day of demand". For the critical strategic and economic reasons Leading Edge Technologies-LET is championing desalinated water storage by Desalination Aquifer Storage and Recovery (DASR). For the Middle East, there is a tremendous seasonal variation in both water and power demand. Peak demand for both water and power is in summer, but in winter water demand falls by around 10% while power demand power demand decreases by more than

70%. By installing water storage capacity at integrated sites, operators would be able to deploy power capacity during the winter which would otherwise be idled, to continue producing water which could be stored in readiness for summer peak demand."

1. Introduction

The hybrid desalting concept is the combination of two or more processes in order to provide a better and lower cost product than either alone can provide. In desalination, there are distillation and membrane, which under hybrid conditions can be combined to produce a more economic process. Thus, two or three elements that are integrated to make hybrid desalination are:

- Distillation: multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC)
- membrane desalination: reverse osmosis (RO), nanofiltration (NF)
- Power: steam power plants, combined cycle power plants

Large dual-purpose power-desalination plants are built to reduce the cost of production of electricity and water. Over 30,000 MW of power is combined with desalination plants in the largest use of cogeneration concepts. In many countries, particularly in the Middle East, peak power demand occurs in summer and then drops dramatically to 30–40%. In contrast the demand for desalinated water is almost constant around the year.

The focus of this paper is on examination of hybrid systems and hybrid technology in order to take full advantage of both thermal and electrical energy as well as membrane processes. This article is based and updated from Awerbuch hybrid chapter contribution to book by M. Wilf *The Guidebook to Membrane Desalination Technology* [1]. Two comprehensive studies were carried out on hybrid desalination systems by Daniel Hoffman and Amnon Zfati [2] and by Sherman May [3], and full review by Awerbuch [4].

2. Description of hybrid systems

Simple hybrid. In the simple hybrid MSF/RO desalination power process, a seawater RO plant is combined with either a new or existing dual-purpose MSF/power plant to offer some advantages. Several plants currently installed are using some of these advantages. Examples are in Jeddah RO, Jubail and Madina-Yanbu II in Saudi Arabia and Fujairah in UAE.

Integrated hybrid. The fully integrated MSF/RO desalination power process, which is particularly suitable for new seawater desalting complexes, takes additional advantage of integration features.

Power/water hybrid. Integration of the power and water cycle aims to obtain the optimum cost for both water and power. Important parameters in the design of these systems include:

- seasonal demands for electricity and water
- power-to-water ratio
- minimization of fuel consumption and increase in the power plant efficiency
- minimization of the environmental impact of carbon dioxide including potential consideration of CO_2 tax credit.

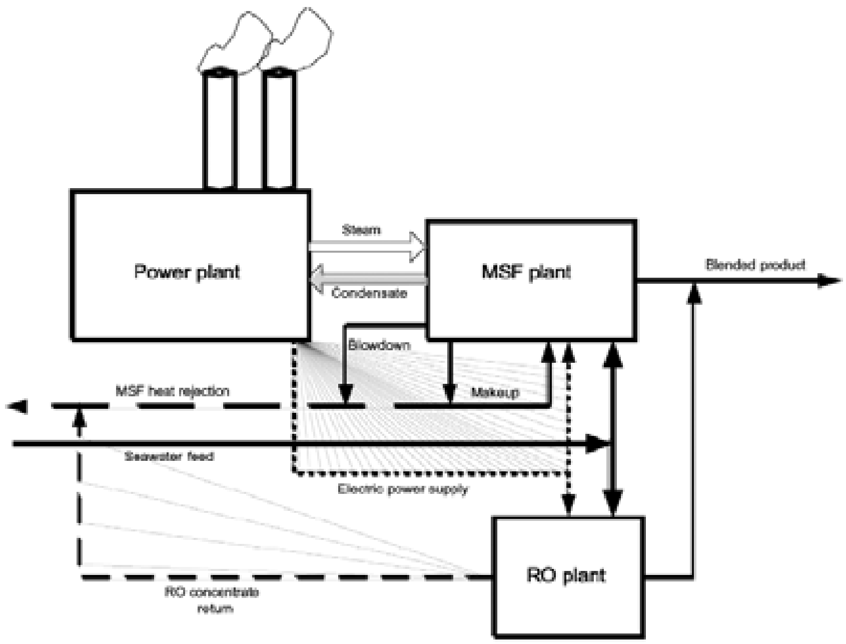

FIG. 1. Example of hybrid system components and their relations.

Some of the earlier analyses in the references showed that when seasonal and daily variations occur; electrically driven technology could provide an excellent choice for hybridization with more conventional dual-purpose plants. The hybrid approach could achieve the lowest cost of total investment, flexibility in production and the lowest cost of power and water production. Water can be stored while electricity storage is not practical. In this case excess electricity can be diverted to water production incorporating electrically driven seawater reverse osmosis (SWRO) and/or vapor compression (VC) and combined with low pressure steam driven technology of MSF or MED, making it advantageous to design an integrated hybrid plant. One method of making use of idle power capacity is the use of electrically driven RO or VC plants in combination with Desalination Aquifer Storage Recovery (DASR) both for averaging the desalination capacity, for strategic fresh ground water storage or improving quality of the basin.

The increase in the unit size of MSF, MED, VC and RO will lead to reduction of capital costs, but combined with unique application of hybrid ideas will offer reduction in water cost. Effective integration of membrane/thermal desalination and power technology can reduce the cost of desalination and electrical power production (hybrid desalination).

Early suggestions for hybrid desalination were based upon elimination of the requirement for a second pass to the RO process so that the higher-salinity RO product could be combined with the better quality product from an MSF plant. This is the simplest application of hybrid desalination. Since then, other concepts have been proposed for hybrid desalination. Today although RO can produce product of potable TDS in one pass, blending allows reducing the requirements for second and third partial pass to solve the critical boron issue.

The dual-purpose power-desalination plants make use of thermal energy extracted or exhausted from power plants in the form of low pressure steam to provide heat input to thermal desalination plants for MSF or MED distillation processes. The electrical energy can be also effectively used in the electrically driven desalination processes like RO and VC processes

In the simple hybrid MSF/RO desalination power process, a SWRO plant is combined with either a new or existing dual-purpose MSF/power plant with the following advantages:

- A common, considerably smaller seawater intake can be used.
- Product waters from the RO and MSF plants are blended to obtain suitable water quality.
- Product waters from the RO and MSF plants are blended, therefore allowing higher temperature of distillate.
- A single pass RO process can be used.
- Blending distillation with membrane products reduces strict requirements on boron removal by RO.
- The useful RO membrane life can be extended.
- Excess power production from the desalting complex can be reduced significantly, or power to water ratio can be significantly reduced.

The fully integrated MSF/RO desalination power process, which is particularly suitable for new seawater desalting complexes, takes additional advantage of integration features, such as:

- The feed water temperature to the RO plant is optimized and controlled by using cooling water from the heat-reject section of the MSF/MED or power plant condenser.
- The low-pressure steam from the MSF/MED plant is used to de-aerate or use de-aerated brine as a feed water to the RO plant to minimize corrosion and reduce residual chlorine.
- Some components of seawater pretreatment process can be integrated.
- One post-treatment system is used for the product water from both plants.
- The brine discharged-reject from the RO plant is combined with the brine recycle in the MSF or is used as a feed to MED.
- The hybridization of nanofiltration as softening membrane process of the feed to distillation plants MSF and MED could lead to significant improvement in productivity of desalination plants.
- The hybridization of MSF with MED can offer many improvements in energy utilization between two thermal processes operating at two different temperature regimes.

The energy conservation using a hybrid system

In view of dramatic rise in fuel prices in excess of US$ 60/barrel, which is equivalent to US$10.3/MMBTU hybrid (RO + distillation) system offers significant saving in fuel cost in comparison with only distillation option (Fig. 2). This is well demonstrated by simple presentation provided by Dr. Corrado Sommariva in his course on Thermal Desalination Processes and Economics.

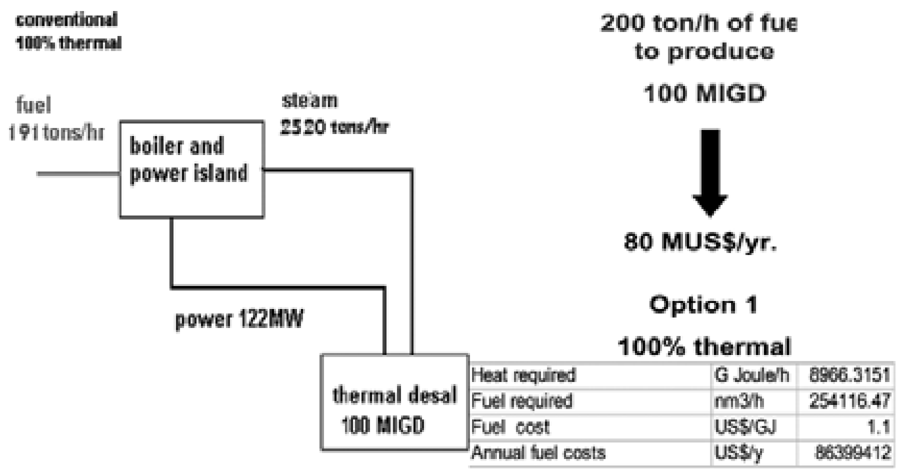

FIG. 2. A case study of a hybrid system. The thermal plant configuration 400 MW power + 100 MIGD: PWR = 4 (courtesy of Dr. Corrado Sommariva)

In this case (Fig. 3) for 100 MIGD (455,000 m^3/d) MSF desalination and 400 MW of electric power generation plant the annual fuel cost requirement will exceed 86 million US $ based on historic fuel cost of only 1.1 US$/GJ. By comparison a hybrid 100 MIGD (455,000 m^3/d) desalination plant based on 60% thermal and 40 % RO will operate at reduced fuel consumption of only 55 million US$ per year (Fig. 3). This annual fuel cost difference of over 30 million US$ per year is based on 1.1 $/GJ, considering the impact of today's fuel price of 10. $/GJ the annual cost differential will exceed 300 million dollars and will pay back for the total Capex in less then 3 years. Of course in base case we produce more power and to some extent this compensates the additional cost, but this assumes that we need the power.

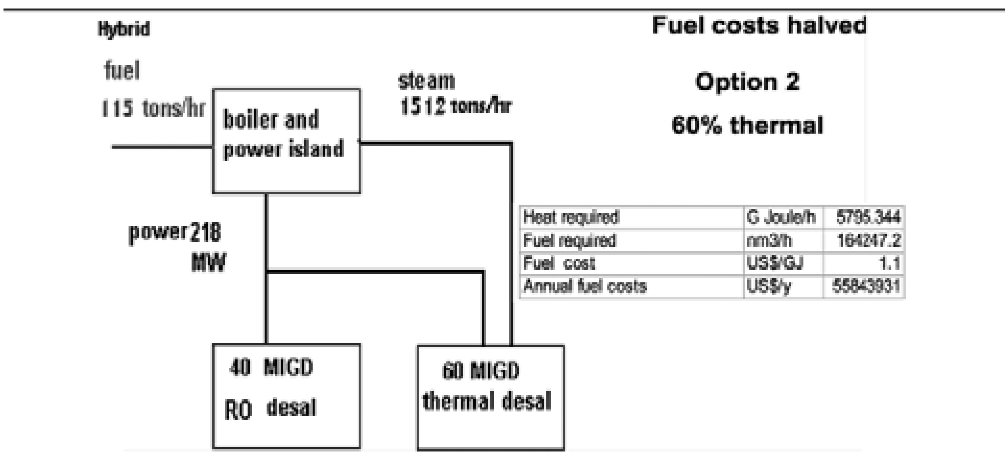

FIG. 3. A case study of a hybrid system. The thermal + RO plant configuration. (courtesy of Dr. Corrado Sommariva. Consider impact of fuel prices at 60$/BBL = 10.3$/MMBTU

A full review of the impact of the high energy and material cost on desalination technology is described by Awerbuch [4].

There are unique conditions in the Gulf countries where peak demand for electricity rises significantly during summer mainly because of the use of air-conditioning, and than drops dramatically to 30–40% of summer capacity. This creates situation that over 50% of power generation is idled. In contrast, the demand for desalinated water is almost constant. This inequality of demand between electricity and water can be corrected by diverting excess of available electricity to water production incorporating electrical driven technology of SWRO and/or VC and combined with low pressure steam driven technology of MSF or MED, making it advantageous to design an integrated hybrid plant.

3. Hybrid—the new alternative

The idea of combining electrical power, MSF, and SWRO has been reported in a number of publications. Initial publications were in the early 1980s. The Hybrid Desalting Systems idea of combining power, MSF distillation plant and a membrane SWRO plant was previously reported to offer significant advantages (5-9).

In the simple hybrid MSF/RO desalination power process, a SWRO plant is combined with either a new or existing dual-purpose MSF/power plant with the following advantages:

- A common, considerably smaller seawater intake can be used.
- Product waters from the RO and MSF plants are blended to obtain suitable water quality.
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- Some components of seawater pretreatment process can be integrated.
- One post-treatment system is used for the product water from both plants.
- The brine discharged-reject from the RO plant is combined with the brine recycle in the MSF or is used as a feed to MED.
- The hybridization of nanofiltration as softening membrane process for feed of distillation plants MSF and MED could lead to significant improvement in productivity of desalination plants.

3.1. The classic scheme

This is the most common and straightforward hybrid plant scheme (Fig. 4). It has been adopted in Jeddah to blend higher TDS RO permeate with distillate from existing MSF plants, and is described in detail by Awerbuch et al. [5,10] and by many other papers. In general in this scheme part of the MSF plant's heated coolant reject is de-aerated, using low-pressure steam from the MSF plant (to reduce corrosion and residual chlorine), and used as the feed to the SWRO plant. The higher temperature of the feed improves membrane performance (flux, at constant pressure, increases by 1.5–3% for each °C). This is particularly important during the winter, when seawater temperatures can drop to as low as 15°C (59°F). The MSF plant's distillate, at less than 20 ppm TDS, is blended with the SWRO plant's product, making it possible to meet potable water standards for maximum TDS and chloride concentrations with higher SWRO plant product salinity. This, in turn, means that the SWRO plants can be operated at higher conversion ratios, thereby reducing consumption of energy and chemicals and extending membrane useful life.

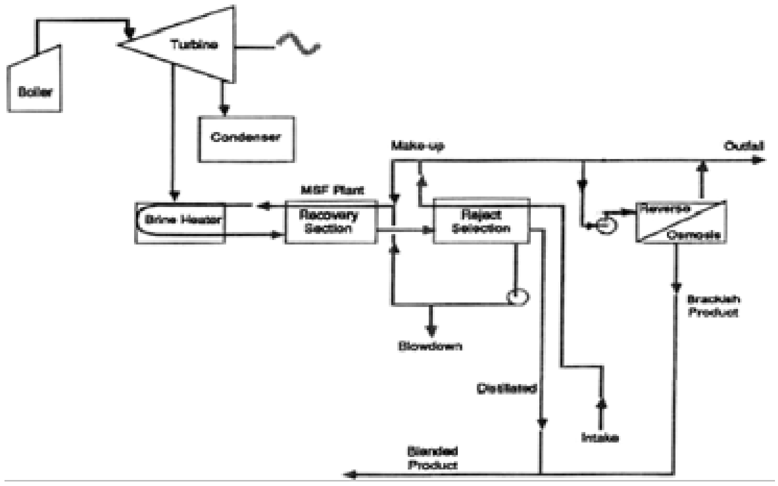

FIG. 4. The basic classic scheme hybrid system configuration.

3.2. The classic scheme variant

In one variant of the classic scheme, the SWRO plant's reject brine becomes integrated into the feed to the MSF plant, utilizing its high pressure, with a special turbocharger, to boost the MSF plant's recirculation pump (Fig. 5).

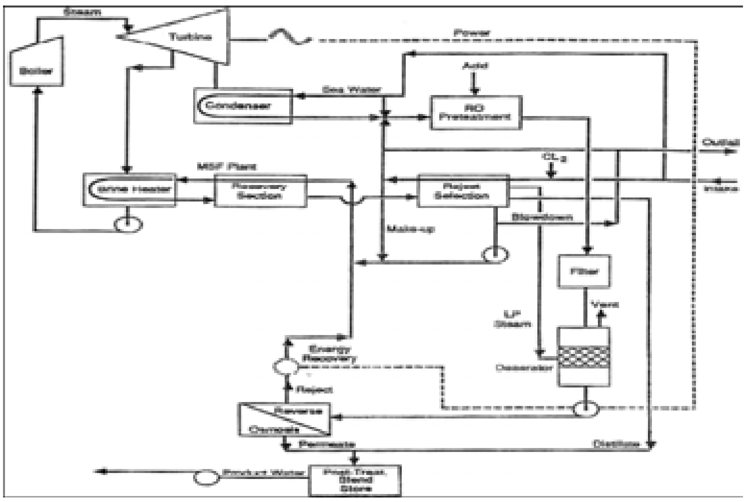

FIG. 5. The alternative integrated configuration of "classic scheme" hybrid system

The conversion ratio of the SWRO plant is then limited by the maximum brine recirculation concentration possible. With a once-through MSF plant this limitation is avoided.

3.3. The once-through MSF scheme

In this scheme, described by Kamal et al. [9] Al-Sofi et al. [5], Awerbuch et al. [6,7,8] and others, a once-through MSF plant is specified, and it's preheated and de-aerated reject, at about 47,000 ppm TDS (with Gulf 42,000 ppm TDS seawater), is used as SWRO plant feed. This scheme has the same advantages as the "classic scheme", but benefits also from the continued de-aeration of the feed by the Non Condensable Gases (NCG) removal system, as the seawater flows through the MSF plant's heat recovery section, and from the reduction of the seawater's bio-fouling potential due to the high temperature sterilization effect at the MSF plant's heat input section.

3.4. The duo-cycle ROMED scheme

This is Hornburg's duo-cycle ROMED hybrid system [11]. The main feature of this scheme is the use of a high-GOR TVC (or MVC) plant in lieu of an MSF plant, but the flow scheme is also different from that of the above variant schemes. The seawater is first fed to the SWRO plant, i.e., without preheating and de-aeration in the distillation plant (TVC plants normally do not include feed de-aerators). The SWRO plant's reject is directed, after passing through an energy recovery turbine, into the TVC plant's heat discharge section, serving as its coolant (TVC plants' heat rejection sections normally utilize falling-film, heat-transfer surfaces, whereas MSF plants utilize pressurized, forced circulation-flow shell and tube condensers). Part or all of this coolant is then used as the feed to the TVC plant's heat recovery section.

3.5. The direct-drive steam turbine scheme

The fifth scheme was is the one proposed by Hazen E. Nelson in US Patent 3,632,505 "Evaporation-Reverse Osmosis Water Desalination System" assigned to Stone and Webster Engineering Corporation as early as 1972. It is based on an MSF-SWRO plant combination; with motive steam directed first to back-pressure steam turbines that drive directly the SWRO plant's high-pressure pumps. The steam exhausted from the turbines is then fed to the MSF plant's brine heater. The SWRO plant's brine discharge energy-recovery turbines generate the electric power required for all other pumps and the system's auxiliaries.

5. R&D related to improving hybrid systems

The R&D activities pursued today that are most relevant to cogeneration and/or hybrid systems are those relating to the creation of a wider range of nanofiltration and SWRO membranes and the pilot-plant testing and prototype plant designing of low-cost high-GOR high-temperature MED plants. As Awerbuch [6] suggested, an optimal hybrid system would benefit from SWRO membranes with higher fluxes and lower rejections than currently being offered commercially. The minimal accepted membrane rejection will be that which will give permeate with a salinity sufficient to provide, after dilution with the MSF plant's distillate and permeate post-treatment, a combined product salinity of 500 ppm TDS. Some membrane manufacturers have been investigating the potential performance and markets for such high-flux SWRO membranes. The ongoing work on nanofiltration membrane softening technology combined with distillation and hybrid options of NF-MSF-RO or NF-MED-RO offer new potential for improving hybrid systems.

6. Quantifying the benefits of the hybrid SWRO/thermal plant scheme in cogeneration stations.

The magnitudes of these potential savings are a function of the relative outputs of the SWRO and distillation plants Fig. 6. They are quantified below for preferred hybrid scheme developed by Hoffman et al. [2]

6.1. Savings due to reduced seawater requirements

The use of distillation plant coolant reject as feed to a SWRO plant within selected hybrid plant scheme reduces both seawater supply and brine and coolant rejection requirements vis-à-vis non-hybrid, separate and independent (stand-alone) thermal and SWRO plants. The cost savings are derived from four sources:

— reduced investment in the seawater intake and supply system
— reduced investment in the brine and cooling water discharge system
— reduced seawater pretreatment costs
— reduced seawater-pumping energy

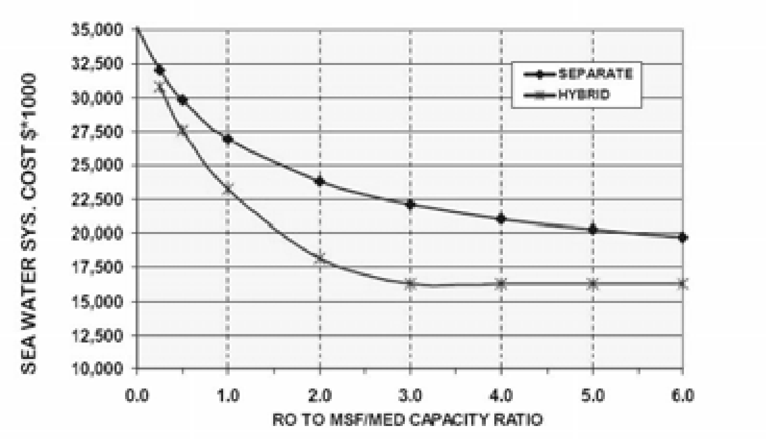

FIG. 6. Effect of distillation to RO capacity ratio on combined system cost.

6.2. RO membrane life

For all membranes, water permeability (i.e., permeate production) declines with operating time while product salinity and chloride concentration increases. The drop in production with time can be compensated by installing extra membrane rack space and installing additional membranes as required. The increase in product salinity cannot be compensated for except with large-scale membrane replacement. Therefore, to maintain the product water quality within WHO standards, the designer of stand alone seawater RO plants has the option to replace membranes more frequently or install a two pass (seawater RO and brackish water RO) system. In the case of hybrid systems (RO + distillation), a single pass RO system can be specified while maintaining a long membrane life. This is made possible by blending the RO product water with the high purity distilled water produced by the thermal desalination unit.

6.3. Membrane performance as a function of seawater temperature

The use of all or some of the preheated cooling water discharge from a thermal desalination plant as feed to a SWRO plant enables elevating and controlling the SWRO plant's operating temperature at its optimal or any other higher desired value. Feed water temperature affects the two main performance characteristics of a membrane: flux and salt rejection. Higher feed water temperatures increase not only flux but also salt passage. Operation at higher temperature may also reduce membrane life (due to membrane compaction), but, as there are no definite *quantitative* figures relating to this effect, we will not include it in our considerations.

For all membranes, water production is a function of temperature, at constant feed pressure. Production will go up with temperature increasing by 1.5% to 3% per degree Celsius for nearly all membranes, thereby enabling reduction of the number of RO membrane modules required for a given permeate capacity.

This is of course condition to that feed water quality is sufficiently good that membrane fouling rate will not increase during operation at higher flux. For the fully integrated hybrid process, the above advantage can be utilized by operating the RO plant at optimum temperature and pressure conditions by using cooling water from the reject section of the MSF plant. El-Sayed et al. [12] conducted pilot study of MSF/RO hybrid systems in Kuwait and observed a significant increase in RO product water flow rate. It was demonstrated on basis of experimental data that 42–48% gain in the product water flow could be achieved for a temperature of 33°C (91.4°F), over that of an isolated RO plant operating at 15°C (59°F) during winter season. The results imply that the energy consumption of RO can be reduced without involving any form of energy recovery, to the level of 5.2 kWh/m^3 (19.7 kWh/kgal) using a simple integration of MSF/RO hybrid arrangement in which the RO plant is fed the preheated seawater rejected from the MSF heat rejection section. A very interesting study was conducted recently by Nisan et al. [13]. It summarizes an investigation on conceptual studies with preheating of feed water, which is expected to lead to lower specific power consumption, higher water production, thus further reducing the cost of desalination. The results were based on Dow- FilmTec ROSA software and performance of membrane SW 30 HR 380.

The results obtained by the author based on simulation work with the ROSA program are presented for feed TDS values of 28,127, 32,163, 39,086 and 47,400 mg/L. The feed temperature was varied from 10°C to 44°C (50–111°F). The results included in these figures show the variation of the permeate production and recovery ratio as a function of feed temperature at different feed TDS values and at constant design parameters of feed flow, number elements and pressure vessels and at a constant feed pressure.

Figure 7 indicates the possibility of increased desalted water production with increased feed water temperature applying constant feed pressure. The rate of capacity increase levels off at the higher end of the temperature range evaluated. The calculation was based on a constant feed flow rate to reflect the usual design conditions of RO pumping and pretreatment equipment. Therefore, higher permeate flows with increased temperature are associated with increased recovery rate (Fig. 8). It is quite obvious that higher recovery can be obtained with lower salinity feed, which has clear process implication when we consider Nanofiltration in front of RO system or use of blending seawater feed with lower salinity water (concentrate of brackish RO for example) to lower the feed salinity to RO system.

Higher membrane permeability at elevated temperature may also result in higher recovery rate. However, higher feed water temperature and recovery rate is associated with an increase of osmotic pressure (Fig. 9).

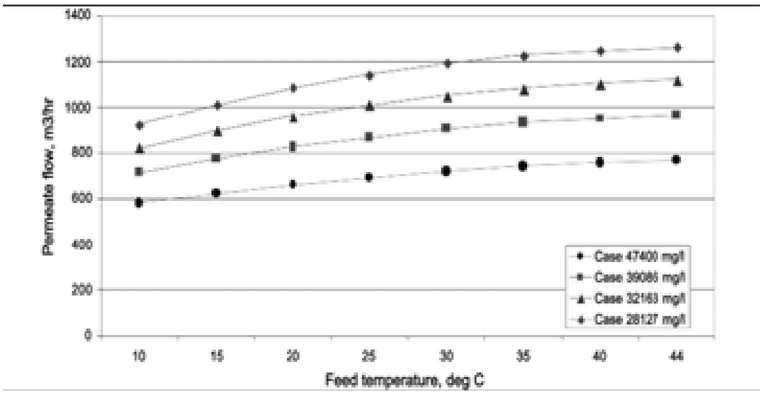

FIG. 7. Permeate flow rate (for constant feed rate) as a function of temperature.

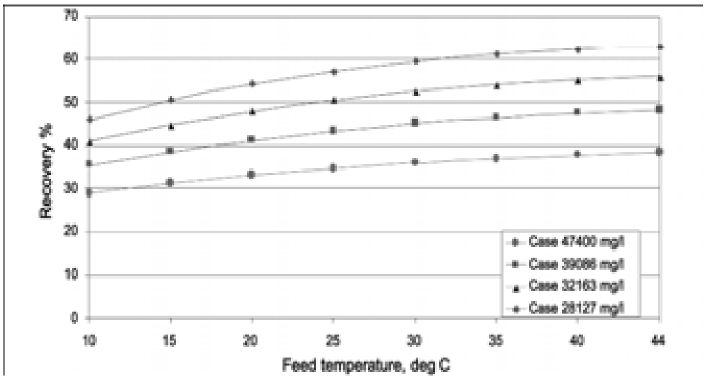

FIG. 8. Recovery ratio as function of feed temperature and TDS.

The permeate TDS systematically increases as the feed temperature and recovery rate are increased (Fig. 10). Fortunately, this salinity increase can be easily compensated in hybrid systems (RO + thermal desalination unit) where the ratio of distilled water to membrane permeate can be controlled to achieved required product TDS.

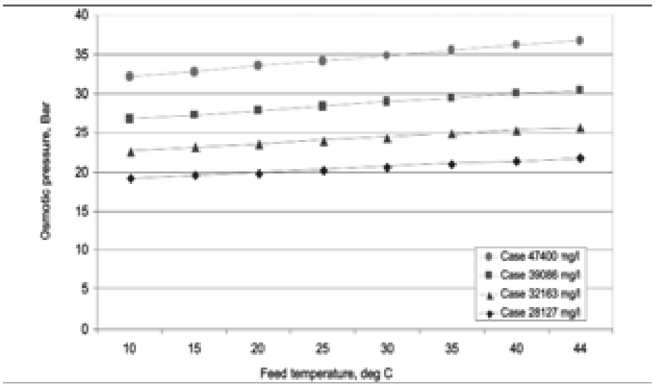

FIG. 9. Osmotic pressure as function of feed temperature and TDS.

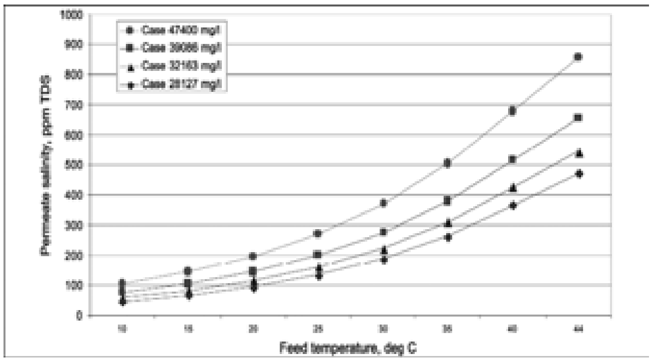

FIG. 10. Permeate salinity as a function of feed temperature and TDS.

The increase of recovery rate at constant feed pressure at increased temperature in a RO hybrid system leads to reduction of specific power consumption (Fig. 11).

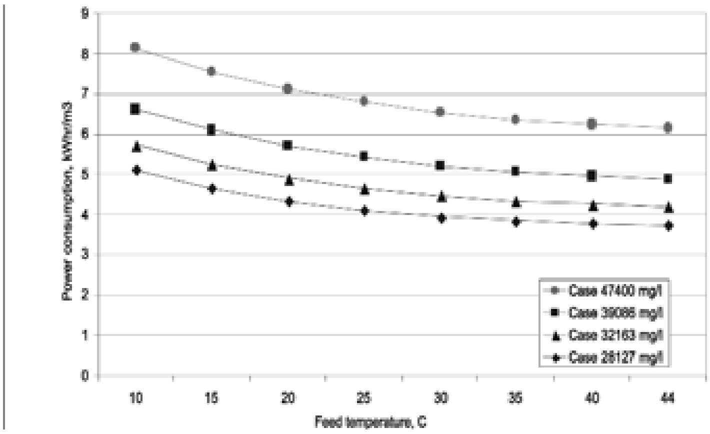

FIG. 11. Power consumption as a function of feed temperature and TDS.

A direct consequence is the reduction of the desalination costs with increased feed temperature as shown in the Fig. 12.

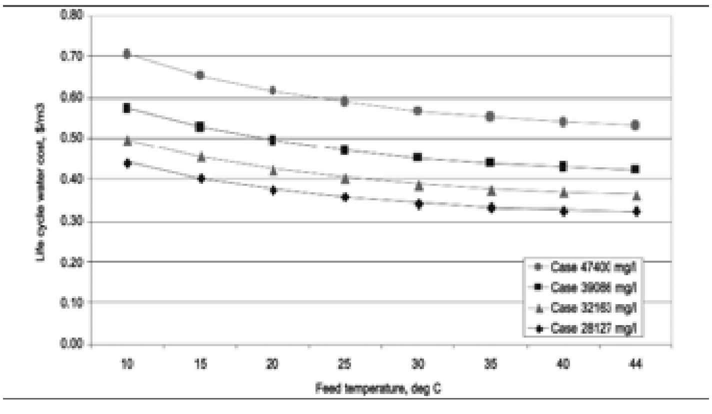

FIG. 12. Life cycle water cost as a function of feed temperature and TDS.

Naturally, for given temperature the desalination cost increases with higher feed TDS. The economics of RO operation was calculated using DOW EVA Elements Value Analysis program. All computer runs included as input values the same feed flow rate, number of elements and feed pressure, which gave good approximation of impact of temperature and feed salinity on a life cycle cost. The above calculations illustrate the potential for improved economics of operation of RO at elevated feed water temperature in hybrid systems (RO + thermal desalination unit). The full economic benefits of increased membrane permeability can be realized if it would be possible to operate RO membranes at much higher permeate flux rate then it is custom today. Operation at high flux rate will require feed water of high quality. It is very likely that it will require incorporation of membrane pretreatment seawater RO process to achieve sufficiently improved feed water quality. Some of the critics of higher temperature of operation of RO and NF membranes suggest higher rate of fouling due to increased biological activities. If this is the case, an effective method of biological control would have to be developed for high temperature operation. The increase of seawater temperature, which is happening inside the condenser or rejects section of the distillation plant, is being achieved in a matter of seconds. The assumption is that these rapid rates of temperature increase my act as a thermal shock, possibly reducing biological activity in seawater feed to the membrane unit. Another issue of concern is the compaction of membrane material (permeability decline) during long-term operation at high feed pressure and elevated temperature. Both of these issues will have to be tested in field conditions and their effect evaluated against economic benefits of operation of RO unit at elevated temperature in a hybrid system configuration.

6.4. Performance of nanofiltration membranes as a function of temperature

In nanofiltration systems the increase of temperature of seawater feed could result in higher rate of water permeability increase than it is expected in RO unit. This was one of conclusions of theoretical evaluation work by Agashichev published recently [14]. According to author concentration polarization is a significant factor in reduction of available net driving pressure (NDP). In nanofiltration membranes concentration polarization increase with temperature is lower then in RO membranes due to significantly higher salt transport through NF membranes. In hybrid systems use of Nanofiltration membranes operating also at higher temperatures, due to available heat from power plant condenser or reject section of distillation plants in combination with RO and MSF/MED, has some additional opportunities to reduce desalination costs.

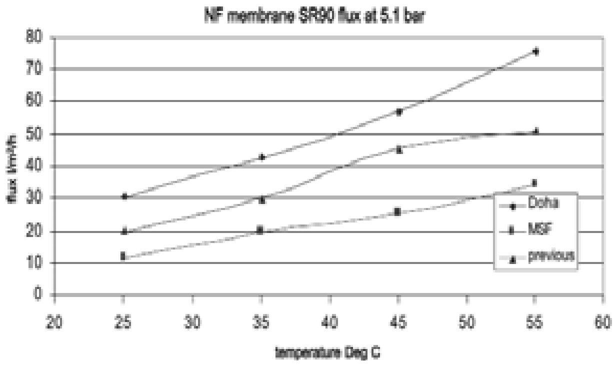

FIG. 13. Membrane flux vs. temperature at constant feed pressure.

This is shown in the data from the joint research on the new LET NF process conducted by DOW FilmTec and Toray under the direction of LET. As shown in Fig. 13 the improvement in productivity is from 2.5 to 3 times at 55°C vs. 25°C (131°F vs. 77°F) for specific Nanofiltration membrane SR 90. For other Toray NF membrane the dependence on temperature of operation is shown in Figs. 14 and 15.

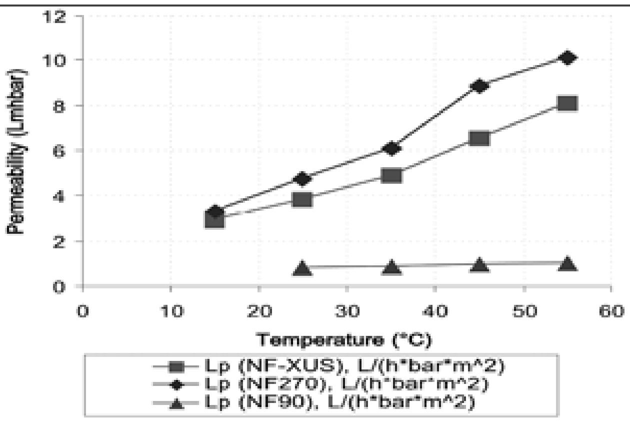

FIG. 14. Passage of ions and flux as a function of temperature.

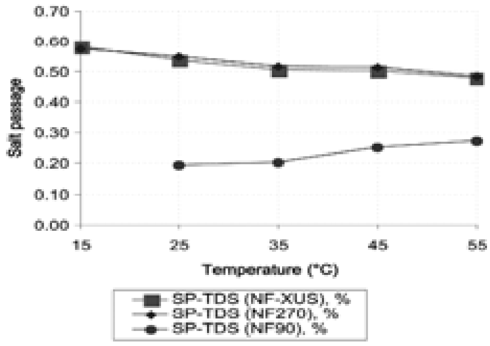

FIG. 15. Passage of ions and flux as a function of temperature.

Specifically by using feed comprising variable proportions of softened seawater and water containing a higher concentration of hardness ions than the softened stream, concentration of hardness is sufficiently reduced, thereby allowing a beneficial increase in the TBT of the distillation desalination process.

Higher operating temperatures provide an increase in productivity, recovery and performance at lower energy and chemical consumption. As a result, the cost of desalinated water production, including operation and maintenance could be significantly reduced.

6.5. Savings due to control of SWRO plant feed temperature

The feed water temperature elevation in any hybrid plant will be a function of the mix ratio of seawater and reject cooling water forming the feed. This mix, in turn, depends on the amount of cooling water available (i.e., the GOR and design temperature rise in the heat rejection condenser of the distillation plant) and the ratio of the outputs of the SWRO and the thermal plants.

The main results are:

(a) Hybrid plants have the potential to increase the average annual membrane permeate flow through increased flux rate and reduce the required membrane surface in the SWRO plants from 10.5%, when only thermal plant cooling water is used as SWRO plant feed, to 4.6%, when the ratio of the outputs of the SWRO and thermal plants is 6:1.

(b) The corresponding increases in salt passage and SWRO plant product salinity will range from 4% to 9%. The US ¢0.6/m^3 (¢2.3/kgal) membrane cost saving figure will be compounded by the savings due to the reduced investment in a range of other items of equipment related to the number of membranes in the plant. These include the membrane pressure vessels, the stainless steel high-pressure connection pipes and fittings, membrane racks, etc. Hoffman estimated the investments in these items as US \$90–100/m^3/d, or about 10% of total plant investment.

6.6. Savings due to blending SWRO and distillation plants' products

The blending of SWRO and thermal plants' products makes it possible to use the low-salinity (less than 20 ppm TDS) distillation plant product to compensate for higher salinity SWRO plant product. Based on past operating parameters of low recovery rate with current SWRO membranes performance (initial salt rejections of 99.6–99.8%), it is possible to obtain a lower than 500 ppm TDS product water in only one pass operation, even with high-salinity Gulf and Red Sea seawater (rather than with two passes, as required ten years ago, when membrane salt rejections were only 99.2%). However, if the plants are designed to operate at the high conversion ratios used today in most modern SWRO plants, 45–50%, it is projected that product salinity will exceed 500 ppm TDS after about four years of operation, as a result of membrane performance degradation. In fact, the maximum operating pressure allowed for the selected membrane turned out to be the critical factor limiting membrane lifetime. This limit was 12 years, an extension of seven years to the guaranteed five-year lifetime and eight years above the four-year limit, corresponding to operation without any blending (i.e., the expected lifetime in non-hybrid SWRO plant). Thermal desalination plant product salinity was assumed to be constant, at 20 ppm TDS.

The membrane replacement cost savings due to the blending of products within a 150,000 m^3/d hybrid plant, within the above range of SWRO and thermal plants' output ratios, are shown at the optimal output ratio of 2:1. The savings in membrane replacement costs in the corresponding 100,000 m^3/d (26.4 MGD) hybrid SWRO plant, compared with its equivalent 100,000 m^3/d non-hybrid plant, are about US \$1,172,000 per year, or about US ¢3.6/ m^3 (¢13.6/kgal).

6.7. Increased recovery ratio

Recovery ratio (conversion) is one of the key RO design parameters. It determines the size of the feed water handling system (e.g., intake, pretreatment, high pressure pumping) for a given plant size. Higher recoveries decrease the cost of the feed water handling system and the required electrical and chemical consumption while increasing the initial and replacement costs of the membrane system. Some of the reasons why higher recovery ratios have not been used in the past are related to the performance characteristics of the membranes and the product water quality specifications. Higher recovery ratio increases required feed pressure due to increase of the average osmotic pressure in the RO system. Also, due to the salt rejection property of available membranes, product water specifications (typically 500 ppm TDS and/or 250 ppm chloride) could not be easily met at higher recovery ratios. In a hybrid system, higher recovery ratios of RO unit can be incorporated into the plant design. Operation at increased feed water temperature requires lower NDP therefore provides some compensation for increased osmotic pressure. Blending of RO permeate with very low salinity distillate enables attaining the overall product water quality specifications.

6.8. Feedwater deaeration

Most aromatic composite membranes require dechlorination of the feed water, as they are very sensitive to even very small concentrations of residual chlorine and/or bromine. If feed water to an RO system is being chlorinated then addition of large quantities of sodium bisulphite is required to reduce free chlorine in the feed water. As an alternative, free chlorine removal can also be accomplished by use of a deaerator, followed by significantly reduced quantities of sodium bisulphite. Deaeration of the feed water also reduces corrosion significantly. In the case of hybrid systems, low- pressure steam suitable to operate the deaerator is readily available from the MSF plant at low cost. Deaeration can reduce the specification for high pressure piping from SMO-254, SS-317L to lower grades and more economical SS 316L.

7. Examples of existing hybrids

7.1. Jeddah hybrid

The results of conceptual and design work (5, 6) led to construction of the simple hybrid project at Jeddah 1, phase I and II plants. The Jeddah 1RO plant is 30 mgd (113,600 m^3/d) combining Phase I, which has been operated since 1989 and Phase II has been operated since March 1994. The plant is owned by the Saline Water Conversion Corporation (SWCC), design by Bechtel, constructed by Mitsubishi Heavy Industries, Ltd., under the supervision of SWCC technical committee. Al-Badawi et al. (15) reports the operation and analysis of the plant, which utilized Toyobo Hollosep double element type hollow fiber RO modules. The Jeddah complex in addition to 30 mgd RO permeate, produces 80 mgd distillate from Jeddah II, III and IV and 924 MW electricity. Jeddah I RO plant adopted successfully an Intermittent Chlorine Injection method (ICI) in order to prevent membrane degradation by oxidation reaction and bio fouling.

7.2. Yanbu –Medina hybrid

Objective to minimize power to water ratio lead to construction of Madina and Yanbu Phase II. Nada et al. [16] describes the design features of the largest SWRO plant in the Saudi Kingdom of 130,000 m^3/d (33.8 mgd) in Madina and Yanbu. The plant is able to produce power 164 MW electricity and 288,000 m^3/day (76 mgd) of desalinated water. Two 82 MW back pressure steam turbine (BTG) provides steam to four 36,000 m^3/d (9.5 mgd) MSF distillation units and the electricity to fifteen RO units of 8,500 m^3/day (2.25 mgd), each. Although the plant was not design as an integrated hybrid it provided very good example of significant reduction of the power to water ratio (PWR).

7.3. Fujairah hybrid

This seawater desalination and power plant is the largest in the world hybrid configuration of thermal processes and reverse osmosis to be implemented up to now. The paper presented by Ludwig [17] describes in the design considerations for this hybrid plant. The latest excellent description of the Fujairah Hybrid is contained in a paper presented by Doosan [18] describing the design and two years of operation. The Fujairah plant due to hybridization generates only 500 MW net electricity for export to the grid, and 662 MW gross for water production capacity amounts to 455,000 m^3/d (100 MIGD) shown in Fig 16. Otherwise similar MSF only plant in Shuweihat required 1500 MW for the same 455,000 m^3/d (100 MIGD) capacity.

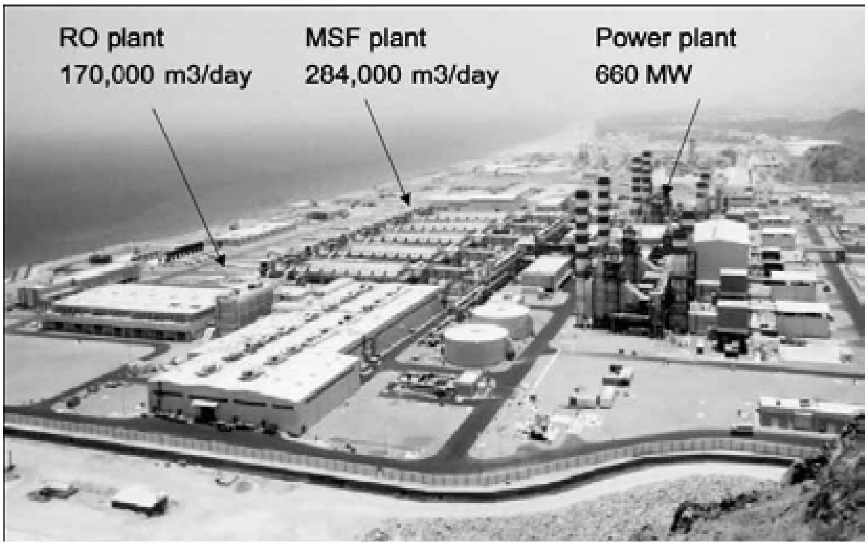

FIG. 16. Fujairah hybrid desalination complex, net output: power 500 MW 454,000 m^3/d (Courtesy Doosan Engineering).

The Fujairah desalination plant is split into 284,000 m^3/d (62.5 MIGD) from the thermal part and 170,000 m^3/d (37.5 MIGD) from the membrane process. The power plant is configured as a combined cycle with supplementary firing. It comprises four gas turbines each rated 109 MW (oil- or gas-fired) and four heat recovery steam generators each of 380 t/hr at steam parameters of 68 bars/537°C that supply the two steam turbine generators. The expanded steam from the turbines serves as process steam for the MSF units.

The Fujairah Project uses gas that is currently imported from the Sultanate of Oman, and will soon be imported from Qatar, when the Dolphin project is completed at a fuel cost of $1.6 per million Btu. At a rather low power-to-water ratio of 500 MW-to-100 MIGD, a hybrid MSF/RO technical solution was extremely attractive for the Fujairah project. Doosan Heavy Industry and Construction Company were selected as the EPC contractor through an open and competitive bidding process. The main contract was awarded in June 2001. Doosan selected Degremont as a subcontractor to receive the basic design and major equipment supply of the SWRO Plant. During the design stage an extensive pilot plant testing of the RO process was conducted to confirm the performance of the technical solution selected for pretreatment and to determine the impact of dosing of various pretreatment chemicals.

The 100 MIGD (455,000 m^3/d) water productions started on June 31 2003, with a total construction, commissioning, and startup time of less than two years. The Total Dissolved Solids (TDS) of the product water from MSF units was specified as 25 mg/L, whereas, that from RO plant was not specified in Request for Proposal (RFP) documents from the client. However, the TDS of potable water after remineralization was specified as less than 200 mg/l. In order to meet the potable water quality of the MSF/RO hybrid process, RO plant should produce desalinated water having less than 180 mg/L of total dissolved solids at the end of fifth year to make blended product water having 60 mg/L of TDS. The RO plant is designed as a two-pass system, specifically to obtain the low chloride and TDS contents of the drinking water required for corrosion suppression.

The seawater desalination processes are designed for seawater TDS of 40,000 ppm and a seawater temperature design range of 22–35°C. Specified for the drinking water product is a maximum TDS of 200 mg/L and its chloride content should not exceed ~85 mg/L. The blended product from MSF and SWRO is treated in a joint potabilization facility, supplied by CO_2 from the MSF vent gases.

To compensate for the conditions that one of the MSF units being taken out of service or for enhanced hardening of the water, the CO_2 demand can be met by an additional CO_2 generation plant.

Seawater intake. The seawater intake is located at 320 meters from the seashore at 6 m above the seabed and 6 m below the surface of the mean sea level. The seawater intake system consists of three submerged pipes 1200 mm diameter, and 500 meters long. Minimum depth at intake point is 9–10 meters. The seawater intake serves RO Plant, MSF Plant and as well as Power Plant. Two of the pipes are dedicated to the MSF Plant for which seawater is chlorinated continuously. The third pipe is allocated to the SWRO Plant only. This to allow intermittent shock chlorination of the seawater used for RO to be carried out rather then continuous chlorine dosing applied to MSF feed. Two of the ten raw seawater pumps are assigned to the RO Plant. For this plant a design decision was made to separate intake for the RO plant, through which the specific chlorination requirements for SWRO can be maintained. It was chosen over the use of a common seawater extraction system. Feeding of preheated cooling water from the MSF reject section to the RO plant was also rejected because, here too, only water that had been chlorinated continuously, and in part shock dosed, was available.

In my opinion this decisions are controversial and in the future more considerations could be given to take clear advantage of common intake and feed temperature control. A study of shock chlorination on top of residual chlorine or de-aeration/dechlorination of RO feed could allow the benefits of hybrid integration.

SWRO plant. The RO Plant consists of two independent identical lines, called Line A and Line B. Each Line includes nine First Pass RO trains and four Second Pass RO trains. The First Pass RO train is designed to produce desalinated permeate water with a TDS of maximum 590 ppm at design condition at the end of fifth year. However, if the permeate water with a TDS of 590 ppm, set as design salinity limit from a single pass of RO plant, is blended with 25 ppm of desalinated water from MSF plant, the specified potable water quality target of 200 ppm could not be accomplished. Should the required quality (TDS) of potable water were above 300 ppm, which is still far better than WHO recommendation, only single pass of RO plant could have been enough for the hybrid plant. Then, this would have resulted in a more attractive economics of the MSF/RO hybrid water plant. The first pass is design for a recovery rate of 43% and consists of 18 trains, with 17 normally being in operation and one on standby. The second pass that consists of eight trains has a capacity of 74% of the maximum total output of the SWRO, and is designed for a recovery rate of 90%.

MSF plant. The MSF plant consists of five MSF units, each producing 57,000 m^3/d (12.5 MIGD). The evaporators contain sixteen heat recovery stages and three heat rejection stages. It have been manufactured as a single module in South Korea and transported to the site on a barge. The thermal desalination segment of the facility comprises five MSF units each of 57,000 m^3/d (12.5 MIGD) capacity, with a performance ratio of 8 and a top brine temperature (TBT) range of 107–109°C (224.6–228.2°F). Fujairah plant-MSF area overview is shown in Fig.17.

FIG. 17. Arial view of the Fujairah MSF desalination plant.

7.4. Performance of the Fujairah hybrid plant

Fujairah hybrid performance as reported by Sung W. Woo et al. [18] of Doosan deserves a more detailed review but is briefly summarized.

MSF plant performance. The performance of each MSF unit in terms of distillate flow rate and distillate conductivity is much better than the design and guaranteed values. The average performance ratio of the MSF units was in the range of 9.1~9.5, which was higher than guarantee value of 8.0 at design condition. During the reliability and performance test, specific power consumption of MSF plant including potable water plant was about 4.4 kWh/m^3 (16.7 kWh/kgal) of product water, which is less than guaranteed value 5.1 kWh/m^3 (19.3 kWh/kgal).

Plant performance (SWRO). The SWRO plant commenced operation on June 31, 2003. The plant has performed satisfactorily, complying with all contract obligations as regards to water quantity and quality in accordance with performance specification defined in tender document. The RO plant is shown in Fig. 18.

Performance of pretreatment section

During the last year, the Silt Density Index (SDI) remained between 3 and 4, which is much below the SDI limit value of 5.0, as specified by the membrane manufacturers. Backwash frequency of media filters also remained at design frequency, one backwash per 24 hours.

RO membrane performance

Normalized permeate flow rate and salt passage. The normalized permeate product flow rates are higher than the projected initial permeate flow rates and the initial normalized salt passages are less than that of the projected salt passages until the beginning of October 2004. Therefore, since their loading on April 2003, the membranes need not be cleaned nor replaced. All trains showed a trend of improving conductivity with time when operated continuously. Projected pressure is 67.6 bar (972 psi) while the actual pressure ranges between 67 and 67.5 bar (971–972 psi). Based on this comparison of projections with trains in Line B, the membranes are performing as expected, even though the operation of the trains was intermittent and for short periods of time. Performance trend indicates that continuous operation of the trains will produce permeate conductivities equivalent to or below the projected values. The performance of SWRO membranes is good enough up to now even without chemical cleaning or membranes replacement. Boron concentration was not of RO permeate quality specifications. Therefore, no particular equipment such as pH control or ion exchange bed, etc. has been installed. However, RO plant provided eighty percent (80%) of boron rejection, resulting in 0.7 ppm content in desalinated permeate water. When the permeate water from the SWRO plant was blended with the product water from MSF plant, the boron content in the mixed water was 0.3 ppm, which is less than WHO recommendation (0.5 ppm). In conclusion, the overall membranes performance is good till today.

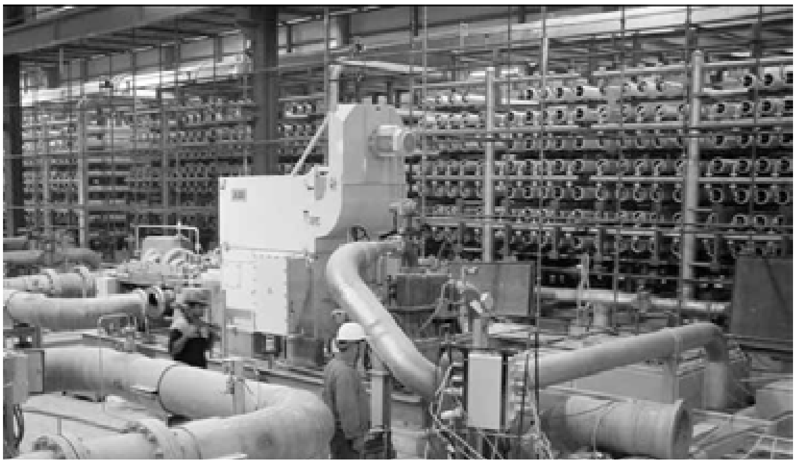

FIG. 18. Fujairah plant SWRO racks and feed pump/ER turbine

7.5. Overall Fujairah conclusions

The combined power consumption of the Fujairah hybrid (SWRO + MSF) plant is lower than would be required by an MSF plant of the same capacity. The possibility of blending of RO permeate with MSF distillate enables reliable production of potable water of very low salinity in respect of every constituent, including boron. A proper combination of MSF/RO hybrid desalination plant to reduce capital and water cost depends on various parameters such as power-to water ratio, potable water quality, system configuration, etc. Up to now, the potable water quality (TDS) from MSF plants in Middle East has been specified as less than 150 ppm. However, if the potable water TDS of an MSF/RO hybrid desalination plant is specified to be around 250–300 ppm, which is still quite less than WHO recommendations, then MSF/RO hybrid plant water will become much more competitive against MSF plant only, resulting in lower water cost.

8. Hybrid variations

As the concepts and applications of hybridization are accepted between distillation processes and RO, we believe that membrane manufactures will develop a new generation of membranes. This new generation of membrane [7,19,20] is characterized by a very high specific flux about double the flux of the current generation with small reduction in salt rejection. The current high flux membranes, developed for brackish water desalting demonstrated the ability to significantly reduce the cost of desalting and will be ideal for hybrid plants that include distillation units.

8.1. Hybrid system using multi-effect distillation

Multi-effect distillation (MED) is in our opinion the most important large- scale evaporative process offering significant potential for water cost reduction. The major potential advantage of MED process is the ability to produce significantly higher Performance Ratio (PR) in excess of 15 pounds of the product per pound of steam where MSF practical limits PR to 10. The size of MED units is growing rapidly. In Sharjah, SEW operated for last two years the largest commercial MED units of 22,700–36,4000 m^3/d (5–8 MIGD). Similar capacity unit is under construction in SEWA Layyah Station, and the design and demonstration module already exist for 45,500 m^3/d (10-migd) unit. MED recently received a lot of attention, as a result of numerous commercial successes of Thermocompression like MED for Al Taweelah A1 a 53 MIGD (240,000 m^3/d) capacity plant. In general MED capital cost today varies from US$ 1000–1300/m^3/d (US$ 4.5–6.00/igpd) capacity. The future calls for increasing top operating temperature, finding new ways to improve heat transfer performance to reduce heat exchange area, search for an increase in heat transfer performance by tube enhancement, and use of very thin wall in tubular materials. The critical challenge is to adopt Nanofiltration as means to dramatically increase output and increase efficiency of MED plants.

9. Hybrid using nanofiltration-membrane softening

Membrane softening technology adapted to hybrid with distillation processes could lead to significant increase in productivity of existing and future distillation plants as well as resulting in better process economics. Similar to reverse osmosis, nanofiltration (NF) is based on solution-diffusion as major transport mechanism; however, nanofiltration membranes contained fixed (negatively) charged functional groups on the membrane surface.

As a result, the selectivity of NF membranes for monovalent and bivalent anions is significantly different as compared to regular RO membranes. Specially designed NF membranes have capability of high rejection for divalent ions (Ca, Mg and SO_4), while allowing relatively high passage of monovalent ions (Cl, Na and K).

9.1. Nanofiltration hybrid background

The basic idea of use of ion selective membranes as a presoftening process for seawater distillation goes back to early publication in 1980 by Wensley et.al. [21] and Furukawa communication [22]. Today pioneering work on Nanofiltration membrane NF softening technology as applied to desalination processes and specifically to seawater desalination is under active development by two groups the Leading Edge Technologies Ltd (LET) based on granted patents Awerbuch [23] and the Saline Water Conversion Corporation (SWCC) of Saudi Arabia based on Hassan patent [24]. Numerous publications described the concept Awerbuch [8, 25-27] and SWCC published extensively the results on tests of NF at the Research Desalination Center at Jubail and the plant at Umm Lujj, Hassan, Sofi et.al. [28-30]. The latest status of both NF Technologies are described in the proceedings of IDA World Conference in Singapore 2005 Awerbuch [31] and Hamad et al. [32]. The LET and SWCC have two different solutions but both are based on effective use of Nanofiltration softening membranes to increase efficiency of desalination process.

In case of LET the basic claim is that:

An improved desalination process to produce potable water, which comprises:

(i) passing a first stream of water containing a high concentration of hardness ions through an ion selective membrane to form a softened water having a reduced content of hardness ions;
(ii) blending the softened water with a second stream of water containing a higher concentration of hardness ions than the softened water to form a feed to a desalination system;
(iii) introducing the feed to the desalination system to form a water product of potable quality,

wherein the improvement comprises the introduction of a feed of variable proportions of the softened and second stream of water to the desalination system to increase the top operating temperature of the system and increase recovery of potable water.

The LET invention of partial softening of the stream feeding desalination processes sufficient to achieve reduction in scaling potential can be directed to both to thermal processes like MSF, MED and VC and membrane processes like RO and as well as is an improvement on hybrid system. The inventions comprises the operation of ion selective membrane at variable pressure as a function of the cost of electricity, use of waste or reject heat to improve fluxes and soften only variable portion of the stream to be able to increase the operating temperature and recovery.

The scaling of seawater concentrate or recycle brine occurs due to inverse solubility of calcium sulphate at higher temperatures. At higher operating temperatures and high recovery or concentration factor the stable crystal form is Anhydrite and Hemihydrate. In order to take advantage of higher productivity of distillation plants, through operation at higher temperature, we need to reduce calcium hardness and/or sulfate ions concentration in the feed water.

9.2. Design experience with nanofiltration hybrid for MSF.

The great potential of nanofiltration membrane softening technology was brought to focus by recent award by Sharjah Electricity and Water Authority (SEWA) to Besix Leading Edge Water Technologies for the first commercial LET Nanofiltration System to increase capacity of existing MSF plant from nominal 22,7000 m^3/d to 32,800 m^3/d (5 MIGD to 7.2 MIGD) see Fig 19. This over 40% increase in capacity of MSF unit was a result of a two year demonstration and simulation program developed jointly with SEWA.

The data analysis and modeling of the Test Data provided extremely valuable information allowing improvements in operations as well the development of an integrated program for the optimization of the power-desalination plant.

The results demonstrated that the output of the existing plant described by Sommariva et.al. [33] was increased from the designed capacity of 1,010.5 t/h at 105°C (221°F), or the designed capacity of 1,044.4 t/h at 110°C (230°F) to an output of 1253 t/h.

FIG. 19. MSF 5MIGD Layyah plant subject of integrated upgrading

This is equivalent of raising output from 5.33 MIGD to 6.61 MIGD, a 24% increase in plant output without any major modifications having been made to the plant. The maximum production of 1,260 t/h, equal to 6.65 MIGD, was achieved when the TBT was increased to 117°C (242.6°F) with conductivity of product at 454 S/cm^2 (Fig. 20).

This was the first time anywhere that a commercial MSF plant using chemical additives was operated at these TBT temperatures. At these elevated temperatures the major concern is scale formation of calcium sulfate. Due to the simulated conditions of the LET NF System, no fouling of hard scale or soft scale was encountered at these elevated temperatures, and the plant operated in a reliable fashion throughout the test period. In fact the subsequent analysis of the critical

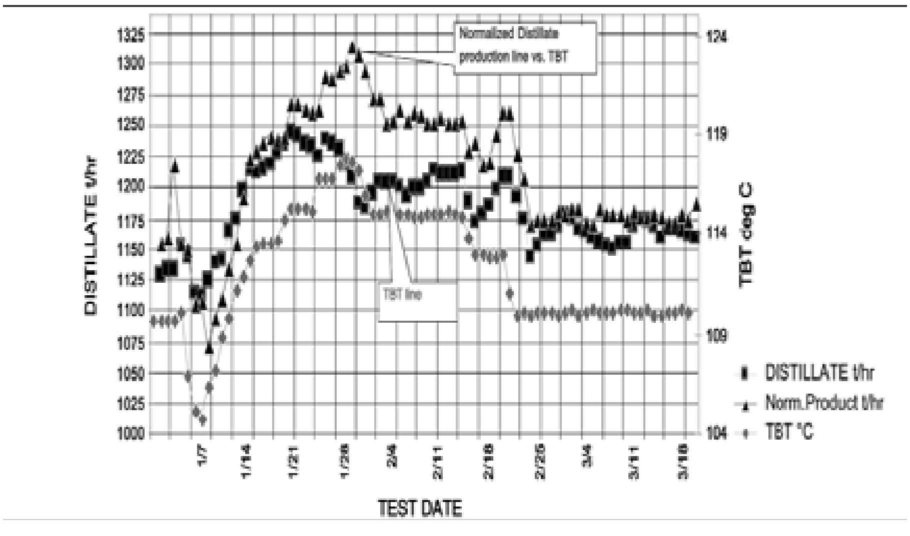

FIG. 20. Distillate production as a function of TBT at the Sharjah plant.

Fouling Factor (FF) in the brine heater indicated a decline. This reduction in the FF was possible due to an increased dosing of chemical anti-scalant and was stabilized applying a Tapproge procedure (on-line continuous mechanical cleaning system utilizing specially engineered sponge rubber balls which are cycled with seawater through the condenser tubes.

These very good FF results were achieved not withstanding the fact that during the runs the recycle brine concentration was higher then specified by LET. The on-line acid cleaning which removed soft carbonate scale and brought the MSF to higher production than before the test demonstrated that there was no build up of hard scale and the lower FF implied that also there was no build-up of soft scale during high temperature runs. Not withstanding these good FF results the team developed additional means to protect the MSF plants from scale.

Any MSF plant will produce more output with an increased flashing range (defined as TBT minus blowdown temperature), or with an increased recycle flow or both (Fig 21). The analysis clearly demonstrated that with achievable increased flashing range and brine recycle flow (normalized) it is possible to produce 1,309 t/h of distillate at 118°C (244°F). One of the main constraints was the increased conductivity in the last stage during the periods of highest temperatures, which forced a reduction in the flashing range, and therefore, reduced the maximum output. The data analysis identified many reasons why the last stage vapor velocity exceeded significantly the normal design. The data analysis identified excessive flashing of the makeup in the deaerator, stripping steam flow from stage 13, and heat transfer from upper, high temperature, stages to the last stage, due to the "double-deck" construction of the plant.

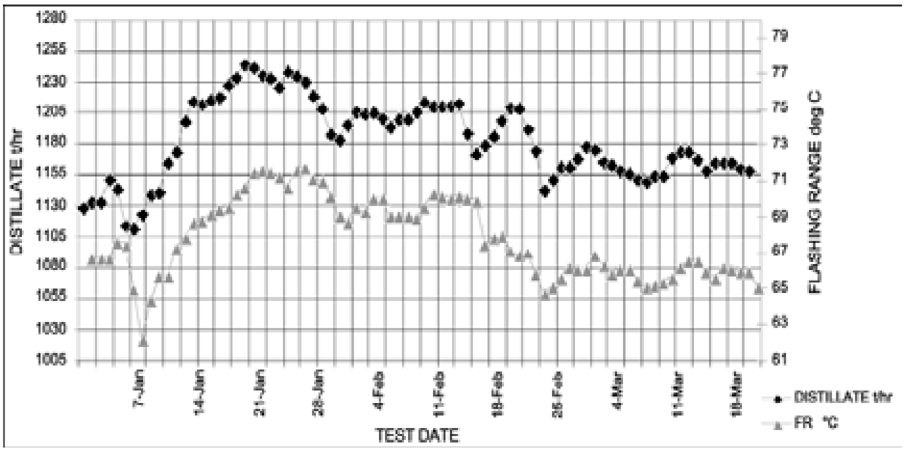

FIG. 21. Distillate production as a function of flash range at the Sharjah plant.

While certain features of the plant need to be adjusted to further increase and maximize the plant output, in response to higher operating temperatures and increased product volumes, no major technical issues were encountered that could prevent the application of the LET technology. Once the plant has been suitably modified and upgraded in accordance with mutually agreed recommendations the MSF plant will operate reliably at maximum output [34].

FIG. 22. Layyah integrated upgrading the NF system

The additional capacity (Fig. 22) is achieved without building new intake structure or new power plant in a very limited space, which would not allow construction of new desalination plant. The system involves construction of NF plant to provide partial membrane softening of feed to MSF as well as modifications to existing MSF plant to be capable to achieve the increased capacity.

The concentration of sulfate and calcium ions determines in the distillation process the top temperature and concentration factor. Even partial elimination of calcium and sulfate from the feed will dramatically improve the performance of distillation plants. By increasing top temperature from current 95–110°C to 120–125°C would increase water production from existing MSF plants by 25% to 45%. The partial removal of sulfate and calcium ions from the feed has a multiplying positive effect on reduction of scale potential. With the current high quality materials of construction the negative corrosion effects of higher temperature would be minimal. The NF system will substantially increase water production from MSF plants.

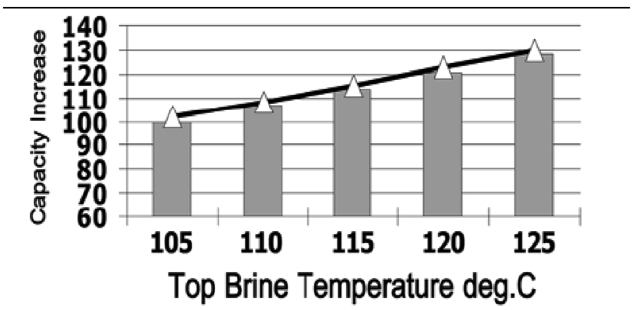

FIG. 23. MSF capacity increase vs. TBT.

9.3. Design and construction of the commercial LET NF plant.

The construction of first commercial nanofiltration Hybrid plant with existing MSF awarded to Besix Leading Edge Water Technologies JV is now completed and the final performance testing boosted the output of the MSF unit to over 7.5 MIGD of desalinated water in the Sharjah Emirate [35].

— Projected benefits of NF—MSF plant at Sharjah:

— Increase the capacity of the existing MSF plant by 44%, from 22,700 m^3/d to 32,800 m^3/d (5 MIGD to 7.2 MIGD)
— Minimum footprint (site has no room new additional plants)
— Reduction of operating cost
— No change to existing intake structure
— No increase of power facilities
— Reduction of capital cost for additional capacity by 40%

The additional capacity is achieved without building new intake structure or new power plant in a very limited space, which would not allow construction of new desalination plant Fig. 23.

The main features. The softening process is based on nanofiltration technology, apart from an optimized hydraulic operation; the implementation of the technology allows the thermal units to be safely operated at an increased Top Brine Temperature (TBT) thus allowing to substantially increasing the potable water production.

The plant incorporates the following features:

(a) A blending system for hot and cold seawater to keep the feed water temperature in the right range. The blending facilities are located at MSF plant. After blending, the water is pumped to the nanofiltration plant Fig.24.

FIG. 24 Integrated upgrading temperature blending system at Layyah

(b) The raw seawater needs to be pre-treated to avoid fouling and clogging of spiral wound NF membrane elements. Therefore, the water is first pre-treated by means of sand filtration. In order to enhance the efficiency of this pre-treatment, before it enters the sand-filters, the water is pre-treated by means of pH control and coagulation/flocculation.

(c) After sand filtration, the water passes a cartridge filter system, which acts a final barrier to retain water contaminants. This filter system is to be considered as a guard cartridge filter system, which "boosts" the feed water quality after the sand filters and which protects the membranes in case the efficiency of the sand-filtration units is reduced.

(d) Prior to the injection of the pre-treated seawater in the membrane, the water is conditioned in order to maximize membrane life time and in order to reduce the risk of bio fouling and scaling. The treatment incorporates the injection of SBS to remove free-chlorine, the shock dosing of biocide to control bacteriological growth and the continuous, on-line dosing of anti-scalant.

(e) Water then passes a two-stage nanofiltration membrane system. In order to pass the water through the membranes, medium pressure pumps are used. After the membranes, seawater is partially discharged as permeate—which is the softened water—and as concentrate—this is rejected and pumped back to the sea.

(f) Each membrane system is subject to clogging. This clogging can be caused by biological fouling as well as through scaling phenomena. When this "clogging" reaches a certain level, the system pressures will reach their maximum operational values. Membranes need than to be cleaned by means of different chemicals. This is executed "in situ" (after which the system can be taken back into service.

(g) Due to the specific site conditions at the power plant, the gravity discharge of the rejected concentrate and drains is not possible. Therefore, all waters are collected in a pump-pit below grade level after which the water is pumped to the existing outfall culvert.

(h) After leaving the membranes, the softened water is discharged to an intermediate storage tank. From this tank, the water is pumped at a controlled flow to MSF where is injected in the deaerator and/or in the hot well. The storage tank offers a spare capacity of approx. 1–1/2 hour, which allows TBT of MSF to be reduced when softened water feed is interrupted due to failure of the nanofiltration plant. The feed water source for the NF system is tied in to the seawater piping of the existing MSF unit from where it is pumped to the location of the NF facilities.

In order to obtain the most optimum feed water temperature for the NF membranes, "cold"— and "hot" seawater can be "mixed" before the NF supply pump to achieved constant temperature to NF around the year. Maximum temperature of the water actually entering the membrane should be in range and not exceed 38–40°C with today available membranes.

In order to optimize the performance of the pre-treatment and the NF-membranes, the feed water flow is pre-conditioned by chemicals. This main purpose is to obtain better SDI values after the pre-treatment and to control the pH range of the feed water to optimize the water chemistry with respect to membrane scaling and softened water production. The pH control is obtained through the in-line addition of HCl. Better SDI values are obtained by enhancing the filterability of the feed water flow through the addition of chemicals which favor floc-formation. All chemicals are dosed in line and mixed with the feed water by an in-line static mixer prior to the sand filters. There are 8 sand filters, which can be operated as a single stage unit or as a dual stage unit Fig 25. The sand filters are pressurized and are of the dual media type which means that two filter media are used (filtration sand 0.45 mm and hydro-anthracite) in the same vessel. The cartridge filter serves as safety filter prior to the main booster pump and the membrane system. The system incorporates 12 separate pressure vessels, which contain each a cartridge filter with high filtration efficiency. Water can only be directed to this cartridge filter if the sand filtration units work properly and the water after the sand filters meets the quality requirements (SDI <4).

NF-membrane system. The system is of the two stage design and incorporates the following features using Dow Filmtec Nanofiltration XUS229323 elements:

1. *One main-booster pumps* to pressurize the feed water prior to injection in the membrane system. System pressure: 12.5 to 17.5 bar (181–254 psi).

2. *First stage NF membrane treatment*—80 pressure vessels with 480 membranes. The first stage is split-up in two identical skids (arrays), which 40 pressure vessels each and 240 membranes each. During the membrane filtration process, the feed water is split-up into two flows: the permeate (the softened water) which passes the membrane and the concentrate which did not pass the membrane and is "rejected." The permeate from the first stage is collected and flows to the product water tank, the concentrate serves as feed water for the second stage

3. *One intermediate booster pump,* which re-pressurizes the concentrate of the first stage (= feed water the second stage) prior to injection in the second stage. System pressure: 15–20 bar (218–290 psi).

4. *Second stage NF membrane treatment*—40 pressure vessels with 240 membranes. The second stage incorporates one skid. During the membrane filtration process, the feed water (which is actually the concentrate of the first stage) is split-up into two flows: the permeate (the softened water) which passes the membrane and the concentrate which did not pass the membrane and is rejected. The permeate from the second stage is collected and collected in a product water tank; the concentrate is discharged to the outfall pit from where it is returned to the sea.

The two- stage design allows to obtain a high recovery rate (recovery = ratio between useful softened water output and total feed water flow to the membrane system). The recovery rate of this system is approx. 70%. When the NF plant is into operation, the softened water storage tank is full and no alarms from the NF plant are communicated back to the MSF automation system, the output of MSF 9 can be gradually increased until an output a potable water of 7.2 MIGD is reached. Throughout this process, plant data should be monitored (including the plant fouling factor). At first, total NF permeate flow (softened water) is be directed to MSF 9. The water will be injected by preference prior to the de-aerator. However, flooding of the de-aerator should be avoided. Flow can be directed to the de-aerator up to the point of flooding; the remaining softened water flow to be directed to the hot well. This will be tested prior to increasing the TBT. The TBT shall not be increased by more than 2°C (3.6°F) at a time and should never exceed 121°C (250°F). When a capacity of 32,800 m^3/d (7.2 MIGD) is reached, TBT should not be further increased, even if TBT at that moment is lower than 121°C. The Control system is arrange in such a way that MSF plant can return safely to lower temperature of operation below 110°C (230°F).

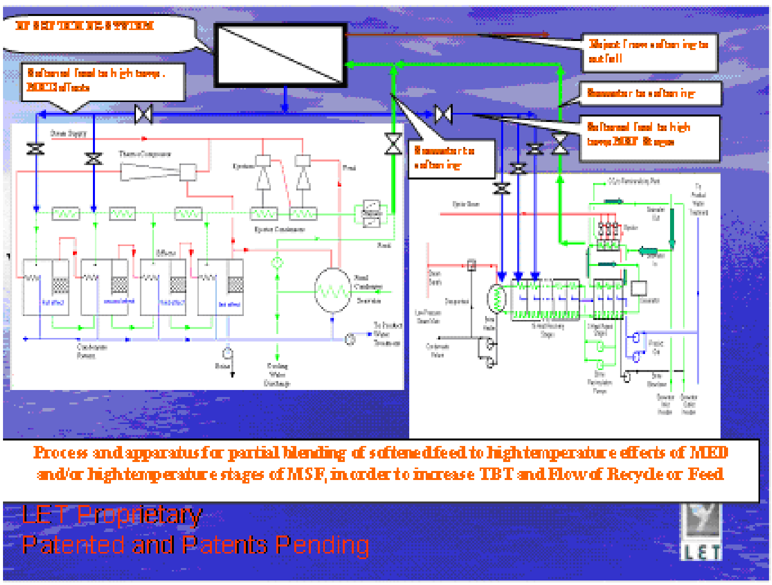

FIG. 24. Alternative arrangements of LET NF system for upgrading MSF and MED capacity

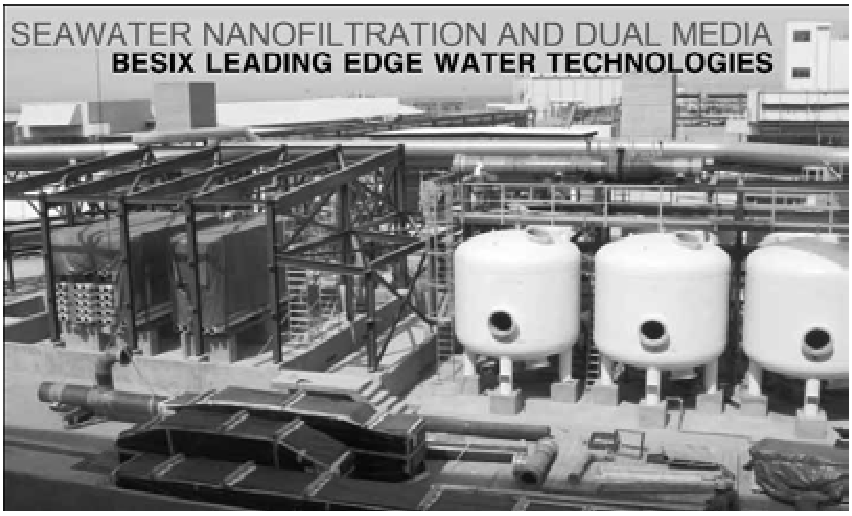

FIG. 25. NF trains and media filtration units.

9.4. Nanofiltration hybrid variations

There are many potential variants for NF hybridization with NF-MSF-RO as well as NF-MED-RO. Below are a few examples developed by Bechtel-LET and proposed for large scale implementation.

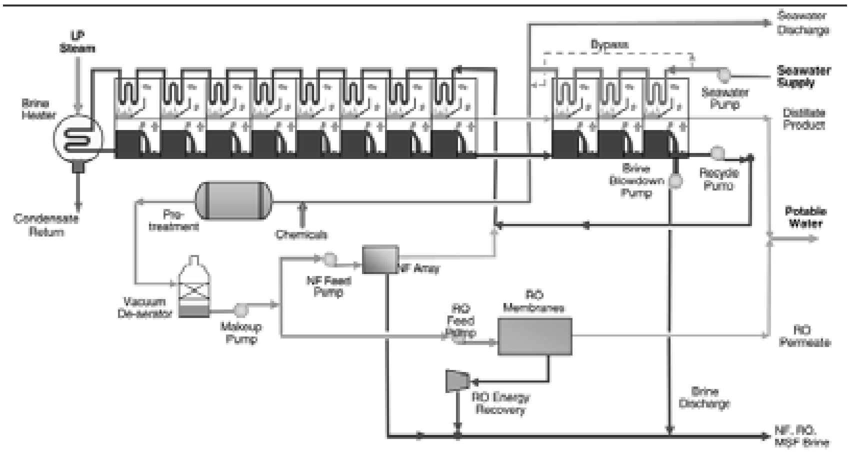

FIG. 26. Hybrid is with NF prior to MSF.

The case above (Fig. 26) is the basic case of NF system similar to previously described as SEWA project. The following schematics (Fig. 27) shows a combination of preheated feed being softened and fed to MSF and RO based on optimum split between to desalination processes to achieve the lowest product cost.

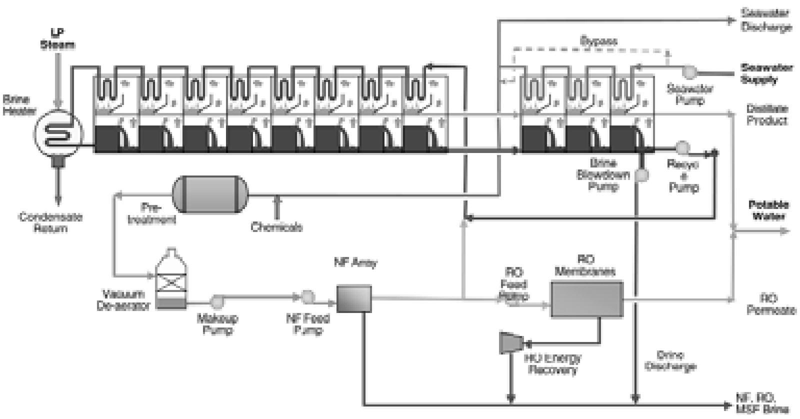

FIG. 27. The hybrid solution with NF prior to MSF/RO

In the final scheme (Fig. 28) the seawater is preheated in MSF reject section, and then is softened by nanofiltration membrane, follow by SWRO. The reject brine of SWRO has significantly reduced level of scaling ions sulfate, calcium and magnesium and therefore the reject brine can be the feed for distillation plant.

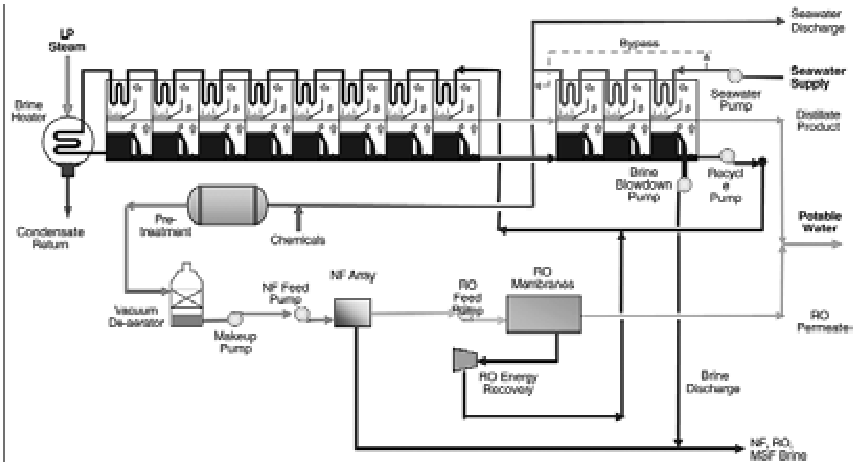

FIG. 28. The hybrid with NF and RO reject feeding MSF.

NF membrane softening technology could significantly improve operation and reduce the cost of the MED process, specifically when applied to MED processes using advanced heat transfer surfaces like double fluted tubes, by eliminating the risk of scaling and fouling. NF technology will permit increase in the top temperature resulting in significant increase in output and performance ratio.

10. Hybrid systems using vapor compression distillation

The Vapor Compression distillation (VC) technology offers unique potential. Today power/MSF/MED/RO plants can be hybridized with VC to take advantage of increase distillation output, using electrically driven technology. Currently the largest scale unit of VC is 3000 m^3/d capacity or 0.8 mgd in a single unit, which consists of three evaporator-condenser effects couple to a single high volumetric compressor. This large scale VC guarantees unit specific electricity consumption of 7.5–8.5 kWh/m^3 (28.4–32.2 kWh/kgal) of product (excluding sea water supply). They produce high purity 10–20 ppm distillate at high plant availability of 94–96%. In future vapor compression distillation units, will grow in capacity and number of effects. Design of VC over four and more effects, staging compressor in series or parallel will allow effective hybridization of power with MED, MSF and RO. This particularly will be important in cases where power to water ratio has to be minimized in favor of water production.

11. Hybrid systems using MSF-MED

In distillation processes there is no interaction between MSF and MED energy process streams. Substantial efficiency improvements could be obtained if process streams between MSF and MED are exchanged in order to take advantage of the different operating temperature conditions of each plant. In particular, due to the low MED operating temperature (61–67°C, 142–153°F), this process could be thermally driven by process streams properly sourced by an adjacent MSF plant. A number of novel technology options for distillate hybridization (LET–Mott McDonald patent pending Fig.29) and feed and heat MSF-MED process coupling (LET patent pending Fig.30) that have been studied and their possible implementation in a real scale plant should be available soon.

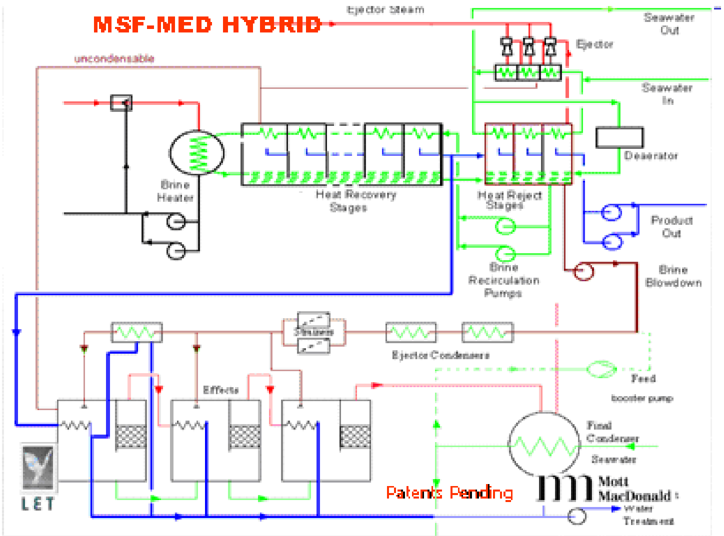

FIG. 29. Integrated hybrid MSF-MED using distillate

The objective of the MSF-MED hybrid is to increase energy efficiency, distillate production and minimize operational costs. Results of such hybridization combined also with RO and NF is well described Sommariva et al. [36].

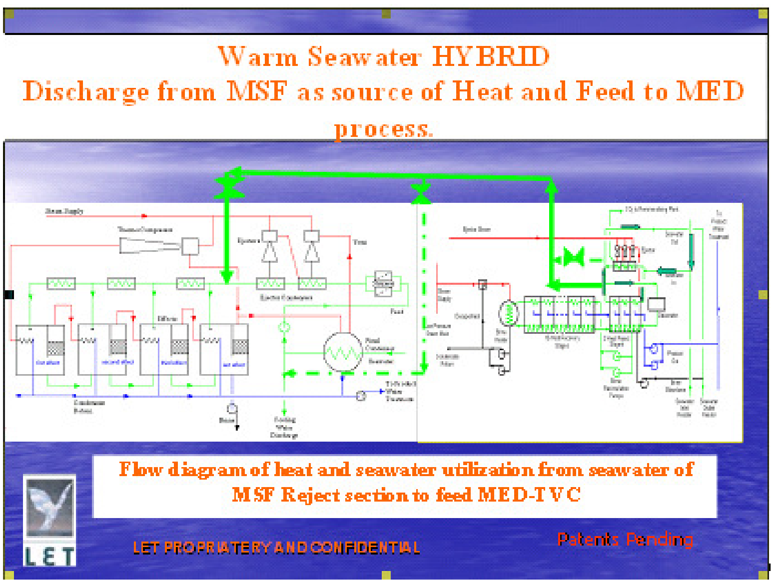

FIG. 30. Integrated Hybrid MSF-MED using heat and feed

12. Hybrid systems and Desalination Aquifer Storage Recovery (DASR)

Cost-effective integration of three proven technologies, desalination, power and aquifer storage recovery (ASR) can secure a reliable, sustainable and high quality fresh water supply for the Gulf States. LET pioneered in the Middle East the concept of strategic and economic storage and recovery of desalinated water (DASR) and waste water (WASR) to the security of its communities. The idea is covered in many papers [37-40].

The seasonal surplus of unused idle power could be used by electrically driven desalination technologies RO and Hybrid Systems including NF/RO/MSF process in combination with ASR creating a system of Desalination/ Aquifer Storage and Recovery (DASR). The ability to store and recover large volumes of water can contribute to the average downsizing of power and water facilities with substantial operational cost savings. DASR provides strategic reserves of potable water, to prevent damage or depletion to existing oasis or aquifers, for controlling salt-water intrusion, or improvement in water quality.

DASR is of strategic importance to the Middle East Principle of DASR technology

— Electricity demand drops 30–40% of peak demand during the winter months
— During that period over 50% of power generation plants are idle
— The idle power can be utilized to produce low cost water using hybrid technologies
— Produced water is stored in underground aquifer for summer use

A desalination plant will operate continuously with modulating its output depending on power demand. Typical water storage volumes for desalinated water are limited to providing less than one day of water supply, a highly vulnerable situation.

13. Hybridization conclusions

Combining thermal and membrane desalination processes and technologies within a single plant or in hybrid plant schemes can *reduce desalinated water costs*, and, as part of dual-purpose stations; *add flexibility* to the combined water and power production and *reduce any existing water and power demand mismatch problems*

It can be seen that applying hybrid solutions will reduce desalinated water costs, compared with non-hybrid schemes, from as little as 2–3% to as much 15%. In large desalination plants, there should also be little loss of economies of scale due to the use of two or more different processes, in two or more smaller units, in lieu of one large, single-technology plant. Many such plants, at the same site, are based on the same process (MSF), but utilize different designs and have different performance figures. All the solutions whether stand-alone high-GOR plants (LT-MED/TVC, HT-MED) or hybrid schemes (MSF/SWRO, MVC/MED, MVC/TVC, etc.) requires use of the largest size plants available. The hybrid of power-desalination systems, from its early concept of power– MSF–RO to blend the products and minimize power generation, leads to many new ideas.

— Hybrid of MED-RO has many of the same advantages than the MSF-RO, but has the ability to cut significantly power water (PWR) ratio
— Hybrid of MSF–MED with VC has the potential of boosting water output through simple or full integration and at the same time reduces power to water (PWR) ratio.

— Hybrid with Nanofiltration–Softening Membrane will provide the ability to increase desalination output of distillation plants MSF and MED, by reducing scaling potential of the feed, increase the top brine temperature and provide significant better concentration factors and recovery for all distillation processes.
— Hybrid with electrically driven desalination technologies RO and VC would allow use off peak power for water production, and minimize power capacity by shutting down RO or VC daily during the peak.
— The seasonal surplus of unused idle power could be used by electrically driven desalination technologies RO and VCR in combination with aquifer storage and recovery to create effective DASR solutions. All of the above ideas have a goal to maximize and optimize benefits of power and water generation in order to provide lower cost water the "Essence of Life."

Revisions: Leon Awerbuch, February 10, 2007, Winchester USA

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NUCLEAR ENERGY FOR NON-ELECTRIC APPLICATIONS: TECHNOLOGY AND SAFETY

(SESSION 2) (Plenary)

Chairpersons

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JAEA

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Opportunities, challenges and strategies for innovative SMRs incorporating non-electrical applications

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Abstract: In the near term, most new nuclear power plants (NPPs) are likely to be evolutionary water cooled reactor designs building on proven systems while incorporating technological advances and often the economics of scale, resulting from the reactor outputs of up to 1600 MW(e). For the longer term, the focus is on innovative designs aiming to provide increased benefits in the areas of safety and security, non-proliferation, waste management, resource utilization and economy, as well as to offer a variety of energy products and flexibility in design, siting and fuel cycle options.

This paper discusses the salient aspects including safety, economics and proliferation resistance of innovative small and medium sized reactors (SMRs) currently under consideration or in design/ development stage in a number of Member States. Some small reactors without on-site refuelling have also been looked in to.The opportunities and challenges to the innovative SMRs are outlined. Progress towards near deployment of some of the SMRs and their use for non-electric applications has been presented.

1. Introduction

There is an ongoing interest in Member States in the development and application of small and medium sized reactors (SMRs[1]). In the near term, most new NPPs are likely to be evolutionary water cooled reactor designs building on proven systems while incorporating technological advances and often the economics of scale, resulting from the reactor outputs of up to 1600 MW(e). For the longer term, the focus is on innovative designs aiming to provide increased benefits in the areas of safety and security, non-proliferation, waste management, resource utilization and economy, as well as to offer a variety of energy products and flexibility in design, siting and fuel cycle options. Many innovative designs are reactors within the small-to-medium size range, having an equivalent electric power less than 700 MW(e) or even less than 300 MW(e). In most of the cases, deployment potential of innovative SMRs is supported by their ability to fill niches in which they would address markets or market situations different from those of currently operated large-capacity nuclear power plants, e.g., more distributed electrical supply, matching the energy demand growth rate, siting flexibility, potable water production or district heating, hydrogen production, etc.

In 2006, more than 50 concepts and designs of innovative[2] SMRs were analyzed or developed within national or international programmes in Argentina, Brazil, China, Croatia, France, India, Indonesia, Italy, Japan, the Republic of Korea, Lithuania, Morocco, Russian Federation, South Africa, Turkey, USA, and Vietnam [1, 2]. Innovative SMRs are under development for all principal reactor lines and some non-conventional combinations thereof [2]. The targeted timelines of readiness for deployment are between 2010 and 2030. Innovative SMRs aim to

[1] According to the classification used by IAEA, small reactors are reactors with an equivalent electric power less than 300 MW, medium sized reactors are reactors with an equivalent electric power between 300 and 700 MW

[2] The IAEA-TECDOC-936 [3] defines an innovative design as the design "that incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice" and would, therefore, "require substantial R&D, feasibility tests and a prototype or demonstration plant to be implemented".

provide increased benefits not only in safety and economics, but also in proliferation resistance, energy security and other areas of concern relevant to future nuclear energy systems.

2. State-of-the-art in design and technology development for SMRs

2.1. Safety

Protection of population from consequences of accidents resulting from internal and external initiators and combinations thereof relies on traditional defence in depth strategies [2]. However, in addition to active safety systems, nearly all SMR designs reinforce the first and subsequent levels of the defence in depth by broad incorporation of inherent and passive safety features into design concept. The goal is to eliminate as much accident initiators as possible by design, with the remaining part then being dealt with by appropriate combinations of active and passive systems. The prerequisites are certain common features of smaller reactors, such as larger reactor surface-to-volume ratio facilitating passive decay heat removal and smaller core power density. The expected outcome is greater plant simplicity with a highly assured level of passive safety response to enable near-urban plant siting with enhanced protection against natural and human-induced external events.

Designers of innovative water cooled SMRs pursue an enhanced prevention or elimination of abnormal operation and failures by design. For example, they use integral layout of the primary circuit incorporating the steam generators and the pressurizer, providing for the elimination of large-diameter piping and large-diameter reactor vessel penetrations in order to prevent large-break loss of coolant accidents, Fig. 1. In some cases, they also apply the in-vessel location of control rod drives to eliminate inadvertent control rod ejection and to prevent transient overpower accidents, as well as to reduce the number of reactor vessel penetrations.

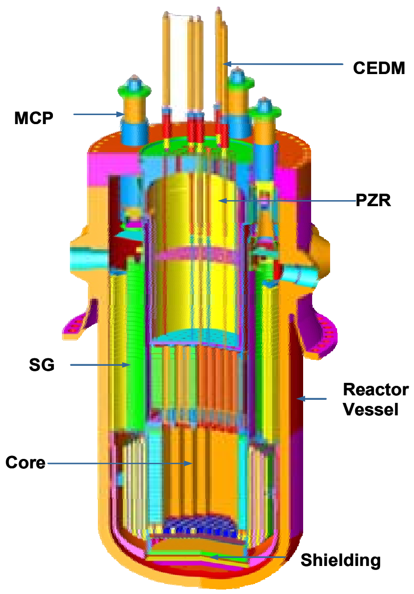

FIG. 1. Layout of the SMART integral primary coolant system. MCP = main circulating pump; CEDM = control element drive mechanism; PZR = pressurizer; SG = steam generator. (Source: KAERI-MOST, the Republic of Korea).

Alternately, compact loop-type designs with short piping and reduced physical connections between main equipment are applied, for the enhanced prevention of loss of coolant accidents, see Fig. 2. SMRs of such design are proven by more than 8000 reactor-years of operating experience of the Russian marine-propulsion reactors and have a high potential of being deployed in the very near term.

The designers of high temperature gas cooled reactors (HTGRs, see Fig. 3) exploit the outstanding fission product confinement capability of TRISO coated particle fuel at high temperatures – an inherent safety feature making a very important contribution to the overall defence in depth concept of such reactors. Proven in previous tests and operation, this capability is definitive for the prevention of consequences of severe accidents and also allows reducing the mitigation measures. Essentially, it may be important to release helium at an early stage of an accident, and only natural processes of conduction, convection and radiation in the static structures and media then effectively accomplish passive decay heat removal. This feature is complemented by slow and stable response to transients caused by both internal and external initiating events, due to large heat capacity of core graphite.

All fast reactors offer extended possibilities to 'build' the desired combinations of reactivity coefficients and effects by an appropriate selection of the design parameters of the core and reactor internals at the design stage. This possibility, resulting from a larger leakage rate of fast neutrons as well as from high core conversion ratio, can be effectively used to eliminate transient overpower accidents by design, to ensure the reactor self-control in a variety of anticipated transients without scram, to enable passive load follow capability of the plant, or to allow power control executed only via freed water flow rate adjustment in the steam-turbine circuit [2].

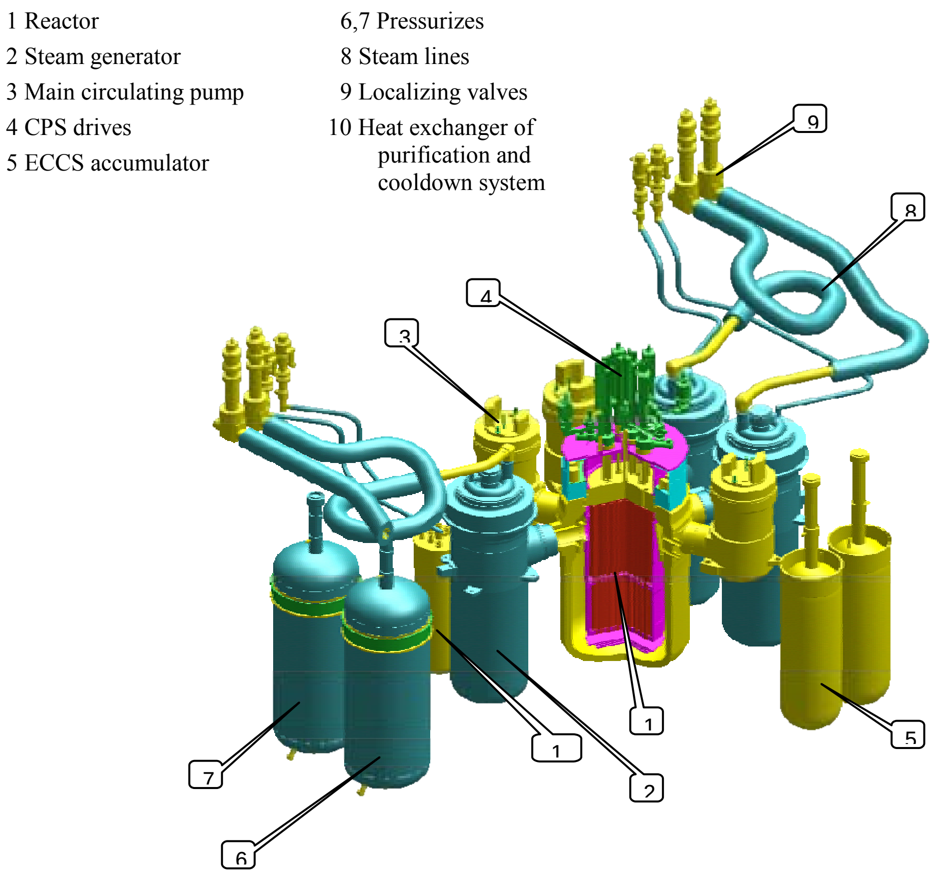

FIG. 2. Modular layout of the KLT-40S reactor plant (OKBM, Russian Federation).

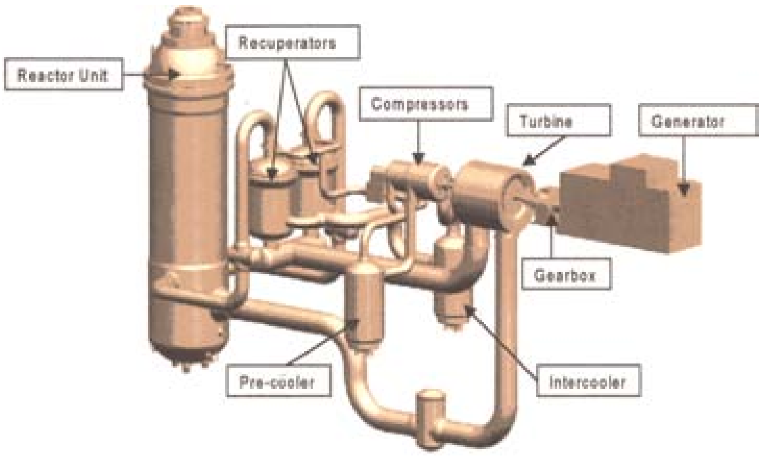

FIG. 3. Conceptual layout of the PBMR primary system, offering >41% energy conversion efficiency with direct gas turbine cycle (PBMR Ltd., South Africa).

2.2. Economics

To meet the needs of targeted customer groups, the designers of innovative SMRs all over the world examine new design approaches making use of certain advantages provided by smaller reactor capacity to achieve reduced design and operational complexity, simplified maintenance, and to incorporate higher overall energy conversion efficiency [2]. The design approaches used for such SMRs are unique, i.e., cannot be reproduced in reactors of larger capacity and, therefore, represent alternative strategies to the economies of scale, see Fig. 1,2, and 3.

The common strategies to improve economic performance of SMRs are [1, 2]:

- To reduce plant complexity by eliminating as many possible accident initiators and/or consequences as possible by design;
- To reduce site construction time and/or construction cost and achieve an early start of investment return by:
  - Sizing the reactor for transportability (or transportability of modules);
  - Targeting a standardized pre-licensed design with no site-specific modifications provided for;
- To benefit from factory mass production through serial manufacture of standardized plant modules, incorporating unified structures, systems and components;
- To incorporate an option of incremental capacity increase to achieve economic benefits of "just in-time" incremental capacity additions, taking a benefit of smaller module sizes to:
  - Achieve learning curve acceleration and discount rate savings per total capacity installed; and
  - To minimize investment risk.

The approaches to incremental capacity increase include:

- Setting aside space for future incremental plants;
- Sizing the switchyard, water and district heat distribution pipelines, etc. for growth;
- Sharing of railroad, road, and seaway access facilities among future increment plants; as well as
- Providing multi-module plant configuration with certain shared components, see Fig. 4.

SMR designers also target to reduce operation and maintenance (O&M) costs by reducing the number of structures, systems and components that require maintenance and, in some case, by targeting a passive load follow or autonomous operation. The example is small reactors without on-site refuelling that require no refuelling equipment and fresh and spent fuel storages at the site.

Even more can be done on the plant itself by improved conversion efficiency per unit of capital cost in the balance of plant.

Almost all of the water cooled SMR concepts use a Rankine steam cycle with saturated or slightly superheated steam for energy conversion. The energy conversion efficiency has a maximum of ~ 33% based on reactor core outlet temperatures from 270 to 345°C. Contrary to that, in most of the HTGRs, high efficiency of energy conversion ~ 41 − 50% is achieved through the use of direct Brayton cycles (see Fig. 5) or through purposeful use of the rejected heat. The use of higher core outlet temperatures and gas turbine Brayton cycles, is also considered for several longer-term liquid metal cooled, gas cooled and molten-salt cooled SMRs, see Fig. 6.

Bottoming co-generation cycles, incorporated in many SMRs to produce potable water, heat for district heating or process heat applications, and in some cases based on the use of heat otherwise rejected in the thermodynamic cycle, provide another option to increase overall plant efficiency [1, 2].

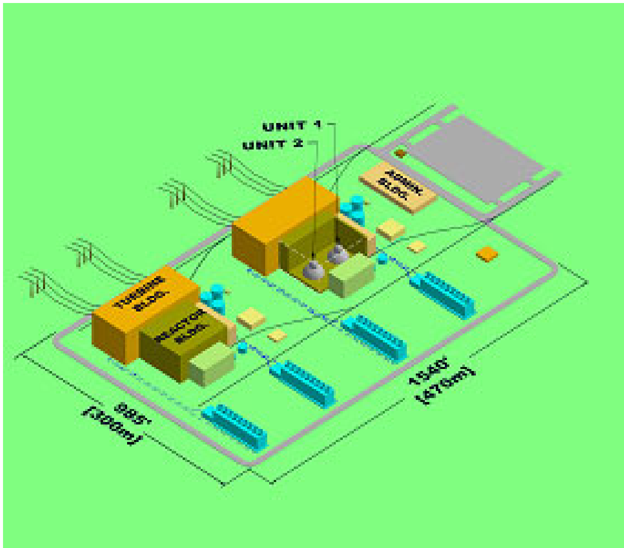

FIG. 4. Perspective view of IRIS multiple twin-unit site layout (Source: Westinghouse, USA)

2.3. Proliferation resistance

All NPPs with innovative SMRs will provide for the implementation of the established safeguards verification procedures under the agreements of member states with the IAEA. In addition to this, SMRs offer certain intrinsic proliferation resistance features to prevent the misuse, diversion or undeclared production of fissile materials and to facilitate the implementation of safeguards [2].

The features contributing to proliferation resistance of water cooled SMRs are essentially similar to those of presently operated PWRs and BWRs. They include low uranium enrichment, an unattractive isotopic composition of the plutonium in the discharged fuel, and radiation barriers provided by the spent fuel.

The intrinsic proliferation resistance features common to all HTGRs include high fuel burn-up (low residual inventory of plutonium, high content of ^{240}Pu); a difficult to process fuel matrix; radiation barriers; and a low ratio of fissile to fuel-block/fuel-pebble mass. Although several HTGRs make a provision for reprocessing of the TRISO fuel, the corresponding technology has not been established yet and, until such time as when the technology becomes readily available, the lack of the technology is assumed to provide an enhanced proliferation resistance. TRISO fuel is also considered for some innovative water cooled, molten salt cooled and lead-bismuth cooled SMRs.

Most of liquid metal cooled SMRs are fast reactors that can ensure a self-sustainable operation on fissile materials; some medium sized reactors are being designed to realize fuel breeding to feed other reactors present in nuclear energy systems. In both cases, and if the fuel cycle is closed, the need of fuel enrichment and relevant uranium enrichment facilities would be eliminated, which is a factor contributing to enhanced proliferation resistance.

However, a distinct group of SMRs – small reactors without on-site refuelling, accounting for more than a half of innovative SMR concepts developed worldwide – suggests another approach to increased proliferation resistance, which is to outsource all operations with fuel to a centralized factory or to limit them to an infrequent whole-core refuelling performed by a specialized vendor team. With all operations with fuel being outsourced, the reactor requires no refuelling equipment and fresh and spent fuel storage at the site; some designs of such reactors provide for lifetime operation with weld-sealed reactor, which suggests an option of applying item accountability on the reactor as a whole [1].

2.4. Small reactors without on-site refuelling

Small reactors without on-site refuelling are the reactors designed for infrequent replacement of well-contained fuel cassette(s) in a manner that impedes clandestine diversion of nuclear fuel material [1, 2]. Small reactor without on-site refuelling incorporate increased refuelling interval (from 5 to 30 years and more), consistent with plant economy and considerations of energy security. Small reactors without on-site refuelling are either factory fabricated and fuelled or undergo a once-at-a-time core reloading performed at the site by a dedicated service team provided by the vendor; such team is assumed to bring in and take away the fresh and spent fuel load and the refuelling equipment.

About 30 concepts of small reactors without on-site refuelling are being analyzed or developed within national and international programmes in Brazil, India, Indonesia, Japan, Morocco, Russian Federation, Turkey, U.S.A., and Vietnam [1, 2], see Fig. 4 as an example. Small reactor designs without on-site refuelling are being considered for both nearer-term and longer-term water cooled, liquid metal cooled and molten salt cooled reactor lines and some non-conventional fuel/coolant combinations.

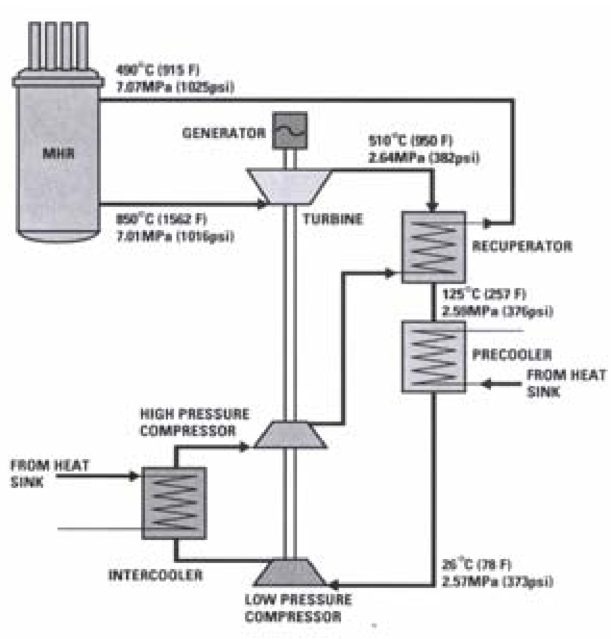

FIG. 5. GT–MHR power cycle diagram (GA-OKBM/USA-Russia) [2].

Whether for fast or for thermal neutron spectrum concepts of such reactors, the fuel discharge burn-up and the irradiation of core structures never exceeds standard practice from the conventional or typically projected designs. The refuelling interval is then extended by derating core specific power, and the power densities never significantly exceed ~100 kW(th)/litre and often are much lower. Burn-up reactivity loss is mitigated by using burnable poisons and active control rods in thermal systems and by designing for internal breeding in fast systems. Although the specific inventories of fissile materials (per unit of power and energy produced) are higher than for reactors with conventional refuelling schemes, some concepts of fast spectrum reactors without on-site refuelling are capable of self-sustainable operation on fissile materials within a closed nuclear fuel cycle.

3. Opportunities for SMRs

The deployment progress of innovative SMRs is in many ways defined by their ability to meet the needs of those diverse categories of users that cannot benefit from the economy of scale plant deployments. Notwithstanding the fact that SMRs may still have higher specific costs, they offer other features that could be of prime importance for certain categories of users, such as:

- Countries with small and medium electricity grids or limited energy demand growth;
- Villages, towns and energy intensive industrial sites in off-grid locations;
- Rapidly growing cities in developing countries with limited investment capability;
- Future merchant type plants[3] in both developed and developing countries, including those for non-electric energy services, such as hydrogen production.

[3] Merchant generation companies are those who operate outside the regulatory framework of regulated utilities and sell their product on a competitive market, i.e., they receive no guarantee of profitability in exchange for a guarantee of providing services to consumers.

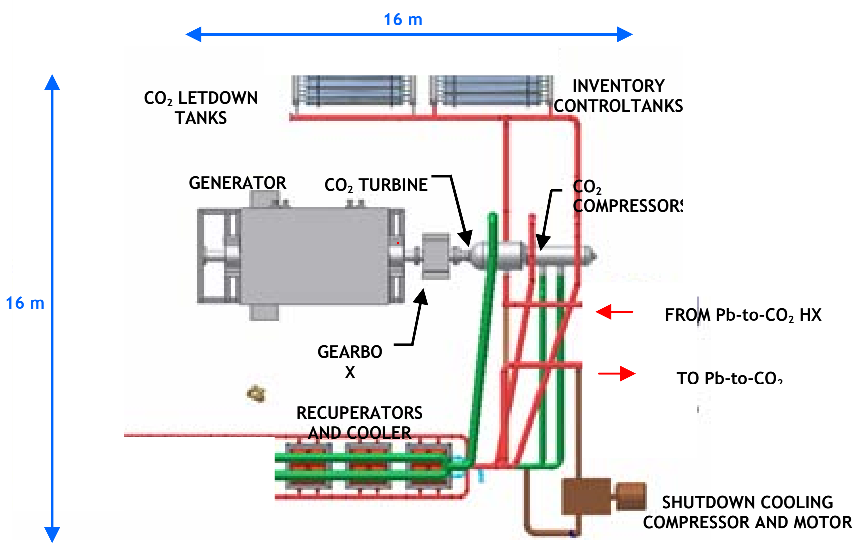

FIG. 6. S-CO_2 Brayton cycle layout of the SSTAR small lead cooled reactor without on-site refuelling (ANL, USA) [1]

The first category of includes users in small and medium sized countries where overall targeted energy production is limited, as well as countries with large territories but relatively small and sparse population, such as Argentina.

Regarding the second category, much of the world's land mass supports sparse populations and is unsupportable by an electric grid [4]. The examples northern extremes of the North American and Eurasian continents that are sparsely populated and where the villages and towns and industrial sites are widely separated and are un-serviced by road, rail, or electrical grid. Island countries face a similar challenge for electricity delivery to widely dispersed population centres located on scattered islands separated by miles of ocean. Indonesia, a country of 13 700 islands, is perhaps the most dramatic example [5]. The government of India has identified 80 000 in-land villages that are likely never to be connected to the grid [6]; the vast reaches of Brazil contain hinterlands of low population density where grid emplacement is not cost effective; besides, many of these locations are short of cooling water to serve as an ultimate heat sink for large-capacity power plants. The economic activity of a majority of the remote settlements is tied to harvesting of natural resources, such as mining, drilling, logging, fishing, etc. Along with permanent villages, dedicated work camps can be established temporarily to staff those harvesting activities.

For users of this category, the difficulties attendant to fuel supply cause busbar energy cost to significantly exceed the rates experienced on well-developed urban grids. For example, across Alaska the rates vary between 9.3 and 45 US$ cent/kW(e)-hour [4], these exceed typical costs in the U.S. contiguous forty-eight states by factors of three to ten. Many users in this category will require more than electricity to support residential loads and industrial applications – desalinated water or district heating often comprises an additional necessary energy service.

Regarding the third category, it is expected that the growth of developing countries would take place faster in the coming decades [7]. The truly massive future growth in energy demand would be for support of cities throughout the developing world; that is where energy infrastructure deployments could dominate throughout the 21st century [8]. By 2015, more than 368 of cities in Asia, Africa, and Latin America will have more than 1 million people each; collectively, these cities would account for about 1.5 to 2.0 billion people.

Nuclear power may eventually come to play a major role here because of its large resource base, its avoidance of greenhouse gas emissions, its large energy intensity per unit area, and its relatively short payback period – the features that are cumulatively favourable for sustainable development [4]. However, the characteristics of nuclear deployments must be tailored to the users' situation. Local grids can be small as city development starts and the investment capabilities may be insufficient to import a large economy of scale plant. To accommodate rapid growth but shortage of initial financing, a "just-in-time" capacity growth plan would be appropriate, with incremental additions deployed as population grows, as energy input per capita increases, and as the city becomes wealthier. SMRs could meet the needs of these emerging energy markets where industrial/technical infrastructure is generally poor, if they are designed to be easily expandable into clusters comprising ever-larger power installations.

In the future, as fossil fuel resources become depleted and as the share of nuclear power increases in both developed and developing countries, the advantages of incremental addition of small or medium generating capacity to match the demand growth "perfectly" might become more attractive to the utilities operating in the deregulated competitive markets. These advantages may become even more important if nuclear energy broadly enters the non-electric markets for seawater desalination, district heating, low temperature process heat, and high temperature heat, including hydrogen manufacture by thermochemical processes. These markets are likely to be served by commercial entities, which are separate from electric utilities, and for which financing relies on commercial bank loan rates or usual rates of return on investor equity. For such entities to succeed, payback period must be short, internal rate of return on investment must be high, and financial risk minimization would be at a premium. Design requirements for extreme levels of reliability and safety apply to the non-electric applications because of the necessity to site process heat sources close to industrial centres [1].

Well over a third of all innovative SMR concepts developed worldwide are fast spectrum nuclear reactors that can ensure high conversion or self-sustainable operation on fissile materials with breeding ratio slightly in excess of 1 [1, 2]. Several medium sized concepts go to even higher breeding ratios of 1.1 – 1.3, suggesting the breeding of fissile materials to feed thermal-spectrum reactor present in nuclear energy systems. Therefore, regarding the transition from a once through to a closed nuclear fuel cycle, SMRs generically fit under the same strategy as considered for larger capacity reactors and nuclear power in general [9].

Several approaches to constrain global dispersal of fuel cycle facilities, which handle fissile material in bulk form, while at the same time not impeding the global dispersal of nuclear power plants, which handle fissile material only in a discrete form, amenable to item accountability, are under consideration currently [10]. Having a long refuelling interval and being designed specifically for the outsourced front-end and back-end fuel cycle services, small reactors without on-site refuelling could be employed in any of the institutional approaches currently considered to constrain the global dispersal of fuel cycle facilities. For the user, they could relax the dependence on outsourced suppliers, fuel cost changes, political and economic tensions and conflicts between countries – altogether, increasing the energy security and reducing the obligations for spent fuel and waste management. Factory fabricated and fuelled reactors may also appear more environmentally clean, more simple and safe and secure, just because the reactor actually appears as a long-life "battery", perhaps, weld sealed and not requiring any operations with nuclear fuel during the whole period of its operation on the site.

A possibility of local participation and gradual technology transfer to the user-country are features commonly mentioned by many potential users in developing countries; with them, nuclear power plants are viewed not only as energy sources but as vehicles of the overall national economy development. Design features that support this request could also contribute to better economy of the plant, e.g., if certain parts of it are built to local standards by local constructors using local labour with financing denominated in local currency. In the meantime, several developing countries have matured their nuclear industries to offer domestically produced or even designed SMRs to world markets in the very near-term[4].

4. Challenges for SMRs

As it was already mentioned, innovative SMRs in most cases do not attempt to compete with large economy of scale plants in the established markets; they rather attempt to meet the needs of those users to whom large economy-of-scale deployments are not suited. To be competitive in anticipated alternative markets, innovative SMRs rely on approaches alternative to economy of scale. Such approaches include the economy of multiple prefabricated reactor or equipment modules, reduced design complexity resulting from the application of those design features that are most appropriate for the reactor of a given capacity, an option of incremental capacity increase with possible benefits resulting from "just in time" capacity addition and learning curve factors, shorter construction period and, possibly, greater involvement of local labour [2], as illustrated by a generic scheme in Fig. 7. The effectives of all these approaches for the conditions of targeted markets should be demonstrated, which is a challenge of prime importance for all innovative SMRs.

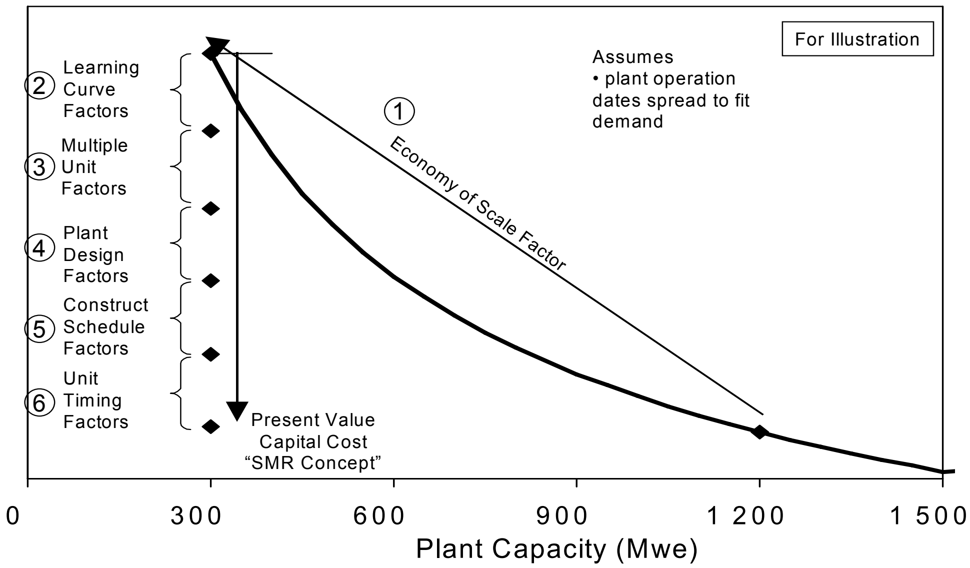

FIG. 7. A generic scheme illustrating potential SMR economic factor advantages (courtesy of Westinghouse, USA).

Many of the innovative SMR concepts incorporate design approaches and system configurations that are not proven in operating practice of reactors for civil nuclear power; also, many innovative SMRs are just non-water cooled reactors. Licensing of such reactors within current light water reactor based and sometimes overly prescriptive regulatory

[4] The examples are the Republic of Korea, India, and Argentina.

frameworks will pose a challenge, and adjustments of regulatory rules toward a risk-informed approach may be required on many occasions [1, 2]. In addition to incorporating many inherent safety features, some innovative SMR concepts suggest stronger reliance on passive systems of innovative design. Reliability of such systems needs to be proven to enable risk-informed qualification and licensing.

Many potential applications of SMRs may require them to be located in proximity to the users:

- In industrial cogeneration applications, such as hydrogen production, they must be sited adjacent to the industrial site for delivery of process heat;
- They could supply energy to cities in regions where only a local electrical grid exists;
- They could produce energy products such as potable water and district heat, which cannot be transported to significant distances; and

These siting considerations lead to a requirement for very high levels of safety and reliability. Collocating a nuclear and a chemical plant on a single site will require developing new safety rules and regulations to be applied to both of them. Licensing of a nuclear power plant with a reduced or eliminated emergency planning zone, which is aimed by the designers of many innovative SMRs, will require risk-informed regulations be emplaced.

Many small reactors without on-site refuelling incorporate substantially increased refuelling interval, ranging from ~5 to 20 – 25 years and beyond. The operating experience for such elongated refuelling intervals is generally unavailable in civil nuclear power [1]. The known experience of marine reactors confirms the possibility of a 7 to 8-year continuous operation of small reactors. Therefore, the construction of a prototype would be a must for many small reactors without on-site refuelling. Once built, the prototype could be subjected to a pre-agreed set of anticipated transient without scram (ATWS) and other accident initiators. By demonstrating safety based on passive response, on the prototype, the licensing authority might be able to certify the design, permitting the manufacture of many tens (or hundreds) of replicate plants to the set of prints and design specifications used for the prototype [1]. In order to assure that aging effects do not degrade the passive safety features of deployed plants, the licensing authority could prescribe the performance of periodic in-situ tests on the plant to confirm continued presence of reactivity feedbacks in the required range and of passive decay heat removal continuously operating at the required rate. Such an approach, referred to as "licence-by-test", needs to be further examined and established, which is a challenge for many small reactors without on-site refuelling.

5. Progress towards deployment

Design and technology development for a dozen of innovative SMRs shows good progress towards deployment within the next decade [1, 2]. Construction of a pilot floating cogeneration plant of 400 MW(th)/70 MW(e) with two water cooled KLT-40S reactors has been started in the Russian Federation in June 2006; the deployment is scheduled for 2010. In July 2006, an agreement was reached between the Russian Federation and Kazakhstan to create a joint venture to complete design development for the VBER-300[5] reactor of 300 MW(e) for a floating or land-based co-generation plant, and to promote nuclear power plants with such reactors to the markets of both countries and abroad. Three of the integral type PWRs – IRIS of 335 MW(e) (International consortium led by Westinghouse, USA); SMART

[5] The VBER-300 is basically an up-scaled version of the KLT-40S reactor.

of 330 MW(e) (the Republic of Korea); and prototype CAREM of 27 MW(e) (Argentina) – have progressed toward advanced design stages and hold a potential to be deployed within the next decade; their commercialisation could then start around 2015. The 165 MW(e) pebble bed modular gas cooled reactor (PBMR), developed in South Africa, is planned for demonstration at full size by 2012. But there are additional designs from France, India, Japan, and the Russian Federation that may be proven on a similar timescale, thus providing a number of potential choices to interested countries in the nearer-term.

Contrary to that, only a few small reactors without on-site refuelling might be ready for deployment within the 10 years. The only concept that has reached detailed design stage is the Russian lead-bismuth cooled SVBR-75/100 of 101.5 MW(e) with the refueling interval of 6 – 9 effective full power years. This design is backed by 80 reactor-years of operating experience of the Russian submarine reactors and is flexible in applications and fuel cycle options; its further development with a link to a specific deployment site will be supported by the Federal Agency of Russia for Atomic Energy starting from 2007. The VBER-150 and KLT-20 with the refueling intervals of 6 and 8 years, which are de-rated power versions of the KT-40S and VBER-300 respectively, could be developed in the Russian Federation within a few years, upon a customer request. The ABV integral type water cooled reactor of 11 MW(e) for a floating NPP, offering a refueling interval of 8 years, is at the basic design stage.

In Japan, Toshiba Corporation in cooperation with CRIEPI and several other organizations develops the 4S sodium cooled reactor of 10 or 50 MW(e) offering a refueling interval of 30 years. The design allows the power control to be executed via the feed water control from the steam-water power circuit. The conceptual design and major parts of the system design have been completed. A pre-application review by the US NRC is planned to be initiated by March 2007. Constructions of the demonstration reactor and safety tests are planned for early 2010s.

6. Concluding remarks

Continued operation, construction of new power plants, and progress in design and technology development for future SMRs indicate the continued interest of many countries to the development and application of such reactors. The observed multiplicity of design approaches and user-related features of SMRs suggest that further progress in their development and deployment could benefit from a continued dialogue among possible vendors and potential customers. To support such a dialogue, common criteria need to be developed to help interested stakeholders re-examine and assess the need for SMRs in their countries or for certain regions and applications in their countries. Such criteria could be developed using one or more examples of national analyses of the needs for SMRs in member states where the experience with SMRs is positive (e.g., India, Argentina), and they should incorporate all components of costs (hardware and services) that are influenced by localization or optimum outsourcing. The criteria could also reflect on the customer demands for vendor support services, such as licensing issues for innovative NPPs that have limited experience of operation, operational reliability issues for novel equipment, training of domestic operational personnel, use of local sub-contractors, and other relevant factors.

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The Indian high temperature reactor programme

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Abstract. Bhabha Atomic Research Centre (BARC), in India, is currently developing concepts of high temperature nuclear reactors capable of supplying process heat at a temperature around 873-1273K. These nuclear reactors are being developed with the objective of providing energy to facilitate combined production of hydrogen, electricity, and drinking water. Under the programme, currently India is developing a Compact High Temperature Reactor (CHTR) as a technology demonstrator for associated technologies. CHTR is a mainly ^{233}U-thorium fuelled, lead-bismuth cooled and beryllium oxide moderated reactor. This reactor, initially being developed to generate about 100 kW(th) power, will have a core life of around 15 years and will have several advanced passive safety features to enable its operation as compact power pack in remote areas not connected to the electrical grid. The reactor is being designed to operate at 1273K, to facilitate demonstration of technologies for high temperature process heat applications such as hydrogen production by splitting water through high efficiency thermo-chemical process. Molten lead based coolant has been selected for the reactor so as to achieve a higher level of safety. For this reactor, developmental work in the areas of fuel, structural materials, coolant technologies, and passive systems are being done in BARC. Experimental facilities are being set up to demonstrate associated technologies. In parallel, design work has been initiated for the development of a 600 MW(th) High Temperature Reactor for commercial hydrogen production by high temperature thermo-chemical water splitting processes. Technologies being developed for CHTR would be utilized for the development of this reactor. Various analytical studies have been carried out in order to compare different options as regards fuel configuration and coolants. Initial studies carried out indicate selection of pebble bed reactor configuration with either lead or molten salt-based cooling by natural circulation.

1. Introduction

For India, high temperature reactors development programme is significant mainly for non-electric applications. The requirement for high temperature reactors has originated because of a need to develop alternate energy carrier to substitute fossil fuel based transport fuel. It is well known that hydrogen production processes by splitting water, whether by electrolysis or by thermo-chemical processes, are highly energy intensive. These processes need either electricity or process heat at high temperatures, or both depending upon the process of hydrogen production selected. The efficiencies, in general, for these hydrogen-producing processes are higher at higher temperatures. Thermo-chemical processes have been reported to have higher efficiencies (40-57%) as compared to electrolysis based processes, but need process heat at temperatures greater than 823K [1], depending on the thermo-chemical process selected. High temperature nuclear reactors capable of supplying process heat have a large potential for sustainable supplying energy for these hydrogen production processes at required high temperature conditions.

2. Indian high temperature reactor programme

The current Indian high temperature nuclear reactor programme is mainly based on requirements related to production of hydrogen by splitting water using high efficiency thermo-chemical processes. BARC is currently developing concepts of high temperature nuclear reactors capable of supplying process heat at a temperature around 1273K. These nuclear reactors are being developed with the objective of providing energy to facilitate combined production of hydrogen, electricity, and drinking water. The reject and waste heat in the overall energy scheme are proposed to be utilized for electricity generation and desalination respectively. Presently, technology development for a small power Compact High Temperature Reactor (CHTR) capable of supplying high temperature process heat at 1273K is being carried out. In addition preliminary design of a 600 MW(th) reactor, capable of supplying heat at 1273K for large scale hydrogen production, is also being carried out.

3. Compact High Temperature Reactor (CHTR)

The Compact High Temperature Reactor (CHTR) [1,2,3] is being developed as a prototype reactor for the development and demonstration of technologies associated with high temperature reactors. The reactor is modular in design. It is being designed to be compact in weight and size for ease in its deployment in remote locations for its use as a compact power pack. It has a prismatic core configuration. The reactor core consists of nineteen hexagonal shaped beryllium oxide (BeO) moderator blocks. These 19 blocks contain centrally located graphite fuel tubes. Each fuel tube carries fuel inside longitudinal bores made in its wall. The fuel tube also serves as coolant channel. Molten lead-bismuth eutectic alloy has been proposed as cooling medium. Thorium-^{233}U based fuel compacts are made-up of TRISO coated particle fuel, facilitating high burnup and high temperature process heat production. Eighteen blocks of BeO reflector surround the moderator blocks. These reflector blocks centrally accommodate passive power regulation system. This system works on temperature feedback, and in case of rise of coolant outlet temperature beyond design value, inserts negative reactivity inside the core. Graphite reflector blocks surround these beryllium oxide reflector blocks. This part of the reactor is contained in a reactor shell of a material resistant to corrosion against lead-bismuth eutectic alloy coolant, and suitable for high temperature applications. Cross-sectional layout of the reactor core is shown in Fig. 1.

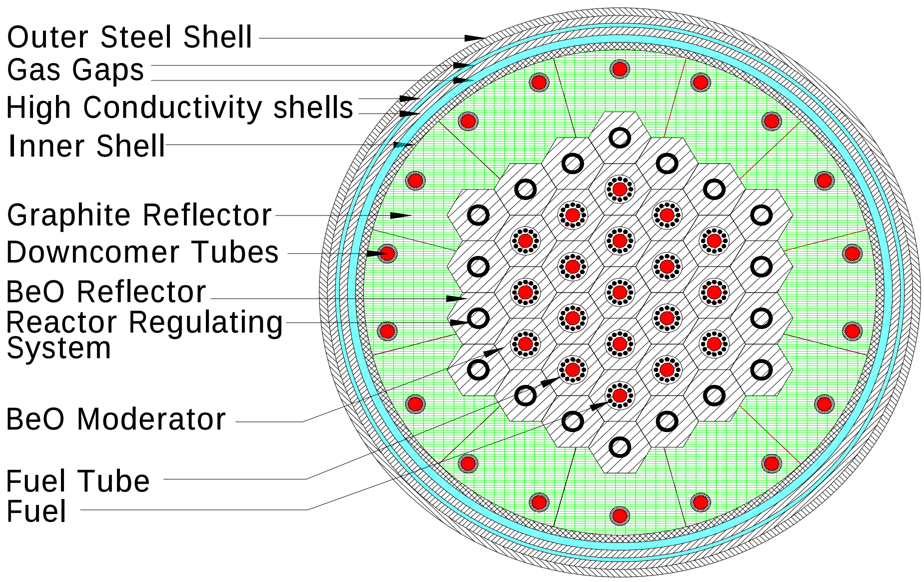

FIG. 1. Cross-sectional view of compact high temperature reactor

Top and bottom closure plates of similar high temperature and corrosion resistant material close this reactor shell. Above the top cover plate and below the bottom cover plate, cyclindrical vessels called coolant plenums are provided for coolant exit and entry into the core respectively. These plenums have graphite flow guiding blocks, having passages for coolant flow, to increase the velocity of the coolant between the fuel tube and down comer tube provided for return of the cold coolant to lower plenum. The reactor shell is surrounded by two gas gaps that act as insulators during normal reactor operation and reduce heat loss in the radial direction. These gas gaps help in dissipating neutronically limited power to an external sink, in case of a postulated accident. A passive system has been provided to fill these gas gaps with molten metal in case of abnormal rise in coolant outlet temperature. There is an outer finned steel shell, surrounded by heat sink. Nuclear heat from the reactor core is removed passively by natural circulation based flow of coolant between the two plenums, upward through the fuel tubes and returning through the downcomer tubes. On top of the upper plenum, the reactor has multi-layer heat utilization vessels to provide an interface to systems for high temperature process heat applications. A set of sodium heat pipes is provided in the upper plenum of the reactor to passively transfer heat from the upper plenum to the heat utilization vessels. Another set of heat pipes transfers heat from the upper plenum to the atmospheric air in the case of any postulated accident. To shut down the reactor, a set of seven tungsten shut-off rods has been provided, which fall by gravity in the central seven coolant channels. Appropriate instrumentation like neutron detectors, fission/ ion chambers, various sensors, and auxiliary systems such as a cover gas system; purification systems, active interventions etc. are being incorporated in the design as necessary. Component layout of CHTR is shown in Fig. 2 and major design and operating parameters are listed in Table-I.

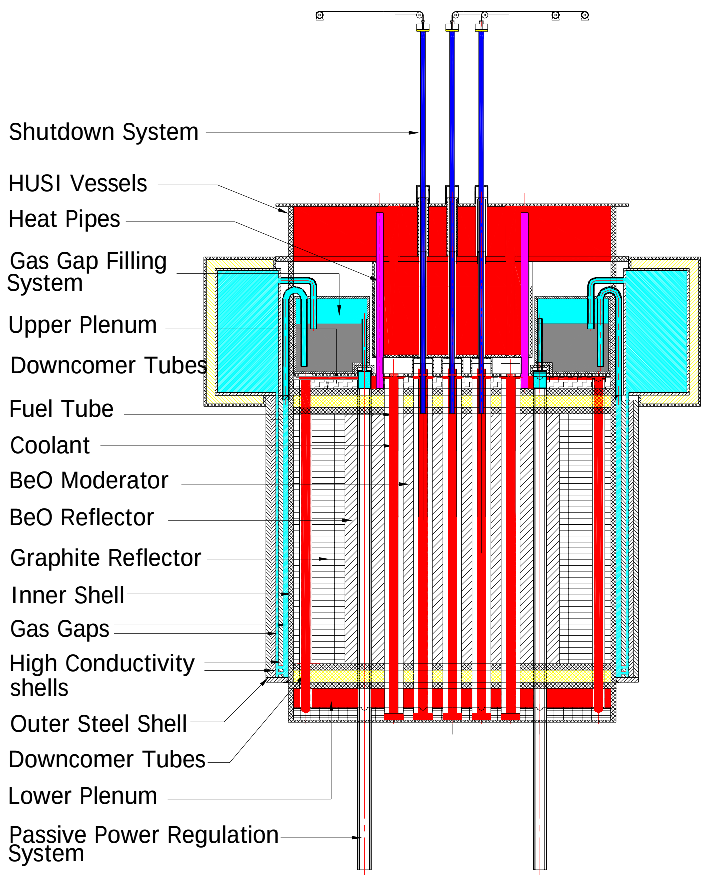

FIG. 2. Components layout for CHTR

Table I. Major design and operating characteristics of CHTR

Attributes	Design Parameters
Reactor power	100 kW(th)
Core configuration	Vertical, prismatic block type
Fuel	$^{233}UC_2$+ ThC_2 based TRISO coated fuel particles shaped into fuel compacts with graphite matrix
Fuel enrichment by ^{233}U	33.75%
Refuelling interval	15 effective full power years
Fuel Burnup	≈ 68000 MWd/t of heavy metal
Moderator	BeO
Reflector	Partly BeO and partly graphite
Coolant	Molten Pb-Bi eutectic alloy (44.5% Pb and 55.5% Bi)
Mode of core heat removal	Natural circulation of coolant
Coolant flow rate through core	6.7 kg/s
Coolant inlet temperature	1173K
Coolant outlet temperature	1273K
Loop height	1.4 m (actual length of the fuel tube)
Core diameter	1.27 m
Core height	1.0 m (Height of the fuelled part and axial reflectors)
Primary shutdown system	18 floating annular B_4C elements of passive power regulation system
Secondary shutdown system	7 mechanical shut-off rods

3.1. CHTR Fuel

The CHTR fuel [4] is designed to operate at high temperatures, withstand high burn up, and have long core resident time. Thorium and burnable poisons make the fuel temperature coefficient negative, thus making the reactor inherently safe. A typical CHTR fuel bed consists of prismatic BeO moderator block with centrally located graphite fuel tube carrying fuel compacts. Schematic of fuel particle, fuel compact, and single fuel bed are shown in Fig.3.

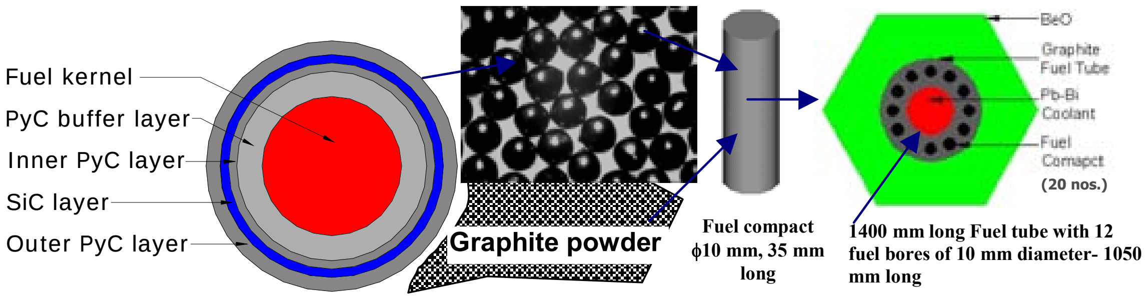

FIG. 3. Schematics of TRISO fuel particle, fuel compact, and single fuel bed for CHTR

The neutron-physical design of the CHTR has been carried out with the following objectives:

(a) All power must be generated from Th/ ^{233}U based fuel;
(b) The temperature reactivity coefficient for fuel should be negative;
(c) The fuel should be capable of high-temperature performance;
(d) The fuel burn-up should be high;
(e) The refuelling interval should be large.

At present stage of design, the reactor fuel consists of a combination of 2.7 kg of ^{233}U mixed with 5.3 kg of thorium and small amount of gadolinium (added only in central fuel tube) [5]. This combination of fuel satisfies the reactivity control requirements. Variation of keff with respect to burn-up is shown in Fig. 4.

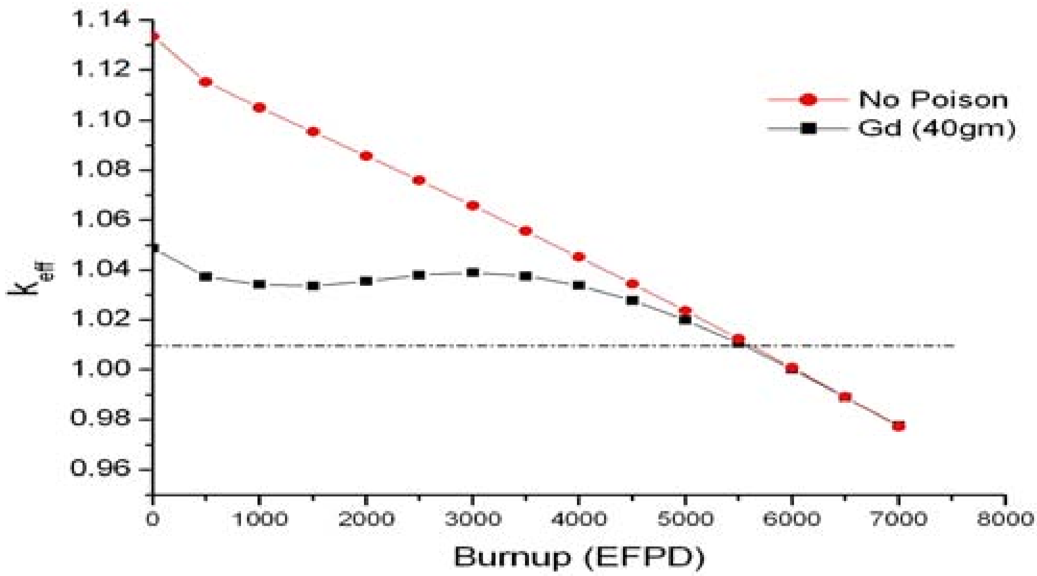

FIG. 4. Variation of keff with respect to burn-up

3.2. Inherent safety features and passive systems

CHTR is being designed to have many features, which make it inherently safe. In addition, many passive systems for reactor control, reactor shutdown and reactor heat removal under normal and postulated accident conditions, have been incorporated. These are listed below:

3.2.1. The reactor possesses following inherent safety features

(a) A strong negative Doppler coefficient of the fuel for any operating condition results in reactor power reduction in case of fuel temperature rise during any postulated accident scenario;

(b) High thermal inertia of the all-ceramic core and low core power density results in very slow temperature rise of the reactor core components as well as fuel during a condition when all heat sinks are lost;

(c) A large margin between the normal operating temperature of the fuel (around 1373K) and the allowable limit of the TRISO coated particle fuel (1873K) to retain fission products and gases results in their negligible release during normal operating conditions. This also provides a healthy margin to take care of any unwanted global or local power excursions;

(d) A negative moderator temperature coefficient results in lowering of reactor power in case of increase in moderator temperature due to any postulated accident condition;

(e) Due to use of lead-bismuth (Pb-Bi) eutectic alloy based coolant having very high boiling point (1943K), there is a very large thermal margin to its boiling, the normal operating temperature being 1273K. This eliminates the possibility of heat exchange crisis and increases the reliability of heat removal from the core. The coolant operates at low pressure, there is no over pressurization and hence no chance of reactor thermal explosion due to coolant overheating;

(f) The high temperature Pb-Bi coolant, which is maintained in inert gas atmosphere, is itself chemically inert. Even in the eventuality of accidental contact with air or water, it does not react violently with explosions or fires;

(g) Due to above atmospheric coolant melting point (393K), even in case of a primary system leakage, it solidifies and prevents further leakage;

(h) The thermal energy stored in the coolant which is available for release in the event of a leak or accident is small;

(i) Very low pressure in the coolant, allows use of a graphite/ carbon based coolant tube having low neutron absorption cross section, thus improving neutronics of the reactor;

(j) A low induced long-lived gamma activity of the coolant. In case of a leakage, the coolant retains iodine and other radionucleides.

(k) For Pb-Bi coolant, the reactivity effects (void, power, temperature, etc.) are negative; thus reducing the reactor power in case of any inadvertent power or temperature increase.

3.2.2. Passive systems: CHTR incorporates many passive systems as listed below:

(a) Passive core heat removal under normal operation [6]: During normal operation of the reactor, the core heat is removed by natural circulation of lead-bismuth eutectic alloy coolant. The main coolant-circulating loop comprises fuel tubes, downcomers and top and bottom plenums. The coolant at 1173K enters the fuel tube in lower plenum, takes the reactor heat, and at 1273K it is delivered to the upper plenum.

(b) Passive power regulation system [7]: This system works on the principle of increase of gas pressure with temperature thereby pressurizing and forcing a column of molten metal with floating absorbing material into the core. This introduces negative reactivity in the core. Depending on the temperature rise sensed, the system would stabilize at a particular value of reactivity insertion.

(c) Passive shutdown system [7]: This system consists of a set of seven shut-off rods, made of tungsten, and held on top of the reactor core by individual electro-magnets. Magnetic power of these magnets are energized by a set of low power batteries. These shut-off rods are passively released under abnormal conditions when the temperature of the coolant or core goes up. These shut-off rods fall in the central bore of the fuel tubes provided for coolant flow. This is a fail safe system, so that in case of loss of power from batteries, the shut-off rods would fall and shutdown the reactor.

(d) Passive transfer of heat to secondary system: A set of twelve high temperature sodium heat pipes passively transfer heat from upper plenum of the reactor to a set of heat utilization vessels which are kept directly above the upper plenum.

(e) Passive heat removal under postulated accident conditions [8]: CHTR has three independent and redundant passive heat removal systems to cater to different postulated accident conditions. These heat removal systems, which are individually capable of removing neutronically limited power of 200 kW(th), which is 200% of normal reactor power, may operate together or independently to prevent the temperature of the core and coolant from increasing beyond a set point. For the loss of load condition, when coolant circuit is intact, a system of six variable conductance sodium heat pipes dissipates heat to the atmosphere. A system of twelve carbon-carbon composite variable conductance heat pipes provided in reactor core caters to the need when coolant is lost. Another passive heat removal system involves filling of the two gas gaps, provided outside the reactor vessel, by siphon action with a molten metal to provide a conduction heat path from reactor core to heat sink provided outside the outer steel shell.

3.3. Current status and schedule

CHTR calls for research and development activities in many areas of nuclear engineering. There are requirements of high chemical purity special materials like beryllium oxide, carbon based materials like graphite and carbon-carbon composites, refractory metal alloys with oxidation and corrosion resistant coatings, and TRISO coated particle based fuel. In addition, the reactor design incorporates many passive systems for reactor control and heat removal. There is also need to establish design rules for brittle as well as high temperature components. At present, a feasible design of the CHTR has been established after completing the conceptual design of the reactor and associated systems. Experimental facilities are under various stages of development to carry out various studies related to liquid metals, passive safety and heat removal systems. The manufacturing capabilities for BeO, carbon components, and fuel micro-spheres have been demonstrated. Trials for TRISO coatings have started. Subsequent to the manufacture of fuel, materials and other systems, an experimental facility for CHTR would be set up.

4. 600 MW(th) Indian high temperature reactor

India is carrying out design of a 600 MW(th) reactor for commercial hydrogen production. For this reactor various design options as regards fuel configurations, such as prismatic bed and pebble bed were considered for thermal hydraulics and temperature distribution analysis. Coolant options such as molten lead, molten salt and gaseous medium like helium were analyzed. Besides these, other criteria such as ease in component handling, irradiation related material and fuel degradation, better fuel utilization and passive options for coolant flow etc. were also considered. Initial studies carried out indicate selection of pebble bed reactor core with either lead or molten salt-based coolant. Table-II shows proposed specification [1,9] for this reactor. Figure-5 shows schematic of 600 MW(th) Indian HTR design. These would be finalised after carrying out further studies. Many of the technologies developed for CHTR would be utilised for this reactor. There are plans to setup engineering laboratories for carrying out research and development related to reactor components, coolant technologies, reactor safety, fuel and material development, and other aspects related to such high temperature reactors.

Table II. Proposed general specifications of the reactor for commercial hydrogen production

Reactor power	600 MW(th) for following deliverables – Hydrogen: 80,000 Nm^3/hr – Electricity: 18 MWe – Drinking water: 375 m^3/hr (Optimized for hydrogen production)
Coolant outlet/ inlet temperature	1273K/ 873K
Moderator	Graphite
Coolant	Molten lead or molten salt
Reflector	Graphite
Mode of cooling	Natural circulation of coolant may be considered
Fuel	$^{233}UO_2$ & ThO_2 based high burn-up TRISO coated particle fuel
Control	Passive power regulation and reactor shutdown systems
Energy transfer systems	Intermediate heat exchangers for heat transfer to system for hydrogen production + High efficiency turbo-machinery for electricity generation + Desalination system for potable water
H_2 production	High efficiency thermo-chemical processes

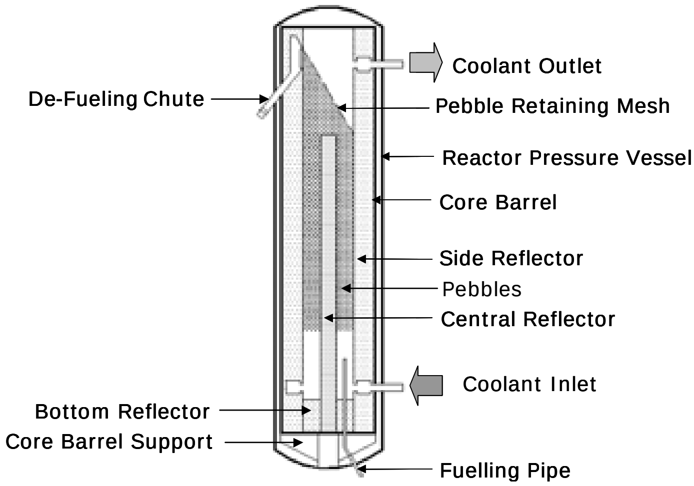

FIG. 5. Preliminary schematic of core configuration of 600 MW(th) pebble bed design

5. Summary

India has very limited reserves of fossil fuel required for transport applications. Nuclear option for hydrogen production is the most sustainable option. High temperature reactors have large potential to provide necessary high temperature process heat required for hydrogen production. BARC is carrying out developmental work related to all aspects of high temperature nuclear reactors. R & D work encompasses development of materials and their fabrication technologies for component manufacture, compatibility studies, oxidation and corrosion related studies and development of coatings, joining technologies, development of high temperature high burn-up fuel, studies for irradiation behaviour of fuel and materials, and development of characterisation techniques. These have opened many new avenues of research in BARC.

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Feasibility study on deployment of the first unit of RUTA-70 reactor in Obninsk: District heating, technological, and medical applications

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Abstract. This report presents a feasibility study on deployment of the first-of-kind RUTA-70 heat supply facility in Obninsk and prospects of various nuclear technological applications of the reactor. Major technical data of the reactor facility and a description of design are presented. The feasibility of using low-grade thermal energy generated by the reactor for district heating is shown. Aspects of using the reactor as a neutron source to implement modern nuclear technologies and using it for desalination of seawater are considered.

1. Introduction

The understanding that it is technically feasible to use nuclear heat sources both in domestic district heating systems and in industrial processes, e.g. in seawater desalination systems, was shaped at the very onset of nuclear power development. The currently existing experience shows that there are no technical obstacles to such use of nuclear reactors and any reactor of any power can be used for these purposes [1, 2].

Utilization of nuclear power in domestic district heating has a long history supported by an extensive experience in practical operation of nuclear facilities of various types. However, nuclear power has not yet made any great advance into the commercial heat market. Nowadays, nuclear reactors in the world generate less than 1% of the heat used for district heating and in industrial processes [3] while the share of nuclear power plants in electricity production worldwide being ~15%.

Still, Russia has been recently showing signs of a newly emerging interest in employing atomic energy for district heating, specifically to solve the problem of fuel supplies in remote isolated regions and in connection with reforming of the housing and communal sector. One of the directions of work in this area is creation of specialized district heating facilities based on pool-type reactors intended to generate low-grade heat to meet the demands of the housing and communal sector [4].

One of the advanced projects in this field is the reactor facility RUTA (Reactor Facility for Heat Supply with Atmospheric Pressure in the Primary Circuit) developed originally for dedicated use in district heating systems.

2. Basic engineering approaches and design of the RUTA-70 reactor

The RUTA-70 reactor (see Figure 1) is a special modification of a pool-type water-cooled water-moderated reactor. To date, options of the RUTA reactors with a thermal power from 10 to 70 MW have been studied to a different extent [5]. The basic technical data of the RUTA-70 reactor facility are presented in Table I.

Table I. Basic technical data of the RUTA-70 reactor

Maximum thermal power of the reactor (N_{nom}), MW	70
Primary coolant circulation:	
- up to 30% N_{nom}	Natural
- from 30 to 100% N_{nom}	Forced
Core heat removal	Two-circuit*
Pressure in the air space over the reactor	Atmospheric
Core dimensions (equ. diameter/height), m	1.42/1.4
Fuel	Cermet (0.6 UO_2+ 0.4 Al alloy)
Fuel enrichment in ^{235}U, %	4.2
Uranium core load, kg	4 165
Number of fuel assemblies	91
Nuclear fuel life, eff. days	2 332
Refueling cycle with capacity factor of 0.7, years	3
Share of refueling	1/3
Water inventory in the reactor tank, m^3	250
Core temperature (inlet/outlet), °C	75 / 101

* The tertiary circuit is considered as a system external to the reactor facility.

The major advantages of the RUTA reactor facility are as follows:

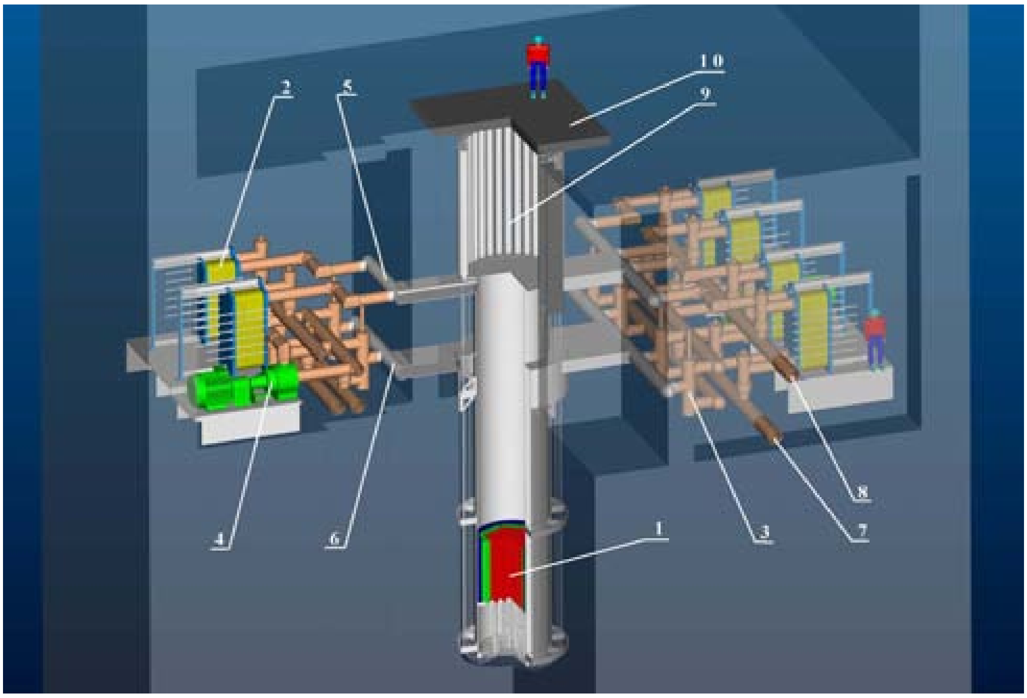
- Basically simple design and, as a consequence, low cost of the reactor facility construction and operation.
- High level of safety achieved through design specific features and using intrinsic safety mechanisms.

The following factors largely define these advantages:

— absence of excessive coolant pressure in the primary circuit (reactor pool);
— presence of a large heat accumulating capacity of the water in the pool;
— low heat rating in the core;
— core cooling in a range from the lowest level up to 30% N_{nom}, as well as in cool down modes thanks to the natural coolant circulation in the reactor;
— a three-circuit system of heat supply to consumers with the lowest water pressure being in the primary circuit.

Safety as well as reliability and simplicity of the RUTA reactor design depend largely on the absence of excessive coolant pressure in the primary circuit (reactor pool). Such reactors have intrinsic safety properties and can be deployed in the immediate vicinity of heat consumers. This has been also confirmed by long-term experience of operating a great deal of research reactors (in total, 225 such reactors were built in the world, including 23 reactors designed by NIKIET).

The radiation effects of the RUTA facilities on the environment not only during normal operation but in any credible emergencies will not exceed the natural radiation background level.



1 – Core; **2** – Primary heat exchanger; **3** – Check valve; **4** – Pump;
5 – Primary circuit distributing header; **6** – Primary circuit collecting header;
7 – Secondary circuit supply pipeline; **8** – Secondary circuit discharge pipeline;
9 – CPS drive; **10** – Upper ceiling.
FIG. 1 – RUTA-70 reactor facility

3. Use of the RUTA reactor for district heating

Marketing studies [6] have shown that Russia has rather a large number of regions where heating supplies can be efficiently ensured through using the RUTA facilities. These are primarily many residential areas covered by local or united centralized power supply systems but lacking sufficient fuel required by heat supply facilities.

The key feature of pool-type reactors is absence of excessive pool pressure and, consequently, low temperature of the system water, so rational ways to achieve reliable heat supply define the following approach to shaping heat supply systems using RUTA facilities:

— for heat supply systems with the maximum required temperature of main water exceeding the temperature level achievable at the RUTA facility, the latter can and should operate in the base segment of the annual heat load schedule. In this case, system water should be heated to the temperature required in the cold period of the year by fire or electric peak water heaters with the capacity factor of the nuclear power facility to be within 0.6 - 0.8;
— for small low-temperature heat supply systems, the RUTA can ensure full heat supply of consumers throughout the year. Still, the facility will normally operate with a very low (not more than 0.3 - 0.4) capacity factor, which will affect adversely its economics. So, in these cases it is also preferable to use the RUTA facilities in the base segment of the heat load schedule, i.e. jointly with peak non-nuclear heat generators.

Therefore, this heat supply technology normally suggests combined use of nuclear sources (covering the base portion of the heat loads) and non-nuclear sources (operating in the peak and half-peak mode).

In most of the cases, this is the best approach to integrating the RUTA facilities into heat supply systems and enables reliable and economic heat supply.

At the same time, this does not make it impossible to operate the RUTA facilities independently in district heating systems operating in the 90/60°C schedule or in a quantitative load control mode.

The most promising of the sites under consideration for deploying the first-of-kind (pilot) model of such facility is the Institute of Physics and Power Engineering in Obninsk. This site has a unique long-term experience of erecting and operating nuclear power facilities of various types, designs and purposes. It includes the required infrastructure, scientific potential and personnel, which enable implementation of such a project in such short time and at such low cost as possible.

In 2004, enterprises of the Federal Agency for Atomic Energy had prepared a feasibility study (FS) on deploying the first-of-kind RUTA nuclear heating plant (NHP) with a thermal power of 70 MW on the FEI site in Obninsk.

The FS was developed jointly by IPPE (Research Supervisor), NIKIET (General Designer) and AEP (General Architect-Engineer) of the facility.

The FS development has helped to update some of the design approaches for the basic layouts and assemblies of the RUTA reactor facility and consider the issues of integrating the RUTA NHP into the Obninsk heat supply system as well as the basic project concepts.

In particular, the master plan of the NHP has been developed, the construction cost has been estimated and economic, financial and budget efficiency of the plant in the commercial conditions of heat supply to the Obninsk heat supply system has been calculated.

The results of the studies show that, apart from its major purpose of demonstrating the technology to be subsequently commercialized, the first-of-kind RUTA NHP unit at IPPE will ensure pays back of the investments.

Sales of generated heat to consumers in Obninsk gives a notable profit (about 3 million rubles in the 1991 prices) that can be used, in particular, to ensure safe operation of the Institute’s engineering infrastructure.

It should be also noted that an important factor making this project more economically competitive is an expected growth in the organic fuel price. Thus, recent years have shown a major rise in heat tariffs because of a gas price increase, including in the European part of Russia (in Obninsk, the heat tariffs was growing at a rate of ~30% per year in 2002 – 2004).

4. Use of the RUTA reactor as a neutron source

Given diverse tasks and interests of scientific and production organizations in the city, no less important factor favoring the implementation of the project to build the first-of-kind RUTA facility in Obninsk is feasibility of its multi-purpose application:

- production of a broad range of radionuclides for medical and industrial purposes;
- neutron and transmutation doping of silicon monocrystals for the needs of modern microelectronics;
- creation of neutron beams for ray and capture therapy;
- irradiation of thin polymer films for subsequent production of track membranes;
- performance of operations on neutron activation analysis of ores, mineral, etc.

For these purposes, the following irradiation devices can be used in the reactor:

- irradiation channels in the reflector blocks:
  - not less than 8 channels for production of radio isotopes;
  - 2 channels for neutron and transmutation doping of silicon ingots;
  - 2 pneumatic rabbit system channels for neutron activation analysis;
- external irradiation devices based on produced neutron beams:
  - 1 channel for fast-neutron therapy (FNT);
  - 1 channel for neutron-capture therapy (NCT);
  - 1 channel for irradiation of the polymer film used to produce track membranes (TM).

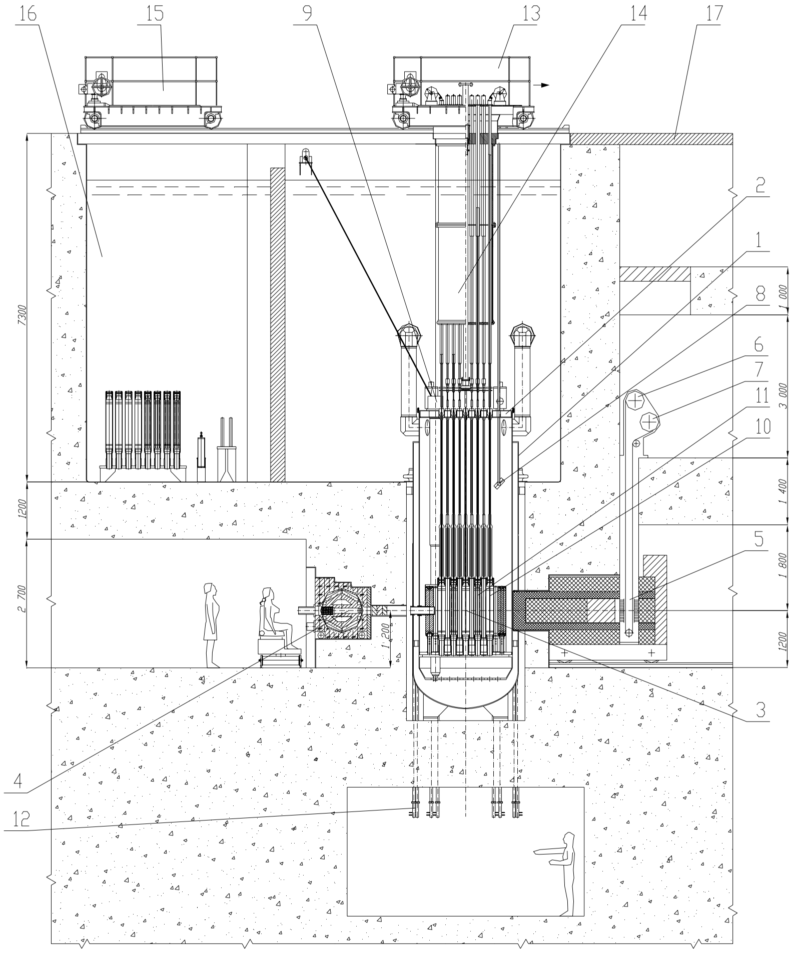
The results of preliminary design studies into the arrangement of irradiation devices at the RUTA reactor are shown in Figure 2.

Table II. presents characteristics of fluxes for groups of neutrons specifically designated as fast (f), epithermal (at) and thermal (t), at the core center and at locations of special channels and devices at the beginning (b) and at the end (e) of the working cycle. For cells of the reflector's first row, it shows the spreading of the neutron flux values caused by the location of cells and fuel burn-up.

Table II. Neutron fluxes at the core center and at locations of irradiation channels and devices for the beginning and the end of the life, 10^{13} /(cm^2·s)

Energy of neutrons in group	Central FA		First row of the reflector (radioisotope production channel)		Silicon doping channel		FNT channel, bottom (Al)		NCT channel, bottom (Al)		Graphite column for TM (layer in the water down comer region)	
	b	e	b	e	b	e	b	e	b	e	b	e
φ_f (0.1-10 MeV)	12.1	7.6	1.0÷2.6	1.4÷2.1	0.13	0.16	1.3	1.5	0.83	1.0	0,012	0,011
φ_{at} (1 eV – 100 keV)	5.8	3.7	1.1÷2.4	1.3÷1.9	0.11	0.13	1.2	1.4	0.76	0.89	0,036	0,037
φ_t (less than 1 eV)	3.8	2.6	7.0÷9.6	6.0÷6.5	1.8	2.3	4.6	5.4	2.8	2.9	1,28	1,38

The adopted design approaches stipulate such in-pile arrangement of special-purpose channels and devices, which provides for their smallest influence on the neutronic and fuel characteristics of the core with specific requirements to parameters of neutron fluxes in irradiation channels and devices being met.



1 - reactor vessel; 2 – cover; 3 – core; 4 – FNT channel; 5 – film irradiation devices; 6 – fresh film cartridge; 7 – irradiated film cartridge 8 – TV camera; 9 – silicon nuclear doping channel; 10 – power density monitoring sensor; 11– CPS cluster; 12 – IC channel; 13 – CPS drive area; 14 – drive area trunk; 15 – handling trolley; 16 – cooling pool; 17 – upper ceiling.

FIG. 2. Irradiation devices at the RUTA reactor

5. Use of the RUTA reactor for seawater desalination

The RUTA reactor facility can be used efficiently as a source of low-grade heat for desalination of seawater as part of a nuclear desalination complex (NDC). In the reactor and desalination facility coupling, the tertiary circuit of the reactor facility is the circuit for heating agent of multi-stage distillation evaporators (MED technology). The RUTA NDC uses Russian-developed DOU GTPA desalination facilities (distilling desalination facilities with horizontal-tube film apparatuses) adapted to the reactor parameters.

The self-evaporator operation parameters make it possible to produce a brine boiling temperature of about 85^{o}C at the DOU head stage. The capacity of the NDC based on the RUTA-70 reactor will be about 30 000 m^3/day with acceptable distillate cost values.

Economic estimates show that NDCs with the RUTA-70 reactor are capable of competing similar fossil-fuel desalination units relying on expensive outside fuel supplies in the regions of the world with water shortage.

6. Conclusions

Thanks to technical concepts used in reactor design and low coolant parameters, the RUTA-70 reactor facility features high reliability and as high level of safety and environmental friendliness as possible. This enables deployment of NHPs with the RUTA reactor in the immediate vicinity of the heat consumers. The design simplicity of the reactor and the reactor facility's essential systems ensures good economic indices with relatively low capital costs contributing to reducing the cost of thermal energy.

The results of studies show that, apart from its basic purpose of demonstrating the technology to be subsequently commercialized, the first-of-kind unit of the RUTA NHP at IPPE pays back the investments.

Developing and introducing based on the RUTA facilities innovative nuclear technologies to ensure knowledge-intensive production for the medical and industrial applications may be also promising at other deployment sites of NHPs with the RUTA reactors. Cities relating to nuclear power both in Russian and abroad as well as territories of scientific centers are most attractive sites for such applications.

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Pre-conceptual hydrogen production modular helium reactor designs

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Abstract. Hydrogen and electricity are expected to dominate the world energy system in the long term. The world currently consumes about 50 million metric tons of hydrogen per year, with the bulk of it being consumed by the chemical and refining industries. The demand for hydrogen is expected to increase, especially if the U.S. and other countries shift their energy usage towards a hydrogen economy, with hydrogen consumed as an energy commodity by the transportation, residential, and commercial sectors. There is strong motivation to not use fossil fuels in the future, as a feedstock for hydrogen production, in part because the greenhouse gas carbon dioxide is a byproduct. An advanced reactor technology receiving considerable international interest for both electricity and hydrogen production is the Modular Helium Reactor (MHR), which is a passively safe concept that has evolved from earlier high-temperature gas-cooled reactor designs. For hydrogen production, this concept is referred to as the H_2-MHR. Two different hydrogen production technologies are being investigated for the H_2-MHR; an advanced sulfur-iodine (SI) thermochemical water splitting process and high-temperature electrolysis (HTE.) This paper describes pre-conceptual designs and economic evaluations for full-scale, n^{th}-of-a-kind SI-Based and HTE-Based H_2-MHR plants. Full-scale plants include four MHR modules. Preliminary economic evaluations show both concepts are capable of producing hydrogen at a cost of approximately \$2/kg.

1. Introduction

The Very High Temperature Reactor (VHTR) is one of the advanced reactor concepts within the internationally supported Generation IV program. Because of its design features and design maturity, the VHTR was selected by the U.S. Department of Energy as the U.S. Generation IV concept for the Next Generation Nuclear Plant (NGNP). The mission objectives for the NGNP include high-efficiency production of both electricity and hydrogen. Other countries, including Russia, Japan, South Korea, China, South Africa, and France are also developing this technology, and large-scale deployment of VHTR technology is a realistic element of future energy growth scenarios. In the U.S., General Atomics (GA) has developed a VHTR concept known as the Modular Helium Reactor (MHR), which operates at a power level of 600 MW(t). For hydrogen production, the concept is referred to as the H_2-MHR. Two concepts that make direct use of the MHR high-temperature process heat are being investigated in order to improve the efficiency and economics of hydrogen production. The first concept involves coupling the MHR to the SI thermochemical water splitting process and is referred to as the SI-Based H_2-MHR [1]. The second concept involves coupling the MHR to high-temperature electrolysis (HTE) and is referred to as the HTE-Based H_2-MHR [2].

The MHR does not require active safety systems to ensure public and worker safety. Because of its high efficiency, the MHR rejects less waste heat than other reactor concepts. This design feature, combined with passive safety, allows for more flexible siting options. The MHR can operate efficiently and economically with several different fuel cycles, including low-enriched (LEU) uranium fuels, high-enriched uranium (HEU) fuels, mixed uranium/thorium and plutonium/thorium fuels, and surplus weapons-grade plutonium fuels. More recently, an MHR design has been developed to deeply burn plutonium and other transuranic (TRU) actinides recovered from light-water reactor (LWR) spent fuel. The flexible fuel cycle capability of the MHR, combined with its flexible energy output capability, result in a design concept that is very well suited for a wide variety of energy-growth scenarios (see Fig. 1).

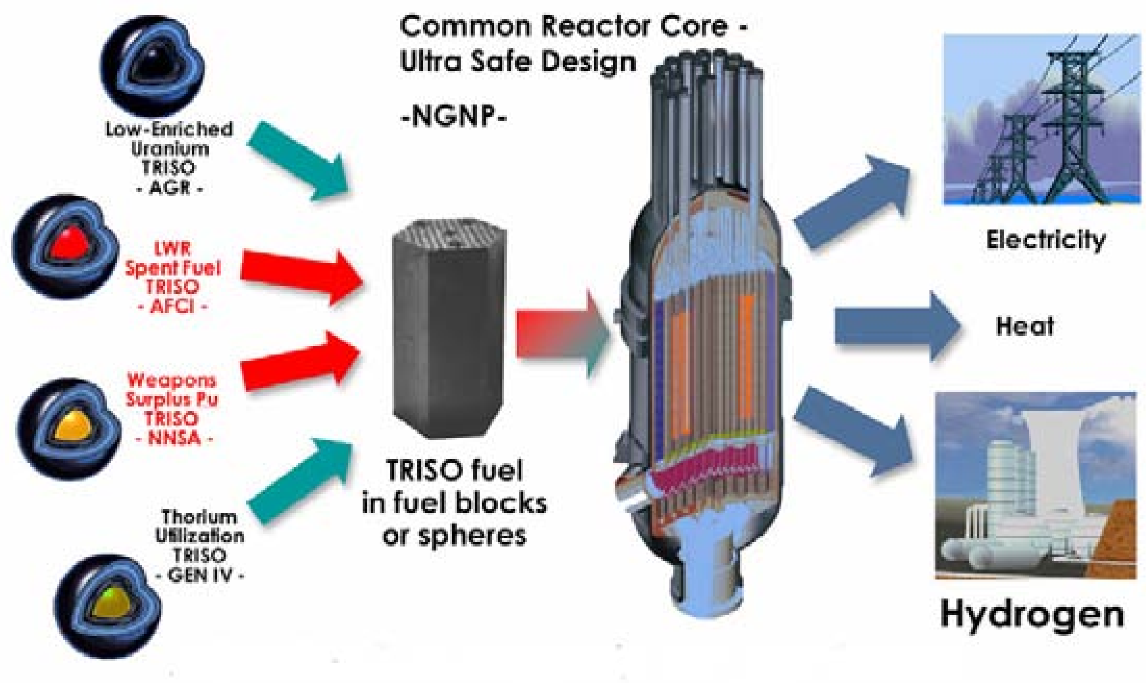

FIG. 1. MHR fuel cycle and energy output options

2. MHR design and passive safety features

The MHR concept and its fuel-element design are shown in Fig. 2. Passive safety features of the MHR include the (1) ceramic, coated-particle fuel that maintains its integrity at high temperatures during normal operation and loss of coolant accidents (LOCAs); (2) an annular graphite core with high heat capacity that limits the temperature rise during a LOCA; (3) a relatively low power density that helps to maintain acceptable temperatures during normal operation and accidents; (4) an inert helium coolant, which reduces circulating and plate out activity; and (5) a negative temperature coefficient of reactivity that ensures control of the reactor for all credible reactivity insertion events. The fuel, the graphite, the primary coolant pressure boundary, and the low-pressure vented containment building provide multiple barriers to the release of fission products.

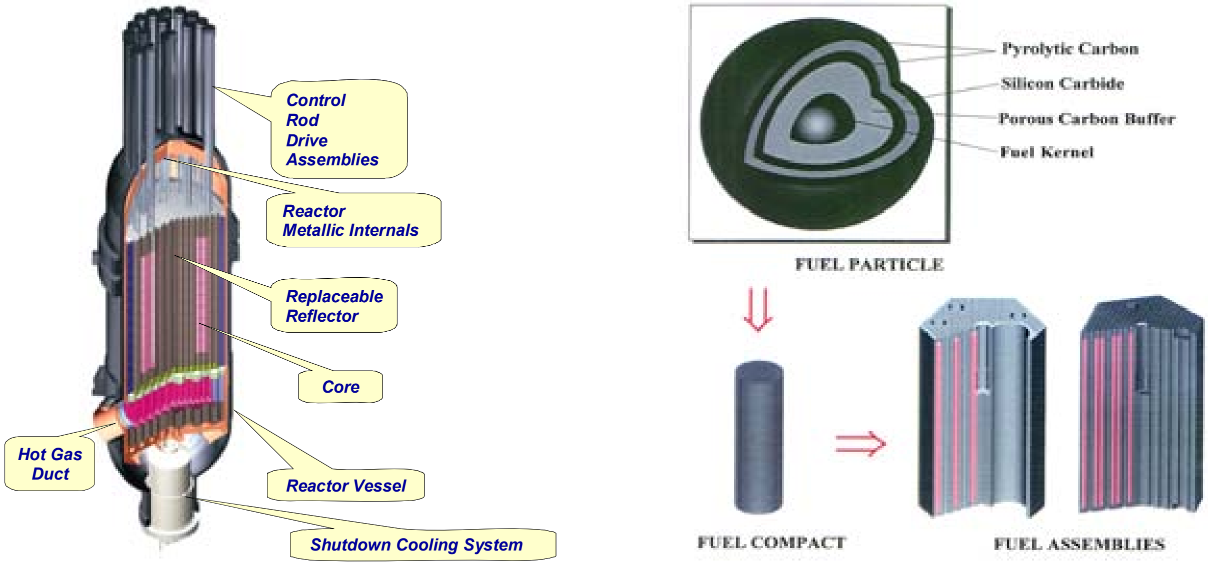

FIG. 2. MHR concept and fuel-element design

The H_2-MHR fuel consists of micro spheres of heavy-metal oxides or oxycarbides that are coated with multiple layers of pyrocarbon and silicon carbide. For an LEU fuel cycle, the H_2-MHR core is designed to use a blend of two different particle types; a fissile particle that is enriched to 19.8% U-235 and fertile particle with natural uranium (0.7% U-235). The fissile/fertile loading ratio is varied with location in the core, in order to optimize reactivity control, minimize power peaking, and maximize fuel cycle length. The buffer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC) layers are referred to collectively as a TRISO coating. The coating system can be viewed as a miniature pressure vessel that provides containment of radionuclides and gases. This coating system is also an excellent engineered barrier for long-term retention of radionuclides in a repository environment.

The H_2-MHR is not expected to present any significant licensing challenges relative to other MHR concepts for electricity production. However, a key consideration for safety and licensing of the H_2-MHR is co-location of the MHR modules with a hydrogen production plant. As illustrated in Fig. 3, it is proposed to locate the two facilities as close as possible (within 100 m or less) in order to minimize the distance over which high-temperature heat is transferred. Idaho National Laboratory (INL) has performed an engineering evaluation for these separation requirements and has concluded separation distances in the range of 60 m to 120 m should be adequate in terms of safety [3]. This conclusion is consistent with a safety assessment performed by Japan Atomic Energy Agency (JAEA) for their GTHTR300C co-generation concept [4].

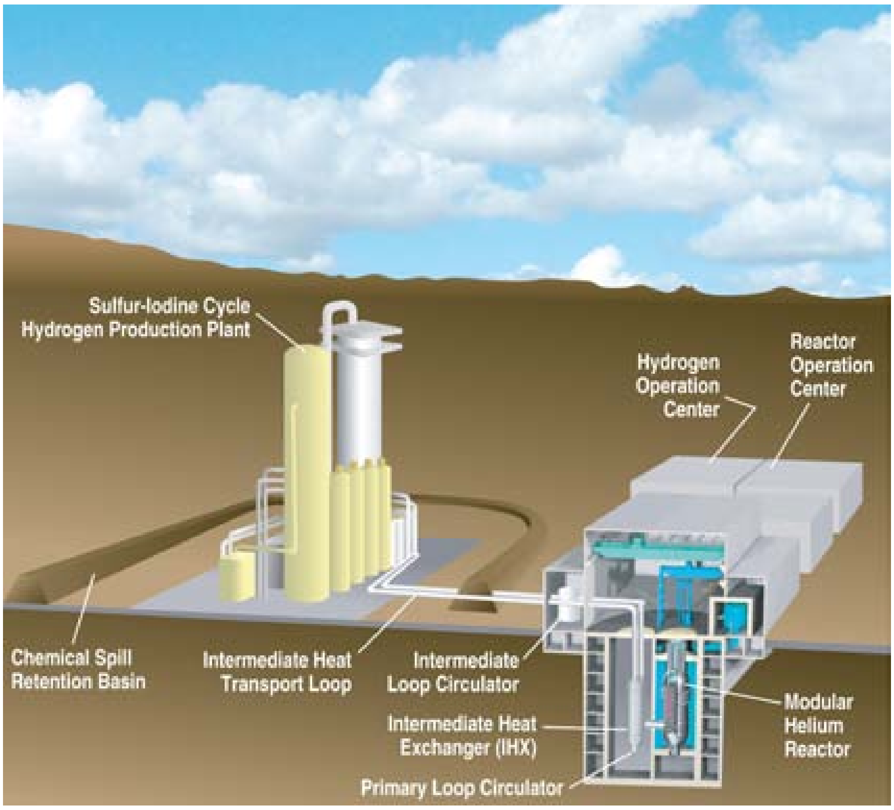

FIG. 3. Concept for co-location of MHR with hydrogen production plant

3. SI-Based H_2-MHR

As indicated in Fig. 4, the SI process involves decomposition of sulfuric acid and hydrogen iodide, and regeneration of these reagents using the Bunsen reaction. Process heat is supplied at temperatures greater than 800°C to concentrate and decompose sulfuric acid. The exothermic Bunsen reaction is performed at temperatures below 120°C and releases waste heat to the environment. Hydrogen is generated during the decomposition of hydrogen iodide, using process heat at temperatures greater than 300°C.

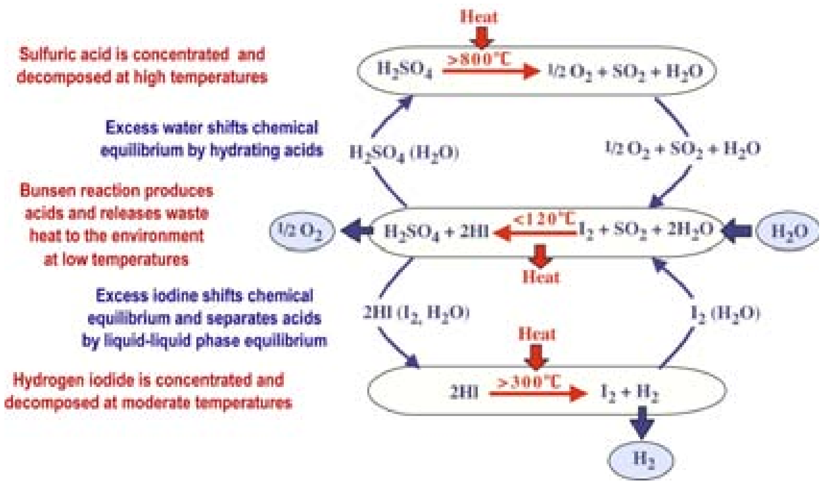

FIG. 4. The SI thermochemical water splitting process

As shown in Fig. 5, the heat required to drive the SI process is supplied by MHR modules, with each module coupled to an Intermediate Heat Exchanger (IHX) to transfer the heat to a secondary helium loop. The heat is then transferred to the SI-based Hydrogen Production System. In addition to the heat required to drive the SI process, the plant requires approximately 800 MW(e) to power pumps and compressors that are part of the Hydrogen Production System. For this study, it is assumed that the electricity is supplied by MHRs operating with a Brayton cycle power conversion system with 48% thermal efficiency. Nominal plant design parameters are given in Table I. At a 90% capacity factor, the plant produces 3.68×10^5 metric tons of hydrogen per year at an efficiency of 45.0% (based on the higher heating value of hydrogen) with a product gas pressure of 4.0 MPa.

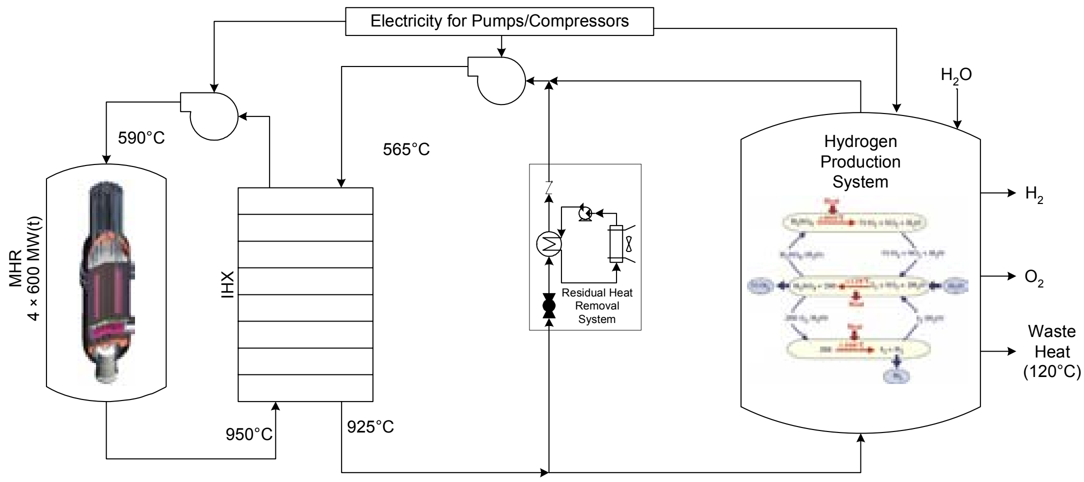

FIG. 5. SI-Based H_2-MHR process schematic

Table I. SI-Based H_2-MHR nominal plant design parameters

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Heat Transport System	
Primary coolant fluid	helium
Primary coolant pressure	7.0 MPa
Primary coolant flow rate	320 kg/s
Total pressure drop – primary circuit	100 kPa
Secondary coolant fluid	helium
Secondary coolant pressure	7.1 MPa
Secondary coolant flow rate	320 kg/s
Secondary coolant cold leg/hot leg temperatures	565°C / 925°C
Total pressure drop – secondary circuit	146 kPa
Hydrogen Production System	
Peak process temperature	900°C
Peak process pressure	7.0 MPa
Product hydrogen pressure	4.0 MPa
Annual hydrogen production	3.68×10^5 metric tons
Plant hydrogen production efficiency	45.0%

4. HTE-Based H_2-MHR

High-temperature electrolysis is performed using solid-oxide electrolyzer (SOE) modules. A single SOE module would contain 40, 500-cell stacks and consume 500 kW(e). As shown in Figure 6, eight modules could be installed within a structure that is similar in size to the trailer portion of a typical tractor-trailer. Approximately 292 of these 8-module units would be required for a full-scale plant with four 600-MW(t) MHR modules.

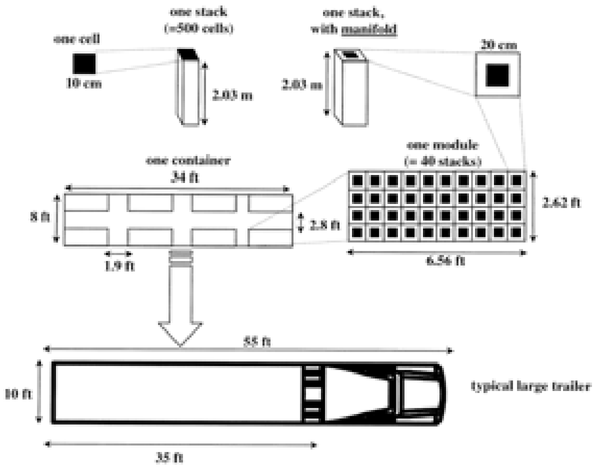

FIG. 6. SOE module concept

As shown in Fig. 7, MHRs supply both the heat to generate steam and the electricity to split the steam into hydrogen and oxygen. Approximately 90% of the heat generated by the MHR modules is used to produce electricity. The remainder of the heat is transferred though an IHX to produce steam. Nominal plant design parameters are given in Table II. At a 90% capacity factor, the plant produces 2.68×10^5 metric tons of hydrogen per year at an efficiency of 55.8% (based on the higher heating value of hydrogen) with a product gas pressure of 4.95 MPa.

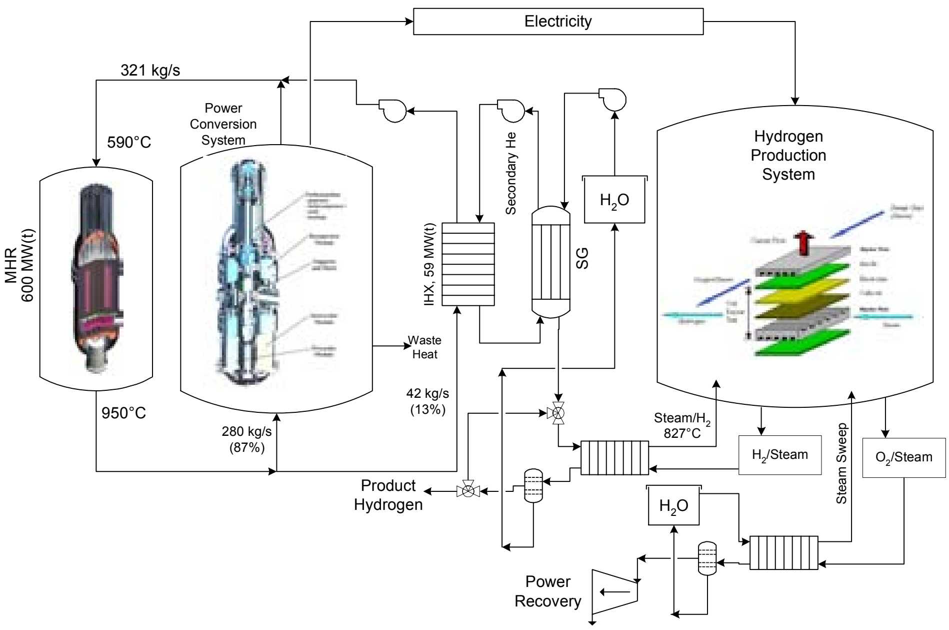

FIG. 7. HTE-Based H_2-MHR process schematic

4. Economic evaluations

Economic evaluations were performed assuming n[th]-of-a-kind H_2-MHR plants could be constructed in 36 months with an annual interest rate of 7% and a fixed charge rate of 12.6% (corresponding to a regulated utility). Hydrogen production costs are summarized in Table III. The total hydrogen production costs for the SI-Based and HTE-Based plants are estimated to be approximately the same ($1.97/kg and $1.92/kg, respectively). For the SI-Based plant, electricity costs contribute to about 30% of the hydrogen production costs. If the pumping power required by the SI process could be reduced by 50%, the hydrogen production costs could be reduced to about $1.62/kg and the overall efficiency of the process would increase from 45% to 55%. For the HTE-Based plant, the SOE module cost has significant uncertainty and was assumed to be $500/kW(e) for this study. If the SOE module cost is increased to $1,000/kW(e), the hydrogen production cost increases to $2.55/kg.

Figure 8 shows a comparison of nuclear hydrogen production costs with the costs for producing hydrogen using steam-methane reforming (SMR). In December 2005 the wellhead price for natural gas was $10.02 per 1000 cubic feet, which corresponds to $9.72/MMBtu. At this price, nuclear hydrogen production is economically competitive with SMR. Nuclear hydrogen production is economically competitive with SMR for natural gas prices in the range $6 to $8/MMBtu, if a CO_2 sequestration/disposal cost for SMR and an O_2 credit for nuclear hydrogen production are assumed.

Table II. HTE-Based H_2-MHR nominal plant design parameters

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Helium mass flow rate	321 kg/s
Total MHR System pressure drop	80 kPa
Power Conversion System	
Mass flow rate	280 kg/s
Heat supplied from MHR System	542 MW(t)
Turbine inlet/outlet temperatures	950°C / 600°C
Turbine inlet/outlet pressures	7.0 MPa / 2.8 MPa
Generator efficiency	98 %
Electricity generated	292 MW(e)
Electricity generation efficiency	53.9%
Heat Transport and Recovery System	
Primary helium flow rate	42 kg/s
Secondary helium flow rate	18.1 kg/s
IHX heat duty	59 MW(t)
IHX primary side inlet/outlet temperatures	950°C / 679°C
IHX secondary side inlet/outlet temperatures	292°C / 917°C
Steam production rate	23.6 kg/s
Mass flow rate of hydrogen added to steam	0.3 kg/s

Temperature of steam/hydrogen supplied to SOE	827°C
Hydrogen Production System	
Peak SOE temperature	862°C
Peak SOE pressure	5.0 MPa
Product hydrogen pressure	4.95 MPa
Annual hydrogen production	2.68×10^5 metric tons
Plant hydrogen production efficiency	55.8%

Table III. Summary of hydrogen production costs

	SI-Based H_2-MHR		**HTE-Based H_2-MHR**	
Account	**Cost ($M/yr)**	**Percent of Total**	**Cost ($M/yr)**	**Percent of Total**
MHR Plant Capital Charges	181.2	24.9	178.8	34.8
H_2 Plant Capital Charges	135.3	18.6	145.8	28.3
MHR Plant O&M Costs	37.4	5.2	37.8	7.3
H_2 Plant O&M Costs	76.6	10.6	81.1	15.8
Nuclear Fuel Costs	71.2	9.8	71.2	13.8
Electricity Costs	224.1	30.9	0	0
Total Annual Costs	725.8		514.7	
	kg/yr		kg/yr	
Hydrogen Produced	3.68×10^8		2.68×10^8	

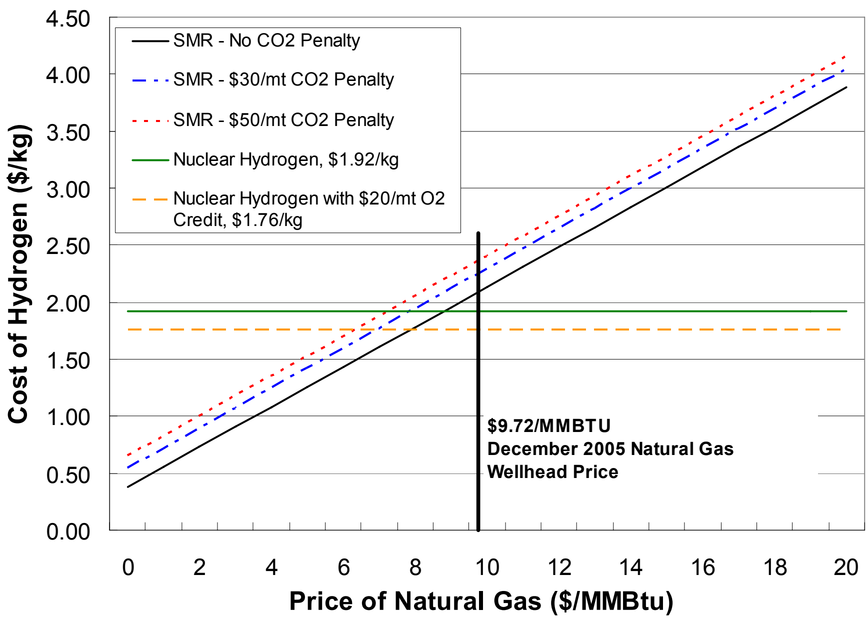

FIG. 8. Comparison of nuclear and SMR hydrogen production costs

5. Conclusions

Because of its passive-safety features, high-temperature capability, and flexibility with regard to fuel cycles and energy outputs, the MHR is well suited for supplying a wide range of future energy needs, including hydrogen production. Based on pre-conceptual design studies, the H_2-MHR is capable of producing hydrogen efficiently, economically, safely, and with minimal environmental impact using either SI-based thermochemical water splitting or HTE. The NGNP project should provide the basis for commercialization of the H_2-MHR.

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Non-electricity application of nuclear energy: some general issues and prospects

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Abstract. At present, nuclear power systems are used predominantly at nuclear plants for electricity generation. Meanwhile, there has been a growing interest in using nuclear sources for the other purposes. This paper presents the combined heat and power applications of nuclear energy utilizing existing reactor designs in Russian Federation. District heating and desalination experiences have been particularly discussed in detail. Developments in high temperature reactors and their applications have also been described.

Introduction

At present, nuclear power systems are used predominantly at nuclear plants for electricity generation.

Meanwhile, there has been a growing interest in using nuclear sources for the other purposes. Non-electricity application of nuclear energy may serve to:

- improve efficiency and cost-effectiveness of nuclear sources, hence making them more attractive for investments;
- expand the area of nuclear energy application;
- replace fossil fuel in the new areas and further reduce the greenhouse effect.

The non-electricity benefits of nuclear are most evident in case of heat and electricity cogeneration, with the heat quality required in different non-electricity applications.

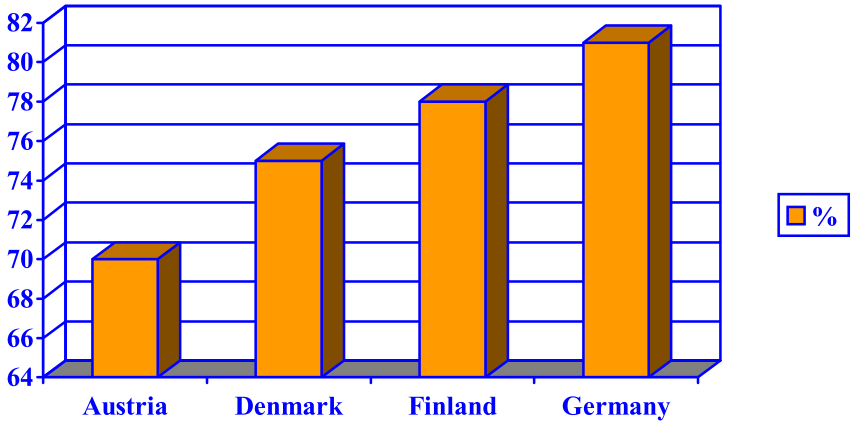
1. District heating

The use of nuclear sources for heat and electricity cogeneration may prove a very promising and low-effort option for the countries with a well-developed district heat supply system.

Thus, in Russia, heat supply for the household and industrial needs is of an utmost importance for the national economy and national security. Nearly half of the fuel and energy resources of Russia go in heat supply.

The power sector is the largest commercial producer of heat. Most of the heat generated at power stations (82-85%) is produced in the most efficient way – with heat and electricity cogeneration at cogeneration power plants (CPP), which is reflected in the term “district heating”. The thermodynamic efficiency of cogeneration is almost twice higher than the efficiency of producing the same amount of electricity separately at a condensing fossil-fuel plant and heat in a boiler plant [1] The cogeneration power plants are the largest energy sector in Russia, in terms of both installed capacity – about 50% of the total capacity of the fossil-fuel plants, and energy output (as regards cost, the product of cogeneration power plants surpasses to the product of fossil-fuel plants).

Cogeneration power plants play a very important role in district heat supply in the EC countries as well (Fig.1). Furthermore, there are administrative and economic incentives there to increase the application of such plants.



Average share 67%

FIG. 1. CHP share in DH production

Nuclear sources have significant advantages owing to which they have been successfully competing with other energy alternatives and hence could and should play a prominent role in the growing cogeneration sector. The Energy Strategy of Russia gives an annual target of 30 million. Gcal for nuclear heat generation by 2020.

As suggested by the heat generation experience, nuclear cogeneration power plants (NCPP) should meet a number of specific requirements. They should:

– have very high safety level so that it will be safe to build in the immediate vicinity of large towns (long-distance heat transport has not been engineered yet);
– be economically competitive, even with the high safety level and medium power (no more than 200 – 300 MWe);
– have dependable heat supply, especially, in respect of the household needs;
– be environmentally clean;
– have a robust transparent safety case proving that they satisfy the above requirements, acceptable for the public;
– be practically off-the-shelf.

It is difficult for the existing nuclear systems to meet these requirements. This means that it is necessary to develop reactor facilities specially designed for being used at nuclear cogeneration power plants.

The major difficulty in selecting a reactor system concept for a nuclear cogeneration plant is the challenge of making the plant economically competitive with capacity several fold (5 times and more) smaller than that of NPP and the safety considerably higher (next to fully assured).

The road to resolving this problem lies through innovative design solutions that would be effective at low-power cogeneration plants.

In pressurized water reactors, such innovations come as with an integral arrangement of the reactor facility, when all primary circuit components are placed inside a reactor vessel. An example of such configuration is IRIS project [2] In fact, this is the way towards unnecessary sophistication of the design, giving rise to a number of weaknesses, primarily, associated with the reactor operation.

In case of boiling water reactors with the power level under discussion, the innovations translate into simplification of the reactor system and plant design, with a maximum use of passive features in the reactor and safety system operation.

NIKIET has designed along with other Russian institutes a VK-300 reactor system with an innovative simplified passive boiling reactor, specially tailored to nuclear cogeneration.

Many nuclear designers have been looking at innovative simplified boiling water reactors as facilities of the next generation. Owing to their features, such reactors are especially good for nuclear cogeneration power plants. Several innovative solutions that can successfully address the above requirements can be implemented in these reactors.

Consistent implementation of the principles of simple design and passive operation of the main systems and components, based on the use of the well-proven off-the-shelf equipment, and the existing world experience in the design, construction and operation of more than a hundred of nuclear plants with boiling water reactors, helps meet the specific requirements for nuclear cogeneration power plants.

A VK-300 reactor has one circuit with a natural circulation of coolant and internal steam separators (Fig.2). The VK-300 design uses the basic equipment developed and manufactured for reactors of other types. Thus, the VK-300 design uses the VVER-1000 reactor vessel. It is evident that it is difficult, time-consuming and expensive to design and launch into production a new pressure vessel for a power reactor. The VK-300 reactor uses VVER-1000 fuel elements and experimentally optimized cyclone separators that were designed for use in VVER-1000 vertical steam generators. CPS drive mechanisms are the same as for RBMK-1000 reactors. Hence, the basic equipment for the innovative boiling-water reactor VK-300 is off-the-shelf and has been in operation for many years.

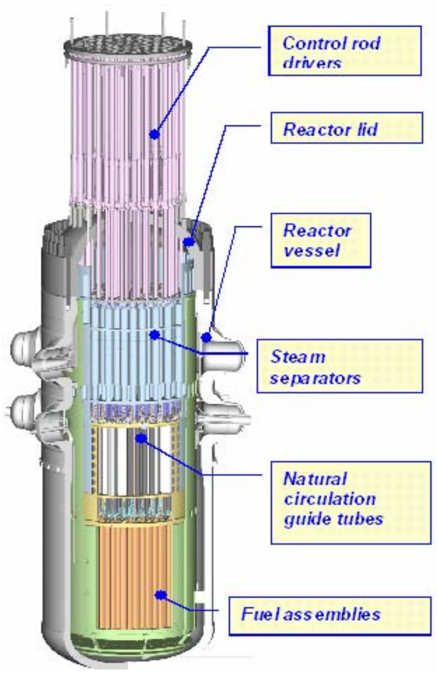


FIG. 2. VK-300 reactor

The VK-300 was developed relying on the experience with the VK-50 boiling reactor with natural coolant circulation that has been successfully operated in the national research centre NIIAR (in Dimitrovgrad) for many years. Owing to this, only a limited R&D work will have to be done to validate the new design features.

In normal operation and in any off-normal conditions, the core cooling is provided by a natural circulation of coolant. The VK-300 has an innovative process of coolant circulation and multi-stage separation in the reactor, which ensures the demanded rate of natural circulation in a reactor vessel of a relatively small height.

Special attention has been paid to the provision of a high safety level of the reactor. The facility was developed to meet the safety requirements that are an order of magnitude more stringent than those for NPP. The high safety level of VK-300 is provided due to the consistent implementation of the defense-in-depth philosophy, inherent safety features, very reliable multi-train passive shutdown systems ensuring reactor shutdown in any accident, and efficient passive multi-train core cooling systems.

The reactivity coefficients and effects have been optimized and the burn up reactivity margin has been reduced to a minimum, which provides a basis for reliable reactor control and stable operation of the facility. There are two diverse reactivity control systems – rods and liquid boric acid.

An innovative solution is small (~2000 m^3) primary containment made of reinforced concrete lined with metal. The primary containment helps ensure the plant safety in a cost-effective and reliable way, due to the use of simple passive safety features, which provide coolant cooling and return to the reactor in various accidents. The hydraulic configuration includes safety system components, located inside the primary containment, and the emergency cooling tanks (under atmospheric pressure) and heat exchangers providing heat removal from the latter to an ultimate heat sink (atmospheric air), which are located outside the containment. These solutions provide for the core damage probability of $2 \cdot 10^{-8}$ 1/year.

At the same time, considering that the reactor has one loop and is to be sited in urban areas, which increases the requirements for the environmental protection in case of abnormal events, the entire plant is placed in a leak tight enclosure – the main containment, which is another innovative solution (Fig. 3).

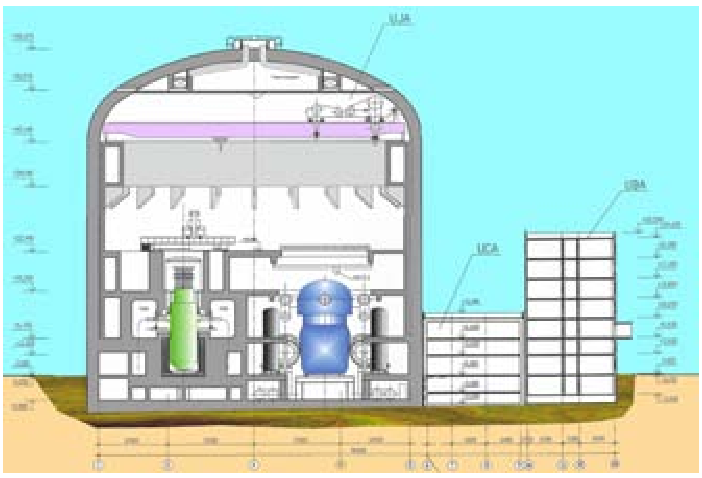


FIG. 3. Cogeneration nuclear power unit with VK-300 layout

The main performance data of VK-300 are shown in the Table I.

Table I. Main performance data of VK-300

Nominal thermal power of the reactor, MWth	750
Nominal steam generation, t/h	1370
Steam pressure, MPa	6.8
Steam temperature, ^{o}C	285
Moisture content in steam at reactor outlet, %	0.1
Feed water temperature, ^{o}C	190
Average steam quality at the core outlet, %	15.6
Core dimensions (height × diameter), m	2.42 × 3.16
Fuel enrichment, %	3.6
Burn up, MW·day/U kg	41.4

In a cogeneration plant with VK-300 reactor system, steam goes directly from reactor to a turbine. After passing several stages, some steam is extracted from the turbine and sent to the primary circuit of the district heat supply facility. Heat from the secondary circuit of the district heat facility is supplied to consumers. The circuit pressures are chosen so as to exclude possibility of radioactivity transport to the consumer circuit (Fig. 4).

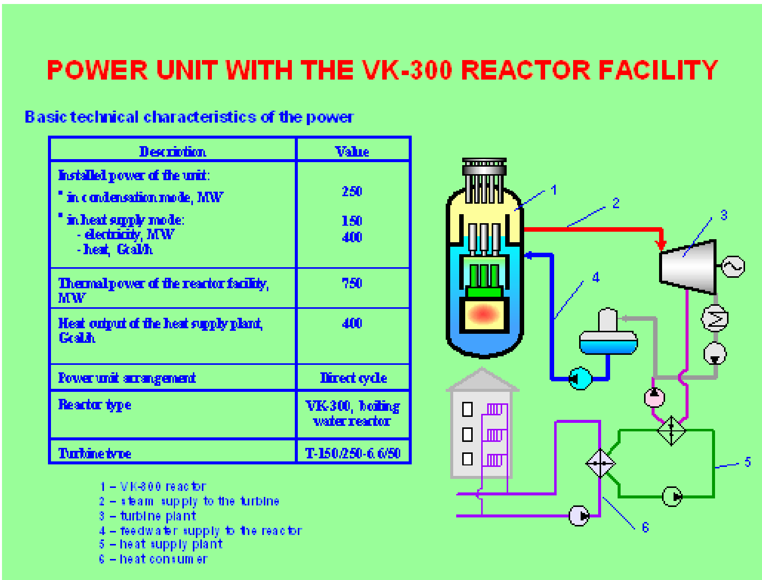


FIG. 4. Cogenegation nuclear power unit with VK-300 reactor facility

Main design data of the plant are given in Table II:

Table II. Design data of cogeneration nuclear power unit with VK-300

VK-300 plant	
Installed capacity: in condensation mode, MWe in a heat supply mode, MWe	 250 180
Capacity of heat supply facility, Gcal/h	up to 400
Estimated production cost of: - electricity, US$/ kW×h - heat, US$/Gcal	 0.01 3.33
Service life, years	60

A Feasibility Study has been produced by now for constructing a four-unit nuclear cogeneration plant with VK-300 with installed electric capacity N_e = 1000 MW and heat supply capacity Q = 1600 Gcal/h in the Arkhangelsk Region. The document has been reviewed by authorities and approved by Rosatom Scientific and Technical Board No. 10, which suggest that the Arkhangelsk nuclear cogeneration plant could resolve the socially important problem of district heating in the Arkhanglesk region. Secure long-term heat supply could be provided in due time, in a cost-effective and commercially profitable way. In particular, very simple design and passive features of the reactor system and the entire plant ensure fast return of investments in the Arkhangelsk region conditions, which is illustrated by the Table III below:

Table III. Return of investments in VK-300

Description	Value
Capital investments in plant construction, million $	880
Estimated cost of supply:	
- power, cent/kWh	~1.0
- heat, $/Gkal	~3.3
- ---	------------------------
Payback period (from the time of the Unit 1 startup)	
- with no discount	5.75
- with discount (at discount rate of 8%)	7.58

Nuclear cogeneration power plants with VK-300 could make a significant contribution in achieving the 30 million. Gcal / year target by 2020, set in the Energy Strategy of Russia. Thus, a preliminary feasibility study performed by several organizations has shown that it would be of benefit to construct such plants also in the towns of Ivanovo, Uliyanovsk, Yaroslavl, Kurgan, Vyatka, Komsomolsk-on-Amur, Murmansk, Tver, Kazan, Ufa, Izhevsk, Khabarovsk. Up to 16 nuclear cogeneration power plants could be constructed in some of the above cities in the framework of the Energy Strategy. If so, they would replace up to 16 billion. m^3 of gas per year.

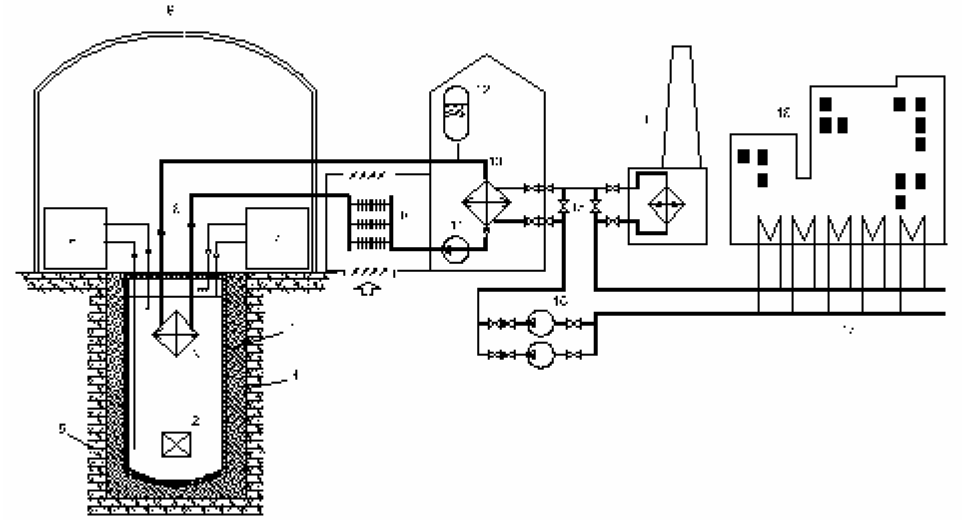
Along with the nuclear cogeneration power plants, Russia has been developing nuclear water heating facilities, which are intended provide district heat supply only. Thus, a nuclear district heating plant AST-500 was built in Nizhniy Novgorod but never put in operation. Incidentally, the power sector experience shows that the water heating niche in energy supply is an order of magnitude smaller than that of cogeneration power plants.

At the same time, with district heating-specific nuclear facilities, a big step could be made towards reducing capital costs of construction – by developing facilities operating under atmospheric pressure, similar to the pool-type research reactors.

Following this approach, NIKIET has developed under the scientific leadership of FEI (Obninsk) and with contributions from other nuclear institutes, a nuclear district heating plant RUTA. A key distinction of a pool-type RUTA reactor, which provides for its simple design, reliability, high safety, and relatively low cost of construction, is atmospheric water pressure in the primary circuit. Owing to the high safety level, such plants may be sited in the immediate vicinity of heat consumers – even in residential areas, which is proved by the good operating record of pool-type research reactor facilities (in all, 225 such facilities have been built in the world).

Another fundamental advantage of RUTA facility is its self-regulating ability. A plant with RUTA reactor can operate in a load-following mode, varying heat production depending on the heat system demand, without operator intervention. RUTA can have the capacity from 10 to 70 MWth, and can supply heat to consumers in rural and urban areas with the population from 5,000 to 100,000.

RUTA design is illustrated in Fig. 5.



- *pool-type reactor*
- *atmospheric water pressure and 100 °C temperature in the primary circuit*
- *good operating record of pool-type research reactor facilities*
- *self-regulating ability*
- *Inherent safety*
- *three circuit arrangement of heat transportation from reactor to consumer*

FIG. 5. District heating plant with RUTA

Cost indicators for RUTA-70 with thermal capacity 70 MWth are given in the Table IV below:

Table IV. Cost indicators for RUTA-70

Capital costs, million. EUR	26.672
Annual expenditures, million. EUR/y	1.8
Heat production cost (with load factor 67%), EUR/Gcal	5.1
Return of investment time (with heat tariff 151 EUR/Gcal), years	11

At the Conference there is another presentation with a detailed description of the results of RUTA development.

2. Desalination

The heat produced at nuclear cogeneration power plants can be efficiently used for seawater desalination.

Considering the global trend towards developing desalination techniques and the steadily growing demand for them, Russia has been attaching great attention to this technology. Two major aspects are of special importance here – provision of power for the desalination process and introduction of new materials that would make desalination plants more reliable and the fresh water production cheaper. These are the areas of the greatest scientific effort, and Russia could contribute to this work because of her nuclear expertise and experience in the development, manufacture and operation of desalination facilities, including nuclear (BN-350 reactor in Aktau, Kazakhstan).

Thus, NIKIET has been developing in league with other companies a nuclear desalination complex based on a nuclear cogeneration plant with an innovative simplified passive boiling reactor VK-300, distillation desalination facilities (DDF) operating based on a Multi Effect Distillation (MED) principle, and horizontal tube film evaporators. Russia has amassed considerable experience in commissioning and long-term commercial operation of domestic desalination facilities with horizontal tube evaporators of different capacity (from 0.1 to 700 m^3/h) at the Aral Sea and Caspian Sea, and at chemical plant effluents. These facilities have significant advantages over other evaporator types [3] Sea water desalination plants developed around such facilities are more cost-effective than other installations: 1.5 – 2.0 times as regards energy consumption, 1.5 –1.8 times in terms of metal amount and site area. Considering the capability of nuclear cogeneration plants to supply heat for desalination (200 – 400 Gcal/h), it would be reasonable to build distillation facilities with large unit capacity.

Figure 6 shows a standard way of coupling a VK-300 cogeneration plant and distillation facilities[4,5]. An evaporating flash chamber is used to produce heating steam for the first stage of the multi-stage evaporator facility. On entering the flash chamber, the intermediate circuit water boils up owing to decompression. Water pressure in the intermediate circuit (1.2 MPa) is higher that that of the heating steam in boilers, which prevents radioactivity transport to the intermediate circuit.

One VK-300 plant can provide thermal energy for a distillation complex with the total capacity over 300,000 m^3/day. Without special quality requirements for the fresh water, membrane facilities could be set up in addition to or instead of MED distillers.

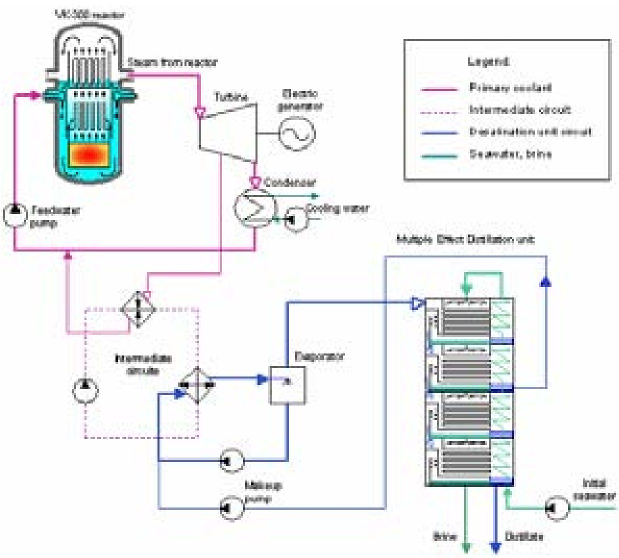


FIG. 6. Coupling diagram of the VK-300 power unit and distillation unit with horizontal-tube film evaporators (MED technology)

A general configuration has been developed for a multi-purpose energy source with VK-300, designed to provide electricity, fresh water and heat (district heating and hot water) for residential areas. Such multi-purpose energy source can be build, e.g., in Uzbekistan and Kazakhstan, which have areas with continental climate with severe winters (average temperature in Kisyl-Kum desert in January is -10 ^{o}C, the same as in Moscow) and underground salt water sources beneath the vast arid territories. The configuration was chosen to suit the operating temperature in the intermediate circuit (130/70^{o}C), which is common to the heat supply and desalination systems. The possibility of reactor power redistribution in case of heat and electricity cogeneration, and seasonal (and daily) redistribution of heat flows between the heating and desalination systems, allow reactor and plant operating with maximum load factor.

Preliminary economic assessments were made in the framework of a conceptual study for a power-and-desalination complex with two VK-300 units with various desalination systems (distillation, reverse osmosis (a stand-alone facility), and a hybrid configuration. The assessment was performed assuming the desalination complex output of 300,000 m^3/day. In MED, this output is provided due to heat supply together with controlled steam extraction from the turbines of the two units (via the intermediate circuit). Table V below shows preliminary technical and economic data of a VK-300 power and desalination complex:

Table V. Techno-economic data of a VK-300 power and desalination complex

Description	Value		
Energy source	Two power units with VK-300		
Nominal electric power with turbines in condensing mode, MWe	(220 × 2)*		
Construction cost, million. US dollars	515	470	515
Desalination technique	MED	RO	Hybrid facility (MED+RO)
Cost of desalination system, million. US dollars	326	260	296
Fresh water output, m^3/day	300,000	300,000	300,000, including MED – 100,000 RO – 200,000
Distillate cost, dollars/m^3	0.59	0.51	0.53
Sale of excess electricity from two VK-300 to the grid, MWE	346	357	352

The high technical and economic indicators of the VK-300 plant resulting in particular from a very simple design (integral arrangement, natural circulation of coolant, one loop, passive safety systems) and reasonably low operating costs provide for the high competitiveness of the power and desalination complex.

A nuclear water heating facility RUTA operating under atmospheric pressure and having high safety, very simple design, high reliability and good environmental characteristics, can be used as a heat source for heat water distillation as well. Low coolant parameters in the consumer (tertiary) circuit call for unusual solutions to couple the reactor and heat distillation facilities. Multi-stage counter-flow boiling steam generators were included in the nuclear desalination complex. The steam produced in the steam generators serves to heat the distillation modules.

Owing to the wide range of RUTA capacities, the desalination complex can be tailored to the needs of a particular region. Cost assessments have shown that a RUTA-based nuclear desalination complex will be competitive in the areas importing fossil fuel.

3. High-temperature reactors

There has been a growing interest recently in nuclear reactors with high coolant parameters (helium, supercritical water). The main purpose is to raise the efficiency of electricity generation and hence ensure the plant competitiveness against fossil-fuel stations, first of all, steam-gas power plants.

High coolant parameters open new prospects for non-electricity applications of nuclear energy.

Much attention has been given to the promising technology of using the high-temperature heat from gas-cooled reactors for hydrogen generation, in particular, in an iodine-sulfur cycle, in which the main challenge is the choice of structural materials because of the very aggressive environment (sulfuric acid, etc.) of the cycle. While leaving the detailed discussion of HTR use in nuclear hydrogen economy to other authors, we will mention only a conceptual proposal of NIKIET on a directional use of water radiolysis by U-235 fission fragments in a solution reactor with weapons grade uranium fuel, which can provide very efficient production of hydrogen.

The use of high-temperature heat, first of all, in gas-cooled reactors, seems to be very promising and realistic for black and slate coal gasification with production of synthesis gas. The most cost-effective approach is to build nuclear cogeneration complexes, in which high-temperature helium reactors will be used to generate electricity in a cycle with supercritical steam parameters (30-37 MPa, 650-700ºC, efficiency 55-60%) and to produce synthesis gas (mixture of CO and H_2) by way of black and slate coal gasification. Coal may be of low quality, high-ash, brown.

Coal gasification reaction is heat absorbing:
$C + H_2O = CO + H_2 - 119$ kJ/mol

It is suffice to have the temperature over 500°C for synthesis gas production.

A sketch of a HTR facility for production of electricity and synthesis gas is given in Fig. 7. The system incorporates a high-temperature reactor, steam generators and reheaters. Steam of supercritical pressure is used in a steam turbine unit to produce electricity. Reheaters reheat the steam coming from the steam turbine unit and provide steam for coal gasification. The number of reheaters and steam parameters depend on the coal gasification facilities.

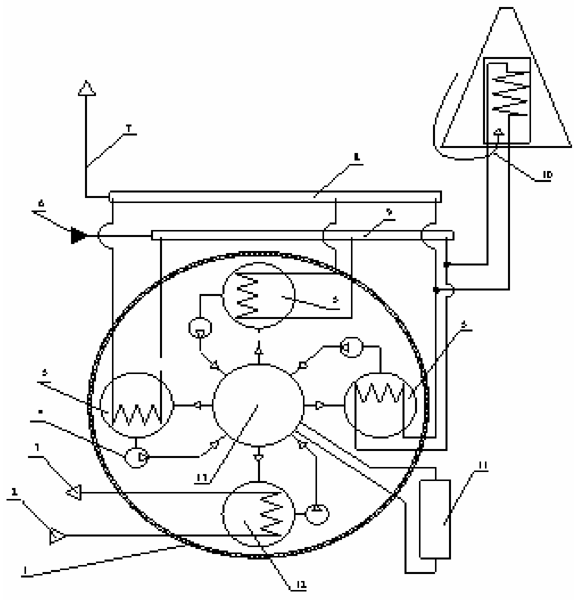


FIG. 7. A power unit with high-temperature reactor

1- containment, 2- from HPC, 3 - to MPC, 4 - gas blower, 5 – steam generator, 6- from HPR, 7- to turbine, 8 – live steam header, 9 – feed water header, 10- air entering passive heat removal system, 12 – intermediate reheater, 13 - reactor

4. Conclusion

Non-electricity application is a very realistic way towards expanding the use of nuclear energy, raising the technical and economic efficiency of nuclear sources, and hence making them more attractive for investments.

The non-electricity benefits of nuclear are most evident in case of heat and electricity cogeneration, of the quality required in different applications, such as district heating systems, desalination facilities, black and slate coal gasification, in hydrogen generation facilities.

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Conceptual system design of non-nuclear grade IS process to be coupled with the HTTR

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Abstract. Hydrogen production from water utilizing nuclear energy offers one of the most attractive zero-emission energy strategies to meet massive demand of hydrogen. Because of its advantage over other water-splitting hydrogen production processes using heat from a VHTR, the IS process has been selected by JAEA as an important research priority for future technologies. Establishing a sufficient technology base for the VHTR-IS hydrogen production system, R&D is being conducted not only for the IS process but also in areas aiming to close several technology gaps between the VHTR and the HTTR, the only existing HTGR in the world capable of supplying 900°C helium for process heat applications. JAEA has launched design studies of the IS process to be coupled with the HTTR (HTTR-IS system) to demonstrate VHTR hydrogen production. It is important from an economic point of view that a non-nuclear grade, rather than nuclear grade, IS process plant be built based on conventional chemical plant construction standards. Some critical safety issues must be studied and clarified prior to the application for safety review from the government in order to construct the IS process as a chemical plant. Effective heat shock absorption method to remove secondary heat in case of abnormal transient or accident triggered by the IS process, tritium permeation from core to product hydrogen, hydrogen explosion and its effect to the nuclear system especially to the engineered safety features are amongst the major safety issues to be resolved in order to permit a conventional or non-nuclear grade IS process plant. This paper describes the conceptual system design of the non-nuclear grade IS process to be coupled with the HTTR.

1. Introduction

Japan Atomic Energy Agency (JAEA) has been conducting R&D on High-Temperature Gas-Cooled Reactors (HTGRs) and on thermochemical water-splitting hydrogen production by the Iodine Sulphur (IS) process. In the development of HTGR technologies, HTTR (High Temperature Engineering Test Reactor) [1] is the first HTGR in Japan which had been constructed and successfully deliverd 950°C helium outside its reactor vessel [1]. During the research work of the IS process, JAEA had developed a control technology of continuous hydrogen production @30NL/h and 175 hours using a bench-scale test apparatus made of glass [3]. The R&D has been conducted in four stages towards commercial system. We are in the third stage and planning a pilot plant which can produce 30Nm^3/h hydrogen [4]. The pilot plant is designed using industrial materials and will demonstrate continuous hydrogen production using helium heat exchanged-type advanced process heat exchanger and getting experimental data in order to validate a safety analysis code of the HTTR-IS system. In the fourth stage, to be conducted parallel to the third stage, we will demonstrate 1,000 Nm^3/h hydrogen production by the HTTR-IS system [5]. The HTTR-IS system is expected to be the world first demonstration of the hydrogen production utilizing nuclear heat directly. The HTTR-IS system will show its way to the commercial nuclear hydrogen plants, *e.g.* Japanese design of VHTR GTHTR300C [6]. From an economic point of view, the IS process should be designed and constructed as non-nuclear grade in the commercial stage. JAEA started R&D to contribute to a non-nuclear designed IS process. This paper describes the conceptual system design of the non-nuclear grade IS process to be coupled with the HTTR.

2. Conceptual design of the HTTR-IS hydrogen production system

A hydrogen production system based on the IS process is planned to be connected to the HTTR. This will establish hydrogen production technologies with VHTRs including a system integration technology. The HTTR-IS system aims to:

- Establish non-nuclear grade hydrogen production system by newly applied safety philosophy and separation technologies from reactor systems to the IS process,
- Establish control technologies for both of the IS process and VHTR system,
- Add to experience of construction, operation, and maintenance, and,
- Show the way towards commercialization of nuclear hydrogen production systems by the IS process including economical feasibility of the produced hydrogen by VHTRs.

Figure 1. shows the candidate flowsheet of the HTTR-IS system. Heat produced by the HTTR core is transferred to the secondary helium at the Intermediate Heat Exchanger (IHX). The secondary helium flows through the inner-pipe of the concentric hot-gas-duct and a high-temperature isolation valve (HTIV), and supplies heat to the Advanced Process Heat Exchangers (APHX) such as H_2SO_4 decomposer and HI decomposer, and the rebolier of the HI distillation column. Finally, after cooled by the steam generator and a helium cooler, secondary helium is pressurized by the helium circulator and returns to the IHX through the outer-pipe of the concentric hot-gas-duct. The IS process consists of three procedures; Bunsen reaction procedure (Bunsen PROC), H_2SO_4 decomposition procedure (H_2SO_4 PROC) and HI decomposition procedure (HI PROC). In the H_2SO_4 PROC, the product acid from Busen PROC flows into the H_2SO_4 concentration unit applying vaccum distillation and concentrated to 88 wt% H_2SO_4 solution. The concentrated solution flows into H_2SO_4 decomposer and decomposed into SO_2, O_2 and H_2O, respectively. The decomposed products flows back to Bunsen procedure. In the HI PROC, the product acid from Bunsen PROC flows into the HI concentration parts consist of electro-electrodialysis (EED) and HI distillation column. The concentrated HI gas flows into HI decomposer and decomposed into H_2 and I_2. The Bunsen reactor is a newly designed mixer-settler type which combined the Bunsen reaction part and liquid-liquid separator part [7]. The H_2SO_4 decomposer is also newly designed which combined SO_3 decompser, H_2SO_4 vapourizer, and process heat exchanger [7]. The detailed HTTR design and summary of candidate HTTR-IS system flowsheet have already been reported elsewhere [1] and [7, 8] respectively.

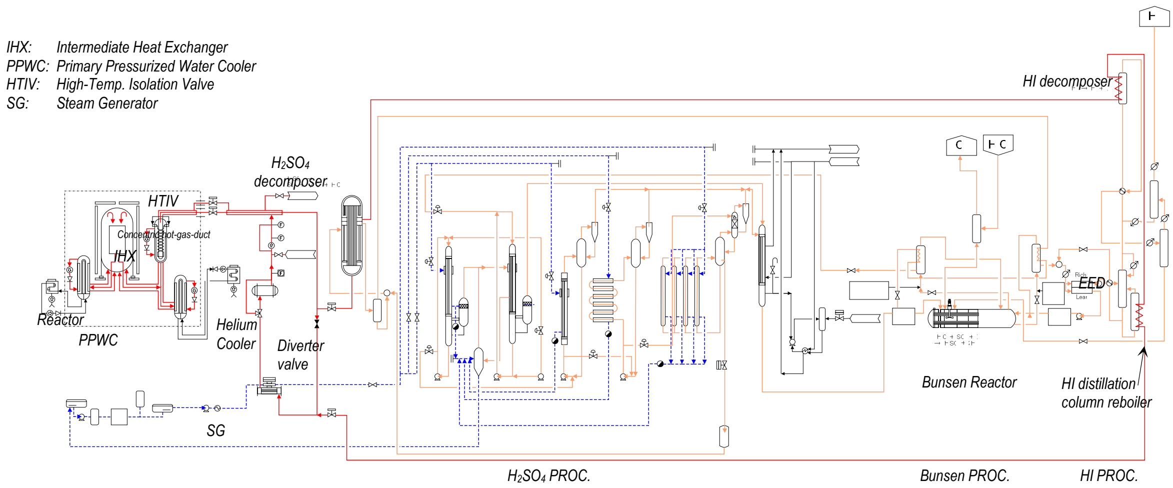

FIG. 1. Candidate flow sheet of the HTTR-IS system.

3. Research items for non-nuclear grade hydrogen production system

3.1. Summary

The IS process coupled with the VHTR system should be designed and constructed as non-nuclear grade. There are two reasons for recommending non-nuclear system. One reason is that the non-nuclear grade IS process can contribute economically for nuclear produced hydrogen. Target cost of nuclear produced hydrogen by, for instance, Japanese VHTR GTHTR300C [6] is 20.5 JPY/Nm^3 [9] which has economic competitiveness compared with cost of hydrogen produced by other method in a future hydrogen society when massive quantity of hydrogen is needed. The IS process cost is assumed as 14 Billion JPY [9] including construction cost and running cost. For reducing construction cost, it is necessary to apply conventional chemical plant design standards to the IS process. The other reason is that non-nuclear grade hydrogen production system can open the door for non-nuclear industries to enter as a construction company. Since it is considered reasonable that the reactor facility will be operated by electric power companies and the hydrogen production system will be managed by gas and oil companies in commercial VHTR-IS systems, the hydrogen production system should be constructed as a chemical plant. Based on above requirements, JAEA started R&D to contribute to a non-nuclear grade IS process. The R&D contents can be divided into two items. One is to establish a safety philosophy, and the other is to develop hardware for separation of nuclear system from hydrogen plant. Fig. 2. shows the R&D map for developing non-nuclear grade IS process hydrogen production system to be coupled with the HTTR.

3.2. Establishment of safety philosophy

Safety philosophy for non-nuclear grade IS process development is consolidated into two items [10] :

- Exempt the IS process from Prevention System 3 (PS-3) [11]and,
- Identify abnormal events initiated in the IS process as external events.

In order to meet these requirements, following R&D are to be conducted.

3.2.1. Establishment of safety criteria

The means to classify the IS process into the non-nuclear-grade system is to keep the safety function for continuous operation by the backup nuclear graded equipments during IS process abnormal conditions. The thermal load disturbance absorption system, (for HTTR-IS system it is steam generator), is one of the backup equipments. Even if they failed, high-level safety functions, having HTGR itself, can be provided to ensure the general nuclear safety and can prevent reactor damage. Hence, the IS process does not need any safety function for continuing reactor operation. The present safety criteria against internal events should be applied to the HTTR-IS system. In the safety design of the HTTR-IS system, an accidental release of flammable and/or toxic gas shall be considered. As mentioned before, the safety means to prevent reactor shut down are proposed. Safety review will be performed to validate their function in accidents. The safety criteria against external event are proposed as Table I.

Table I. Safety criteria of the HTTR-IS system.

Event	Safety Criterion	Function
Flammable gas release	Gas concentration. of intake air from ventilation system is lower than its explosion limit.	Preventing an explosion in the reactor building.
	Overpressure on the reactor building is lower than 20kPa. (In case of wall thickness of 30cm)	Preventing the top-level safety-related systems inside the reactor building.
Toxic gas release	Gas concentration. in the control room is lower than its limits for long-lasting adverse health effects.	Safeguarding reactor operators against hazard.

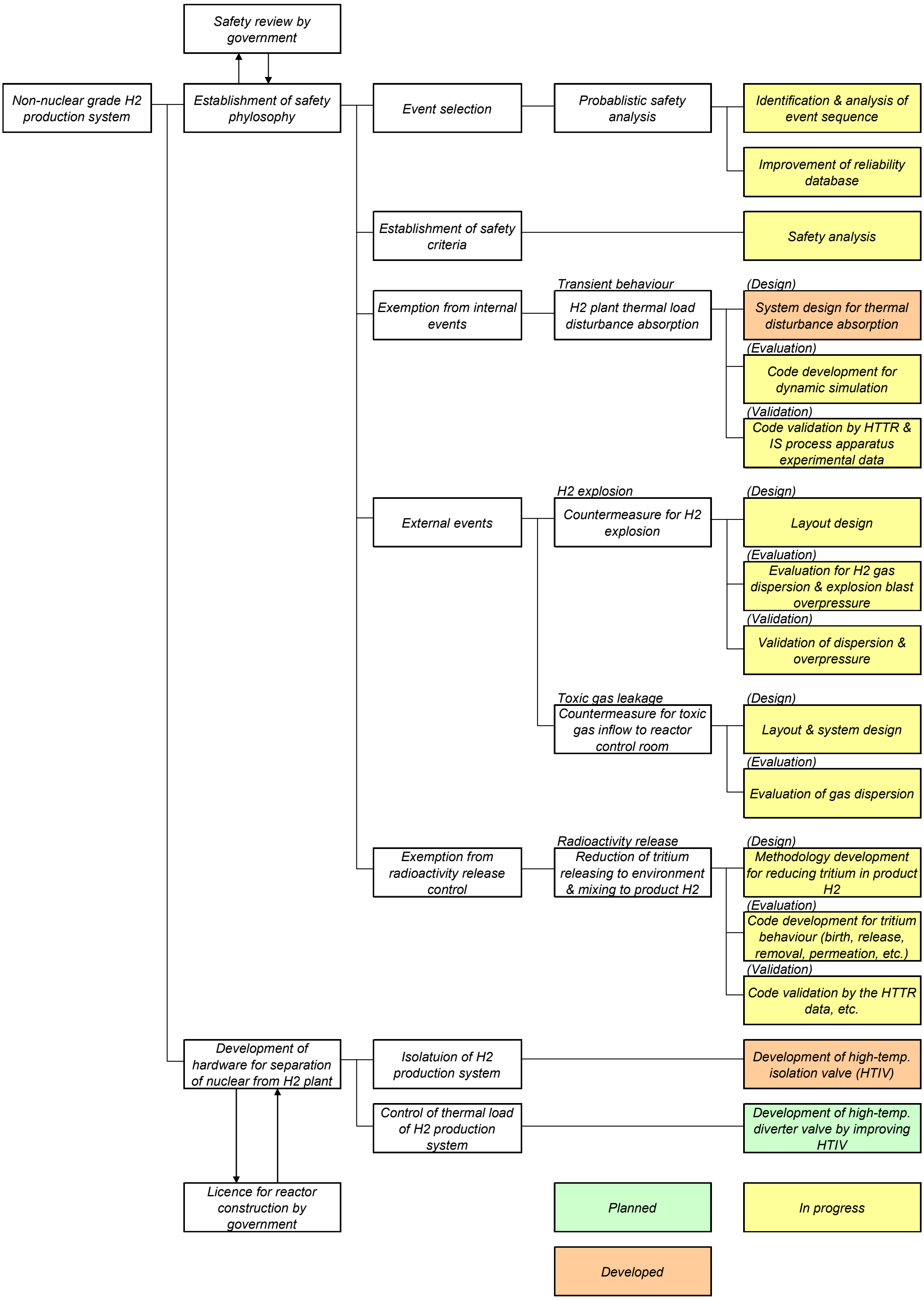

FIG. 2. R&D map for non-nuclear grade IS process hydrogen production system to be coupled with the HTTR.

3.2.2. *Exemption from internal events*

Absorption system which can mitigate the thermal load fluctuation of the IS process can be one of the solution to exempt the IS process from the PS-3. Any abnormal events can be exempt from internal events by applying absorption system to the secondary helium cooling system. JAEA proposed its cooling system consisting of a steam generator with an air cooler for the HTTR-IS absorption system (cf. Fig. 1.). The cooling system is installed downstream of the IS process in the secondary cooling system of the HTTR-IS system. Though the inlet helium gas of the steam generator fluctuates when the IS process thermal load fluctuates by some abnormal events, latent heat of retained water in the steam generator absorps its fluctuation [12]. Evaluating the credibility of the cooling system and plant dynamics of the HTTR-IS system during abnormal events initiated by the IS process, a dynamic simulation code of the HTTR-IS system should be developed. Its code needs to calculate plant dynamics for both of the HTTR and the IS process. Calculation results will be also utilized for the safety review by the government. Analytical model is consisting of the reactor core, primary and secondary cooling system, auxiliary cooling system, steam generator, helium cooler, etc. The dynamic simulation code of the HTTR-IS system has been developed based on RELAP5 MOD3 code. Since RELAP5 code had been developed for light water reactor systems, code modifications such as additioning the thermal properties of helium gas, air and graphite, and experimental heat transfer models of the HTTR apparatuses were already performed to calculate plant dynamics of the HTTR [13]. This code has two-fluid model for two-phase water-steam mixture, which is involved in the volumes of a steam generator with an air cooler. Also non-condensable gas models such as helium and air are able to use. Field equation consists of mass continuity, momentum conservation and energy conservation. Reactor power is calculated by point reactor kinetics equations. The development of the analytical model for the IS process is in progress. The IS process model is developed and will be combined with the RELAP5 code in the next step. Code validation is necessary not only for estimating the validity of the numerical models but also for the safety review by the government. For the models of the reactor facility including reactor core, and primary system apparatus, validation had been perfomed using the HTTR operational data [13]. For the cooling system consisting of a steam generator with an air cooler which is installed in the secondary cooling system, the mock-up test facility [14] was constructed and the models of the cooling system was verified by its operation data, [15]. For the IS process models, the bench-scale operation data was obtained previously, operation data of individual test apparatus for the pilot plant design is in progress, and the pilot plant operation data will be obtained for the next step will be utilized for its code verification.

3.2.3. External events

(a) Countermeasure for hydrogen explosion

Since the IS process includes flammble hydrogen gases and installed next to the reactor facility in the HTTR-IS system, countermeasure for the hydrogen explosion is necessary. JAEA proposed a new evaluation scenario [16] which take into consideration of a decrease of hydrogen concentration and an increase of advection distance during advection dispresion procedure and combined with Multi-Energy method [17]. To, numerical analysis code STAR-CD [18] was utilized for evaluating behaviour of advection dispresion of leakage hydrogen. The calculation results depend upon the hydrogen inventory, piping rupture diameter, leakage point height, blowout angle, and arrangement of the partition walls. Detail layout design considering offset distance between the reactor facility and IS process, and partition wall arrangement using more detailed evaluation results will be studied in the next step.

(b) Countermeasure for toxic gas inflow to reactor control room

Since the IS process generates toxic gases such as SO_2, SO_3 and HI, toxic gas inflow into reactor control room should be prevented. For the countermeasure, layout and system design such as vetilation and air conditioning system, gas-sensing system, layout of the apparatus will be perfomed and evaluated. Toxic gas diffusion and risk analysis are taken into consideration in order to evaluate the toxic gas effect. Detail evaluations are in progress and the evaluation results will be reflected to the HTTR-IS system design in the next step.

3.2.4. Exemption from radioactivity release control

For the non-nuclear grade classification, the IS process should be exempted from radioactivity release control and it means that development of the methodology to reduce tritium permeation to the IS process is very important. JAEA has developed a numerical analysis code, THYTAN (Tritium and HYdrogen Transportation ANalysis code) [19] in order to estimate the tritium movement behavior in the HTTR-IS system. The THYTAN code was initially developed for the steam reforming hydrogen production system and then it was modified for the IS process. Consequently, the THYTAN code can calculate the mass balance of tritium and hydrogen in the HTTR-IS system taking into the following phenomena.

- Tritium production by the ternary fission reaction in the fuel particle and by neutron absorption reaction of ^{6}Li, ^{10}B and ^{3}He in the core, and tritium release into the helium coolant.
- Tritium and hydrogen permeation through the heat transfer tube of the heat exchanger, *e.g.*, IHX, the chemical reactor and the recuperator.
- Tritium and hydrogen permeation at a coaxial pipe in the helium loop.
- Tritium and hydrogen permeation from the helium loop to atmosphere through the outer wall of the component and piping.
- Tritium and hydrogen removal by the purification system installed in the primary and secondary cooling system.
- Tritium and hydrogen leakage to atmosphere and to another loop with a helium leakage.
- Isotope exchange reactions between tritium and hydrogen-containing process chemicals, *i.e.*, H_2O, H_2SO_4 and HI, in the IS process.

Tritium behaviour in the IS process of the HTTR-IS system was evaluated using the THYTAN code. It was confirmed that the tritium permeated from the secondary cooling system through the H_2SO_4 decomposer migrates to the product hydrogen by changing its form from HT to HTO in the components of the H_2SO_4 PROC, from HTO to TI in the Bunsen PROC. and from TI to HT in the HI decomposer by isotope exchange reactions. The effect of some indeterminate parameters was also valuated, *e.g.*, an equilibrium constant of isotope exchange reaction, the permeability of tritium through heat transfer tube, tritium and hydrogen concentration in the secondary helium, and the helium leakage rate from the secondary cooling system to the IS process, on the tritium activity concentrations in the product hydrogen and in each component. The THYTAN code will be validated by actual tritium concentration measured by the HTTR high-temperature long term operation planned in 2008.

3.3. Development of hardware for separation of nuclear from hydrogen plant

For the non-nuclear grade IS process, two developments of hardware equipments to separate the IS process from reactor facility are required. One of the equipments is High-Temperature Isolation Valve (HTIV) which can islolate the IS process from secondary cooling system during the abnormal events occured in the IS process. Figure 3 shows the schematic view of the HTIV. JAEA had performed its R&D [20] which can use under the high temperature helium surroundings about 900°C. We confirmed its structual integrity using half scale model after devising design and developing the material for the valve seat. The other equipments to be developed is a high-temperature diverter valve. Since the IS process requires the supply of high temperature helium to start its closed-cycle operation, some mechanism which can control the thermal load balance between the IS process and the steam generator during the start up and shut down of the HTTR-IS system is required. Specification survey is in progress for the high-temperature diverter valve.

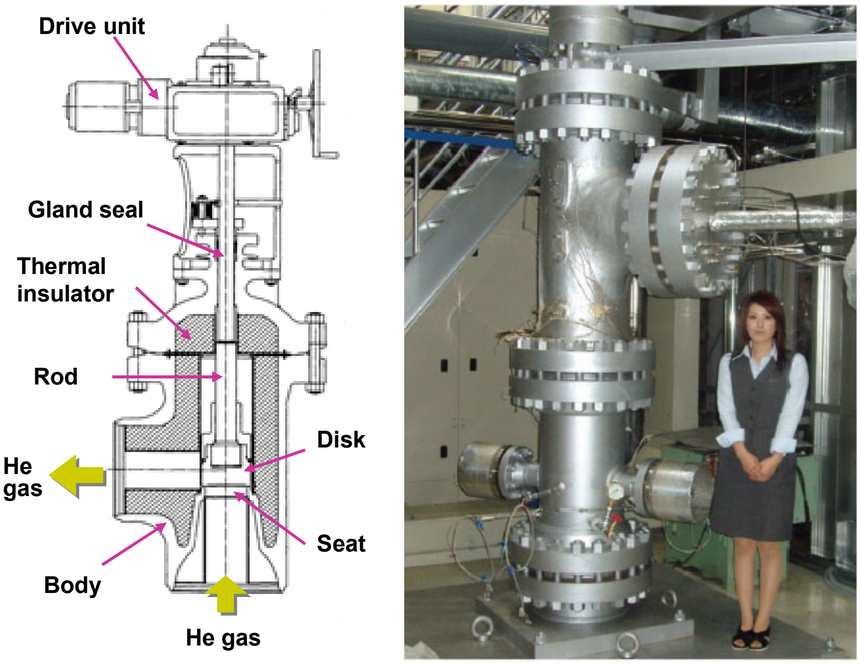

FIG. 3. Half size of high-temperature isolation valve applied to the HTTR-IS system.

4. Concluding remarks

In the commercial stage of the nuclear produced hydrogen, applying conventional chemical plant design standards to the IS process hydrogen production system is required to design and to construct the IS process as a chemical plant. Since one of the important purpose for the HTTR-IS system is showing its way to the commercial VHTR-IS system, JAEA launched design study for non-nuclear grade IS process to be coupled with the HTTR. R&D items to be developed for non-nuclear grade IS process is discussed in this paper.

Acknowledgements

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Status of nuclear hydrogen production technology development project in Korea

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Abstract. The paper describes the current energy situation in Korea and the likely scenario of energy problems in the 21st century. It outlines the vision of the hydrogen economy to help solve the energy problems. Salient aspects of the Korean nuclear hydrogen development demonstration project (NHDD), based on a VHTR, have been presented. These include the details of the fuel, reactor, and materials. The progress of work on a bench scale I/S process unit has been discussed.

1. Introduction

S. Korea has a population of 49 million. The per capita electricity consumption is 584 kWh/month and the oil consumption per capita is 7 litres/day. Due to increasing energy needs and meager fossil fuel resources, a hydrogen economy is envisioned for future energy needs.

Korea has launched a project to develop technologies for hydrogen production using nuclear energy since 2004. In the initial phase, the most promising technology was identified as using a VHTR as heat source and producing hydrogen by a sulfur-iodine process or a high temperature electrolysis process. The material selection to withstand high temperature and corrosive environment required for an economic production scale was part of the study as well. As a tentative goal, the VHTR outlet temperature was set as 950°C so that the highest chemical reaction temperature of >850°C, which is a practical threshold temperature of sulfur decomposition section, is easily achievable. In 2006, the project activities were shifted to resolve the key technological issues.

2. The VHTR development programme

The NHDD plant

Figure 1. shows the sketch of a nuclear hydrogen production demonstration plant. Considering current manufacturing capability of forged pressure vessel, the reactor size is selected as 200 MW thermal. The chemical plant is composed of five identical trains of thermo-chemical cycle process, considering frequent maintenance needs and catalyst replacement. A plant has a design capacity of 5x 4000 t/year enough to meet the requirements of 80,000 H_2 vehicles. Its demonstration is scheduled for 2020 and commercialization beyond 2020.

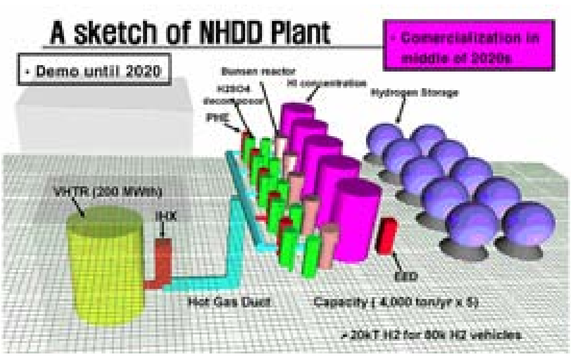

FIG. 1. Sketch of NHDD plant

The Fuel

The VHTR fuel, TRISO, is the most essential part of VHTR concept. The quality of the fuel as proved by the irradiation experiments at 1350°C and the accident simulation test up to 1600°C may be achieved in near term VHTR. Figure 2 shows the fabrication stages of the TRISO particle fuel.

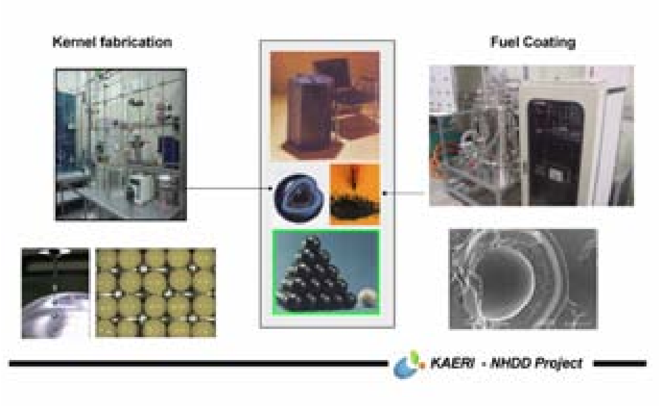

FIG. 2. Fabrication of TRISO particle fuel

Reactor Analysis

Due to high temperature of core, it is impossible to measure the distribution of temperature and neutron flux in core during operation. Better accuracy of computational prediction on the core temperature distribution is required for safe and reliable operation of the VHTR.

The risk analysis of a nuclear hydrogen production plant by coupling of the nuclear reactor and the chemical plant with explosive content is an important issue. The risk can be reduced by the enhanced safety of the VHTR as well as the separation of the reactor and the chemical plant. Releases of any radioactivity such as tritium from nuclear fission that can contaminate the product hydrogen also need to be monitored.

3. Bench scale demonstration

The sulfur-iodine thermochemical process is an economical process since most of the process is composed of easy scale up equipments. However it was never proved at elevated pressure condition and the reliable data for engineering is not sufficient. Figure 3 shows the various stages of the bench scale I/S cycle demonstration unit at KAERI.

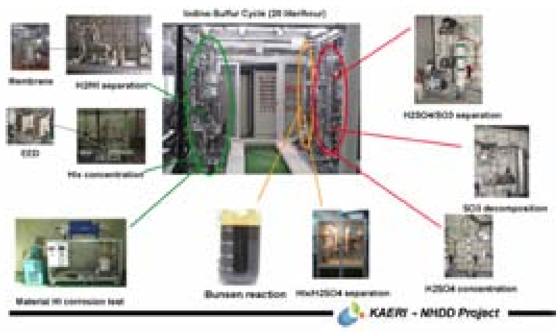

FIG. 3. Bench scale I/S cycle

The most challenging component for the nuclear hydrogen production is a process heat exchanger requiring leak tightness where the environment is of high temperature and high pressure, and highly corrosive. A plate fin type of process heat exchanger with ion beam mixing enhanced SiC coated metal plates are under development. A small gas loop with high pressure nitrogen at primary side and sulfuric acid at secondary side is under construction to verify performance of test process heat exchanger.

On licensing aspect, codes and standards for the VHTR candidate materials such as the graphite, high temperature metals, and ceramics shall be developed in time. The licensing issues such as the leak tight containment, the exclusion zone, and the in-service inspection, are to be clarified.

4. Conclusion

There are still many technical challenges to realize the hydrogen production using a nuclear energy. However, there is time for resolving technical issue to meet the hydrogen economy. International information exchange is important to follow right direction.

Hydrogen production options for water-cooled nuclear power plants

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Abstract. Supercritical water cooled reactors have the potential to reach outlet temperatures of 550°C. Although most hydrogen production technologies currently being pursued require higher temperatures, a few are compatible with these lower temperatures. Of these, low-temperature water electrolysis is the only technology currently available commercially. The high cost of electricity, however, makes hydrogen from these systems more expensive than hydrogen from current fossil-based methods. Other hydrogen production options that would be compatible with water-cooled reactors, such as membrane-assisted steam methane reforming and lower-temperature thermo-electrochemical cycles, are at various stages of research. None are close to having demonstrated commercial viability. Nonetheless, process flowsheets suggest that system efficiencies can be higher than for low-temperature water electrolysis.

1. Introduction

Nuclear-generated hydrogen has important potential advantages over other sources that will be considered for a growing hydrogen economy. Nuclear hydrogen requires no fossil fuels, results in lower greenhouse-gas emissions and other pollutants, and lends itself to large-scale production. These advantages do not ensure that nuclear hydrogen will prevail, however, especially given strong competition from other hydrogen sources. There are technical uncertainties in nuclear hydrogen processes, certainly, which need to be addressed through a vigorous research and development effort.

As a greenhouse-gas-free alternative, the U.S., Japan, and other nations are exploring ways to produce hydrogen from water by means of electrolytic, thermochemical, and hybrid processes. Most of the work has concentrated on high-temperature processes such as high-temperature steam electrolysis and the sulfur–iodine and calcium-bromine cycles [1-3]. These processes require higher temperatures (>750°C) than can be achieved by water-cooled reactors. Advanced reactors such as the very high temperature gas cooled reactor (VHTGR) can generate heat at these temperatures, but will require many years for commercial deployment. Hydrogen production using nearer-term reactor technology requires processes that are consistent with the temperatures that can be achieved by evolutionary water-cooled reactors (~300°C) or supercritical water reactors (~550°C). This paper will summarize hydrogen generation technologies compatible with these water-cooled nuclear power plants.

2. Steam methane reforming

Steam methane reforming (SMR) is currently the primary commercial technology for hydrogen production. The SMR process requires high process temperatures, which are usually provided by burning natural gas. The process reactions are as follows:

Reforming:	$CH_4 + H_2O \rightarrow CO + 3H_2$,	endothermic (750-800°C)
Shift:	$CO + H_2O \rightarrow CO_2 + H_2$,	exothermic (350°C)

Heat from nuclear reactors has been considered as an alternative to the burning of natural gas, which is used for supplying the heat for the endothermic reaction. Water cooled reactors and supercritical water cooled reactors cannot reach the temperatures required for conventional reforming technology. The heat from these types of reactors can be used, however, if the reforming technology is modified.

For example, a membrane reformer system, composed of a steam reformer equipped with catalytic membrane modules, can perform the reforming reaction, the shift reaction, and the hydrogen separation process simultaneously, without an independent shift converter and a pressure swing adsorption separator. The simultaneous hydrogen generation and separation drives the chemical reaction forward and, thus, can lower the reaction temperature to 500 to 600°C, offering the opportunity to couple lower-temperature heat sources to the SMR process [4-5]. A nuclear-heated SMR process would save about 30% in methane consumption, or reduce by about 30% the carbon dioxide emissions, compared with a conventional SMR process.

A concept for the nuclear production of hydrogen that combines sodium-cooled fast reactors (SFRs) with the membrane reformer technology has been studied jointly by Mitsubishi Heavy Industries Ltd. (MHI), Advanced Reactor Technology Co. (ARTEC), Tokyo Gas Company (TGC), and Nuclear Systems Association (NSA) [4-5]. TGC, in fact, demonstrated in 2004-2005 the operation of a methane-combusting membrane reformer at a hydrogen fueling station for fuel cell vehicles in downtown Tokyo. The system performance, efficiency, and long-term reliability were confirmed by producing >99.99% hydrogen at 3.6 kg/h for more than 3,000 hours with a hydrogen production efficiency of about 68% (lower heating value).

3. Low-temperature water electrolysis

Low-temperature water electrolysis is commercially available today for generating hydrogen with no external heat input, making it suitable to be supported by nearer-term water cooled reactors. Low-temperature water electrolysis results in the direct decomposition of H_2O into H_2 and O_2. Its market adoption has been limited by two factors. First, since all the energy for water cracking is derived from electricity, the cost of electricity from current low-temperature reactors makes water electrolysis uncompetitive with steam methane reforming. The development of lower-cost, carbon-free electricity generation (through, for example, high-temperature nuclear reactors that can achieve generating efficiencies greater than 45%) might make lower-cost electricity and, consequently, make low-temperature electrolysis more cost effective. The second factor limiting the use of this technology is its reliance on noble metal catalysts such as platinum. The high price and scarcity of noble metals make large-scale use of current water electrolysis systems impractical. Research in water electrolysis technology, which will be described shortly, holds the promise to reduce these two barriers.

Commercial water electrolysis technologies fall into two categories: (1) solid polymer cells using proton exchange membranes (PEMs) and (2) liquid electrolyte cells, most commonly using a potassium hydroxide (KOH) solution. PEM electrolyzers are essentially PEM fuel cells operating in reverse polarization mode. Protons diffuse in the PEM electrolyte whereas oxygen ions diffuse in the liquid electrolyte of these systems.

Currently the cost of hydrogen from PEM and KOH systems are roughly comparable. Reaction efficiency tends to be higher for the KOH system because of better conductivity of the liquid electrolyte. But this advantage is offset by the higher purification and compression energy requirements compared to PEM systems, especially at small scales. Thus, the development of relatively higher temperature, higher conductivity, and lower cost electrolyte membranes for PEM cells remains a goal for reducing the cost of hydrogen produced.

Development of alternative catalyst structures with less expensive materials would significantly influence the economics of hydrogen production through electrolysis. Moreover, new advances in high-pressure systems are being explored to lower the cost by reducing the need for hydrogen gas compression.

Several groups are pursuing the development of low-temperature, high-pressure electrolysis systems to mitigate the high cost of hydrogen compression. For instance, a high-pressure, low-temperature water electrolyzer system is being developed by Giner Electrochemical Systems of Newton, Massachusetts [6]. The Giner system is currently operable at 2000 psid (14 MPa). Their goal is to increase the operating pressure to 5000 psid (35 MPa) through advanced design features and to replace high-cost components with lower-cost materials and fabrication methods. The use of higher pressures does require the use of higher cell voltages in the electrolyzer. Nevertheless, it is more energy efficient to run the electrolyzer at high pressures than to operate a cell at low pressures and then use a compressor to achieve the hydrogen pressure required for efficient distribution and delivery. Giner developed an economic model of electrolyzer capital and operating costs to determine the cost of hydrogen as a function of the price of electricity and the capital and operating costs of the electrolyzer plant components. The scenario they investigated was a neighborhood refueling station with a hydrogen production rate of 432 kg/day. The electrical load for such a station is approximately 1 MW. Giner determined that to meet the DOE target cost of hydrogen produced (US$ 2.00-3.00/ kg H_2) [7] they would need to have an installed equipment cost of US$1100 per kW_e, a plant that operates at 90% capacity with a ten-year plant life, and an electricity price of less than 3.6 ¢/kWh. This price is only 20% lower than the price for commercial off-peak electricity in the metropolitan Chicago area (approximately 4.5 ¢/kWh) [8]. To meet the installed equipment cost target, they would need to have a large cell active area to reduce the number of cells and ancillary components.

In parallel, Teledyne Energy Systems of Hunt Valley, Maryland, is developing an alkaline hydrogen generator that has a high overall efficiency, a low maintenance cost, and a final output pressure of 5000 psig (35 MPa) [9]. This work is being done as a part of the U.S. DOE program on Design for Manufacture and Assembly. Again, operation at higher pressures greatly reduces the energy-intensive need otherwise to compress hydrogen. In a recent assessment, however, Teledyne has concluded that the increased costs of manufacturing a high-pressure electrolyzer (and the added safety systems required) may not offset the reduced gas compression costs.

Because of the need for electricity for water electrolysis, its efficiency and economics depend on electricity production efficiency and price. The electrochemical efficiency of present electrolysis units can vary between 65 to 90%. It is currently possible to couple an electrolysis unit to a nuclear power plant in order to produce electrolytic hydrogen. Thermal efficiencies typical for current water cooled reactors (approximately 34%) result in relatively low thermal-to-hydrogen energy efficiencies. The overall efficiency for electrolysis supported by water cooled reactors is limited to 21-30%. Significantly higher efficiencies, up to about 40%, can be achieved if an advanced, higher-temperature power conversion system, such as He or supercritical CO_2 turbine systems with thermal efficiencies of about 45%, provide the electricity for low-temperature electrolysis.

Since low-temperature water electrolyzer technology does not require heat input, the interface between the electrolyzer unit and a nuclear plant requires only the transfer of electricity. Thus, the heat load from the nuclear reactor is needed only for electricity production. This feature can allow the electrolyzer to be placed at a large distance from the reactor if required for safety without any loss of efficiency due to heat losses. This also allows for distributed or regional hydrogen production that could be customized for different markets and would minimize hydrogen transportation costs. However, advanced water electrolyzers at relatively higher temperatures require heat input that would have to be retrieved from the balance of the plant, which would require on-site hydrogen production.

Cogeneration of hydrogen and electricity is possible with low-temperature electrolysis, with excess electricity available for the grid. With fast start-up times, it is possible to control the operation such that the rates of hydrogen and electricity production can be varied in order to follow electricity and hydrogen demands without changing the nuclear reactor thermal power. This means that load following and hydrogen production can be accomplished without the need for energy storage methods. A regenerative low-temperature PEM system [10] to produce hydrogen and electricity reversibly can be a candidate component of a nuclear hydrogen plant with cogeneration capability.

4. Thermochemical and hybrid processes

Thermochemical and hybrid thermo-electrochemical cycles have the potential for hydrogen production with higher efficiencies than low-temperature water electrolysis. Over 200 thermochemical and hybrid electro-thermochemical hydrogen production cycles have been identified in the literature [11]. Only eleven of those listed in Reference 11 have maximum reaction temperatures below 550°C. These lower-temperature cycles can reduce the thermal burden, mitigate demands on materials, and potentially be coupled with nearer-term nuclear reactors.

Five such cycles have been the subject of active research within the past five years: a hybrid sulfur-based cycle [12], a family of copper-chloride cycles (530 - 550°C) [13], an active metal (potassium-bismuth) cycle (475 – 675°C) [14], a magnesium-chloride cycle (500°C) known as the Reverse Deacon Cycle [15], a U-Eu-Br heavy-element halide cycle [16]. Argonne National Laboratory has done exploratory work on all five thermochemical cycles.

4.1. Hybrid sulfur-based cycle

A thermo-electrochemical hydrogen production system in the medium temperature range has been developed by the Japan Atomic Energy Agency (JAEA) to produce hydrogen from water using the heat from a sodium-cooled fast reactor (SFR) that could be applied to an SCWR [12].

The system is based on a sulfuric acid (H_2SO_4) synthesis and decomposition process that was developed earlier as the "Westinghouse process." The sulfur trioxide (SO_3) decomposition process is facilitated by electrolysis with an ionic oxygen conductive solid electrolyte to reduce the operation temperature by 200°C-300°C compared with the Westinghouse process.

The system is composed of the following three reactions:

1. $2H_2O + SO_2 = H_2SO_4 + H_2$ electrochemically at 80°C
2. $H_2SO_4 = H_2O + SO_3$ >450°C
3. $SO_3 = SO_2 + 1/2\ O_2$ electrochemically at 550°C

Alternatively, the SO_3 electrolysis step could be applied to the sulfur-iodine thermochemical cycle to reduce the maximum temperature required. In that case, the first electrolysis step shown above (reaction 1) would be replaced by a purely thermochemical reaction that would involve iodine.

The theoretical thermal efficiency of the system based on chemical reactions shown above was evaluated within the range of 35% to 55%, depending on the H_2SO_4 concentration and heat recovery [12]. The thermal efficiency of the hydrogen production plant with an SFR of 395 MWt was evaluated to be 42%, where electrolysis efficiencies of reactions (1) and (3) were assumed to be 90 and 85%, respectively [17]. This thermal efficiency was higher than that for water electrolysis, which was 38% assuming a power generation efficiency of 42% and an electrolysis efficiency of 90%.

An apparatus to substantiate the hydrogen production system was manufactured and several hydrogen production experiments were performed. The maximum duration of any single period of operation was about 5 hours, and the total operation duration was about 9 hours [18]. In the experiments, stable generation of hydrogen and oxygen was observed, and hydrogen and oxygen production rates in the experiments were about 5 mL/h and about 2.5 mL/h, respectively. Improvement of the apparatus is planned to increase the hydrogen production rate (1 normal liter per hour) and to operate for longer durations. In parallel, Argonne National Laboratory is developing improved SO_3 electrolysis cells to lower the needed voltage and increase overall efficiency for reaction 3.

4.2. Copper-chloride hybrid thermochemical cycle

The Cu-Cl cycle offers a number of advantages over other cycles: (1) the maximum cycle temperature (530 - 550^{o}C) allows the use of a wider range of heat sources; (2) the intermediate chemicals are relatively safe, inexpensive, and abundant; (3) minimal solids handling is needed; and (4) all reactions have been proven in the laboratory and no significant side reactions have been observed. As a hybrid cycle, one of the reactions is electrochemical, which imposes a sizeable energy cost. However, the electrolytic step requires voltages significantly lower than needed for direct water electrolysis.

The copper-chloride cycle that has been examined at Argonne National Laboratory [13] consists of three thermal reactions and one electrolytic reaction:

1. $2Cu(s) + 2HCl(l) = 2CuCl(l) + H_2(g)$ 430 - 475°C
2. $4CuCl(s) = 2CuCl_2(aq) + 2Cu$ electrochemically at 25 - 75°C
3. $2CuCl_2(s) + H_2O(g) = CuO{*}CuCl_2(s) + 2HCl(g)$ 350 - 400°C
4. $CuO{*}CuCl_2(s) = 2CuCl(l) + 1/2O_2(g)$ 530 - 550^{o}C

H_2 and O_2 are produced thermochemically in the reaction between Cu and HCl (Reaction 1), and between CuO and $CuCl_2$ (Reaction 4) at 450^{o}C and 530^{o}C. Water enters the system as steam and reacts with $CuCl_2$ to produce HCl and $CuO{*}CuCl_2$ at 350-400^oC (Reaction 3). The electrochemical reaction consists of the disproportionation of CuCl (Reaction 2) to give Cu metal for recycle to the hydrogen production reaction and $CuCl_2$ to produce HCl and oxygen through steps 3 and 4.

Experimental work has been done at Argonne to study the reaction kinetics for the hydrogen and oxygen production reactions. The experiments were conducted in beds of solid material with a continuous flow of excess gaseous reactants. The individual steps in the Cu-Cl cycle been verified, the kinetics of the hydrogen and oxygen generation reactions have been studied, and the temperatures of the reaction steps have been verified.

The reaction between HCl and Cu is a heterogeneous exothermic and reversible reaction. Reports in the literature suggested that the reaction proceeds rapidly at 230°C. Experiments at Argonne, however, detected no hydrogen production at this temperature. At this temperature the kinetics of the reaction are slow, and the rates of reaction are controlled by the mass transfer of HCl through a passivating film of CuCl formed on the Cu surface. Hydrogen starts to be produced in significant amounts at temperatures above 350°C. The kinetics of the reaction are further accelerated at temperatures higher than 430°C, the temperature at which CuCl melts, facilitating the interaction between HCl and Cu.

The oxygen production reaction (Reaction 4) was studied in a vertical reactor connected to a mass spectrometer to monitor the oxygen evolution. At 500°C, the yield of O_2 was 85% and at 530°C the reaction was virtually complete. From mechanistic studies it was found that the oxygen generation reaction proceeds in two steps: (1) the decomposition of $CuCl_2$ to CuCl and Cl_2 and (2) the reaction of CuO with Cl_2. In the reaction between CuO and $CuCl_2$, O_2 starts to evolve at 450°C (the temperature at which pure $CuCl_2$ starts to decompose) and Cl_2 is liberated. The Cl_2 reacts with the CuO to produce CuCl and free oxygen. From this work, the kinetics of the cycle have been established.

All the work described above has been at a small laboratory scale. No integrated-cycle test has yet been conducted. The next work that must be done to prove the viability of the process is to develop an appropriate electrochemical cell for Reaction 2. Only after a viable engineering design of an appropriate electrochemical cell is developed can an accurate economic analysis of this cycle be achieved. Nonetheless, a preliminary engineering flowsheet analysis for the cycle suggests that it is capable of reaching 40% efficiency (lower heating value) [19].

4.3. Active metal (potassium-bismuth) hybrid thermochemical cycle

The potassium-bismuth cycle, which is being studied by Argonne National Laboratory and Pennsylvania State University, is conceptually one of the simplest of the hydrogen generation cycles [14]. It consists of only two reactions:

1. $2K_3Bi\ (l) + 6H_2O\ (g) = 6KOH\ (l) + 3H_2(g)$ 475 – 675°C
2. $6KOH\ (l) + 2Bi\ (l) = 3H_2\ (g) + 3O_2\ (g) + 2K_3Bi\ (l)$ electrochemically

Indeed, it may be possible to design a system that performs both reactions in a single vessel, making operations simple and with low capital cost. Bismuth, however, is a relatively rare element, so the cycle may not be suitable for commercial operations. Similar cycles with other active metals (e.g., the Na-Sn cycle) may overcome this limitation.

Little is known about the thermodynamics and chemistry of the K-Bi cycle. No experimental data exist to determine potential side products, the optimum operating temperature, or the necessary over potential of the electrochemical reaction. Under a number of simplifying assumptions, the efficiency of the cycle was estimated to lie between 29 and 46% (lower heating value).

Proof-of-concept experiments are planned for the two reactions in this cycle. The work will start with the design, fabrication, and testing of an electrochemical cell that will be tested over a range of temperatures. The gaseous products will be analyzed to determine if side reactions exist.

4.4. Magnesium-chloride hybrid thermochemical cycle

The magnesium–chloride Reverse Deacon Cycle that was studied at Argonne National Laboratory and then Idaho National Laboratory [15] is a three-step process:

1.	$MgCl_2 + H_2O = 2HCl + MgO$	450°C
2.	$MgO + Cl_2 = MgCl_2 + ½ O_2$	500°C
3.	$2HCl = H_2 + Cl_2$	electrochemically at 80°C

$MgCl_2$ is impregnated into the structure of a microporous material such as a zeolite. This essentially results in the Mg compounds being in the form of dispersed nanoparticles. Reactants can readily diffuse into the zeolite to react with all of the Mg compounds and products can readily diffuse out of the zeolite. No solid particle degradation occurs, provided that the zeolite is stable in the presence of water and HCl at temperatures up to 500°C. Silicalite has been tested and was durable in the presence of these species at 500°C and supported the $MgCl_2$ hydrolysis reaction.

$MgCl_2$-loaded silicalite (10 wt%) was prepared. Under flowing steam, HCl was successfully generated through reaction 1. Reaction 2 has not been tested to date, but is thermodynamically favorable. Side reactions may demand a higher temperature than 500°C, though. Reaction 3 has been demonstrated and optimized by Weidner et al. at the University of South Carolina.

Further proof-of-principle tests would have to be run to establish the viability of this process, but there is no ongoing work on this cycle. Instead, research has shifted to the *magnesium-iodine* cycle, a purely thermochemical cycle that was first studied in Japan [20-24], where proof-of-concept experiments were completed and process design was started. Research in the U.S. is continuing at Argonne National Laboratory and the University of South Carolina [19]. The maximum temperature for the Mg-I cycle, however, is 600°C, beyond the range of water-cooled reactors, so the cycle will not be discussed further here.

4.5. Heavy-element halide thermochemical cycle

A fifth low-temperature hydrogen production cycle has been studied. The cycle is based on heavy-element halide chemistry with a maximum reaction temperature of 300°C — the lowest known temperature for a purely thermochemical hydrogen production cycle [16]:

1.	$2(UO_2Br_2 \bullet 3H_2O) = 2\text{“}UO_3 \bullet H_2O(s)\text{”} + 4HBr(g) + 2H_2O(g)$	300°C
2.	$4EuBr_2 + 4HBr = 4EuBr_3 + 2H_2(g)$	exothermic
3.	$4EuBr_3 = 4EuBr_2 + 2Br_2(g)$	300°C
4.	$2\text{“}UO_3 \bullet H_2O\ (s)\text{”} + 2Br_2 + 4H_2O = 2(UO_2Br_2 \bullet 3H_2O) + O_2(g)$	exothermic

This reaction sequence is consistent with present relevant chemical knowledge. That knowledge, however, is for related, but not identical, reactions with the exception of Reaction 1. The notation “$UO_3 \bullet H_2O(s)$” is used in the above reaction scheme because the exact stoichiometry of the species has not been determined [25]. Reactions 2 and 4 are expected to be exothermic and to proceed spontaneously. Reactions 1 and 3 are endothermic and require application of heat to the drive the reaction to the desired products.

Work was performed at Argonne National Laboratory to

- Determine the products that result from thermal decomposition of $UO_2Br_2{\cdot}3H_2O$ (Reaction 1);
- Investigate and model the factors that influence reaction of Eu^{2+} ions with H^+ ions in aqueous hydrobromic acid to generate H_2 gas (Reaction 2);
- Study the thermal reduction of $EuBr_3$ to $EuBr_2$ (Reaction 3) and establish the degree of completion at 300°C and whether a potentially interfering EuOBr side product is produced;
- Determine the chemical consequences of reacting hydrated uranium trioxide ("$UO_3{\cdot}H_2O$ (s)") with an excess amount of "bromine water" (elemental bromine dissolved in H_2O) (Reaction 4);

No integrated-cycle test has been performed. The work demonstrated the production of HBr through Reaction 1 with the reaction going to completion at 300°C. The studies on Reaction 2 showed that $EuBr_2$ reacts with aqueous HBr to produce hydrogen. Nevertheless, the rate of the reaction is slow (typically several hours are required for completion) under the experimental conditions that have been investigated to date. A suitable catalyst might increase the reaction rate.

For Reaction 3, vacuum pyrolysis was found to allow the reaction to proceed without the complications that can arise from water entrained in the system. For Reaction 4 bromine and water can react to form HOBr, which can interfere with the desired reaction.

Thermodynamic data are largely unknown for this system. Such data would be required to assess the efficiency of the system. As with other thermochemical cycles, an engineering application of the U-Eu-Br cycle would need to consider corrosiveness of the chemicals. The low operating temperature of 300°C, however, may make these concerns more tractable than for higher-temperature cycles.

5. Conclusions

Water-cooled reactors are likely to be the nuclear power technology of choice for many years. Their output temperature limitation of ~350°C leaves only one current option for hydrogen production: low-temperature water electrolysis. Other hydrogen production options require higher temperatures. Short of the temperatures achievable by liquid-metal-cooled or gas-cooled reactors, few hydrogen production methods are known. Supercritical water cooled reactors have the potential to reach 550°C. At this temperature, hydrogen production methods include membrane-assisted steam methane reforming and a handful of thermo-electrochemical cycles. Experimentation has been limited on these systems. None are close to having demonstrated commercial viability. Nonetheless, process flow sheets suggest that system efficiencies can be higher than for low-temperature water electrolysis. This makes ongoing laboratory research worth pursuing.

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Nuclear power for the production of liquid hydrocarbons

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Abstract. CO_2 can be used as the carbon feedstock together with water, nuclear heat and electricity for producing synthetic hydrocarbon fuels, which may be better energy carriers than hydrogen. Several processes to produce synthetic hydrocarbons are described and compared, and methods are outlined as to how nuclear power in the form of electricity, process heat and hydrogen could help reduce CO_2 emissions or even act as a CO_2 sink. An estimate is given about the requirements in terms of nuclear power, carbon feedstock and clean water to provide synthetic hydrocarbon fuel for a major European airport. The involved organic chemistry processes are already largely used in today's industry and operate at temperatures that require process heat the production of which is feasible with nuclear power. The market potential for combined nuclear-chemical complexes is very big, and massive savings in CO_2 emissions could be achieved. Certain references claim that synthetic hydrocarbons could be produced at prices that are not only comparable to fossil fuel but also more stable, with no tax loss for the governments.

1. Introduction

Synthetic hydrocarbons can be produced from syngas, which is a mixture of hydrogen and carbon-monoxide widely used in today's chemical industry and which can be produced from a carbon feedstock and water using nuclear heat and/or electricity. Several existing processes are compared including those using CO_2 as the carbon feedstock, thus making such installations an effective CO_2 sink. The requirements were estimated for fueling a major European airport with nuclear produced synthetic hydrocarbons.

2. Hydrocarbons: Ideal energy carriers

Fossil hydrocarbon fuel is consumed in very large quantities, in particular for road and air transport as well as for domestic heating. Table 1 provides a few figures.

Table 1. Selected energy consumption figures

Energy end use	Energy consumed [10^{18} J/yr]
Passenger road transport (EU25)	6.05
Commercial vehicles (EU25)	approx. 6
Small-scale combustion installations for Domestic heating, hot water etc. (EU25)	12
Air transport UK	0.51
Air transport Germany	0.3

Today, this energy is almost exclusively delivered by fossil fuel. Apart from still being readily available, in particular liquid hydrocarbons have convincing properties that make them ideal energy carriers. Table II immediately makes it clear that good examples for ideal energy carriers are the known fossil hydrocarbon products such as gasoline, diesel fuel or kerosene.

Table II. Criteria for ideal energy carriers [1]

Property	liquid hydrocarbons	Hydrogen
1. Liquid between – 40°C and + 80°C even at high altitudes	✓	requires pressurization or cooling
2. Easy, inexpensive and energy efficient production, handling, storage, transport	✓	high pumping power, losses through leakage and permeation, special safety requirements
3. Limited needs for new infrastructure	✓	completely new infrastructure
4. Suitability for use in internal combustion engines	✓	✓
5. Suitability for use in fuel cells	✓ (methanol)	✓
6. Non-toxic	✓ (in handled quantities)	✓
7. High energy density per volume	✓	high energy density per mass but not per volume
8. Ability to be synthesized from H_2 and CO_2 using heat and electricity	✓	✓

The energy density per m^3 is 2 - 4 times greater in numerous hydrocarbons than in liquid H_2. Also, the hydrogen density per m^3 is mostly greater than in liquefied or 800 bar compressed H_2. It can be concluded that hydrocarbons are in general better hydrogen carriers than hydrogen itself.

Furthermore, a well-to-wheel analysis shows that liquid hydrocarbon fuel (instead of hydrogen) uses much less primary energy and emits much less CO_2 than H_2. This is mainly due to energy costs (approx. 40% of the lower heating value of H_2) related to compression or liquefaction, transport and leakage. Hydrogen is today mainly produced by steam reforming of natural gas which itself is a premium energy carrier. From an energy point of view it would thus be sensible to use the natural gas directly instead of converting it to hydrogen, unless a high efficiency hydrogen end user can offset this energy cost. In many cases though, the use of in particular liquid hydrocarbons largely decreases primary energy consumption and costs for new and highly specific infrastructure.

Hydrogen has to compete with the energy source for its production in terms of cost and energy efficiency and will therefore necessarily remain more expensive. This is one of the reasons why certain experts [1], [question the economic and energetic attractiveness of a hydrogen economy.

3. Perspectives for nuclear power to provide new hydrocarbon sources

Nuclear power today is mainly used for base-load electricity production. Electricity represents only about a third of primary energy consumption in developed countries and only about a third of this electricity is produced by nuclear power. When using sustainable nuclear power for the extraction of unconventional fossil hydrocarbons [10] which is not discussed here, and even more for the synthesis of liquid hydrocarbons, it could provide a much larger fraction of the primary energy market thus making its potential for the replacement of fossil fuel and for CO_2 emission reductions truly huge.

3.1. Synthesis of liquid fuel using nuclear heat, hydrogen and electricity

Nuclear power can be used to synthesize hydrocarbons, which are clean fuels. Various possibilities exist depending on the available carbon feedstock, chemical processes and desired end products. All processes require:

- a carbon feedstock (coal, crude oil, natural gas, biomass or recycled CO_2)
- water (for the production of steam and hydrogen)
- process heat for the production of steam (and hydrogen if thermochemical cycles are used for production)
- suitable catalysts
- electricity for process use (and for hydrogen if produced by electrolysis)

Synthetic hydrocarbon fuel production would rely on centralized H_2 production and local conversion to synthetic liquid hydrocarbons with consecutive distribution to the consumer via existing or little modified infrastructure. In the following, the basic chemistry to produce liquid hydrocarbons is outlined.

In most cases, the production of syngas ($CO + H_2$ mixture) is required using thermal energy. Syngas is the raw material and is largely used in industry for manufacture of chemicals and plastics, including hydrogen for ammonia (fertilizer production). The processes require large amounts of water for steam and hydrogen production which must be cleaned prior to use. Three possibilities can be considered:

a) from carbon feedstock and water:

$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$ $\Delta H° = +131.3$ kJ/mol (high temperature)

b) from carbon feedstock, oxygen and water:

$2\ C(s) + ½\ O_2(g) + H_2O(g) \rightarrow 2\ CO + H_2$ "Shell entrained gasifier"

c) from carbon-dioxide and hydrogen:

$CO_2(g) + H_2(g) \rightarrow CO(g) + H_2O(g)$ $\Delta H° = +41.2$ kJ/mol
$2\ H_2O \rightarrow 2H_2 + O_2$ from electrolysis or thermochemical

The production of different hydrocarbons may require different fractions H_2/CO. By adding steam to syngas, the fraction of H_2 increases (water gas shift reaction):

$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$ $\Delta H° = -40.6$ kJ/mol
This reaction produces hydrogen, heat and CO_2.

Another known reaction is the direct synthesis of ethanol from CO_2 and H_2:

$2\ CO_2(g) + 6\ H_2(g) \rightarrow C_2H_5OH(l) + 3\ H_2O(g)$

Example 1: Coal liquefaction ($H_2/CO = 2$)

Invented by Fischer/Tropsch in 1923, the process uses special Fe or Co catalysts. Such plants were operating in Germany until 1941, currently in South Africa (Sasol), and two new complexes are planned in China.

1. Syngas production

Coal is brought to high temperature through combustion and is then exposed to steam.

$$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g) \qquad \Delta H° = +\ 131.3\ kJ/mol\ (high\ T)$$

2. H_2/CO adjustment

1 CO and 1 H_2 are coming from the syngas, the second required H_2 comes from the Water-Gas Shift Reaction (WGS):

$$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g) \qquad \Delta H° = -\ 41.2\ kJ/mol$$

3. Hydrocarbon synthesis

$$CO(g) + 2\ H_2(g) \rightarrow (\text{-}CH_2\text{-})_n(l) + H_2O(g) \quad \Delta H° = -\ 165\ kJ/mol\ (227°C)$$

or $$2\ CO(g) + H_2O(g) \rightarrow (\text{-}CH_2\text{-})_n(l) + CO_2(g) \quad \Delta H° = -\ 206\ kJ/mol\ (0.1\ MPa,\ 250\text{-}300°C)$$

4. Overall reaction

$$3C(s) + 2\ H_2O \rightarrow 2\ (CH_2)_n(l) + CO_2(g)$$

The overall reaction is exothermal, however heat is consumed at high temperature and released at lower temperature. The process consumes coal as the carbon feedstock, high temperature heat (from coal combustion) and high temperature steam. It produces liquid hydrocarbons, rejecting heat at 227°C and CO_2. The heating for coal and steam for syngas production is currently provided by coal combustion thus adding to CO_2 emissions. CO_2 release from coal liquefaction could be reduced or eliminated by:

— step 1: heating the coal with nuclear process heat instead of coal combustion;
— step 1: producing the steam with nuclear heat;
— step 2: using nuclear-produced H_2 instead of the WGS to reach $H_2/CO = 2$.

Example 2: Methanol synthesis ($H_2/CO = 2$)

The production process is very similar to coal liquefaction, only the synthesis step 3 is different.

1. Syngas production

Coal is brought to high temperature through combustion and is then exposed to steam.

$$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g) \qquad \Delta H° = +\ 131.3\ kJ/mol\ (high\ T)$$

2. H_2/CO adjustment

1 CO and 1 H_2 are coming from the syngas, the second required H_2 comes from the WGS:

$$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g) \qquad \Delta H° = -\ 41.2\ kJ/mol$$

3. Hydrocarbon synthesis

$CO(g) + 2\ H_2(g) \rightarrow CH_3OH(l)$ $\Delta H° = -90.6$ kJ/mol, ≈250°C, 5-10 MPa, now with new catalysts down to RT

4. Overall reaction

$3C(s) + 4\ H_2O \rightarrow 2\ CH_3OH(l) + CO_2(g)$

This process consumes carbon feedstock, high temperature heat and high temperature steam. As methanol is richer in hydrogen as the product from the Fischer/Tropsch process, methanol synthesis also consumes more water. The reaction produces liquid methanol, rejecting heat at low temperature and CO_2. The heating for coal and steam for syngas production is currently provided by coal combustion thus adding to CO_2 emissions.

Similarly to Example 1, the CO_2 release from methanol synthesis could be reduced or eliminated by:

- step 1: heating the coal with nuclear process heat instead of coal combustion;
- step 1: producing the steam with nuclear heat;
- step 2: using nuclear-produced H_2 instead of the WGS to reach $H_2/CO = 2$.

Methanol can be used directly as fuel (in IC engines or fuel cells) or be converted into gasoline using special catalysts. Today it is produced at large scale as a gasoline additive.

Example 3: Production of syngas using nuclear energy

The process involves the separate production of CO and H_2, which can then be combined for the synthesis of various hydrocarbons. It must be noted that these options not only enable the massive reduction of CO_2 emissions, they can even serve as a CO_2 "sink" that uses CO_2 as the carbon feedstock through the reduction of CO_2 to CO using H_2.

1. Production of CO from nuclear heat:

a) With carbon feedstock (fossil or biomass) and CO_2:

$C(s) + CO_2(g) \rightarrow 2\ CO$ $\Delta H° = +172.5$ kJ/mol

b) With CO_2 and H_2:

$CO_2(g) + H_2(g) \rightarrow CO(g) + H_2O(g)$ $\Delta H° = +41.2$ kJ/mol

These reactions use CO_2 (captured e.g. from flue gas of a neighboring fossil power plant) fully or partly as the carbon feedstock. This may turn out to be an alternative to CO_2 sequestration as the same carbon atom is then used at least twice before rejection into the atmosphere.

2. Production of H_2: using nuclear electricity and/or heat (electrolysis/ thermochemical)

Possible water splitting processes include (in increasing order of technological difficulty):

- Low-temperature electrolysis (η= 50 – 70%) using electricity only (< 100°C)
- High-temperature electrolysis (η = 41 – 64%) using heat and electricity (100 – 800°C)
- Medium-temperature hybrid cycles (η = 15 - 30%) using heat and electricity (500 – 600°C)

— High-temperature thermochemical cycles (η = 40 – 48%) using heat only (> 850°C)
Clean water required for water splitting is produced using nuclear electricity and (waste-) heat for water desalination (where required) and purification.

It should be noted that there are at least two other possibilities not involving syngas, namely the Sabatier reaction and electrolysis of CO_2 and steam [15], which would use CO_2 to produce CH_4 as a product or as an intermediate for liquid hydrocarbons.

Example 4: Production of methanol from fossil CO_2 and nuclear H_2

The process involves the direct conversion of a CO_2/H_2 mixture to methanol. Again, this option may act as a CO_2 "sink". $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

Various temperatures, pressures and catalysts are used:

- High pressure: 30–35 MPa, 320–380°C, ZnO/Cr_2O_3 catalyst
- Medium pressure 10–15 MPa, 230–260°C, $CuO–ZnO–Cr_2O_3$ catalyst
- Low pressure 5–10 MPa, 240–260°C, $CuO–ZnO–Al_2O_3$ catalyst

The process is applied industrially at large scale to recycle waste products from petrochemical and coal processing plants. The German production from 1992 amounted to 1.29 Mt. Details related to this technology can be found in [4], [5], [6]. According to [, this process can also be established in a reversed fuel cell.

3.2. Comparison of processes for production of ethanol C_2H_5OH

(1) Through coal liquefaction:
overall reaction: $3\ C + 3\ H_2O \rightarrow C_2H_5OH + CO_2$
Coal liquefaction without CO_2 recycling is a strong, localized CO_2 emitter: at least a third of the used carbon feedstock is released as CO_2.
(2) From CO_2 feedstock (flue gas recovery):
overall reaction: $2\ CO_2 + 3\ H_2O \rightarrow C_2H_5OH + 3\ O_2$
(3) From coal liquefaction with CO_2 recovery:
overall reaction: $2\ C + 3\ H_2O \rightarrow C_2H_5OH + O_2$

Coal liquefaction with CO_2 recycling using nuclear produced hydrogen costs (nuclear) energy but saves at least 1/3 of coal resources and potentially makes carbon dioxide sequestration superfluous.

In all three cases, the production of 1 mole ethanol consumes 3 moles of water that needs to be available, desalinated where necessary, and purified. The following may be concluded:
- The use of nuclear power to produce syngas or syngas products from coal would save 1/3 of coal resources and would lead to an equivalent reduction in CO_2 emission.
- Nuclear power would enable coal-to-liquid processes without CO_2 rejection.
- Nuclear power can even act as a CO_2 sink and fully recycle CO_2 to liquid hydrocarbons.
- CO_2 from fossil fuel combustion can be employed as a valuable carbon feedstock.

4. Nuclear power for aviation fuel

In the following the raw material consumption and emissions are calculated to produce a full fuel load (150 t) of ethanol for a long-haul jet and for a major airport consuming the equivalent of 50 such fuel loads per day. Ethanol is used here for the sole purpose of illustrating the orders of magnitude concerning the requirements when nuclear power is employed for the production of liquid hydrocarbons although a variety of more complex hydrocarbons can be synthesized from syngas or ethanol. Three processes are compared, i.e. classical coal liquefaction, coal liquefaction with CO_2 recycling and ethanol production from CO_2 feedstock.

Classical coal-to-liquid processes are extremely dirty with the mass of waste (CO_2 and ash) together being almost a third more than the product (ethanol) itself.

$$3\ C(s) + 4\ H_2O(g) \rightarrow 2\ CO(g) + 4\ H_2(g) + CO_2(g) \rightarrow C_2H_5OH(l) + H_2O(g) + CO_2(g)$$

The production of 150 t ethanol from coal can be resumed as:

168 t coal + 176 t water → 150 t ethanol + 144 t CO_2 + 50.6 t ash

Production of ethanol for a single 150 t fuel load/day would:

Table III. Raw material consumption and emissions from 3 different ethanol synthesis processes to produce a single 150 t ethanol load per day

	Classic Coal Liquefaction	CO_2 feedstock	Coal Liquefaction with CO_2 Recycling
consume carbon	117.4 t ≈ 168 t raw coal	0	78.3 t ≈ 112 t raw coal
consume H_2	0	39.12 t	19.6 t
power equivalent for H_2 production (40% efficiency) LHV = 120 MJ/kg H_2	0	136.1 MWth	68.1 MWth
produce CO_2	143.5 t	(– 287 t)	0
produce ash	50.6 t	0	33.7 t
consume water (incl. for H_2 prod.)	176.1 t	176.1 t	176.1 t

Considering that the energy content per mass of ethanol (LHV = 26.74 MJ/kg) is only 61% of the one of kerosene (LHV = 43.74 MJ/kg), the figures below must be almost doubled to reach the *energy equivalent* of 50 B747 fuel loads of kerosene. Ethanol is only little lighter than kerosene (789.2 vs. 817.15 kg/m^3) so that the density difference can do little to offset the aircraft range penalty from lower energy density. For the synthesis of fuel for an airport consuming the *mass equivalent* of 50 complete B747 fuel loads of ethanol per day (50×150 t/d), the following conclusions can be drawn.

— CO_2 production from a classic coal liquefaction process of > 14,000 t/d practically imposes CO_2 recycling with large quantities of hydrogen. The amount of released CO_2 is equivalent to the emission from a 2.43 GWe coal-fired power plant (LHV 33.3 MJ/kg coal, η = 45%). The amount of coal used corresponds to 50 × 168 t/d × 33.3 MJ/kg = 3.24 GWth, whereas the amount of ethanol produced corresponds to 50 × 150 t/d ×

26.74 MJ/kg = 2.32 GWth. The conversion efficiency is then 2.32 GWth/3.24 GWth = 71.7%.

- With CO_2 recycling, the fuel production complex itself is CO_2 neutral and no sequestration is required. The CO_2 is used twice before emission into the atmosphere. The daily ethanol flow corresponds to an installed thermal power of 50 × 150 t/d × 26.74 MJ/kg = 2.32 GWth. The used coal has an energy content corresponding to 50 × 112 t/d × 33.3 MJ/kg = 2.16 GWth. The power needs for a major European airport based on coal liquefaction with CO_2 recycling can be matched with approx 6 HTRs of 600 MWth each for the production of hydrogen as an intermediate, for water cleaning/desalination, process steam and for electricity generation. The conversion efficiency is then 2.32 GWth/(2.16 GWth + 3.41 GWth) = 41.7%.
- The liquefaction complex for this airport with CO_2 recycling would consume the water of a town of 63,000 (based on a consumption of 140 L/person-day).
- When based on CO_2 feedstock only, CO_2 sequestration could be avoided while still decreasing CO_2 emmissions by a factor 2. The power requirements for H_2 production would double against coal liquefaction with CO_2 recycling. If centralized, a very large fossil-fired power plant (2.16 GWth or 972 MWe) would need to be in the neighborhood of the liquefaction plant in addition to a nuclear complex of 6.8 GWth. The conversion efficiency is then 2.32 GWth/6.8 GWth = 34%. Alternatively, the fuel could be produced in a more decentralized manner by twinning smaller fossil-fired power plants with nuclear reactors of approx. three times the thermal power of the fossil fired plant.

5. Cost considerations

A US study for military applications [14] showed that even CO_2 extraction from air with nuclear synfuel production for maritime transport and aircraft carrier-based fighter planes would lead to a liquid hydrocarbon cost of the order of 3.67 $/gal. Although we think that these figures would deserve verification, we will use them in the following for comparative purposes. Using flue gas instead of ambient air or, if feasibility can be demonstrated, thermochemical processes with HTR technology instead of electrolysis would reduce this cost. By using fossil CO_2 as the carbon feedstock, carbon-dioxide sequestration can be avoided and the CO_2 be used twice before being emitted into the atmosphere with strongly positive impact on the economics.

Table IV. Synthetic liquid hydrocarbon cost as a function on carbon feedstock and production method [14] for a fixed charge rate of 5%.

Cost in [US$/gal]	Coal-to-Liquid		CO_2 from fossil power plant		Atmospheric CO_2	
	LWR	HTR	LWR	HTR	LWR	HTR
Fuel cost without CO_2 credit (30 $/t)	2.36	2.06	3.31	2.75	3.67	N/A
Fuel cost with CO_2 credit (30 $/t)	1.61	1.32	3.02	2.46	N/A	N/A

Kerosene (or similar) contains 35.74 GJ/m^3 or 37.6 kWh/gal chemical energy or (considering a typical IC engine efficiency of 30%) 11.28 kWh/L mechanical energy. Considering a price of 3.31 $/gal (fossil CO_2, LWR H_2, no CO_2 credit, no tax, cf. Table), this would lead to a cost of 0.223 €/kWh mechanical work. Assuming a tax of 0.7 €/L on this liquid hydrocarbon fuel (similar to what is current practice in many European countries today), this would increase to 0.294 €/kWh mechanical work.

Table V. Energy prices for mechanical work from synthetic kerosene, diesel fuel and electricity

	Synthetic kerosene*	Diesel**	Electricity*** (household)
Price****	3.31 $/gal = 0.665€/L	1 €/L (at pump)	0.196 €/kWh
Energy density	9.93 kWh/L	10.1 kWh/L	
Conversion efficiency	30%	30%	85%
Price of mechanical energy w/o tax	0.223 €/kWh		
Price of mechanical energy w/ tax	0.294 €/kWh (tax = 0.7 €/L)	0.33 €/kWh	0.231 €/kWh

*: fossil CO_2, LWR H_2, no CO_2 credit **: price quoted for December 2006 in the Netherlands
: price quoted for January 2006 in the Netherlands [1] *: 1 € = 1.315 US$

This price for mechanical energy can be compared to today's fuel costs and to electricity as follows: Diesel fuel in the Netherlands costs today approx. 1 €/L at the pump. Diesel contains 36.4 MJ/L or 10.1 kWh/L in chemical energy. Assuming again an efficiency of 30% of the IC engine, this would lead to a cost of 0.33 €/kWh of mechanical work which is quite comparable to the cost of synthetic kerosene.

Electricity costs in Europe are varying greatly from one country to the other. In the Netherlands which is at the higher end, the January 2006 price was 0.096 €/kWh for industrial users and 0.196 €/kWh for households [1]. Assuming that with suitable batteries and electric engines, the electric energy can be converted into mechanical work at an efficiency of 85% (charger, engine), the cost would become 0.113 €/kWh from industrial electricity and 0.231 €/kWh from household electricity.

From the above one may conclude that synthetic hydrocarbons could already today be produced at prices, which are not only comparable to fossil fuel but which are also more stable with no tax loss for the governments. Further cost advantages for synthetic hydrocarbons could be obtained by:

- Cheaper and more efficient H_2 and syngas production methods
- Cheaper and more efficient electricity production
- More efficient engines
- Introduction of a CO_2 tax, incl. for fossil-fired power plants
- Lower taxes on synthetic fuels from recycled CO_2
- Higher taxes on fossil fuels

6. Conclusion

There is huge potential for nuclear-produced syngas, methane or liquid hydrocarbons in the chemical industry and in those parts of the transport sector (trucks, aviation, maritime) where hydrocarbon fuel is merely impossible to substitute. The potential applications are such that even massive deployment of new nuclear power plants cannot quickly satisfy the demand. If it could, both Fast Breeder Reactors and the Th-U fuel cycle would be required quickly to prevent mid-term shortage of nuclear fuel.

We share the opinion that in view of scarce resources (i.e. fossil fuels and R&D funds to displace them) a serious factual discussion is already overdue to make a policy choice between a synthetic hydrocarbon economy and a hydrogen economy. While the latter is still politically attractive due to its apparent cleanliness and simplicity, it is challenging technically, energetically and economically, with hydrocarbons appearing as the more realistic option for short- and mid-term CO_2 reductions, in particular because existing infrastructure for liquids and gas could be used. The downside of this approach is that it encourages fossil fuel burning (for CO_2 recovery) and continued use of low-efficiency combustion engines like for cars (20-30%) which could run more efficiently on cheaper (nuclear) electricity but which, for better success on the market, would require higher-capacity electricity storage media.

Nuclear-powered synthesis of hydrocarbon fuel is attractive from many points of view as it enables in particular applications where H_2 or electricity are unsuitable, e.g. in aviation. It could also act as an efficient means to reduce CO_2 emissions and to avoid technically risky and expensive CO_2 sequestration. The quoted economic assessment requires verification. It suggests that synthesis of liquid hydrocarbons from flue gas and nuclear hydrogen would lead to cost of mechanical energy that is more stable and very similar to what is paid today for mechanical energy from fossil fuel.

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High temperature process heat generation with medium temperature heat source

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Abstract. There is a substantial market for nuclear energy in non-electric applications such as hydrogen production or water desalination. Among the Generation IV reactor concepts, the VHTR (Very High Temperature Reactor) with a reactor outlet temperature close to 1000˚C and a power conversion efficiency of approx. 50% is believed to be the most suitable concept for cogeneration of process heat. Its high coolant exergy would enable centralized hydrogen production and other process heat applications. In this paper it is shown that a reactor with lower coolant outlet temperature or another near-term heat source can also meet the VHTR objectives which are high power conversion efficiency and capability to deliver high temperature process heat in the narrow temperature window required by thermochemical hydrogen production cycles. The approach was to separate the requirement for high temperature process heat production from the nuclear part of the plant, in other words the nuclear part of the power plant would run at acceptably low temperature while the high temperature heat production via a heat pump system would be limited to a conventional external circuit, thus avoiding nuclear constraints. The separation of these high temperature constraints from the reactor would avoid massive R&D requirements on materials, components and fuel with uncertain outcome thus unnecessarily delaying introduction of this otherwise very attractive reactor concept.

We then show that the proposed technology is equally suitable for the generation of cold (e.g. for air conditioning) and for desalination of sea water.

1. Introduction

The sustainability of nuclear power increases linearly with power conversion efficiency and can be further raised by co-generation of electricity and heat for various process heat applications. As an example, the Generation IV VHTR reactor concept aims at approx. 50% power conversion efficiency and, according to the prevailing opinion, a temperature close to 1000˚C would be required to enable centralized hydrogen production. These high temperatures put severe constraints on materials, components and fuel and imply massive R&D requirements with uncertain outcome thus unnecessarily delaying introduction of this otherwise very attractive reactor concept.

The first objective of this paper is to develop an alternative option to both reach the VHTR power conversion efficiency target and the capability to deliver high temperature process heat with a reactor or other heat source with lower temperature output that would be feasible in the near-term. The approach was to separate the requirement for high temperature process heat production from the nuclear part of the plant, in other words the nuclear part of the power plant would run at acceptably low temperature while the high temperature heat production would be limited to a conventional external circuit, thus avoiding nuclear constraints. Two such methods would be feasible: electric superheating to the desired temperature level or the use of heat pump (HP) technology via compression to the desired temperature level. While the heat thus generated is then delivered to a heat exchanger, some of the compression work can be recovered in a turbine, which makes this option energetically more efficient than electric heating.

The second objective of this paper is to show how the same heat pump technology can be used for combined desalination and district cooling which corresponds to market needs in arid regions.

While classical gas-cooled reactors are proven technology, the GIF VHTR still requires a strong R&D effort. Based on already available technology, the power conversion options proposed here would introduce a near-term solution to provide nuclear produced high temperature process heat.

2. Reverse brayton cycle

The principal objective of a heat pump [3] is to remove heat from a low temperature environment and to release it to a high temperature environment. This transformation requires mechanical work, which is exactly the opposite of the working process. To achieve that goal, a fluid is used as energy carrier: It undergoes transformations to be colder than the low temperature environment (to remove heat there) and then hotter than the high temperature environment (to release heat there).

If the energy gained from the cold source is considered as a loss that would otherwise be simply rejected, energy input into a heat pump is the compression work only. Both heat and compression work increase the energy in the fluid: The efficiency of this system is then higher than unity. In this study, the cold energy source cannot be considered as a loss such that efficiency is < 100%, but still much higher than the working cycle efficiency.

This gas cycle is the opposite of a Brayton cycle:

- Heating at low temperature,
- Compression and superheating,
- Cooling at high temperature,
- Expansion for extra cooling.

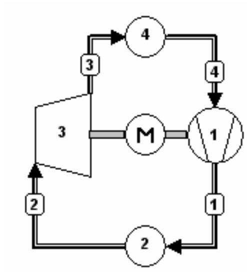


FIG. 1. Reverse brayton HP

The fluid remains in gaseous form. It is heated in the low temperature environment and superheated by compression. It delivers heat to the high temperature environment and is finally expanded in the turbine to recover some of the mechanical work from compression.

This method can be applied in a wide temperature range and reduced losses compared to a reverse Rankine heat pump or even electric heating. Although the compression work is much higher than for a liquid, a large part of it (around 60%) is earned back in the turbine. This enhances efficiency.

Shortcomings are:

- Poor heat transfer to and from the gaseous fluid implying high mass flows. As the sensible heats are smaller (per unit masson a unit mass), latent heats, mass and volume flow are larger.
- The gas state, which implies non-isothermal heat exchanges.

In a reverse Brayton cycle, both mechanical power and low temperature power are transformed into high temperature power. As the goal is to maximize the contribution of the low temperature power compared to the valuable mechanical work, a reverse Brayton cycle with single compression and no recuperation (RB1CNR) is needed for the heat pump system. This implies production of process heat over a large temperature span. A reverse Brayton cycle with multiple recompressionmore would lead to an efficiency decrease but would provide process heat in a narrow temperature window.

3. Process heat in a large temperature span: Grid motorized reverse brayton cycle

For this cycle, the reactor is considered as the lower temperature heat source. The gas from the reactor outlet is compressed to reach the required process heat temperature. Then, this gas transfers its heat to the high temperature process. It is then expanded in a turbine to cool it before returning to the reactor. During expansion, some mechanical work is recovered to power the compressor thus reducing external power needs.

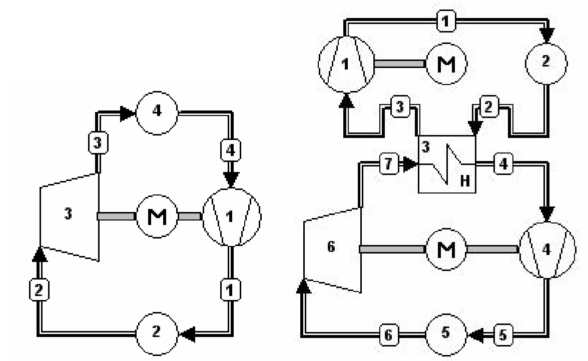


FIG. 2. Direct and indirect reverse brayton HP

In a reverse Brayton cycle, mechanical power converts low temperature heat into high temperature heat with a thermal efficiency of 1. Losses (pressure drops or turbomachinery efficiencies) only increase mechanical work required to transform the reactor power into high temperature process heat. Even if losses do not deteriorate the efficiency here, a distinction has to be made between the two power sources because mechanical power is more valuable than heat. For optimum overall efficiency, the contribution of the thermal power compared to the valuable mechanical work has to be maximized.

Prior to efficiency calculation, the following conditions were selected as design point:

Table I. Operating conditions of the RB1CNR cycle

Medium	Helium	-
Compressor Outlet Pressure	7	MPa
Reactor Inlet Temperature	400	°C
Reactor Outlet Temperature	850	°C
Process Heat High Temperature	1000	°C
Reactor Power	400	MWth

Table II. Powers and efficiency of the RB1CNR cycle

Mechanical Power	82.44	MW
Process Heat	682.44	MW
Efficiency	100%	-

In this case, process heat is produced between the targeted 1000°C and 457°C, determined by the compression ratio of the cycle and the reactor inlet temperature.

Besides the high efficiency of this cycle, its simplicity implies reliability and low capital investment. Capital investment might be lower compared to a conventional power conversion unit for HTR due to the fact that the compression ratio is much lower: Here, compression is used only for superheating, thus between 850°C and 1000°C, leading to a compression ratio of only 1.257, although high temperature materials are required.

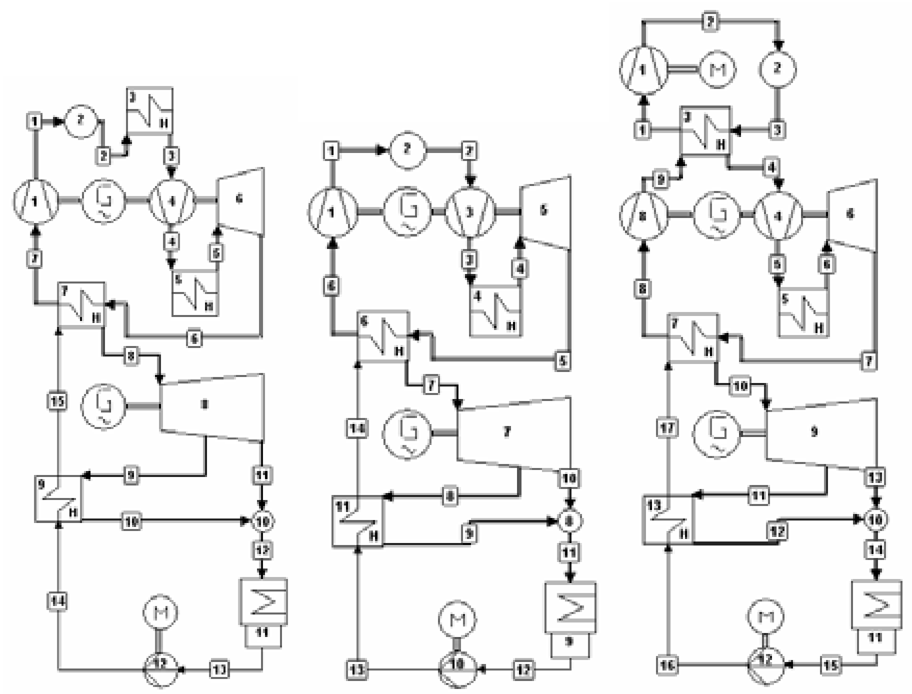
More cycles for process heat in a large temperature span are described in [1].

4. Concentration of high temperature process heat to a narrow temperature span

The issue of thermochemical H_2 production is related to the narrow temperature window in which process heat can be delivered to the thermochemical processes. In case of a VHTR with RIT/ROT = 400/1000°C, and process heat supply between 1000°C and 950°C, only 8.3% of the nuclear power would be used for H_2 production. This fraction can be enhanced using recompression: once the coolant exits the IHX, it can be recompressed several times to attain again the required 1000°C. More detailed information can be found in [3].The effect on the heat/electricity ratio and overall efficiency is shown on Fig. 4.

We have checked to what extent a “low-tech” approach for high temperature process heat production (e.g. for large-scale H_2 generation) based on experience and specifications of AGR technology [4]. could satisfy the requirements of a VHTR as proposed within GIF with less stringent conditions on fuel, materials and components. A 600 MWth HTR (pebble bed or hexagonal block type) was assumed as the primary heat source with a primary top cycle temperature of 640°C (same as AGR). At this temperature, the primary He coolant may be replaced by less expensive CO_2. This would avoid He leakage issues, enable the use of AGR technology with positive effects on feasibility and cost of components. This circuit was then coupled to a secondary reverse Brayton cycle for high temperature process heat generation and completed by a bottoming cycle for efficiency maximization. Between 3 and 4 recompressions, the system turns into a net electricity consumer.

For comparison purposes the results for a typical HTR with a He outlet temperature of 850°C are also presented. The effect of recompression on efficiency is shown on Fig. 4. For both AGR and HTR, the first compression step is used to raise the reactor outlet temperature to the desired process heat temperature as shown in Fig. 3.



direct (VHTR) direct (HTR) indirect (AGR)

FIG. 3. Direct Brayton cycle for VHTR and direct/indirect Brayton cycle for HTR with single recompression and bottoming Rankine cycle

Figure 4 summarizes process heat and electricity production of VHTR, HTR and AGR cycles depending on the number of Intermediate Heat Exchanger. It also illustrates that an AGR with three IHX produces more high temperature process heat than a VHTR with five. This is paid by a significant overall efficiency penalty (from 68.7% to 51.6%) and can be explained by the primary coolant flow-rates: due to different reactor inlet and outlet temperatures of the three compared heat sources, the flows are not the same in all computations.

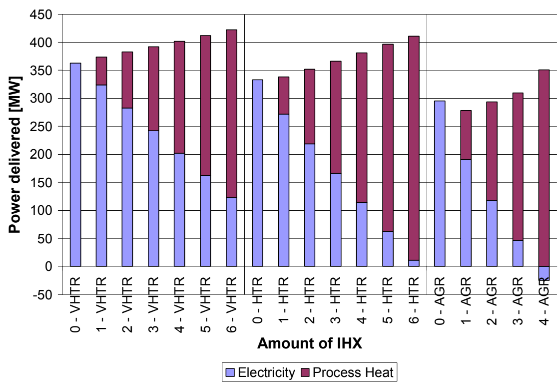


FIG. 4. Process heat and electricity production of VHTR, HTR and AGR per IHX

As illustrated in Table , a higher reactor inlet temperature requires higher coolant flow-rates to remove the heat from the reactor thus increasing the flow through IHX and compressors which then require more compression work.

Table III. Influence of primary coolant heat-up span on process heat and compression work

	Coolant heat-up [K]	Mass Flow [kg/s]	Process Heat & Compression Work per IHX [MW]
VHTR	600	192.6	50
HTR	450	256.8	66.7
AGR	342	337.9	87.7

From this, the following dependency can be derived:

$$\uparrow RIT \Leftrightarrow \uparrow \mathrm{Pr}\,oceess\ \ Heat\ \ \& \downarrow Electricity$$

Owing to this observation, tuning of heat and electricity supply to various customer needs can be achieved, very roughly first by the number of recompressions and Intermediate Heat Exchangers, then finely through variation of reactor inlet temperature. Limits to this approach are materials (e.g. graphite and reactor pressure vessel) and throughput limits in reactor (pressure drop) and turbo-machinery (size).

5. Reverse brayton cycle for combined cooling and desalination

Arid regions are in demand for both seawater desalination and cooling systems both requiring significant power. Reverse Brayton have the capability to simultaneously respond to this dual demand.

In [5], several desalination systems are reviewed. Among them, distillation requires the highest temperature (between 110°C and 130°C). For large air conditioning systems, a temperature of 15°C might be foreseen with a counter flow heat exchanger. This is why we assume here delivery of cold at 15°C and delivery of heat at 130°C.

The layout shown in Fig. 1 is only an idealized situation, whereas in reality one has to account for entropy increase in turbomachinery. This increases turbine outlet temperature which is further raised by entropy increases in compressors. (By decreasing the high pressure required to match the targeted 130°C leading to a lower expansion in the turbine). Raising turbine outlet temperature (or Cold Exchanger Low Temperature) increases the required mass flow and thus compression work.

Two solutions are then possible: Either decreasing the hot exchanger low temperature below 110°C or using recompression to produce more heat for desalination and enable the temperature match of the cold exchanger. This option is shown in Fig. 5.

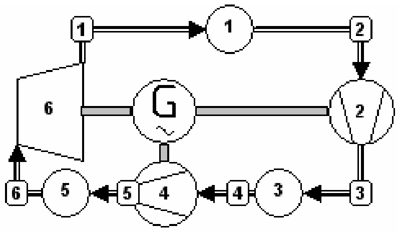


FIG. 5. RB2C1ENR cycle with recompression for combined cooling and desalination applications

Due to the assumption that a mass flow increase would lead to a heat exchanger size increase, the pressure drop calculation is not depending on mass flow. According to this assumption and in the conditions described above, the pressure drops in heat exchangers can be calculated. In the order of 8×10^{-2} bar, they do not significantly influence results including turbomachinery entropy:

Table IV. Parameters of the cold and desalination RB2C1ENR cycle

Parameter	Value	Unit
Air Conditioning Power	1.00	MWth
Compression Work	-20.87	MWm
Desalination Power	6.18	MWth
Expansion Work	15.69	MWm
COP	-1.39	
Cold Exchanger Low Temperature	282.23	K

The small temperature windows in heat exchangers lead to a high coolant mass flow, which increases the required compression work. Therefore more recompressions and expansions might be used:

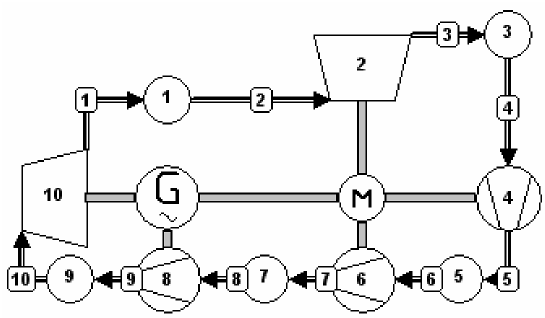


FIG. 6. RB3C2ENR cycle with recompression for combined cooling and desalination applications

Table V. Parameters of the cold and desalination RB3C2ENR cycle

Parameter	Value	Unit
Air Conditioning Power	2.00	MWth
Compression Work	-17.31	MWm
Desalination Power	6.70	MWth
Expansion Power	12.61	MWm
COP	-1.85	
Cold Exchanger Low Temperature	279.74	K

Coefficient of Performance can be further raised by adding extra compressions and expansions. An economic assessment will determine the optimum number of recompressions.

6. Use of other reactors as the heat source

So far, only High Temperature Reactors were considered as the heat source. As shown in section IV.B, a CC_B2CR_RB1CNR based on an HTR with an outlet temperature of 550°C would still achieve a thermal efficiency above 75%. Therefore, all Generation IV International Forum concepts [6] may actually be used as the primary heat source in combination with a heat pump cycle to produce high temperature process heat, e.g. for hydrogen production, although at different efficiencies. This would further enable reducing the temperature requirements on a VHTR to values that are feasible in the nearer term.

Table VI. Primary coolant outlet temperatures of GIF concepts

GIF system	Coolant outlet temperature
VHTR	1000°C
GFR	850°C
LFR	550 - 800°C
MSR	> 700°C
SFR	550°C
SCWR	550°C

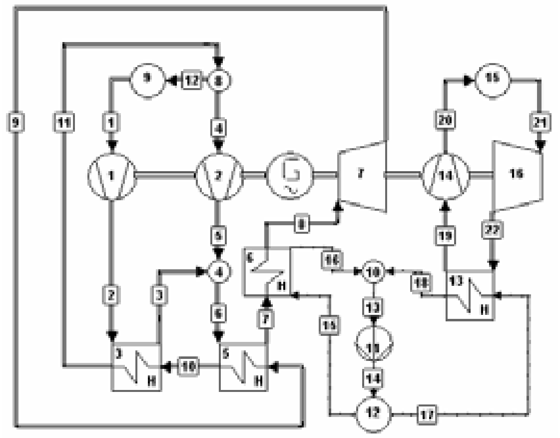


FIG. 7. Possible LFR, MSR, SFR or SWCR power conversion cycle: CC_SCO_2_R1BCNR

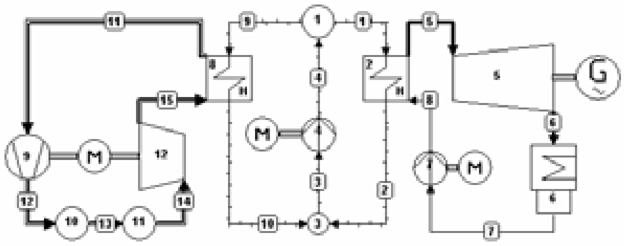


FIG. 8. Possible LFR, MSR, SFR or SWCR power conversion cycle: CC_SCW_R1BCNR

Figures 7and 8 show possible layouts for various GIF concepts in view of co-generation of high temperature process heat and electricity.

7. Conclusions

This paper discussed the use of the reverse Brayton cycle as a heat pump to reach VHTR process heat and efficiency objectives. This opens opportunities to design innovative, flexible and efficient power conversion cycles that can be adapted to virtually all Generation IV International Forum reactor concepts as well as to existing or near-term reactor designs such as the Advanced Gas Cooled Reactor (AGR), HTR or other heat sources. While so far only HTR technology was investigated as the primary heat source, it is planned to pursue efforts towards other concepts and to enable feasible configurations with significantly less stringent technology requirements, in particular for the VHTR.

Based on this enabling technology and the expectation that switching to a hydrogen or methanol economy would require much more high temperature process heat than produced by current VHTR designs, innovative layouts were developed enabling delivery of high temperature process heat in the required narrow temperature window.

This study showed the feasibility of nearer term hydrogen production and other high temperature process heat applications while avoiding costly and time consuming R&D of VHTR. The induced penalty for replacing VHTR by AGR is approx. 17% points of overall efficiency with the resulting efficiency still exceeding 50%.

Finally, a short feasibility study for combined cold and desalination based on the technology developed in the previous objectives was performed. For these combined applications, a coefficient of performance significantly larger than unity was calculated. This figure can be further raised but complicates the cycle layout.

In all three objectives, an economical study is required to assess whether these technical achievements make economically sense.

8. GLOSSARY

AGR	Advanced Gas Cooled Reactor
B1CNR	Brayton cycle with one Compressor and no Recuperator
CC	Combined Cycle
GIF	Generation IV International Forum
HP	Heat Pump or RB1CNR
IHX	Intermediate Heat Exchanger
LFR	Lead-Cooled Fast Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
PBMR	Pebble Bed Modular Reactor
RB1CNR	Reverse Brayton cycle with one Compressor and no Recuperator
S-CO_2	Supercritical Carbon Dioxide
SFR	Sodium-Cooled Fast Reactor
SWCR	Supercritical-Water-Cooled Reactor
V/HTR	Very/High Temperature Reactor

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ECONOMICS AND DEMAND FOR NON-ELECTRIC APPLICATIONS

SESSION 3 (Plenary)

Chairpersons

L. Brey
United States of America

M. Megahed
Egypt

Allocating costs for non-electricity products from generation IV nuclear energy systems

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Extended Synopsis

This paper discusses the calculation of the levelized unit costs for non-electricity products and jointly produced outputs, such as electricity with fresh water, hydrogen, heat, or actinide destruction services. Where nuclear energy systems produce multiple products, each of which is sold in a fully functioning market (as is usually the case for electricity), market prices can be used to determine whether total costs are less than total revenues, i.e., whether a joint-product nuclear energy system is competitive. Problems in allocating fixed costs (for example, the cost of the reactor) arise when at least one of the joint products is sold under contract, for example, where heat or water are sold to a municipal utility for local distribution. In these cases, the price, based on cost, of the product is negotiated. How should this cost be determined?

Although there is a vast literature on how to allocate common costs in nuclear energy systems, there is no clear consensus. The method adopted in the framework of the Generation IV International Forum (GIF) Economic Modeling Working Group (EMWG) is the Power Credit (PC) approach, which has been adopted by the IAEA in DEEP (Desalination Economic Evaluation Program) to evaluate the economics of nuclear desalination.

The paper presents the power credit method in details and develops the concept of a "product credit" approach. Under the PC approach, all of the savings from joint production are allocated to the product other than electricity, reducing its cost. Under the "product credit" approach, all of the savings are allocated to electricity. While one approach is as valid as the other is (and neither method guarantees an economically efficient allocation), the EMWG suggests following the PC method as implemented in DEEP to evaluate the economics of joint production.

The first step in determining the Levelized Unit Cost (following the PC approach) is to determine costs for the reference *electric*-only facility. The sum of these costs is "C." Further, net energy in each period is discounted to the present and summed. This sum of discounted energy output is "E." Then the Levelized Unit Electricity Cost (LUEC) for the electric-only plant LUEC = C/E.

In a second step, costs are determined for the joint-production facility. The resulting costs are discounted to the present. Their sum is equal to C_2. Also, net electricity for the joint production facility is discounted and summed to E_2 (less than E, lost electricity is equal to E – E_2, it is evaluated at the cost C_{kWh}). Further, the net output of the other product in each period is discounted to the present and summed. For example with desalination, saleable water is discounted and summed to W (let W represent any non-electric product, e.g., heat or hydrogen). Then the Levelized Unit Product Cost (LUPC) is equal to (C_2 - E_2 LUEC) / W. The LUEC and LUPC can then be used to determine whether the electric-only or joint

production nuclear energy system is competitive in both the electricity market and with alternative sources of the non-electric product.

The approach is applied to the estimation of the costs of producing electricity and hydrogen with an advanced nuclear energy system. High-temperature gas reactors, e.g., the Modular Helium Reactor (MHR), can be configured to produce electricity or hydrogen using thermo-chemical processes with a projected average cost of \$15/GJ. However, natural gas prices of \$8/GJ make MHR electricity generation extremely competitive with respect to Combined-Cycle Gas Turbines. Therefore, following the EMWG *Cost Estimating Guidelines,* the MHR is likely to be more profitable in electricity markets than in hydrogen markets using the PC method.

The joint production of energy and desalinated water is examined in the context of the construction of a Reverse Osmosis (RO) plant at the site of the (fossil-fired) Encina Power Station in Carlsbad, California. The application reproduces cost estimates of water at the Carlsbad Desalination Project and reproduces these cost estimates using the IAEA's DEEP. The paper shows that the cost of desalinating water with nuclear power is cheaper than at fossil-fired plants, given the high cost of fossil fuel. However, this depends on "free heat." For example, consider Bogart and Schultz, "Water Desalination as a Possible Opportunity for the GT- and H2-MHR." Proceedings of the ICAPP '04, Pittsburgh, PA, USA (June 13-17, 2004), "It is important to compare the COW (Cost of Water) for a GT-MHR plant providing low-cost electricity (\$0.029/kWh) to a reverse osmosis plant and the COW for a GT-MHR or H2-MHR plant providing low-cost electricity and 'free heat' to a MED (multi-effect distillation) plant." (p. 8) "Free heat" implies the PC method because water is not charged with the expenses of heat generation.

The paper concludes with a discussion of whether applying the power credit method to the allocation of joint electricity production and actinide destruction leads to a cost allocation that would encourage the commercialization of actinide burning reactors.

The Japanese industrial activities on non-electrical applications of nuclear energy, mainly related to HTGR plant

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Abstract. "Japanese industry" has long been (a) studying, (b) evaluating the commercial feasibility of nuclear energy "Non-electrical applications", high temperature applications by "High Temperature Gas Cooled Reactor (HTGR)" plant in particular, through participation in the High Temperature Engineering and Test Reactor (HTTR) project, etc. and (c) proposing to the government. Recently new possibilities of such applications have been listed up by Japanese industry, such as "Fuel cell vehicles (FCVs), "Hydrogen towns" and "Chemical complexes (Kombinates)", for example, in which high temperature nuclear heat, hydrogen, oxygen, and/or steam are to be supplied.

1. Introduction

Whereas, "Japanese industry" or "The industry" means here (a) Japanese electric power companies, (b) nuclear power plant/ fuel makers, (c) gas suppliers, (d) car and battery makers, (e) steel makers, (f) engineering, and (g) trading houses, as members, and (h) research institutes including Japan Atomic Energy Agency (JAEA) and (i) academia, as advisors.

Japanese industry established two research and proposing groups on the HTGR plant and its related nuclear heat applications, as shown below;

(a) "HTGR Future Deployment Committee" (in Japan Atomic Industrial Forum (JAIF)) (deployed from "Multi-purpose Nuclear Applications Committee" and "Nuclear Heat Applications Committee")

Currently chaired by Dr. H. Sekimoto (Prof., Tokyo Institute of Technology)

- Information submittal, appeal or proposal to the government, industry and public
- Activities since 1969

(b) "Research Association of HTGR Plant (RAHP)"

Long chaired by Dr. S. An (Prof. Emeritus, University of Tokyo)

- Research (Needs, world R&D status, technology, safety, economy, etc.)
- Information submittal, appeal or proposal to the industry and public
- Activities since 1985

Whereas, "Non-electric applications" of nuclear energy means here nuclear heat uses, mainly of high temperatures of about 800-1,000ºC to be obtained from high temperature nuclear reactors, represented by HTGR or Very High Temperature Reactor (VHTR) plants, such as;

(a) Highly efficient hydrogen production
(b) Coal gasification / liquefaction (synthetic fuel production for transportation), and
(c) Process heat (for chemistries, etc.)

As shown above, since 1960's, Japanese industry has been continuously (a) studying on the feasibility of "Multi-purpose nuclear heat applications" like "Nuclear steel making", (b) contributing to HTTR Project of JAEA (ex. JAERI) and its related R&D like hydrogen production technology, high temperature heat exchangers, etc., (c) investigating and evaluating on the feasibility of such applications, and (d) grasping the R&D status and trend of commercialization in the world.

Viewpoints of the industry are technology, safety, public acceptability, international marketability, and then commercial feasibility.

Since 2000's, the industry has made a series of appeals or proposals (a) to the government and Atomic Energy Commission (AECJ) on positioning of such nuclear reactor plant systems and heat uses in the national strategic energy /economic development programs and the Japanese role in the world, and (b) to the industry itself and public for the recognition of the state of the arts and the importance of such development.

The main results of investigations on several topics, such as unique characteristics of HTGR plant, world R&D status, economy, HTGR positioning in the energy strategy and hydrogen society, recognitions, proposals, and new findings, are described in the following sections.

2. Properties, characteristics and usages of HTGR plant

HTGR plants have many unique and important properties as shown below. The main ones of them are hydrogen production and a wide temperature range of heat uses;

(a) Sustainability
(b) Wide applications and world marketability (in both advanced and advancing countries)
  – Electrical production
  – Hydrogen production
  – Fuel gas (for car, ship and aircraft), FCV, stationary fuel cell, etc.
  – A variety of heat uses (from high to mid and low temperatures)
  – Coal gasification/ liquefaction (synthetic fuel production), steel making, oil refinery, process chemistry, district heating, seawater desalination, etc.

(c) Safety
  – Fuels and in-core materials mainly made of refractory ceramics
  – Enhanced safety by means of strictly suppressed design of power density (ensured "inherent safety")

(d) Economy
  – Modularized or standardized design
  – Component/ Equipment fabrication in factory under stable quality control/ assurance
  – Plant siting near demand areas (low cost for electricity or heat transportation)

(e) Environmental-friendly
  - No emission of global warming gases and high heat use efficiency

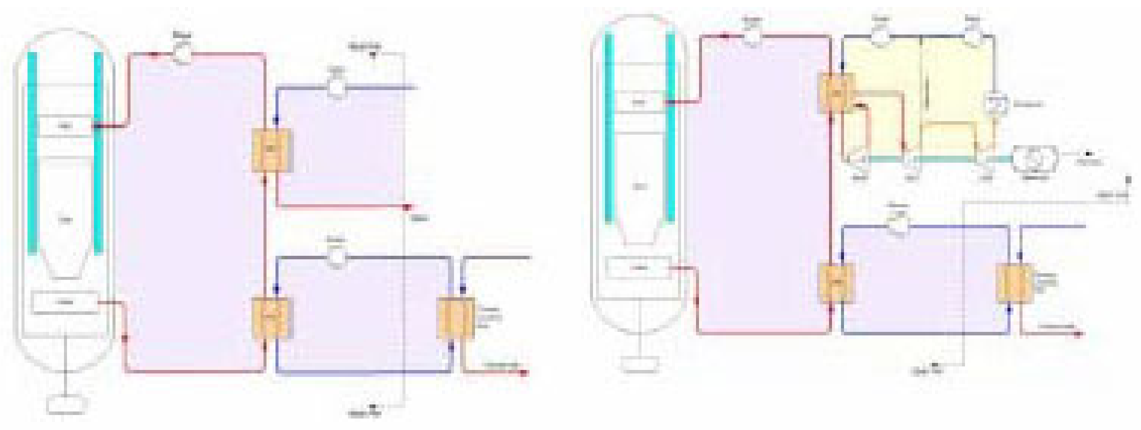
3. World development status of HTGR and high temperature nuclear heat applications

Many R&D programs are currently under way in the world, ranging from the basic study to the demonstration and/or commercialization programs of HTGR plant and various nuclear heat applications, as well as electrical production.

It is emphasized that;

(a) R&D and commercialization programs on heat uses, mainly of high temperatures, are becoming very eminent and practical, towards their commercialization in mid- 2010's (for HTGRs) or early 2020's (for VHTRs), as shown in Tables 1 to 3 and Fig.1.

(b) Those are under execution on national or governmental basis with international supports in case of other countries. In Japan, however, R&D has long been promoted on national basis, then taking the world leadership in the technology development, but is now seemed to become slowing down and actually there is no commercialization program.



(1) PBMR PHP for steam methane reforming (Supply of steam and process heat)

(2) PBMR PHP for hybrid sulfur (Supply of electricity and process heat)

FIG. 1. Typical examples of HTGR heat applications under R&D or proposal in the world [5]

Table I. Current HTGR test reactor programs in the world [1], [2]

Program / Country / Main activities

(a) HTTR Program / Japan (in operation since 1998)

- Safety demonstration, R&D on high temperature materials, hydrogen production technology, as well as a series of HTGR plant conceptual design

(b) HTR-10 Program / China (in operation since 2000)

- Safety demonstration, R&D on heat applications and hydrogen production

Table II. Current HTGR plant demonstration / commercialization programs in the world [1], [2], [5]

	Program /	Country /	Electricity and/or high temperature applications, operational start
(a)	PBMR	Africa	Electricity production, 2013
(b)	PHP	(ditto)	Coal liquefaction, hydrogen production, etc., 2016
(c)	HTR-PM	China	Electricity production, 2013
(d)	GT-MHR	US/Russia	Electricity production, heat uses, 2015?
(e)	NGNP	US	Electricity / hydrogen co-production, 2021
(f)	ANTARES	France	Electricity / hydrogen / heat applications, 2015?
(g)	NHDD	S. Korea	Hydrogen production, 2020

Table III. Examples of proposal on nuclear high temperature heat applications [6], [7]

	Company	Country	Theme
(a)	JGC	Japan	Bitumen upgrading (Oil sand reforming)
(b)	ARTECH	Japan	Clean coal usage

4. Economics

Economics of heat applications by HTGR is based on the cost of plants for electrical production. PBMR (S. Africa) and GA (US) indicated their estimates and targets of less than 1,000 $/kWe and 1-2 cents/kWh on N-th module basis.

To investigate the feasibility of the next generation nuclear reactors, Japanese industry sorted out so-called “Users requirements”. Typical ones are the costs less than 2,000 $/kWe and 6 (preferably 4) cents/kWh [1], [4].

Later, JAEA has basic-designed GTHTR300 series, including GTHTR300 (for electricity), 300H (for hydrogen) and 300C (for co-generation), responding to the requirements, and reported that the GTHTR300 plant can be basically designed for the costs less than 2,000 $/kWe and 4 cents/kWh [4].

The greater the number of modules in production and sale the world wide, the lower the cost of production, and then the above target costs shall be attained in due time.

5. HTGR positioning in the hydrogen society

RAHP committed a study on “Adaptability of hydrogen by HTGR to hydrogen society” to the hydrogen specialists of The Institute of Applied Energy (IAE) for independent review. Results showed that HTGR plant can supply hydrogen to FCVs competitively with the gasoline and the hydrogen can become even cheaper, due to its environmental / taxation effect in future.

6. Recognitions by Japanese industry

Japanese industry, through these long activities, is now recognizing that such HTGR plants and high temperature heat applications are considered feasible and desirable to be commercialized world wide, from view points shown below, contributing to the resolution of global energy security and environmental problems, which are worsening year by year;

(a) Remarkably enhanced energy utilization
(b) Expansion of nuclear energy applications
(c) Clean energy and hydrogen society in future
(d) "Synergy" development between "nuclear" and "fossil" fuels like coal and oil sand, which are to emit global warming gases when fired without any reforming etc., but their significant quantities are still laid down as natural resources in the globe
(e) Plant exportation
(f) Technology transfer to the next generations
(g) Current and future role of the Japanese industry, etc.

7. Proposals to the Government

Japanese industry has made a series of appeals or proposals to the government and the industry itself on the desirability of commercialization of HTGR plant and nuclear heat applications [4].

(a) "Outlook on HTGR development and its commercialization", JAIF, March 2000
(b) "Proposal on HTGR commercialization", JAIF, June 2004

Nevertheless the government has positioned the nuclear energy in "The Nuclear Energy Policy" (October 2003) as basic source of "electricity", and HTGR development or nuclear heat applications like hydrogen production as one of the fundamental R&Ds.

Therefore, the above mentioned proposals seem to have not been necessarily successful so far, and then still needed to refrain but now with more practical and persuading proposals, with exemplified "introductory scenarios" and/or "commercialization road maps" to realize as early as possible like 2020's –2030's, rather than to slow down the R&D on nuclear heat applications in Japan, which has been taking the world leadership in the technology development so far, centered to the JAEA's HTTR Project.

8. New findings on possibility of non-electrical nuclear heat applications in Japan

It is emphasized, however, that recently Japanese industry, through investigation activities, has found out several candidates or potentials of future high temperature heat applications, as introductory scenarios in Japan. Their possibilities can be said to be newly arising from global and local needs or thinking for improvement of economy and environment. Their examples are shown below and in Fig.2;

(a) "FCVs" are under development by the government and industry, which utilize a quantity of hydrogen, which can be produced in large scale by nuclear plants like HTGR. The government assumes that cars are to be electrified (EVs) or hydrogenized (FCVs) by 100% by 2100. Japanese industry and JAEA assume that about 30 HTGR modules of 600 MWt size are needed for hydrogen supply to the FCVs by the time.
(b) "Kombinates" in regional areas, such as Ibaragi, Tokyo / Chiba / Kanagawa, Osaka /

Kobe, Fukuoka /Yamaguchi, etc., now have many aged energy supply facilities like coal fired power plants, which need to be renewed after their 30-40 years operation, not with coal fire but hopefully nuclear like HTGR plant, due to their confrontations with now very strict national regulations and/or international pressures against global warming gas emissions, and possible availability of process heat, hydrogen / oxygen / high and mid temperature steam, as well as electric power, which could be organically improving total energy use efficiency in the facilities and Kombinates. Through these the Kombinates can survive.

(c) "Hydrogen towns" are being proposed and planned to be established in local areas, such as Aomori, Ibaragi and Yamaguchi Prefectures, which are aimed to develop and establish energy-independent, environmental-friendly and re-vitalized towns or prefectures. They are to be facilitated with a quantity of hydrogen to be produced from wind, solar, bio, etc. and nuclear energy to be supplied by HTGR plants, for example.

Appearance of these realistic potential users or non-electrical applications in Japan and the world will make the above mentioned proposals as more practical ones in near future.

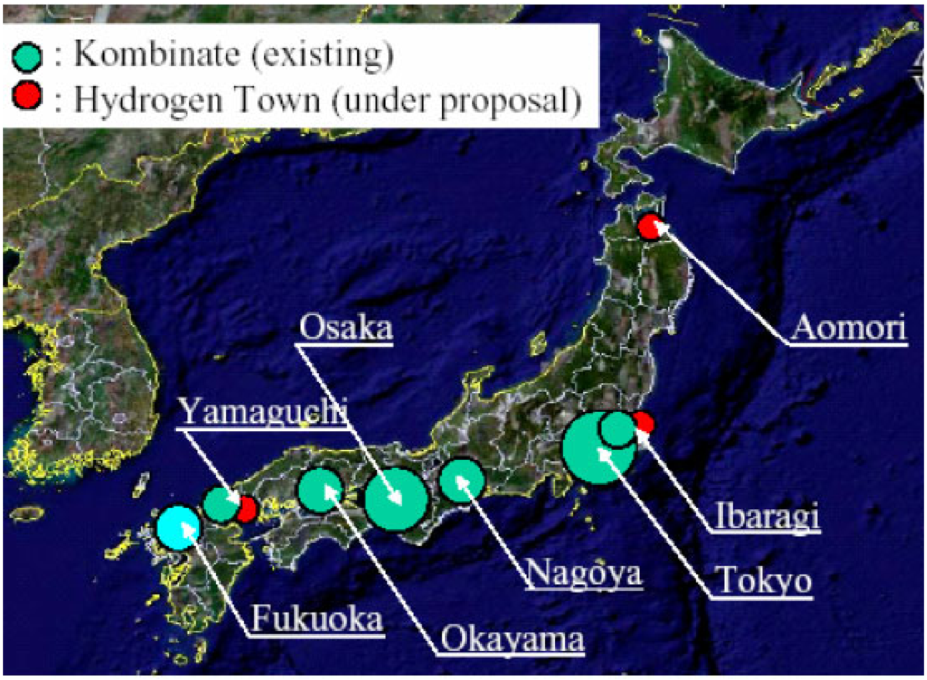


FIG. 2. Potential sites for high temperature nuclear heat applications in Japan (Heat, hydrogen, oxygen, steam and/or electricity)

9. Summary and Conclusion

Japanese industry has long been studying, investigating, evaluating and proposing on the feasibility of large-scale non-electrical applications of nuclear energy, of high temperatures in particular, as well as electrical production.

HTGR plant systems are considered very suited for such applications as hydrogen production, coal gasification / liquefaction, oil sand reforming, etc. and currently many plant wise demonstration / commercialization programs are in progress in the world.

It is true, as of now, that there is no program on commercialization of HTGR plant and/or nuclear heat applications in Japan, and that there are very few companies indicating their practical interests in the introduction of such nuclear plant in Japan, but Japanese industry has recently found out several future potential applications to start with, such as hydrogen supply for FCVs, hydrogen towns, and high temperature heat / steam / hydrogen/ oxygen / electricity supply for Kombinates based upon quality and quantity of their demands.

For solving the global problems of energy security and environment, all these global, national and local efforts should be pursued. Japan, the government and industry, should take a leadership in these fields.

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A comprehensive economic evaluation of integrated desalination systems, using fossil fuelled and nuclear energies, and including their environmental costs

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Abstract. Seawater desalination is now widely accepted as an attractive alternative source of freshwater for domestic and industrial uses. Despite the considerable progress made in the relevant technologies desalination, however, remains an energy intensive process in which the energy cost is the paramount factor.

This study is a first of a kind in that we have integrated the environmental costs into the power and desalination costs. The study has focused on the seawater desalination cost evaluation of the following systems. It is supposed that they will be operating in the co-generation mode (simultaneous production of electrical power and desalted water) in 2015:

– Fossil fuelled based systems such as the coal and oil fired plants and the gas turbine combined cycle plant, coupled to MED, and RO
– Pressurized water reactors such as the PWR-900 and the AP-600, coupled to MED, and RO.
– High temperature reactors such as the GT-MHR, the PBMR, coupled to MED, with the utilization of virtually free waste-heat provided by these reactors.

The study is made in real site-specific conditions of a site in Southern Europe.

Sensitivity studies for different parameters such as the fossil fuel prices, interest and discount rates, power costs etc., have also been undertaken.

The results obtained are then used to evaluate the financial interest of selected integrated desalination systems in terms of a detailed cash flow analysis, providing the Net Present Values, Pay Back Periods and the Internal Rate of Returns.

Analysis of the results shows that among the fossil fuelled systems the power and desalination costs by circulating fluidized bed coal fired plant would be the lowest with current coal prices. Those by oil fired plants would be highest. In all cases, integrated nuclear energy systems would lead to considerably lower power and water costs than the corresponding coal based systems.

When external costs for different energies are internalised in power and water costs, the relative cost differences are considerably increased in favour of the nuclear systems. Financial analysis further confirms these conclusions.

1. Introduction

As the standards of living increase, the demands for water also increase. Water scarcity and shortages already account for the death of more than 2 million persons (most of them children) per year. If business as usual continues, the figure for people suffering from water stresses could swell to 3.5 billion persons in 2025.

Water related problems are numerous. They are so diversified that there is no single solution to meet the water demands in a given country. All alternate solutions of water supply, notably water recycling, more efficient use of water, modernization of water distribution networks to avoid leakages and the desalination of brackish or seawater, are thus required to meet the ever increasing water demands.

From a technical and economical standpoint seawater desalination, as an alternate source of fresh water, has become particularly attractive due to continuous innovations in the relevant technologies, leading to a very significant reduction of desalination costs.

Desalination, however, remains an energy intensive process. A future desalination strategy based only on the use of fossil fuelled systems is not sustainable: fossil fuel reserves are finite and must be conserved for more important uses such as transport, petrochemical industry etc. Besides, the demands for desalted water would continue increasing as population grows and standards of living improve. Conservation measures such as the modernization of water networks to minimize leakages, the recycling of used water etc. will certainly reduce the future water demands slightly but they would not be able to halt the dissemination of desalination plants and consequently of the fossil fuelled based systems for the production of needed electricity and heat.

The following paragraphs illustrate the damaging consequences of such a policy by taking the example of the Mediterranean region.

Many papers have already been published on desalination economics but a comprehensive study, based on the exhaustive analysis of a combination of energy sources and desalination processes, using state of the art economic models and realistic assumptions, is still quite rare. In addition, to our knowledge, the environmental costs of integrate desalination systems have so far been not integrated into the published costs.

The aim of this paper is to fulfill this gap with a view to provide clear choices of techno-economic options to decision makers in a wide range of countries be they from the developed regions or emerging countries. It is for this reason that the environmental impacts of selected systems are first analyzed and the corresponding costs are presented with and without the internalization of these external costs.

2. Environmental impact of desalination by fossil fuelled systems

2.1. Green house gas (GHG) emissions

Following the recent Blue Plan [1], the current balance (Balance 2) of the available water resources (1), based on the statistics from 1990 to 1998}, in some of the main countries of the Mediterranean region, is as shown in Table I.

The projected demands (2) for the year 2025 [8] are also included in Table I.

It is obvious that available natural water resources would rather decrease in 2025 because of increased pollution, over exploitation and other human activities. However, to keep matters simple, it would be supposed that they would remain at the same level as in 1998.

It can be observed that, in 2025, the total projected water deficit (balance) in the Mediterranean region would of the order of 294 km^3/per year. Not all this required capacity would be met by desalination plants. Current contribution of desalination is of the order of 1 to 2 %. If it is supposed that in 2025, this contribution would be about 2.5 %, then the total required desalting capacity would be 7.3 km^3/year (20.1 million m^3/day).

Table I. Balance of water resources and demands in some major Mediterranean countries

Country	Estimated natural water resources [2] (1)	Projected demands for 2025 [8] (2)	Balance (= 1-2)
	10^9 m^3/year	**10^9 m^3/year**	**10^9 m^3/year**
Algeria	2.25	12.3	-10.04
Cyprus	0.3	0.9	-0.6
Egypt	23	115	-92
France	35	50.0	-15
Greece	10	11.2	-1.2
Israel	0.7	2.8	-1.1
Italy	30	44.4	-14.4
Libya	0.6	14.2	-13.6
Morocco	1.4	20.3	-18.9
Spain	10	40.7	-30.7
Syria	2.5	28.7	-26.2
Tunisia	1	5.02	-4.02
Turkey	20	71.3	-51.3
Total	144.25	362.43	-293.57

The specific heat and electricity consumptions of three main desalination plants are given in Table II, [2].

Table II. Specific energy consumption of desalination plants

Process	Specific heat consumption	Specific electricity consumption)
	$kW_{th}.h/m^3$	**$kW_e.h/m^3$**
MSF	100	3
MED	50	2-3
RO	0	3.5 to 4.5

According to the EC ExternE study[1], the total emissions of GHG per MWe.h of electricity produced by representative fossil fuelled power plants in France are as presented in Table III.

[1] From the project report by A. Rable et al, www.externe.info,

Table III. GHG and particle emissions from some representative fossil fuelled plants

	Coal	Oil	Gas
Plant characteristics	Hypothetical new plant Pulverized fuel, flue gas, desulphurisation, steam turbine	Existing plant Low Sulphur oil Low NOx burner Steam turbine	Hypothetical, new, gas turbine, combined cycle plant
Plant size (**MWe**)	600	700	250
Annul production(GWe.h)	2100	1050	1500
Conversion efficiency (**%**)	38	39	52
Emissions (**g/kWe.h**)			
PM_{10}	0.17	0.13	0.04
CO_{2eq}	1085	866	433
SO_x	1.36	5.26	0.04
NO_x	2.22	1.2	0.71

The data presented in the above Tables allows to calculate the approximate[2] total GHG emissions produced by the fossil fuelled plants and the three desalination plants.

Results for a total desalting capacity of 20.1 million m^3/day are presented in Table IV.

Table IV. Estimated quantities of GHG emissions by diverse fossil fuelled plants and Desalination processes

Power Plant	MSF (Mt/year)				MED Mt/year)				RO (Mt/year)			
	CO_2	SO_x	NO_x	Particles	CO_2	SO_x	NO_x	Particles	CO_2	SO_x	NO_x	Particles
Coal fired	264.45	0.33	0.54	0.04	141.90	0.1779	0.2903	0.0222	32.25	0.04042	0.06559	0.00505
Oil fired	216.22	1.31	0.3	0.03	115.83	0.0.7036	0.1605	0.0174	25.74	0.15635	0,03567	0.00386
Gas turbine, CC	141.58	0.01	0.23	0.01	74.65	0.0.00781	0.1224	0.0069	12.87	0.00135	0.0211	0.00119

It can thus be concluded that for a desalting capacity of 20.1 million m^3/day in the Mediterranean region alone, required in 2025, one would produce, depending upon the energy source and the desalination process used,

13 to 264 million tonnes/year of CO_2.
1350 to 1 310 000 tonnes/year of SO_x.
21 100 to 540 000 tonnes/year of NO_x.
1190 to 40 000 tonnes/year of particles.

The potential levels of GHG and particle emissions on the world scale could then be more than double these figures.

These could naturally be avoided through the use of nuclear energy.

[2] In fact, the water source data as presented in Table 2 is based on the amount of water actually pumped in the countries mentioned

3. Impact of externalities on power and desalination costs

3.1. Background

An obvious corollary to the discussion on GHG are the costs related to the environment. It is now generally recognised that the production and consumption of energy and related activities is linked to a wide range of environmental and social problems such as the health effects of pollution of air, water and soil, ecological disturbances and species loss, and landscape damages. The costs of such damages are generally referred to as external costs or externalities.

An externality arises when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted or paid for by the main actors of the damages caused. In the particular case of energy production, fuel cycle externalities are the costs imposed on the society and the environment that are not accounted for (i.e. not integrated in the market accounting system) by the producers and consumers of energy.

In the context of European Commission's 5th FP (Framework Programme) ExternE project, a comparative evaluation has been made for the following technologies and fuel cycles:

– Fossil fuels: coal and oil technologies, with varying degrees flue gas cleaning, natural gas, centralised systems and CHP (combined production of heat and power) etc.
– Nuclear: A PWR, and associated Fuel cycle services, with and without reprocessing.
– Renewable: On-shore and offshore wind, hydro-electricity, a wide range of Biomass fuels (e.g. waste wood, crops) and technologies.

Results of comparison of damage costs/kWh for various technologies are presented in Table V.

This Table leads to the following conclusions:

– Results are extremely site dependent.
– In general, wind technologies are most environmentally friendly with respect to GHG pollutants and particles. However, not every site is appropriate for wind power generation, which has a definite cost regarding the noise.
– Nuclear generates the lowest external costs after the wind power, even when the low probability accidents with high consequences are integrated into the calculation. These results are generated for 0 % discount rates. At 3 % discount rate, the external costs by nuclear are lower.
– Photovoltaic is the cleanest technology regarding the use. It has, however, considerable life cycle impacts.
– Gas fired technologies are relatively clean.
– Coal technologies are the worst in view of the high generation of CO_2. They appear to have high impacts due to the primary –secondary aerosols.

Table V. External costs of electricity production in the EU from existing technologies (10^{-2} \$/kW.h*)

Country	Coal and lignite	Oil	Gas	Nuclear	Biomass	Hydro	Solar PV	Wind
Austria			1.3 to 3.8		2.5 to 3.8	0.13		
Belgium	5.1 to 19		1.3 to 2.5	0.64				
Denmark	5.1 to 8.9		2.5 to 3.8		1.3			0.13
Finland	2.5 to 5.1				1.3			
France	8.9 to 12.7	10.2 to 14.0	2.5 to 5.1	0.38	1.3	1.3		
Germany	3.8 to 7.6	6.4 to 10.2	1.3 to 2.5	0.25	3.81		0.76	0.063
Greece	6.4 to 10.2	3.8 to 6.4	1.3		0 to 1.01	1.3		0.32
Ireland	7.6 to 10.2							
Italy		3.8 to 7.6	3.8 to 7.6			0.38		
Netherlands	3.8 to 5.1		1.3 to 2.5	0,89	0.64			
Portugal	5.1 to 8.9		1.3 to 2.5		1.3 to 2.5	0.038		
Spain	6.4 to 10.2		1.3 to 2.5		3.8 to 6.4**			0.25
Sweden	2.5 to 5.1				0.38	0 to 0.89		
United Kingdom	5.1 to 8.9	3.8 to 6.4	1.3 to 2.5	0,32	1.3			0.19

*Sub-total of quantifiable externalities (global warming, public health, occupational health, material damage); on the basis of 1€ = 1.26959 \$.

**biomass co-fired with lignite

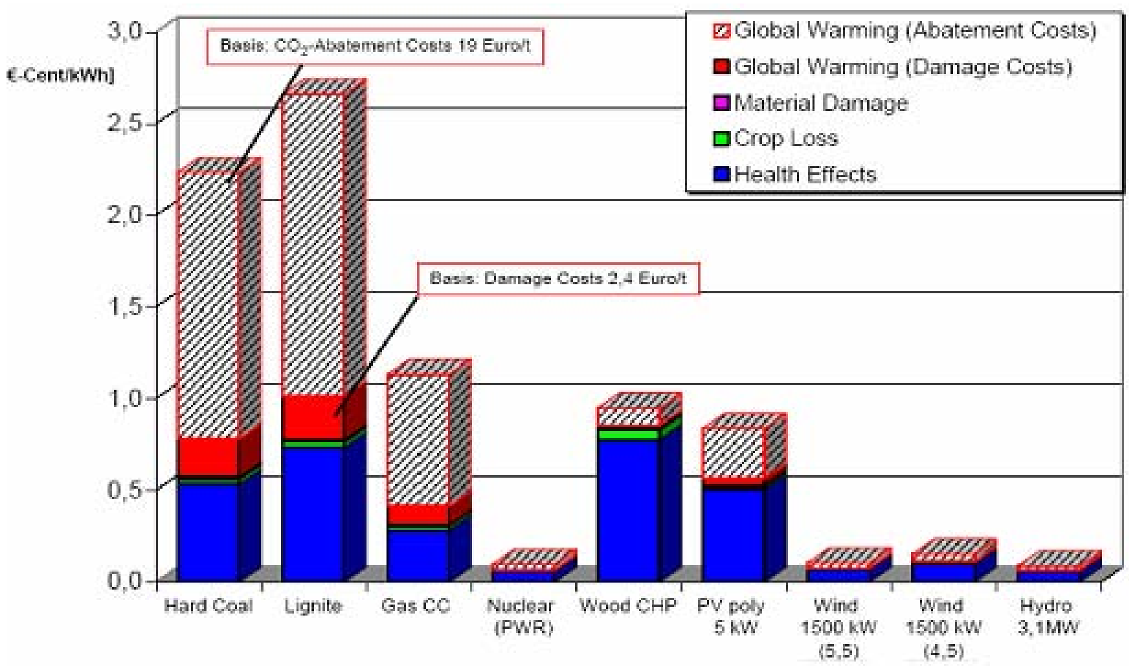

FIG. 1. External costs of power stations in Germany (CO_2 =19 euros/t, 1 year of life lost = 50 000 euros)

Figure 1[3] shows an illustrative example of the external costs from various power plants for selected sites in Germany, with 2010 technologies.

It is observed that for the fossil fuelled electricity systems, human health effects, acidification of ecosystems and the potential global warming impacts are the major sources of external costs. Although the analyzed power plants are all supposed to be equipped with abatement technologies, the emissions of SO_2 and NO_x due to the subsequent formation of sulphate and nitrate aerosols lead to considerable health risks.

External costs arising from the nuclear fuel cycle are significantly lower than those estimated for fossil fuel cycles.

External costs from renewable fuel cycles and hydropower mainly result from the use of fossil fuels for material supply and during the construction phase. External costs from current PV (photo voltaic) technologies are higher than nuclear and are close to that from the gas fired plants.

Impacts from wind and hydropower cycles are the lowest.

3.2. Internalisation of the power costs

A logical and sustainable way to permit the choice between various technologies is to integrate the external costs in the production costs of these technologies.

Taking the above external costs and current generating costs of electricity in Germany, one would thus obtain the results as shown in Fig. 2[4].

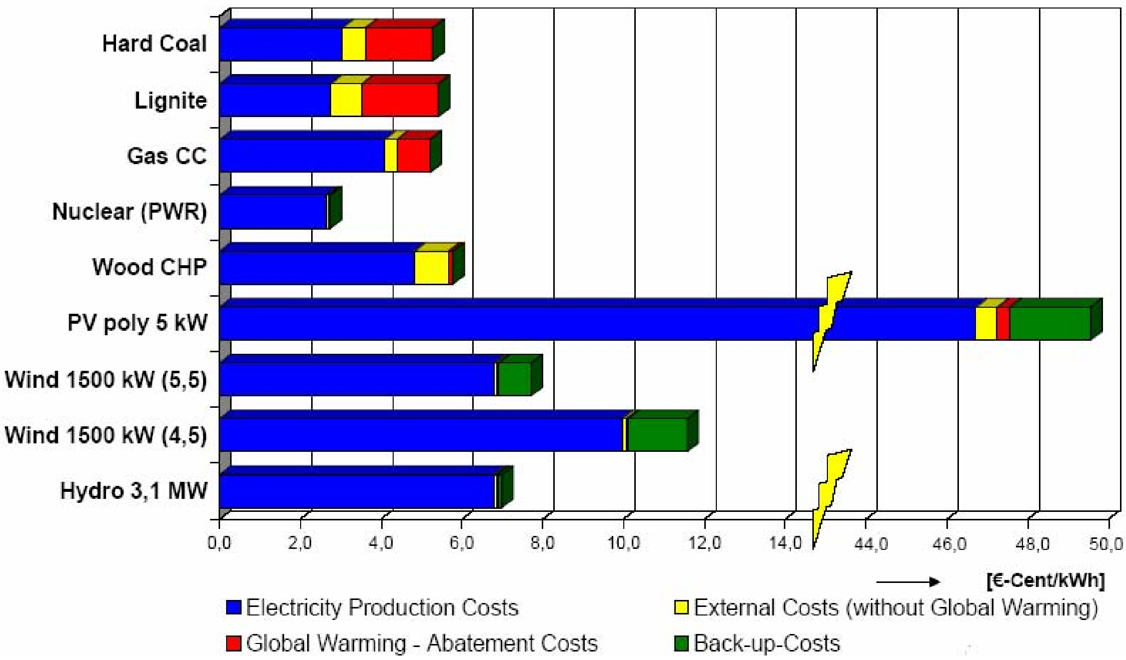

FIG. 2. Total costs of various electricity generating technologies in Germany

[3] From A. Voss, www.ier.uni-stuttgart.de
[4] From A. Voss, www.ier.uni-stuttgart.de

It is clearly seen that the power generation costs by renewable energies, especially by solar energy, is much higher than fossil energies or nuclear energy. It is also obvious that the full integration of external costs in the nuclear case would render it economically the most attractive option.

A future world desalination strategy would therefore be a mix of technologies, depending upon the particular conditions of a given county or site. The need for alternative sources of water would be such that all solutions would play an important role.

4. Evaluation of real power and desalination costs

All power and desalination costs have been calculated with the help of IAEA's DEEP code version-3, which was issued recently. Some of the models for MED and RO were modified and some others were replaced by CEA's own, more precise models.

4.1. Power costs

4.1.1. Basic assumptions

The nuclear power plants considered were four nuclear reactors: PWR-900, AP-600, GT-MHR and PBMR. For the purposes of realistic comparisons, we have also included three fossil fuelled power plants:

A 600 MWe circulating fluidized bed coal-fired plant (CFB-900).
A 900 MWe gas turbine combined cycle plant (CC-900).
A 500 MWe oil-fired turbine (OIL-500)

It is presumed that all installations will operate in 2015 and will be nth of a kind.
Data for the fossil fuelled systems is derived from the official reference prices in France as published by the Ministry of Economy, Finance and Industry [3].

The values given in [3] are in terms of 2001€. They were converted into 2006 $ as follows:
1 € = 1.26959 $ (as on 1/10/06)
2006 € = $(1.02)^{(2006\text{-}2001)}$

The range of oil and gas prices retained for our calculations was determined from the study of gas and oil price variations, from January 1, 2005 to June 2006, as given at the website: www.wtrg.com/daily/oilandgasspot.html. These prices have varied between 8 and 10 $/Mbtu (average of 7$/Mbtu) for gas, and between 58 and 60 $/bbl for oil. Similarly, according to www.cbs.nl/en-GB/menu/themas/bedrijfsleven/energie-water/publicaties, coal prices have varied, from1986 to 2006, between 45 and 80 $/t with an average of about 45 $/t most of the time.

The ensembles of calculation hypotheses are presented in Table VI.

Table VI. Main hypotheses used for power cost calculations. (Values updated to 2006 $)

Parameters	Units	Power plants						
		PWR-900*	AP-600*	GT-MHR**	PBMR**	CC-900*	CFB-900*	OIL-500*
Currency reference year		2006						
Interest/discount rate	%	5, 8 and 10						
Electrical power/unit	MWe	951	610	286.2	114.9	900	900	500
Number of units on site	-	1	1	2	5	1	1	1
Efficiency*	%	33	33	48.3	43.2	59.1	47.1	34.7
Plant availability*	%	91,2	91,2	91.2	91.2	94.5	90.2	90.2
Construction lead time	months	60	48	48	24	30	36	36
Plant life time	years	40	40	40	40	25	35	25
Specific construction costs	$/kWe	1763	2194	1055**	1530**	685	1500	368.6
Additional construction cost & contingencies	$/kWe	0	0	0	0	20	60	8.4
O&M cost	$/MW.h	10.4	10.4	3.25	3.1	5.9	7.8	4.44
Fossil fuel prices	$/Mbtu ($/t)	N/A	N/A	N/A	N/A	3.8, 7.4 and 11	(25, 45 and 65)	3.8, 7.4 and 11
Fossil fuel escalation rate	%/year	N/A	N/A	N/A	N/A	2	2	2
Nuclear fuel cycle costs	$/MW.h	7.2		8.01	5.1	N/A	N/A	N/A
External cost E1	$/kW.h	0.0025				0.013	0.038	0.064
External cost E2	$/kW.h	0.0038				0.051	0.127	0.14

* Expected values for 2015 [3]; ** updated values from those announced by respective constructors [4, 5]; E1: lower limit of the external costs in France and/or Germany; E2: upper limit of the external costs in France and/or Germany.

4.1.2. Results of conventional and nuclear power plant cost calculations

According to Table 5, above, the external costs in France and Germany for the coal fired plant would be from 3.8 to 12.7 $-cents/kWh, and for oil fired plants from 6.4 to 14 $-cents/kWh. For the gas turbine, combined cycle plant, these costs would vary from 1.3 to 5.1 $-cents/kWeh, where as for the nuclear plants they would be from 0.25 to 0.38 $/kWeh. For wind and solar energies, the external costs are respectively 0.76 and 0.05 $-cents/kWh. For the purposes of comparison, no backup costs will be included.

To integrate the effects of externalities, it would thus suffice to make a sensitivity study, in which the calculated power costs would be augmented by the above amounts. It would be assumed that external costs are not affected by discount rate variations nor by fossil fuel prices or by different reactor types. The lower and upper limits of the external costs, as observed in France and Germany or each type of plant would be hereafter respectively referred to as E1 and E2, with the corresponding values from Table V.

It should be recalled that these costs are based on CO_2 abatement cost of about 19 $/t CO_2. Presently many authors assume much higher values, but in the absence of well agreed international values, we shall retain the one considered in the ExterneE study.

The new power production costs of the CFB-600, the CC-900 and OIL-500 plants are respectively given in Tables VII to IX. Those for the nuclear reactors are presented in Table X.

Table VII. Electricity production costs by the CFB-900 coal-fired plant

Parameters	Units									
Annual production	GWh/y	7111								
Coal price at start up	$/MBtu	0.9			1.62			2.34		
	$/t	25			45			65		
Disc. rate	%	5	8	10	5	8	10	5	8	10
Spec. invest. cost	**$/kWe**	1678	1751	1800	1678	1751	1800	1678	1751	1800
KWh costs (in 10^{-2} $/kWh)										
Investment		1.2973	1.9013	2.3618	1.2973	1.9013	2.3618	1.2973	1.9013	2.3618
Fuel		1.3078	1.2463	1.2133	2.3541	2.2434	2.184	3.4003	3.2404	3.1546
O&M		0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Total		**3.3851**	**3.9276**	**4.3551**	**4.4314**	**4.9247**	**5.3258**	**5.4776**	**5.9217**	**6.2964**
Total with E1									**9.722**	
Total with E2									**18.622**	

Table VIII. Electricity production costs by the gas turbine combined cycle plant, CC-900

Parameters	Units									
Annual production	GWh/y	7450								
Gas price	MBtu	3.79	7.36	11.04						
	$/toe	151.1	293.2	439.8						
	$/bbl	20.62	40	60						
Disc. rate	%	5	8	10	5	8	10	5	8	10
Spec. invest. cost	**$/kWe**	749	776	794	749	776	794	749	776	794
KWh costs (in 10^{-2} $/kWh										
Investment		0.6423	0.8784	1.0569	0.6423	0.8784	1.0569	0.6423	0.8784	1.0569
Fuel		3.6483	3.5627	3.4967	7.0773	6.8917	6.7831	10.6150	10.3376	101747
O&M		0.59								
Total		**4.8806**	**0.05021**	**5.144**	**8.310**	**8.360**	**8.430**	**11.848**	**11.806**	**11.822**
Total with E1									**13.106**	
Total with E2									**16.906**	

Table IX. Electricity production costs by the OIL-500 plant

Parameters	Units									
Ann. Elec. Prod.	GWh/y	3951								
Oil price	$/MBtu	3.79			7.36			11.04		
	$/bbl	20.62			40			60		
Discount rate	%	5	8	10	5	8	10	5	8	10
Spec. invest. cost	**$/kWe**	396	407	415	396	407	415	396	407	415
KWh costs (in 10^{-2} $/kWh)										
Investment		0.3555	0.4828	0.5783	0.3555	0.4828	0.5783	0.3555	0.4828	0.5783
Fuel		4.6516	4.5297	4.4583	9.0235	8.7869	8.6485	13.5353	13.1804	12.9727
O&M		0.444								
Total		5.4511	5.4565	5.481	9.823	9.7137	9.6708	14.3348	14.1072	13.995
Total with E1									**20.5072**	
Total with E2									**28.1072**	

Table X. Electricity production costs of selected nuclear reactors

Parameters	Units	PWR-900			AP-600			GT-MHR*			PBMR**		
Annual production	GWe.h	7598			4873						2714		
Net electrical power	MWe	1 X 951			1 X 610			2 X 286			5 X 114.9		
Discount rate	%	5	8	10	5	8	10	5	8	10	5	8	10
Specific investment cost	$/kWe	1992	2137	2237	2419	2559	2655	1163	1231	1277	1607	1652	1683
		kW.h costs (in 10^{-2} $/kW.h)											
Investment.		1.4529	2.2432	2.8638	1.7645	2.6862	3.398	0.8485	1.2917	1.6340	1.1719	1.7345	2.1542
Fuel cycle cost		0.72			0.72			0.801			0.51		
O&M		1.04			1.04			0.325			0.31		
Decommissioning		***			***			0.6820			0.6820		
Total		3.2129	4.003	4.6238	3.5245	4.4462	5.158	2.6565	3.0997	3.442	2.6739	3.2365	3.6562
Total with E1			**4.2532**			**4.6962**			**3.3497**		**3.4865**		
Total with E2			**4.3832**			**4.8262**			**3.4797**		**3.6165**		

* According to its developers [4]; kWh cost, as estimated by DEEP-3, includes additional site related construction cost and the dismantling cost (= 0,7% of the construction cost)

** According to PBMR company [5]; kWh cost, as estimated by DEEP-3, includes additional site related construction cost and the dismantling cost

*** Decommissioning cost included in the specific construction cost.

4.2. Desalination cost calculations

4.2.1 Calculation hypotheses

The desalination costs were obtained from the DEEP3 code for various combinations of power plants and desalination processes. With the exception of the two HTRs, all other energy sources have been coupled to MED and RO systems. Furthermore, the combinations such as the GT-MHR + RO and the PBMR + RO are not calculated because we believe that the main interest of these two reactors lies in the utilization of waste heat. The costs with the RO process, which only requires electricity, would be in direct proportion to the electricity costs of these reactors compared to the other two PWRs.

There are at present no models in the DEEP-3 code for the utilization of waste heat from the GT-MHR and the PBMR. These models were separately developed at CEA [6] and then used in DEEP-3 as follows:

- Adaptation of the DEEP-3 mode (NBC[5] + MED case) to calculate the power costs of the GT-MHR and the PBMR from the economic data provided by [4, 5].
- Calculation of the total amount of waste heat that can be transferred to a MED plant coupled to these two reactors through an intermediate circuit.
- Input of these values of the total heat in the modified DEEP-3 models to obtain the desalination costs. Because the waste heat is evacuated to the heat sink in any case, it was assumed that the heat cost in the models was zero.

The main hypotheses of the desalination costs calculations are given below:

Average seawater temperature = 21°C.

Average seawater salinity = 38375 ppm.

Only the combinations of all renewable energy sources with RO systems have been considered. Due to the fact that solar photovoltaic and wind energy don't produce waste heat the combinations PV + MED and W + MED are not considered.

The combinations of power sources and the desalination plants are summarized in Table XI:

Table XI. Calculated integrated desalination systems

Energy source	Desalination process	
	MED	RO
PWR-900	X	X
AP-600	X	X
GT-MHR	X	
PBMR	X	
CFB-900	X	X
CC-900	X	X

[5] NBC Nuclear Brayton Cycle

4.2.2 MED desalination cost results

The results of desalination cost calculations, with and without the effect of external costs, are presented in Tables XII to XIV for the fossil fuelled plants and Tables 15 for the nuclear power plants, all coupled to MED plants.

Table XIIa. Desalination cost for the CFB-900 +MED system, **without externalities**.

Coal Price	$/t	**25**			**45**			**65**		
	$/MBtu	0.9			1.62			2.34		
Discount rate	%	5	8	10	5	8	10	5	8	10
Production	m^3/day	97 416								
Water plant const cost	M$	133.5								
Water plant investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7	139.6	143.2	145.7
Annual plant O&M cost	M$/year	4.3								
Annual plant heat cost	M$/year	6	7	7.7	7.8	8.7	9.4	9.7	10.5	11.1
Annual plant electricity cost	M$/year	3.2	3.7	4.1	4.1	4.6	5	5.1	5.5	5.9
Water cost	**$/m^3$**	**0.6570**	**0.7971**	**0.9035**	**0.7366**	**0.8729**	**0.9774**	**0.8161**	**0.9487**	**1.0512**

Table XIIb. Desalination cost for the CFB-900 +MED system, at 8 % discount rate, **with externalities**.

Coal Price	$/t	**65**	
	$/MBtu	2.34	
External cost		E1	E2
	cents/kWe.h	3.8	12.7
Total electricity cost	cents/kWe.h	9.7217	18.6217
Annual plant heat cost	M$/year	17.2	33
Annual plant electricity cost	M$/year	9.1	17.4
Water cost	**$/m^3$**	**1.2378**	**1.9147**

Table XIIIa. Desalination costs by the CC-900 +MED system, **without externalities**

Coal Price	$/bbl	**20.62**			**40**			**60**		
	$/toe	151.1			293.2			439.8		
	$/MBtu	3.79			7.36			11.04		
Production	m^3/day	97 416								
Discount rate	%	5	8	10	5	8	10	5	8	10
Water plant const cost	M$	133.5								
Water plant investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7	139.6	143.2	145.7
Annual plant O&M cost	M$/year	4.5								
Annual plant heat cost	M$/year	9.9	13.4	16	15.42	15.51	15.64	21.98	21.9	21.93
Annual plant electricity cost	M$/year	4.77	4.91	9.54	8.13	8.18	8.25	11.59	11.55	11.56
Water cost	**$/m^3**	**0.7566**	**0.8617**	**0.9416**	**1.0174**	**1.1156**	**1.1915**	**1.2866**	**1.3777**	**1.4495**

Table XIIIb. Desalination cost for the CC-900 +MED system, at 8 % discount rate, **with externalities**.

Coal Price	$/t	**65**	
	$/MBtu	2.34	
External cost		E1	E2
	cents/kWe.h	1.3	5.1
Total electricity cost	cents/kWe.h	13.106	16.906
Annual plant heat cost	M$/year	24.31	31.36
Annual plant electricity cost	M$/year	12.82	16.54
Water cost	**$/m^3**	**1.4766**	**1.7656**

Table XIVa. Desalination costs by the OIL-500 +MED system, **without externalities**

Oil Price	$/bbl	**20.62**			**40**			**60**		
	$/toe	151.1			293.2			439.8		
	$/MBtu	3.79			7.36			11.04		
Production	m^3/day	97 416								
Discount rate	%	5	8	10	5	8	10	5	8	10
Water plant const cost	M$	133.5								
Water plant investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7	139.6	143.2	145.7
Annual plant O&M cost	M$/year	4.3								
Annual plant heat cost	M$/year	9.7	9.7	9.7	17.4	17.2	17.1	25.4	25	24.8
Annual plant electricity cost	M$/year	5.1	5.1	5.1	9.2	9.1	9.0	13.4	13.2	13.1
Water cost	**$/m³**	**0.8141**	**0.9134**	**0.9891**	**1.1466**	**1.2372**	**1.3078**	**1.4898**	**1.5713**	**1.6367**

Table XIVb. Desalination cost for the OIL-500 +MED system, at 8 % discount rate, **with externalities**.

Coal Price	$/bbl	**60**	
	$/MBtu	11.04	
External cost		E1	E2
	cents/kWe.h	6.4	14.0
Total electricity cost	cents/kWe.h	20.5072	28.1072
Annual plant heat cost	M$/year	36.3	49.8
Annual plant electricity cost	M$/year	19.1	26.2
Water cost	**$/m³**	**2.0581**	**2.6361**

Table XVa. Desalination cost for the nuclear reactors coupled to MED, with and without externalities

Parameters	Units	PWR-900			AP-600			GT-MHR*			PBMR*		
Average daily production	m^3/day	98496			98496			47526			52 292		
Discount rate	%	5	8	10	5	8	10	5	8	10	5	8	10
construction cost	M$	147.1			147.1			73.6			88.3		
Investment cost	M$	153.9	157.9	160.6	153.9	157.9	160.6	76.2	77.7	78.7	91.6	93.5	94.8
Annual O&M cost	M$/year	4.4			4.4			2.3			2.5		
Annual heat cost	M$/year	5.8	7.2	8.3	6.3	8	9.2	0			0		
Annual electricity costs	M$/year	3.2	4.0	4.6	3.5	4.5	5.2	1.3	1.6	1.7	1.6	1.9	2.2
Water cost	**$/m^3**	**0.6758**	**0.8451**	**0.9739**	**0.7001**	**0.8795**	**1.0155**	**0.5209**	**0.6418**	**0.7320**	**0.5579**	**0.6942**	**0.7957**

* Production lower than the PWRs because using waste heat only

Table XVb. Desalination cost for the Nuclear +MED system, at 8 % discount rate, **with externalities**.

		PWR900+MED		AP-600+MED		GT-MHR+MED		PBMR+MED	
		E1	E2	E1	E2	E1	E2	E1	E2
External cost	Cents /kWeh	0.25	0.38	0.25	0.38	0.25	0.38	0.25	0.38
Total electricity cost	Cents /kWeh	4.2532	4.3832	4.6962	4.8262	3.3497	3.4797	3.4865	3.6165
Annual plant heat cost	M$/year	7.6	7.8	8.4	8.6	0	0	0	0
Annual plant electricity cost	M$/year	4.3	4.4	4.7	4.9	1.7	1.7	2.1	2.2
Water cost	**$/m^3**	**0.86447**	**0.87458**	**0.89894**	**0.90904**	**0.64901**	**0.65277**	**0.70207**	**0.70615**

4.2.3 RO desalination cost results

The results of desalination cost calculations, with and without the effect of external costs, are presented in Tables XVI to XVIII for the fossil fuelled plants and Tables 19 for the nuclear power plants, all coupled to RO plants.

Table XVIa. Desalination cost for the CFB-900 +RO system, **without externalities**.

Coal Price	$/t	**25**			**45**			**65**		
	$/MBtu	0.9			1.62			2.34		
Discount rate	%	5	8	10	5	8	10	5	8	10
Production	m^3/day	108 000								
Water plant const cost	M$	133.5								
Water plant investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7	139.6	143.2	145.7
Annual plant O&M cost	M$/year	5.98								
Annual plant electricity cost	M$/year	4.3	4.9	5.5	5.6	6.2	6.7	6.9	7.4	7.9
Annual purchased power cost	M$/year	0.5								
Water cost	**$/m^3**	**0.5227**	**0.6291**	**0.7095**	**0.5561**	**0.6609**	**0.7404**	**0.5894**	**0.6928**	**0.7714**

Table XVIb. Desalination cost for the CFB-900 +RO system, at 8 % discount rate, **with externalities**.

Coal Price	$/t	**65**	
	$/MBtu	2.34	
External cost		E1	E2
	cents/kWeh	3.8	12.7
Total electricity cost	cents/kWeh	9.7217	18.6217
Annual plant electricity cost	M$/year	12.2	23.4
Water cost	**$/m^3**	**0.814**	**1.0979**

Table XVIIa. Desalination costs by the CC-900 + RO system, **without externalities**

Coal Price	$/bbl	**20.62**			**40**			**60**		
	$/toe	151.1			293.2			439.8		
	$/MBtu	3.79			7.36			11.04		
Production	m^3/day	97 416								
Discount rate	%	5	8	10	5	8	10	5	8	10
Water plant const cost	M$	133.5								
Water plant investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7	139.6	143.2	145.7
Annual plant O&M cost	M$/year	5.98								
Annual plant electricity cost	M$/year	6.4	6.6	6.8	10.9	11	11.1	15.6	15.6	16
Annual purchased power cost	M$/year	0.1								
Water cost	**$/m³**	**0.5687**	**0.6625**	**0.7333**	**0.6833**	**0.7741**	**0.8432**	**0.8016**	**0.8893**	**0.9565**

Table XVIIb. Desalination cost for the CC-900 + RO system, at 8 % discount rate, **with externalities**.

Coal Price	$/bbl	**60**	
	$/MBtu	11.04	
External cost		E1	E2
	cents/kWeh	1.3	5.1
Total electricity cost	cents/kWeh	13.106	16.906
Annual plant electricity cost	M$/year	17.3	22.3
Water cost	$/m³	0.9328	1.0598

Table XVIIIa. Desalination costs by the OIL-500 + RO system, **without externalities**

Oil Price	$/bbl	20.62			40			60		
	$/toe	151.1			293.2			439.8		
	$/MBtu	3.79			7.36			11.04		
Production	m^3/day	108 000								
Discount rate	%	5	8	10	5	8	10	5	8	10
Water plant const cost	M$	133.5								
Water plant investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7	139.6	143.2	145.7
Annual plant O&M cost	M$/year	5.98								
Annual plant electricity cost	M$/year	6.9	6.9	6.9	12.4	12.2	12.2	18	17.7	17.6
Annual purchased power cost	M$/year	0.5								
Water cost	**$/m³**	**0.5889**	**0.6779**	**0.7454**	**0.7281**	**0.8137**	**0.879**	**0.872**	**0.9539**	**1.017**

Table XVIIIb. Desalination cost for the OIL-500 + RO system, at 8 % discount rate, **with externalities**.

Coal Price	$/bbl	**60**	
	$/MBtu	11.04	
External cost		E1	E2
	cents/kWe.h	6.4	14.0
Total electricity cost	cents/kWe.h	20.5072	28.1072
Annual plant electricity cost	M$/year	25.8	35.5
Water cost	$/m^3	1.1581	1.4005

Table XIXa. Desalination cost for the nuclear reactors coupled to RO, with and **without externalities**

Parameters	Units	PWR-900			AP-600		
Average daily production	m^3/day	108 000					
Discount rate	%	5	8	10	5	8	10
construction cost	M$	133.5					
Investment cost	M$	139.6	143.2	145.7	139.6	143.2	145.7
Annual O&M cost	M$/year	5.98					
Annual electricity costs	M$/year	4.1	5.1	5.9	4.5	5.7	6.6
Annual purchased power cost	M$/year	0.4					
Water cost	**$/m^3**	**0.5162**	**0.6308**	**0.7176**	**0.5263**	**0.6451**	**0.7348**

Table XIXb. Desalination cost for the nuclear +RO system, at 8 % discount rate, **with externalities**.

		PWR900		AP-600	
		E1	E2	E1	E2
External cost	Cents /kWeh	0.25	0.38	0.25	0.38
Total electricity cost	Cents /kWeh	4.2532	4.3832	4.6962	4.8262
Annual plant electricity cost	M$/year	5.4	5.6	6.0	6.1
Water cost	**$/m^3**	**0.6389**	**0.6431**	**0.6532**	**0.6574**

5. Discussion of the results

For purposes of the comparison of desalination costs by all the power sources considered, the results are summarised in Tables 20 and 21 for 8% discount rate, with the average current prices for fossil fuels in the world markets. The figures in parentheses give the differences (in %) as compared to the desalination cost of the CFB-900 as reference, since it is the least expensive fossil fuelled option (without externalities). These differences are calculated for a given process as :

Δ = 100 X [desalination cost (reactor- CFB-900)/ desalination cost CFB-900].

Table XX. MED water costs with/without externalities in France and Germany; 8% discount rate

	CFB-900	CC-900	OIL-500	PWR-900	AP-600	GT-MHR	PBMR
Water costs ($/m3)	0.9487	1.3777	1.5713	0.84505	0.8795	0.6418	0.6942
Δ (%)		**+45**	**+66**	**-10**	**-7**	**-32**	**-27**
Water costs E1 ($/m^3)	1.2378	1.4766	2.0581	0.86447	0.8989	0.6490	0.7021
Δ (%)		**+19**	**+66**	**-30**	**-27**	**-48**	**-43**
Water costs E2 ($/m^3)	1.9147	1.7656	2.6361	0.87458	0.9090	0.6528	0.7062
Δ (%)		**+7.8**	**+38**	**-54**	**-52**	**-65**	**-63**

Table XXI. RO water costs with/without externalities in France and Germany; 8% discount rate

	CFB-900	CC-900	OIL-500	PWR-900	AP-600
Water costs ($/m^3)	0.6928	0.8896	0.9539	0.63084	0.6451
Δ (%)		**+28**	**+38**	**-8.9**	**-6.9**
Water costs E1 ($/m^3)	0.8140	0.93276	1.1581	0.63891	0.6532
Δ (%)		**+14.6**	**+42**	**-22**	**-20**
Water costs E2 ($/m^3)	1.0979	1.05976	1.4005	0.6431	0.6574
Δ (%)		**+-3**	**+28**	**-41**	**-40**

The above Tables lead to the following observations:

- Because of rather low external values for nuclear systems, their power costs are least affected by the internalization of environmental costs (5 to 10%).
- The power costs of fossil fuelled systems are strongly affected by the internalization. The highest change is in coal fired plant in which the power costs are almost doubled and tripled when the external costs E1 and E2 are internalized.
- The coal based system, CFB-900, leads to the lowest power costs in normal conditions and with the internalization of E1. The tendency is reversed with E2 for the CC-900 plant. The oil-fired plant has the highest costs in all cases.
- The power costs of nuclear options are 24 to 45% lower than the power cost of the CFB-900 in normal conditions. They are 51 to 64% lower in E1 scenario and 74 to 80% lower in E2 scenario.
- The desalination costs are also influenced by these power cost differences although the corresponding decreases in the water costs are not directly proportional to the differences in power costs.
- Thus, compared to the CFB-900 + MED system, the desalination costs of the integrated MED plants with nuclear reactors are respectively 7 to 32% lower in normal conditions, 27 to 48% lower in the E1 scenario and 52 to 65 % lower in the E2 scenario
- The lowest costs with the MED plants are obtained by the GT-MHR and the PBMR, utilising virtually free waste heat. Compared to the cost by the CFB-900 +MED system, these reactors coupled to MED give desalination costs, which are respectively 32 % and 27 % lower in normal conditions.
- Compared to the CFB-900 + RO system, the corresponding desalination costs by the PWR-900 + RO and AP-600 + RO are respectively 8.9 and 6.9 % lower. In the E1 scenario, these costs are 22 and 20% lower. The differences increase to 40 to 41 % in the E2 case.
- For all energy sources considered, the desalination costs with RO are 25 to 40% lower than those with MED

6. Financial analysis[6]

6.1. The profitability study

The financial analysis of the above cases was performed in order to evaluate their economic profitability.

The profitability study of a given project is realized using three main criteria, which are: the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Pay-Back Period (PBP). The profitability study of a given project requires the estimation of the net cash flows generated by the project's operation [7]. It is to be noted that energy tariffs are to be fixed by the energy utility in a given country (or site) and water tariffs are fixed by the corresponding water utility. Table 22 shows the calculation of net cash flows in case of the combination PBMR+MED system, assuming hypothetical but realistic values of the tariffs, which are obviously commercial confidential**.**

The hypothesis concerning water and energy tariffs was fixed relatively to the starting date of the plant (2015). It is supposed that, till this date, the tariffs will be escalated at a rate of 3%.

The current average water and energy tariffs are respectively assumed to be 1.70 $/m3 and 0.15 $/kWh. Then, the tariffs at 2015 will be:

⇨ Water tariff (2015) = current water tariff x $(1.03)^{2015\text{-}2006}$ = 1.7 x $(1,03)^{9}$ = 2.2 $/m3.
⇨ Energy tariff (2015) = current energy tariff x $(1.03)^{2015\text{-}2006}$ = 0.15 x $(1,03)^{9}$ = 0.2 $/kWh.

Since we do not have the exact escalation rates of water and energy tariffs during the project operation, a sensitivity study was realized on the basis of 3 hypotheses: 1/ tariff escalation rate of 0% per year; 2/ tariff escalation rate of 1% per year; and 3/ tariffs escalation rate of 2% per year.

We will then have 3 scenarios:
- Case 1: Production capacity = 72 000 m^3/d / Tariffs escalation rate = 0%;
- Case 2: Production capacity = 72000 m^3/d / Tariffs escalation rate = 1%;
- Case 3: Production capacity = 72000 m^3/d / Tariffs escalation rate = 2%;

[6] Work performed in partial fulfilment of the Ph.D.G thesis, jointly directed by CEA and the Grenoble University

Table XXII. Cash flows estimation for the case PBMR+MED

Estimation of water and energy sales:

	2011	2012	2013	2014	2015e	2016e	2017e	2018e	2019e
Water production (Mm3)					19	19	19	19	19
Water tariff ($/m3)					4,30	4,34	4,39	4,43	4,47
Water sales (M$)					**82**	**83**	**84**	**85**	**85**
Energy production (GW(e)h)					4 530	4 530	4 530	4 530	4 530
Energy tariff ($/kWh)					0,200	0,202	0,204	0,206	0,208
Energy sales (M$)					**906**	**915**	**924**	**933**	**943**

Cash Flow estimation

M$ / year	2011	2012	2013	2014	2015e	2016e	2017e	2018e	2019e
Turnover (water)					82	83	84	85	85
Turnover (energy)					906	915	924	933	943
Total Operating income					**988**	**998**	**1 008**	**1 018**	**1 028**
Operating expenses for Energy component:					***38***	***38***	***38***	***38***	***38***
Annual fuel cost					23	23	23	23	23
Operation and maintenance (O&M) costs					14	14	14	15	15
Operating expenses for water component:					***13***	***13***	***13***	***13***	***13***
Heat cost					0	0	0	0	0
Operation and maintenance (O&M) costs					3	3	3	3	3
Annual water plant electric power cost					2	2	2	2	2
Annual purchased electric power cost					0	0	0	0	0
Fixed expenses					9	9	9	9	9
Total Operating expenses					**51**	**51**	**51**	**51**	**52**
Earnings Before Interest Taxes and Amortization	**0**	**0**	**0**	**0**	**937**	**947**	**957**	**967**	**977**
(EBITA - Amortization) * Taxes					320	323	326	330	333
Working capital requirements									
Operating cash flows	**0**	**0**	**0**	**0**	**618**	**624**	**630**	**637**	**643**
Net investment costs	237	239	325	330					
Total construction costs	220	220	282	246					
Construction cost of power plant	220	220	220	220					
Construction cost of desalination plant	0	0	62	26					
Interest During Construction (IDC)	18	19	43	84					
Net cash flows	**-237**	**-239**	**-325**	**-330**	**618**	**624**	**630**	**637**	**643**

NPV (8%)	**4991**
IRR	**35,4%**
PBP (8%)	**7 ans**

If we choose the case 2 (production capacity of 72000 m^3/d and tariffs escalation of 1% per year), the results of the profitability study would be as presented in tables 24 and 25, respectively for nuclear options and for fossil energy options. The fuel price retained for the study is 65$/t for coal and 60$/bbl for the CC plant. These are the current prices averaged over a year. We do not consider the oil fired plant because it has already been shown that it is too expensive. For all cases, the discount rate is 8% is retained.

Table XXIII. Results of the profitability study for the nuclear desalination options

	PWR900		AP600		GTMHR	PBMR
	MED	**RO**	**MED**	**RO**	**MED**	**MED**
NPV (M$)	6326	6584	4352	4636	4896	4742
IRR (%)	26.9	27.5	28.2	29.4	43	34.4
PBP (yrs)	9	9	9	9	6	7

Table XXIV. Results of the profitability study for the fossil fuelled option

	CFB-900		CC-900	
	MED	**RO**	**MED**	**RO**
NPV (M$)	6066	6351	3076	3636
IRR (%)	33.1	34	37.3	41.7
PBP (yrs)	6	6	6	6

We note from these results that:

- The NPV of all combinations are positives, which means that these projects are all profitable.
- The most interesting combinations are those with PWR900 and CFB-900, and the least advantageous option is with CC900:

  NPV of PWR900+MED (6326M$) > NPV of CC900+MED (3076M$).

  NPV of GTMHR+MED (4896M$) > NPV of PBMR+MED (4742M$).
- Based on IRR criteria, the most profitable are GTMHR+MED (IRR=43%) and CC900+RO (IRR=41,7%). But, as is widely known, the NPV criteria is the most reliable.

However, we have to take into account the differences in the initial investments of these coupling schemes. For example, the investment cost of PWR900+MED is 2190M$ while that of GTMHR+MED is only 782M$.

That's why we used a supplementary criterion called the Profitability Index (PI), which is equal to the present value of the future cash flows divided by the initial investment. It's also called the benefit cost ratio. The higher is the profitability index the more profitable is the project.

The PI of the nuclear desalination options and those of the fossil fuelled options are respectively shown in tables XXV and XXVI.

Table XXV. The profitability index for the nuclear desalination options

	PWR900		AP600		GTMHR	PBMR
	MED	RO	MED	RO	MED	MED
PI	3.89	4.03	3.53	3.72	7.26	5.55

Table XXVI. The profitability index for the fossil fuelled options

	CFB-900		CC-900	
	MED	RO	MED	RO
PI	4.53	4.69	4.65	5.32

Basing the analysis on the PI criteria, which is more realistic, we find that the coupling schemes GTMHR+MED and PBMR+MED are the most profitable. Their profitability indices are respectively of 7.26 and 5.55. The combinations with CC-900 become more profitable than those with CFB-900. For example, the PI of CC900+RO is 5.32 while the PI of CFB-900 + RO is of 4.69.

7. Conclusions

Integrated seawater desalination systems are likely to deployed intensively in the future in view of the very large demands for water and electrical energy in many regions of the world.

A future desalination strategy based uniquely on the utilization of fossil fuelled systems is not sustainable because of the very large amounts of greenhouse gas emissions from both power generation and desalination. At the moment, the only solution to avid GHG for integrated desalination systems appears to be the use of nuclear and renewable energies.

This paper presents a detailed comparative economic study of selected nuclear reactor systems, coupled to well known desalination processes such as the MED and RO. To quantify the relative interest of nuclear systems, power and desalination costs have been compared with three commonly used fossil fuelled plants using coal, gas (combined cycle) and oil.

For the same reason, two renewable energy based systems using solar and wind power have been included.

The economic comparisons have been made in two conditions: without the internalization of calculated environmental costs and with the external costs included in the electricity and heat costs. A range of fossil fuel prices has been considered.

Awaiting an international consensus on Eco-taxes, a rather low value of the CO2 tax has been assumed (19 €/t) as an illustrative example.

Result show that in all conditions, the desalination costs of nuclear options are 10 to 80% lower as compared to the cheapest of fossil fuelled options: the coal fired plant, CFB-900, using state of the art improvements and current coal prices of 60 $/t.

Internalization of the external costs hardly affects the power and desalination costs by nuclear systems but strongly influences those by the fossil fuelled systems.

A financial analysis of the above systems confirmed the economic results. Thus for example, we find that the coupling schemes GTMHR+MED and PBMR+MED are the most profitable. Their profitability indices are respectively of 7.26 and 5.55. The combinations with CC-900 become more profitable than those with CFB-900. For example, the PI of CC900+RO is 5.32 while the PI of CFB-900+RO is 4.69.

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Economic evaluation of nuclear desalination in the northeastern region of Brazil.

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Eletronuclear – Brazil

Abstract. This paper deals with evaluation of economic viability of the nuclear desalination process in the northeastern region of Brazil. A comparison is made with desalination using natural gas as fuel source. Based on geopolitical and social factors, the state of Ceara was selected as the best site for the nuclear desalination plant. Due to higher capital investments for nuclear desalination it was found less competitive to natural gas alternative even though the nuclear fuel has a much lower price than natural gas fuel. In a medium or long-term strategy decrease in capital and operational investment for nuclear plants and increase in natural gas fuel cost may make the nuclear option attractive.

1. Introduction

Although nearly 70% of the planet is covered by water, in reality 97,5% of all water that exists on earth is salted, remaining just 2,5% as fresh water. Approximately 70% of this fresh water is frozen in the ice caps of Antarctica and Greenland and the remaining relies as humidity in soil or in deep underground sources not accessible to human consumption. As result less than 1% of the fresh water, or more precisely 0,007% of all water on earth, is accessible for human needs. This is the water that is easily found in rivers, lakes, reservoirs and underground sources on an acceptable cost. This amount is regularly renewed by rain and snowfall and is accessible in a sustainable basis.

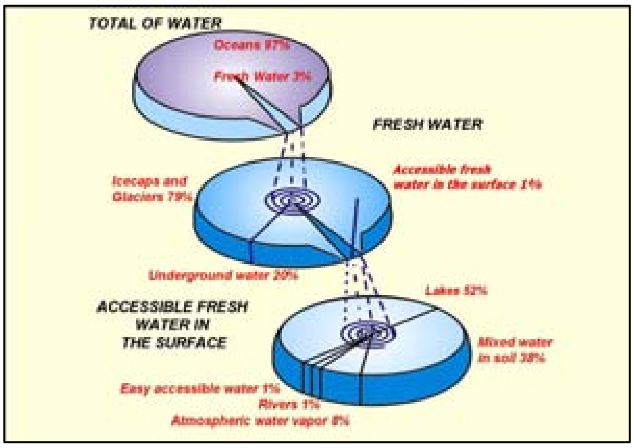

FIG. 1. Water distribution in the world

According to the Food and Agriculture Organization of the United Nations [6] approximately 65% of the fresh water used in the planet is dedicated to agriculture and the remaining 35% are shared by the industry, domestic use and losses as can be seen in Fig. 2 below:

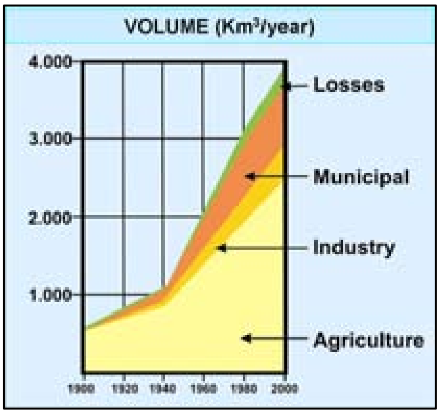

FIG. 2. Use of water in the world

Considering a population increase of 50% in the next 50 years and the associated increase in water demand as consequence of economic growth and changes in life style, it is possible to conclude that there will be no sufficient water for the expected consumption. Water must also remain in rivers to keep ecosystems healthy, allow fishing activities, navigation, and electricity generation. For all these human requirements, it must be preserved and carefully used. When a global evaluation is performed, even today, some countries still have large amounts of water resources per capita while others are already facing serious difficulties. Future increments in demand due to population increase and economic activities will certainly worsen the present situation.

As result of this unequal global availability, fresh water shortage is a reality today in many countries as well as in semi arid and arid regions of the world. The great variability that now can be noticed between seasons is another factor that only contributes to the water scarcity generally when it is most needed.

This is exactly the case in the northeastern region of Brazil. Although large water resources are available in other regions of the country, the northeastern has always had serious problems with water shortage mainly in its interior where many social problems are consequence of this fact.

Historically many alternatives were tried to overcome this problem but most of the results were not successful as expected.

Seawater desalination will be the focus of this work and it is a proved process to obtain fresh water for human use. There are no technical reasons that could avoid the use of nuclear reactors as energy source for desalting seawater. Nuclear reactors can also provide electricity for the grid or energy for the process or even both if so desired. The safety aspects, principles and criteria are the same, which apply to any other kind of existing nuclear power plant today.

Many types of nuclear reactors are in use today. In principle any reactor is capable to provide energy for the desalting process. Another point to be considered is that nuclear reactors have a better efficiency in base load operation. Considering that seawater desalination is base process, desalting using nuclear reactors certainly have inherent advantages over other processes.

According to the size and to particularities of each region electrical system, nuclear desalination plants can also provide electricity to the grid. The size and output of each unit will depend on optimal grid configuration.

2. Brazilian water requirements and resources

According to data obtained from IBGE - Brazilian Institute of Geography and Statistics [19], the Brazilian water resources and consumption during 2003 were the following:

	Km³/year
Total Consumption	**59,30**
Agriculture	36,63
Domestic Consumption	10,65
Industrial	12,02

	km³/year
Water Resources	**7.292,00**
Surface	5.418,00
Underground	1.874,00

This means that technically Brazilian water reserves would last approximately 123 years, nevertheless, great part of these reserves are concentrated on rivers in the Amazon forest which are very far from the large consumer areas, which also means very high costs for distribution from this source and consequently a very difficult option for implementation. In agriculture 81% of the required fresh water has its origin on proven surface reserves from which 56% is used in many areas by means of mechanical irrigation.

	km³/year
Consumption In Agriculture	**36,63**
Surface	29,67
Underground	6,96

Brazil is recognised as one of the countries that will have to invest in large infrastructure projects for fresh water production. If this does not occur the country will also be a potential importer of foods by 2025 mainly due to the shortage of fresh water for agriculture [3]. Such prediction seems pessimistic for a country, which has 15% of the entire world fresh water resources. The explanation for such fact comes from the high unequal distribution of fresh water throughout the 5 Brazilian geographical regions. See Fig. 3 below.

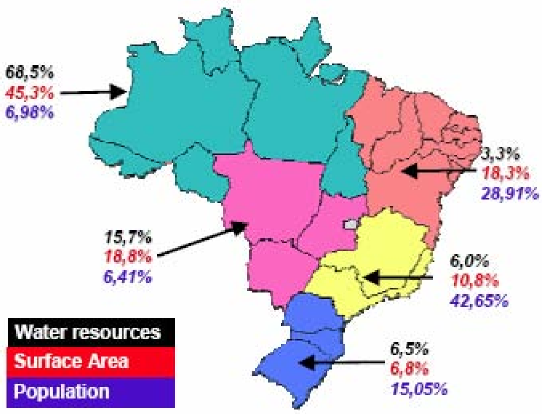

FIG. 3. Distribution of water resources and population in Brazil

correlated to the amount of energy required from the plant according to the table below. Linear regression was used for estimation of values not in the range of this table.

Although natural gas plants have a higher efficiency (~45%) than nuclear ones, it was assumed that the amount of energy used for the desalting process in gas plants would affect total energy production in a similar way as it does in nuclear power units.

Table I Fresh water production in terms of energy required from the plant

Production Capacity (m^3/day)	Thermal Energy Required (MWe)	Loss in Shaft Power (MWe)	Decrease in Power Output (MWe)
216,000	121	51	172
264,000	145	61	206
312,000	174	73	247
336,000	188	79	267
504,000	282	119	401

6. Estimation of capital costs for desalting units, nuclear and gas power plants

These costs were estimated for three alternatives of nuclear power plants according to the table below (approximately US$ 2000/kWe). For the desalting unit the capital cost estimated for a production of 115,000 m^3/day of fresh water was US$ 70 000 million [26/27].

Although the main focus of this study is oriented towards desalting units coupled to nuclear power plants, a comparison of the same desalting process performed by natural gas plants is also presented for better evaluation of alternatives in Brazil.

For three alternatives of natural gas plants, the capital costs were estimated on US$ 500/kWe on a linear basis.

	US$ x 10**3			US$ x 10**3		
	Nuclear Generation (MWe)			Gas Generation (MWe)		
	300	600	1000	300	600	1000
Capital Cost for Power Plant	600.000	1.200.000	2.000.000	150.000	300.000	500.000
Capital Cost for Desalting Unit	70.000	70.000	70.000	70.000	70.000	70.000
Total	670.000	1.270.000	2.070.000	220.000	370.000	570.000

7. Main considerations for the economic evaluation of alternatives

- Plants life time: 40 years.
- Depreciation time: 25 years.
- Decommissioning at the end of plant life.
- Construction Period: 5 years for nuclear plants and 3 years for natural gas plants.
- Nuclear plants O&M costs similar to Angra 1 and Angra 2 NPP.
- Return rate required: Brazilian rate SELIC (13% per year)
- Capital for plants construction provided according to BNDES[*] rules and taxes (TJLP[**]= 6,5% per year). It was assumed for both kind of plants 10 years for payment, grace period of 4 years after ending of construction and interest costs capitalized during construction period.

[*]BNDES: Banco Nacional de Desenvolvimento Econômico e Social – National Bank for Economic and Social Development

[**] TJLP: Taxa de Juros de Longo Prazo - Interest Rate for Long Term.

Table II. Long term payments for 300 and 600 MWe plants

US$ x 10**3

		300 Mwe Nuclear Power Plant			
Year	Description	Interest	Payment	Amortiz.	Balance
1	Construction	8.710		0	142.710
2	Construction	17.986		0	294.696
3	Construction	27.865		0	456.561
4	Construction	38.386		0	628.948
5	Grace period	49.592		0	812.540
6	Grace period	52.815	52.815	0	812.540
7	Grace period	52.815	52.815	0	812.540
8	Grace period	52.815	52.815	0	812.540
9	Grace period	52.815	52.815	0	812.540
10	Amortization	52.815	167.845	115.030	697.510
11	Amortization	45.338	167.845	122.507	575.003
12	Amortization	37.375	167.845	130.470	444.533
13	Amortization	28.895	167.845	138.950	305.583
14	Amortization	19.863	167.845	147.982	157.601
15	Amortization	10.244	167.845	157.601	0
		548.330			

Interest Rate: TJLP= 6.5% per year 6,5

US$ x 10**3

		300 Mwe Natural Gas Power Plant			
Year	Description	Interest	Payment	Amortiz.	Balance
1	Construction	4.767		0	78.100
2	Construction	9.843		0	161.277
3	Construction	15.250		0	249.859
4	Grace period	16.241	16.241	0	249.859
5	Grace period	16.241	16.241	0	249.859
6	Grace period	16.241	16.241	0	249.859
7	Grace period	16.241	16.241	0	249.859
8	Amortization	16.241	51.613	35.372	214.487
9	Amortization	13.942	51.613	37.671	176.816
10	Amortization	11.493	51.613	40.120	136.696
11	Amortization	8.885	51.613	42.728	93.968
12	Amortization	6.108	51.613	45.505	48.463
13	Amortization	3.150	51.613	48.463	0
		154.642			

Interest Rate: TJLP= 6.5% per year 6,5

US$ x 10**3

		600 Mwe Nuclear Power Plant			
Year	Description	Interest	Payment	Amortiz.	Balance
1	Construction	16.510		0	270.510
2	Construction	34.093		0	558.603
3	Construction	52.819		0	865.422
4	Construction	72.762		0	1.192.185
5	Construction	94.002		0	1.540.187
6	Grace period	100.112	100.112	0	1.540.187
7	Grace period	100.112	100.112	0	1.540.187
8	Grace period	100.112	100.112	0	1.540.187
9	Grace period	100.112	100.112	0	1.540.187
10	Amortization	100.112	318.154	218.042	1.322.145
11	Amortization	85.939	318.154	232.214	1.089.931
12	Amortization	70.846	318.154	247.308	842.623
13	Amortization	54.770	318.154	263.383	579.239
14	Amortization	37.651	318.154	280.503	298.736
15	Amortization	19.418	318.154	298.736	0
		1.039.371			

Interest Rate: TJLP= 6.5% per year 6,5

US$ x 10**3

		600 Mwe Natural Gas Power Plant			
Year	Description	Interest	Payment	Amortiz.	Balance
1	Construction	8.017		0	131.350
2	Construction	16.554		0	271.238
3	Construction	25.647		0	420.218
4	Grace period	27.314	27.314	0	420.218
5	Grace period	27.314	27.314	0	420.218
6	Grace period	27.314	27.314	0	420.218
7	Grace period	27.314	27.314	0	420.218
8	Amortization	27.314	86.804	59.490	360.729
9	Amortization	23.447	86.804	63.356	297.372
10	Amortization	19.329	86.804	67.475	229.898
11	Amortization	14.943	86.804	71.860	158.037
12	Amortization	10.272	86.804	76.531	81.506
13	Amortization	5.298	86.804	81.506	0
		260.079			

Interest Rate: TJLP= 6.5% per year 6,5

Table III. Long term payments for 900 MWe plants

US$ x 10**3

		1000 Mwe Nuclear Power Plant			
Year	Description	Interest	Payment	Amortiz.	Balance
1	Construction	26.910		0	440.910
2	Construction	55.569		0	910.479
3	Construction	86.091		0	1.410.570
4	Construction	118.597		0	1.943.167
5	Construction	153.216		0	2.510.383
6	Grace period	163.175	163.175	0	2.510.383
7	Grace period	163.175	163.175	0	2.510.383
8	Grace period	163.175	163.175	0	2.510.383
9	Grace period	163.175	163.175	0	2.510.383
10	Amortization	163.175	518.566	355.391	2.154.993
11	Amortization	140.075	518.566	378.491	1.776.501
12	Amortization	115.473	518.566	403.093	1.373.408
13	Amortization	89.272	518.566	429.294	944.114
14	Amortization	61.367	518.566	457.198	486.916
15	Amortization	31.650	518.566	486.916	0
		1.694.093			

Interest Rate: TJLP= 6.5% per year 6,5

US$ x 10**3

		1000 Mwe Natural Gas Power Plant			
Year	Description	Interest	Payment	Amortiz.	Balance
1	Construction	12.350		0	202.350
2	Construction	25.503		0	417.853
3	Construction	39.510		0	647.363
4	Grace period	42.079	42.079	0	647.363
5	Grace period	42.079	42.079	0	647.363
6	Grace period	42.079	42.079	0	647.363
7	Grace period	42.079	42.079	0	647.363
8	Amortization	42.079	133.725	91.646	555.717
9	Amortization	36.122	133.725	97.603	458.114
10	Amortization	29.777	133.725	103.947	354.167
11	Amortization	23.021	133.725	110.704	243.463
12	Amortization	15.825	133.725	117.900	125.563
13	Amortization	8.162	133.725	125.563	0
		400.663			

Interest Rate: TJLP= 6.5% per year 6,5

The operational assumptions for the plants will be:

Table IV. Electricity and fresh water production

	Nuclear Generation (MWe)			Gas Generation (MWe)		
Electricity & Water Production	300	600	1000	300	600	1000
Maximum Electrical Power (MWe)	200	500	900	200	500	900
Maximum Water Production (m^3/day)	115.000	115.000	115.000	115.000	115.000	115.000

Table V. O & M costs

Power Generation Costs		Nuclear	Gas 25 years	Gas +15 years
O & M	US$/MWh	8,00	6,25	5,00
Decommissioning	Years	40	-	-
Depreciation	Years	25	25	0
Fuel	US$/MWh	6,00	17,06	17,06
Desalting Costs				
O & M	US$/m³	0,138	0,138	0,138
Depreciation	Years	25	25	0
Chemical Products	US$/m³	0,025	0,025	0,025

Table VI. Federal taxes, contributions for social security and electricity tariffs considered

Federal Taxes and Tariffs		Nuclear	Gas
Electric Energy Tariff	US$/MWh	58,00	44,81
CONFIS	%	7,00	7,00
PASEP	%	1,30	1,30
ICMS	%	17,00	17,00
Income Tax Rate	%	25,00	25,00
Social Contribution	%	9,00	9,00

8. Costs of fresh water in the State of Ceará.

As already mentioned, the site considered for the construction of the power plant coupled to the desalting unit is located near the city of Fortaleza, which is the capital of the State of Ceará. The company in charge of fresh water production, distribution and sewer services in the state of Ceará is CAGECE – Companhia de Água e Esgosto do Ceará. These services are provided to 233 different locations in the state including 149 cities.

According to information provided in this company website [4] the scheme adopted by the company to specify tariffs provides sufficient financial support to cover all its costs. The fresh water supplied by CAGECE to the consumers is charged according to Table VII below:

Table VII. Fresh water tariff charged to consumers

RESIDENTIAL		
	Consumption (m³)	Tariff (US$/m³)
Normal	0 - 10	0,49
Normal	11 - 15	0,78
Normal	16 - 20	0,83
Normal	21 - 50	1,40
Normal	> 50	2,48
Social	0 - 10	0,29

COMMERCIAL 1	
Consumption (m³)	Tariff (US$/m³)
0 - 13	0,82
COMMERCIAL 2	
Consumption (m³)	Tariff (US$/m³)
0 - 50	1,65
> 50	2,48

INDUSTRIAL	
Consumption (m³)	Tariff (US$/m³)
0 - 15	1,44
16 - 50	1,65
> 50	2,48
PUBLIC SERVICES	
0 - 15	0,95
16 - 50	1,38
> 50	2,06

9. Economic evaluation of alternatives

Case 1

The main objective of this case was the determination of the minimum allowable tariff for selling the desalted water in each of the alternatives proposed. Such evaluation was realized for an assumption of null Net Present Value for all the cash flows determined.

The minimum values obtained are summarized in table VIII below:

Table VIII. Minimum desalted water tariffs

Power Levels (Mwe)	Nuclear 300	Nuclear 600	Nuclear 1000	Gas 300	Gas 600	Gas 1000
Minimum Desalted Water Price (US$/m³)	1,60	1,72	1,89	1,09	0,77	0,35

Net Present Value	Nuclear 300	Nuclear 600	Nuclear 1000	Gas 300	Gas 600	Gas 1000
SELIC return rate: 13% aa	**0**	**0**	**0**	**0**	**0**	**0**

For values above US$1.89/m^3 for the fresh water tariff, all alternatives considered for power plants are attractive. It must be remarked that as the investment for natural gas power plants is lower, they can be attractive for water tariffs reasonably lower than the corresponding tariffs for equivalent nuclear power plants.

What is really important to notice according to Table VII above is that tariff charged by CAGECE to large consumers (> 50 m^3) provides margin to sell desalted water to these clients. Such option may be carried out by an agreement where CAGECE, as local distributor, buys desalted water and sells it to these special clients by its usual tariff (US$2.48/m^3). The acquisition tariff may be defined as a value between the minimum required for viability of the plant in consideration, and the value that is already practiced by the company today for these special clients. This alternative will provide an extra profit for the company. It will also permit that the amount of water that usually is provided for large consumers to be redistributed and routed to new clients (not necessarily large ones) that today do not have the benefits of a regular provision of treated fresh water.

Case 2

In this case it was verified how the coupling of the desalted unit can affect the economic viability of any of the alternatives considered for investment.
A cash flow analysis was performed assuming that the plants in consideration will supply only electric power. Table IX summarizes the results:

Table IX. Economic viability for electric power supply only

Power Levels (MWe)	Nuclear 300	Nuclear 600	Nuclear 1000	Gas 300	Gas 600	Gas 1000
No Desalted Water	0	0	0	0	0	0

US$ x 10**3

Net Present Value	Nuclear 300	Nuclear 600	Nuclear 1000	Gas 300	Gas 600	Gas 1000
SELIC return rate: 13% aa	**-136.904**	**-49.718**	**-60.561**	**33.563**	**115.715**	**191.932**

It can be concluded from the figures above that there will be no economic viability for nuclear plants if their purpose is just selling electric energy. The high investment and financial costs associated are responsible for such fact. The same does not happen to natural gas plants, which are viable for all alternatives considered.

Case 3

Finally a study was conduct to evaluate how the tariff for fresh water production can interfere with the originally selected electric energy tariff for the two kinds of plants coupled to a desalting unit. Again an analysis for minimum NPV (NPV=0) was realized to determine the minimum electrical tariff that would be required for the economic viability of the plants .The fresh water tariff was considered as high as possible to allow the maximum reduction of the electrical tariff. In such case the maximum possible value for this tariff is the one by which CAGECE sells the water to large consumers. Table X below shows the minimum tariffs allowed for electrical tariff considering US$2.48US$/m^3 for desalted water tariff.

Table X. Minimum electrical tariffs

Initial Eletricity Tariff US$ 58/MWh

Initial Gas Tariff US$ 44,81/MWh

	Nuclear			Gas		
Power Levels (Mwe)	300	600	1000	300	600	1000
Lowest Electric Tariff US$/Mwe	**36,84**	**50,74**	**54,86**	**11,46**	**28,44**	**33,47**
Max. Desalted Water Price US$/m³	2,48	2,48	2,48	2,48	2,48	2,48
	Nuclear			**Gas**		
Net Present Value	**300**	**600**	**1000**	**300**	**600**	**1000**
SELIC return rate: 13% aa	**0**	**0**	**0**	**0**	**0**	**0**

The cash flow for the maximum water tariff is shown bellow for the three nuclear power plants in concern. The cash flow for natural gas plants is very similar and will not be presented here.

Cash Flow — US$ x 10**3

300 MWe Nuclear Power Plant	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 20	year 30	year 40
Gross Operational Revenue	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**185.988,00**	**1.859.880,00**	**1.859.880,00**	**1.859.880,00**
(-) Tax on sales	47.054,96	47.054,96	47.054,96	47.054,96	47.054,96	47.054,96	47.054,96	47.054,96	47.054,96	47.054,96	470.549,64	470.549,64	470.549,64
Net Operational Revenue	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**138.933,04**	**1.389.330,36**	**1.389.330,36**	**1.389.330,36**
(-) O & M Costs	34.277,35	34.277,35	34.277,35	34.277,35	34.277,35	34.277,35	34.277,35	34.277,35	34.277,35	34.277,35	342.773,50	342.773,50	342.773,50
(-) Amortization	0,00	0,00	0,00	0,00	115.029,85	122.506,79	130.469,73	138.950,26	147.982,03	157.600,86	0,00	0,00	0,00
(-) Financial Costs	52.815,07	52.815,07	52.815,07	52.815,07	52.815,07	45.338,13	37.375,19	28.894,65	19.862,89	10.244,06	0,00	0,00	0,00
(-) Decommissioning	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	182.000,00
(-) IR + Social Contributions	0,00	5.583,69	5.583,69	5.583,69	5.583,69	5.583,69	7.621,16	9.791,06	12.102,01	14.563,16	196.966,49	236.054,99	269.517,99
Cash Balance on Year	**51.840,62**	**46.256,92**	**46.256,92**	**46.256,92**	**-68.772,92**	**-68.772,92**	**-70.810,39**	**-72.980,29**	**-75.291,23**	**-77.752,39**	**849.590,37**	**810.501,87**	**595.038,87**
(+/-) Previous Balance	0,00	51.840,62	98.097,54	144.354,47	190.611,39	121.838,47	53.065,55	-17.744,84	-90.725,13	-166.016,36	-243.768,75	605.821,62	1.416.323,49
Accumulated Balance	**51.840,62**	**98.097,54**	**144.354,47**	**190.611,39**	**121.838,47**	**53.065,55**	**-17.744,84**	**-90.725,13**	**-166.016,36**	**-243.768,75**	**605.821,62**	**1.416.323,49**	**2.011.362,35**
Discounted Cash: 13% per year	35.928,15	28.370,24	25.106,41	22.218,06	-29.232,66	-25.869,61	-23.571,70	-21.499,14	-19.628,25	-17.937,93	106.383,93	29.897,58	6.466,11
Net Present Value	**116.631**												

Cash Flow — US$ x10**3

600 Mwe Nuclear Power Plant	year 1	year 2	Year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 20	year 30	year 40
Gross Operational Revenue	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**323.796,00**	**3.237.960,00**	**3.237.960,00**	**3.237.960,00**
(-)Tax on sales	81.920,39	81.920,39	81.920,39	81.920,39	81.920,39	81.920,39	81.920,39	81.920,39	81.920,39	81.920,39	819.203,88	819.203,88	819.203,88
Net Operational Revenue	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**241.875,61**	**2.418.756,12**	**2.418.756,12**	**2.418.756,12**
(-) O & M Costs	69.269,35	69.269,35	69.269,35	69.269,35	69.269,35	69.269,35	69.269,35	69.269,35	69.269,35	69.269,35	692.693,50	692.693,50	692.693,50
(-) Amortization	0,00	0,00	0,00	0,00	218.041,65	232.214,36	247.308,29	263.383,33	280.503,24	298.735,95	0,00	0,00	0,00
(-) Financial Costs	100.112,14	100.112,14	100.112,14	100.112,14	100.112,14	85.939,44	70.845,50	54.770,46	37.650,55	19.417,84	0,00	0,00	0,00
(-) Decommissioning	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	200.000,00
(-) ITR + Social Contributions	0,00	4.549,15	4.549,15	4.549,15	4.549,15	4.549,15	8.411,21	12.524,31	16.904,75	21.569,93	313.005,70	384.024,06	450.187,06
Cash Balance on Year	**72.494,12**	**67.944,97**	**67.944,97**	**67.944,97**	**-150.096,68**	**-150.096,68**	**-153.958,74**	**-158.071,84**	**-162.452,28**	**-167.117,46**	**1.413.056,92**	**1.342.038,56**	**1.075.875,56**
(+/-) Previous Balance	0,00	72.494,12	140.439,09	208.384,06	276.329,03	126.232,36	-23.864,32	-177.823,06	-335.894,90	-498.347,18	-665.464,65	747.592,27	2.089.630,83
Accumulated Balance	**72.494,12**	**140.439,09**	**208.384,06**	**276.329,03**	**126.232,36**	**-23.864,32**	**-177.823,06**	**-335.894,90**	**-498.347,18**	**-665.464,65**	**747.592,27**	**2.089.630,83**	**3.165.506,38**
Discounted Cash: 13% per year	50.242,06	41.671,92	36.877,81	32.635,23	-63.800,19	-56.460,35	-51.250,53	-46.566,12	-42.350,93	-38.554,98	176.940,04	49.504,77	11.691,21
Net Present Value	**100.580**												

Cash Flow — US$ x 10**3

900 Mwe Nuclear Power Plant	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 20	year 30	year 40
Gross Operational Revenue	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**507.540,00**	**5.075.400,00**	**5.075.400,00**	**5.075.400,00**
(-) Taxes on sales	128.407,62	128.407,62	128.407,62	128.407,62	128.407,62	128.407,62	128.407,62	128.407,62	128.407,62	128.407,62	1.284.076,20	1.284.076,20	1.284.076,20
Net Operational Revenue	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**379.132,38**	**3.791.323,80**	**3.791.323,80**	**3.791.323,80**
(-) O & M Costs	115.925,35	115.925,35	115.925,35	115.925,35	115.925,35	115.925,35	115.925,35	115.925,35	115.925,35	115.925,35	1.159.253,50	1.159.253,50	1.159.253,50
(-) Amortization	0,00	0,00	0,00	0,00	355.390,72	378.491,12	403.093,04	429.294,09	457.198,20	486.916,08	0,00	0,00	0,00
(-) Financial Costs	163.174,91	163.174,91	163.174,91	163.174,91	163.174,91	140.074,51	115.472,59	89.271,54	61.367,43	31.649,55	0,00	0,00	0,00
(-) Decommissioning	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	218.000,00
(-) ITR + Social Contributions	0,00	3.210,63	3.210,63	3.210,63	3.210,63	3.210,63	9.505,49	16.209,51	23.349,29	30.953,17	468.133,41	581.724,91	691.487,91
Cash Balance on Year	**100.032,12**	**96.821,49**	**96.821,49**	**96.821,49**	**-258.569,23**	**-258.569,23**	**-264.864,09**	**-271.568,11**	**-278.707,89**	**-286.311,77**	**2.163.936,89**	**2.050.345,39**	**1.722.582,39**
(+/-)Previous Balance	0,00	100.032,12	196.853,61	293.675,10	390.496,59	131.927,37	-126.641,86	-391.505,94	-663.074,05	-941.781,95	-1.228.093,71	935.843,18	2.986.188,57
Accumulated Balance	**100.032,12**	**196.853,61**	**293.675,10**	**390.496,59**	**131.927,37**	**-126.641,86**	**-391.505,94**	**-663.074,05**	**-941.781,95**	**-1.228.093,71**	**935.843,18**	**2.986.188,57**	**4.708.770,97**
Discounted Cash: 13% per year	69.327,28	59.382,43	52.550,83	46.505,16	-109.907,60	-97.263,36	-88.169,24	-80.000,80	-72.658,49	-66.053,81	270.963,66	75.632,60	18.718,78
Net Present Value	**79.027**												

10. Conclusions

The combined analysis of the three cases in the previous section provides many conclusions on the alternatives for nuclear or natural gas power generation coupled to desalted water production. The first point that must be observed is that with the premises adopted, the nuclear option is not more competitive than the natural gas one. This fact is explained by the capital and financial costs of the nuclear option, which are considerably higher than those for the natural gas. Another point that should not be forgotten is that double purpose plants are in analysis here. The nuclear plants are not entirely devoted for desalting but also to electricity generation too. This explains the high costs of these units. If a nuclear plant is only devoted to the desalting process, the entire turbo generating unit and its associated systems are not required. This represents a substantial reduction in capital costs and financial costs.

Another very interesting point is that desalting water production can add value to nuclear power plants. The latter ones will not be economically viable if not coupled to desalting units. The same does not happen to natural gas plants. The gas units can produce only electricity in a viable way. Again the explanation relies on costs and on interest rates assumed for this study.

The reduction in electric energy tariffs as consequence of specially selected desalted water tariffs is probably the most remarkable conclusion in this study. It is interesting to observe that with in the limit, up to 36.5% reduction can be achieved in electric energy tariffs for the smaller nuclear plant and even a higher reduction for the 300 MWe natural gas plant! Such fact can be the key point in the selection of a competitive tariff or in a decision on any enterprise like the ones proposed here.

If it is assumed that 300 MWe is an output typical of "small plants", it is also possible to conclude that these "small plants" will have more flexibility for adjustment to adverse economic and competitive environments than the larger ones.

Finally what is important to conclude is that nuclear plants will be viable if coupled to desalting units in the northeastern area of Brazil. So if a medium or long-term strategy is considered, it is possible to foresee the decreasing of capital investment and operational costs of nuclear plants as well as the rising costs of natural gas plants. Together with the political world tendencies related to environmental issues it is possible that, in a future not so far, even for Brazilian standards, the option for nuclear double purpose desalination plants becomes as attractive as the natural gas option.

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Economic-environmental effects analysis of process steam supplied by a 200 MW nuclear heating reactor using the clean development mechanism (CDM)

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Abstract The new application area of low temperature nuclear heating reactor (NHR) process steam was studied. The method of economic evaluation used is as per current international practice. A full economic analysis of process steam at 1.5 MPa supplied by 200MW nuclear heating reactor (PSNR200) for industrial complexes was carried out. The results of calculation on economic analysis indexes show its economics as very significant; internal rate of return is 13.18%, net present worth (discount rate 10%) is RMB Yuan 357.14 million, capital recovery or payback time is about 6 years after project constructed. Meanwhile, amount of carbon dioxide (CO_2) emission from the same heat capacity coal fired boiler was calculated, which was considered as revenue to the PSNR200. The economics of the PSNR200 is thus significantly improved on account of the environmental benefits using the clean development mechanism (CDM).

Keywords nuclear heating reactor; process steam; economic analysis; clean development mechanism (CDM)

1. Introduction

The need for energy, specially process steam with 1.5~2.0 MPa and 150-200°C to be supplied to industies located in the southeast coastal cities in China is growing rapidly, while its GDP annual growth rate always remained around 9.4% in the past three decades. The nuclear heating reactor (NHR) can be constructed near by a city due to its better safety characteristics, which includes integrated arrangement, natural circulation, self-pressurized performance, hydraulic control rod drive and passive safety system [1]. The NHR is one of the most suitable energy (process heat) producing unit which can be used in process heat in industry and in seawater desalination.

2. Input parameters

2.1. Design parameters

The design parameters of a $200MW_{th}$ NHR was adjusted to satisfy with the process steam at saturation with 1.5 MPa (PSNR) applications in the area of industrial development assumed site at Shanghai city, as given in Table I.

Table I. Design parameters of PSNR200

Thermal-hydraulic parameters:	
Thermal power output / MW_{th}	200
Operation pressure of core loop /MPa	4.0
Coolant flow rate of core loop /kg/s	1334.7
Temp. of core inlet/outlet /°C	228/250
Temp. of middle loop inlet/outlet /°C	210/230
Pressure of middle loop /MPa	4.5
Temp. of steam supply loop outlet /°C	197
Pressure of steam supply loop /MPa	1.50
Structural parameters of the reactor loop:	
Inner-diameter of pressure shell /m	4.5
Height of pressure shell /m	13
Shape of fuel assemblies	12×12
Number of fuel assemblies / sets	120
Number of control rod / sets	32

2.2. Cost parameters

The design of PSNR200 was carried out based on the design of NHR heating to district in winter in Daqing, Heilongjiang province of China. The engineering investment of PSNR200 was estimated based on above according to the account code of nuclear power project investment. The estimated capital investment is adjusted as the price of currency reference year (2005 RMB): the overnight cost, RMB Yuan 615.67 million (USD 76.96 million, 1USD=8.0RMB Yuan); the total capital investment, RMB Yuan 898.35 million (USD 112.29 million); the specific investment cost, RMB Yuan 4491.74 (USD 561.45) per kW_{th}.

3. Economic effect analysis

3.1. Assessment parameters

During the course of economic assessment, the lead time period is 42 months, nuclear fuel average burn up (equilibrium enrichment is 3% U^{235}) is 30 $GW{\cdot}d{\cdot}t^{-1}$ U. The depreciation of fixed asset is defined as a 30-year linear depreciation, which is typical for nuclear power plants. Annual maintenance costs are 1.5% of the total capital investment. The economic life is 30 years.

Other parameters include: currency reference year (2005 RMB), annual average loan interest rate (6.50%), annual price inflatable escalation rate (4.00%), fixed assets form @ (95%) and amortized years (10 years) as defined by China State Planning Commission and Ministry of Construction [2]. Average labour cost (RMB Yuan 60,000/year/person), water and electric price (RMB Yuan 5.14/GJ) were given as the prices referenced from the Shanghai region in 2005. Total operating availability was (85%) as designed. Value added tax (17%), enterprise income tax (33%).

3.2. Methodology of evaluation

Methodology of cost-benefit analysis was used as in [2, 3] which included costs and revenues calculation, payback or capital recovery time, maximum net present worth values, internal rate of return, etc. Economic calculation programme dedicated to nuclear power plant was developed by the INET (of Tsinghua University) based on the performance of nuclear heating reactors [4].

The total plant costs include total capital investment costs, operation and maintenance costs (O&M costs) and nuclear fuel cycle costs. The largest of the three major components of the total plant costs is the total capital investment cost which is defined as the total costs in building the nuclear power plant and bring it to commercial operation. It was described as the depreciation of fixed assets costs, amortized costs and interest costs. The operation and maintenance costs include all non-fuel costs. Such as costs for plant staffing, consumable operating materials (wear parts) and equipment, repair and interim replacements, purchased services and nuclear insurance, as well as taxes and fees, decommissioning allowances and miscellaneous costs. The term 'nuclear fuel cycle costs' means those costs that must be recovered in the course of energy generation. These include the costs of nuclear materials, fuel fabrication, fuel transportation, fuel intermediate storage, chemical reprocessing associated with waste management, (which includes storage and final disposal of wastes), as well as any credits realized through the sale and use of uranium, and other materials. The most common economic index on which to base investment decisions may be classified into two main groups:

a) Indexes which consider the cash flow without taking into account the time of their occurrences (which is its main disadvantage); This group includes:
   (i) total net cash flow per monetary unit disbursed
   (ii) average annual net cash flow per monetary unit disbursed
   (iii) payback or capital recovery time.

(b) Indexes which do consider the time associated with the cash flow by using the discounting procedure to equalize the amounts of money at different time; This group includes:
   (i) net present worth value
   (ii) internal rate of return

Of the first group, only the payback method will be discussed, and of the second group, both methods will be described.

In general, the payback time T of an investment with revenue and cost streams of R_t and C_t, respectively, is defined by the equation:

$$\sum_{t=T_0}^{T}(R_t - C_t) = 0 \quad (1)$$

where T_0 is the reference time of the calculation.

The most comprehensive of all, the net present worth method ranks all alternatives according to their net discounted profits, i.e. the difference between the present value of total revenues and the present value of total costs.

The net cash flow at time t of an investment is equal to the difference between the expected revenues, R_t, and the cash flow of the expected expenditures, C_t. If the discount rate is the same throughout the life time of the project, the net present worth (N_{pw}) is given by the following formula:

$$N_{pw} = \sum_{t=T_0}^{T_L} \frac{(R_t - C_t)}{(1+d)^t} \quad (2)$$

where d is the discount rate, and T_L is economic life of the project.

Note that this formula assumes that all cash flows take place at the end of a certain time period. It is clear that investments with a higher present worth are preferable. The discount rate may be real or nominal, as appropriate.

The internal rate of return, r, of an investment with revenue and cost streams of R_t and C_t, respectively, is defined as the discount rate at which the net present worth becomes zero.

$$\sum_{t=T_0}^{T_L} \frac{R_t - C_t}{(1+r)^t} = 0 \quad (3)$$

It will be of economic interest to commit only those investment projects whose internal rate of return, r, is greater than actual interest (or discount) rate. First priority will be given to those alternatives whose rates of return are the highest.

3.3. Results from calculations

3.3.1. Calculation of costs

Associated with the total capital investment costs are the depreciation cost, the amortized cost and the loan interest cost. The depreciation cost is equal to the fixed assets, which constitute of 95% of the total investment capital, divided by 30 years. The interest cost is difference with year-by-year profit difference, because the more profit of a project will be more used in payback the loan, so the interest cost will be reduced. Annual operation time of PSNR200 is 310.25 days, process steam production is 253 ton per hour, and its annual production of process steam is about 1883838 ton. More detailed total annual plant cost is given in Table II-III.

3.3.2. Results of economic calculations

It is assumed the process steam from PSNR200 will be used in the area of industrial development assumed site at Shanghai city, where price of water is RMB144Yuan/ton. The total annual revenue is RMB 271.27 million Yuan. The results of economic assessment indexes calculated using equations (1)-(3) are given in Table IV.

Table II. Cost component of PSNR200 at first year of operation with full load

Cost items	PSNR200 (RMB thousand Yuan)
Nuclear fuel cycle cost	27.92
Materials cost	3.32
Purchased water and electrical cost	26.97
Labor/ manager salaries	7.50
O&M cost	19.77
Depreciation of fixed asset	38.63
Payment interest cost	46.71
Annual total cost	170.82
Unit production cost (Yuan/ton of steam)	90.68
Average Unit production cost (Yuan/ton of steam) in economic life	64.23

Table III. Annual cost of PSNR200 during the calculation life

Time /a	1	2	3	4	5	6	7 ~10	11~25	26~30
Annual total cost /RMB million Yuan	170.82	163.73	156.25	148.36	140.46	132.16	124.11	119.62	85.48
Unit cost /RMB	90.68	4.76	4.59	4.43	4.36	4.46	4.56	4.14	45.37
Average unit cost /RMB	64.23	64.23	64.23	64.23	64.23	64.23	64.23	64.23	64.23

4. Economic calculation under the CDM

4.1. Greenhouse gas reducing emissions calculations

The nuclear power plant (NPP) option is a virtually non-CO_2 emitting energy, which avoids the emissions of about total weight of carbon (T_C) each year compared to a coal-fired plant of the same electrical output is given by the following formula,

$$T_A = \frac{P_{we}}{R_e} \times 3600 \times 24 \times 365 \times O_A,$$

$$T_{ce} = \frac{T_A}{R_{ce}} \div R_B,$$

$$T_C = T_{ce} \times R_C$$

T_A – is total annual thermal quantity for a nuclear power plant, GJ
P_{we} – is reference power plant unit net electrical output, MWel
R_e – is reference net thermal efficiency, %
O_A – is operating availability

T_{ce} – is total annual coal-fired weight, ton of coal
R_B – is average coal-fired boiler efficiency, 70%
R_{ce} – is average heat value of reference coal equivalent per kilogram, 29680 kJ/kg [5]
R_C – is exchange rate of coal equivalent and carbon equivalent, 0.714 [6]

The results of greenhouse gas reducing emissions in PSNR200 were calculated by based on Table 1 and above formulae. The T_C of PSNR200 is 184.243 thousand tonnes of carbon (675.559 thousand tonnes of CO_2) per year during their 30 years economic lifetime.

4.2. Carbon taxes assumed

The cost disadvantage of the nuclear power plant must be weighed against the value of the carbon emissions avoided (1.8 million tonnes per year over 40 years). From the perspective of an Annex-I (High income countries specified in Kyoto Protocol) utility forced to contribute to its national emissions reductions may either curb emissions from its generating portfolio (at a certain cost) or make use of the flexible mechanisms, in this case the CDM – at lower cost compared to domestic action. The cost to the Annex-I partner would be the investment difference between the nuclear and coal option or $1.3 billion. In return, the Annex-I utility would receive CERs reflecting the avoided carbon emissions. The crucial question, therefore, is what would be the value of a CER in terms of $/ ton of carbon?. Based on generating cost differentials, the present value of the avoided carbon emissions is about $60 per ton of carbon (or $17 per ton of CO_2). Based on investment costs alone, the mitigation costs amount to $73 per ton of carbon (or $20 per ton of CO_2). To put these mitigation costs in perspective, in the absence of flexible mechanisms the International Energy Agency (IEA) projects carbon tax rates as high as $70 per ton of CO_2 (or approximately $250 per ton of carbon) for Annex-I countries to accomplish compliance with their Kyoto commitments.

The recent CO_2 trade price between England and China is USD 25 per ton of carbon dioxide [7]. So the present value of the avoided carbon emissions was assumed $15, $25, $35, $45 and $55 per ton of CO_2, which was assumed as revenue to the PSNR200 [8], compared to fossil baseline, and the total present value of those was put in the row of the total annual revenue of power plant cost in the Economic calculation program as a additional extensional profit. The results calculated increased extensional profit and economic indexes sensitivities are shown in Table V.

Table IV. Results of calculation economic data of PSNR200

Option	PSNR200 (million RMB Yuan)
Total capital investment costs	898.35
Nuclear power plant	808.35
Heating steam pipe net	90.00
Total annual revenue	271.27
Average unit cost in economic life time, RMB/ton of steam	64.23
Annual total profit of initial operation	70.44
Annual total profit of after payback	97.49
Capital recovery time (include lead time)/ years	8.34

Payback time (include lead time)/ years	9.98
Internal rate of return/ %	13.18
Net present worth (discount rate: 10%)	357.14

Table V. Carbon taxes and economic indexes sensitivities of PSNR200

Carbon Taxes, \$/ton of CO_2	0	15	25	35	45	55
Annual increased extensional profit/million RMB Yuan	0	81.07	135.11	189.16	243.20	297.25
Payback time (include lead time)/ years	9.98	7.88	7.14	6.64	6.29	6.02
Internal rate of return/ %	13.18	17.99	20.86	23.53	26.03	28.38
Annual net present worth (discount rate: 10%)/million RMB Yuan	357.14	845.29	1170.71	1496.14	1821.57	2147.00

5. Conclusion

Methodology of cost-benefit analysis used was as per current international practice, which included costs and revenues calculation, payback or capital recovery time, maximum net present worth values, internal rate of return, etc. Economic calculation programme dedicated to nuclear power plant was developed by the INET (of Tsinghua University) based on the performance of nuclear heating reactor.

The calculation results indicated a significant economic benefit in process steam application in oil and chemical industry from the PSNR200. Meanwhile, the economics of the PSNR200 is significantly improved on account of the environment benefits using the clean development mechanism (CDM), the total annual revenue is increased from RMB Yuan 271.27 million to RMB Yuan 406.27 million, internal rate of return is from 13.18 to 20.86%, maximum net present worth values (discount rate: 10%) is from RMB Yuan 357.14 million to RMB Yuan 1170.04 million.

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Sensitive economic analysis of nuclear desalination by using DEEP

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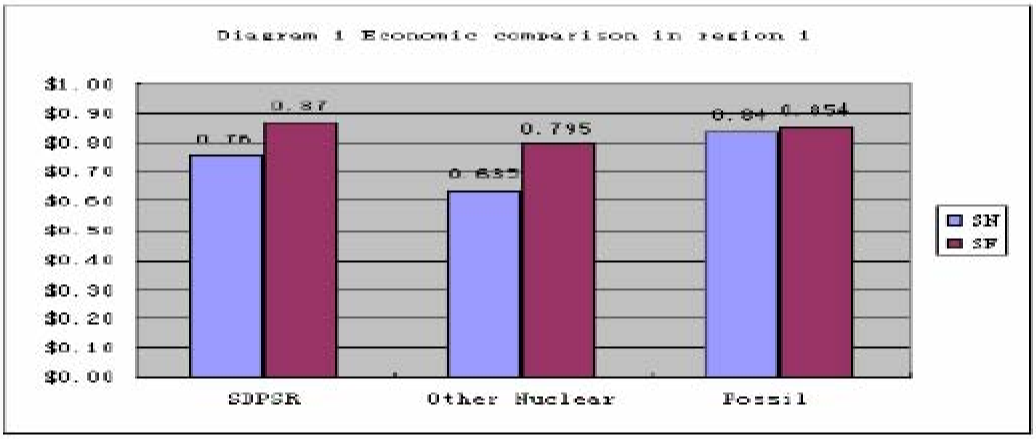
Extended Synopsis

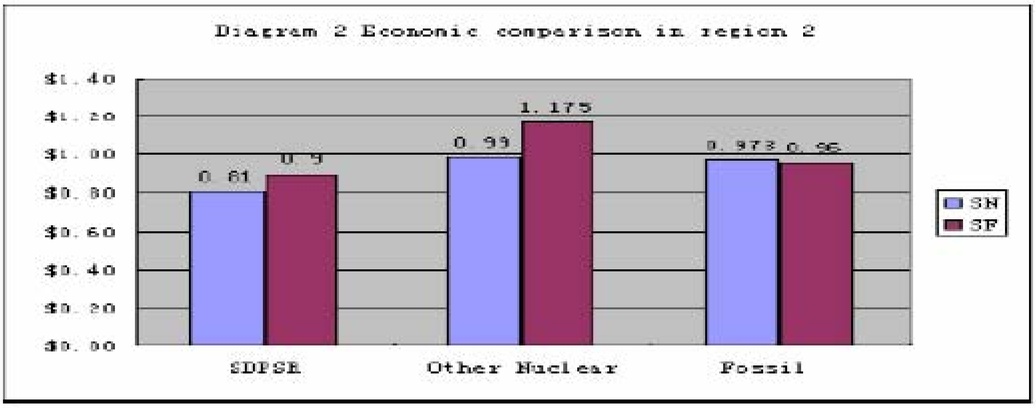
In order to promote nuclear technology in electricity production or portable water production, The IAEA has developed its economic evaluation model and established the Desalination Economic Evaluation Program (DEEP) by using levelized discounted costs method. Nuclear seawater desalination plant consists of a seawater desalination pool shell type reactor (abbreviation SDPSR) and several low temperature multi effect distilling facilities and their correlated systems. SDPSR is a low temperature, normal pressure (atmosphere pressure at the surface of the pool) nuclear reactor that uses the same fuel as that of commercial nuclear power plant.

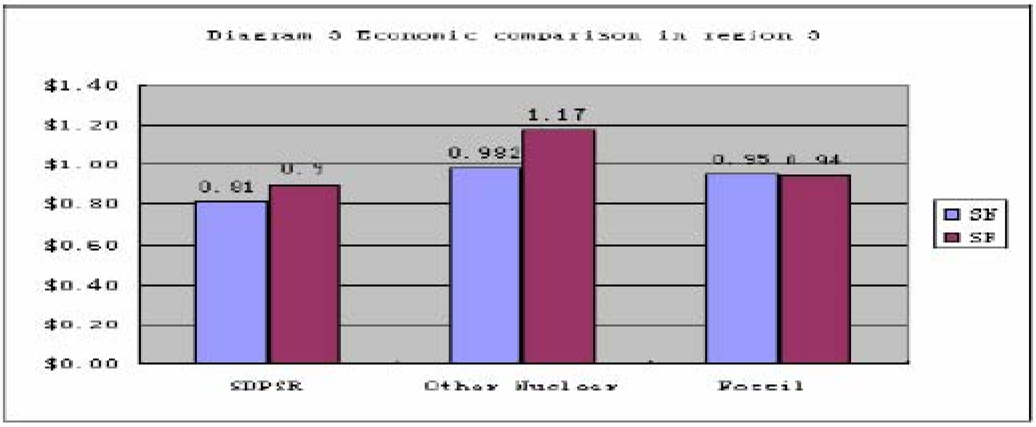
The calculations were carried out with the same conditions in the paper [1] and the report [2], i.e., dividing the world into three regions with similar seawater economical conditions with respect to seawater desalination. The three regions are defined as follows: Region 1, corresponding to southern Europe (south of France, Italy, Greece, Turkey and Spain); Region 2, corresponding to southeast Asia, the Red Sea region and the North African region; Region 3, corresponding to the Arabian Gulf region (average seawater salinity and temperature). In each region there are two economic scenarios, favouring nuclear (Sn) and fossil (Sf) options, respectively. The input data assumptions for the DEEP calculation for different regions and economic scenarios, the interest rates, seawater conditions and labour costs are identified in paper [1]. All cost data are given in 2005 US dollars. The default input data for nuclear and desalination plants are provided by the DEEP (DEEP Version 3.04 - July 2005).

The results from DEEP calculations of the PWR-600 (600 MWe pressurized light water reactor), the PWR-900 (900 MWe pressurized light water reactor), PHWR-600 (600 MW(e) Pressurized heavy water reactor), PHWR-900 (900 MW(e) Pressurized heavy water reactor), HTR-100 (100 MW(e) High temperature reactor), HR-200 (200 MW(th) Nuclear Heating reactor, PC-600 (600 MW(e) pulverized coal Superheated steam boiler), PC-900 (900 MW(e)pulverized coal Superheated Fossil steam boiler), CC-600 (600 MW(e) Combined cycle gas turbine) for Sn and Sf economic scenarios are taken from the report [2]. The economic comparison of fresh water production by SDPSR, other kind of nuclear reactors and fossil plant (Sn and Sf are the same meaning and value in Table 1) in different regions are shown in Diagram 1, 2 and 3 respectively.

From the comparison and analyses above, we can conclude: Discount rate is a very sensitive factor to water price; Sea water TDS is not a very sensitive factor to water price; Person cost is almost no affect to water price; SDPSR is competitive with other nuclear technology and fossil plant in water production in Region 1 and Region 2; In Region 1, SDPSR is competitive with fossil plant and in water production.







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The IAEA desalination economic evaluation programme (DEEP)

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1. Introduction

DEEP is derived from desalination cost evaluation package developed in the eighties by General Atomics on behalf of the IAEA. The old version, named "Co-generation and Desalination Economic Evaluation" Spreadsheet, CDEE) was used for feasibility studies related to nuclear desalination in the IAEA and other Member States. Subsequently, with its increasing popularity, a user-friendly version was issued by the Agency towards the end of 1998 under the name of DEEP. Through the next years the software was updated constantly within DEEP-1 family (versions 1.0, 1.1, 1.2 and working version 1.7). Both the user interface and model structure were further developed and in 2000 a new upgrade – first version from the DEEP-2 family was released. Its salient feature was the complete modularization of various cases. As the user group enlarged, new ideas as well as criticisms of the DEEP models appeared. Some of them were implemented gradually in different working versions (versions 2.0, 2.1, 2.2, 2.3, 2.4, 2.6). The four year period of continuous development culminated in the development of DEEP 3.0, released in August 2005. Following further development, the latest version of DEEP 3.1 is currently available for user to down load freely from the web site of the IAEA at no cost.

This paper summarizes the salient features of DEEP software and echoes some of the information presented in the TECDOC draft prepared as a result of the CRP on “Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies” which was closed at the end of 2006.

2. General structure of DEEP application

DEEP package consists of several parts, which are implemented as EXCEL files. The tool separates the performance and cost calculations called “case” on one side and the support for data input and change and output presentation on the other side. As a by-product, the interface between these two parts is defined so that the future development of the whole package may be performed by independent developers and new cases might be incorporated into **DEEP.** An example of file structure is given in Fig. 1.

DEEP provides a user-friendly interface when working with a single case, changing input data and browsing in the output sheets as well as when comparing variations with different input parameters. **DEEP** is particularly developed with a typical user, without much knowledge of the technical features of the models used for evaluation.

2.1. Case file

The user can select several cases and a comparison table is made automatically based on the selected cases. This table is then stored as a usual EXCEL file within one worksheet. This sheet is named “CP" and it contains values from selected cases. The file “Sample CP.xls" is provided as an example for beginners and is placed in the directory of C:\Deep\CPs. Primarily other Comparative Presentations (created by DEEP users) can be stored. However, there are some new DEEP software features, which are convenient for upgrade (e.g. a possibility to add an opened case to the CP and a possibility to open more than one case at one moment – e.g. all ones from the CP), but this is a subject for future decision and planning.

Desalination plant models, data & formulas **Definitions of groups (of cases) for comparison**

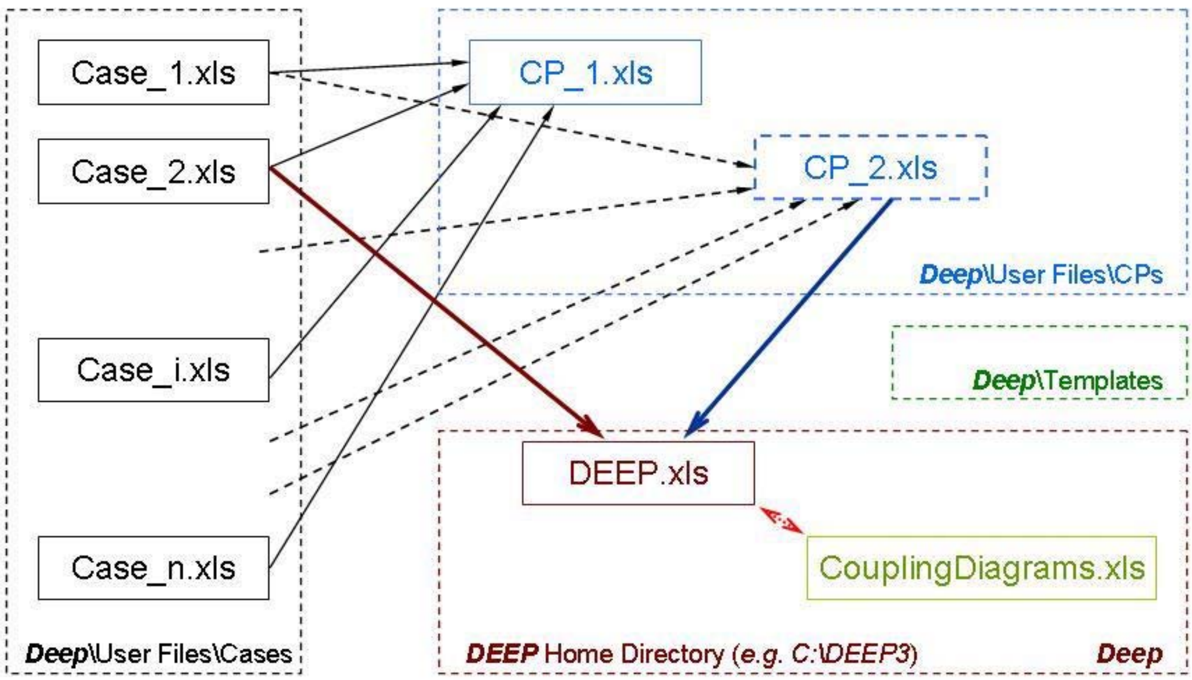

FIG. 1. General architecture of DEEP

2.2. Control file

The other type of EXCEL files used in **DEEP-*3*** package is a single copy of "**DEEP-3.XLS**" file stored in the directory of C:\Deep3. This file contains the user-friendly interface, which helps the user to work more comfortably. It helps the user to create and maintain Cases and Comparative Presentations. Both user types of EXCEL files - "Calc" and "CP" sheets which are inside **DEEP-3.XLS** are provided with set of predefined graphs. These graphs are updated according to values of selected cases. New cases are generated using the knowledge basis imbedded in the **DEEP-3 package** in the Templates directory. Using the ***New case*** and ***New case by modification*** commands, the user can easily generate many cases which differ only in some input data values.

The main DEEP design principle was to keep all the EXCEL functions available for the user and to leave the calculation spreadsheet open for user to change. However, this openness is contradictory to the user friendliness. This fact poses quite large burden on DEEP developers and on advanced users who wish to make changes and improvements within a predefined Excel environment on their own.

DEEP and its subsequent versions are freely available from the IAEA, at the nuclear desalination website (www.iaea.org/nucleardesalination), under a license agreement. Its user manual provides all the details for installing and running DEEP cases.

2.3. Scope of DEEP

The DEEP main calculation sheet supports both nuclear and fossil power options. It considers heating and power plants as well as heat-only plants, distillation processes MSF and MED and membrane process reverse osmosis. Table I shows the options considered for energy sources.

Table I. The Various energy options available in DEEP

Energy source	Description	Plant type
Nuclear	Pressurized light water reactor (PWR)	Co-generation plant
Nuclear	Pressurized heavy water reactor (PHWR)	Co-generation plant
Fossil - coal	Superheated steam boiler (SSBC)	Co-generation plant
Fossil - oil/gas	Superheated steam boiler ((SSBOG)	Co-generation plant
Fossil	Open cycle gas turbine (GT)	Co-generation plant
Fossil	Combined cycle (CC)	Co-generation plant
Nuclear	Heat only reactor: steam or hot water, (HR)	Heat-only plant
Fossil	Boiler: steam or hot water, (B)	Heat-only plant
Nuclear	Gas turbine modular helium reactor (GT-MHR)	Power plant
Fossil	Diesel (D)	Power plant
Nuclear	Small PWR (SPWR)	Co-generation plant

The commercially established desalination processes included in DEEP are presented in Table II.

Table II. The desalination processes considered in DEEP

Process	Description
Distillation	Multi-Effect Distillation (MED)
	Multi-Stage Flash (MSF)
Membrane	Stand-Alone Reverse Osmosis (SA-RO)
	Contiguous Reverse Osmosis (C-RO)
Hybrid	Multi-Effect Distillation with Reverse Osmosis (MED/RO)
	Multi-Stage Flash with Reverse Osmosis (MSF/RO)

2.4. New developments in DEEP

The DEEP-3 version includes improved performance and cost models for both thermal and reverse osmosis (RO) systems, as well as an improved program structure and user interface, [1-12].

The changes of the thermal performance model include a revision of the Gain Output Ratio (GOR) calculation and its generalization to include thermal vapour compression effects in conjunction with Multi Effect Distillation (MED) or Multi-Stage Flashing (MSF) units. Since energy costs continue to represent an important fraction of seawater desalination costs, the lost shaft work model has been generalized to properly account for both backpressure and extraction systems. In addition, improved estimates of feed make-up and re-circulation flows in the new version allow a more accurate calculation of pumping power requirements.

For RO systems, changes include improved modelling of system recovery, feed pressure and permeate salinity, taking into account temperature, feed salinity and fouling correction factors. In order to be able to accommodate continuing design improvements in energy recovery systems, the energy recovery fraction is left to the designer as an input parameter.

2.5. Thermal performance model

The flow chart for this model is shown in Fig. 2.

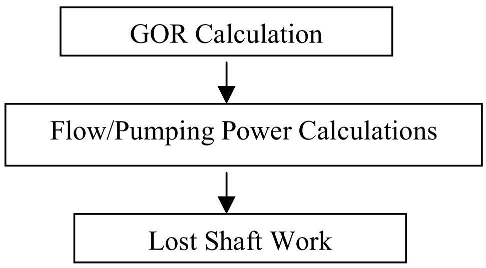

FIG. 2. DEEP-3 thermal performance model

2.6. GOR model

In the DEEP-3 model, the top brine temperature Ttbt is retained as a design parameter and as such, can be input by the user or alternatively, calculated given an input steam temperature as follows:

$$T_{tbt} = T_{steam} - \Delta T_{approach} \quad (1)$$

For the case of thermal vapour compression units coupled to MED or MSF systems, the GOR model is generalized as follows:

$$GOR_{tvc} = GOR(1+R_{tvc}) \quad (2)$$

Where Rtvc is defined as the ratio of entrained vapour flow to motive steam flow, an input design parameter..

Once the GOR is known, the required steam flow could be calculated in a straightforward manner.

Given as input the salt concentration factor CF, the cooling seawater temperature gain ΔTc and the produced distillate flow Wd, estimates for reject brine flow Wb,, make-up feed flow Wf and condenser cooling water flow Wc, could also be calculated as follows,

$$W_b = W_d / (CF\text{-}1) \quad (3)$$

$$W_f = CF.W_b \quad (4)$$

$$W_c = Q_c / (C_c \Delta T_c) \quad (5)$$

Where Qc refers to the final condenser heat load and Cc refers to the specific heat capacity of cooling water. Pumping powers can then be easily calculated. While specific heat transfer areas could also be calculated in DEEP in a straightforward manner, the current approach where user input is expected for specific capital costs ($\$/m^3/day$) is considered adequate for the purposes of DEEP, and is therefore retained. The new version allows values for top brine temperature, steam temperature and GOR parameters to be specified by the user, or alternatively, calculated by DEEP.

2.7. Lost shaft work model

In previous versions of DEEP, the lost shaft work was only calculated for a backpressure configuration, and the lost shaft work for thermally- coupled units, was calculated as follows:

$$Q_{ls} = (Q_{cr}/(1-\eta)).\eta \quad (6)$$

Where $\mathbf{Q_{cr}}$ refers to the condenser heat load,

$$\eta = \eta_{lpt} .(T_{cm}-T_c)/(T_{cm} + 273) \quad (7)$$

Where,

η_{lpt} refers to low pressure turbine isentropic efficiency, and

T_c and T_{cm} refer to the condenser reference and modified temperatures in °C.

In order to properly account for steam extraction cases, equations (6) and (7) are replaced by the following equations:

For the backpressure case,

$$Q_{ls} = (Q_{st} /(1-\eta)).\eta \quad (8)$$

With $Q_{st} = Q_{cr}$

For the extraction case,

$$Q_{ls} = Q_{st}.\eta \quad (9)$$

With $Q_{st} = W_{st}.h_{fg}$

Where hfg is the steam latent heat in J/Kg, assuming saturation conditions and η is redefined as,

$$\eta = \eta_{lpt} .(T_{st}-T_c)/(T_{st} + 273) \quad (10)$$

Where $T_{st} = T_{extracted\ steam}$ in °C

Note that the cases involving available waste heat, such as gas cooled reactors correspond to a backpressure configuration with,

$$T_{cm} = T_{c,} \text{ and } Q_{ls} = 0$$

Which implies free available heat and no lost shaft work.

2.8. RO performance model

The flow chart for the Reverse Osmosis (RO) model is shown in Fig. 3.

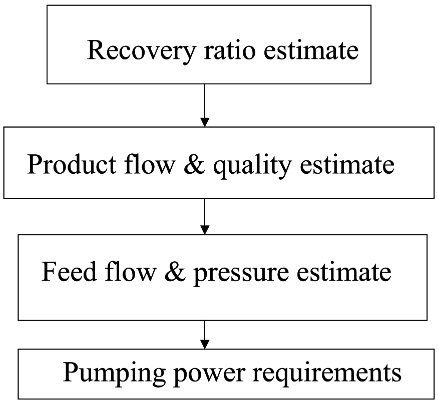

FIG. 3. DEEP-3 RO performance model

Here, again, the user can either specify the system recovery ratio, or have it estimated by DEEP, as follows:

$$R = 1 – C. S_f \tag{11}$$

Where

S_f refers to the feed salinity in ppm and C is a constant defined as

$$C = 1.15E\text{-}3/P_{max} \tag{12}$$

Pmax refers to the maximum design pressure of the membrane in bars.

As feed salinity becomes small, the recovery ratio approaches unity and as it approaches the numerical equivalent of maximum membrane pressure (in millibars), recovery goes to zero, as would be expected in practice. For permeate salinity and feed pressure, the expressions given by Wilf [11] is used. They take into account the feed temperature and salinity correction factors and have been verified against commercial design code data.

The feed pressure Pf is calculated as follows:

$$P_f = \Delta p_d + P_{osm} + \Delta p_l \tag{13}$$

Where

$$\Delta p_d = \varphi_d / \varphi_n. \Delta p_n.c_t.c_s.c_f \tag{14}$$

And

P_{osm} is the average osmotic pressure across the system;
Δp_l is the corresponding pressure loss;
Δp_d and φ_d are the design net driving pressure and flux;
Δp_n and φ_n are the nominal net driving pressure and flux; and
c_t, c_s and c_f are correction factors related to temperature, salinity and fouling.

Permeate salinity S_p on the other hand, is calculated as follows:

$$S_p = (1\text{-}r_m). S_f. \varphi_n / \varphi_d. c'_r. c'_t \tag{15}$$

Where

S_f refers to feed salinity; and

c'_r and c'_t are correction factors related to recovery and temperature.

r_m refers to the membrane salt reject fraction.

For the calculation of energy recovery, previous versions of DEEP considered only the Pelton wheel design. With the emergence of various new technologies such as pressure and work exchangers, and the design variations involved, the energy recovery fraction is introduced as an input design parameter, to properly account for pumping power savings.

3. Further development

In the context of CRP on economic evaluation, various participants have started working on some new developments, which are expected to be available for integration into future DEEP versions: For example, CEA is currently in the process of finishing three developments: Elaboration of detailed correlations for main RO performance parameters such as the recovery ratio, feed pressure, permeate flux etc as functions of three variables: the feed temperature, the feed flow and the feed salinity. These correlations established initially for Filmtec. SW30-HR-380 membranes will be generalised to other membranes and seawater compositions under the Indo-French collaboration agreement and experimentally verified on Indian RO installations.

Development of an MED plant simulator (under a specific IAEA contract), based on the analytical treatment of thermal-hydraulic phenomena, utilising general energy and mass conservation laws. Thermodynamic parameters calculated by the simulator will then be input into DEEP for more precise calculations of desalination costs. Development of an economic method, based on the exergy principle, is made to remove some elements of arbitrary allocations in the power credit method.

Egyptian and Syrian participants in the CRP have developed spread sheet software to estimate the desalted water transport costs, which are expected to be included in future DEEP versions.

4. Conclusion

The IAEA DEEP software has been distributed free to more than 350 scientists/ engineers and researchers from 50 countries interested in cost estimation of desalination plants using nuclear/ fossil energy sources. A number of Member States engaged in nuclear desalination activities in their countries have used DEEP for conducting the feasibility studies of establishing large size nuclear desalination projects based on different nuclear reactors types and desalination processes.

The preliminary cost estimates made by them indicate the water costs from such plants in the range of US$ 0.70 to 1.0 per cubic meters of water. As the cost parameters of both the nuclear reactors and the desalination processes are changing with time due to numerous innovations in the technologies, it is proposed to continuously upgrade the software utilizing the inputs received from the users.

DEEP is not a design code. It should therefore expect parameter input from the designer. Current developments are included in the new version (DEEP-3.1). The code is available for download from the internet. Any feedback from any user is very much welcome.

Acknowledgement

The author acknowledges the valuable effort made during the review of the TECDOC draft by the representatives from the CRP participating Member States: Argentina, China, Egypt, France, India, Republic of Korea, Pakistan, the Russian Federation, Syrian Arab Republic and the United States of America. A special thank is due to S. Nissan and B. Misra for the great work they made during the preparation of this publication.

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Technical and economical evaluation of nuclear water desalination in Tunisia

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Abstract. The present study is a technical and economical evaluation of a co-generation project i. e. a nuclear power plant to generate electricity and desalinate seawater in the Skhira site, in the south east of Tunisia. Four desalination capacities, namely 48000, 144000, 156000 and 192000 m^3/d, were considered in order to examine different scenarios of water supply projects realizations.

The computer code DEEP v3. 04 (2005) was employed. DEEP is a tool developed, by the International Atomic Energy Agency (IAEA), under Microsoft Excel© environment. It estimates the cost of electricity and desalinated water productions for different combinations of power generations (nuclear and non-nuclear) and desalination processes. Several options of these exist in DEEP, among which we've used: Pressurized Water Reactors (PWR), GT-MHR, fossil or Combined Cycle power plants; and the desalination processes MED (with heat recovery or steam racking), RO and MED/RO hybrid system. Several cases of couplings of power plants and desalination processes were considered in this study. Three scenarios for the price of fossil fuels were considered, namely 70, 100 and 120 $/bbl. An 8% interest rate was assumed.

The calculations showed that nuclear power plants have an electricity production cost well below fossil fired plants. In fact, the lowest price is that of the GTMHR, 21% lower than the PWR900, while the latter generates a kWh of electricity 81% cheaper than a CC600 combined cycle.

Also, nuclear desalination is less expensive than fossil desalination. For example, the cost of PWR +RO produced water is 37% lower than that for CC + RO. The lowest cost is obtained by the combination GTMHR + RO. In general, the reverse osmosis (RO) has a lower cost than the MED process regardless of the energy source. The configurations integrating HTR reactors such as the GTMHR are particularly interesting with MED desalination systems.

1. Introduction

The average drinking water supplies in Tunisia are currently 4,5 million m^3/year i.e. around 450 m^3/year and per capita which is below the poverty threshold. Approximately 40% of these resources are underground waters, with salinities between 0.5 and 3.5 mg/m^3. The salinity of the entire resource is relatively high with only 54 % having salinities lower than 1. 5 mg/m^3. Furthermore, 84 % of these good quality drinking waters are located in the north of the country [1].

On the energy side, Tunisia changed status during the last decade from a country with a production surplus (3 Mtep at the beginning of the Eighties and 1,5 Mtep at the beginning of the Nineties) to a net importer of energy (0,6 Mtep in 2004). This is a consequence of the decline of the country oil production and the sustained high growth of the national energy needs (average growth of 4.1% per year for primary energy demand) [2].

The present study is part of a program aimed at finding a technically reliable and economically viable solution to the country drinking water and electricity needs around the year 2020.

2. Assessment of water and electricity demands

a. Electricity demand

Based on the economical performance of Tunisia (a 6.8 % growth of the GDP per year), the electricity demand is expected to grow by an average 6.5 % per year to reach 31 260 GWh in 2020 [1].

An analysis of the peak power demand and the average yearly production and consumption indicates that the Tunisian electrical supply network would be able to support a 600 MWe power plant around 2020 for a consumption peak of 5920 MWe. Consequently, several nuclear solutions can be considered, including:

— One PHWR (600 MWe) or one PWR (900 MWe) if the network gets interconnected with neighbouring countries.
— two modules of the innovating GTMHR reactor (280 MWe each one) if it gets commercialized.
— three modules of the PBMR reactor if it gets commercialized.

It is to be noted that the equipment program of the Tunisian utility, STEG, plans the introduction of the 600 MWe power plant level in 2018 [3].

b. Water needs:

The water demand, for the area comprising Sfax, Skhira and Gabès (the region were most likely the nuclear power plant would be built), was evaluated according to the following two approaches:

— ***i^st^ approach:*** use the current resource assessments (established by the SONEDE, the drinking water supply company in Tunisia) for the area and project the resource needs for 2020. The difference between the needs and current resources gives a deficit, in this case, of 150,000 m^3/day. This represents the high-end estimate of the water supply deficit.
— ***2^nd^ approach:*** Account for the projects planned by the SONEDE, including for example the transfer of 129,600 m^3/day of water from the north to Sfax (project started in 2005) and the addition in 2006 of the 4^{th} line of reverse osmosis (8,500 m^3/d) in the Gabès brackish water desalination station, in the evaluation of the supply. In this case the deficit is reduced to 48,000 m^3/day, which would be the low-end estimate of the water supply deficit.

3. Methodology

The economical evaluation of possible options to fulfil the drinking water and electricity needs for the year 2020 is performed using the DEEP3.04 Computer code developed by the International Atomic Energy Agency (IAEA). DEEP allows:

— the estimation of the costs of electricity, in \$/kWh, and desalted water, in \$/m^3, according to the selected power generation technology and desalination process, and taking into account the site specific parameters
— the comparison of different coupling schemes of the power and desalination plants,
— the identification of the most economical option among the studied schemes.

The DEEP computer code was widely used in studies published by the IAEA and others. In particular, earlier DEEP versions were used in the feasibility studies of the Tunisian desalination project TUNDESAL [1, 4]. However, it was observed that the estimates provided by DEEP 3 differ significantly from those provided by DEEP 2. This is the result of improvements, in the later version, of several models (in particular those dealing with the couplings with the Reverse Osmosis desalination process to take into account advances in the technology). This prompted the update of the study. Furthermore, the comparisons with conventional plants have to take into account the oil price escalation of the recent years.

Presented below are the main hypotheses that served as a basis for the study. Some are related to the power generation while others deal with the desalination plant.

Table I summarizes the hypotheses employed in the economic evaluation of the various electricity production schemes. As the fossil electric generation cost is highly dependent on the price of the primary energy i.e. oil or natural gas, a sensitivity study of the results on fuel prices was conducted. It considers 70 \$/bbl, 100\$/bbl and 120\$/bbl.

According to the Tunisian economic context, the discount rate sensitivity study adopted rates of 5, 8 and 10%.

Table I. Assumptions for the economic evaluation of electricity production [1]

Parameters	Units				
Power station Type		GTMHR	PWR900	CC600	TV600
Estimation year		2006			
Interest Rate	%	5 - 8 – 10			
Total power plant net output	MW_e	286	951	600	600
Total power plant thermal power	MW_{th}	600	2882	1069	1538
Number of power plant units	-	2	1	1	1
Efficiency	%	48	33	51	39
Availability	%	90.2	90.2	90.2	90.2
Construction lead time	Year	4	5	2	3
Specific construction cost	\$/kWe	975	1417	713	1135
Power plant life span	Year	60	40	25	30
Average salary	\$/month	4761	4761	1625	1625
Fossil fuel annual real escalation	%/year	-	-	2	2
Specific nuclear fuel cost (interest rate of 5.8 and 10%)	\$/MWh	6.48, 6.48 and 6.54		-	-

The assumptions related to the desalination plant comprise site -specific data such as the average seawater temperature and salinity, which are for the Skhira site respectively 21°C and 38375 ppm. For the desalination processes, the retained hypotheses are presented in Table II.

Table II. Assumptions related to the desalination processes [1]

Parameters		Units		
Desalination plant type			MED	RO
Estimation year			2006	
Interest rate		%	5 - 8 – 10	
Reference unit size		m^3/d	24000	
Specific construction cost		$\$/(m^3/d)$	900	800
Average salary	Management	$/y	20000	20000
	Labor		7000	7000
Availability			0.91	0.91
Construction lead time		month	12 + number of units	

4. Economical evaluation of different alternatives

a. Electricity production costs

The cost of electricity produced by the various power stations for a discount rate of 8% and 100$/bbl were as follows: 0.023 $/kWh for a (GTMHR), 0.039 $/kWh for a PWR, 0.204 $/kWh for a combined cycle plant (CC) and 0. 273 $/kWh for a fossil fuel steam turbine plant. The nuclear produced electricity is definitely less expensive than the fossil produced electricity. In fact, the 900MWe PWR produces the kWh 81% less expensive than the 600 MWe combined cycle plant CC600. The GTMHR presents the lowest electricity cost: 21% less expensive than the PWR. However, this reactor is yet to be commercialised. So, in case it is not, and since interconnection of the Tunisian network with that of the Great Maghreb is being established, a 900 MWe PWR plant could be envisaged.

The electricity production costs are independent of the desalination technology (MED or RO) and capacity, for values of the latter between 48,000 and 192,000 m^3/day. This is expected since the electricity cost is established independently of the water desalination processes. In fact, for the RO process, the electricity is consumed after its production. While for the MED process, in either case of possible cogeneration, i. e. whether steam extraction from the last stage of the low pressure turbine or recovery of the waste heat from the cold source, heat is extracted after having been used to produce electricity and does not influence the price of produced electricity.

b. Desalted water production costs

As mentioned above, the desalination needs would vary between 48000 m^3/d and 150000 m^3/d according to the estimation approach used. However, considering the fact that the desalination plants present an availability factor around 91%, these values should be raised in order to ensure the daily water production. Also, it is necessary to take into account the commercial modules capacity, usually equal to 24000 m^3/d. Therefore, the following desalination capacities are studied here: 48000, 144000, 156000 and 192000 m^3/d.

All possible combinations of the power (PWR, GTMHR, CC and Fossil steam cycle) and desalination (MED and RO) plants are considered. Usually the GTMHR+RO coupling is not of interest since the main benefit, as far as desalination is concerned, of using a GTMHR is to recover the significant quantity of heat rejected at the cold source, which means that a distillation process would be more adapted. It is covered here for completeness. Furthermore, the case of the hybrid couplings (power station + MED + RO) is studied with the aim of determining if such couplings would make it possible to obtain lower costs of desalination than those with only one process of desalination.

The coupling with the RO process is an electric coupling and as a result does not require any particular optimization. However, to provide the necessary heat to the thermal MED process, two cases are studied, namely steam extraction from a stage of the low pressure turbine (Fig. 1) and waste heat recovery from the cold source (Fig. 2).

Steam extraction case

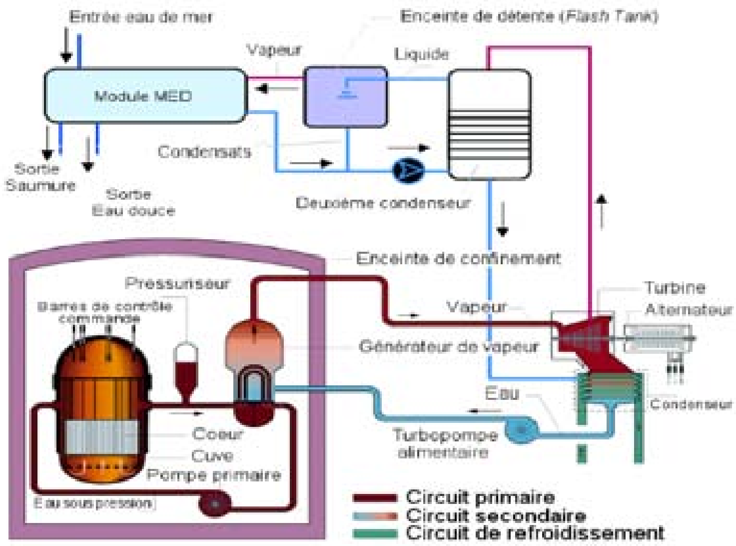

FIG. 1. Schematic of the steam extraction coupling for a PWR+MED combination [1]

As an example, Table III reports the 2020 exploitation costs of the desalted water for different couplings established with the hypotheses of 100 $/bbl of petroleum and 8% discount rate. It is to be noted that for these combinations the desalted water cost is independent of the desalination capacity as long as the latter is a multiple of a unit capacity.

Table III: Desalted water costs for different power-desalination plants couplings.

Power Plant	Desalted Water Cost ($/M^3)	
	MED	RO
Fossil	2.16	0.98
CC	2.14	0.87
PWR	0.73	0.54
GTMHR	0.54	0.47

As evident from Table III, the RO offers lower costs than MED no matter which power generation alternative is used. In fact, for a fossil station combined to an RO desalination plant yields water costs 54% lower than the MED process coupled to the same power station. Similarly for the Combined Cycle, the PWR and the GTMHR, for which the RO coupling produces desalted water respectively 60%, 26% and 13% less expensive than the MED coupling.

It is also obvious that nuclear desalination is way less expensive than its fossil counterpart. Indeed, the most expensive nuclear option, the PWR, would produce desalted water with 37% lower cost than the least expensive fossil fired station, the CC.

Cold source heat recovery case:

This combination is of significant interest especially if high-temperature reactors, such as the GTMHR, are used. In fact, these reactors reject a considerable quantity of heat, enough to operate an MED plant.

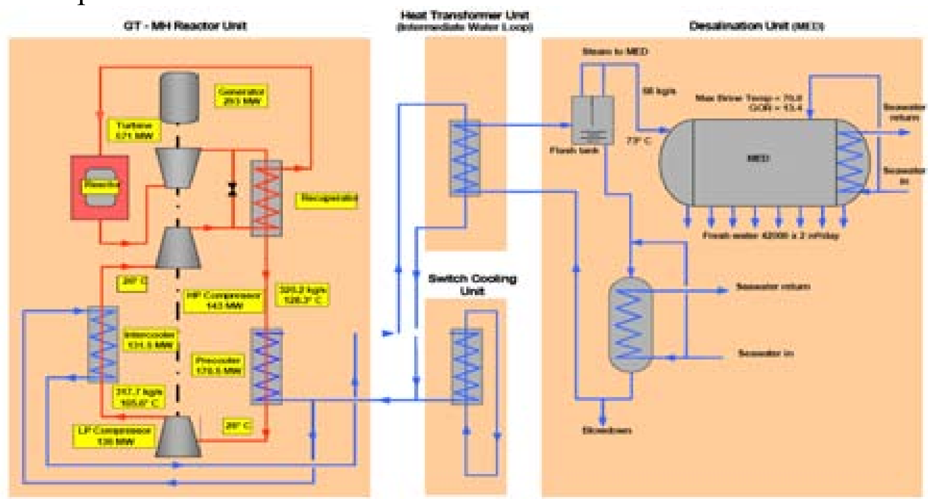

FIG. 2. Schematic of the cold source waste heat recovery for the GTMHR+ MED combination [7]

The characteristics of the GTMHR+MED coupling are presented in Tables IV and V. It can be seen that there is a significant quantity of heat available at the level of the Intercooler and the Precooler, respectively 134,3 MWth and 171,6 MWth for a total of 306 MWth. This substantiates the interest to use a HTR for desalination.

Table IV. GTMR characteristics

Elements	Flow rate (kg/s)	Inlet Pressure (bar)	Inlet Temperature (°C)	Outlet Pressure (bar)	Outlet Temperature (°C)	Power (MW th or e)
Reactor core	320	71.6	493.2	71.5	854.6	**592.6 (th)**
Turbine	320	70.8	854.6	26.1	512.2	**565.5 (e)**
Hot Side Recuperator	320	26.1	512.2	25.8	136.6	**616.7 (th)**
Cold Side Recuperator	320	72.1	117	71.6	493.2	
Hot Side Precooler	320	25.8	136.3	25.6	31.7	**171.6 (th)**
Cold Side Precooler	556.9	8.5	26.4	7	100	
Compressor Low pressure		25.6	31.7	43.2	114	**136.8 (e)**
Intercooler Hot Side	320	43.2	114	42.8	32.2	**134.3 (th)**

Intercooler Cold Side	435.9	8.5	26.4	7	100	
Compressor High Pressure	320	42.8	32.2	72.4	117	**142.1 (e)**

Table V: Characteristics of the GTMHR-MED coupling circuit

Elements	Inlet Flow rate (kg/s)	Inlet Temperature (°C)	Inlet Pressure (bar)	Outlet Temperature (°C)	Outlet Pressure (bar)	Outlet Flow Rate (kg/s)	Power (MWth)
Mixer	556.9 435.9	100 100	7 7	100	6.8	992.8	
Hot Side Heat Exchanger	992.8	100	6.8	26.4	6	992.8	**306.1**
Cold Side Heat Exchanger	1092	23	8.5	90	7.5	1092	
Flash Tank	1092	90	7.5	Liquid: 75 Vapour: 75	0.4 0. 4	1062 29.9	**69.3 to MED**
Mixer (water from Flash Tank and condenser)	1062 29.9	75 75	0.4 0.4	75	0.4	1092	
Hot Side Intermediary Heat Exchanger	1092	75	0.4	23	0. 4	1092	**237.5**
Cold Side Intermediary Heat Exchanger	-	20	3	30	3	-	

In this section, the simulations were carried for an integrated standard hybrid system, combining Power station + MED + RO with different percentages of the water production associated with either of the two processes. The MED is assumed to use the cold source heat recovery. The presented results (Fig. 3) are for the case of a desalination capacity of 192000 m^3/d, an interest rate of 8% and fossil fuel price of 100 \$/bbl.

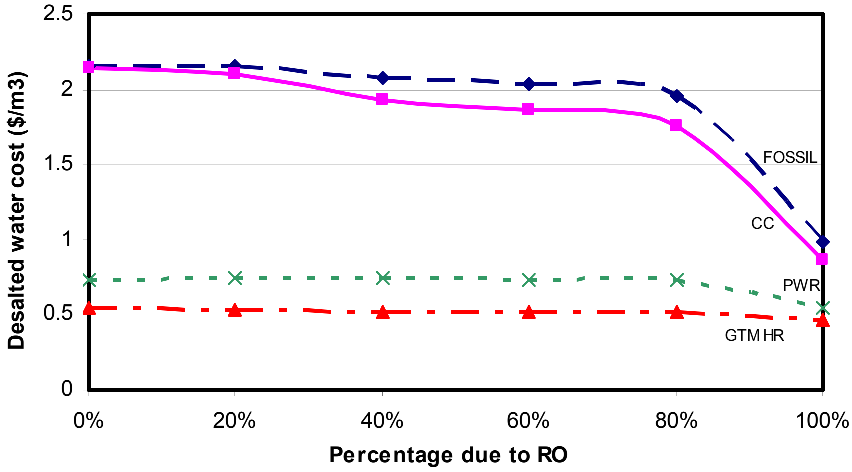

FIG. 3. Desalted water cost as a function of the relative contribution of the RO and MED processes to the total desalination capacity (for waste heat recovery from the cold source).

It can be observed that the nuclear solution, whether PWR or GTMHR, is essentially insensitive to the MED-RO relative contributions. This is actually due to the fact that the annual maintenance costs are increased when two processes are used instead of only one. This offsets the lower cost of RO and gives a nearly constant water rate that decreases only at 100% RO. It can be concluded that hybrid couplings (power station + MED + RO) does not lead to lower desalination costs. It is then recommended to use an RO desalination plant coupled to a nuclear station. The same trends, though not shown here, were also found for hybrid couplings where the heat source for the MED is obtained by steam extraction from a stage of the low pressure turbine.

5. Project profitability

The profitability criterion used here is the Net Present Value (NPV). It is defined as the difference between the sum of the revenues, R_n, and the sum of the operating expenditures, D_n, during the lifetime, T, of the installation, minus the capital investments, A, assumed to be paid the year preceding the start of the project:

$$NPV = -A + \sum_{n=1}^{T} \frac{R_n - D_n}{(1+i)^n}$$

where *i* is the discount rate.

The project with a largest positive NPV is the most profitable.

The Internal Rate of Return (IRR) is another criterion used to measure profitability. The project is profitable as long as its IRR is higher than the discount rate, *i*.

Table VI. Assumptions used in the cost-benefit analysis of the projects

Current year	2006	
Execution year	2020	
Actual water cost	0.14 DT/m^3	0.108 \$/m^3
Actual Electricity cost	0.117 DT/ kWh	0.09 $/ kWh
Price inflation	3 %	
Price of fuel	Fuel : 75$/bbl	Uranium : 6.48 $/MWh

Water sale rate	0.163 $/m^3
Electricity sale rate	0.136 $/kWh
Interest rate	8%
Discount rate	8%
Corporation tax rate	35%
Rate of exchange	1.3 $US/DT
Equipment financial amortization period	40

The economic assessment, according to the hypotheses of Table VI, of the various power and sea water desalination plant options for a capacity of 192000 m^3/d showed that all four alternatives are profitable, with the nuclear option being more profitable than the fossil, as illustrated in Table VII. Similar result trends are obtained for other desalination capacities.

Table VII. Cost-benefit analysis of the projects

Power Plant	Fossil		CC		PWR		GTMHR	
Desalination Plant	MED	RO	MED	RO	MED	RO	MED	RO
NPV (M$)	1774	1873	372	47	5064	5141	3645	3698
IRR (%)	24	25	14	9	29	30	39	41

In fact, the NPV and IRR values of the nuclear desalination projects are higher than those of fossil energies. The highest IRR corresponds to the GTMHR-RO and corresponds to around five times the discount rate. The NPV of the systems integrating the PWR is the largest. This is due to the significant size of this type of installation.

6. Conclusions and prospects

The present study showed the economical advantage of the use of nuclear power for the purposes of power generation and water desalination, in order to meet the drinking water and electricity needs of Tunisia around the year 2020.

The most profitable option seems to be the use of a IVth generation reactor, such as the GTMHR being developed by an International Consortium, or perhaps the projected South African PBMR. These reactors could be coupled to either an RO desalination plant or the MED thermal distillation process with a coupling through waste heat recovery from the cold source. However, in view of their under-development status and in case of the delay of their commercialization, the adoption of a Pressurized Water Reactor (PWR900) or Pressurized Heavy Water reactor (PHWR600) coupled with an RO station would be the best solution.

The economical data for a PWR900 power plant coupled with an RO process (for a discount rate of 8% and a desalination capacity of 48000 m^3 /d), are as follows:

Total investment	: 1850 M$
Cost of the m^3 of produced water	: 0.548 $/m^3
Cost of the produced kWh	: 0.040 $/m^3

Compared to a Combined Cycle standard fossil power station coupled to an RO plant (for the same 8% discount rate and 48000 m^3/d desalination capacity and for an oil price of 100$/bbl), for which:

Total investment	: 555 M$
Cost of the m^3 produced water	: 0.87 $/$m^3$
Cost of the produced kWh	: 0.204 $/$m^3$

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Economic and financial assessment of nuclear desalination plant in Madura Island

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Abstract. In some regions of Indonesia, especially those of coastal boundary, supply of clean water, potable water as well as industry qualified water is not adequate. One of such regions is Madura Island. Besides its water demand that is always increasing, Madura demand for electricity increases more and more. One of alternatives to overcome the scarcity of water supply is seawater desalination plant based on the fact that seawater is available abundantly and it is relatively clean. To operate seawater desalination plant, the required heat and electricity come from power plant. Therefore, a power plant that is coupled with desalination plant need to be constructed. In this study, SMART-type nuclear power plant with capacity of 100MWe is assessed. SMART *(System integrated Modular Advanced ReacTor)* is a pressurized nuclear reactor developed by KAERI (Korea Atomic Energy Research Institute). Meanwhile, MED (Multi Effect Distillation) technology is used due to its economic advantage. The economic and financial assessment of nuclear desalination plant in Madura Island need to be implemented. The assessment of economic feasibility is implemented to see whether the project can produce profit, while that of financial feasibility is implemented to explore any possible source of fund to run the project. Economic assessment covers calculation of electricity generation cost, water production cost and construction cost. Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period will be used as the feasibility criteria in financial assessment. The calculation of economic feasibility shows that electricity generation cost and water production cost of nuclear desalination plant is 4.06 cents/kWh and 104.3 cents/m^3 respectively. While, the total construction cost of nuclear desalination plant is US$ 599.2 million included escalation, Interest During Construction (IDC) and financial fees. The financial feasibility shows that with electricity tariff in amount of 5.417 cent/kWh, for total project funded by foreign loan, local loan and equity, obtained FIRR 12.73%, FNPV in amount of US$ 75.29 million and Payback Period is 8 years. Based on that feasibility criteria indicators, nuclear desalination project in Madura Island can be said as feasible, and from the investment point of view this project is very beneficial.

1. Introduction

It is known that the availability of potable water as well as water for industry is important factor for social development. In some regions of Indonesia, especially those of coastal boundary, supply of clean water, potable water as well as industry qualified water is not adequate. One of such regions is Madura Island. Besides its water demand that is always increasing, Madura demand for electricity increases more and more.

Madura is now connected to Java and Bali electricity grid system—the system is called as Java-Madura-Bali grid or JAMALI grid. Due to this connection, supply of electricity to Madura could be provided by the JAMALI grid, but the water supply is scarce.

One of alternatives to overcome the scarcity of water supply is seawater desalination based on the fact that seawater is available abundantly and it is relatively clean. There are many methods for desalination. In this paper, feasibility of use of nuclear power plant is assessed by considering only economic and financial aspects. This nuclear power plant, produces electricity and also fresh water from its desalination unit. The added value of seawater desalination plant is the side product of concentrated reject water that can be used to produce salt.

The assessment of economic feasibility is implemented to see whether the project can produce profit, while that of financial feasibility is implemented to explore any possible source of fund to run the project. Economic assessment covers calculation of electricity generation cost, water production cost and construction cost. Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period will be used as the feasibility criteria in financial assessment.

In this study, SMART-type nuclear power plant with capacity of 100 MWe is assessed. SMART *(**S**ystem integrated **M**odular **A**dvanced **R**eac**T**or)* is a pressurized nuclear reactor developed by KAERI (Korea Atomic Energy Research Institute). Meanwhile, MED (Multi Effect Distillation) technology is used due to its economic advantage. The target of water production capacity that can be achieved by MED is approximately 40,000 m^3/day [2]. The assessment is carried out using Desalination Economic Evaluation Program (DEEP) version 2.1, from the IAEA [3].

2. Desalination processes [4]

Desalination processes are divided into (i) thermal methods, which involve heating water to produce water vapour, and (ii) membrane processes, which use a relatively permeable membrane to transport either water or salt to induce two zones of differing concentrations to produce fresh water. The main thermal method is distillation, where saline water is progressively heated in subsequent vessels at lower pressures. Brief descriptions of the main desalination processes are provided below.

2.1. Distillation processes

Multi Stage Flash (MSF) is the most widely-used desalination method worldwide. It involves heating saline water to high temperatures and passing it through vessels of decreasing pressures to produce the maximum amount of water vapour (fresh water).

Multi-Effect Distillation (MED) operates at lower temperatures but uses similar principles as that of MSF distillation.

Vapour Compression (VC) is generally used in combination with other processes, where the heat for evaporating water comes from the compression of vapour, rather than the direct exchange of heat.

2.2. Membrane processes

Reverse Osmosis (RO) is a pressure-driven process which forces saline water through a membrane, leaving salts behind.

Electrodialysis is a voltage driven process and uses an electric potential to move salts selectively through a membrane, leaving fresh water behind.

Desalination processes are used commercially to provide fresh water for many communities and industrial sectors around the world. The Middle East region has the majority of the desalting capacity, whereas Australia has only one percent of the total world capacity. The installed world capacity consists mainly of multistage flash (MSF) and reverse osmosis (RO) processes, with the remainder made up of multi-effect distillation (MED), electrodialysis and vapour compression. The installed capacity of membrane and thermal processes is about equal, but most older plants are distillation units which become aged and need replacement, so it is probable that the total operating capacity of membrane units will progressively exceed that of thermal units. Reverses osmosis (RO) desalination for brackish water is the most utilised method in Australia.

3. Financial feasibility criteria[1]

In carrying out financial analysis, technique or criteria should be develop or used as feasibility measure of the project. The criteria applied in the study are as the following:

(a) Financial Net Present Value, FNPV;
(b) Financial Internal Rate of Return, FIRR, and
(c) Capital Payback Period

3.1. Financial net present value, FNPV

FNPV is present value of revenue flow, which is produced by investor. This parameter is multiplication between *cash flow* and *discount factor*. Cash flow is calculated from total revenue minus total cost, which mathematically can be written as follows:

$$FNPV = \sum_{t=1}^{n} (Pn - Cn)(1+i)^{n} \qquad (1)$$

with

Pn is total gross revenue year-*n*.
Cn is total gross cost year-*n*
i is interest rate

This value of FNPV is different in use of different discount factor. There is trend that the smaller discount factor the bigger FNPV would be obtained.

This feasibility criteria of FNPV gives indication as follow:

FNPV = positive Project feasible/can be received, higher FNPV better
FNPV = negative Project not feasible/can not be received
FNPV = 0 neutral/break even

3.2. Financial internal rate of return, FIRR

FIRR of an investment can be defined as interest rate *i* that will cause the value of cost/investment equals to the value of benefit.

Calculation method of FIRR is different with that of B/C method. In B/C method, the discount factor is selected *a-priori*, but in FIRR, the discount factor is calculated. Therefore, optimum FIRR value can be obtained if:

$$B - C = 0 \qquad (2)$$

where

B = *discounted benefits*
C = *discounted cost*

Some analysts sometime prefer to use value of *Net Benefit* than that of *Gross Benefit* since the usage of net benefit, obtained FIRR parameter is more assuring.

In FIRR calculation, *trial and error calculation* is needed for obtaining FNPV equals to zero. . . . . . The method that was often used is with interpolation based on calculation of biggest and smallest discount factor[1]. This method is mathematically written as follows:

$$FIRR = i_1 + \Delta i(AK_{i1} /(AK_{i2} - AK_{i1})) \quad (3)$$

where

i_1 = lowest capital interest
Δi = difference of highest and lowest capital interest
AK_{i1} = cash flow at lowest interest
AK_{i2} = cash flow at highest interest

FIRR calculation is implemented by assuming that all revenues in one single year will be reinvested in the subsequent year. FIRR calculation method is also used by the World Bank or other international Finance Institutions.

Feasibility criteria of FIRR gives indication as follows:

FIRR > wanted interest rate (i), project feasible/accepted
FIRR < wanted interest rate (i), project not feasible/not accepted
FIRR = wanted interest rate (i), project not feasible/not accepted

3. 3. Capital payback period (Payback period, p)

Payback Period (p) is duration needed to return investment capital, which is calculated from *net cash-flow*. Net cash flow is a difference between revenue and expenditures every year. Payback Period is an indicator on how many years are needed for the project to cover the investment cost.

Calculation of *Payback Period (p)* method is as follows:

$$\sum_{t=1}^{t=p} b = M \quad (4)$$

with

t = time
p = *Payback period,,* is time needed so that investment can return

b = benefit of project
M = capital

This *Payback Period* method seems simple and easy to be carried out quickly; however in practice it has sometime also difficulty, especially in calculating benefit. But if the project has been executed well without obstacles, this method is very usefull because *Payback Period* can be used as tool for checking level of FIRR value. As is known, the realtionship between FIRR and *Payback Period (p)* is expressed as follows:

$$FIRR = 1/p \quad (5)$$

This feasibility criteria of *Payback Period* gives indication that a project with faster payback period will be preferred by investor.

The feasibility criteria that indicate feasibility of a project is summarized in Table I.

Table I. Project feasibility indication

Feasibility Criteria	Unit	Feasibility Indication
FNPV	(US $)	positive
FIRR	%	> *i* (where *i* is wanted interest rate)
Payback Period	years	Faster better

4. Assumption and input data

4.1. Assumptions

Assumptions used in this calculation are as the following:

(a) Construction period: 3 (three) years (year 2012 - 2014).
(b) Level of financing disbursement during construction period
1st year: 19%
2nd year: 43% and
3rd : 38%.
(c) Local portion level of *Total Basic Costs* :17.08%.
(d) Tariff (selling price) of desalination water product produck is assumed 0 US$/$m^3$ because it is subsidized totally from electricity tariff.

4.2. Input data

Data used in this study are noted in Table II to Table VI covering technical and economic parameters, data of SMART and desalination plant and estimation of SMART investment cost.

Table II. Technical parameter

Technical parameter	Unit	Value
Average annual seawater temperature	^oC	30
Environmental air temperature	^oC	32
Total Dissolved Solid (TDS)	ppm	34,000

Based on *Indonesia Key Requirement* in joint study between BATAN and KAERI, the seawater reference temperature is 30^{o}C, whereas for TDS is 34,000 ppm.

Table III. Economic parameter

Item	Reference Value
Reference Currency	US $ (January 2004)
Operation Date	1 January 2015
Economic Plant Life of SMART	40 years
Availability	
- Base power plant	80%
- Desalination Plant	96%
Discount Rate	10%
Interest Rate	8%
Nuclear fuel escalation	0%/year

Real escalation for nuclear is 0%/year based on *The Study of Comprehensive Energy Assessment in Indonesia.* Discount rate is set at a number of 10% and interest rate is assumed to be 8%. All technical and economic data of SMART, such as specific construction cost, O&M cost and specific fuel cost are taken from KOPEC *(**KO**rean **P**ower **E**ngineering **C**ompany)*. Economic Life-time for nuclear is 40 years, whereas capacity factor is assumed to be 80%.

Table IV. Data of SMART

Item	Unit	SMART
Capacity	MWe	2 x 100
Net thermal efficiency	%	33
Construction lead time	Month	36
Specific construction cost	US$/kWe	1,615
O&M cost	US$/MWh	5.59

Table V. Data of MED desalination plant [5]

Item	Unit	MED
Unit size	m^3/d	4,000
Base unit cost	$\$/(m^3/d)$	926.7
Water plant lead time	Month	12
Average management salary	$/a	6,000
Average labour salary	$/a	3,600
Specific O&M spare part cost	$\$/m^3$	0.03

***C**omponent and **C**ost **B**reakdown **S**tructure* (CCBS) data of SMART is not obtained yet, so it is estimated in Table VI. This data of SMART investment cost estimation is taken from KOPEC.

Table VI. Estimation of SMART investment capital cost

Item	Scope of supply	SMART 1 Unit	SMART 2 Units
NSSS & T/G	NSSS Package including system design and T/G Package	48,938	95,429
Civil/Structure, Architecture	Equipment & Site Materials for construction works, including consumable, construction equipment and tools, etc.	27,883	52,978
Electrical and Mechanical Work	- Equipment & Site Materials for Installation work, including site materials, consumable, construction equipment and tools, etc. - Commissioning and Start-up testing	67,262	127,797
Direct Cost (1000 US$)		144,083	276,204
Engineering	Design and Engineering including civil/arch., piping, electric and I&C, etc., Project Management	13,403	20,105
Owner's cost	Ocean Freight & Insurance, Owner's Organization	6,717	12,897
Indirect Cost (1,000 US$)		20,121	33,002
Project Contingency (1,000 US$)		7,204	13,810
Total Cost (Defined as Overnigh Costs) (1,000 US$)		171,408	323,017
Capacity (MWe)		100	200
Unit Capital Cost (US$/kW)		1,714	1,615

* Cost reference : 1 January 2002

* Unit Capital Cost (US$/kW):

= (Total Cost (Defined as Overnight Costs)) / Capacity

= (Direct Cost + Indirect Cost + Project Contingency) / Capacity

= (144,083 + 20,121 + 7,204) / 100 and (276,204 + 33,002 + 13,810) / 200

= 1,714 US$/kW (for 1 unit) and 1,615 US$/kW (for 2 unit)

The estimation of SMART investment capital cost (Table VI) and that of desalination plant that are divided according to the level of foreign component and local component for every item is shown in Table VII.

Table VII. Level of foreign and local components of SMART and desalination plant

No.	Item			Total (10^6 US$)
1	NSSS/TG			
	a. base cost			95.4
	- Korea			95.4
	- Local (0%)			-
2	Civil/Structure, Architectual			
	a. base cost			53.0
	- Korea			26.5
	- Local (50%)	26.5		
3	Electrical and Mechanical Work			
	a. base cost	127.8		
	- Korea	115.0		
	- Local (10%)	12.8		
4	Design & Engineering			
	a. base cost	20.1		
	- Korea	20.1		
	- Local (0%)	-		
5	Desalination plant			
	a. base cost	3.7		
	- Korea	2.2		
	- Local (40%)	1.5		
6	Owner's costs			
	a. base cost	12.9		
	- Korea	-		
	- Local (100%)	12.9		
7	Contigency			
	a. base cost	13.8		
	- Korea	11.7		
	- Local	2.1		
Local Portion		55.8	17.08%	
Foreign (Korea) Portion		270.9	82.92%	
Total Basic Costs		326.7	100%	

It is known from Table VII that the base cost of desalination plant (3.7 x 10^6 US$) is obtained from multiplication between base unit cost (4,000 m^3/d) and base unit size (926.7 US$/($m^3$/d)) in Table V. It is also known that the level of local and foreign portion in basic costs is 17.08% and 82.92% respectively.

4.3. Sources of fund

Source of funds is assumed based on conventional schemes: funded by the vendor that come from local loan and foreign loan, and equity. Source of foreign fund come from EXport IMport Bank *(EXIM Bank)* of SMART vendor country, Korea. For local financing, funded by local Commercial Bank with interest rate that valid in market. Meanwhile, the equity is the rest of total loans.

Foreign loan

Source	: Korean EXIM Bank
Amount	: 85 % of total suply of foreign component US$ 230,290,000
Currency	: Dollar Amerika (US$)
Interest Rate	: 7.65 % / year
Financial Fees	: Commitment fee: 0.5 %, Insurance fee: 3.4 %, Management fee: 0 %

Domestic loan

Source	: Local Commercial Bank
Amount	: 85 % of total suply of local local component US$ 47,400,000
Currency	: US Dollar (US$)
Interest Rate	: 13 % / year
Financial Fees	: Commitment fee: 0.5 %, Insurance fee: 0 %, Management fee : 0 %

<u>Equity</u>

Amount	: 16.3 % of total suply of local and foreign component US$ 48,600,000
Currency	: US Dollar (US$)
Interest Rate	: 13 % / year

5. Result and analysis

5.1. Electricity generation cost and water production cost

Levelized power generation cost which is obtained from running DEEP Program is 0.0406 US$/kWh or 4.06 cents/kWh. It is relatively cheaper than that of fossil power such as combined cycle and gas turbine with equivalent capacity. While, total water production cost with using desalination technology of MED is 1.043 US$/m^3 or 104.3 cents/m^3. The cheaper production cost does not mean that the project will obtain benefit. Economic feasibility based on its construction cost should be done.

5.2. Construction cost of nuclear desalination plant (coupling of SMART & MED)

Calculation results of contruction cost of electricity plant (NPP SMART) that is coupled with desalination plant (MED type), is obtained as follows:

Table VIII. Construction cost of nuclear desalination plant (coupling of NPP SMART & MED)

No.	Investment Profile	Base Cost (10^6 US$)
1	NSSS & T/G	95.4
2	Civil/Sturcture, Architectual	53.0
3	Electrical and Mechanical Work	127.8
4	Design & Engineering	20.1

No.	Investment Profile	Base Cost (10^6 US$)
5	Owner's Cost	12.9
6	Contigency	13.8
	Overnight Cost of SMART	**323.0**
7	Desalination plant (MED)	3.7
	Basic cost of SMART + MED	**326.7**
8	Escalation	217.0
	Fixed cost of SMART + MED	**543.7**
9	Interest	40.4
10	Financial Fee	15.1
	Construction Cost of SMART + MED	**599.2**

Construction cost of nuclear desalination plant (coupling of NPP SMART and MED) can be obtained with using calculation as follow:

$$\text{Construction Cost Of SMART + MED} = \underbrace{\underbrace{\text{Overnight Cost Of SMART} + \text{Desalination Plant Investment}}_{\textit{Basic Cost of SMART+MED}} + \textit{Escalation}}_{\textit{Fixed cost of SMART+MED}} + \textit{Interest} + \textit{Financial Fee}$$

Overnight cost of SMART is in the amount of US$ 323.0 x 10^6 plus investment cost of desalination plant (MED) of US$ 3.7 x 10^6 yaitu US$ 326,7 x 10^6 is basic cost of SMART & MED. The base cost will be fixed cost in amount of US$ 543.7 x 10^6 with added escalation. This fixed cost after addition of interest and financial fees will be the total construction cost of SMART & MED,i.e. in amount of US$ 599.2 x 10^6.

5.3. Economic feasibility of nuclear desalination plant (Coupling of NPP SMART & MED)

Based on construction cost of nuclear desalination plant (coupling of SMART & MED) and by using available data and assumptions, DEEP Program shows the level of financial feasibility criteria of nuclear desalination project which in Table IX.

Table IX. Financial feasibility criteria of nuclear desalination plant (SMART & MED)

No.	Parameters	Unit	Value
1.	Rate of Return (Total)	%	10.00
2.	Financial Internal Rate of Return (FIRR) for PROJECT	%	12.73
3.	Financial Net Present Value (FNPV) for PROJECT	M US $	75.29

No.	Parameters	Unit	Value
4.	Tariff	cent/kWh	
	Before VAT		4.733
	After VAT		5.417
5.	Investment Payback Period for PROJECT	Year	8

VAT = *Value Added Tax*

The Level of FIRR from nuclear desalination project funded by foreign loan, local loan and equity is 12.73%. For determining wether this project feasible or not, we need to compare it with investment in the other sector, such as interest rate of bank, level of stock divident, or other investment. If compared with interest rate of US $ currency, which taken average 6%, so this project is very feasible and interesting for investor.

The level of FNPV from nuclear desalination project funded by foreign loan, local loan and equity is positive, in amount of US$ 75.29 million. Based on this value of FNPV one can say that this project is feasible because it will produce benefit at the end of its economic lifetime at about US$ 75.29 million.

The level of payback period from nuclear desalination project funded by foreign loan, local loan and equity is 8 years. This payback period is very short compared to the economic lifetime of nuclear desalination plant (40 years). This means that total investment of nuclear desalination plant can be covered before its economic lifetime, so that this project can be said very feasible.

From discussion of each criteria or indicator of economic feasibility above one can conclude that with electricity tariff (after VAT) about 5.417 cent/kWh, the project of nuclear desalination is still very beneficial. From investment point of view, all the calculation results show that the project is in good prospect.

In this study, the electricity tariff is calculated to be 5.417 cent/kWh, and it may be too high. This result is obtained based on assumption that the tariff of desalination water product is nil US$/$m^3$ because it is subsidized totally from the electricity tariff. The electricity tariff can be reduced by other means such as setting the tariff of water, taking into account the salt production, finding low interest rate, etc.

6. Conclusion

Economic and financial assessment of nuclear desalination plant in Madura Island has been done, and some insight can be concluded as the following: From this study can be taken some conclusions, such as:

(i) Calculation results, with electricity tariff in amount of 5.417 cent/kWh, for total project funded by foreign loan, local loan and equity, obtained FIRR 12.73%, FNPV in amount of US$ 75.29 million and Payback Period is 8 years.

(ii) Based on the indicators, nuclear desalination project in Madura Island can be said as feasible, and from the investment point of view this project is very beneficial.

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HIGH TEMPERATURE APPLICATIONS

SESSION 4 (PARALLEL SESSION)

Chairpersons

S.J. Herring
United States of America

A.I. Miller
Canada

A review of Canadian advances in thermochemical hydrogen production within the context of conventional hydrogen production

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Abstract. The paper discusses the AECL programme on nuclear hydrogen production. As a near term solution, the conventional low temperature electrolysis (LTE) using off-peak electricity has been considered. In the long term goals, use of super critical water cooled reactors (SCWR), a reactor concept under development at AECL, has been proposed for part of the sulphur thermochemical cycle namely decomposition of sulphur tri oxide using direct electric heating over a catalyst. The cooperative programme with USDOE Argonne National Laboratory on copper chloride cycle using SCWR has been discussed. This involves the electrolytic conversion of cuprous chloride to cupric chloride. AECL cooperates with Generation IV International Forum with expertise on the behaviour of tritium (produced in the primary circuit of helium coolant in Very High Temperature Reactors) and its clean up.

1. Introduction

Conventional production of hydrogen preponderantly uses steam-methane-reforming (SMR) but its advantage has been severely eroded by the recent rise in price of hydrocarbons and the need to sequester the carbon dioxide that is co-produced. This is strengthening the economic case for using electricity from a nuclear (or other non-CO_2 producing source) to produce hydrogen by conventional low-temperature electrolysis (LTE). To compete with SMR technology, LTE is best applied intermittently when the value of electricity is low. While we believe LTE is likely to become a widespread and entrenched hydrogen production technology, high temperature processes may come into contention after about 2025.

AECL is collaborating with international partners in several technologies that could lead to enhancements of hydrogen using in direct cycles of thermochemical decomposition. Processes based on thermochemical decomposition of sulphur trioxide are currently seen as the leading contenders for this application. AECL is developing technology using direct electric heating for sulphur trioxide decomposition over a catalyst. A small amount of electricity could then supplement heat energy provided at the lower temperature obtained from SCWRs. For a process with an intrinsically lower temperature requirement, AECL is collaborating with the USDOE's Argonne National Laboratory to develop thermochemical cycles based on CuCl $CuCl_2$. The 510°C temperature needed for the thermochemical production of CuCl from $CuCl_2$ and cupric oxide (CuO) is within the reach of AECL's SCWR reactor concept.

2. Technologies for hydrogen production

Figure 1. shows the evolution of CANDU rectors from current generation CANDU to CANDU X in the next twenty years. As mentioned above, most of the research work on hydrogen production is based on the heat and electricity from SCWRs by appropriately applying the relevant electrochemical techniques in some stages of the SI or CuCl cycle.

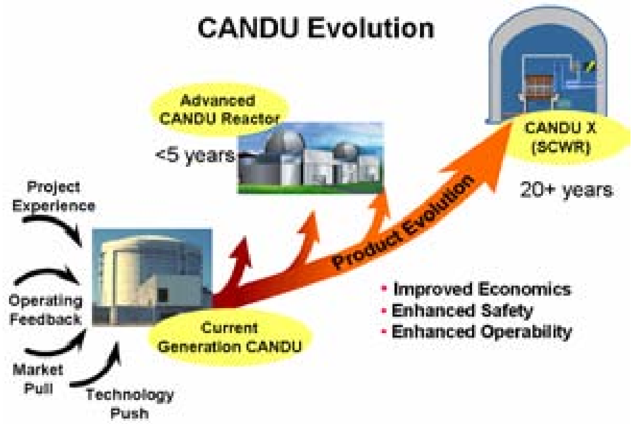


FIG. 1. CANDU evolution

The salient aspects of CANDU X concept are as below:

- Started in 1994 as Candu X Program
- Establish the design limits and ultimate potential
- Main CANDU features are retained.
  - Horizontal modular channels.
  - Heavy water moderator.
- Supercritical light water coolant (higher efficiency).
- Advanced fuel channel design (internal insulation without calandria tube).
- Options systematically studied
  - Mark 1: indirect cycle $T_{out} \sim 400^{+}$ °C set by existing Zr
  - Mark 2: direct cycle $T_{out} \sim 600^{+}$ °C set by existing turbine
  - Mark 3: multiple cycle T_{out} $>850^{+}$ °C set by known materials

3. Comments on hydrogen deployment

The vision of the "Hydrogen Economy" is often presented as the introduction of road vehicles powered by fuel cells, perhaps starting in significant numbers during the second decade of the 21st century. We see this as an incomplete view and believe extensive deployment of hydrogen fueled road vehicles will lag other demands for hydrogen. Already, as light, sweet crude become increasingly rare, huge amounts of hydrogen production capacity are being added both to remove sulphur and to improve the crude's quality. This is particularly the case with the bitumen produced in the Athabaska oil sands in northern Alberta. Even where hydrogen will be used directly as a transportation fuel, trains and ships are more likely centres for early demand than road vehicles. There is an important similarity between both these transportation applications and oil upgrading: the demands will occur much sooner and be far more localized with substantial quantities produced in a few locations. These demands are likely to emerge well before readiness of any processes depending on deployment of high temperature nuclear reactors. For nuclear to play a significant role in the early phases of the Hydrogen Economy, we predict that it will be through deployment of LTE technology in quite large plants.

4. High temperature H_2 production technologies

While we believe LTE is likely to become a widespread and entrenched hydrogen production technology, high temperature processes may come into contention after about 2025. AECL is collaborating with international partners in several technologies that could lead to enhancements of hydrogen using in direct cycles of thermochemical decomposition.

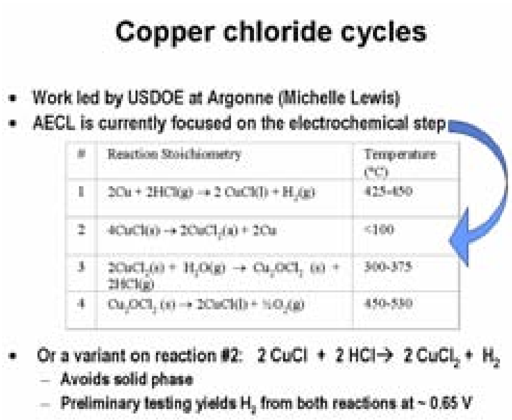
Processes based on thermochemical decomposition of sulphur trioxide are currently seen as the leading contenders for this application. They require process heat at 850°C, which is well beyond the capacity of several lines of advanced reactors under development (e.g. Super Critical Water Reactors (SCWRs), Sodium Cooled Fast Breeders, and other Liquid Metal Reactors). However, this sulphur trioxide decomposition requires comparatively little energy for decomposition relative to the requirement for the preceding dissociation of sulphuric acid (at about 500°C). So AECL is developing technology using direct electric heating for sulphur trioxide decomposition over a catalyst. A small amount of electricity could then supplement heat energy provided at the lower temperature. The proposed scheme is indicated as below:

The H_2SO_4 Side of I/S and other S Cycles

- $H_2SO_4 \rightarrow SO_3 + H_2O$
  - Majority of energy; lower temperature (< 500ºC)
- $SO_3 \rightarrow SO_2 + ½ O_2$Minority of energy; higher temperature (> 700ºC)
  - Could avoid a high temperature reactor by providing direct electric heating of a substrate on which catalyst deposited
  - Work so far on selecting catalysts

For a process with an intrinsically lower temperature requirement, AECL is collaborating with the USDOE's Argonne Laboratory to develop thermochemical cycles based on CuCl $CuCl_2$. With the reaction proceeding to the right, hydrogen is co produced; to the left, and oxygen is co produced. Electrolysis is needed for the conversion of cuprous chloride (CuCl) to cupric chloride ($CuCl_2$) and AECL's role in the partnership is development of this step.

The 510°C temperature needed for the thermochemical production of CuCl from $CuCl_2$ and cupric oxide (CuO) is within the reach of AECL's SCWR reactor concept. For higher temperatures, AECL also envisages adaptation of its pressure tube technology to provide reheater channels as a way of delivering higher temperatures than emerges from the main channels. The reaction scheme is as below:



AECL is, in addition, providing its international partners in the Hydrogen Production Project Management Board of the Generation IV International Forum with expertise on the behaviour of tritium (produced in the primary circuit of helium coolant in Very High Temperature Reactors) and its clean up.

Survey on 20 years of research & development on nuclear process heat applications in Germany

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Abstract. Germany looks back to more than two decades of comprehensive R&D activities on non-electricity applications of nuclear power. Efforts were basically centered around the High-Temperature Gas-Cooled Reactor (HTGR) which is deemed to represent a suitable concept for safe, efficient, and economic generation of both electricity and heat for high temperature industrial processes including the production of hydrogen and/or liquid hydrocarbons for the transportation sector. Due to the large coal resources available, German activities starting in the 1970s were focusing on the utilization of nuclear energy in the heat-intensive process of coal gasification. The "Prototype Plant Nuclear Process Heat" (PNP) project was launched in cooperation with partners from the coal and the nuclear industries with the main objectives to upgrade the pebble-bed HTGR for high coolant outlet temperatures of 950°C and to develop and test respective heat exchanging components. Different methods of gasification for the two types of coal, hard coal and brown coal (lignite), have been developed for a power level representative for large and medium-sized plants (~125 MW) and successfully tested in the 10 MW range demonstrating their industrial feasibility at a high reliability. Further studies included the production of hydrogen by nuclear steam reforming of methane for energy storage, transportation, and recovery of the stored energy. This closed-cycle process was experimentally verified under nuclear conditions at a 10 MW scale in the test facilities EVA and ADAM. The particular safety aspects of a nuclear process heat complex have been studied in detail targeting, e.g., the tritium contamination of the product and the consequences of potential explosions of flammable gas mixtures. Future activities should concentrate on a re-evaluation of the above mentioned studies from the past by comparing against current technologies and market conditions with the goal to select highly promising projects, and should also include respective safety considerations.

1. Introduction

High Temperature Gas-Cooled Reactors (HTGR) are characterized, among other beneficial features, by their operation at an average coolant exit temperature of up to 950°C which is mainly limited by the material properties of the metallic components. Such high temperatures make this concept ideally suitable for more than just power production. The high temperature provided by an HTGR could be rather utilized as process heat and/or steam in numerous industrial processes.

The Federal Republic of Germany has spent around 4 billion US $ on R&D for HTGRs. A significant part of the efforts was dedicated to the design and demonstration of the ability of HTGRs to be used for process heat applications. The 45 MWt AVR in Jülich, the world's first pebble-bed reactor, was operated over more than 20 years until shutdown in 1988, successfully proving the feasibility of the HTGR concept under high temperature process heat conditions with a high availability.

The two decades of R&D, as mentioned in the title, refer to the time period starting at the beginning of the 1970s. Under the impact of the former oil crises, most work was done within the frame of the so-called "Prototype Plant Nuclear Process Heat", PNP, project. In the following chapters, this long-term project and its achievements will be described in further detail completed by additional information from congenial activities in Germany.

2. The development of an HTGR for nuclear process heat applications in Germany

The German PNP project was a cooperation between the HTR industries (Hochtemperatur-Reaktorbau GmbH, Mannheim, and Gesellschaft für Hochtemperaturreaktortechnik mbH, Bensberg), the coal industries (Bergbauforschung GmbH, Essen, and Rheinische Braunkohlenwerke AG, Cologne), and the nuclear research center Kernforschungsanlage Jülich (today: FZJ). The project was funded by the Federal Government, the State Goverment of Northrhine Westphalia, and the participating industries.

Motivation for the PNP project was to take advantage of the large resources of the energy carriers coal and uranium and to find for the coal an additional spot on the heat market in order to diversify the energy supply in Germany and to reduce its dependency on imports of oil and natural gas. Furthermore a great advantage was seen in the nuclear production of easy-to-handle energy carriers such as substitute natural gas (SNG), synthesis gas (H_2 + CO), reductive gas, or – on a longer term – hydrogen by thermochemical water splitting cycles, and having at the same time a reduction of the specific noxious gaseous emissions.

The main objective was the development, design, and construction of an energy system based on a combination of German coal and nuclear power, including the developing and prototype testing of a nuclear heat generating system to be operated at a 950°C gas outlet temperature, intermediate circuit, heat extraction, coal gasification processes and nuclear energy transport.

2.1. Reactor design

The concept for a nuclear process heat reactor was originally based on thermal power sizes of 500 MW (PR-500) and 3000 MW (PNP-3000), respectively. The PR-500 pebble bed reactor was designed to produce 523 t/h of steam at a temperature of 265°C and a pressure of 2 MPa plus an electric power of 55 MW. Helium coolant was heated up from 265°C to 865°C. The reactor was placed in a prestressed concrete pressure vessel surrounded by three units each containing heat exchanger and blower [1]. The large-size reactor concept of the PNP-3000 was foreseen to be connected to steam reforming with 1071 MW heat input (to eight units in four loops) and electricity cogeneration with 540°C/19.5 MPa turbine steam.

As most chemical processes are performed at lower pressures some adaptation of the reactor design and of the chemical process has been necessary. Therefore, the reactor pressure had been fixed in the PNP project to 4 MPa being much below the pressure for electricity generating plants (~7 MPa). The choice of the pressure is also important to reduce the loads on the high temperature barriers in case of depressurization accidents either in the primary or in the secondary circuit. Other important aspects of reactor design are the amount of cogenerated electricity, high availability requirements as well as an optimization towards significant simplification of the nuclear island. Heat transfer under varying operational load conditions, hot gas mixing in the core bottom, or the lifetime of hot gas thermal insulation have been comprehensively investigated in experiments. Seismic behavior of the core structures was examined using the SAMSON three-axial vibrational test facility confirming the good-natured behavior with no significant compaction of the pebble bed core.

More concepts of nuclear process heat HTGRs of smaller size have been proposed later, among them the modified versions of the HTR-Module and the AVR reactor, or the “RUHR-

100” dedicated to syngas generation from hard coal. All are characterized by a supply of energy at high temperature levels in the order of 950°C, which allows the yield of high chemical reaction rates. Respective heat exchanging components, a steam reformer with a steam generator installed in series or a He/He intermediate heat exchanger (IHX), were developed, manufactured, and tested as well as the hot gas duct connection to the nuclear core. Unlike conventional fossil-fueled components, the helium-heated components of the HTGR have to meet the more stringent requirements of a „nuclear“ component in terms of construction, quality assurance, and scheduled re-testing. They have the important function of forming a radioactivity barrier between the primary helium and the process gas.

2.2. Coal gasification

Because of its abundant resources on earth, the conversion of coal to gaseous or liquid fuels has been worldwide commercially applied. In Germany, hydrogen-rich coal gas produced from the coke furnace process, was already in use more than 100 years ago, when it was fed into the municipal gas grids. With the FZJ located in the coal-rich State of Northrhine-Westfalia, a central subject of R&D was here the utilization of nuclear energy in the heat-intensive processes of coal gasification. Within the German PNP project, two processes of coal gasification have been investigated in detail (see schematic in Fig. 1): hydro-gasification of brown coal (lignite) and steam-coal gasification of hard coal where the gasification medium is either steam or hydrogen.

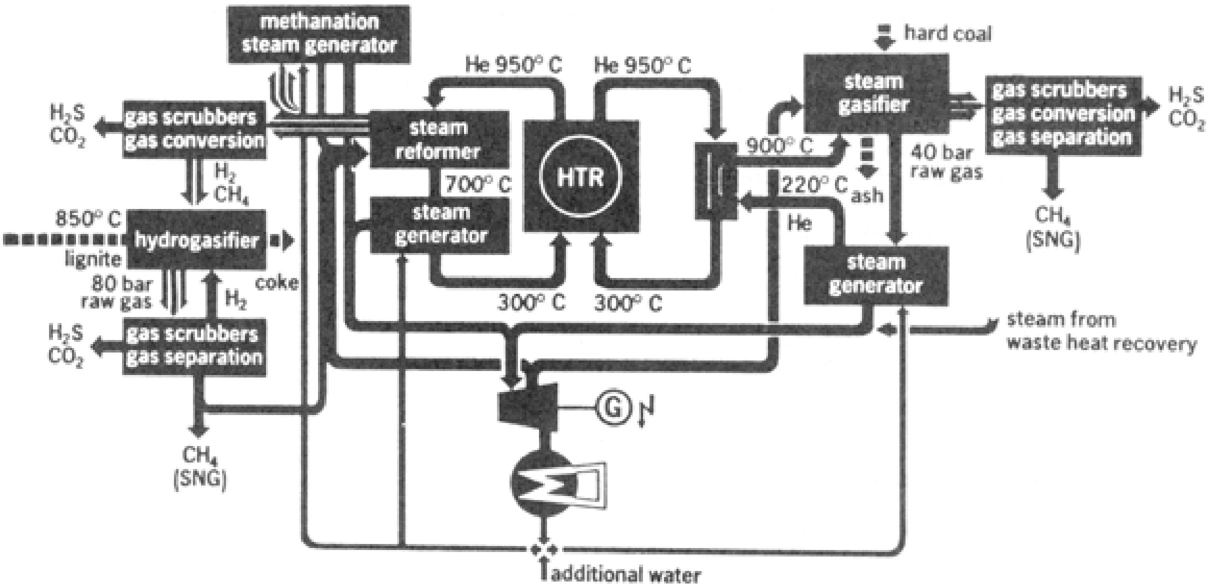

FIG. 1. Schematic of process heat HTGR connected to a system of coal gasification by either hydrogen (left-hand side) or steam (right-hand side)

In the conventional steam-coal gasification process, a part of the coal is partially oxidized in a preceding step, before in the much slower heterogeneous water gas reaction, the residual organic solids are converted to synthesis gas with some CO_2 and steam. With an HTGR as heat source, the heat provided by the hot helium coolant can be introduced directly into the gas generator, with another part being used for the steam production, and the remainder still usable for electricity production. Synthesis gas output is optimal at high temperatures and low pressures.

Various types of gasification reactors have been developed, e.g., from Lurgi, Winkler, Koppers-Totzek, Texaco, which differ by the type of reactor, temperature and pressure range, grain size of the coal, and its residence time. Depending on the customers' requirements, respective downstream processing allows the optimized generation of either hydrogen or methane or synthesis gas. Coal conversion rate was estimated to be around 95 % and the total efficiency (based on higher heating value) to be ~ 68 %. Main disadvantages of coal gasification are the handling of solid material streams and the large amounts of CO_2, SO_2 and ash requiring a complex cleaning system.

In the hydro-gasification process, hydrogen is added to convert - in an exothermal reaction - the coal to SNG, before the synthesis gas is produced in parallel steam reforming and water-gas shift reactions. The nuclear heat input is used here in the steam reforming process to supply the "feedstock" hydrogen. The advantage of hydro-gasification compared with steam-coal gasification is its 200 K lower pre-heating temperature which reduces potential corrosive attack. A major drawback is the low conversion rate of not more than 50-60 % of the coal. Again, subsequent processes would allow the generation of synthetic natural gas or methanol.

For both types of gasification, respective test plants were constructed and operated under nuclear-typical conditions to investigate the influence of the essential process parameters such as, e.g., the temperature which strongly determines both the heat transfer from the helium coolant into the reactor and the reaction of the coal. Catalytic and non-catalytic steam coal gasification was tested in a 1.2 MW semi-technical scale experimental facility, where the heat was provided by helium electrically heated up to 950°C [2]. The plant was in hot operation for approx. 26,600 hours with more than 13,600 hours under gasification conditions (750-850°C, 2-4 MPa). Maximum capacity was 0.5 t/h of coal, the total quantity of coal gasified was 2400 t.

The hydro gasification process was verified first in a 1.5 MW semi-technical test facility employing a fluidized-bed reactor of 8 m height and 0.2 m diameter [3]. System pressure could be varied between 4-8 MPa. The reactor was able to gasify hard coal and lignite using a gasification medium of either pure hydrogen or mixtures of H_2, CO, and steam. The test facility was operated for about 27,000 h with more than 12,000 h under gasification conditions. The throughput was 320 kg/h of brown coal, the total quantity gasified was 1800 t. From 1983 to 1985, a follow-up pilot plant was operated with a throughput of 9.6 t/h corresponding to a total power of 50 MW. Gasification of 40,000 t of coal was made at 850-950°C and 6-12 MPa. The SNG production was at a rate of up to 6400 Nm^3/h.

2.3. Coupling between nuclear and chemical plant

For the nuclear steam coal gasification process, it was suggested within the PNP project that the heat from the reactor coolant is transferred via an additional heat exchanger, a helium-helium intermediate heat exchanger (He-He IHX) in order to avoid the handling of coal and ash in the reactor containment. Primary helium of 950°C flowing on the outside of the tubes is passed to a secondary helium circuit with secondary helium entering the steam gasifier at 900°C and a slightly higher pressure than on the primary side for the purpose of preventing radioactivity to enter the secondary circuit in case of a leak. The hot steam produced is routed into the coal bed to be gasified. For hydro-gasification where the hot helium is entering the steam reformer, an intermediate heat exchanger was – at least in those days –not considered necessary.

Two different IHX components, one with a helical tube bundle and the other one with U-tubes, designed for a power level representative for large and medium-sized plants were constructed by German companies (see Fig. 2). Both components were tested with 950°C helium on the primary side. The hot helium enters the heat exchanger flows via a mixing and deflecting device at the bottom of the component upwards through the bundle and is cooled down to 300°C. The cooled primary helium flows back into the gap between the wall of the reactor pressure vessel and the gas shroud of the heat exchanger to the blower at the bottom of the component. The secondary helium with a temperature of 200°C is entering the component at the top into a ring conduit where it is uniformly distributed over the tube bundle and heated up to 900°C in counter flow. The cycle is closed by the hot header which is insulated on the inside. The hot helium is leaving the IHX again at the top of the component. The maximum wall temperatures in the tubes in normal operation are 920°C, the maximum pressure difference between primary and secondary side is 0.2 MPa under operational conditions. In depressurisation accidents, they have to withstand the full pressure difference in a limited time period.

The two IHX components were tested under nuclear coal gasification conditions in a 10 MWt component test loop (KVK), operated by INTERATOM within the PNP project [4]. The facility consisted of a primary and a secondary helium loop. The helium flow rate was 3 kg/s in both circuits. Heat sources were a natural gas fired heater and an electrical heater. The test components examined included, apart from the two IHX, hot gas ducts with a total length of 140 m, hot gas valves, water cooler, and a steam generator (as the heat sink). KVK was operated for 18,400 h with 7000 h above 900°C and 11,000 h above 700°C, respectively, demonstrating the industrial feasibility of the tested components at a high reliability and an almost 100 % availability. Parallel to the integral tests of the components, additional testing was carried out in the KVK for a hot gas header of the helical tube bundle, for hot gas ducts (including bends and expansion bellows), hot gas valves, and a steam generator.

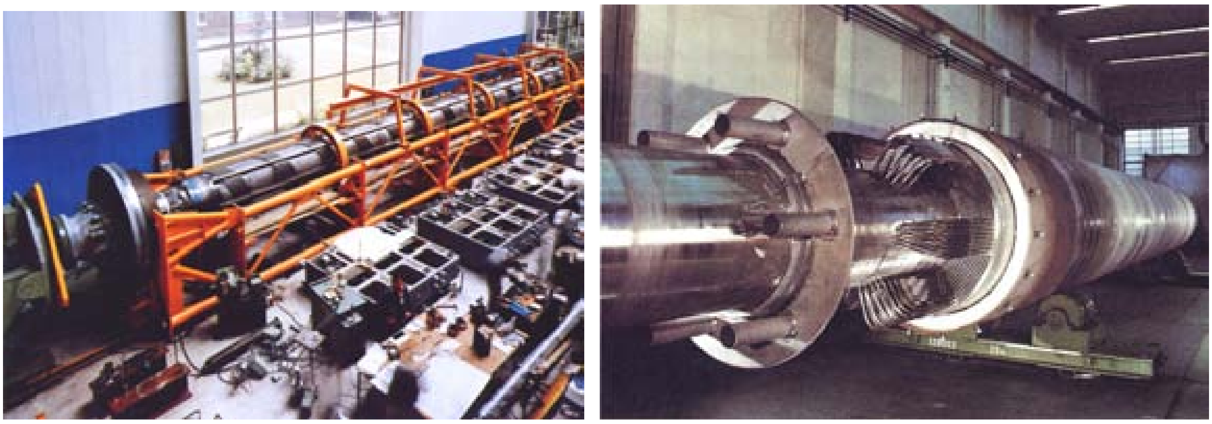

FIG. 2. IHX components tested in KVK with helical tube bundle (left) and U-tubes (right).

In the qualification program for high temperature metallic materials, steam reformer lifetimes and IHX materials have been approved to achieve the required lifetime of more than 100,000 h [5]. The specific data of the test components were very similar to those which are planned for the nuclear application. Gas temperatures, pressures and material temperatures in the KVK facility were even identical to those of the nuclear design. Also the predicted thermodynamic data of the heat exchanger designs have been confirmed by the experiments showing that average heat fluxes of around 40 kW/m² can be realized at reasonable pressure drops. Still, the experience gained so far has disclosed that the technical solution of material problems require further efforts in longer-term projects.

2.4. Steam reforming

Steam reforming of natural gas is since long a mature and well established technology practiced on industrial scale and presently most commonly used for H_2 production. Typical operating conditions are temperatures in the range of 750-850°C, pressures of 2-3 MPa, and steam-methane ratios of 2-5, depending on the application of the product gas. If the primary energy required for the endothermal reaction would be provided by nuclear energy, some 35 % of the methane feedstock could be saved compared with the conventional process, or in other words, based on the same amount of CO_2 produced, the hydrogen output from the reforming process would be significanly increased

Steam reforming of methane under nuclear conditions was experimentally verified in the EVA-I (single splitting tube) test facility at FZJ representing a complete, helium-heated system at 4 MPa. A reaction tube with dimensions typical for industrial plants (length: 15 m; inner diameter: 130 mm; wall thickness: 21 mm) was connected in a closed loop to an electrical heater with a power input of 0.3 MWe simulating the nuclear source to provide helium at 950°C. The helium flows in a ring gap on the outside of the reaction tube and provides its heat to the process gas mixture flowing in a counter-current flow inside the tube filled with a metallic nickel catalyst.

The follow-up facility, EVA-II, consisted of a steam reformer bundle with 30 splitting tubes, later a second one with 18 tubes, operated with an electric power of 10 MW. Heat transport medium was helium gas flowing at a rate of 4 kg/s and reaching a temperature at the heater exit of 950°C and a system pressure of 4 MPa. Heat source, steam reformer, and steam generator were arranged in separate steel vessels side by side, interconnected by coaxial hot gas ducts. The feed gas methane was introduced at a rate of 0.6 kg/s and reformed at a temperature of 820°C. The experiments confirmed the expected thermodynamic and chemical processing behavior and the validity of respective computer models.

For EVA-II, a respective ADAM (three adiabatic methanation reactors) was constructed, a test facility for the reverse process, the methanation of the synthesis gas in three steps. The peak temperature during methanation was 650°C releasing heat at a rate of 5.3 MWt. The helium system was operated for 13,000 h with 60 % of this time at a temperature of 900°C. From 1981 until shutdown in 1986, the complete EVA/ADAM system was operated for approximately 13,000 hours, of which 7750 h were at 900°C and 10,500 h as a complete cycle. The operation was both under steady-state and transient and partial load conditions. It thus demonstrated successfully a long-distance chemical energy transportation system based on the energy carrier hydrogen (see Fig. 3) [4].

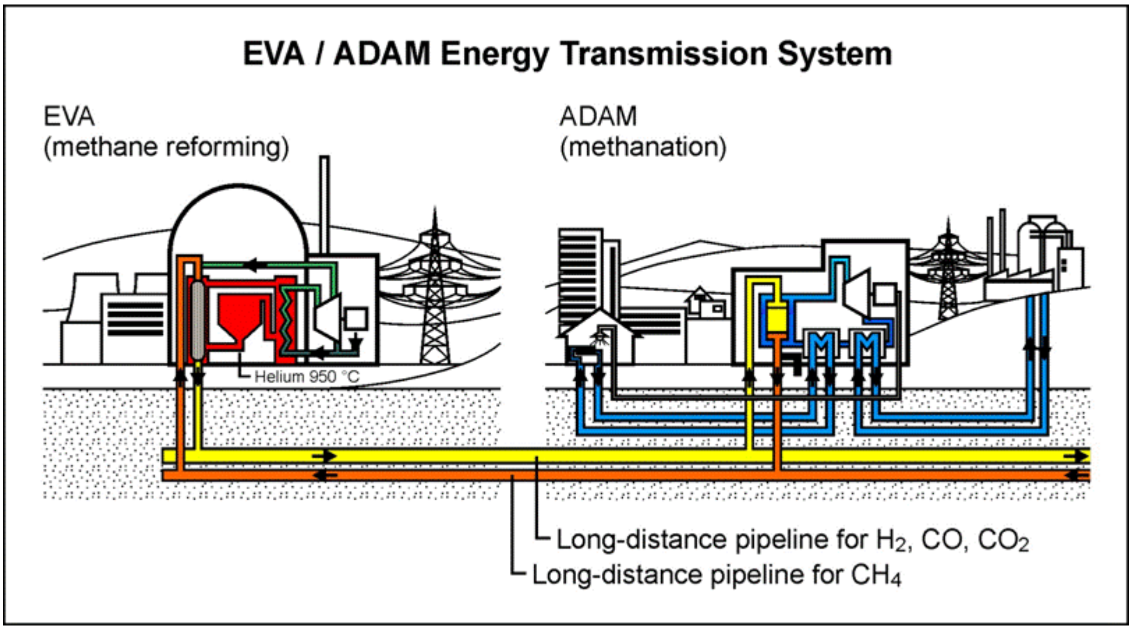

FIG. 3. EVA/ADAM long-distance energy transmission system based on methane reforming and the energy carrier hydrogen

2.5. Safety research

With regard to combined nuclear and chemical facilities, apart from their own specific categories of hazards, a qualitatively new class of events will have to be taken into account which is characterized by interacting influences. Arising problems to be covered by a decent overall safety concept are the question of safety of the nuclear plant in case of a flammable gas cloud explosion, or the tolerable contamination of the product. In addition, there are the comparatively more frequently expected situations of thermo-dynamic feedback in case of a loss of heat source (nuclear) or heat sink (chemical). As part of the PNP project, potential hazardous events in connection with a process heat application system extensively investigated were

- tritium transportation from the core to the product, e.g., hydrogen and methanol; and
- fire and explosion of flammable mixtures with the process gases.

2.5.1. Tritium contamination

Within the frame of the PNP project in Germany, experimental investigations were made on the permeation process in high temperature alloys. Test facilities allowed both long-term (1000-3000 h) at temperatures up to 1000°C and pressures up to 3.2 MPa. Short-term analyses were used for pre-selection of materials. Results have shown that in-situ oxide layers show a large inhibition of permeation at temperatures above 650°C. Still the uncertainty is relatively large at lower temperatures and also if looking at respectively measurements from operated HTGRs. Assuming a gas purification system in the IHX cycle of the PNP reactor, the tritium release rate was estimated to be less than 0.2 GBq ($5*10^{-3}$ Ci) per MWt. For the product hydrogen, this translates into a contamination of less than 0.37 Bq (10 pCi)/g of H_2. This figure was deemed tolerable in the PNP-project in comparison to other allowed levels of radioactive contamination.

According to the German Preventive Radiation Protection Ordinance, neither licensing nor announcement is required for the use of fossil products refined by nuclear process heat, whose tritium content does not exceed 5 Bq/g. This special case is the exception from the rule, where for any fabricated product, the specific radioactivity limit is lower by a factor of 10 compared to the above figure, i.e., 500 mBq/g [6]. The background for this special rule resulting from discussions in the context of the PNP project is the fact that, depending on the origin of the feed natural gas, the natural activity content would be already close to the free limits given by the law.

2.5.2. Fire and explosion hazards

Fire and explosion hazards resulting from the leakage of flammable materials such as methane, hydrogen, and carbon monoxide should be considered because they have the potential of causing significant damage to safety components. Within the PNP project, a gas explosion program was conducted to improve understanding of the complex processes in vapor cloud explosions and their effects on the environment, in particular on nuclear plants. It included comprehensive experimental series employing representative combustible gasesto examine flame speeds, overpressures, as well as criteria for the transition from deflagration to detonation (DDT), and on the other hand, the identification of PNP typical accident scenarios. An overall final statement was made that mechanisms of flame acceleration were qualitatively well understood, but could hardly be described on a quantitative basis.

One of the consequences from the experimental activities was the guideline on the "Protection of Nuclear Power Stations from Shock Waves Arising from Chemical Explosions", drafted by the German Federal Ministry of the Interior (BMI) in 1976 [7] which defined a pressure-time history to be sustained by any future nuclear containment as well as a safety distance relation ($R = 8 * M^{1/3}$ where R is the safety distance in meters and M the mass of the flammable substance in kg) for nuclear power plants. The guideline is valid for NPP of present design; it is explicitly mentioned that "no statement can be given at present concerning its application to future nuclear process heat plants".

3. Other industrial nuclear process heat activities in Germany

Economic analyses at the end of the 1980s, however, showed that competitiveness of nuclear SNG from expensive German coal with the cheap oil and gas available on the world markets was not given. Still, as was pointed out in a study by the Lurgi company in 1988 [8], alternatives were seen in various industrial sectors such as oil refineries and petrochemical industries (recovery of heavy oil and oil shale/sand, naphtha cracking), iron production, aluminum oxide production, and also in biomass gasification (production of energy alcohols) [9], where nuclear energy could be used to meet their needs of process heat/steam, electricity and/or hydrogen.

German activities on nuclear process heat application with HTGRs were partially embedded in international cooperation, e.g., with Japan on steel-making processes, with Indonesia on concepts to retrieve and upgrade CO_2-rich natural gas from the Natuna gas field, with Switzerland on the development of a 10-20 MWt HTGR for district heating, and also with China on the exploitation of heavy-grade oil, where high-pressure steam is pressed into oil fields lowering the oil viscosity and enhancing its recovery.

With respect to the CO_2 emission free H_2 production, the sulfuric acid hybrid or Westinghouse cycle was experimentally investigated under HTGR typical conditions at FZJ.

In a three-compartment electrolytic cell, the cathodic production of H_2 at 1.5 MPa and 80°C and at a rate of 10 NL/h over 600 h was demonstrated [10]. Cycle efficiency was found to be 40 %, an increase to 46 % was thought possible by optimizing the electrolysis step. Another thermochemical cycle investigated was the so-called methane-methanol-methanal hybrid cycle which includes, after the methanol (CH_3OH) synthesis, the subsequent steps of methanal (CH_2O) synthesis and methanal electrolysis for the generation of SNG, which is then routed to the steam reformer for further H_2 production.

4. Conclusions

The results of the long-term PNP project in Germany confirmed the technical feasibility of allothermal, continuous coal gasification and the licensing capability of the nuclear process heat HTGR. The nuclear supported process promises a saving of 35-40 % of the coal resources. The idea of construction of a PNP plant was eventually abandoned at the beginning of the 1990s due to the fact that the nuclear process would not be economically competitive with the conventional process under the given economic conditions at that time.

By the manufacture and successful operation of high temperature heat-exchanging and heat-transporting components under simulated nuclear conditions, highly valuable practical experience with high-temperature helium plants on a representative scale has been acquired. Furthermore the closed-cycle EVA/ADAM chemical energy transportation system based on H_2 was demonstrated.

From the broad experimental program conducted in KVK and other related test facilities, it could be concluded that both IHX have been successfully tested on the 10 MW power level in steady state operation and under transient conditions and at maximum helium heating temperatures of 950°C (primary) and 900°C (secondary), respectively. The operation time of the helical tube bundle was more than 5000 h, that of the U-tube bundle was more than 4000 h. On the basis of the available experience, both IHX were considered appropriate to be designed for a power of 170 MW and an operation time of 140,000 h at 950°C. However, it still needs additional work for nuclear applications and qualification of these methods and materials.

Future activities could take benefit from a re-evaluation of the above mentioned studies on HTGR process heat applications by comparing against current technologies and market conditions. The goal should be to select promising applications under the current industrial practice within existing and evolving markets. Superior safety features and high reliability are considered prerequisites for the introduction of nuclear process heat and nuclear CHP.

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Integration of nuclear energy and chemical production: High temperature gas cooled reactor for chemical syntheses of hydrogen, oxygen, methanol and hydrocarbons

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Abstract. The paper presents the role of high temperature gas cooled reactors for chemical synthesis of hydrogen, oxygen and many hydrocarbons as synthetic fuels. The reaction kinetics details of the synthesis and separation of the reaction products are highlighted. The reaction schemes and the flow sheets of all these processes are presented. The techno-economics of energy generation/ hydrogen production using HTGCR is looked in to.

1. Introduction

The design, engineering, technologies, processes, materials, operation and manufacturing of electricity, steam, hydrogen, oxygen, methanol and Fischer Tropsch (GTL = Gas-to-Liquids) - Liquids by means of an integrated Helium-cooled High-Temperature Gas-Cooled Reactor (HTGCR) plus chemical processing units is described. The integrated plant comprises the generation of high-temperature helium (~1000°C), catalytic splitting of water into hydrogen and oxygen, separation of hydrogen and oxygen, hydrogen separation with Pd-membrane, oxygen separation with ceramic membrane (solid electrolyte), extraction of carbon dioxide from air with membrane process, reaction of carbon dioxide with hydrogen to methane (Sabatier reaction), generation of synthesis gas (syngas), synthesis of hydrocarbons, synthesis of methanol.

The processes and equipment are described in detail (reaction kinetics, thermodynamics, conversion efficiencies, reactor design, materials of construction, catalysts, operation, investment cost, manufacturing cost for electricity, steam, methanol, and GTL-liquid (electricity 0.03 – 0.04 €/kWh, methanol 30 – 40 € per ton, GTL-liquid 80 – 90 € per ton). A thermionics unit for direct conversion of heat to electricity with high conversion efficiency is also included. Novel materials for high temperature processes are presented. The design is calculated at 1000 MW electrical energy and 2 million tons-per-year of hydrocarbons.

The integrated plant provides a replacement of fossil fuels for generation of energy, hydrogen and hydrocarbons, production of non-fossil hydrogen, extraction of carbon dioxide from atmosphere (climate change abatement), synthesis of non-fossil hydrocarbons with direct applicability for chemical and energy uses (C1-chemistry, petrochemical substitution, hydrogen for fuel cells). The basic scheme is given below:

High-Temperature Gas-Cooled Reactor

↓

Splitting of Water into Hydrogen and Oxygen

↓

Hydrogen for Hydrogen Economy
(Fuel Cells, Energy, Transport, Chemicals)

↓

Hydrogen + Carbon Dioxide (from atmosphere)
(Sabatier-Reaction)

↓

Methane

↓

Syngas

↓

Methanol
Fischer-Tropsch – Liquids
GTL – Liquids (Naphtha & Gasoline)

2. HTGCR and energy / hydrogen

Nuclear Energy is a non-fossil source of energy. HTGCR (High-Temperature Gas-Cooled Reactor) provides thermal energy at ~ 1000°C. HTGCR ('pebble-bed reactor') is inherently safe. Uranium resources are a long-term (uranium ores, sea water) energy source. High temperature heat is suitable for endothermic chemical syntheses. Combination of nuclear energy with chemical syntheses provides energy, hydrocarbons & materials. The reaction schemes and salient details of the various applications of the HTGR in our study are reported below;

2.1. Water dissociation reaction

$2\ H_2O \rightarrow 2\ H_2 + O_2$ (delta H = + 118 kcal) (endothermic reaction)

Production of
- 100,000 tons of Hydrogen and
- 800,000 tons of Oxygen

requires input of
- 900.000 tons of water and
- 3×10^{12} kcal = 3.5×10^{9} kWh = 3.5×10^{3} GWh

2.2. Hydrogen and oxygen separation

- At 1000 °C and equilibrium, water vapour is dissociated less than 0.1 %, containing < 0.05% Hydrogen and <0.02% Oxygen

- Hydrogen and Oxygen need to be removed to generate industrial amounts
- Extraction of Hydrogen and Oxygen has to be at high (dissociation) temperatures to avoid recombination (reassociation)

Technologies for hydrogen extraction

- Palladium Membranes
- Ion-Transfer-Membranes (ITM)
- Mixed-Ion-Membranes (Proton-Conducting-Membrane)

Technologies for oxygen extraction

- Ion-Transfer-Membranes (ITM)
- Mixed-Ion-Transfer-Membranes (OTM = Oxygen-Transfer-Membrane)

Oxygen ion conductor

- Gd-doped or Y-doped Cerium Oxide CeO_2 plus electronic conductor (e.g. Ni) (dual-phase ceramic-metal composites)
- SrFeCoyOx (single-phase mixed oxygen / electron conductor)
- Dissociation / Reduction Catalyst Surface

Proton-Conductor:

- SrCexYby/ScyOz

2.3. Carbon dioxide separation

- Membrane Separation
- Amine Absorption and Dissociation

3. A few chemical syntheses

3.1. Chemical syntheses with hydrogen

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (-165 kJ/Mol CO_2)
(Sabatier Reaction) (exothermic)

Ammonia
$N_2 + 3H_2 \rightarrow 2NH_3$

Methanol (from Synthesis Gas)
$CO + 2H_2 \rightarrow CH_3OH$

Methanol (from Carbon Dioxide)
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Fischer-Tropsch – Hydrocarbons (from Synthesis Gas)
$CO + H_2 \rightarrow (CH)n + H_2O$

$$CO + 2H_2 \quad CH_3OH \quad \Delta H_{298K} = -21.7\,kcal.mol^{-1}$$
$$CO_2 + 3H_2 \quad CH_3OH + H_2O \quad \Delta H_{298K} = -9.8\,kcal.mol^{-1}$$
$$CO_2 + H_2 \quad CO + H_2O \quad \Delta H_{298K} = 11.9kcal.mol^{-1}$$

3.2. Hydrocarbon syntheses

Fischer-Tropsch Synthesis of Hydrocarbons from Methane:
$CH_4 + O_2 + H_2O \rightarrow CO + H_2 \rightarrow$ Fischer-Tropsch Hydrocarbons + H_2O

Oxidative Coupling of Methane to Hydrocarbons:
$2CH_4 + O_2 \rightarrow C_2H_6 + H_2O$

Partial Oxidation of Methane to Methanol:
$2CH_4 + O_2 \rightarrow 2CH_3OH$

Methanol-to-Propylene (Olefins) (MTP)

4. Nuclear hydrogen

- Nuclear Hydrogen is Hydrogen (H_2) derived from Nuclear Energy by Thermal Splitting of Water
- Nuclear Hydrogen is produced without fossil fuels (natural gas or petroleum)
- Nuclear Hydrogen does not contribute to depletion of hydrocarbon resources and to the addition of Carbon Dioxide to the atmosphere (global climate change)
- The Hydrogen can be used for the 'Hydrogen Economy' (fuel cells, energy production) as well as for Chemical Syntheses
- It is advantageous for large-scale hydrogen-consuming processes such as ammonia synthesis, methanol, methane, hydrocarbons
- The Nuclear Reactor deployed is a HTGCR (High-Temperature Gas-Cooled Reactor) (a 'pebble-bed reactor', "Kugelhaufen-Reaktor"), which provides the thermal energy at about 1000°C (Helium gas) and is inherently safe.

5. HTGCR and energy / hydrogen

- The production of 100,000 tons-per-year of Hydrogen plus 300 GWh of Electricity requires a 600 MW HTGCR.
- At 8000 h per year, this represents an installed thermal capacity of 500 MW (at 90% energy conversion efficiency)
- The additional production of 300 GWh of electricity involves a capacity of ~ 100 MW (thermal), thus the total installed (thermal) capacity of the HTGCR is 600 MW.
- A Nuclear Reactor designed to deliver 100,000 tons-per-year of hydrogen consumes 900,000 tons-per-year of water (~ 110 tons-per-hour) and delivers hydrogen plus 800,000 tons-per-year of oxygen.
- The HTGCR delivers hydrogen at ~ 1.00 € / kg plus electricity at ~0.04 € / kWh
- Methanol production cost 30 – 40 € / tonne
- GTL-Liquid production cost 80 – 90 € / tonne

Investment:

- Investment for a 600 MW HTGCR with Hydrogen plus Electricity Production ~ 450 Million Euro
- "HTGCR + Hydrogen Production Plant" is constructed, financed and operated by project financing.
- Design, Technologies, Construction:
- Advanced Design, Systems Engineering and Technologies for Water Splitting, Hydrogen and Oxygen Separation, Heat Exchange and Materials-of-Construction
- GTL-Plants with ITM / OTM Reactors (1000 bpd) under construction ("numbering-up") (GTL = Gas-to-Liquids)
- ITM-Membrane-Reactor with ~1000 m^2 of dense Ceramic Membrane
- Realization as EPCM and EPC Project (Turn-Key Lump Sum)

Heterogeneous Bunsen reaction : Analysis & experimental study of chemical absorption of sulfur dioxide and dissolution of iodine into aqueous reacting system

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Abstract. Bunsen reaction is one of the three main reaction steps of Iodine-Sulphur (I-S) thermochemical water splitting process for production of hydrogen, utilizing nuclear heat. This complex multiphase- multispecies reaction has to be carried out optimally for harnessing the potential of I-S process for large scale production of hydrogen. Apart from strong influence of operating conditions, contacting scheme, reactor type and size have severe bearing on issues like overall process efficiency, product purity, separation, conversion etc. In this study sulphur dioxide (gas) and iodine (solid) are reacted in aqueous solution (liquid) with gas sparging and mechanical agitation at room temperature. Experimental results of this reacting ternary system are analyzed in terms of film theory of mass transfer. Chemical absorption of sulphur dioxide and enhanced dissolution of iodine solid into Bunsen reacting system are interpreted to deduce crucial engineering information like controlling resistance, regime, enhancement factor etc, which will help in selection of suitable contacting scheme and design of multiphase absorber-reactor for large- scale production of hydrogen. Behavior of this fluid-fluid-solid absorber – reactor can be construed kinetically as 'Fast psuedo first order reaction system'.

1. Introduction

In future energy scenario, hydrogen, a clean energy vector, produced from water and nuclear heat, is poised to play a crucial role. Thermochemical water splitting Iodine-Sulphur (I-S) process, a potentially attractive technique is being widely studied. Bunsen reaction which constitutes one of the three main reaction steps of I-S process can be considered as the 'key' step [1,2] as overall process feasibility, stability & efficiency are determined by the conditions of operation of this non-ideal reacting system. In this process step, water is reacted with iodine (I_2) and sulfurdioxide (SO_2) to obtain hydriodic acid and sulphuric acid. Excess water and iodine are used to make the reaction and product phase separation feasible.

$$SO_2 + xI_2 + y\,H_2O \longrightarrow 2\,HI + H_2SO_4 + (x-1)\,I_2 + (y-2)\,H_2O \qquad (1)$$

Operating conditions like temperature, composition etc [3] have to be optimally selected to achieve high purity of product phases, conversion, yield etc. Phase and chemical equilibria of this highly nonideal reacting system are not completely studied [4], though some practical information is available about SO_2 absorption in iodine containing aqueous systems [5]. Contacting scheme, reactor type and size also have severe bearing on all critical issues. Published literature on these aspects of I-S process is scanty. Main focus of the paper is therefore to derive useful engineering information which will permit proper selection and design of Bunsen reactor. Experimental results of chemical absorption of SO_2 gas and dissolution of iodine solid into aqueous reaction system are analyzed by classical film theory of mass transfer [6,7].

Bunsen reactor system under the conditions of the study transforms from gas-liquid-solid system to gas-liquid aqueous multiphase system as the reaction proceeds. The chemical nature of the system also changes.

2. Experimental apparatus, materials and methods

A sketch of the apparatus used in the experiments of SO_2 chemical absorption in water containing iodine is shown in Fig. 1. The absorber-reactor is a jacketed stirred cylindrical glass vessel (diameter 125 mm, height 260 mm) with a provision for feeding metered and controlled amount of SO_2 and nitrogen. Gases emerging out of reactor are passed through series of bubblers to trap unabsorbed SO_2. The reactor has charging port, sampling port to draw liquid samples periodically for analysis, thermo-well and agitator.

Experimentation is carried out in semi-batch mode with precharged batch of distilled water and AR grade iodine (spherical particles of ~ 2mm dia). Iodine loading, batch volume, total gas flow rate, SO_2 concentration in feed gas, stirrer speed are the variables. Experiments were carried out at room temperature and atmospheric pressure.

Iodine loading in water is limited to region A of reference [5] where the product solution is transparent. Sharp color change has facilitated precise termination of gas feeding and measurements of batch reaction time. Batch liquid is thoroughly agitated for sufficient time before feeding SO_2.

Batch liquid samples and bubbler samples were analyzed by standard techniques of iodometry for SO_2.

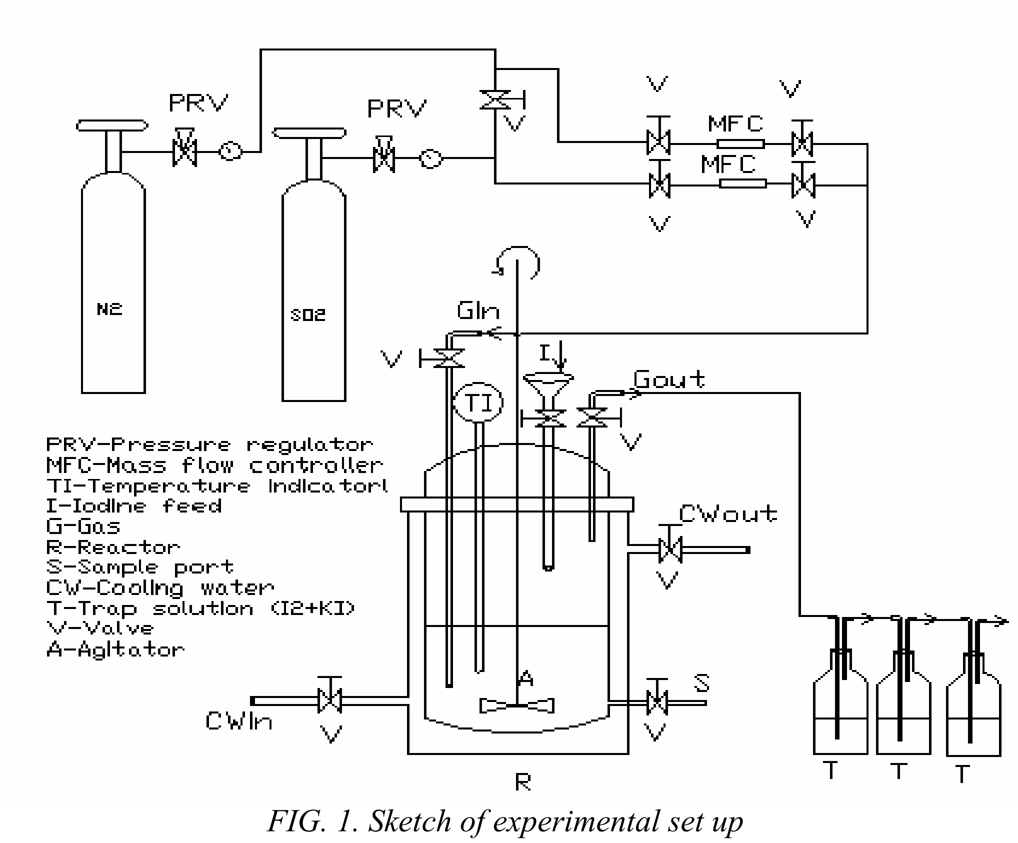

FIG. 1. Sketch of experimental set up

3. Theory

The stoichiometric Bunsen Reaction is

$$SO_2 + I_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

and can be represented with excess of iodine and water as

$$SO_2 + xI_2 + y2H_2O \rightarrow 2HI + H_2SO_4 + (x-1)\,I_2 + (y-2)\,H_2O \qquad (3)$$

wherein (x-1) is iodine excess and (y-2) is water excess and the reaction proceeds through intermediate sulfur species like hydrolyzed SO_2 (H_2SO_3) and it is quasi-monomolecular w.r.t. SO_2 concentration under appropriate iodine concentration and pH condition with a first order rate constant of $10^2 - 10^3\ s^{-1}$ [5]. This heterogeneous reaction study is primarily focused to generate useful engineering information for the selection and design of metallic Bunsen reactor. The reaction is represented as follows for analysis purposes.

$$SO_2, A + I_2, B + H_2O, Aq \rightarrow (H_2SO_4 + HI), \text{Products} \ldots\ldots\ldots\ldots(4)$$

with the following series/parallel steps

$$A(g) \rightarrow A(aq) \ldots\ldots\ldots\ldots\ldots\ldots \qquad (5)$$

$$B(s) \rightarrow B(aq) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

$$A(aq) + zB\,(aq) \rightarrow \text{Products} \ \ldots\ldots(7)$$

Chemical absorption process involving SO_2 (solute, A) with iodine (reactant, B) in water is analyzed by adopting classical film theory to derive practical engineering information like controlling resistances, regimes, coefficients, enhancement factors etc. Overall multiphase reaction is visualized as follows:

1. Diffusion of gaseous species A through the gas film (whenever SO_2 is diluted with Nitrogen)
2. Dissolution of solid species B
3. Diffusion and simultaneous chemical reaction in the liquid film. Figure 2 of concentration profiles illustrates these steps

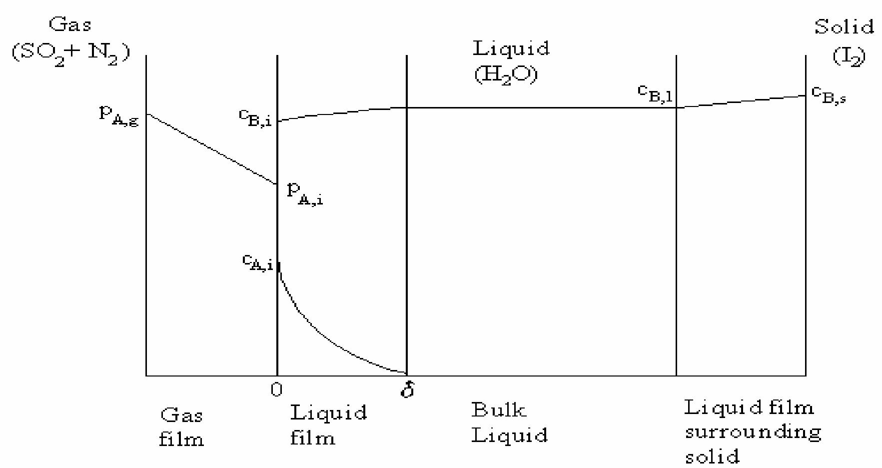

FIG. 2. Concentration profiles based on film theory for gas (sulphur dioxide) – liquid (water) – solid (Iodine) system.

Diffusion of SO_2 in the liquid film and chemical reaction are taken as parallel processes while iodine dissolution and chemical reaction are taken as processess in series in this model. The rates of diffusing gas, A and dissolving solid, B and chemical reaction are given by equations (8), (9) & (10) respectively.

$$-r_A = k_g a\,[p_{Ag} - p_{Ai}] \qquad (8)$$

$$-r_B = k_s a_p\,[c_{Bs} - c_{Bl}] \qquad (9)$$

$$-r_A = k_1 c_A = \frac{-r_B}{z} \qquad (10)$$

Mass balances for the diffusing gas A and dissolving solid species B in the liquid film are as follows:

$$D_A\, d^2c_A / dx^2 = k_1 c_A \qquad (11)$$

$$D_B\, d^2c_B / dx^2 = z\, k_1 c_A \qquad (12)$$

Mathematical solution and boundary conditions applied are as per regimes in references [6,7].

4. Results and discussions

The experimental results for the SO_2 absorption into aqueous solution containing iodine are shown in Fig.3. Figure 3 shows SO_2 absorption rate as a function of SO_2 partial pressure in the inlet gas for different values of iodine loading in the batch of liquid. For the low iodine to water ratio considered in this Bunsen reaction study i.e. Region A of reference [5], the overall

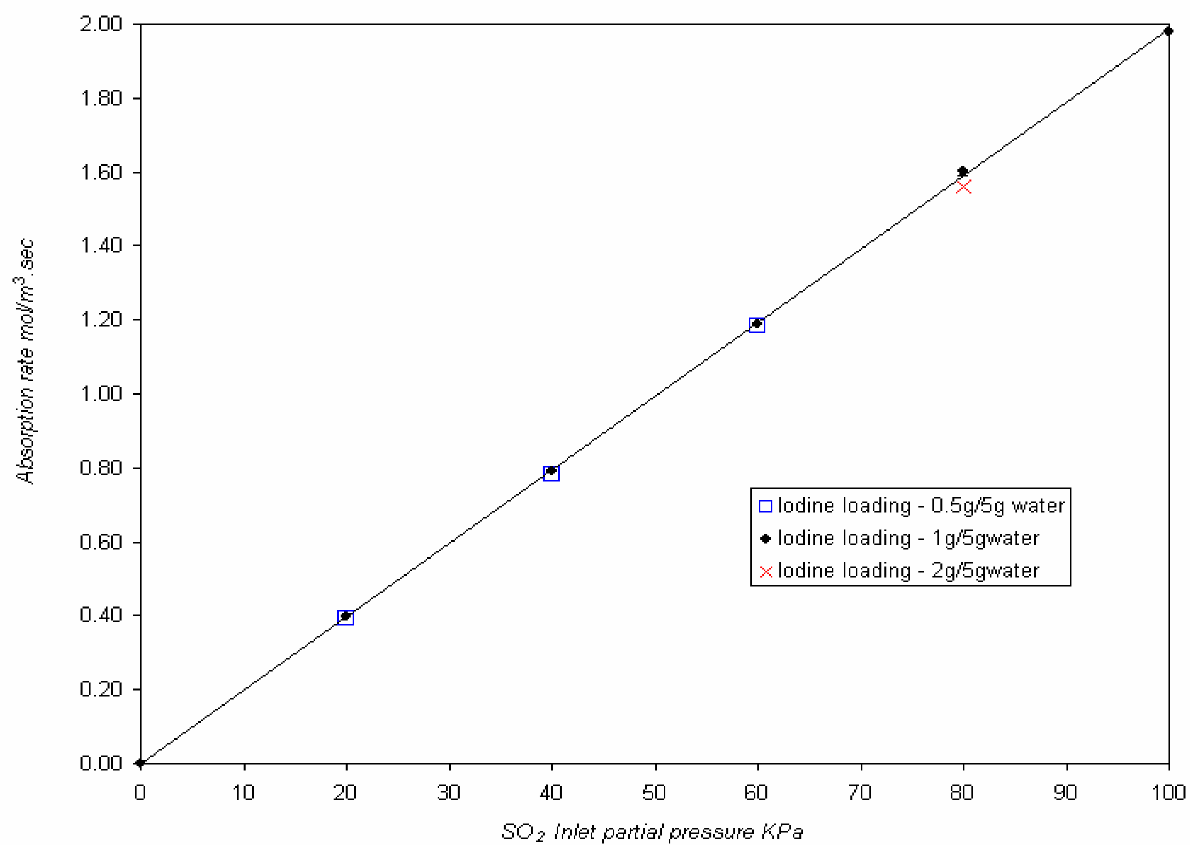

FIG. 3. SO_2 absorption rate vs. SO_2 partial pressure for different Iodine loading

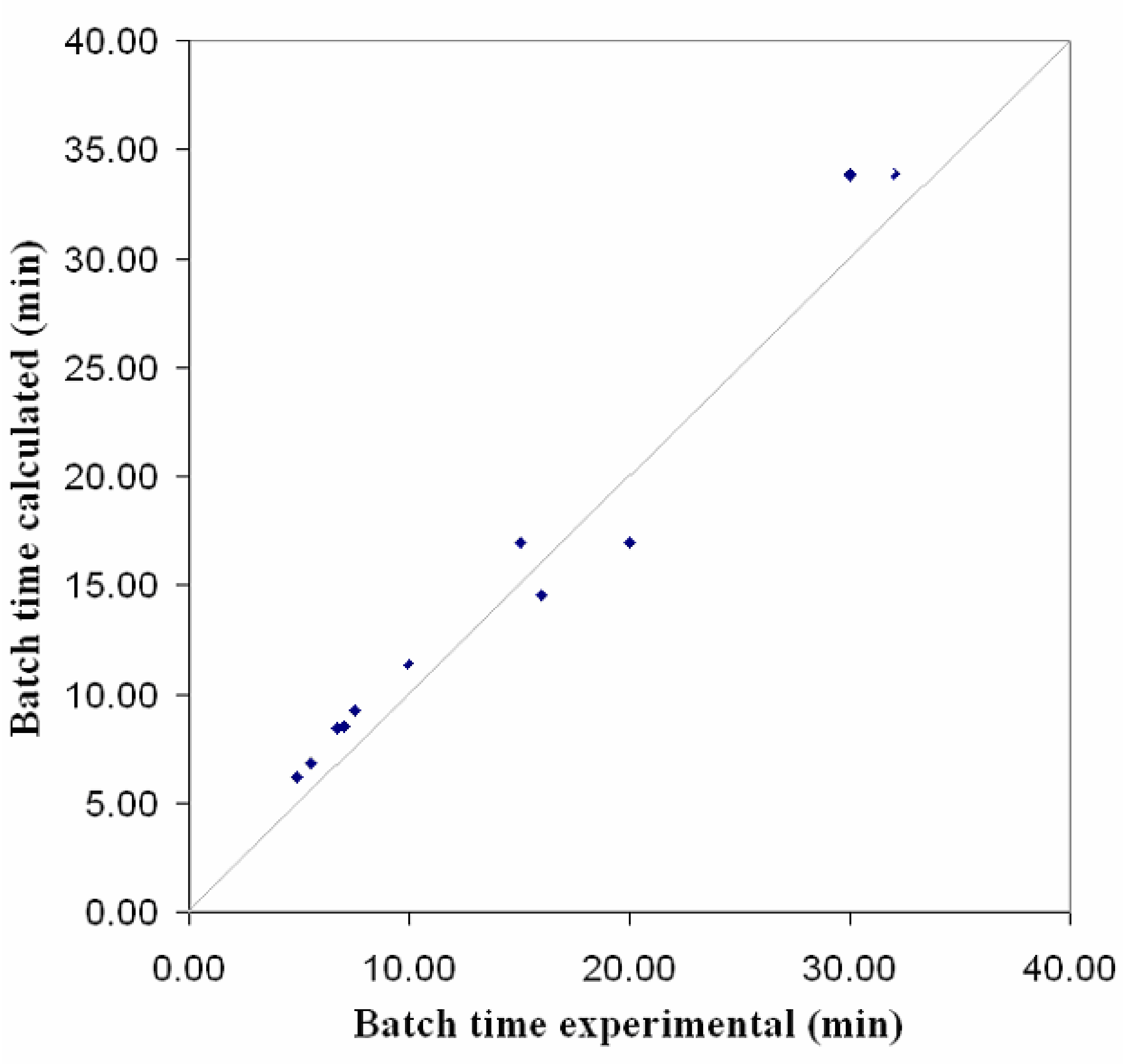

FIG. 4. Batch time calculated vs. Batch time experimental

absorption rate increases linearly with SO_2 partial pressure and does not depend on iodine loading. This is remarkable that, but for a small duration for triggering iodine dissolution in the initial stages, overall rate of reaction is independent of iodine loading for the entire range of SO_2 partial pressure of feed gas. Iodine availability at reaction region does not influence the overall reaction rate due to high phase equilibrium concentration and rates of dissolution. The rate of reaction is SO_2 concentration dependent i.e. aqueous Bunsen reaction is 'pseudo first order' in SO_2.

Dependence of overall reaction rate on other parameters has also been studied. Variation of superficial velocity, stirring speed, batch volume in the range of study did not effect the overall rate of reaction and slope of linear relation remains constant which includes gas film mass transfer coefficient, liquid side mass transfer coefficient, intrinsic kinetic constants, solubility parameters like Henry's constant. Presuming that this complex multiphase reacting system will behave like fast pseudo first order reaction system and SO_2 in water Henry's constant is applicable for vapor-liquid equilibrium, calculations are made to obtain batch time. Comparison of experimental and calculated batch time are indicated in Fig 4. Results indicate that this model is adequate for Bunsen reaction preliminary analysis. However as we approach prototypical conditions appropriate correction factors for Henry's constant, diffusivity etc. may be called for. These are the issues, which need to be investigated further for evolving an exact model yielding overall kinetic parameter (OKP), which is independent of hydrodynamics thereby facilitating design of any type of absorber-reactor. OKP is a lumped parameter, which takes into consideration intrinsic kinetics, solubility and diffusivity only. OKP values combined with the mass transfer coefficients k_l, k_g will help in the selection and design of proper contacting device.

Table I lists applicable resistances and parameters like Hatta number, enhancement factor etc.

Table I. Typical parameters and values for Bunsen reaction analysis

Batch time (calculated)	t_{calc}	34
Batch time (experimental)	t_{exp}	30
Gas film resistance	$1/(k_g a)$	$1.1x10^6$
Liquid film resistance	$H/(k_l aE)$	$1.0x10^7$
Liquid bulk resistance	$H/(k_1(1-\varepsilon))$	$7.5x10^2$
Hatta no	Ha	3.4
Enhancement factor	E	2.1
Solid dissolution parameter	$(k_s a_p D_A^2)/(4k_l D_B)$	$1.6x10^{-6}$

5. Conclusions

SO_2 absorption rate in chemically reacting system of Bunsen reaction is experimentally studied and found to be a linear function of partial pressure of SO_2 in inlet gas stream. Low iodine loading, which is very much less than the prototypical Bunsen reaction conditions did not effect the rate of chemical absorption. This aspect renders the reaction to be 'Pseudo first order' in SO_2. The heterogeneous chemical absorption can be analysed by applying two film-theory. Comparison of experimental and calculated values of batch time based on above theory indicate the reaction regime can be classified as 'Fast reaction' with high iodine concentration and reaction region is in liquid film at gas-liquid interface. Dissolution of iodine and reaction are processes in series whereas diffusion of SO_2 and reaction are processes in parallel. Liquid film resistance constitutes main resistance (~90 %). Gas film resistance is ~10 % of overall resistance and kinetic resistance is negligible. Overall kinetic parameter OKP, which includes intrinsic kinetic constant, solubility and diffusivity is a suggested lumped parameter for design of Bunsen reactor. Experimental and theoretical results have indicated that analysis of this complex reaction system can be approached by invoking judicious simplifying assumptions. Rigorous model requires accurate thermodynamic, transport and physical properties like Henry's constant, diffusivity, kinetic constants under prototypical conditions.

Notation

a	gas liquid interfacial area per unit volume, m^2/m^3
a_p	solid liquid interfacial area per unit volume, m^2/m^3
c	concentration in liquid phase, $kmol/m^3$
D	diffusivity, m^2/s
H	Henry's constant, Pa m^3/kmol
Ha	Hatta number= $\frac{\sqrt{k_1 D_A}}{k_l}$
k_g	gas phase mass transfer coefficient, kmol/s m^2 Pa
k_l	liquid phase mass transfer coefficient,m/s
k_s	solid side liquid phase mass transfer coefficient, m/s
k_1	first order rate constant, s^{-1}
OKP	overall kinetic parameter = $\frac{\sqrt{k_1 D_A}}{H}$ kmol/m^2 Pa s
p_A	partial pressure of A, Pa
r	reaction rate, kmol/m^3 s
t	Batch time, min
x	coefficient
y	coefficient
z	coefficient
	Greek Letters
δ	liquid film thickness, m^3/m^3
ε	gas holdup, m^3/m^3
	Subscripts
A	for component A, SO_2
B	for component B, I_2
g	for gas phase
l	for liquid phase
i	for interface
p	for particle
r	for reactor
s	for solid
calc	calculated
exp	experimental

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A new approach to improve the hydrogen yield for HI_x system of I-S process

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Abstract. Iodine-Sulfur (I-S) closed loop cycle for water splitting integrated with high temperature nuclear reactors is one of the futuristic cycles for commercially viable production of hydrogen. I-S process consists of three steps namely Bunsen reaction, H_2SO_4 decomposition and HI reactive distillation. Efficient operation of reactive distillation of HI_X system will improve the overall economics of hydrogen production. In the absence of conclusive simulation data and definite thermodynamic models, fresh approach for generating independent process scheme and design data based on proper material and energy balance, using NRTL thermodynamic model is presented. Various conceptual flow schemes are tried to improve equilibrium as well as kinetic yield of hydrogen production. Effect of total number of theoretical plates, various streams qualities and their locations on hydrogen yield was estimated. Present proposal advocates a fresh approach to a new scheme, completely different from previously published schemes. In this scheme no side stream is withdrawn from the column. Reasonably good reflux is experienced by whole column. It is observed that there exists a proper combination of HI and water composition in the column at which yield of hydrogen is significantly increased. Increased reflux in the column helps in insitu flushing of iodine generated by HI decomposition which in-turn improves the yield. It is to be noted that iodine enrichment for higher hydrogen yield scheme will be lower as compared to lower hydrogen yield schemes. Nevertheless, gain in yield will be more desirable to highly enriched iodine requirement, which is limited to the requirement of the boost reaction only. Due to lack of experimental data available in the literature, we feel, absolute value of hydrogen yield may vary from the reported. However, relative gain in various schemes can't be ignored.

1. Introduction

In the quest of new energy sources for replacing the fast diminishing reserves of conventional energy sources, the world is pinning its hopes on the process of water splitting by thermochemical cycles for production of hydrogen. These cycles are considered to be one of the most promising futuristic alternatives to energy generation program. Thermochemical water splitting integrated with high temperature nuclear reactor heat makes the attempt worth exploring as direct water decomposition occurs at a very high temperature (>2500°C).

In recent years hydrogen as the main energy carrier has received a lot of thrust due to growing demand of energy security to cater to the fast growing economies. Hydrogen is a future choice of fuel in a fuel cell due to its eco-friendly combustion products and water as a primary feed material. In the last two decades extensive research on various thermochemical cycles has been pursued and iodine-sulfur is suggested to be one of the most promising cycles for commercialization. It is reported that thermodynamically, this cycle can result in efficiency of the order of 52% at 950°C, which is comparable to that of conventional overall water electrolysis process.

Overall efficiency of the IS process is highly dependent on the individual stage efficiency. Reactive distillation of HI_X system is an important stage of thermochemical splitting of water in IS process. In this paper an attempt has been made to estimate the design and operating parameters of a reactive distillation column to achieve better equilibrium yield of hydrogen.

2. Process description

Thermo chemical water splitting by Iodine Sulfur process as shown in Fig. 1, is basically a three-stage process. First stage commonly known as Bunsen reaction stage consists of exothermic gas - liquid reaction between iodine in aqueous phase and sulfur dioxide in gaseous phase at 400 K. Products formed in Bunsen reaction constitute two separate liquid phases. Sulfuric acid phase forms lighter phase and HI_X system forms the heavier phase. In the second stage sulfuric acid is decomposed to sulfur dioxide, oxygen and water. Third stage is hydrogen production stage via HI decomposition. Two approaches are found in the literature. In the first approach, HI is enriched to a higher value and then decomposed in a reactor. While in the second approach, enrichment and decomposition is done simultaneously in reactive distillation column. Hydrogen is separated from rest of the un-reacted constituents, which are further sent back to first stage. Effectively water acts as a major raw material, while other reactants remain in close-loop cycle.

HI decomposition stage is highly complicated due to its complex hetro azeotropic vapour liquid equilibrium. Lower HI azeotropic concentration can be obtained either by increasing the pressure or by increasing the iodine concentration. At high pressures azeotrope can completely disappear. As HI_X system is highly corrosive at high pressure and high temperature, little information in terms of experimental as well as theoretical model is available on VLE data [6,7,8] for complete concentration range.

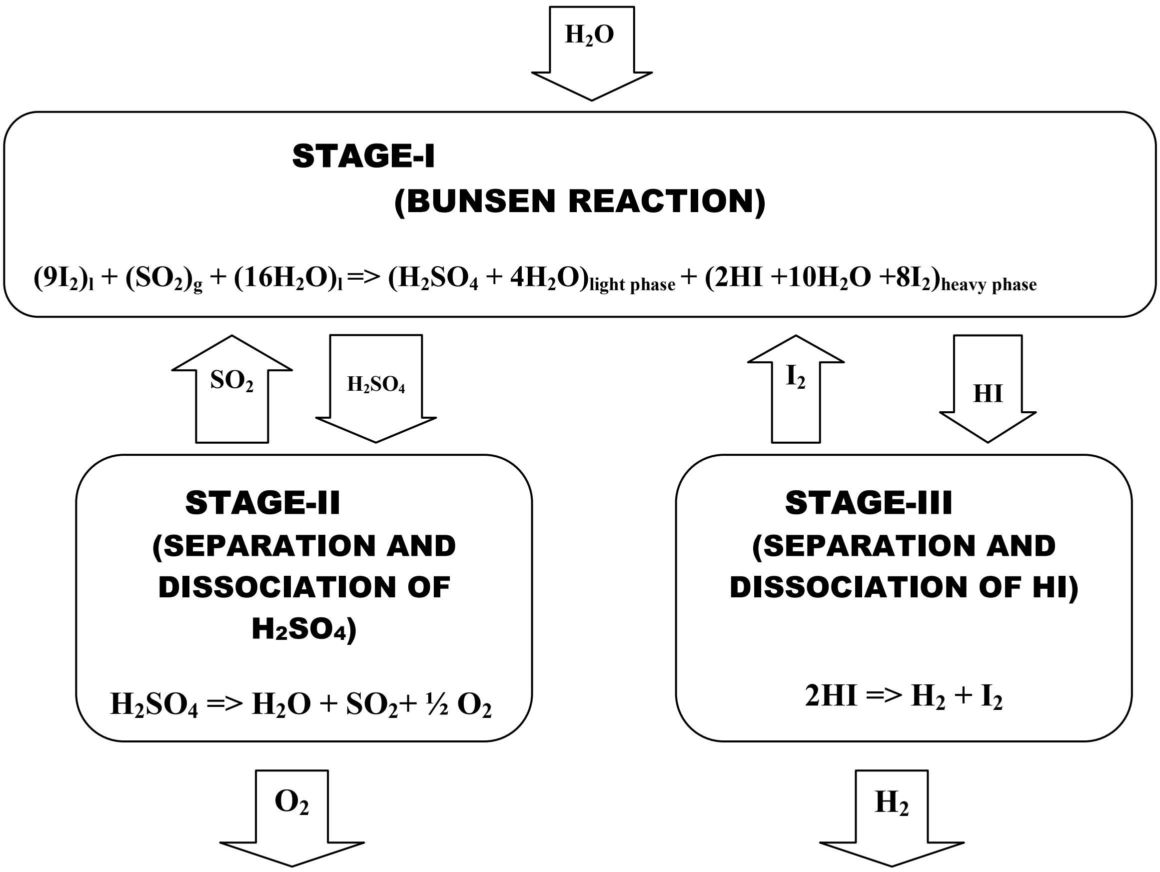


FIG. 1. Outline of I-S process for thermochemical hydrogen production

3. Work methodology

General Atomics [1] has carried out substantial work for the development of IS process. Overall efficiency of the cycle depends on maximizing the efficiency of each stage. Efforts made to improve the efficiency of reactive distillation stage are discussed here. There is not much agreement in the data reported by earlier authors [1,2&3]. In fact many authors have used Roth's paper [2] as a reference paper and could not converge the program due to complete mismatch of material and energy balance. Thus, it is appropriate to study this system independently with fresh approach for generating design data based on proper material and energy balance.

Computer simulation studies for HI_X system were carried out to estimate the effect of various alternative options for enhancing the equilibrium yield of hydrogen production. Equilibrium tray concept is used for physical as well as reactive zone of distillation column. Hydrogen generation is based on decomposition of HI vapour. Equilibrium constants as shown in Table-I for the reaction is based on standard free energy change of HI decomposition [5]. Equilibrium yield is taken as the ratio between the hydrogen produced to HI in the feed. In addition to operational ease, pressure of the column is decided by increasing the difference between the feed composition and azeotropic concentration.

Table I. Reaction equilibrium composition is calculated for the reaction $2HI(g) \leftrightarrow H_2(g) + I_2(g)$ from the following NIST-JANAF Thermo chemical data

Sl. No.	Temperature K	ΔG^o kJ/mole of HI	K_{eq}
1	350	2.698	0.156567
2	400	6.428	0.020951
3	450	9.279	0.007012
4	500	10.088	0.007803
5	600	10.948	0.012411
6	700	11.756	0.017601
7	800	12.528	0.023122

Initial simulation studies were focused to analyze previously published literature schemes on reactive distillation of HI_X system. We have chosen Roth's scheme for reference simulation case study, as this is the most referred scheme in the recent past. Design basis in terms of number of theoretical plates, reboiler load, column pressure and partial condenser temperature of all schemes are kept same. Reactive distillation column feed throughput, feed and product composition are equivalent to previously published literature [1,2&3]. Quality of feed and side stream is modified as compared to Roth scheme to match the material and energy balance. In addition to this, a scrubber is added to attain desired purity of hydrogen. Systematic variation of performance affecting data was conducted to enhance the equilibrium yield of hydrogen production. Estimation of equilibrium yield with the variation in number of theoretical plates, feed and side stream plate locations, column reflux, scrubber effluent recycle were amongst the major parameters considered for simulation. Major design data of all schemes as presented in Table II and Fig. 2 is as follows:

Table II. Major design data of all schemes

Sl. No.	Design parameters	Values
1	Number of theoretical plates	10
2	Feed plate location	9
3	Feed quality	Saturated vapour
4	Column operating pressure	22 bars
5	Re-boiler load	237MJ/hr
6	Partial condenser temperature	221^0C

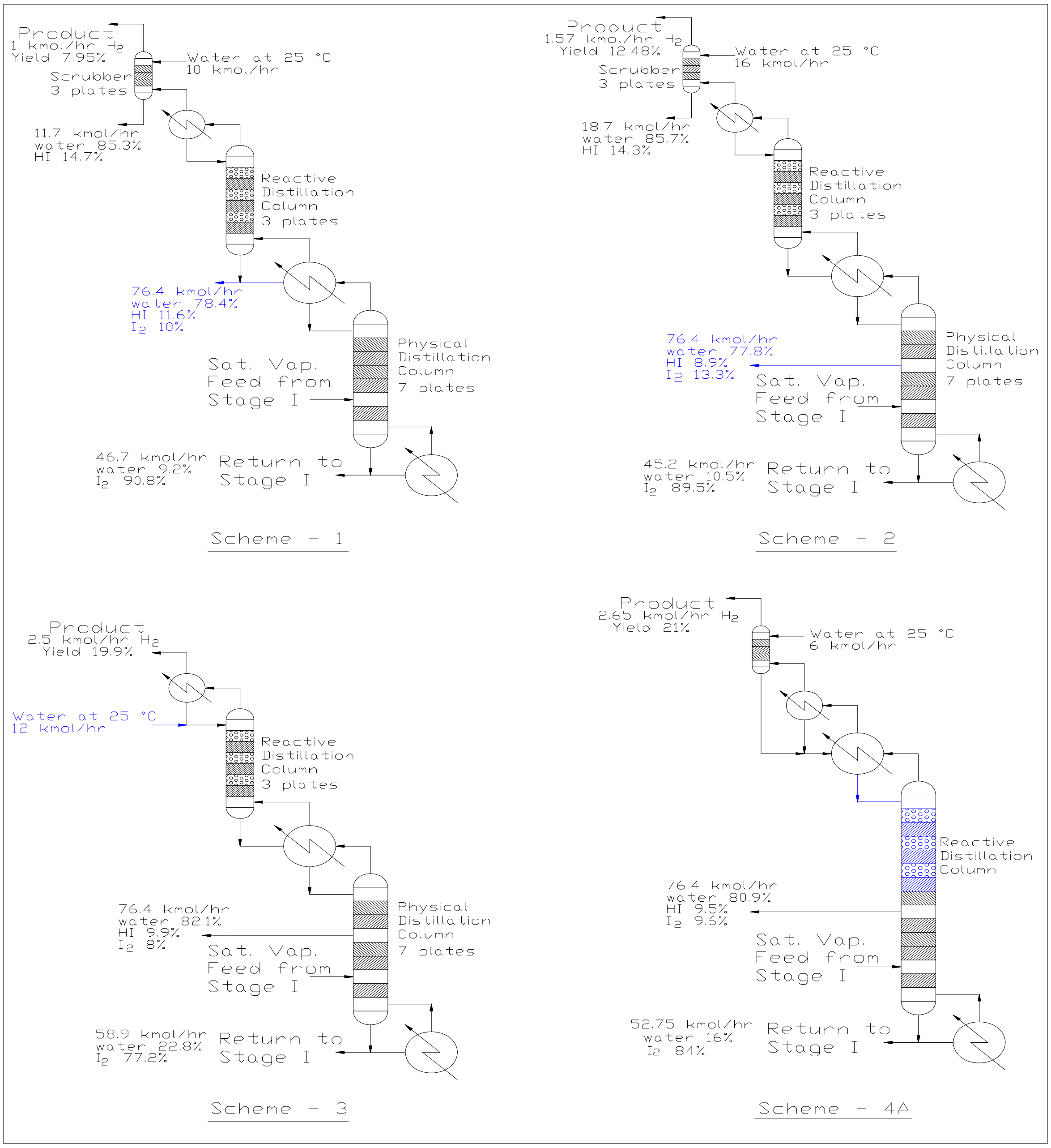


FIG. 2. Schematic schemes for thermo chemical hydrogen production

4. Results and discussions

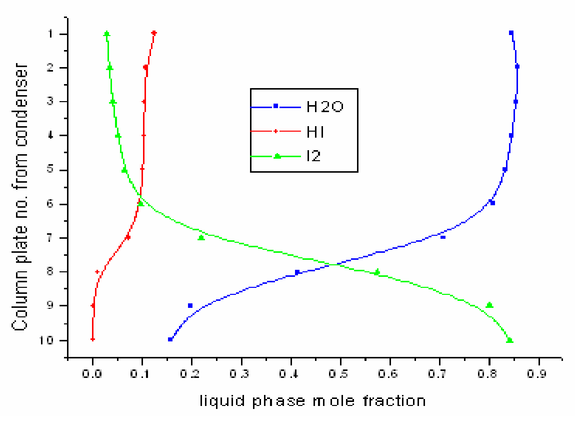
Effect of total number of theoretical plates on hydrogen yield was estimated. It is observed that as we increase the number of plates from 8 to 18 initially equilibrium yield increases and after 10 plates there is no significant change in equilibrium yield. Thus 10 plates were taken as optimum for further investigations.

Scheme 1 is taken as a reference scheme of Roth's paper with corrected material balance and liquid and vapour flow along the column for 1 kmol/hr hydrogen production having 99.8% purity at room temperature. In this scheme Saturated Vapour feed is sent to first physical distillation column having seven plates and saturated liquid side stream is removed from top plate. First column partial condenser temperature is maintained at 22°C. Distillate of first column is flashed in second reactive distillation column and condensate from partial condenser of second column at 25°C is sent back as reflux to second column. Un-reacted HI solution as bottom product of second column is sent back to top tray of first column, Water scrubber is used as a final purification unit to improve the concentration of hydrogen from 37% to 99.8%. In this scheme bottom product and side stream after heat recovery along with scrubber effluent are sent back to Bunsen section. Hydrogen yield for this scheme is estimated to be 7.95%.

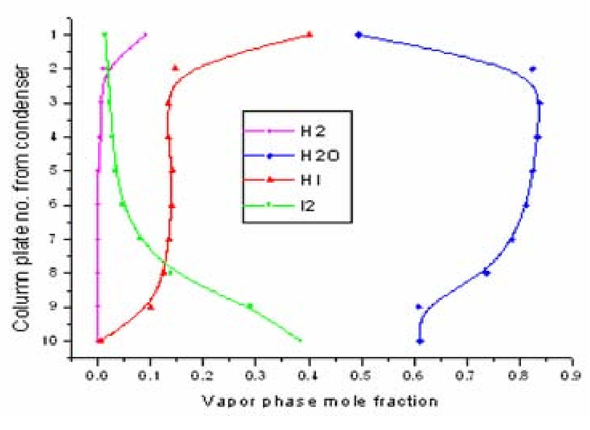
Effect of location of side stream on the equilibrium yield of hydrogen production is shown in Scheme 2. Saturated liquid side stream is removed from 3rd plate instead of top plate. It is observed that, as we move down along the column for side stream removal, HI concentration in the side stream decreases which in turn increases the hydrogen yield. Hydrogen yield for this scheme is estimated to be 12.48%.

Influence of additional water flushing on hydrogen production is addressed in Scheme 3. In this scheme water scrubber is removed and water stream is directly added to the top plate of the second reactive distillation column. This improves the hydrogen yield to 19.87%.

Effect of higher reflux and availability of additional liquid moles by scrubber recycle for stripping iodine and replenishing decomposed HI entering the reaction zone is considered in Scheme 4A. This improves the hydrogen yield to 21% by utilizing the HI content of scrubber waste. Vapor and liquid concentration profiles along the column height are shown in Fig. 3



Liquid phase conc. profile for scheme 4A



Vapor phase conc. profile for scheme 4A

FIG. 3. Vapor Liquid column concentration profiles

In order to understand reactive distillation better, it is appropriate to compare it with physical distillation of HI_X system. Column is simulated without reaction for various partial condenser temperatures. It is interesting to note that HI concentration increases from 50% to 99% for the variation in partial condenser temperature from 221°C to 50°C. Typical column concentration profile for physical distillation column having partial condenser temperature of 221°C is shown in Fig 4. Reduction in top column temperature increases the HI concentration. However this will not be desirable from reaction kinetics and equilibrium yield point of view. This finding clearly indicates that gain in HI concentration may not always result in gain in hydrogen production

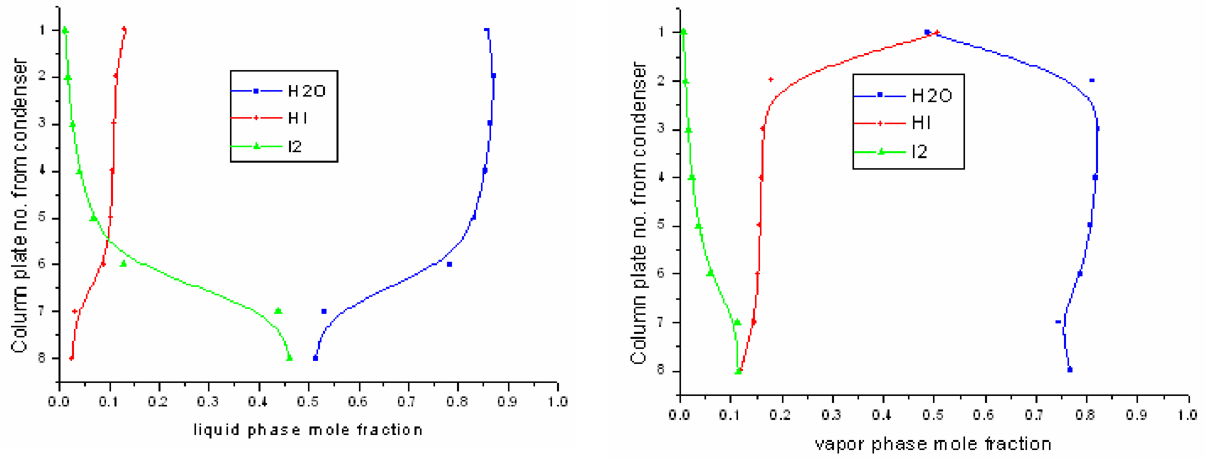
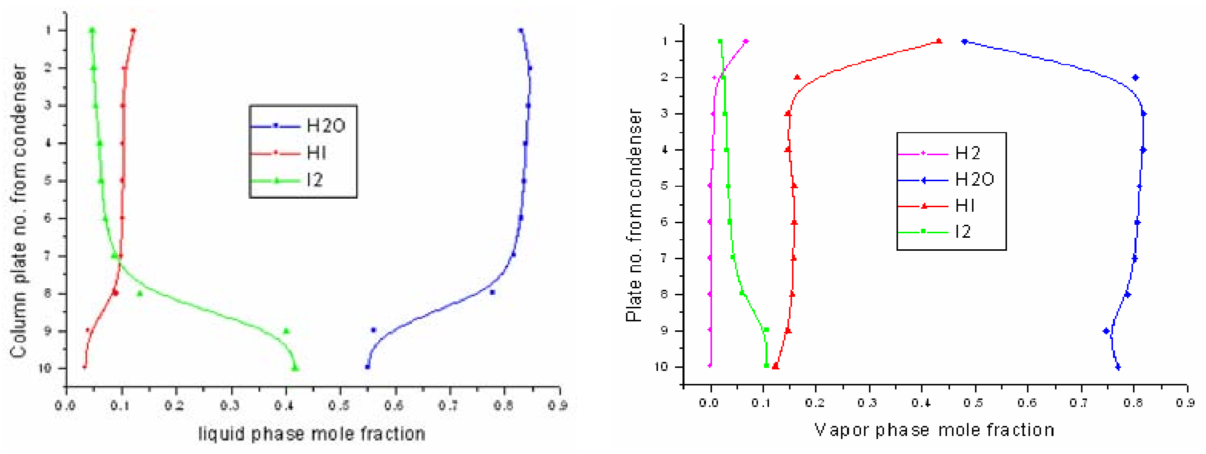


FIG. 4. Vapor Liquid column concentration profiles for physical distillation

4.1. Generation of new scheme

Based on the advantages obtained by computer simulation studies data for various schemes, we propose a new scheme that integrates all the beneficial issues of all above-mentioned schemes. To improve equilibrium yield, side stream is completely removed and almost whole column is used for stripping of iodine. Reasonably good reflux is observed by whole column. Scrubber reject is utilized to improve the hydrogen production by recycling it to main reactive distillation column. This improves the equilibrium yield to 33.0%. Vapor and liquid concentration profiles of all the components along the length of the column are shown in Fig. 5.



Liquid phase conc. profile for scheme 4 Vapor phase conc. profile for scheme4

FIG. 5. Vapor Liquid column concentration profiles

It is observed that there exists a proper combination of HI and water composition in the column at which yield of hydrogen is significantly increased than at higher vapor HI concentration alone. Increased reflux in the column helps in insitu flushing of the iodine generated by HI decomposition which in-turn improves the hydrogen yield. It is to be noted that iodine enrichment for higher hydrogen yield scheme will be lower as compared to lower hydrogen yield scheme. Hydrogen yield from the analyzed schemes are compared and shown graphically in Fig. 6.

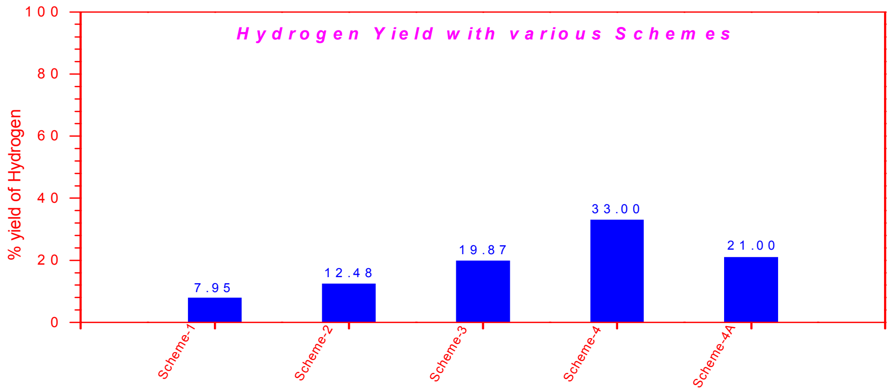


FIG. 6. Hydrogen yield from various considered schemes

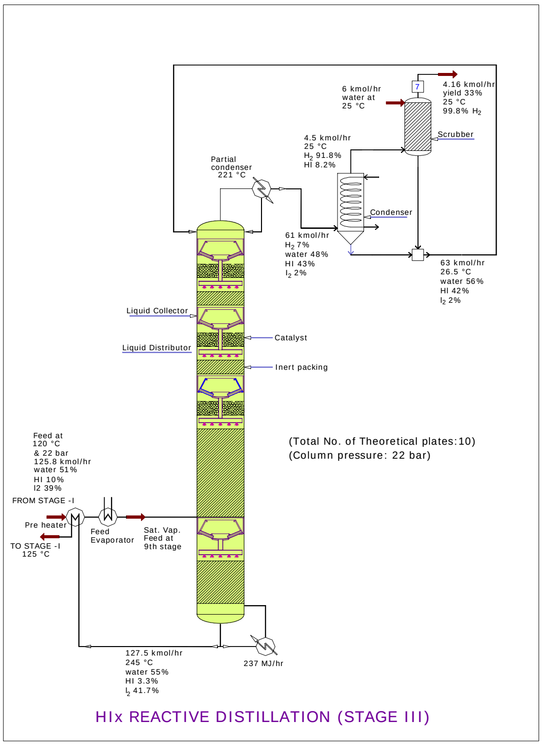


FIG. 7. Details of scheme-4 configuration

It is reported in Ref. [4] that, to have a reasonable height of theoretical plate, use of alumina based catalyst loaded with either of the noble metals such as platinum, palladium and ruthenium is a must. Based on our experience in similar catalyst development for hydrogen water exchange reaction and hydrogen oxygen recombination reaction, we propose a different conceptual scheme to reduce catalyst poisoning in the longer run. In this scheme reaction trays and mass transfer trays are addressed separately in terms of liquid loading. It is experienced that higher liquid loading reduces the catalytic activity with time due to capillary condensation. With the proposed scheme, liquid loading is reduced in catalytic region while maintaining the proper wetting in mass transfer region. Details of this proposed scheme 4 are shown in Fig. 7. This scheme will be further incorporated in our pilot plant studies in near future.

5. Conclusion

In the absence of definite thermodynamic model available in the literature we feel absolute value of hydrogen yield may vary from the actual one. However, relative gain in various schemes cannot be ignored. We have used NRTL model, which exhibits Hetro azeotrope for a given concentration at lower pressure than the reported one. Thus absolute value of yield obtained will correspond to higher pressure in actual case where azeotropic concentration of HI tends to reduce. Nevertheless we are initiating the efforts to conduct experiments and improve the model to reduce the uncertainties. It is concluded that reflux in the column can influence the hydrogen yield significantly. However, increased yield is obtained at the cost of lower iodine enrichment of the bottom stream. We strongly feel that efforts to improve hydrogen yield are more desirable than iodine enrichment as iodine stream is any way going to mix with aqueous stream before it enters the Bunsen reactor.

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The future of nuclear energy as a primary source for clean hydrogen energy system in developing countries

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Abstract. The limited availability of fossil fuels compared to the increasing demand and the connected environmental questions have become topics of growing importance and international attention. Many other clean alternative sources of energy are available, but most of them are either relatively undeveloped technologically or are not yet fully utilized. Also, there is a need for a medium which can carry the produced energy to the consumer in a convenient and environmentally acceptable way. In this study, a fission reactor as a primary energy source with hydrogen as an energy carrier is suggested. An assessment of hydrogen production from nuclear energy is presented. A complete nuclear-electro-hydrogen energy system is proposed for a medium size city (population of 500,000). The whole energy requirement is assessed including residential, industrial and transportation energies. A preliminary economical and environmental impact study is performed on the proposed system. The presented work could be used as a nucleus for a feasibility study for applying this system in any newly established city.

1. Introduction

The risk of global climate changes is of great concern to policy makers and to the public. The relation between the energy generation sector and environmental pollution is being carefully considered in industrialized countries. Before executing any power generation project, extensive and comprehensive studies are performed concerning the impact of such a project on the environment. Measures for decreasing climate change and environmental pollution are considered.

When it comes to the developing countries, the situation is more complicated. Environmental pollution problems are less considered. Also, the rate of increase of power generation is much more than in the case of the developed countries. This means that the environmental impact in the developing countries is much more magnified, which means that the use of nontraditional solutions for less polluting power generation cycles in developing countries is needed.

In this study, the gap in power consumption between developed and developing countries are briefly delineated. The rate of increase of power requirements in developing countries is discussed. The case of Egypt, as example of developing country is considered. Moreover, a clean nuclear-electrical-hydrogen energy cycle is suggested to be considered by the policy makers. The benefits and the drawbacks of such a system in the developing countries are discussed. The economics of a prototype system in a rural area is also presented.

2. World energy requirements

Energy consumption growth is closely linked to population growth, although changes in life styles and efficiency improvements have a substantial influence on the per capita annual consumption. The structure of population and the share between urban and rural populations also affect energy demand.

In a recent study [1], two scenarios were considered for the worldwide future energy demand till the year 2050. The two scenarios assume similar levels of global economic growth: 2-3%

per year to 2050, with higher growth in developing countries than in industrialized countries. The first scenario (S1) aims to reduce CO_2 emissions to a sustainable level. This scenario will require a dramatic change in attitudes towards energy use. In our opinion, such a change is far from being achieved.

The second scenario (S2), which is more feasible, assumes that the average energy demand per capita in the developing countries increases threefold, to reach 1.5 toe/a by 2050. For the industrialized group, the energy demand per capita will stabilize at the present level of some *5* toe/a.

Assuming that the world population will reach 10,500 million in 2050, the energy demand will increase from 7.9 Gtoe/a in 1988 to 20.5 Gtoe/a in 2050. Table I summarizes the results of the mentioned study. Another study [2] shows that, by considering moderate world economic growth of 3%, the world energy demand by 2020 will be between 13 and 17 Gtoe/a. These results are comparable to those given by the previous study [1].

Table I. World energy demand projections and the concomitant growth in annual CO_2 emissions for scenarios S1 and S2 (adapted from Ref [1])

Item	Scenario	Year		
		1990	2010	2050
Energy demand (Gtoe/a)	S1	8.0	9.9	12.6
	S2	8.0	12.3	20.6
Electricity share of primary energy (%)	S1	33	35	39
	S2	33	35	40
CO_2 emissions Gt C/a	S1	6.9	7.5	8.6
	S2	6.9	10.8	14.0

3. Regional perspectives

Comparative studies [2-4] indicate that 70% of the world population lives at a per capita energy consumption level one-quarter of that of Western Europe and one-sixth of that of the United States. Detailed comparisons show more discrimination. For example, the electrical consumption per year per capita is 100 kWh in Pengaladish, while it is 25,000 in Norway and 6700 in France [3]. Other studies [5] showed that 20% of the world population is expected to consume 75% of the total world energy consumption by the year 2000.

Concerning energy supplies, more than 70% of the world energy is to be supplied by the developing countries by the year 2000 [5]. Contrary to general belief, the industrialized countries' natural resources exceed those for the developing countries. The case of the U.S. is a clear example of disparity [5]. Such a situation indicates that the natural resources in the developing countries are depleted in order to satisfy the developed countries energy needs.

In the developed countries, the possibility of using new energy resources is much more foreseen than in the case of developing countries. For example, during the 1973 oil crisis, many researches were initiated in the industrialized world for oil substitutes, such as coal liquefaction, fast breeder nuclear reactors, etc. Most of these research projects slowed down after securing an oil supply and the end of the crisis.

4. Specific case within the developing countries

If we consider the energy consumption in Egypt as a specific example of developing country, we can abstract the following results:

(1) The annual electricity consumption per capita in Egypt was 654.2 kWh in 1990 [3] and was increased to about 800 in 1994.

(2) The rate of increase in the per capita consumption in Egypt is 15.4% during the period 1974-1990 [3]. It is obvious that such a rate is very high and could not be maintained. However, we can consider a rate of *5%* per year in the subsequent years after 1990, which is higher than the worldwide projection of 3.3% [1]. Accordingly, we can say that the consumption at the year 2050 will be 17 fold that of 1973 (see Fig. 1). Such consumption needs a lot of increased power generation in subsequent years.

(3) The only two sources of electricity production in Egypt are fossil fuel thermal power and hydropower generation. Table II gives some information concerning power generation in Egypt. It is observed that the ratio between thermal and hydropower generation is about 1:3. No other essential sources are available in the county.

The previous information shows two important facts, which are:

(1) The need for tremendous new power generation in Egypt to satisfy the requirements of population growth and to increase the per capita consumption to a reasonable value.

(2) The lack of diverse sources for power generation, since the only two main sources are fossil thermo power and hydropower.

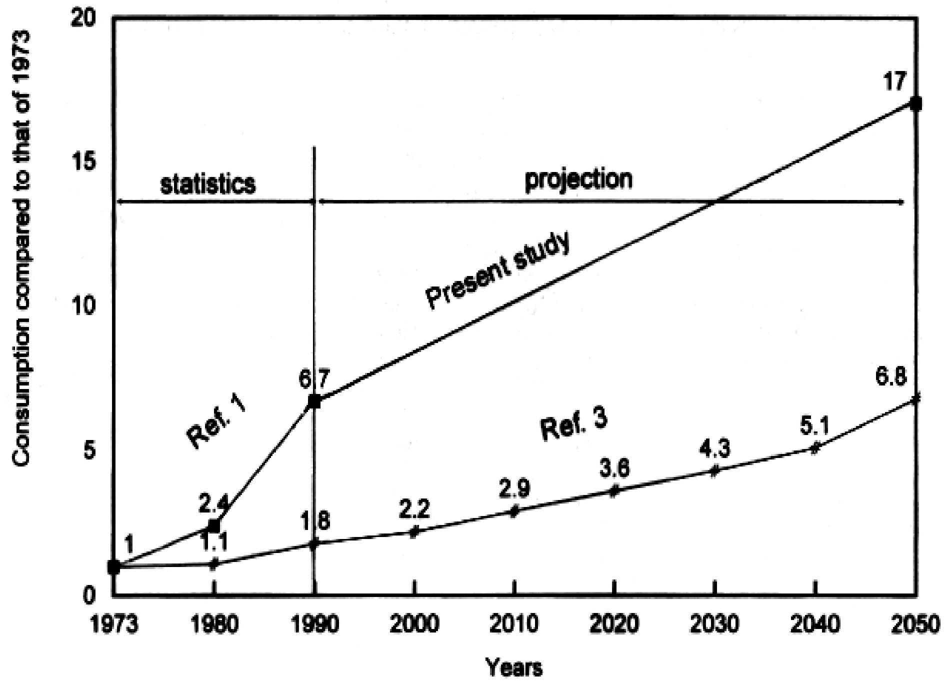

FIG. 1. Present and projected annual electricity demand in Egypt and worldwide in the period 1973-2050

Table II. Sources of electricity generation in Egypt (1990)

Sources	Number of stations	Nominal capacity (MW)	% of the total produced (1990)
Oil	9	1200	
Thermal Oil + Nat. gas	5	5600	76.7
Coal	1	100	
Hydropower	3	2700	23.3

In this context, it is essential for policy makers to comprehensively assess and compare alternative options, integrating economic, social, health and environmental aspects into the process of preparing the national power generation plan. Energy options, strategy and policy must represent an integrated part of overall socio-economic development.

Among the various alternatives, only nuclear power with the highest practical reliability could have a share with oil, coal and hydropower in the generation of the large amounts of electricity necessary for socio-economic development in developing countries. The technical feasibility of nuclear power in developing countries needs fine assessment. We have to notice that nuclear power represents only 3% of the total electricity production in developing countries and 18% in the industrialized countries.

5. Nuclear energy in developing countries

According to previous discussions, studies on energy balances and possible alternatives in developing countries show the importance of considering nuclear energy as one of the main possible and proven alternatives. We have to accept that introducing nuclear energy to developing countries is associated with some restrictions and problems. Many studies [5,7, and 8] discussed the problems related to the promotion of nuclear power programs in developing countries. We can summarize such problems in the following requirements:

(a) Requirements on the national levels which include: long term policy reasoning for nuclear power, national commitment and legislation, qualified manpower, financial situation and industrial support structure.
(b) Requirements on the international levels including: international agreements, contractual arrangements and channels for technical assistance and technology transfer.

In a recent study [9] concerning the constraints on the Egyptian nuclear program, the author indicated that the claims by Egyptian officials that the country's nuclear progress has been stymied by lack of access to the requisite technology is not true, especially at the present time. The main reasons, according to the author, for the slow progress in the nuclear field in Egypt appears to be more tied to factors such as inadequate political support and an inability to obtain funding. In our opinion, these are the main reasons in most of the developing countries.

However, nuclear power can have a large share in the energy mix proposed to satisfy the growing energy needs in developing countries. One of the main advantages of nuclear power is the low emission of greenhouse gases per unit of electricity produced compared to other energy production sources. For example, fossil fueled chains emit some 50 times more than nuclear energy [10]. Although an expansion of nuclear power alone will not solve the energy/environment problems, these problems cannot be solved without greater use of nuclear power.

6. Nuclear-electric-hydrogen energy system

Development of nuclear energy requires a gaseous vector as a partner for electricity. This partner could well be hydrogen produced by water decomposition as the ultimate gaseous intermediate carrier of energy. A combination of nuclear energy associated with the production of hydrogen gas as an energy carrier could be an excellent solution for remote areas as a clean energy chain. In such a chain, the nuclear power could be a clean source for electricity and also for hydrogen production as a clean energy carrier. This proposed chain may have the following advantages:

(1) Very little pollution, especially greenhouse gas emissions.
(2) Satisfying most, if not all, of the energy needs in any clean, remote and newly developed areas.
(3) Some economical benefits by saving the costs of energy transmission to these remote areas, either as electricity or as fossil fuels.

Hydrogen could be advantageously used as a clean energy carrier for heat supply and transportation purposes. Many studies have been focused on the problems related to the use of hydrogen as a heat supply such as storage and transportation [11,12] production by electrolytic processes [13,14], combustion and direct fuel use of hydrogen [15,16]. We can summarize these research results in the following points:

(1) Hydrogen could be used in its end-use as a non-polluting and versatile fuel or chemical. Also, it has the advantage of being non-fossil. Also, it has the advantage over electricity that it has the fuel nature, which enables direct storability and transmission as a material flow.
(2) The production of hydrogen from nuclear power could be either by electrolysis, or by thermolysis. The efficiency could be as high as 50%, especially in the latter technique. Research in this field is still going on for increasing efficiency and decreasing costs of production.
(3) Storage and transfer of hydrogen could be accomplished with “state-of-the-art” technologies with reasonable cost. Most of these technologies are now in use.
(4) Hydrogen is being used now in many prototype hydrogen automobiles which have been manufactured and tested. The hydrogen motor reaches efficiency close to that of the natural gas motor.

Accordingly, the main advantages of using a nuclear-electric—hydrogen energy chain could be summarized in the following two points:

(1) A pollution free energy chain, especially for greenhouse gases and other air polluting gases.
(2) Saving the cost of long distance transportation costs for energy required to remote areas, either in the shape of electricity (transmission lines) or in the shape of liquid fossil fuel (pipelines, vehicles transportation, etc.).

Taking the above information into consideration, we can propose a specific nuclear-electric-hydrogen system. In the following proposal, the power required for a newly developed area of a population of about half a million inhabitants is given in some detail.

(1) The present electricity consumption in Egypt is around 800 kWh/year. If we consider a three fold increase in the future, an annual consumption of 3000 kWh/capita could be considered reasonable.

(2) If we consider the other direct requirements of the fuel to be nearly the same as the electrical requirements, i.e. 3000 kWh/year/capita, and if this is to be produced with an efficiency of 50%, the required electricity will be 6000 kWh/year/capita to satisfy all other requirements. Therefore, the total annual requirements per capita will be 9000 kWh.
(3) For this proposed consumption, the energy required for half a million inhabitants in any remote area will be a 600 MW(e) nuclear power station (or 2 units of 300 MW(e)) with a power factor of 80%. Such a power station will be enough to satisfy all the energy requirements of this medium sized community.

From the economic point of view, we can consider the following:
(1) In spite of the higher investment costs of nuclear power stations, savings in fuel costs give a comparable power cost for both fossil and nuclear powers (see Table III).
(2) If the proposed system is to be used in a newly developed remote area (e.g. El-Ewyyenat area at the southwest borders of Egypt), the following advantages could be achieved (a) saving the cost of power transmission to this area either in the shape of electric power using transmission lines or in the shape of liquid oil with pipeline. Saving will include investment costs and maintenance costs; (b) saving of losses in electricity transmission and distribution. For the electrical transmission line, the power loss may reach 15% in long lines [17] as a Maximum loss. The loss percentage figures of electrical networks of the developing countries are considerably higher, up to 20-25% and even higher [17].

Table III. Comparative cost of power generation base year 1980 (adapted from [17])

Generation type	**Investment cost $/kW installed**	**Fuel cost C/kWh**	**Power cost C/kWh**
Fossil fuel fired	800-1000	1.0 – 3.0	3-7
Nuclear	1600-2200	2.0 1.0	5-7

7. Conclusions

To satisfy the growing electricity demand and the increasing awareness of environmental issues in developing countries, one of the main power generation chains could be the nuclear-electric- hydrogen chain. Such a chain may have the following advantages:

(1) It can cover a part of the national energy requirements in any developing country, especially in the context of developing diverse energy systems.
(2) Such a chain has the potential to contribute significantly to optimized energy system expansion strategies based upon environmental criteria.
(3) Such a chain may have possible economical effects by saving the cost of power transmission to remote areas.

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Closed cycle and continuous operations by a thermochemical water-splitting IS process

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Abstract. Stable hydrogen production by IS process is quite hard because of its unique characteristics of closed-cycle condition. This issue is of high priority in aiming for industrializing the process as a feasible chemical plant. Essential problems with the closed-cycle operation are identified , due to which the cycle is able to be retained on a steady state in case H_2 production rate, O_2 production rate and H_2O supply rate have just a equal value . The process control methods to maintain mass balance of the process were devised, which are to install accumulators for total system, techniques of maintaining Bunsen reaction composition and so on. For plant operation, the controlled variable and the manipulated variable are found out. By computer simulation and the bench scale H_2 production test, the control methods were confirmed. For closed cycle operation for water splitting driven by helium gas heat, the method to allocate heat for O_2 production section and H_2 production section in strict proportion is defined. By computer simulation for O_2 production system, the key to maintain heat balance on cascade heat absorption system was confirmed.

1. Introduction

A huge demand for hydrogen as an energy carrier is expected for the near future. At present, industry uses fossil fuels as energy sources and as raw materials to obtain hydrogen. The thermochemical water-splitting processes are due to offer massive hydrogen production methods without carbon dioxide to be supplied with heat from the high-temperature gas-cooled reactors (HTGRs). The IS process that uses iodine and sulfur is a variation of the processes proposed by the General Atomic Co [1]. As such attractive characteristics are featured, Japan Atomic Energy Agency have implemented studies to develop a hydrogen production system using the IS process with HTGR.

The IS process should have a desirable and unique feature which is that it can be operated on a closed cycle condition. On the condition, all chemicals circulate through the process as the chemical forms change by two or more reactions, thereby the chemicals must be recycled. Because of influences on the recycling chemicals in the closed-loop, to perform stable hydrogen production is quite difficult in practical operations. Therefore, developments of process control methods for stable hydrogen production to maintain the process in a stable state and demonstrations of stable and durable hydrogen production by the IS process are indispensable to show its possibility for realization as a operational chemical plant. This paper discusses problems with conducting the closed-cycle operation and a fundamental concept of process control methods on helium gas heating. Furthermore, results of a closed-cycle hydrogen production test using bench scale glass facility and computer simulation to confirm the control methods are reported.

2. Problem on closed-cycle operation

2.1. Scheme of IS process

Chemical reactions of the IS process is shown in Fig. 1. The process is composed of the eq. (1), eq. (2) and eq. (3). The Bunsen reaction (eq. 1) is an exothermic sulfur dioxide gas-absorbing reaction in an aqueous phase. The hydriodic acid and the sulfuric acid formed are separated by a liquid-liquid phase separation phenomenon that occurs in the presence of an excess of iodine. The two acids divide into upper and lower solutions with a clear boundary. The separated hydriodic acid dissolves the iodine and is denoted as the HIx phase. After purification, hydriodic acid is separated from HIx by distillation. The HI is then decomposed to produce hydrogen and iodine (eq. 3) around 500°C with small endothermic reaction. Similarly, the separated sulfuric acid denoted as the H_2SO_4 phase is purified, concentrated, vaporized and decomposed to produce oxygen. Here, the decomposition reaction (eq. 2) proceeds endothermically in two stages. Firstly, the sulfuric acid decomposes spontaneously into sulfur trioxide and gaseous water, secondly, the sulfur trioxide decomposes into sulfur dioxide and oxygen around 900°C, The products of the iodine, the water and the sulfur dioxide are reused for the production of acids in the Bunsen reaction.

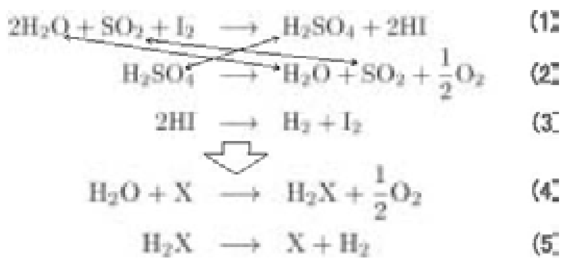

FIG. 1. Reaction scheme of IS process and the simplest thermochemical cycle.

2. 2. Mass balance on closed-cycle condition

The continuous and closed-cycle condition is important for running the IS process using the continuous heat from HTGRs with no waste to the outside. In order to declarer essential problems with the closed-cycle operation, a mass balance is discussed by employing the simplest thermochemical cycle.

Supposing SO_2 is the limiting reactant in eq. (1), amount of producing H_2SO_4 equals decomposed H_2SO_4. In consequence, the simplest reaction scheme of thermochemical cycles is obtained. The cycle consists of two imaginary chemical reactions including only X, imaginary substance, which corresponds to I_2.

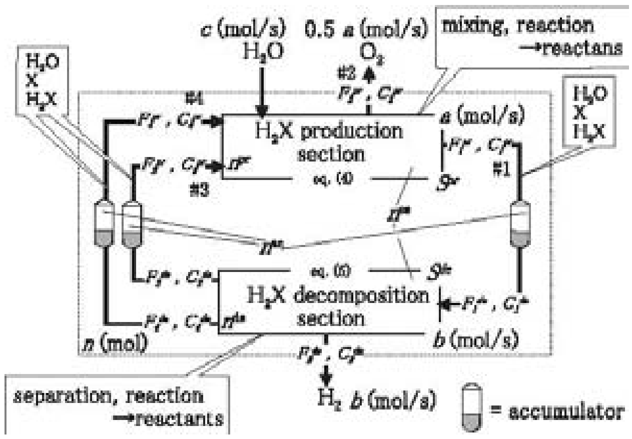

FIG. 2. Simplest thermochemical cycle using imaginary substance X equipped with two reaction sections and accumulators.

Fig. 2 shows the simplest thermochemical cycle using substance X. In eq. (4), the H_2O and X mix to produce H_2X, simultaneously the oxygen is produced. At this reaction, H_2X is produced at a rate of *a* mol/s. In another eq. (5), H_2X decomposes into X and hydrogen at a rate of *b* mol/s. Besides, the water as raw material is supplied at rate of *c* mol/s. To make the closed-cycle, the two reactions are combined together, so that chemicals circulate through the cycle. Thus, the water splits into hydrogen and oxygen on the whole.

Because of the closed-cycle condition, the both reactions have two roles as productions and consumptions of circulatory chemicals, H_2O, X and H_2X. As for H_2O, its quantity increases by the raw material supply, and decreases by the H_2X production. As for X, its quantity increase by the H_2X decomposition, and decreases by the H_2X production. The remain of three chemicals, quantity of H_2X increases by the H_2X production, and decreases by the H_2X decomposition. Therefore, for balances of the circulatory chemicals; variations per unit time of them in the system are given by,

$$\frac{dn_{H_2O}}{dt} = c - a \quad , \qquad (6)$$

$$\frac{dn_{X}}{dt} = b - a \quad , \qquad (7)$$

$$\frac{dn_{H_2X}}{dt} = a - b \qquad (8)$$

where the *n* stands for total amounts of chemicals, the subscripts indicate the components of the circulatory chemicals. From the equations,

$$a = b = c \qquad (9)$$

is obtained, provided these variations are zero. Hence, the cycle is to be retained on a steady state, supposing the three rates, H_2X production rate, H_2X decomposition rate and H_2O supply rate, have just a equal value. In contrast, disagreements between the rates, *a*, *b* and *c*, lead to total quantity changes of each chemical inside the cycle; this changes should cause composition changes of mixtures which consist of the circulatory chemicals. Because of the composition changes, to maintain the cycle in a stable state becomes quite hard.

Consequently, to realize durable productions of hydrogen must be difficult, because the compositions of the mixtures varies easily from the disagreements among the rates about the reactions and the supply. This problem is a high priority to aim for industrializing the IS process as a feasible chemical plant, so that practical control methods for the closed-cycle operation are required to maintain the mass balance of the circulatory chemicals. Achieving the mass balance, the cycle produces the H_2 and O_2 whose rates agree to 1 : 0.5 spontaneously.

3. Process control to maintain mass balance

3.1 Creations of controlled variable and manipulated variable

For conducting stable and durable hydrogen productions using the IS process, eq. (9) should be satisfied. To realize this, the manipulated variable and the controlled variable are required, the controlled variable is to be controlled by the manipulated variable. In Fig. 2, the simplest thermochemical cycle using the imaginary substance X equipped with two reaction sections and accumulators. The cycle contains two reaction sections, H_2X production section and H_2X decomposition section, which are connected via the streams in which the circulatory chemicals flow. Actually, the sections should have plural equipments. As for the H_2X decomposition section, its functions are separation of H_2X from the mixture consist of H_2O, X and H_2X, and decomposition H_2X into X and H_2, thereby a few discharge streams to recycle the circulatory chemicals are connected into the H_2X production section. The several accumulators, which hold the mixture inside, are installed on the streams between the two sections.

Eq. (9) should be considered it is not satisfied in every moment. So, to create controlled variable and the manipulated variable, *dn/dt*, variation per unit time of total amount of chemicals inside the cycle, is divided into two parts.

$$\frac{dn}{dt} = \frac{dn^{se}}{dt} + \frac{dn^{ac}}{dt} \qquad (10)$$

where the superscripts of ac and se mean the section and the accumulator.

3.2. Modularizing reaction sections

The manipulated variable to regulate the rates about the reactions is demanded, since the disagreements among the rates about reaction and supply cause the variation of total amount of chemicals inside the cycle. The mass balance of the H_2X production section, also other section , is given by,

$$C^{pr}F^{pr} + S^{pr} - \frac{dn^{pr}}{dt} = 0, \qquad (11)$$

where matrix *C* indicates compositions of each stream (#1 ~ #4), vector *F* is the flow rate of each stream, vector *S* represents rates about the H_2X production reaction, and n^{de} is a total amount of chemicals inside the section.

To modularize the reaction sections is to satisfy following requirements: C^{-2} exists, *C* is a constant and $dn^{pr}/dt = 0$. Supposing these are satisfied,

$$F^{pr} = C^{pr^{-1}}(-S^{pr}) \qquad (12)$$

is obtained. On eq. (12), the flow rates, *F*, are fixed uniquely and proportioned to *S*. Therefore, the manipulated variable as the feed flow rate into the section is created to regulate the rates about the reactions inside the section. Practically, to be constant for *C* can be carry out, except Bunsen section, by using the phase equilibrium on vapor-liquid separation, and to be $dn^{pr}/dt = 0$ can be carry out by maintaining the liquid level of each equipment.

3.2. *Installing accumulators*

The controlled variable is controlled by the manipulated variable to dissolve the disagreements among the rates about reaction and supply. To examine controlled variables, the variation of mixture amount inside the accumulators is discussed. For simple discussion, the composition of stream #1 is assumed $HI/I_2/H_2O$=1/3.8/5.3 [1], stream #2 is pure oxygen, stream #3 is pure water ($HI/I_2/H_2O$=0/0/1) and stream #4 is mainly iodine ($HI/I_2/H_2O$=0.01/0.98/0.01). *F*, *S* and *C* are

$$F^{pr} = \begin{pmatrix} F_1^{pr} \\ F_2^{pr} \\ F_3^{pr} \\ F_4^{pr} \end{pmatrix}, \quad S^{pr} = \begin{pmatrix} -a+c \\ -a \\ a \\ 0.5a \end{pmatrix}, \quad C^{pr} = \begin{pmatrix} 0.552 & 0 & 1 & 0.01 \\ 0.396 & 0 & 0 & 0.98 \\ 0.052 & 0 & 0 & 0.01 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad (13)$$

The variation of mixture amount inside each accumulator is given by

$$-\begin{pmatrix} F_1^{ac} + F_1^{pr} \\ 0 \\ F_3^{ac} + F_3^{pr} \\ F_4^{ac} + F_4^{pr} \end{pmatrix} = \begin{pmatrix} 21.0(a-b) \\ 0 \\ (c-a) - 11.5(a-b) \\ -9.53(a-b) \end{pmatrix} \quad (14)$$

Therefore, the variations of the amount of circulatory chemicals caused by the disagreements (e.c. *a-b*, *c-a*) among the rates can be integrated in the accumulators. Because of the modularizing reaction sections, *C* is made constant, the changes of liquid level in accumulators can be observed as effects of the disagreements. Hence, the controlled variable as liquid level of the accumulators is created to maintain the cycle at steady state by controlling the manipulated variables [2].

3.3. *Maintaining composition of Bunsen reaction solution*

3.3.1. *Method for maintaining composition*

In modularizing procedure for Bunsen reaction section, to hold *C* constant during the plant operation is very difficult because of multicomponent and corrosive solution. So, we devised a simple and easy method for the Bunsen section control.

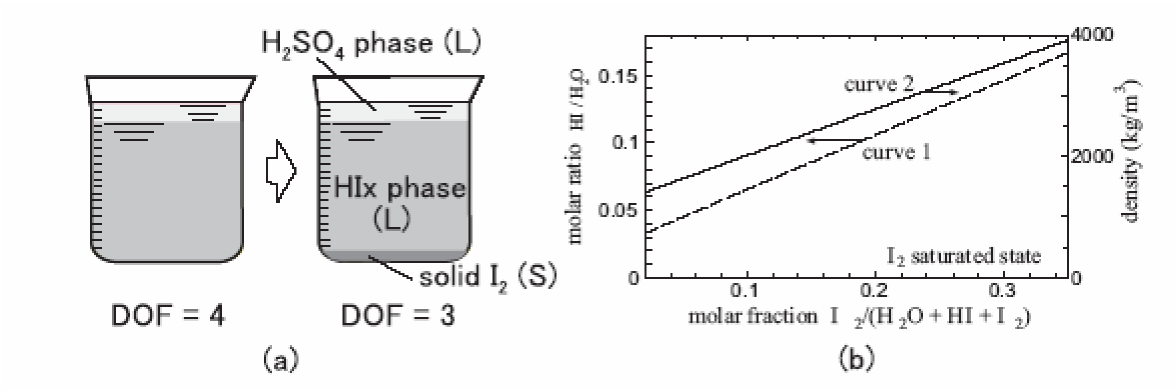

FIG. 3 Method for maintaining composition of Bunsen reaction solution.

Figure 3 (a) shows phases and degree of freedom (DOF) in Bunsen reaction at equilibrium. Number of reaction is 1, number of components of the reaction (eq. 1) is 5, and number of phase is 2 or 3 where gas phase is not at equilibrium, because the gas mixture as reactants flows pass from reaction field on the such flow reactor. To make Solid I_2 on purpose, the DOF is able to reduce. Figure 3 (b) shows molar ratio (HI/H_2O) and density of HIx phase, except H_2SO_4 as minor component, with molar fraction ($I_2/H_2O+HI+I_2$) on I_2 saturated state. On temperature and pressure are constant, the composition varies on the curve 1. Because the curve 1 corresponds one-on-one with the curve 2, the composition of HIx phase is fixed by its density. Therefore to make HIx phase I_2 saturated state and regular density stabilizes the composition of the Bunsen reaction solution.

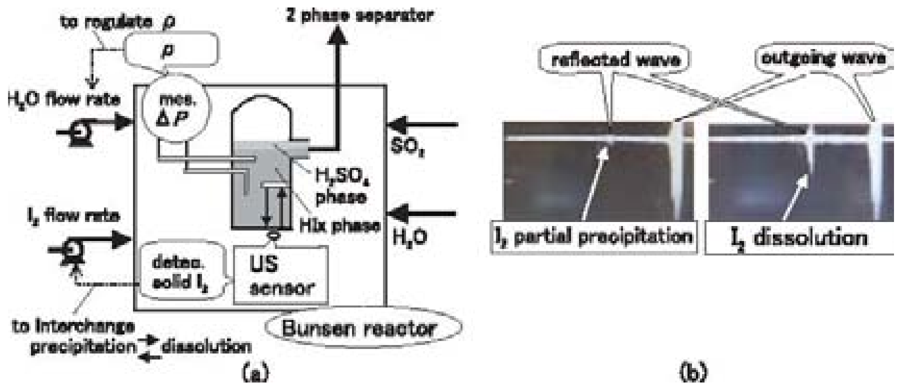

FIG. 4. Techniques of maintaining Bunsen composition in plant operation.

3.3.2. Concrete techniques of maintaining composition in plant operation

Figure 4 (a) shows a system of Bunsen reactor. The vessel of the reactor equipped the ultra sonic sensor (US sensor) at the bottom outside. The sensor releases the outgoing wave, the wave reflects at the reflector in the solution, and then the wave reaches the sensor. In case of existence of the solid substances between the sensor and reflector, the intensity of the reflected wave signal drastically decreases (Fig. 4 (b)). Herewith the US sensor detects information of the solid I_2 existence or not. The pump to manipulate the flow rate of I_2 is controlled acting on interchange I_2 precipitation with dissolution. Also, the differential pressure instrument is equipped for measurement of the HIx phase density. The pump to manipulate the flow rate of H_2O is controlled to regulate HIx phase density. Therefore, the composition of Bunsen reaction solution is able to be maintained at stable condition by applying the techniques.

4. Simulation for methods to maintain mass balance on closed-cycle condition

Computer simulations using a plant simulator (Object DPS, The institute of Japan union of scientist & engineers) were conducted to declare prospect of formulated control method. Figure 5 (a) shows calculation model for simulation. The model consists of three reaction section. They are combined via stream with accumulators and flow rate controllers.

Figure 5. (b) shows calculation results. The horizontal axis indicates operation time, vertical axes indicate relative variation of flow rate A as manipulated variable, ratio of hydrogen to oxygen, relative variation of level of accumulators. At the beginning till 1 hour, process was maintained at stable state. In this condition, production ratio equals to 2, moreover each level did not vary. At 1 hour, flow rate A is manipulated up to 1.1, then production ratio become

under 2. The change of production ratio shows that processing rates disagree between the sections. According to disagreement, the level ② increases.

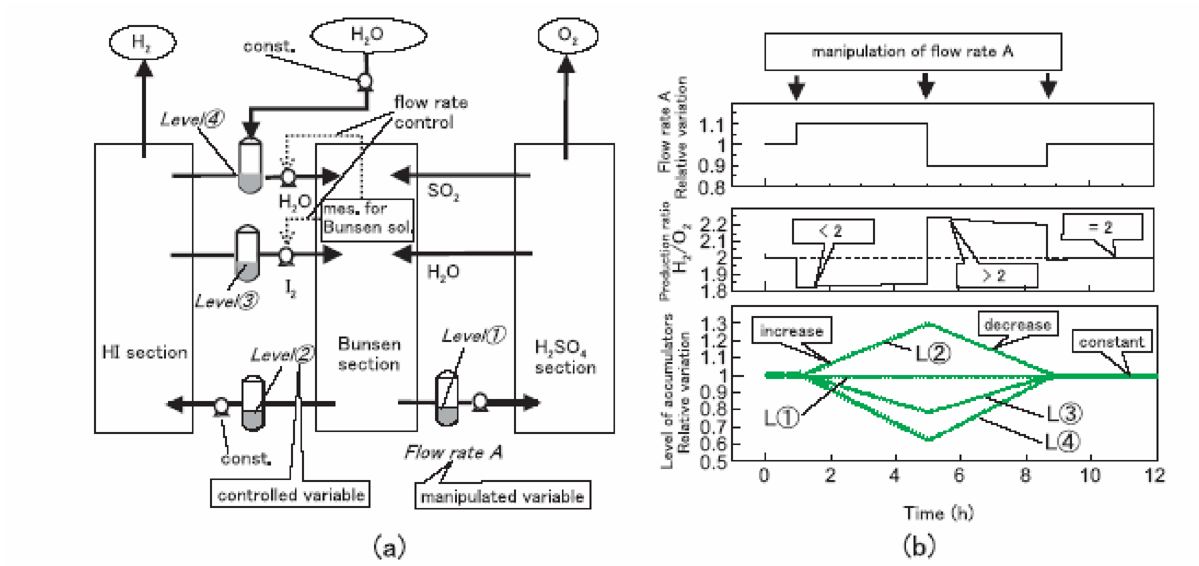

FIG. 5. Computer simulation for control methods to maintain mass balance on closed-cycle condition.

At 5 hour, flow rate A is manipulated down to 0.9. So production ratio became over 2, and level turns over downward direction. At about 7 hour, flow rate B is adjusted, then production ratio agrees to 2, and the level became constant. In this way, we can observe disagreement, and we can control the process to maintain at stable state.

As a consequence, Level ② varies according to production ratio which can be controlled by flow rate A.

Bench scale hydrogen production test was carried out to demonstrate the control method, which was applied to the bench scale test facility with automation. As a result, we accomplished 1 week hydrogen production. H_2 production was stable at a rate of 31L/h for 1week. Moreover production ratio of oxygen to hydrogen agreed to one half. As a result, validity of control method was demonstrated. Closed cycle operation for water splitting driven by helium gas heat

5. Closed cycle operation driven by helium gas heat

5.1. Heat balance on cascade heat absorption system

For IS process driven by specific heat from HTGRs, because of water splitting, the amount of heat should be allocated for O_2 production section and H_2 production section in strict proportion. Supposing the total efficiency for H_2 production is about. 40 %, the required heats for both sections are comparable because of ca. 400kJ-1mol H_2 for O_2 production section [4]. Figure 6 shows a type of configuration for IS process with helium gas supply. The helium gas goes through the O_2 production (reaction A) section and H_2 production (reaction B) section while its temperature decays. In case of gaseous phase reactions for reaction A, B and aqueous phase reaction for reaction C, the evaporating operations is demanded for section A and B. Therefore, the amount of evaporation strongly related to the amount of reaction. Here, the vaporizer type 1 and type 2 can be chosen for section A and B respectively. A function exercises which Q_A increases with decreasing Q_B by what F_A manipulates high flow rate, to allocate the amount of heat for section A and section B in strict proportion. Besides, in this method, IS process system can be matched with helium gas supply varying temperature and flow rate within a defined range.

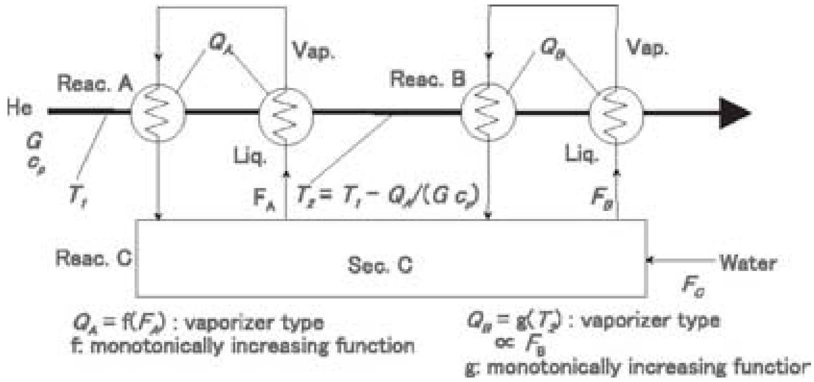

FIG. 6. A type of configuration for IS process with helium gas supply.

5.2. Computer simulation for O_2 production system

In the O_2 production section (Fig. 6), the regenerated heat exchanger must be placed between the reactor and the vaporizer for saving heat. So, helium temperature responses at outlet of the section against the flow rate of feed are not simple. To investigate the responses, simulations for O_2 production system were conducted using a plant simulator (Object DPS, The institute of Japan union of scientist & engineers). Figure 7 (a) shows a simulated configuration of equipments, SO_3 decomposer, regenerated heat exchanger and H_2SO_4 vaporizer, which deal with the helium gas heat exchange. Each equipment is modelled one dimensional heat exchanger. An aqueous phase of H_2SO_4 is fed to the vaporizer, then, vaporized and decomposed into H_2O and SO_3 partially. Gas consists of H_2SO_4, H_2O and SO_3 go through the regenerated heat exchanger, then, gaseous SO_3 decomposes into SO_2 and O_2 in the SO_3 decomposer. The kinetics for SO_3 decomposition reaction is adopted from own experimental data.

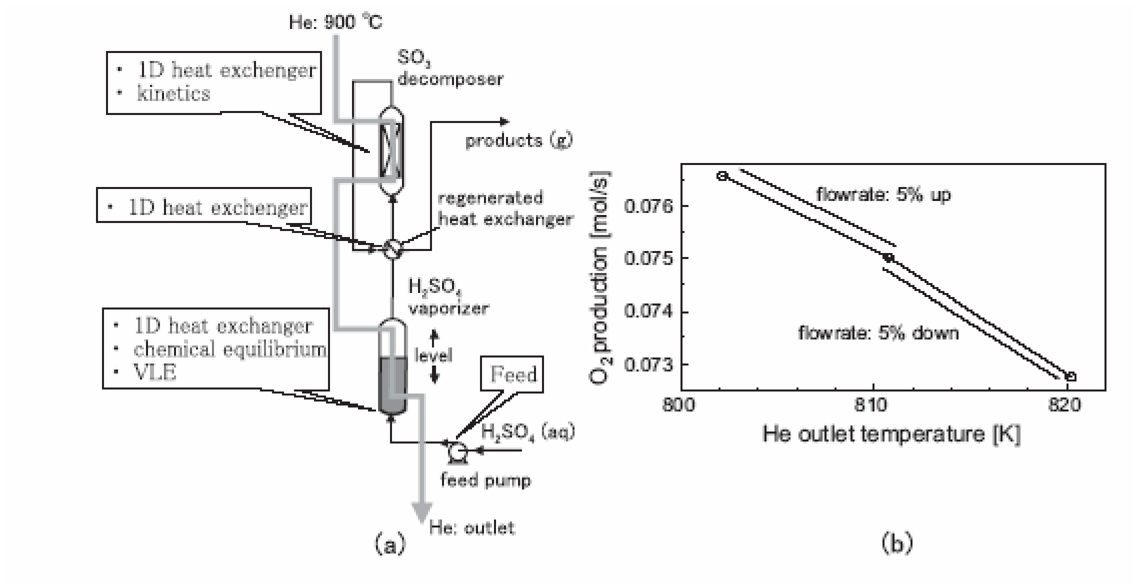

FIG. 7. Computer simulation for O_2 production system.

Figure 7 (b) shows a computed result of O_2 production rates against the He outlet temperature varying H_2SO_4 feed rate. The result highlights that the O_2 production rate decays with the reducing feed rate, while the He outlet temperature increases. From the simulation, the key point to maintain heat balance on cascade heat absorption system is confirmed.

6. Summary

Essential problems with the closed-cycle operation are identified, due to which the cycle can be retained on a steady state in case H_2 production rate, O_2 production rate and H_2O supply rate have just a equal value. The process control methods to maintain mass balance of the process were devised, which are to install accumulators for total system, techniques of maintaining Bunsen reaction composition and so on. For plant operation, the controlled variable and the manipulated variable are found out. By computer simulation and the bench scale H_2 production test, the control methods were confirmed. For closed cycle operation for water splitting driven by helium gas heat, the method to allocate heat for O_2 production section and H_2 production section in strict proportion is defined. By computer simulation for O_2 production system, the key point to maintain heat balance on cascade heat absorption system was confirmed.

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Modeling of evaporation and decomposition processes of H_2SO_4 in SI cycle

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Abstract. The section 2 of the SI cycle (H_2SO_4 decomposition process) consists of several processes including (i) the concentration of H_2SO_4 solution, (ii) the vaporization of concentrated H_2SO_4 solution, (iii) decomposition of H_2SO_4 solution into SO_3 and H_2O at around 400~500°C, and (iv) the decomposition of SO_3 into SO_2 and O_2 at around 850°C under the existence of catalyst. The unit models have been developed for evaporation and decomposition of H_2SO_4 in SI cycle with the chemical process simulator. The overall simulation flow sheet has been developed and several sensitivity analyses have been done for the process equipment.

1. Introduction

The SI (Sulfur - Iodine) cycle, first described in the mid 1970s, is a thermochemical water splitting cycle. It was rejected by early workers due to the severe challenges encountered such as 1) difficult separation of the Bunsen reaction products into a sulfuric acid phase and a hydrogen iodide phase, 2) the low equilibrium conversion rate of hydrogen iodide, 3) the materials endurable to corrosive acids under high temperature and high pressure operating conditions. These challenges have been overcome by many efforts of several investigators, and nowadays it is considered as a well defined hydrogen production method. The SI cycle consists of three processes pertaining to the chemical reactions described in equations (1)~(3), respectively.

$$SO_2 + I_2 + 2H_2O \rightarrow H_2SO_4 + 2HI \quad (1)$$
$$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2\ O_2 \quad (2)$$
$$2\ HI \rightarrow I_2 + H_2 \quad (3)$$

Reaction (2) of the S-I cycle is known as a sulfuric acid decomposition reaction. Reaction (2) takes place in 2 distinctive steps. In the first step, H_2SO_4 decomposes into SO_3 and H_2O at around 400~500°C. In the second step, SO_3 decomposes into SO_2 and O_2 at around 850°C under the existence of catalyst.

In this study, the unit models have been developed for evaporation and decomposition of H_2SO_4 in SI cycle with the chemical process simulator. The overall simulation flow sheet has been developed and several sensitivity analyses have been done for the process equipment.

2. Simulation of sulfuric acid decomposition process

2.1. Process description [1]

The section 2 of SI cycle consists of H_2SO_4 concentrator, H_2SO_4 evaporator, recuperator, and decomposer. The sulfuric acid coming from equation (1), Bunsen reaction, is concentrated prior to decomposition process because it is more cost-effective.

The concentrated H_2SO_4 solution is transferred to the H_2SO_4 evaporator where the sulfuric acid is vaporizing. The H_2SO_4 solution vaporizes more and more as it is further heated up to

650°C. Some of the concentrated sulfuric acid decomposes into H_2O and SO_3 before it enters into the decomposer.

In the decomposer, most of sulfuric acid vapor decomposes into H_2O and SO_3 as the temperature is raised. Upon further heating, the generated SO_3 decomposes into SO_2 and O_2 only in the presence of catalyst, because the decomposition reaction rate is too slow.

The product gases from the decomposer are first cooled in the recuperator, transferring heat to the decomposer feed. They are further cooled down to lower temperature by several coolers and are returning to reaction (1) process. During this process, undecomposed SO_3 combines with water to form H_2SO_4.

2.2. Simulation models [3]

Flow sheet for the sulfuric acid evaporation and decomposition process has been developed with unit operation models provided by the chemical process simulator. It is shown in Fig. 1.

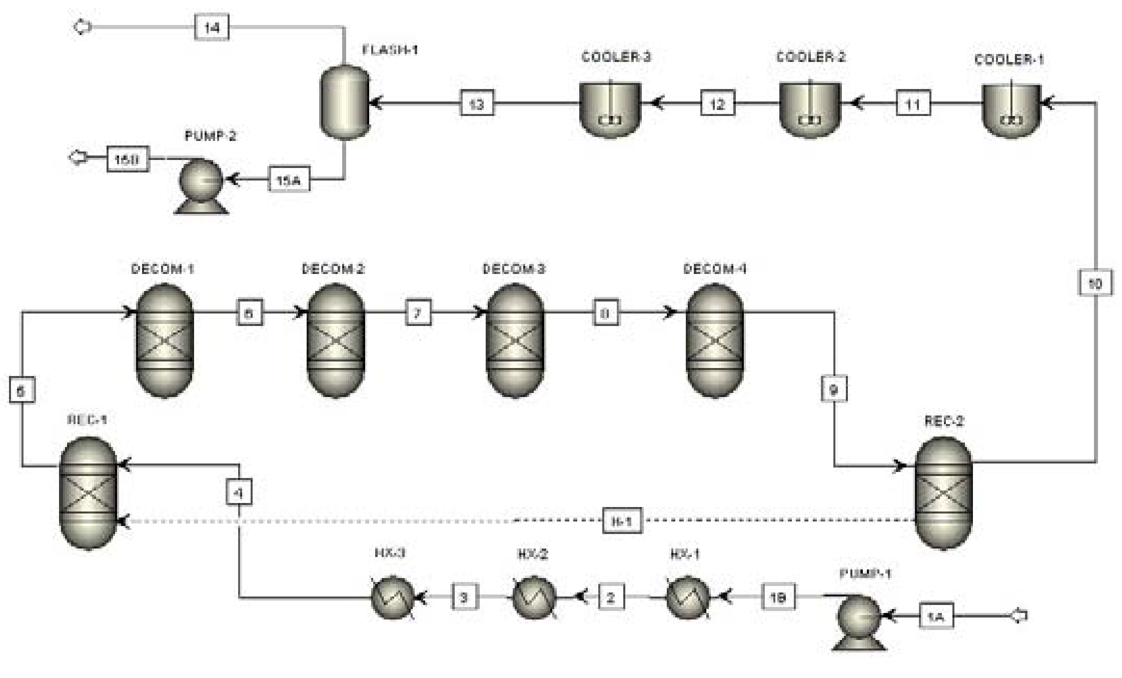

FIG. 1. The simulation flow-sheet of the sulfuric acid evaporation and decomposition process.

2.2.1. Sulfuric acid evaporator

Prior to the decomposition process, the concentrated sulfuric acid is heated to the vaporization temperature. The sulfuric acid begins to vaporize and some of the sulfuric acid decomposes into SO_3 and H_2O. This reaction proceeds further as the vaporized stream is heated in the recuperator. The evaporation process is modeled with three heaters.

2.2.2. Recuperator

The recuperator retrieves much of the heat remaining after sulfuric acid decomposition. Most of the sulfuric acid decomposes into SO_3 and H_2O before it exits the recuperator. The recuperator is modeled as two Gibbs reactors coupled by a heat stream in the chemical process simulator. The Gibbs reactor is normally used to determine the system of independent reactions and to estimate the extent of these reactions based on a Gibbs free energy minimization.

2.2.3. Decomposer

Decomposition is performed in 4 stage decomposer. SO_3 decomposes into SO_2 and O_2. The outlet stream is cooled in the recuperator, transferring heat to the decomposer feed. The decomposer is modeled as a series of four Gibbs reactors, where each stage reaches equilibrium.

2.2.4. Cooler

The cooling process of the reaction (2) products is performed by a cooler. It is simulated as a CSTR (Continuous Stirred Tank Reactor), which can control the reaction kinetics in an aqueous solution. The CSTR, one of the kinetic reactor models, sometimes uses kinetic rate expressions to simulate and it allows for a general sizing of a reactor.

3. Simulation result

In simulation, the sulfuric acid VLE data at high temperature and pressure has been regressed to generate a binary interaction parameters.[2]. The composition of the outlet stream from the decomposer is shown in Fig. 2. as a function of decomposition temperature. The mole fraction of SO_3 reaches its maximum at 550ºC. This means that SO_3 hardly decomposes under 550°C.

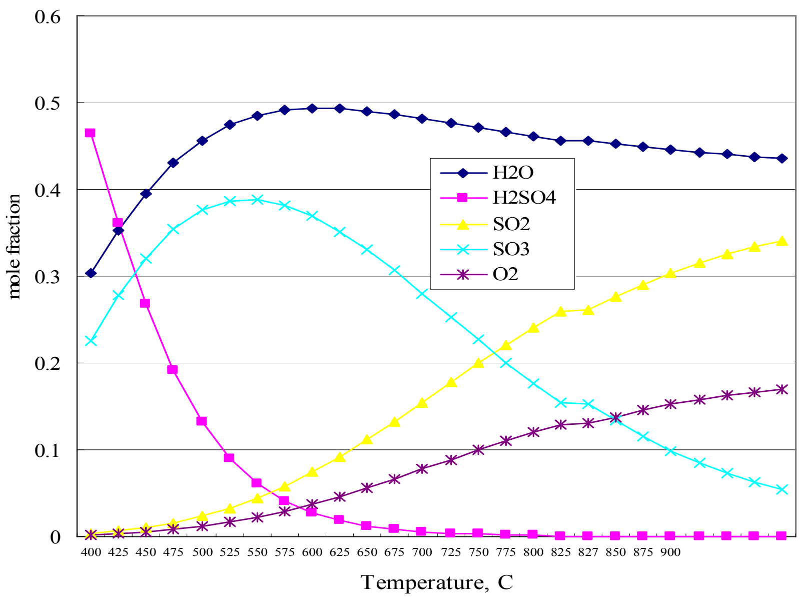

FIG. 2. Mole fraction variation of decomposer outlet stream vs. decomposer operating temperature

The composition of the streams during evaporation and decomposition process is shown in Fig. 3. in terms of mole fraction. It is understood that some of the sulfuric acid begin to decompose into SO_3 and H_2O at the entrance to the decomposer. The sulfuric acid decomposition reaction proceeds further as the vaporized stream is heated until it is completely decomposed into SO_3 and H_2O at the entrance to the second decomposer. Right after the second decomposer, sulfur tri oxide (SO_3) begins to decompose into SO_2 and O_2.

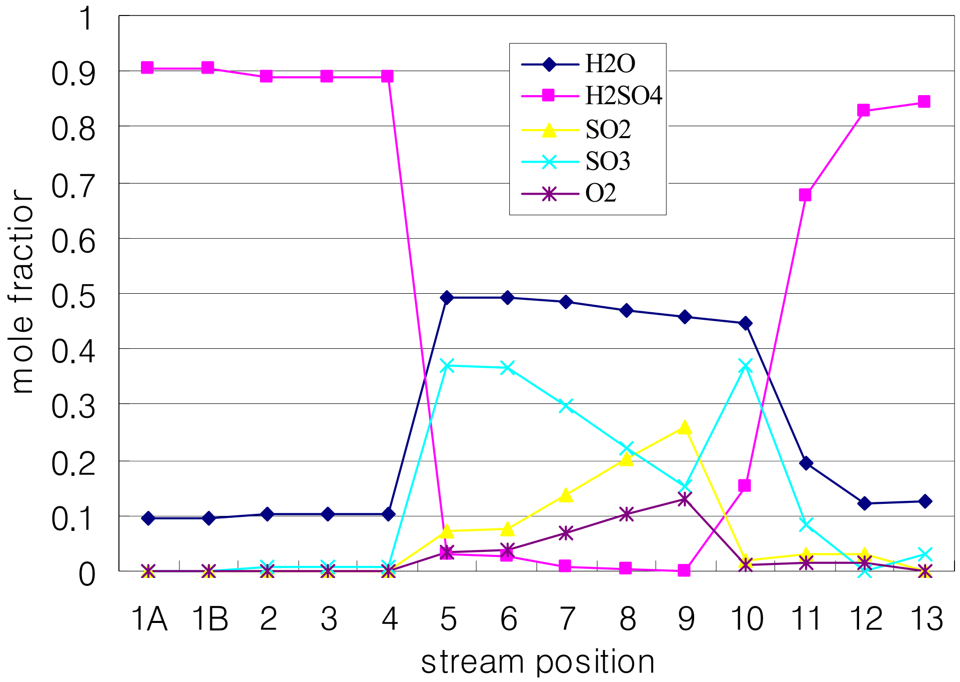

FIG. 3. Mole fraction variation of each component in process streams.

4. Conclusion

The flow sheet for the sulfuric acid decomposition process has been developed based on the S-I cycle. The simulation result seems to represent the sulfuric acid decomposition process well to some extent.

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Carbon recycle hydrogen carrier system using nuclear power

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Abstract. A concept of a thermally regenerative steam fuel reformer for fuel cell vehicles had been proposed. The reformer can realize compact reforming and achieve zero carbon dioxide (CO_2) emission by using chemical fixation of CO_2. Finally, carbon recycle hydrogen carrier system using the reformer and hydrocarbon fuel regeneration process can be established. The system needs energy input for fuel reforming and fuel regeneration processes. Nuclear power plants such as high temperature gas reactor (HTGR) are good candidates as energy source for the system because it emits zero CO_2 in operation. This study discussed the possibility of the carbon recycle hydrogen carrier system for fuel cell vehicles based on this concept. The energy balance of the carrier system combined with an HTGR was estimated. The possibility of the carrier system was discussed with other hydrogen energy systems.

1. Introduction

Transportation field needs alternative energy conversion system for ensuring sustainable society, and being free from fossil fuel markets. Fuel cell (FC) offers the possibility of expanding the electricity utilization market. Vehicles are seen as particularly good candidates for FC application, because FC is more compact, quieter and emit cleaner exhaust gas than conventional internal combustion engines. One of the key technologies that will make the widespread use of FC possible is a hydrogen (H_2) supply system. The uses of liquefied or compressed H_2 are candidates for this technology. However, the storage and transportation of either of these forms of H_2 require large amounts of energy as well as stringent safety precautions. These drawbacks make steam reforming of common fuels, such as methane, propane, methanol and kerosene, more practical solution for storing and supplying H_2. Steam reforming can occur at the site of the FC. The use of these chemical reactants as a H_2 storage medium presents the possibility of a safe H_2 carrier and supply system. On the other hand, the reforming requires additional apparatuses for H_2 production, including at least three: a steam reforming reactor, a burner for reforming heat supply and a carbon monoxide converter. It is especially important for a reformer of FC vehicle to be compact and lightweight. A concept of a thermally regenerative steam fuel reformer for a vehicle had been proposed [1]. The reformer can realize compact reforming and achieve zero carbon dioxide (CO_2) emission by using chemical fixation of CO_2. Finally, zero CO_2 emission H_2 carrier system using the reformer can be established. The system needs energy input for fuel reforming and fuel regeneration processes. Nuclear power plant is good candidate as energy source because it emits zero CO_2 in operation. This study discussed the possibility of the chemical H_2 carrier system based on the above concept. The energy balance of the carrier system combined with a high temperature gas reactor (HTGR) was estimated. The possibility of the carrier system was compared with other hydrogen system.

2. Concept of carbon recycle H_2 carrier system

2.1. Regenerative reformer

2.1.1. Methane regenerative steam reforming

In this study, methane (CH_4) was chosen at first as a candidate reactant for steam reforming, because it is the most popular natural fuel resource and has a simple hydrocarbon fuel structure. The following regenerative reformer methodology is applicable to other hydrocarbons such as kerosene and propane, both of which have reforming temperatures in the range of 700-900°C, similar to that of methane. The CH_4 steam reforming process consists of the following two gas phase reactions with various catalysts.

Methane steam reforming:

$CH4(g)+H_2O(g) \leftrightarrow 3H_2(g) + CO\ (g)$, $\Delta H°_1 = +205.6$ kJ/mol (1)

Carbon monoxide (CO) shift reaction:

$CO(g)+H_2O\ (g) \leftrightarrow H_2\ (g) + CO_2\ (g)$, $\Delta H°_2 = -41.1$ kJ/mol (2)

The study attempts to use calcium oxide (CaO) carbonation to remove carbon dioxide (CO_2) from the reformed gas and fix it.
Carbonation of calcium oxide:

$CaO\ (s) + CO_2\ (g) \leftrightarrow CaCO_3\ (s)$, $\Delta H°_3 = -178.3$ kJ/mol (3)

This study aims to cause Eqs. (1), (2) and (3) reactions in the same reactor at once. These reactions, taken as a whole, are defined as regenerative reforming.
Regenerative reforming:

$CaO\ (s) + CH_4\ (g) + 2H_2O\ (g) \leftrightarrow 4H_2\ (g) + CaCO_3\ (s)$, $\Delta H°_4 = -13.3$ kJ/mol (4)

The reaction realizes methane reforming by self-generated heat by carbonation of CaO with production of CO_2 without outer heating source. Finally, the reaction can realize high-purity H_2 production and CO_2 fixation. Produced calcium carbonate ($CaCO_3$) is regenerated into CaO by thermal heat. CO_2 is also regenerated in hydrocarbon by using extra hydrogen and a catalytic process. Then, the reaction in Eq. (4) is called as a thermally regenerative reforming.

2.1.2. Ethanol regenerative steam reforming

The concept is applicable also to ethanol steam reforming system.

$C_2H_5OH(g) + 3H_2O(g) \rightarrow 6H_2(g) + 2CO_2(g)$, $\Delta H°_5 = +157.0$ kJ/mol (5)

When ethanol reforming is proceeded with Eq. (3) in the same reactor at once, the following reaction is established.

$C_2H_5OH(g) + 3H_2O(g) + {}_2CaO(s) \rightarrow 6H_2(g) + 2CaCO_3(s)$, $\Delta H°_6 = -200.0$ kJ/mol (6)

The reaction has enough exothermic heat to evaporate liquid phase reactants.

$C_2H_5OH(l) + 3H_2O(l) + 2CaO(s) \rightarrow 6H_2(g) + 2CaCO_3(s)$, $\Delta H°_7 = -9.1$ kJ/mol (6)

Eq. (6) means that ethanol water solution can be loaded on a vehicle as fuel, the system can eliminate gas compression work and reduce dramatically awareness of explosion of reactants.

2.1.3. Regenerative steam reforming for fuel cell vehicle

The regenerative reforming systems in Eqs. (4) and (6) would be applicable fuel cell vehicles, because the systems are relatively simpler than conventional reforming systems, and expected to be more small and compact than others. Conventional steam reforming is depicted in Figure 1 (a). CH_4 and water (H_2O) react by Eq. (1) in a catalytic reformer, and the generated CO is shifted by Eq. (2) into CO_2 and H_2 in a catalytic converter. The endothermic reforming process needs a heat supply of $\Delta H°$ 1. The proposed process is shown in Fig. 1 (b-1, 2). This process consists of a reforming process (Fig. 1 (b-1)) while the vehicle is driving and a regenerating process (Fig. 1 (b-2)) for calcium oxide regeneration and CO_2 recovery while the vehicle is turned off.

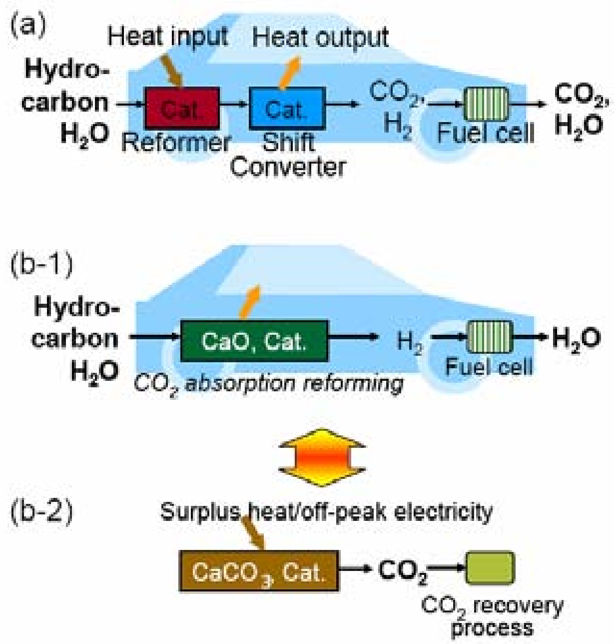

FIG. 1. Concept of a zero CO_2 emission FC vehicle using a thermally regenerative reformer; (a) conventional reforming, (b-1,2) proposed thermally regenerative reforming, (b-1) reforming mode, (b2) regenerating and CO_2 recovering mode

CaO and a reforming catalyst mixture are packed in a regenerative reformer. Reactants are reformed by Eq. (1), and generated CO_2 is removed from the gas phase by the CaO carbonation of Eq. (3). The CO shift reaction of Eq. (2) is enhanced under the non-equilibrium condition realized by the CO_2 removal. Purified H_2 is generated from the reactor finally. The whole reactions of Eqs. (4) and (6) are exothermic, hence the reaction needs no heat supply and can proceed spontaneously. A zero CO_2 emission drive is possible due to CO_2 fixation resulting from the carbonation. In the regenerating process, $CaCO_3$ is decomposed endothermically into CaO in the reactor using high-temperature heat, which is assumed to be supplied as heat from high temperature gas reactor, or as joule heat generated from off-peak electric output of other type nuclear power plants. The reformer is regenerated, and used again for the reforming. The proposed regenerative reformer is intended to be contained in a removable package for use in a FC vehicle. The package is loaded into and recovered from a vehicle at a regeneration station that supplies new packages and regenerates used ones.

Regenerated CO_2 is managed according to a CO_2 recovery process.

2.1.4. Carbon recycle H_2 carrier system

The concept of a carbon recycle H_2 carrier system using the regenerative reforming process depicted in Fig. 1(b) is proposed in Fig. 2. The zero CO_2 emission system consists of FC vehicles using packages of the regenerative reformer, a decentralized package regeneration station, and power systems for energy supply to the system. The regeneration station plays central role in the system. The packages are loaded in FC vehicles. The vehicles are driven by H_2 fuel produced from the packages. The packages after reforming are collected to the regeneration station. The packages are regenerated, that is, decarbonated thermally using thermal output or joule heat produced from nuclear reactors. Regenerated packages are reused repetitively in the vehicles. Generated CO_2 is recovered in a storage vessel, and is regenerated in hydrocarbons at a hydrocarbon regenerator by hydrogenation process using H_2, which is generated from water electrolysis consuming the power plant output. Regenerated hydrocarbons are reused cyclically in the vehicles. A comprehensive Carnot recycle and zero CO_2 emission system is formed using the hydrocarbon regeneration process. The system was expected to contribute on load leveling of nuclear reactor operations by utilizing off-peak electricity or thermal output of the plants as heat source for the CaO and hydrocarbons thermal regeneration processes. Especially, HTGR is appropriate for the reactor because thermal output from the reactor can be used in cascade from CaO regeneration process and CH4 regeneration process.

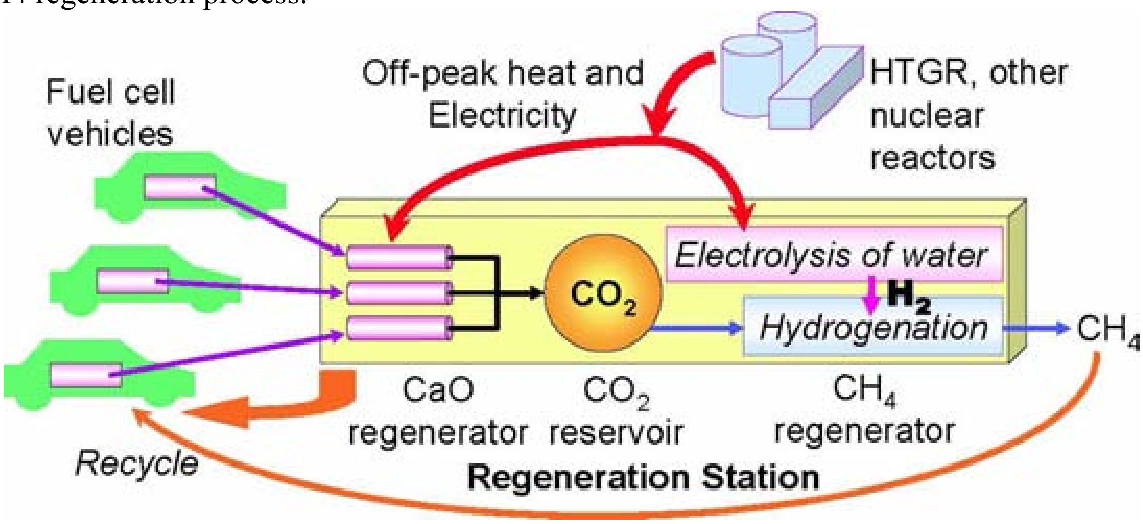

FIG. 2. Carbon recycle H_2 carrier system using the thermally regenerative reformer driven by off-peak electricity and heat from a nuclear reactor.

The proposed H_2 carrier system for FC vehicles has several merits. Firstly, because the FC system using the proposed process emits no CO_2 during operation, a zero CO_2 emission vehicle system could be established, so long as the treatment of CO_2 is managed well after it is removed from the package, and the system can transport H_2 safely under low-pressure and as low-explosive chemicals. The reforming process is simpler than conventional reforming systems. Because the regenerative reforming is exothermic, the reforming proceeds automatically by self-heating, then, heat conduction control step arisen by heating for conventional reforming can be removed. The power-generation efficiency of a FC after with the reformer will be enhanced by the supply of the reformed high-purified H_2. In a conventional system, H_2 effluent gas from the FC is burned for the next reforming, because the CO_2 concentration in the gas is too high for the cell to use. In the proposed system, on the other hand, the H_2 concentration is higher enough than one of a conventional system, enabling the H_2 to be consumed highly in the cell. Therefore, the proposed system also enhances the H_2 economy of the FC. Because the reformation equilibrium temperature is shifted to a lower temperature than in a conventional system, the exothermic CO shift reaction is enhanced naturally. Furthermore, the CO reduction induced by the enhancement is advantageous for FC durability. Carbon plays as hydrogen carrier in this system. The system consists in environmental friendly materials and is operated under atmospheric pressure and relatively mild conditions. This system can eliminate gas and gas compression work, and reduce dramatically awareness of explosion of reactant gas. These points would be unique advantage of the system.

The simultaneous reaction concept for H_2 production from methane steam reforming has been patented by Williams [2]. A fluidized bed concept, using a reforming catalyst and carbon dioxide acceptor for H_2 production, was patented by Gorin and Retallik [3]. Shift reaction and carbon dioxide removal in a single-reactor packed with a calcium oxide mixture were examined by Chun Han [4]. Calcium oxide as a CO_2 absorber was also applied to regenerative H_2 production by Balasubramanian [5]. Those proposals were based on the use of the regenerative reforming process in fixed plants for H_2 production, such as a fluidized bed or a combined system of a packed-bed reactor and gas turbine. Continuous batch-wise H_2 production system using two regenerative reformers is proposed for a vehicle use by Specht [6]. This study proposed a new concept of carbon recycle and zero CO_2 emission H_2 carrier system utilizing the reactions.

3. Combination with nuclear reactors

The carbon recycle H_2 carrier system has compatibility with HTGR. Figure 2 shows combination with the carrier system with an HTGR [7]. The HTGR thermal output is utilized in cascade at the CaO regenerator and gas turbine. CaO package and hydrocarbon fuels are regenerated in the system. CaO regenerator is placed in the primary coolant loop of the HTGR. Regeneration of CaO from $CaCO_3$ of the package is proceeded in the reactor. CaO regeneration process is relatively safe process, and then the reactor can be placed in the primary loop directly. The coolant is used secondary at gas turbine for electricity production. Electricity output is used in a water electrolyzer for hydrogen production. CO_2 generated from the regenerator and H_2 from the electrolyzer are supplied into a methanator, and then, CH_4 is regenerated. Finally this process regenerates CaO and the reforming fuel. The HTGR is zero CO_2 emission energy source to establish zero CO_2 emission H_2 carrier system. Although the carrier system is applicable to use renewable energy sources, nuclear reactor has good combination with the H_2 carrier system on the standpoint of stable and large enough amount energy supply.

3.1. Evaluation of the chemical H_2 carrier system

To evaluate the advantage of the chemical H_2 carrier system depicted in Fig. 2, the system was compared with conventional H_2 production process using water electrolysis. Enthalpy balances of those systems per 1 mole of H_2 production were estimated based on an ideal process. Conventional water electrolysis consumes electricity for water electrolysis process of 282 kJ-electric/H_2-mol, and H_2 compression of 29 kJ-electric/H_2-mol. The compression is assumed isentropic and 5 stages compression up to 700 bar. Total enthalpy of 311 kJ/H_2-mol is required. The H_2 carrier system needs thermal input of 44.6 kJ-thermal/H_2-mol for CaO regeneration, electricity input of 282 kJ- electric/H_2-mol for water electrolysis, and 4.9 kJ-electric/H4-mol equivalent for CH4 compression to 175 bar. The compression is assumed also isentropic and 5 stages compression. Enthalpy of 332 kJ/H_2-mol is needed totally. The H_2 carrier system needs enthalpy input slightly larger than the electrolysis. On the other hand, a methanation process of generated CO_2 and H_2 produces exothermically thermal output of 41.1 kJ-thermal/H_2-mol at around 300-700ºC. When thermal output from the methanation is utilized in some heating process, total enthalpy consumption would be reduced. Enthalpy input for water electrolysis process is dominant in total input at both the conventional and the carrier systems. On-board conventional reforming needs smaller enthalpy input than one of other systems, which have water electrolysis process. However, CO_2 is emitted from the former system.

3.2. E*stimation of the system combined with HTGR*

Thermal performance feasibilities of the H_2 carrier system and conventional water electrolysis systems using the same nuclear reactor were compared [7]. Optimized energy balances of both hydrogen systems based on HTGR was calculated. It was assumed that the gas turbine high temperature reactor named as GTHTR300 designed by JAERI [8] circulating helium coolant was used as the HTGR in the estimation. Output of 600 MWt from the HTGR was used for the regeneration of the reformer and hydrogen production. In conventional water electrolysis system, thermal output from the HTGR at 850ºC is used at a gas turbine for electricity power generation with efficiency of 45.0% [8]. Hydrogen is produced by water electrolysis consuming the electric power with efficiency of 90% [9]. Produced hydrogen is compressed for on-board use up to 700 bar by a compressor consuming a part of the electric power. In the H_2 carrier system, it was estimated that thermal output from HTGR between 835ºC and 850ºC was used for CaO regeneration firstly, and rest of heat was consumed for power production at the gas turbine. Power efficiency for the carrier system is estimated by Carnot's efficiency ratio between the carrier system and the electrolysis system, which is calculated from both inlet coolant temperatures for the turbine. Hydrogen is produced by the same process of the water electrolysis system [9]. Methane is produced exothermically from recovered CO_2 and produced H_2. Produced methane is compressed for on-board use up to 175 bar by a compressor consuming a part of the power. Finally the carrier system is capable to supply hydrogen of 6.78×10^7 mol/day to FC vehicles of 1.356×10^5 cars/day, assuming that H_2 of 500 mol is required for 100 km mileage.

Calculated results of enthalpy balance of both reforming systems were shown in Fig. 3. The vehicle number is almost same with the value of the conventional electrolysis system of 1.363×10^5 cars/day. Because thermal energy consumption for CaO is only 5.8% of the whole HTGR output, and the compression work is fairly smaller than one of the electrolysis system, then, energy for both hydrogen production processes are closed, and finally both vehicles number are quite similar. It is reduced from the evaluation that the carrier system can deliver hydrogen to FC vehicles on-board under the same efficiency with conventional water electrolysis system. The carrier system stores fuel source, CH_4, under relatively lower pressure at 1/4 of the storage pressure for the conventional electrolysis H_2 system. The result shows that the H_2 carrier system has advantage to conventional H_2 system in the point of the reduction of fuel storage pressure and the compressor work cost. The regenerative reforming is applicable for ethanol in Eq. (6) and also higher-hydrocarbon fuels, such as propane and kerosene. Especially the carrier system based on liquid fuel like ethanol would be candidates of attractive hydrogen carrier media because the compression work would be reduced more.

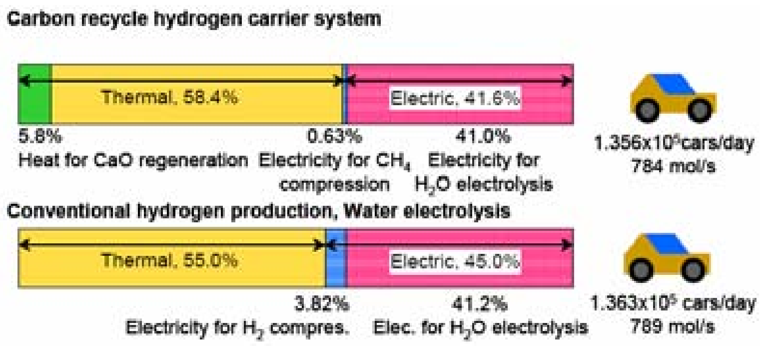

FIG. 3 Enthalpy consumption ratios of HTGR output (600 MWt) for the carbon recycle H_2 carrier system using methane for the fuel and conventional H_2 carrier system using water electrolysis [7]

4. Conclusion

The proposed carbon recycle CO_2 emission H_2 carrier system for FC vehicles using a regenerative fuel reformer based on HTGR and other nuclear power plants has unique performance comparing with conventional H_2 production systems.

The carrier system is capable to reduce hydrogen media storage pressure, and realize more safety H_2 transportation to FC vehicle.

The carrier system has good compatibility with a high temperature gas reactor, because the regeneration process can be joined with the primary loop of the reactor. Power of 600 MWt from a reactor can supply H_2 for FC vehicles of 136 thousands, which is the similar number for conventional electrolysis system under the same thermal input from the reactor. The carrier system shows a new possibility of chemical energy carrier system. Nuclear power would be the first candidate of hydrogen production energy source, because of its supply stability and large enough amount existence compared with other non-CO_2 energy sources. Then, delivery of produced nuclear hydrogen from nuclear reactor site to consumers would be the secondary important subject. The proposed system would be one of candidates for the carrier system.

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Computational analysis of a packed column for SO_3 decomposition in sulfur-iodine process

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Key words: Direct heating, Sulfur-iodine process, Packed column, Sulfur trioxides decomposition, Computational analysis, Nuclear hydrogen production

Abstract. The thermochemical and hybrid hydrogen production processes accompanied with the high temperature and strongly corrosive operating conditions basically have material problems. In order to resolve these problems, the development of a structural material and equipment design technologies is being carried out. A SO_3 decomposer which applies a direct heating concept is one of the candidate technologies to resolve such problems. A directly heated SO_3 decomposer for the sulfur-iodine and hybrid-sulfur processes has been introduced and analyzed by using a computational fluid dynamics code (CFD).

1. Introduction

Hydrogen production technologies will vary depending on the raw materials, the adopted principles, and the quantity and purity of the hydrogen required. Many scientists and engineers are developing a wide range of processes to produce hydrogen economically and in an environmentally friendly way.

Recently, the developing technologies to produce nuclear hydrogen based on the VHTR can be categorized into the sulfur iodine(SI) cycle, the hybrid sulfur(HyS) cycle, and others. In the cases of the sulfur-iodine and hybrid-sulfur cycles, the material problems of thermochemical components for a sulfuric acid decomposition are an issue due to the high temperature (more than 850^{o}C) and strongly corrosive environment of this process. Therefore, many researches [1-3] are on-going for the development of high performance materials for the sulfur-iodine process. On the other hand, a strategy to mitigate these material problems is essential by reducing the temperature of the components.

In this paper, a sulfur trioxides decomposer, which is based on a direct heating concept, for the sulfur-iodine and hybrid-sulfur processes has been designed and analyzed by using a computational fluid dynamics code(CFD) in order to resolve the material issue regarding a reactor. A porous media approach has been used to model the region where a chemical decomposition occurs.

2. Background and concept of a directly heated SO_3 decomposer

The SI and HyS cycles have a sulfuric acid process which is composed of a sulfuric acid concentrator, a sulfuric acid evaporator, a primary decomposer which has a function of a noncatalytic thermal decomposer for sulfuric acid, and a secondary decomposition part which is focused on the decomposition of sulfur trioxide.

In the case of the secondary decomposer, the limitation of a reactor material exists ordinarily due to its severe operating conditions of a very high temperature and pressure and a very corrosive environment. Furthermore a heavy heat-exchanging duty is required in this reactor because the primary and secondary streams are gas phases, and this situation brings about more complex compact heat-exchanger configurations.

Westinghouse Advanced Energy Systems Division has performed a screening test to seclect a structral material for the SO_3 decomposer, and they recommended SiC and some other alloys from the view point of their absolute weight change.[4] One of the recommended alloys is RA330 which is an austenitic heat and corrosion resisting alloy. According to their experimental results, RA330 has good corrosion-resistant properties below than 800°C. However the effect of iodine as an impurity in a SO_3 gas stream on a corrosion is still to be elucidated.

On the other hand, membrane technologies to separate and purify a gas mixture are being developed. Not only a catalytically modified mixed conducting ceramic hollow fibre membrane module, which can be used up to 1000°C, but also a highly selective membrane are under development.

Under the assumptions that i) the temperature of structural material is always maintained below 800°C and ii) that a proper ceramic membrane for the separation of helium and sulfur trioxide should be developed in the near future, a directly heated SO_3 decomposition system can be established as shown in Fig. 1.

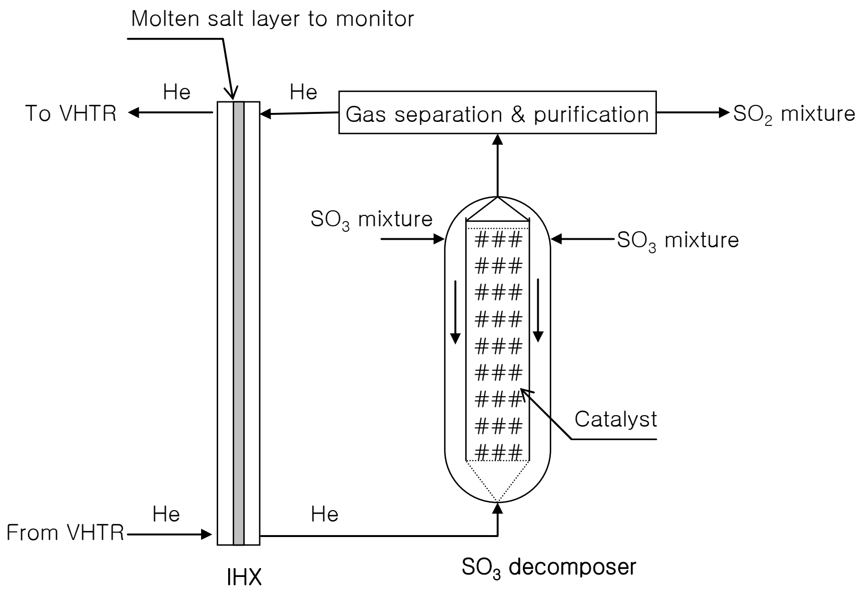

FIG. 1. Conceptual drawing of the directly heated SO_3 decomposer system.

3. Modeling and CFD method of the directly heated SO_3 decomposer

A schematic of the thermochemical reactor modeled in this study is shown in Fig. 2. RA330 was adopted as the material of the vessel and the guide tube. RA 330 has a good oxidation resistance to a high temperature and an excellent resistance to a thermal shock, etc [5]. The decomposer has an inner dimension of 1.8(W)×8(H) m, and is filled with Al_2O_3 catalysts with a 32% porosity. The major design values of the decomposer are given in Table I. The chemical reactions of the mixture gases in the decomposer were not considered. Table II and Table III show the main thermal hydraulic data for the decomposer. The ratio of the flow rate between the mixture gases and helium is 1:1.445, and it is assumed that the decomposer is able to produce hydrogen of about 1000 Nm^3/hr for the given flow conditions. A porous media model was applied to the region of the Al_2O_3 catalyst and to the upper and lower side plates .The CFX 5 code [6] was used for the CFD analysis.

Table I. Design values of the directly heated SO_3 decomposer

	Values
Total decomposer length	16.06m
Decomposer height	8m
Inlet diameter for mixture gases	30cm
He inlet diameter	50cm
Upper & lower Grid plate thicknesses	3cm
Al_2O_3 catalyst diameter	2cm

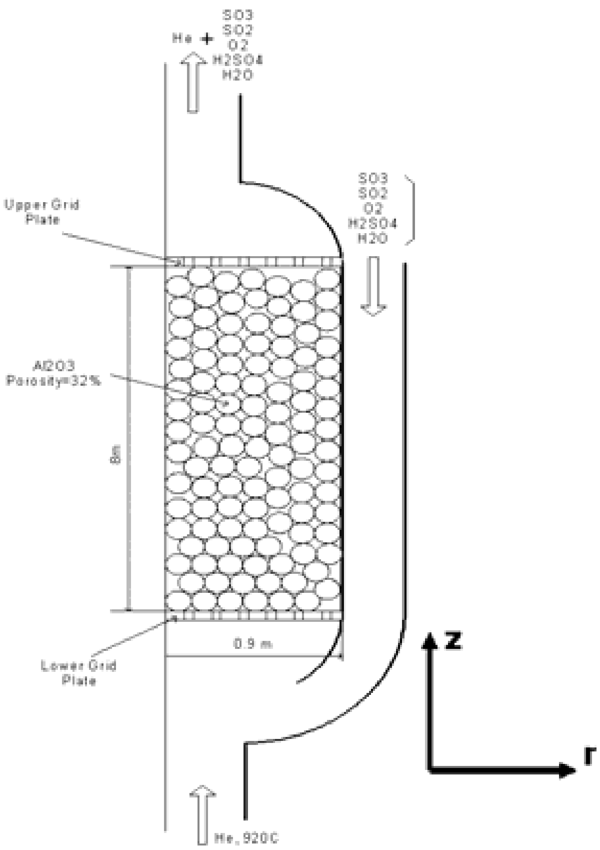

FIG. 2. A schematic of the directly heated SO_3 decomposer.

Table II. Mass & mol fractions of the gas mixture

	H_2O	O_2	SO_2	SO_3	H_2SO_4
Mass Fraction	22.12%	22.12%	22.15%	33.38%	0.22%
Mole Fraction	1.7777	0.5	1	0.6031	0.0033

Table III. Operating conditions of the directly heated SO_3 decomposer

	Flow rate	Inlet temperature	Operating pressure
He	2.0628 kg/s	920 °C	7.09bar
Mixture gas	1.8046 kg/s	450 °C	7.09bar

4. CFD results

Figure 3 shows the calculated velocity profile along the z-direction at r=0. In Fig. 3, the velocity of 9m/s inside inlet pipe was decreased drastically at a bottom engagement section due to a sudden expansion of the cross section (z= around 4 m). The flow emerges from the upper grid plate (z=12 m) and the velocity of 3.1m/s in the SO_3 decomposition zone was increased sharply by about 13 m/s near the outlet of the decomposer due to a sudden contraction of the cross section and the volume expansion of the gas mixture by increasing the temperature. The increment of the velocity at the outlet rather than at the inlet is due to an augmentation of the flow rate by a mixing of the helium and the SO_3 mixture.

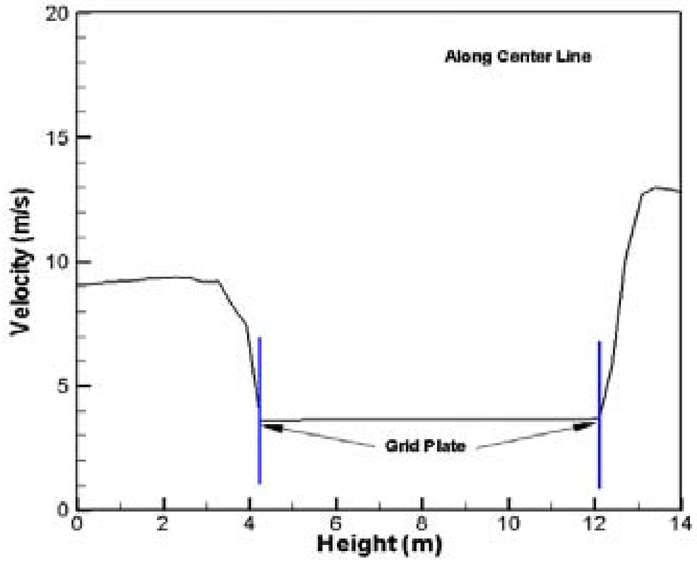

FIG. 3. Velocity profile in the z-direction.

Figures 4 and 5 show the calculated temperature contours of the decomposer and the guide tube. It can be seen in Fig. 4 and Fig. 5 that the maximum temperature of RA330 is lower than 800°C which is considered as a limiting temperature in the study. This means that RA330 can be used as a structural material for the SO_3 decomposer.

Figure 6 shows the temperature profile in the r-direction. In the figure, 'Bottom' represents the upside surface of the lower grid plate, and 'Top' represents the bottom surface of the upper grid plate. 'Middle' indicates the middle position of the Al_2O_3 region. It was also observed that the guide wall in most of the Al_2O_3-packed region maintains a temperature of around 800°C. Most Al_2O_3-packed regions maintain more than 850^{o}C except the near position of the guide wall. This implies that the decomposer modeled in this study satisfies the temperature conditions for a chemical decomposition reaction.

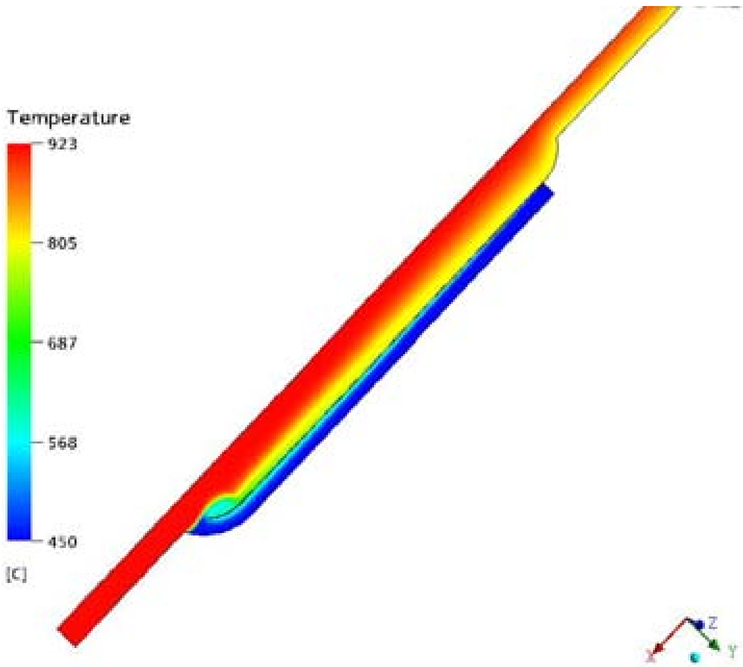

FIG. 4. Decomposer temperature contour

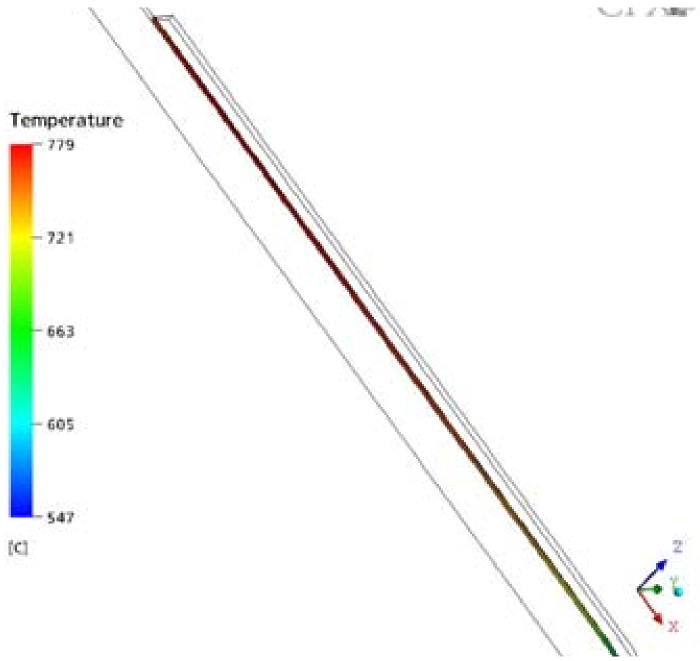

FIG. 5. Guide tube temperature contour

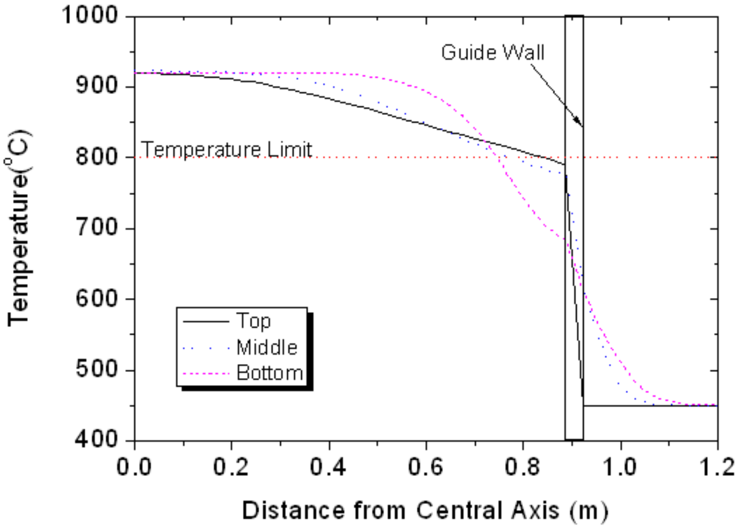

FIG. 6. Temperature profile in the r-direction

4. Conclusions

A numerical analysis for a directly heated SO_3 decomposer has been made. When the conceptual design conditions of the decomposer presented in this research were used, the maximum temperature of the structural material (RA330) could be maintained at 800°C or less. Also, it can be seen that the mean temperature of the reaction region packed with catalysts in the SO_3 decomposition reactor could satisfy the temperature condition of around 850°C which is the target temperature in this study. An improved heat transfer model for a catalyst layer including a chemical reaction is required.

Acknowledgements

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Conceptual design of a natural circulation cooled nuclear battery for process heat applications

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Abstract. A feasibility study has been performed on a natural circulation cooled small nuclear reactor with a molten salt or tin as a coolant. This reactor is called the U-Battery. The study included neutronics calculations to obtain the minimum dimensions required for a critical system during burnup, the calculation of coolant temperature and core temperature reactivity coefficients, and an investigation of the thermal hydraulics to asses the possibilities for natural circulation cooling. For every coolant, core designs are feasible within the dimensions imposed and with natural circulation of the coolant.

1. Introduction

To be economically competitive, industrial energy consumers are in need of affordable power generation with a stable price setting. Since a significant part of the energy price is caused by the usage of the electricity grid, on-site power generation is an economically attractive option. Because of the stable price of nuclear energy, there is a large potential for small nuclear reactors placed on-site.

The U-Battery is a very small inherently safe, self regulating nuclear reactor (20MWth) for electricity generation or process heat applications. It can be operated for fuel cycles of 5-10 years without refuelling and is proliferation resistant. Natural circulation is the preferred cooling mechanism. Auxiliary safety or decay heat removal systems should be minimised. To be competitive with conventional on-site power generators, it should also be operated without intensive monitoring and with no on-site maintenance.

To minimise the impact on the surroundings, the U-Battery must be removable after shutdown. The primary circuit is incorporated into a transportable 'sealed' container. The size of the core is constrained by the fact that the core and primary heat exchanger must be incorporated into this container. The maximum height, width and length of the primary system should remain within 3.5 m, 3.5 m and 20 m, respectively, to make road transport possible.

This article presents the results of a parameter study that was performed to assess the feasibility of the U-Battery. Its dimension restrictions and fuel requirements were analysed for different fuel cycle lengths and coolant candidates, with natural circulation of the coolant as primary choice.

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2. Neutronic feasibility

The U-Battery is graphite moderated and uses TRISO coated UO_2 fuel particles with enrichment up to 20%. TRISO particles retain the fission products up to a fuel temperature of 1600°C for limited periods of time. To reduce neutron leakage, the dimensions of the reactor core without reflector where chosen to minimise the buckling [13]. A prismatic core design was selected because of the freedom in volume fractions of fuel, moderator and coolant.

For the core design of the U-Battery the following boundary conditions were set: 1) a fuel cycle of 5-10 years, 2) the use of maximally 20% enriched fuel, 3) a burnup of at least 10% FIMA, and 4) a combined core and reflector diameter less than 3.5 m. Besides these conditions other important parameters are the core volume, reflector thickness, and the coolant. The effects of these parameters on the feasibility have been assessed by burnup calculations during a desired fuel cycle length and a k_{eff} calculation at the end of the fuel cycle (EOC). When the k_{eff} at EOC is smaller than one, the design is considered not feasible.

2.1. Candidate coolants

As a primary coolant liquid salt is used to allow operation at ambient pressure. The primary coolant candidates for this design are the fluoride salts ^{7}Li-Na-Zr, ^{7}Li-Na-K, Na-Be, Na-Zr and ^{7}Li-Be. Also liquid tin is investigated based on the proposition in [2].

Due to the density and the composition of the liquid coolants they moderate and absorb neutrons. In case of voiding or loss of coolant, the reactivity increases due to less neutron absorption, and decreases due to less moderation. For a safe operation of the reactor it is required that the coolant does not lead to positive temperature reactivity effects. If coolant voiding introduces a positive reactivity this should be compensated by the Doppler effect. Of the candidate salts ^{7}Li-Be has the best neutronic properties [8].

2.2. Neutronic calculation model

To perform the burnup calculations and to calculate the k_{eff} at EOC, the SCALE code system has been used [4]. First the resonance shielding calculations are done using BONAMI and NITAWL after which a zone-weighted cross-section library is produced using XSDRNPM. This library is used to calculate the one-group cross-sections for every nuclide present. The average cross-sections and the normalized neutron flux (which is set to be uniform over the reactor core) are used in ORIGEN for a burnup calculation. The nuclide densities finally obtained are used in a 3D eigenvalue calculation with KENOVa.. The Dancoff factor used in the resonance shielding calculations was obtained by an analytical procedure, which takes into account the double heterogeneity of the fuel design [5].

Some of the calculations performed were validated using a more elaborated burnup calculation method, which uses a space- and time-dependent power profile in the core [6]. For these calculations the reactor core of the U-Battery was divided into 9 cylindrical zones (r,z geometry) of equal volume, and the cycle length was cut into 11 time intervals. The input parameters used for all calculations are shown in Table I.

Table I. Input parameters for the burn up and eigenvalue calculations.

Input parameter	value
Thermal Power	20MWth
Fuel cycle length	5 & 10 years
FIMA	10, 12.5, 15 & 17.5 %
Fuel enrichment	12, 14 & 20 %
TRISO packing fraction (in fuel compacts)	35 %
Core volume (Height =0.924 Diameter)	1- 14 m^3
Reflector thickness	0 – 1.60 m
Uniform core temperature	1073 K
Coolant volume fractions	10 % (liquid salts), 3.5 & 5% (tin)

2.3. *Results neutronic burnup and k_{eff} calculations*

To investigate the effects of the coolants on the core volume and fuel enrichment, burnup calculations were performed with different initial enrichments and core volumes for the coolant candidates ^{7}Li-Be fluoride salt and tin for a 5-year cycle length. The result is shown in Figure 1. The tin coolant volume fraction (cvf) is 5% because no feasible solutions (k_{eff} at EOC >1) were found for larger coolant volume fractions. On the lower left side of the curves, the k_{eff} at EOC is less then one (not feasible) while on the upper right side of the curves the k_{eff} is larger than one (feasible). It can be seen that there is a significant trade off between the initial enrichment and core volume necessary for a feasible design. For both coolants the required fuel enrichment first decreases with increasing volume, reaches a minimum and then increases towards larger enrichments. At the minimum fuel enrichment, the moderating optimum is reached and a further increase of the C/U ratio will result in lower k_{eff} values, due to parasitic absorption in the graphite and coolant. Further it can be seen that the minimum fuel enrichment is much lower for ^{7}Li-Be than for tin, due to the large parasitic neutron absorption of tin.

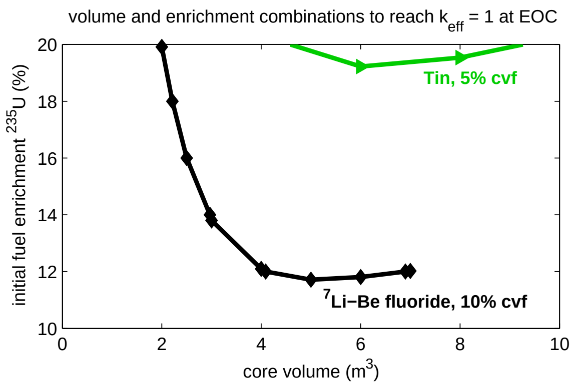

FIG. 1. Core volume and initial fuel enrichment combinations that reach a k_{eff} equal to one at EOC for ^{7}Li-Be fluoride and tin. The calculation was performed for a fuel cycle length of 5 yrs and a burn up of 10 % in both cases. The coolant volume fraction (cvf) was 10% for ^{7}Li-Be and 5% for tin. A 1.2 m thick reflector was used.

The reflector thickness in the calculations above was 1.2 m. When using slimmer reflectors, the core volume can be larger (up to 14 m^3 when using a reflector thickness of 40 cm). Although the reflector effect is reduced for slimmer reflectors, the k_{eff} can increase due to the larger core volume (larger C/U ratio). In Fig. 2 the reflector thickness and core volume combinations are shown that yield a k_{eff} equal to one for an initial fuel enrichment of 20%, 14% and 12% using the ^{7}Li-Be fluoride coolant (black). In red the results are shown for the more elaborate calculation scheme using a space- and time-dependent power profile. Also shown in the figure is the total core diameter (i.e. core plus outer reflector diameter) in a contour plot.

It can be seen that larger core volumes in combination with smaller reflectors give the same k_{eff} values as small core volumes with thick reflectors using less total volume. It appears that the increase in moderation due to an increase in the C/U ratio has a stronger effect on the reactivity than the increase of neutron leakage in case of a slimmer reflector. The results for calculations with fuel enrichments of 14% and 12% also show a moderating optimum. To compensate the neutron balance for larger core volumes (larger C/U), more neutrons should be reflected and therefore the reflector thickness needs to increase to reach a k_{eff} equal to one. For the 20 and 14% cases, core volumes and reflector thicknesses can be found within the 3.5 m diameter constraint. This is not the case for the 12% case. The reference calculations performed with heterogeneous burnup confirm these results.

In Fig. 3 the results are shown for different coolant volume fractions (CVF) of tin with a cycle length of 5 yrs. No combination of reflector thickness and core volume can be found for a CVF of 5% tin. Therefore also a calculation was performed for a CVF of 3.5%. Both the uniform and heterogeneous results show that there are feasible combinations within the 3.5 diameter constraint.

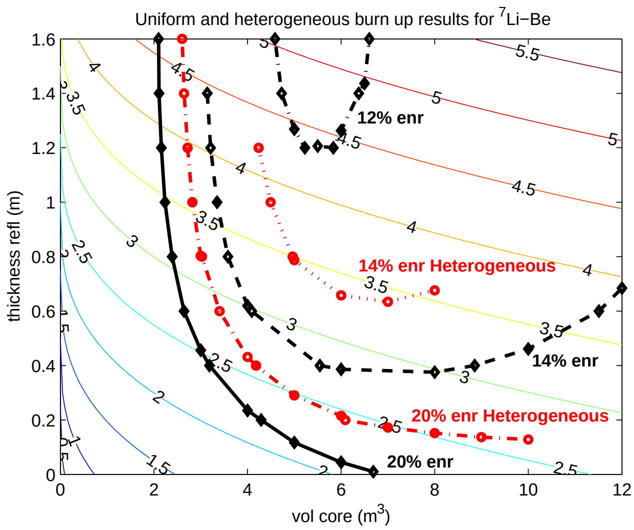

FIG. 2. The reflector thickness and core volume combinations that yield a k_{eff} equal to one for different enrichments using the ^{7}Li-Be fluoride coolant (5yr fuel cycle). In black the results of the uniform burn up calculations are shown; in red the results are shown for the reference calculations using the time dependent power profile and heterogeneous burnup.

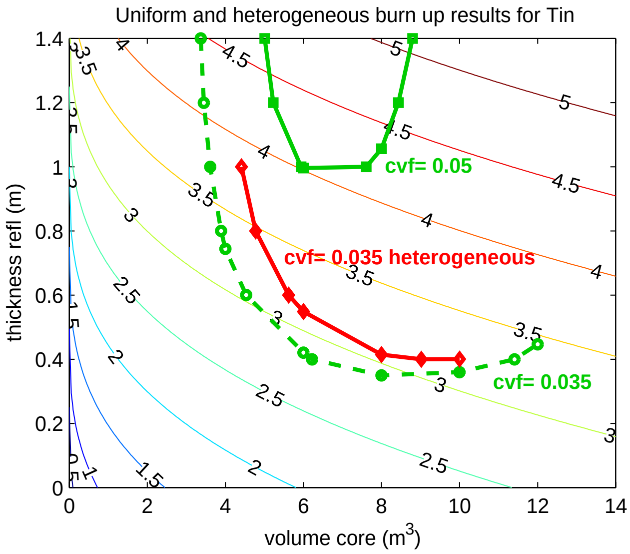

FIG. 3. The reflector thickness and core volume combinations that yield a k_{eff} equal to one for different coolant volume fractions (cvf) using the tin coolant (5yr fuel cycle). In green the results of the uniform burn up calculations are shown; in red the results are shown for the reference calculations using the time dependent power profile and heterogeneous burnup. The x-scale differs from FIG. 2.

If possible a fuel cycle length of 10 years or longeris desirable for the U-Battery. Therefore calculations have been performed for all liquid salts and tin for a fuel cycle length of 10 years. The results are shown in Fig. 4.

Here the reflector thickness and core volume combinations that give $k_{eff} = 1$ at EOC are shown for all coolants. The CVF is 10% for the salt and 3.5% for tin. Again also the total core diameter (i.e. core plus outer reflector diameter) is shown in a contour plot. It can be seen that for each case a wide range of core volumes and reflector thicknesses can be found for a 10year fuel cycle within the 3.5m diameter constraint. The ^{7}Li-Be fluoride salt provides the largest range of feasible combinations (between the 3.5 diameter constraint and the $k_{eff} = 1$ curve). Although design freedom is less for Na-Zr fluoride and tin, both are promising candidates due to the absence of the toxic beryllium and isotopic separation of ^{7}Li.

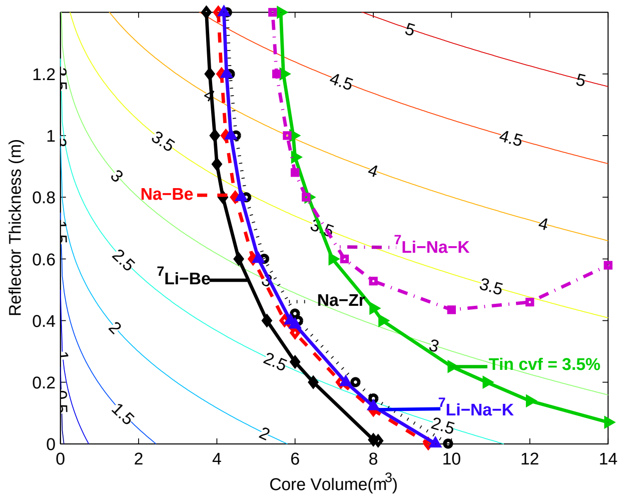

FIG. 4. The reflector thickness and core volume combinations that give k_{eff} = 1 at EOC for the salt coolants. In all cases the cycle length was 10 y with a nominal power of 20 MWth. The coolant volume fraction (cvf) is 10% for the salts and 3.5 % for tin.

2.4. Result coolant voiding reactivity and temperature reactivity effects

For safe operation of the reactor it is necessary that the coolant does not lead to positive voiding or positive temperature reactivity effects. The results of the uniform temperature and voiding coefficients at BOC are shown in Table II. The temperature coefficients were calculated at 1073K by comparing the k_{eff} at the uniform temperature from 973K to 1173K. The complete voiding coefficient was calculated at a uniform temperature of 1073K.

Table II. Results of uniform temperature and complete temperature reactivity coefficient for ^{7}Li-Be, Na-Zr and Tin at 1073 K. The top, bottom and side reflector is 60cm in all cases.

Coolant	Core volume (m^3)	CVF	k_{eff}	Uniform temperature coefficient (10^{-5} K^{-1})	Complete voiding reactivity ($)
^{7}Li-Be fluoride	4	0.1	1.38	-7.86	-1.66
Na-Zr Fluoride	6	0.1	1.39	-5.15	3.55
Tin	6	0.035	1.29	-4.16	12.0

As can be seen, the void coefficients are positive for Na-Zr fluoride and for tin. For Na-Zr the Doppler temperature effect of the fuel can compensate the reactivity increase due to complete voiding by a relatively small core temperature increase of 400K. For tin the temperature increase to compensate complete voiding reactivity is too large for safe operation (1300K). Therefore in this case measures must be taken to prevent complete voiding at all times.

3. Natural convection and heat transfer

To minimise failure risks and operational costs circulation of the primary coolant by natural convection has preference. In this section the possibilities for natural convection are investigated for the coolants ^{7}Li-Be fluoride, Na-Zr fluoride and tin.

3.1. One dimensional natural convection model and heat transfer

To acquire insight into the dimensioning of the core, calculations were performed using a simple one- dimensional model for natural circulation in steady state conditions. The model is representative for incompressible fluids that satisfy the Boussinesq approximation, under the condition that the coolant present in the system is well mixed (turbulent), and that the riser and down comer are adiabatic.

The problem is described by the impulse and energy equations and can be solved by iteration between both. The impulse equation for this problem was found by multiplying the Navier Stokes equation by an elementary displacement *dz* over the loop and consequently integrating over the whole loop. If the Boussinesq approximation is applied the moment equation is then described by:

$$\oint \rho_0 g \beta (T - T_0) dz + F' = 0 \tag{1}$$

Where
ρ_0 is the density of the coolant at reference temperature (kg m^{-3}),
β is the coolant expansion coefficient (K^{-1}),
T is the temperature (K),
T_0 is the reference temperature (K),
dz is the elementary displacement over the loop (m),
F' is the sum of all pressure losses by friction in the system (kg m^{-1} s^{-2}).

The left term in this equation is the sum of all buoyancy forces, while *F'* is the sum of all pressure losses by friction in the system. The pressure losses in the system have been modelled using relations for pressure loss due to a change in velocity, flow geometry or friction and pressure loss caused by dissipation and friction given in [7]. Pressure loss due to friction is not described in the transition zone between laminar and turbulent flow. To prevent discontinuities in the model, the friction factor in this zone is estimated with a glue function. It is assumed that during steady state, the heat produced in the core is completely transferred to the secondary coolant loop in the heat exchanger.

3.2. Conduction and convective heat transfer

To estimate the fuel temperatures during steady state, heat transfer was modelled by defining a unit cell consisting of a coolant channel with radius R_1 surrounded by a cylinder of graphite with radius R_2. It is assumed that the fuel is distributed homogeneously in the core. The temperature profile in the graphite/fuel region at a certain height of the core can be calculated with the Fourier relation for heat conduction using the boundary conditions $T(R_1) = T_{wall}$ and $dT(R_2)/dr = 0$. The temperature at the coolant/graphite interface (T_{wall}) is found by calculating the temperature gradient between the coolant and the graphite with Newton's law of heat transfer [7]. For the Nusselt number, no relation is given between Reynolds numbers 2300-10^4 [8]. In this region the Nusselt is linearly interpolated. Nusselt numbers for tin are probably underestimated since the Prandtl number of tin is less than 0.7.

3.3. Natural circulation calculations

The fuel temperatures and Reynolds numbers for each coolant have been calculated as a function of the height of the primary system using input parameters shown in Table III.

Table III. Natural convection calculation input parameters.

Parameter	Value
Core volume (m^3)	6 (height = 1.87 m, diameter = 2.02 m)
Height heat exchanger (m)	core height
Length heat exchanger (m)	core height
Length riser (m)	Height riser + 3
Top and bottom reflector height (m)	0.6
Diameter coolant channel in core (m)	0.02
Diameter riser and down comer (m)	0.2
Relative roughness	0.01 (core and heat exchanger) 0.001 (riser, down comer)
Coolant inlet temperature(K)	973
System pressure (bar)	1
Coolant volume fraction	0.1 (Li-Be & Na-Zr) 0.035 Tin

3.4. Results natural circulation calculations

The results are shown in Fig. 5. From the maximum fuel temperatures shown on the left it can be seen that tin and ^{7}Li-Be fluoride will provide fuel temperatures lower than 1200°C for all heights of the primary system. Na-Zr fluoride provides solutions for heights of 7.4m and higher.

The Reynolds numbers in the core are shown in the right plot of Fig. 5. Tin has large Reynolds numbers for all primary system heights and will therefore provide a well mixed turbulent flow. For ^{7}Li-Be fluoride the Reynolds numbers are so low that a laminar flow is more likely, which means that the model assumption of a well mixed flow cannot be granted. For primary system heights larger than 7.5m, the Reynolds numbers of Na-Zr fluoride are well above 4000. Therefore, the flow will be in the transition zone between laminar and turbulent flow.

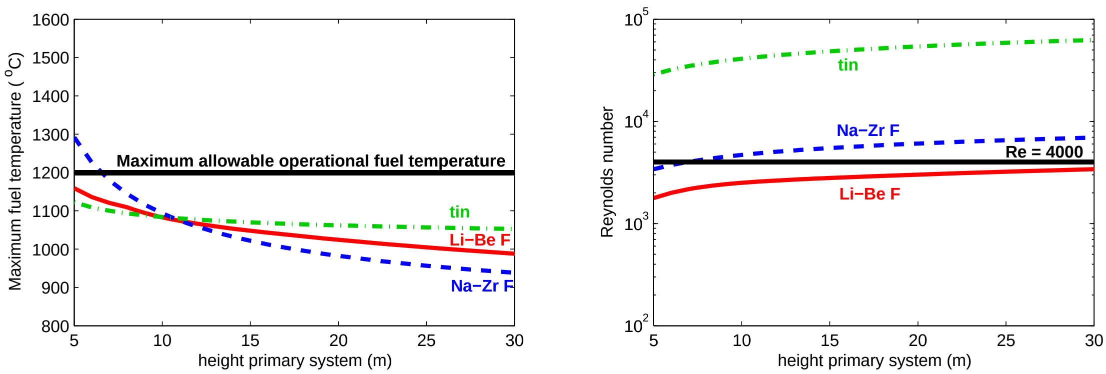

FIG. 4. Results natural circulation calculations: Left the maximum fuel temperatures as a function of the total primary system height. Right the Reynolds numbers as a function of the total primary system height.

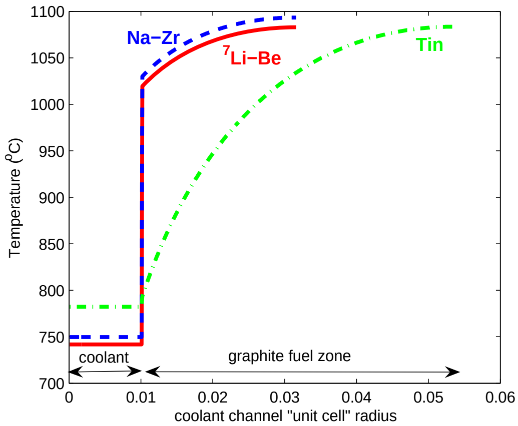

FIG. 5. Temperature profile of coolant and graphite fuel as a function of `unit cell' radius in the core for a primary system height of 10 m.

In Fig. 6, the temperature profile in the coolant and graphite/fuel zone of the core is shown as a function of the coolant channel 'unit cell' radius. The height of the primary system is 10m for all coolants, and the radius of the coolant channel is 0.01m. The coolant temperature in this graph is the coolant outlet temperature. The graphite/fuel zone for Na-Zr and ^{7}Li-Be is smaller than that of tin because their CVF is larger (see Table 3). For a primary system height of 10m, the maximum fuel temperatures are approximately equal for all coolants (see also Fig. 5). Further it can be seen that 1) the temperature difference between the coolant and the channel wall is smallest for tin (due to larger Reynolds numbers and larger heat conductivity), and that 2) the temperature profile in the graphite/fuel zone is equal for the two liquid salts, because of their equal CVF of 10%. For tin the CVF is 3.5%, which means that fewer coolant channels with a diameter of 0.02 m are present in the core. The 'unit cell' diameter is therefore larger and a stronger temperature gradient is visible in the graphite matrix. This might be undesirable because it might increase the thermal stresses in the graphite. The effects of temperature gradients on the thermal stresses in the graphite of the U-Battery core should be subject of future study.

The input parameters of each coolant can be modified to improve the thermal hydraulic natural circulation possibilities. Preferably large Reynolds numbers for good heat transfer between coolant and coolant channel walls are needed and low maximum fuel temperatures. Besides the primary system height, changing the coolant channel diameter, reflector thickness, coolant inlet temperatures or others can give better conditions for natural circulation cooling.

4. Conclusions and recommendations

Feasible neutronic core designs can be made for a liquid cooled U-Battery with natural circulation. The ^{7}Li-Be fluoride salt provides the largest design freedom from the neutronics point of view. It also has a negative coolant voiding coefficient. Of the other salts Na-Zr fluoride is the most promising due to the absence of the expensive ^{7}Li and the toxic beryllium. Parasitic neutron absorption is largest for tin, which decreases design freedom and which leads to a large and positive voiding reactivity coefficient.

Thermal hydraulics calculations show that cooling by natural circulation is possible. Tin is well suited for natural circulation cooling. For the liquid salt, however, it is difficult to obtain a turbulent flow. As a consequence, the heat transfer coefficient along the walls of the coolant channels will decrease leading to higher fuel temperatures. Future work will focus on the thermal hydraulics, burnup and shielding calculations, and further analyses of the reactor physics including passive reactivity control and several accident scenarios such as loss of coolant in combination with a passive decay heat removal assessment.

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Development of a new thermochemical and electrolytic hybrid hydrogen production process for sodium cooled FBR - *Status and future plan*

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Abstract. A new thermochemical and electrolytic hybrid hydrogen production process is under development by Japan Atomic Energy Agency (JAEA) to realize the hydrogen production from water by using the heat (500-600°C) and electric power generation of sodium cooled fast breeder reactor (FBR). The HHLT process is based on sulfuric acid (H_2SO_4) synthesis and the decomposition processes developed earlier (Westinghouse process). Sulfur trioxide (SO_3) decomposition process for oxygen production is facilitated by electrolysis with ionic oxygen conductive solid electrolyte, and sulfuric acid synthesis process for hydrogen production is facilitated by electrolysis with proton conductive polymer electrolyte.

A new experimental apparatus for 1NL/h level hydrogen production was developed to investigate durability, controllability and hydrogen production efficiency of the process. Hydrogen production experiment using the apparatus was started, and 0.4NL/h hydrogen production for 1hour was confirmed.

Hydrogen production experiment using the 1NL/h level apparatus will be continued for a few years, then development of a 100NL/h hydrogen production experimental apparatus will be started and the apparatus will be connected to a sodium loop facility.

1. Introduction

The thermochemical and electrolytic hybrid hydrogen production process (thermochemical and electrolytic Hybrid Hydrogen process in Lower Temperature range: HHLT) for sodium cooled FBR was proposed by Japan Nuclear Cycle Development Institute (JNC) [1], and research and development of HHLT is continued in Japan Atomic Energy Agency (JAEA). The HHLT process is based on the sulfuric acid (H_2SO_4) synthesis and decomposition processes (named “Westinghouse process”) developed earlier [2, 3], and SO_3 decomposition process is facilitated by electrolysis with ionic oxygen conductive solid electrolyte which is extensively utilized for high-temperature electrolysis of water. The hydrogen production by the HHLT was already confirmed using small scale experimental apparatus [1], and conceptual design of hydrogen production plant with HHLT using a small sized sodium cooled reactor was performed [4]. Furthermore, 1NL/h level hydrogen production experimental apparatus was developed and hydrogen production experiment was started in 2006 to investigate durability, controllability and hydrogen production efficiency of the HHLT process.

This paper reviews the present status and future plan of research and development activities of HHLT in JAEA.

2. Current status of research and development at JAEA

2.1. Principle of HHLT

HHLT is composed of the reactions shown below. Electrolysis by ionic oxygen conductive solid electrolyte is applied to increase decomposition fraction of SO_3 in HHLT.

$2H_2O + SO_2 \rightarrow H_2SO_4 + H_2 - \text{electricity}$ > 100°C (1)

$H_2SO_4 \rightarrow H_2O + SO_3$ 300- 400°C (2)

$SO_3 \rightarrow SO_2 + 1/2O_2 - \text{electricity}$ 500°C (3)

Characteristics of HHLT are shown below.

(1) Low electrical energy required
(2) Simple process flow
(3) Decrease in corrosion of structural materials
(4) Higher safety

Details of characteristics are described in references [1, 4].

2.2. Hydrogen production experiment using 1NL/h level apparatus

Hydrogen production by the HHLT was already confirmed in 2004 using small sized apparatus, and the hydrogen production rate was only 5ml/h, but controllability and hydrogen production efficiency of the HHLT could not be evaluated because the hydrogen production rate was too small.

Therefore, a new experimental apparatus for 1NL/h hydrogen production was developed to investigate durability, controllability and hydrogen production efficiency.

The photograph, flow sheet, and the experimental conditions are shown in Fig.1, Fig.2, and Table 1, respectively. The sulfuric acid thermal decomposition reaction was performed in "H_2SO_4 vaporizer" at 400°C. Flow rate of 50wt% H_2SO_4 solution supplied to H_2SO_4 vaporizer by roller pumps was about 3mL/min. The gases (SO_3, H_2O, SO_2, O_2) were carried by N_2 purge gas and flow rate of N_2 purge gas was 300ml/min. Electrolytic SO_3 decomposition reaction was performed in "SO_3 electrolysis cell" at 550-600°C and cell voltage was controlled to be 0.85V by potentiostat. Stainless steel pipes of the SO_3 electrolysis cell exposed to high temperature sulfuric acid were all plated by gold. O_2 generated in the SO_3 electrolysis cell is purged by N_2 and O_2 concentration in N_2 purge gas was measured by O_2 meter. Seven tubular 8mol% yttria stabilized zirconia (YSZ, Nikkato Corp, ZR-8Y) with a dimension of 2 mm in thickness was used as electrolyte in the SO_3 electrolysis cell, and Pt electrodes were manufactured on both (inner and outer) surface of the YSZ tube. In this experiment, Pt electrodes (thickness: about 1μm) were manufactured by Pt plating for higher durability and higher cell current.

H_2 was produced in "H_2SO_3 solution electrolysis cell", and the cell was chilled to about 10ºC. The cell voltage of H_2SO_3 electrolysis cell was controlled to be 1.1-1.2V by another potentiostat and cell current was also measure by the potentiostat. MEA (Membrane Electrode Assembly) made from Nafion 117 (DuPont Corp.) was used to separate anolyte (H_2SO_3 +

50wt% H_2SO_4 solution) and catholyte (50wt% H_2SO_4 solution). The anolyte and the catholyte were circulated by roller pumps at the flow rate of 800mL/min.

Table I Experimental condition of hydrogen production experiment

item	condition
SO_3 electrolysis cell	
temperature	600deg-C -> 550deg-C
cell voltage	0.85V
SO_2 solution electrolysis cell	
cell voltage	1.2V～1.1V
H_2SO_4 concentration	50wt%
Flow rate of H_2SO_4	3ml/min

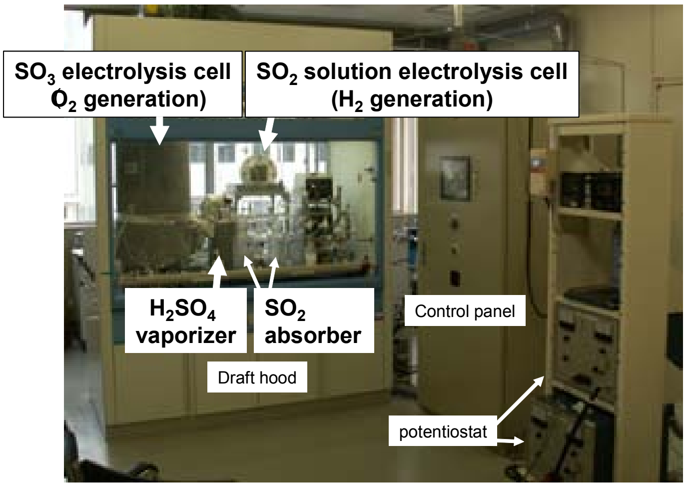


FIG. 1. Photograph of 1NL/h level hydrogen production exprimental appratus

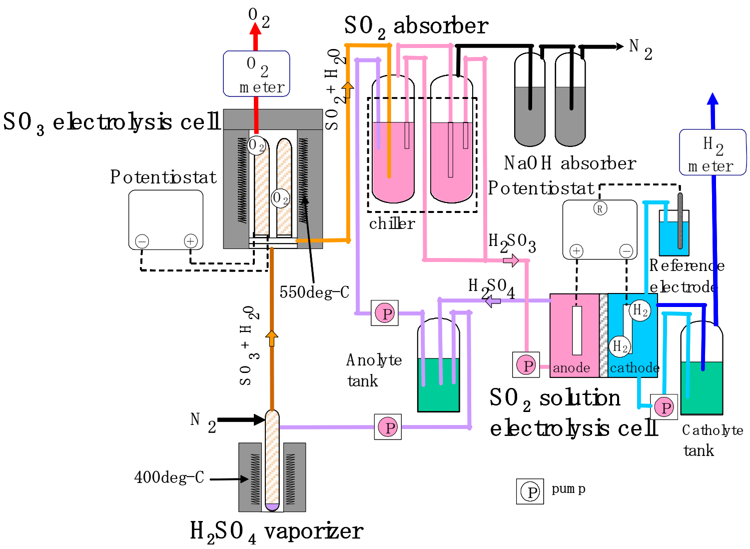


FIG. 2. Flow sheet of 1NL/h hydrogen production experimental apparatus

The cell current of the two elelctrolysis cell measured in the experiment are shown in Fig.3. The temperature of the SO_3 electrolysis cell was set to 600°C when sulfuric acid circulation was started, then lowered to 550°C about 2hours after. The oxygen production rate in the SO_3 electrolysis cell was almost stable during the cell temperature was kept to 600°C, and the rate decreased as the temperature of SO_3 electrolysis cell decreased. The hydrogen production rate gradually increased in one hour after sulfuric acid circulation started and almost stable production rate was obtained for one hour. Nevertheless, hydrogen production rate did not agree with the oxygen production rate when the temperature of SO_3 electrolysis cell was 550°C, because the large amount of H_2SO_3 already dissolved in 50wt% H_2SO_4 solution in the SO_2 absorber and the anolyte tank.

Evaluation of hydrogen production efficiency in the experiment is undergoing, and the result will be presented in the conference.

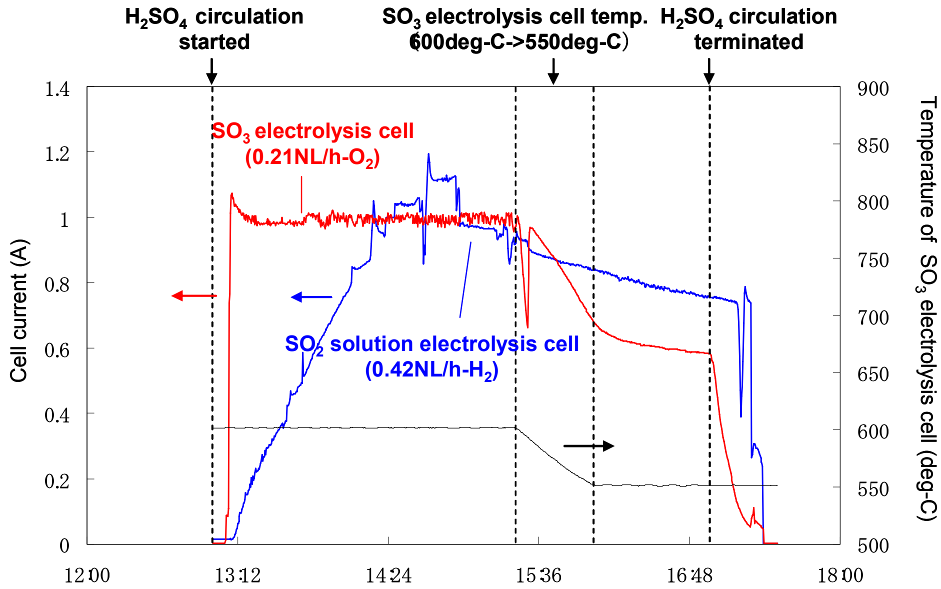


FIG. 3. Measured cell current in hydrogen production experiment

2.3. Development of high performance electrolysis cells

2.3.1. SO_3 electrolysis cell

(a) Investigation on electrode materials

Performance tests of a few noble metals for the electrode are undergoing.

(b) Development of compact cell

Two types of SO_3 electrolysis cell elements were manufactured, and performance tests were performed. One cell element was a narrow YSZ tube (6 mm in diameter, 100 mm in length and 0.5 mm in thickness) and the electrodes were manufactured by plating, and the other element was manufactured by forming thin YSZ layer on porous YSZ tube (12mm in diameter, 100 mm in length and 1mm in thickness). Maximum current density obtained in the performance tests were about $10mA/cm^2$ at 550°C which were about ten times larger than the current density obtained by the former SO_3 electrolysis cell.

2.3.2. SO_2 solution electrolysis cell

(a) Flow type electrolysis cell

Development of SO_2 solution electrolysis cell based on standard PEFC (polymer electrolyte fuel cell) is undergoing. Hydrogen generation was confirmed at the cell voltage of 0.6V in the performance test.

(b) Electrode material

Performance test of non-Pt noble metal electrode is undergoing.

(c) Ion exchange membrane

Performance test of the cross-linked ion exchange membrane development in Takasaki Institute of JAEA is under going. SO_2 permeation rate through the cross-linked membrane is much smaller than the rate through Nafion112, Nafion117, Celemion HSF, and Tokuyama CMB as shown in Fig. 4. Therefore, SO_2 cross over rate from anolyte into catholyte of SO_2 electrolysis cell will be decreased when the cross-linked membrane is used.

2.4 Corrosion test of structural materials for hydrogen production plant with HHLT [5]

Corrosion behavior of structural materials was investigated in liquid and gaseous sulfuric acid in the temperature range of 200-500°C. In this study, corrosion tests of candidate strucutural materials for equipments of the hydrogen production plant were performed at the conditions each equipment will be used as Table II. The concentration of sulfuric acid was 95mass% in all experiments and maximum test duration was 500h. Only high Si cast iron had good corrosion resistance in the boiling sulfuric acid, whereas high Si cast iron and Hastelloy C276 had good corrosion resistance in the sulfurous acid gas atmosphere (vaporized sulfuric acid or mixture of sulfur dioxide and water vapor) as shown in Fig.5.

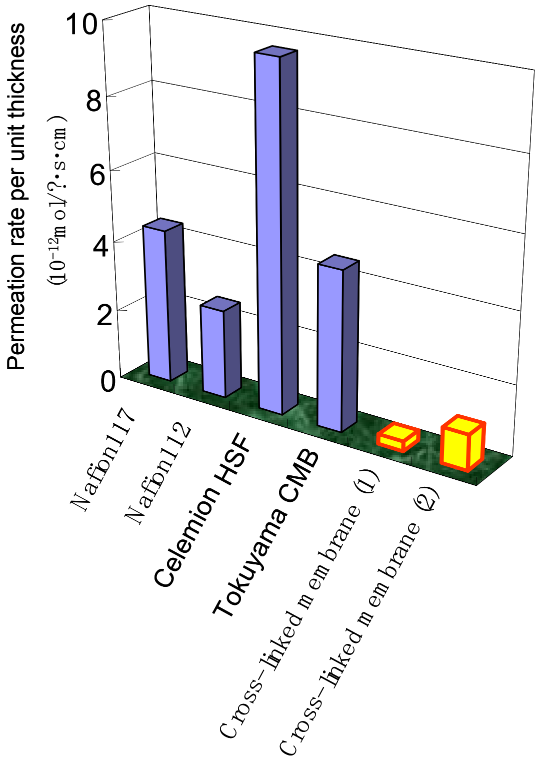


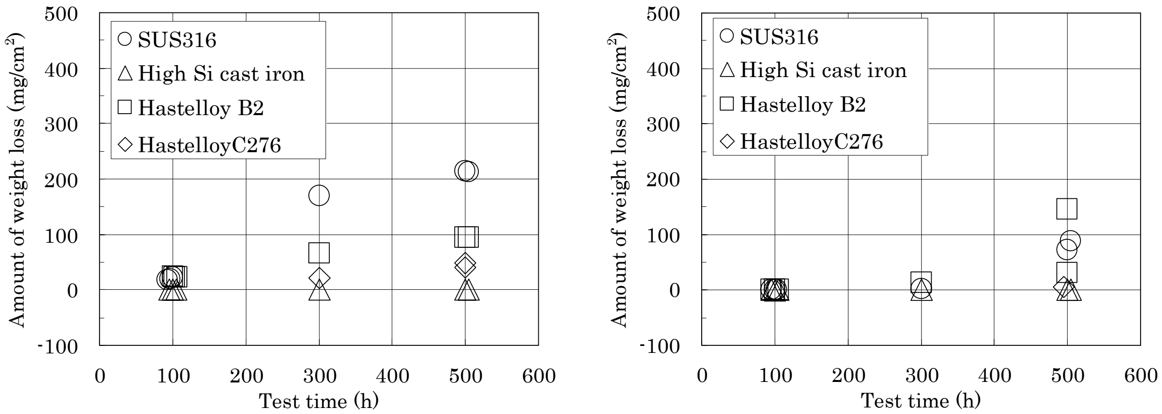
FIG. 4. SO_2 permeation rate per unit thickness of membranes

3. Future plan

Hydrogen production experiment using the 1NL/h level apparatus and the development of higher performance electrolysis cells will be continued for a few years, and the results will be reflected to the development of a 100NL/h hydrogen production experimental apparatus. The apparatus will be connected to a sodium loop facility to realize hydrogen production utilizing the heat from sodium.

Table II. Design condition of each equipment and test condition

Test	Equipment	Design condition: Environment	Design condition: Temp. (°C)	materials	Samples	Test condition: Temp. (°C)	Test condition: Time (h)
A	H_2SO_4 Evaporator	H_2SO_4+H_2O (solution)	200-328	SUS316 (body), High Si cast iron (inner cylinder, decentralized board demister)	High Si cast iron, SUS316, Hastelloy B2, Hastelloy C276	315	100 300 500
		SO_3+H_2O (gas)	328-500				
B	H_2SO_4 Heater	H_2SO_4+H_2O (solution)	50-200	Hastelloy B2	Hastelloy B2, SUS316, Hastelloy MAT, Hastelloy C276	200	100 300 500
		SO_2+H_2O (solution gas)	241-500				
C	SO_3 gas Electrolyzer	SO_3+H_2O (gas)	500	SUS316	SUS316, Hastelloy B2, Hastelloy MAT, Hastelloy C276	550	100 300 500
		SO_2+H_2O (gas)	500				
	SO_3 gas Heater	SO_3+H_2O (gas)	328-500	SUS316			
D	SO_2 Condenser	SO_2+H_2O (solution)	50-241	SUS316	SUS316, Hastelloy B2, Hastelloy MAT, Hastelloy C276	240	100 300 500



(a) H_2SO_4+H_2O solution environment (b) H_2SO_4+H_2O gas environment

FIG. 5. Relationship between test time and weight loss (Test A: 315℃)

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The value of product flexibility in nuclear hydrogen technologies: A real options analysis

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Abstract. Previous economic studies of nuclear hydrogen technologies focused on levelized costs without accounting for risks and uncertainties faced by potential investors. To address some of these risks and uncertanties, we used real options theory to assess the profitability of three nuclear hydrogen production technologies in evolving electricity and hydrogen markets. Monte-Carlo simulations are used to represent the uncertainty in hydrogen and electricity prices. The model computes both the expected value and the distribution of discounted profits from the production plant. It also quantifies the value of the option to switch between hydrogen and electricity production. Under these assumptions, we conclude that investors will find significant value in the capability to switch plant output between electricity and hydrogen.

1. Introduction

The U.S. Department of Energy's Office of Nuclear Energy is supporting system studies to gain a better understanding of nuclear power's potential role in a hydrogen economy and what hydrogen production technologies show the most promise. This assessment includes identifying commercial hydrogen applications and their requirements, comparing the characteristics of nuclear hydrogen systems to those market requirements, evaluating nuclear hydrogen configuration options within a given market, and identifying the key drivers and thresholds for market viability of nuclear hydrogen options. One of the objectives of the analysis presented here is to determine how nuclear hydrogen technologies could evolve under a number of different futures. The output of our work will eventually be used in a larger hydrogen infrastructure and market analysis using a system-level market simulation tool now under development.

This paper expands on our previous work by moving beyond levelized cost calculations to look at profitability, risk, and uncertainty from an investor's perspective. We analyze a number of nuclear hydrogen options and quantify the value of certain technology and operating characteristics.

Our model to assess the profitability of these technologies is based on real options theory and calculates the discounted profits from investing in each proposed production facility. We use Monte-Carlo simulations to represent the uncertainty in hydrogen and electricity prices. Hence, the model can compute both the expected value and the distribution of discounted profits from the production plant. Uncertainty in electricity and hydrogen prices can be represented with two different stochastic processes: Geometric Brownian Motion (GBM) and Mean Reversion (MR). Furthermore, correlation between the two prices can be simulated. We quantify the value of the option to switch between hydrogen and electricity production in order to maximize investor profits by comparing the model's computed expected profit with a flexible and inflexible plant assumption.

2. Hydrogen production technologies considered

Several hydrogen production processes supported by advanced nuclear reactors could contribute to the hydrogen supply in evolving markets. Nuclear hydrogen processes can range from low-temperature electrolysis to high-temperature thermochemical water-splitting cycles. Each technology has challenges before it can become practically available, as well as different properties – such as the process temperature, modular versus larger installations, and cogeneration versus hydrogen as single product [1]. Technology Insights [2] reported a levelized cost analysis for three possible nuclear hydrogen technologies:

(1) Low-temperature, high-pressure water electrolysis (HPWE) supported by an advanced light-water reactor (ALWR).
(2) High-temperature steam electrolysis (HTSE) supported by a high-temperature gas-cooled reactor (HTGR).
(3) The high-temperature sulfur-iodine process (SI) supported by a high-temperature gas-cooled reactor (HTGR).

Although the capital cost and performance input for the levelized cost analysis of these technologies was of a preliminary nature and requires significant refinement by the technology designers, it made a good starting point for our analysis.

HPWE is an existing technology for production of small amounts of highly pure hydrogen, but at a cost exceeding what is needed for large-scale hydrogen markets. Commercial production of hydrogen by electrolysis today is by means of atmospheric or pressurized water electrolysis. In this analysis, an ALWR is assumed to provide the electricity needed for the HPWE process.

The HTSE and sulfur-based processes are currently in the research and development stage. In this analysis, we assume that both SI and HTSE use an HTGR as the primary energy source; the HTGR provides both the electricity and heat needed for the HTSE, and the heat needed for the SI cycle.

3. Plant configurations and operating modes

Each hydrogen market will have characteristics such as the demand, time dependence of demand, geographic location, and desired hydrogen purity. For each hydrogen market, a set of nuclear hydrogen plant configurations can be defined to meet individual market needs while optimizing nuclear hydrogen economics. Thus, it is important to examine the technology choices that can be competitive in different hydrogen markets.

The three nuclear hydrogen production options studied here, HPWE-ALWR, HTSE-HTGR, and SI-HTGR, were subject to an initial profitability analysis. A 47% efficiency was assumed for the electricity generation from the HTGR. Both the low- and high-temperature electrolysis options require electricity production, so they lend themselves to cogeneration plants. Pure thermochemical cycles such as SI do not, in themselves, require cogeneration, but the nuclear units could be designed that way. In this analysis, we assumed that only the HPWE and HTSE configurations would allow for cogeneration of electricity and hydrogen, based on the assumptions of the initial levelized cost analysis by Technology Insights [2].

The required cost parameters for the nuclear hydrogen technologies considered as baseline in this analysis were retrieved from the data base that TI compiled for their levelized cost evaluation. The cost and performance parameters are preliminary, particularly for the HTGR-based cases, but indicate the main differences in profitability that can arise from load/price following capability.

Common assumptions for all technologies used in the TI study and by us are:

- The construction time is 3 years and the lifetime of the plant is 40 years;
- The initial investment is split between the three construction years as 25%, 40%, and 35%, respectively. Additional non-depreciable investment costs are $2M;
- Annual unplanned replacement costs are equal to 0.5% of the initial investment cost. In addition, there are some planned replacement costs that are plant specific;
- The salvage value is 10% of the initial investment cost;
- The working capital is 15% of the annual change in operating costs;
- 90% plant availability, 38.9 % tax rate, and 10% discount rate.

Given these assumptions, Table I lists the production rates and costs of the three nuclear hydrogen technology options.

Table I. Costs and production rates for nuclear hydrogen technologies

Parameter	HPWE - ALWR	HTSE – HTGR	SI – HTGR
Max. annual H_2 production (10^9 g/yr)	246	263	280
Max. annual electricity production (TWh/yr)	12	9.0	-
Fixed annual operation and maintenance cost (M$/yr)	169	120	118
Variable annual O&M cost (M$/yr)	74	88	111
Investment capital investment (M$)	2200	2140	1860

Two operation modes were considered: H_2 as the single product, and H_2 and electricity as co-products from the plant, as shown in Table II. In this latter case, the plant is presumed to operate in a way that allows instantaneous shifting from hydrogen to electricity production. This permits the plant to sell hydrogen or electricity (by following the price), depending on what is more profitable. The flexibility in the potential of switching between output products may have considerable value for an investor interested in maximizing profits. Note that price following is a different operational mode than simple cogeneration in which the plant operator might choose to switch from hydrogen to electricity production for an extended period of time (e.g., for a single shift).

Table II. Operation modes considered for nuclear hydrogen production technologies

Hydrogen Production Technology	Case 1	Case 2
HPWE-ALWR	H_2 as the sole product	Cogeneration of H_2 and electricity with price following
HTSE-HTGR	H_2 as the sole product	Cogeneration of H_2 and electricity with price following
SI-HTGR	H_2 as the sole product	--

The HTSE-HTGR case assumes that the thermal energy equivalent of the highest electricity production rate sent from the plant to the grid can be at most 91% of the reactor’s thermal power. This value is also the fraction of energy required for providing the electricity for the HTSE process. In this case, all the plant output is electricity to the grid, and no hydrogen is produced. The remaining 9% of the thermal energy is used for passing hot steam through the HTSE stacks in order to maintain the HTSE stacks in a hot standby position to avoid thermal cycling during load changes.

In all the cases considered, the capacity of the hydrogen production plant was assumed to be fixed and kept the same over time. Other alternative configurations can include a modular increase of hydrogen production capacity as a function of time in evolving hydrogen markets. The profitability of such modular capacity increase and the preferred time of investment in capacity increase with expected growth in hydrogen demand will be evaluated in our future work.

4. Some challenges in cogeneration operations with price following

Cogeneration and price-following capability at nuclear hydrogen production plants can bring economic advantages. Here we assumed that the HPWE and HTSE technologies are able to follow the market price by adjusting the hydrogen and electricity generation rate (for a constant total thermal power of the reactor). This capability requires that components such as the catalytic materials serving as the electrodes of the HPWE and HTSE cells do not degrade with cycling and, thus, the performance is not compromised by the repetitive reduction and increase of load at the hydrogen plant. Nevertheless, a major concern regarding the durability of HPWE cells is the degradation of the electrode catalyst upon electrical potential cycling, for example, for changing the hydrogen production rate. Therefore, the presence of sufficiently durable HPWE electrodes is necessary for profit maximization through price following of electricity and hydrogen at the plant. Similarly, one of the most important challenges of HTSE cells is their durability against thermal cycling, for example, due to start-up and shut-down that can arise when switching from one energy product (hydrogen) to another (electricity). One way to avoid this is by ensuring that the HTSE cells are kept hot by using some thermal power to heat the HTSE stacks even when they are not under an electrical potential, and thus not producing hydrogen. Developing durable HTSE components that can operate at temperatures as low as 500^{o}C while maintaining high efficiency would be a desired solution.

The SI-HTGR technology, when the HTGR is coupled with an additional turbine-generator system, can also co-produce hydrogen and electricity for the grid. This would require a substantial increase in the capital cost of the plant. Nevertheless, its profitability with the associated price following capability should be assessed. As with HTSE, the catalytic materials that will be used in the SI process can also be subject to activity degradation under thermal gradients and upon thermal cycling. Therefore, the durability of the hydrogen production process materials during repetitive load cycling would also be of concern.

5. Investment under uncertainty and real options

According to traditional finance theory the net present value (NPV) is the best indicator for evaluating a new investment project. The static form of the NPV rule states that a project should be undertaken as long as the sum of discounted cash flows from the project (i.e., the NPV) is positive, while projects with a negative NPV should be rejected. However, it has become apparent that the traditional static discounted cash flow techniques have severe shortcomings, as discussed by Dixit and Pindyck [3]. First of all, the static assessment compares the value of investing today with not investing at all. In most cases the decision maker has the choice of deferring an investment, and then to invest later in the event of favorable investment conditions. Furthermore, the investor has the flexibility to make investment and operational decisions in the future, depending on how uncertainties unfold.

A new direction within investment theory emerged in the 1980s and 1990s to mitigate the shortcomings of the static discounted cash flow techniques. The new approach, frequently referred to as *real options theory*, is based on a dynamic analysis of investment projects. In the real options theory it is recognized that an investment project can have several embedded properties that can be viewed as options. The most common options for investment projects are listed by Trigeorgis [4]:

- The option to defer an investment;
- The time to build option (for staged investments);
- The option to alter operating scale;
- The option to abandon a project;
- The option to switch inputs or outputs from a process;
- Different forms of growth options (e.g., investments in R&D).

In many projects there are interacting effects among these options.
The model for profitability assessment of nuclear hydrogen plants presented in this paper focused on the value of the option to switch output product. We represented uncertainties in hydrogen and electricity prices as stochastic processes, and used Monte Carlo simulations to assess a plant's potential flexibility of switching from hydrogen to electricity production when this is more profitable.

In real options analysis it is common to assume that the uncertain variables follow certain stochastic processes. The most common processes are Geometric Brownian Motion (GBM) and Mean Reversion (MR) processes, which are used to represent uncertainty in electricity and hydrogen price in our investment model. A correlation between the hydrogen and electricity price can also be represented. In our model the user can decide whether a GBM or MR process is used to represent prices, and can estimate parameters in the price model accordingly.

The parameters in the stochastic price models can be based on either historical prices or on expert opinion. Both approaches are described by Copeland and Antikarov [5]. We are analyzing technologies that will not operate until several years into the future. In addition, the lifetimes of the plants are long (40 years). Since the distant future is likely to be quite different from the past, it is difficult to estimate parameters based on historical data. In our current analysis we have therefore estimated parameters based on a judgment of history and likely future trends, but have run sensitivity cases in order to analyze the impact of the price parameters on the model's results.

Figures 1 and 2 show the distributions of simulated prices for electricity and hydrogen with the GBM process. The GBM process gives a significantly higher uncertainty range in the long run compared to the MR process, especially on the more expensive side of the distribution. The mean reversion in the MR process prevents the prices from going too far from the mean, and the MR price distributions are much more symmetric around the mean. Again, it is questionable which of these distributions is more realistic. Hence, profitability assessments were made with both GBM and MR processes. Here we will focus on the results with the GBM assumption. Deterministic reference calculations were also made for comparison, but will not be discussed here. Details about the model, its assumptions, and the analysis results can be found in [6].

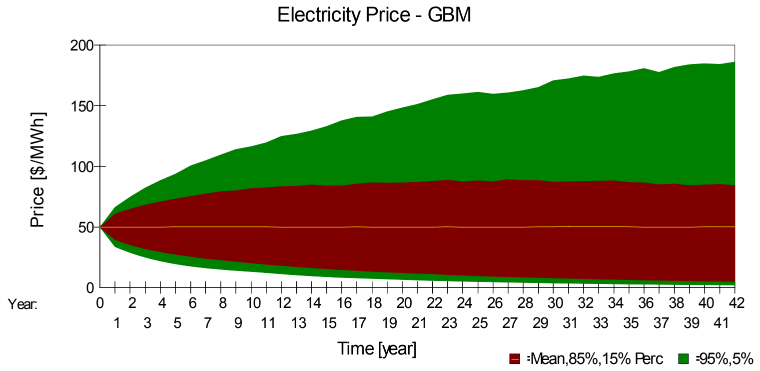

FIG. 1. Simulated electricity prices using the GBM process. Mean, 70%, 90 % confidence bands.

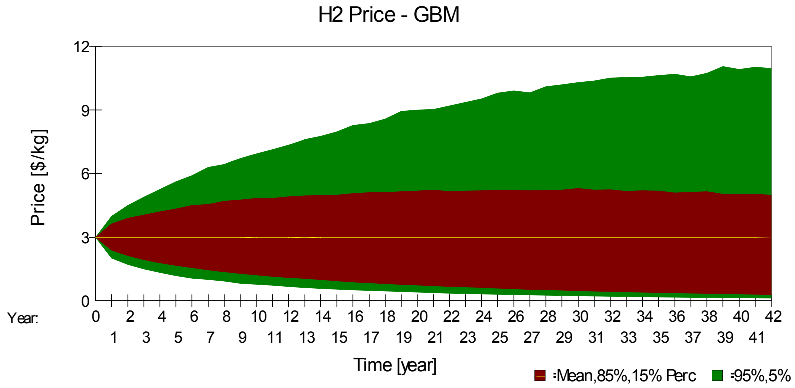

FIG. 2. Simulated hydrogen prices using the GBM process. Mean, 70%, 90 % confidence bands.

6. HTSE-HTGR cases

As an example of the model results, Figures 3 and 4 show the simulated profitability distributions for the HTSE-HTGR plant for pure hydrogen production (Case 1) and flexible hydrogen/electricity production (Case 2) with the GBM price process. When comparing the simulated profit distributions in Case 1 and Case 2 we see that operational flexibility decreases the downside of the distribution, and increases the upside. Hence, the plant owner can clearly reduce exposure to economic risk by having the flexibility to switch output product. Moreover, the expected profit is considerably higher with flexibility (Case 2). The results illustrate that a stochastic analysis is required to properly assess the investor's potential risk and return from investing in nuclear hydrogen technologies.

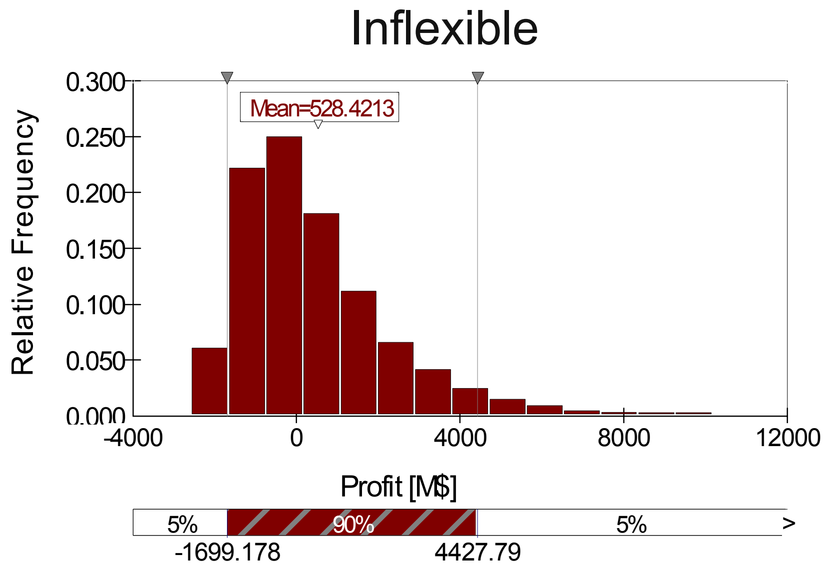

FIG. 3. Profit distribution for HTSE-HTGR Case 1 (H_2 only). The mean lifetime profit is $530M.

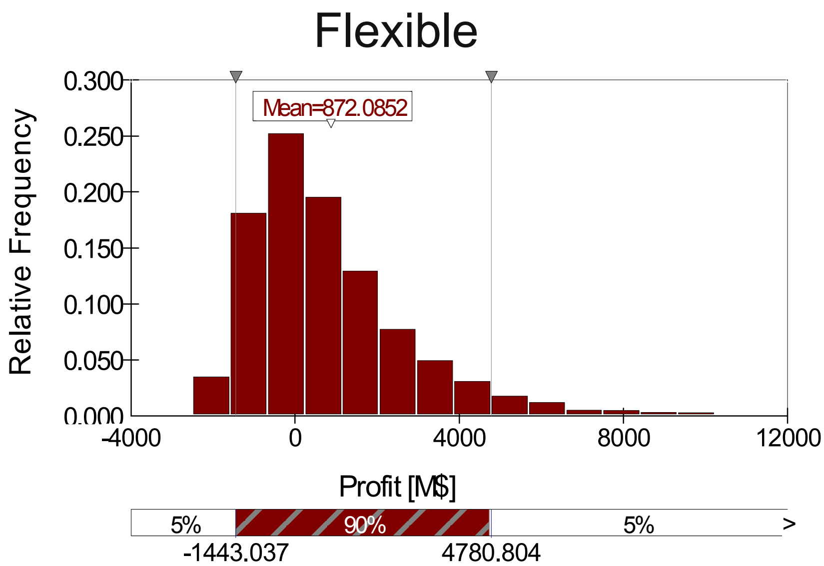

FIG. 4. Profit distribution for HTSE-HTGR Case 2 (cogeneration). The mean lifetime profit is $870M, 65% greater than for the H_2-only case.

7. Results and Conclusions

The expected profits for the three nuclear hydrogen plant alternatives are summarized in Table III for the GBM price assumption. The additional value of having the option to switch output products is substantial for the flexible technologies, and amounts to an expected $670M for the HPWE-ALWR and $340M for the HTSE-HTGR over the lifetime of the plants.

Table III. Expected lifetime profit of different nuclear hydrogen technologies (GBM Assumption)

Nuclear Hydrogen Technology	Expected Lifetime Profit (M$)
HPWE-ALWR, Inflexible	96
HPWE-ALWR, Flexible	770
HTSE-HTGR, Inflexible	530
HTSE-HTGR, Flexible	870
SI-HTGR, Inflexible	860

The following observations were made from the results:

- The profitability analysis under uncertainty gives a different picture of the relative viability of the nuclear hydrogen production technologies compared to a standard levelized cost analysis. Using the same cost assumptions the levelized cost for H_2 production for the three technologies are \$2.26/kg (SI-HTGR), \$2.51/kg (HTSE-HTGR), and \$2.91/kg (HPWE-ALWR).
- The HPWE-ALWR and HTSE-HTGR configurations have an advantage in being able to switch between hydrogen and electricity output. Our analysis indicates that the HTSE-HTGR plant can be at least as attractive as the SI-HTGR plant (Table 3), despite its having a considerably higher levelized cost.
- The option to switch output product adds value for the investor. The added value must be weighed against potential increases in capital and operating costs. For the flexible plants we assumed that they are capable of switching their entire production from hydrogen to electricity instantaneously and frequently without additional cost. In reality, there may be both technical and contractual restrictions for how quickly and often plants can switch their output. The option values of flexibility calculated in this report may therefore be regarded as an upper limit.
- Our findings suggest that research should be directed toward developing better and more durable materials for the hydrogen production processes that are better able to handle switching production output.
- Plant owners should carefully consider how much hydrogen production to sell on long-term contracts, at the expense of losing the value of the option to switch between electricity and hydrogen production.
- There is high uncertainty concerning the assumptions for the analysis, in terms of performance, cost, and price parameters. The conclusions are therefore qualitative rather than quantitative. Sensitivity analysis was performed for price parameters. However, sensitivity studies should also be carried out for the cost and performance assumptions used for the different technologies.
- The study serves to illustrate the advantage of using a stochastic model for analyzing investments and operational flexibility under uncertainty. A deterministic model is likely to underestimate the option value of flexibility.
- The GBM price process gives higher option value of switching compared to the MR process, because of higher variability in prices.

Although the potential for hydrogen markets seems promising, there are also substantial risks and uncertainties that will affect how investors will try to enter this market. Economic studies of nuclear hydrogen technologies have previously focused on levelized costs without accounting for these risks and uncertainties. The analysis presented in this paper is an important extension to the levelized cost calculations and has attempted to identify and address some of the financial risks and opportunities associated with nuclear hydrogen production.

The model we developed uses real options theory to calculate the discounted profits from investing in a production facility. Monte-Carlo simulations are used to represent the uncertainty in hydrogen and electricity prices. The model computes both the expected value and the distribution of discounted profits from the production plant. It also quantifies the value of the option to switch between hydrogen and electricity production while trying to maximize facility profits.

In this study we assessed the profitability of three nuclear hydrogen production technologies under uncertainties in newly emerging markets. Under the assumptions used, we conclude that investors will find significant value in the ability to switch plant output between electricity and hydrogen. This value has to be traded-off against possible higher capital and operating costs.

The flexibility to quickly react to market signals brings technical challenges related to the durability of the components in the hydrogen plant. This challenge holds for both electrolytic and thermochemical processes. Nevertheless, given the potential significant economical benefit that can be gained from cogeneration with the flexibility to react to market signals, we recommend that R&D be aimed toward developing durable materials and processes that can enable this type of operation.

Our ongoing work is focused on analyzing a range of hydrogen production technologies associated with an extension of the financial analysis framework presented here. We are planning to address a variety of additional risks and options, such as the value of modular plant expansion in addition to cogeneration capability (i.e., a modular increase in the hydrogen production capacity of a plant in a market with rising hydrogen demand), and contrast that with economies-of-scale of large-unit designs. We also plan to introduce a more detailed representation of electricity and hydrogen price fluctuations on daily, weekly, and seasonal periods. In this way we hope to better assess the commercial viability of nuclear hydrogen options.

Acknowledgments

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Role of high-temperature reactors in synthetic fuel production

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Abstract. Increasing cost of natural gas and petroleum, energy security and environmental degradation are leading to increased interest in alternate energy sources. For various countries, coal offers a secure domestic alternative to foreign oil as a source of liquid fuels and even more so as oil prices continue to escalate and supplies be constrained. Current technologies offer a means for converting coal into synthetic liquid fuels as a way to become independent from imported oil. However, conventional technologies for converting coal to liquid fuels produce significant quantities of CO_2 that must either be released or sequestered. The Pebble Bed Modular Reactor (PBMR), under development in South Africa, is an ideal energy source to produce hydrogen and oxygen through water-splitting without emitting CO_2. Synthetic fuel processes require hydrogen and oxygen, which could be supplied using PBMR water-splitting which would nearly eliminate CO_2 in producing synthetic liquid fuels from coal. Economic drivers for integrating nuclear water-splitting into coal-to-liquid (CTL) systems include the production cost of oxygen, CO_2 credits, displacement of coal presently used as a source of hydrogen, and major offsets in CTL capital and operating costs. Distribution and storage of hydrogen remain as significant barriers to a transport "hydrogen economy". However, clean liquid fuels from coal – using nuclear energy – is an intermediate step for using nuclear generated hydrogen to reduce pollution in the transport sector when utilising CTL technology; simultaneously addressing energy security concerns. This paper will discuss the opportunity for high-temperature nuclear reactor technologies to impact the transport sector in the medium term by integrating high-temperature reactor technologies with coal-to-liquid processes in the production of synthetic fuels from coal.

1. Introduction

Global concern for increased energy demand, increased cost of natural gas and oil, energy security and environmental sustainability are stimulating investments in technologies that will contribute to clean, secure and affordable energy. Fossil resources supply approximately 80% of global energy [5], but its continued use is constrained by the increasing cost of available reserves and its adverse effects on our environmental well-being.

In 2004, coal provided approximately 25% of global primary energy needs and 40% of the world's electricity. In addition to electricity generation, coal is also used for 66% of global steel production (utilising 13% of global coal use), cement manufacturing and various other uses [7]. Coal emissions of mercury and particulates are a growing concern. Carbon dioxide emissions, which are now accepted by most to be a leading source of global climate change, are a more significant public policy issue which will impact future coal operations. Various clean-coal technologies are under investigation, notably the capture and sequestration of CO_2. Though coal reserves are widely available and remains to be one of the most affordable resources, it is expected that its continued use will be subject to incentives to reduce its environmental footprint through various technological and operational advancements.

Some 96% of all energy used in the transport sector comes from petroleum [13]. Due to the increasing price of oil and uncertainty about its continued supply, various governments are searching for energy independence in especially the transport sector. Synthetic liquid fuels can be produced from solid (e.g. coal) or gaseous (e.g. natural gas) feedstock to be directly used in today's vehicles without significant modification to the existing infrastructure. Liquid fuels from coal provide a viable alternative to conventional oil; and high oil prices and energy security concerns have re-stimulated interest in coal-based liquid fuels.

The conversion of any feedstock to liquid fuels is energy intensive and its associated CO_2 emissions must be considered. Conventional coal-to-liquids (CTL) processes which use coal as hydrogen feedstock are more CO_2 intensive than conventional oil refining. It has been suggested that application of Carbon Capture and Storage (CCS) together with coal-to-liquids technologies may result in 20% less CO_2 emissions over the full life cycle than fuels derived from crude oil [15]. An alternative approach to reduce CTL associated CO_2 emissions and add value to coal products is to apply the technology of high temperature gas-cooled reactors in conjunction with clean hydrogen production.

Hydrogen is needed to produce liquid fuels; and in indirect CTL processes – the only one commercially proven – carbon in coal is used to make the needed hydrogen. In modern CTL processes, coal is gasified with oxygen and about half of the resulting CO is shifted with steam to produce CO_2 and the needed hydrogen, consequently rejecting CO_2. Availability of clean hydrogen could add value to CTL operations by eliminating nearly all CO_2 emissions in producing liquid fuels and reduce CTL capital investment, while avoiding the potential need for sequestration. Water can be a CO_2- free source of both hydrogen and oxygen if clean energy were available to carry out the decomposition. Several water splitting technologies have been proposed by the international community; however the most efficient processes require high temperatures to split water either thermochemically or via steam electrolysis.

Nuclear energy is experiencing a global renaissance. There are some 435 nuclear power reactors in operation around the world [12], some 30 further power reactors are under construction and over 60 are firmly planned [12]. During 2004, nuclear sources contributed 7% to global primary energy needs and 16% to global electricity generation. A key focus of present nuclear energy initiatives is overcoming the institutional barriers that have prevented the deployment of new nuclear power plants in the past. Some issues, such as nuclear weapons proliferation and the disposal of spent nuclear fuel, are important and have both technical and political dimensions. Nuclear energy, however, remains a major proven and available large-scale energy resource that avoids uncontrolled releases of pollutants, and especially carbon dioxide, to the environment.

The Pebble Bed Modular Reactor (PBMR), which is nearing the start of construction in South Africa, is a High Temperature Gas-cooled nuclear Reactor (HTGR) which is capable of providing heat at the high temperatures required to produce hydrogen from water without CO_2 emissions.

This paper discusses how HTGR technology, such as the PBMR, can be used to supply clean energy and hydrogen for the manufacture of synthetic liquid and gaseous fuels from coal, resulting in increased carbon efficiency and potential cost savings, while nearly eliminating CO_2 from the production process.

2. PBMR

Substantial interest has been generated in advanced nuclear reactors over the last few years. Some governments feel that substantially different designs will be needed to address public perception, improved safety, proliferation resistance, reduced waste and competitive economics. The PBMR technology, being developed in South Africa through a world-wide international collaborative effort led by PBMR (Pty) Ltd, will represent a key milestone on the way to achievement of advanced reactor design objectives, but in the much nearer term. The investors in PBMR (Pty) Ltd are the South African Government, the South African Industrial Development Corporation (IDC), the national utility, Eskom, and Westinghouse.

The PBMR project entails the building of a demonstration power reactor at Koeberg near Cape Town and a pilot fuel plant at Pelindaba near Pretoria (Fig.1) The current schedule is to start construction in 2008 and for the demonstration plant to be completed by 2012/13. The first commercial PBMR modules are planned for completion by 2016. In October 2006, the PBMR consortium lead by Westinghouse was awarded a lead contract for pre-conceptual design of the Next Generation Nuclear Plant (NGNP) at the Idaho National Laboratory in the US. The NGNP Project aims to deploy an HTGR for the production of hydrogen.

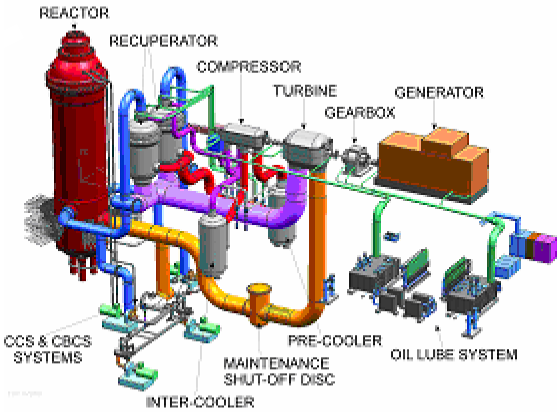
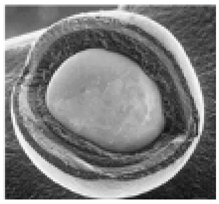


FIG. 1. PBMR DPP building (left) and power conversion unit (right)



PBMR fuel is based on a proven, high-quality German fuel design consisting of low enriched uranium triple-coated isotropic (LEU-TRISO) particles contained in a moulded graphite sphere (see figure to right). The PBMR uses particles of enriched uranium dioxide coated with silicon carbide and pyrolitic carbon. Helium is used as coolant and energy transfer medium, to drive a direct closed Brayton cycle gas turbine-compressor and generator system. The PBMR turbine inlet temperature (reactor outlet temperature) is 900°C, compared to ~350°C for conventional nuclear reactors. Unique features of PBMR technology include:

— High-temperature process heat for a variety of process applications, notably hydrogen production
— Inherent safety since natural characteristics and passive heat transfer design rule out the possibility of a core melt, even with the loss of all active systems
— High efficiency (> 41%);
— High availability (on-line refueling, 6 year turbine maintenance intervals)
— Short construction times (~24 months per module with modular construction) and lower associated cost of capital during construction
— Smaller capital cost increments per module
— Small emergency planning zone (<400 m)
— Proliferation resistance due to high fuel utilization and the small amount of fuel in each pebble

— Waste disposal enhanced due to silicon and graphite fuel form which are geologically stable materials

The high temperature and small size also provide a niche market for PBMR technology in the process heat industry. Promising process applications include using the heat from the PBMR to produce hydrogen (without CO_2 emission) through the process of water-splitting, to supply hydrogen and oxygen to a coal-to-liquids process to produce clean liquid fuels, to reform methane to produce syngas (to be used as feedstock to produce hydrogen, ammonia, methanol) and to generate steam for in-situ Oil Sands and Heavy Oil recovery. PBMR (Pty) Ltd. is presently teamed with USA-based Shaw Company and Westinghouse to develop PBMR process heat markets, projects and technologies.

3. Nuclear hydrogen production

Current hydrogen production technologies include steam reforming of hydrocarbons, for example, steam methane reforming (SMR), autothermal reforming, and partial oxidation or gasification of coal or other hydrocarbon materials. A small amount of special purpose hydrogen is produced by water electrolysis. Over 90% of commercial hydrogen is produced from natural gas by SMR. Any technology currently producing hydrogen from hydrocarbons emits CO_2 because all methods use some form of the water gas shift reaction, which removes oxygen from water and adds it to carbon or CO to form CO_2. Additional CO_2 is produced from burning fossil fuel to supply heat for the endothermic steam reforming reaction. One of the niche markets of HTGR technologies is to provide high temperature process heat (and/or efficient electricity production) for the generation of hydrogen.

Hydrogen produced from water using nuclear energy would avoid both the use of fossil fuels and the emission of greenhouse gas. Hydrogen could be produced using nuclear energy by several means. Promising processes identified by the PBMR Process Heat Team include High-Temperature Steam Electrolysis and thermochemical water-spitting technologies, such as the Hybrid Sulfur (HyS) process.

The energy crisis of the 1970s prompted a large global R&D initiative in thermochemical water-splitting processes. As fossil fuels approach record prices, interest in thermochemical cycles has been revived. Thermochemical water-splitting has not yet been commercialised and international interest is driving R&D in a variety of thermochemical technologies. Although the PBMR Process Heat Team is open to considering any water-splitting technology that requires high temperature heat, the hybrid sulfur process (HyS) is at present the Team's reference thermochemical technology for large-scale hydrogen production. The HyS process uses two thermochemical-electrolytic reactions that result in the dissociation of water:

$$H_2SO_4 \leftrightarrow SO_2 + H_2O + \tfrac{1}{2} O_2 \qquad (>800°C \text{ heat required})$$

$$2H_2O + SO_2 \leftrightarrow H_2 + H_2SO_4 \quad (\text{electrolytic at } 100°C)$$

Figure 2 shows how the heat (via Intermediate Heat Exchanger) and electricity (via Steam Generator) from the PBMR is used to generate hydrogen, oxygen and export electricity using the HyS process. The high temperature heat of the PBMR reactor is transferred to the ***HyS*** process via an intermediate heat exchanger (IHX) to the decomposition reactor ($H2_SO_4 \rightarrow SO_2 + H_2O + \tfrac{1}{2}O_2$). The steam is used in a Rankine bottoming cycle to provide input power to the HyS electrolysis step ($2\ H_2O + SO_2 \rightarrow H_2 + H_2SO_4$). Any remaining power is exported to the grid. Thermochemical water-splitting processes are expected to be more efficient (HyS above 41% based on Lower Heating Value of hydrogen) than conventional electrolysis. However, further development is needed to lower HyS capital and operating costs. Estimated costs for the HyS Process are presented in [1].

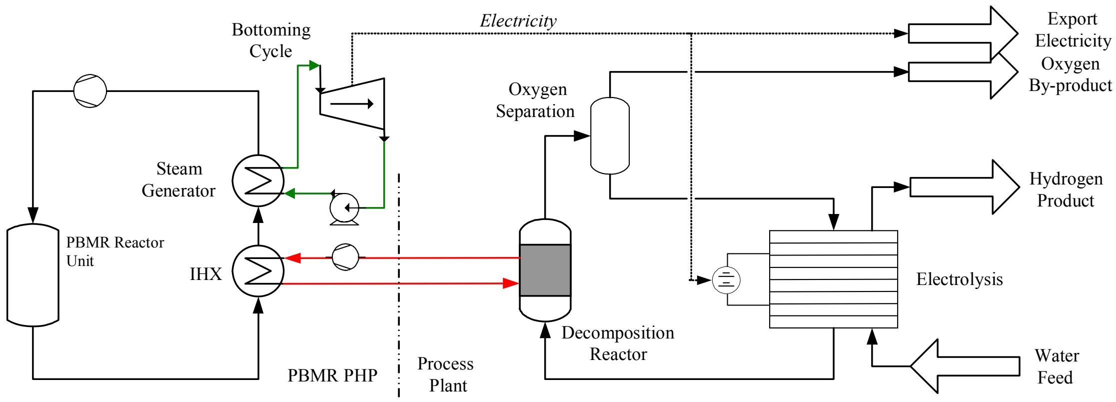


FIG. 2. PBMR-PHP with water-splitting via HyS (Simplified)

4. Synthetic fuel production

The Fischer-Tropsch (F-T) process was initially developed in Germany in the 1920's as a local source of strategic synthetic liquid fuels from coal. The only commercial-scale coal liquefaction process currently in operation worldwide is the Fischer-Tropsch, presently utilized by Sasol to produce some 40% of the gasoline and diesel fuels for South Africa. China is also considering coal liquefaction as a way of utilizing its coal reserves and reducing its dependence on imported oil. Sasol is planning two CTL plants in China [7] and in the USA some nine states are actively considering CTL plants [8]. Global coal-based liquid hydrocarbon production is expected to rise from 150,000 bpd today to 600,000 in 2020; and 1.8 million bpd in 2030 [8].

An indirect coal-to-liquids process first gasifies the coal with steam and oxygen to form "syngas" (a mixture of hydrogen and carbon monoxide), plus excess steam, carbon dioxide, hydrogen sulfide and other volatile materials from the coal.

Partial Oxidation: $CH_{0.8} + 0.7\ O_2 \rightarrow CO + 0.4\ H_2O$

Steam Reforming: $CH_{0.8} + H_2O \rightarrow CO + 1.4\ H_2$

Water Gas Shift: $CO + H_2O \rightarrow CO_2 + H_2$

After the volatiles have been cleaned out of the gas stream, the hydrogen-to-carbon monoxide ratio is improved by "shifting." Oxygen from the water molecule is transferred to the CO molecule producing additional hydrogen and carbon dioxide from steam and carbon monoxide. The sulphur and carbon dioxide are removed using classic acid gas removal techniques. Additional hydrogen is supplied to the feed gas by reforming methane produced in the Fischer-Tropsch (F-T) reactor. The syngas is then reacted over a catalyst in the F-T reactor to produce high quality clean fuels and the aforementioned methane. The F-T process assembles hydrocarbon building blocks in the presence of a catalyst, generally in accordance with the formula [9]. See also the paper from Penfield (2006) for a compelling case for the marriage between nuclear and coal [10]. In coal-to-liquids, over 40% of the syngas is shifted to make the required H_2.

F-T: $(2n + 1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$

Liquid fuels from Fischer-Tropsch have an H:C ratio of approximately 2:1, hence the above equation reduces to:

F-T: $CO + 2H_2 \rightarrow CH_2 + H_2O$

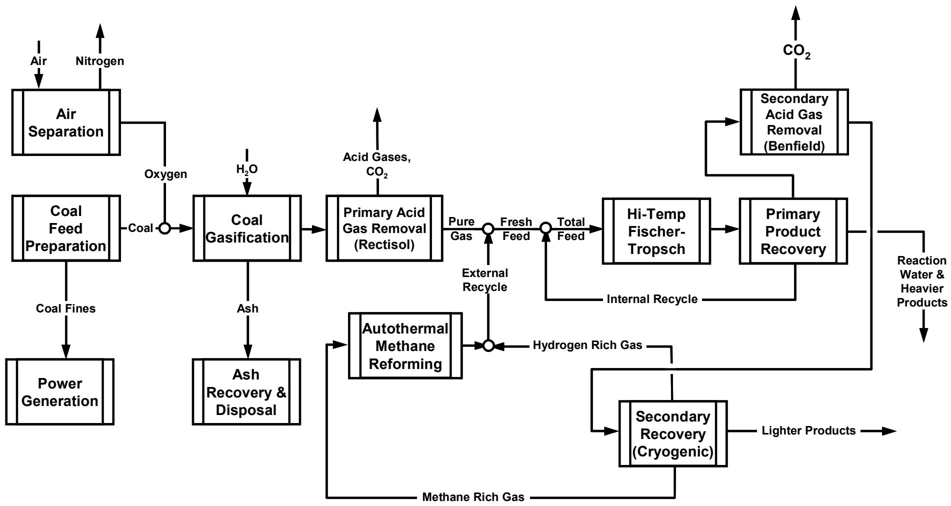


FIG. 3. Conventional CTL process (Simplified)

4.1. Nuclear coal-to-liquids

Current CTL CO_2 emissions result from the production of hydrogen via POX, Steam Reforming and Water Gas Shift using coal as the feedstock, as well as energy sources for needed process heat, steam and electricity. If an independent clean source of oxygen were available, then the air separation step would not be needed. If a source of hydrogen were available, the hydrogen could replace the input of water as a hydrogen source and the steam reforming and WGS reaction steps are no longer required. Such a source of oxygen and hydrogen could be nuclear water-splitting, which will nearly eliminate CO_2 emissions in generating liquid fuels.

Figure 4 shows how the PBMR reactor can be coupled with HyS and the coal-to-liquids process to produce liquid fuels. Note also that some nuclear heat is added directly to the gasification process in the heating of the input oxygen, thus increasing overall efficiency. Value added through nuclear integration includes:

— Extend coal resources
  - Cuts coal use by over 40% by using water as hydrogen feedstock instead of coal

— Overall process simplification
  - Reduces size of coal handling and gasifiers needed (by 40+%)
  - Eliminates air separation / oxygen plant (capital and electric power consumption costs)
  - Eliminates need for input steam (capital and energy costs)

— Environmental benefits
  - Nearly eliminates CO_2 emission in producing liquid fuels and hence also the need for sequestration (the paper of Penfield [10] assumed selling the CH_4 and eliminating the final CO_2 removal step).
  - Reduced waste streams

— Economic drivers
  - Production cost of oxygen and hydrogen
  - CO_2 credits
  - Displacement of coal
  - Major off-sets in CTL capital and operating cost (eliminates approximately half of gasification and all CO_2 sequestration systems when combined with water-splitting)

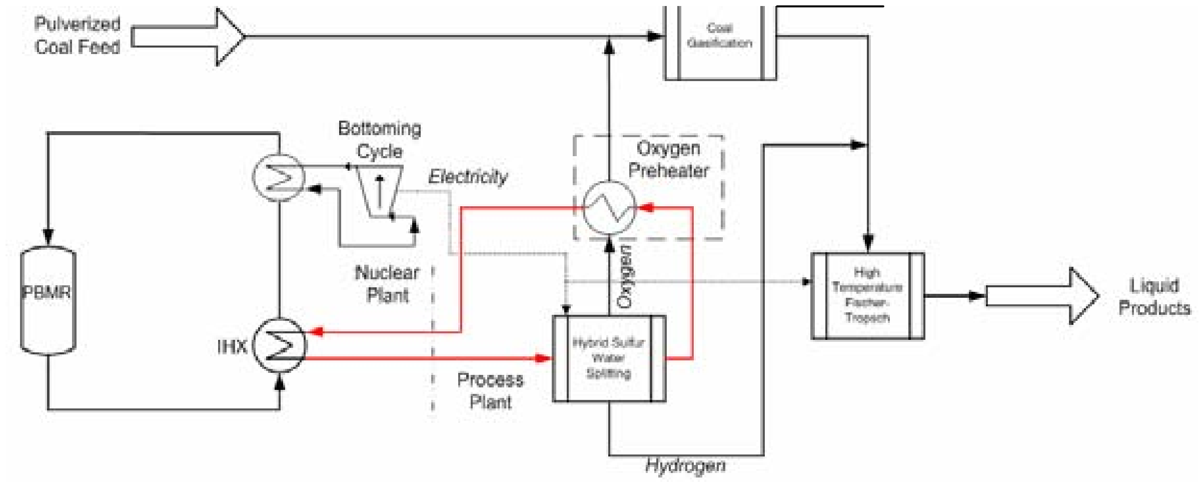


FIG. 4. PBMR PHP coupling to the coal-to-liquids process (Simplified)

4.2. Nuclear coal-to-gas

The same benefits outlined above for coal-to-liquids (CTL) also hold for coal-to-gas (CTG) applications but, potentially, with even greater incentives, depending upon the form and H to C ratio of the required product. Syngas, a mixture of CO and H_2 is distributed today by certain pipelines and used in the petroleum and petrochemical industries. It is typically made from natural gas via gas-fired steam-methane reforming. The syngas can be used to produce high purity hydrogen for industrial use with the CO being converted to additional H_2 via the water-gas shift reaction. It can also be used as a chemical feedstock, with the required H to C ratio a function of the specific chemical process (e.g., ammonia, methanol). If converted back to methane via methanation, the product is Synthetic Natural Gas (SNG). Since the latter is an exothermic process, the reforming-methanation combination has been proposed as a "thermochemical pipeline" for the long-distance distribution of thermal energy.

In CTG, the production of syngas from coal would involve essentially the same steps as described above for CTL. If the ultimate product is to be SNG, however, the required H to C ratio would be 4, versus ~2 for CTL. This implies an even greater advantage for an independent nuclear-driven source of hydrogen and oxygen in terms of feedstock conservation, avoided capital and operating costs and avoided CO_2 emissions. For applications that use the syngas directly, the competition is with natural gas, a higher-value fuel than the coal that replaces it. See Fig. 5 for schematic overview.

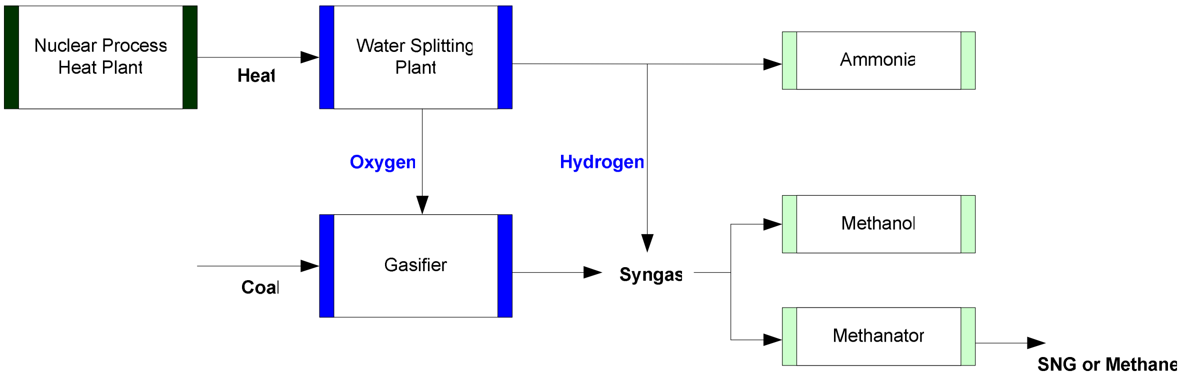


FIG. 5. PBMR PHP coupling to the coal-to-gas process (Simplified)

4.3. Nuclear steam-methane-reforming

Steam-Methane Reforming (SMR) produces syngas ($CO + 3\ H_2$) by reforming natural gas with steam.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

As already noted, the syngas is used in the processing of petroleum products and as feedstock in various chemical processes. The heat from the PBMR reactor can be used to replace approximately 30% of the natural gas which is otherwise burned in conventional SMR processes to supply the heat for steam generation and the endothermic reforming reaction [8]. Nuclear heated SMR would reduce CO_2 and extend the life of natural gas reserves. Economic analyses have shown that PBMR SMR is competitive with new SMR facilities at today's natural gas prices in most international markets [11].

5. Summary

Energy concerns, especially with regard to fuel security in the transport sector, are receiving increased attention from governments and industry. While the "Hydrogen Economy" offers the ultimate conceptual solution, the barriers to replacing our present liquid fuels infrastructure appear challenging in the near term. The proposed combination of two major energy resources, coal and nuclear, offers an alternate approach that takes advantage of our existing transportation infrastructure.

HTGR technology, such as the PBMR, can play a key role in cleanly generating liquid fuels and gas from coal resources. The PBMR has unique characteristics that fit the process heat market. HTGR technology can add value (reduce capital and operating costs and nearly eliminate CO_2) to synthetic liquid fuel operations by supplying hydrogen through water splitting, by supplying high-temperature process heat for syngas production or heat for steam generation. However, for the CTL and CTG applications, nuclear water splitting requires further R&D to reduce capital and operating costs. The PBMR Process Heat Team is presently evaluating the potential of nuclear integrated CTL and CTG operations.

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Status of the sulfur-iodine engineering demonstration loop

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Abstract. The paper deals with work on an engineering demonstration facility of sulfur-iodine cycle for nuclear hydrogen. It presents the details of an International Nuclear Energy Research Initiative (INERI) Integrated Lab Scale (ILS) demonstration. The work is jointly carried out at Sandia National Laboratory, USA, CEA France and General Atomics, USA.

1. Introduction

Thermochemical cycles decompose water rather than carbon-based fuels to produce hydrogen. These are carbon-neutral, unlike steam reforming of methane. Many cycles have been studied, including UT-3, Calcium-Bromide, and Sulfur-Iodine (S-I) cycles. The S-I Cycle was invented at General Atomics in 1970's. Temperatures above 800C required for these operations can be achieved from the HTGRs under development. Unit operations of hydrogen plant, scale economically like a refinery or chemical plant.

Figure 1 shows a simple schematic of the sulfur-iodine cycle

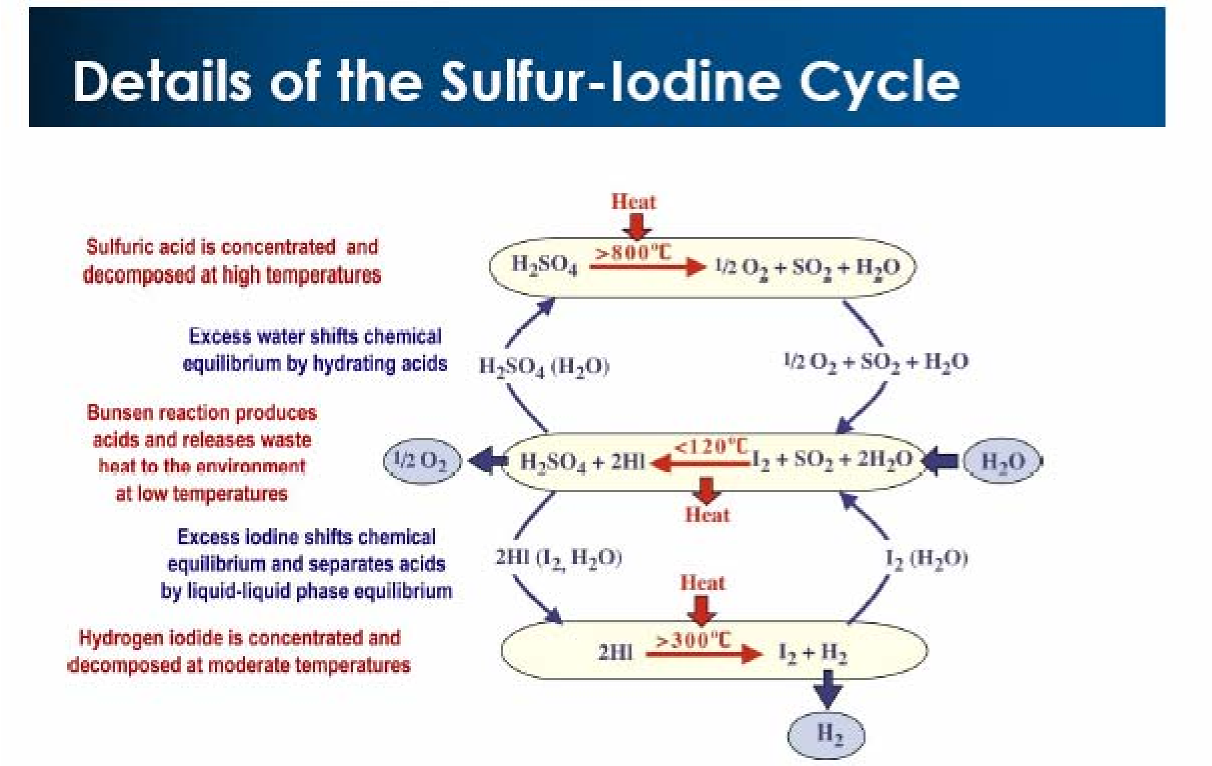

FIG. 1. Details of the sulfur-iodine cycle

Figure 2 shows the milestones of the DOE hydrogen initiative, which has selected sulfur-iodine thermochemical cycle for early demonstration. These include the laboratory, pilot and engineering scale experiments for thermochemical cycles, high temperature electrolysis and system interfaces and supporting systems.

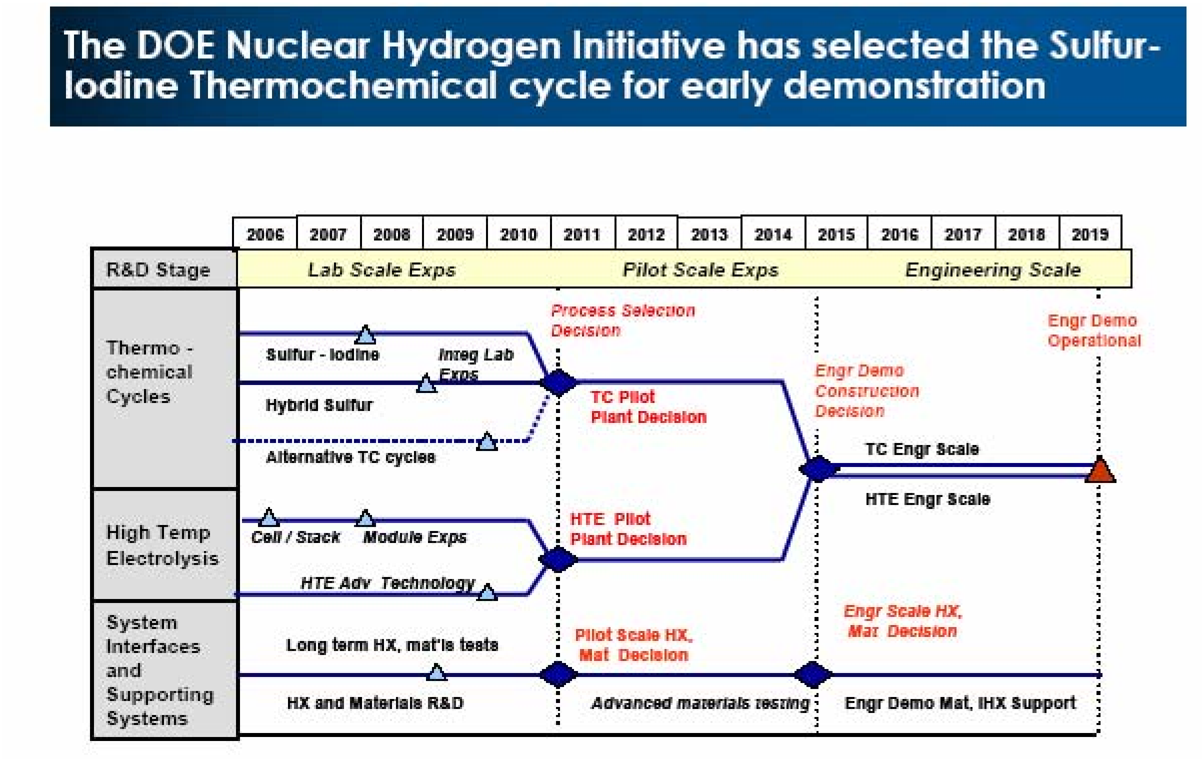

FIG. 2. The DOE nuclear hydrogen initiative has selected the sulfur-iodine thermochemical cycle for early demonstration

2. International Nuclear Energy Research Initiative (INERI) Integrated Lab-Scale (ILS) demonstration

The project objectives are to support pilot plant design including:

- Engineering materials
- Engineering pressures
- 100-200 standard liters per hour of hydrogen
- Possible scale up to 1000 liters per hour

3. Demonstration facility

A closed loop demonstration facility is under construction at General Atomics. The tasks distribution of the three laboratories are as follows:

Sandia National Laboratory- United States of America
- Project lead
- Sulfuric acid decomposition

Commissariat à l'Energie Atomique – France
- H_2SO_4 and HI generation (Bunsen reaction)

General Atomics – United States of America
- Facility coordinator
- HI decomposition

Figure 3 shows the schematics of the Bunsen reaction device constructed by CEA in France.

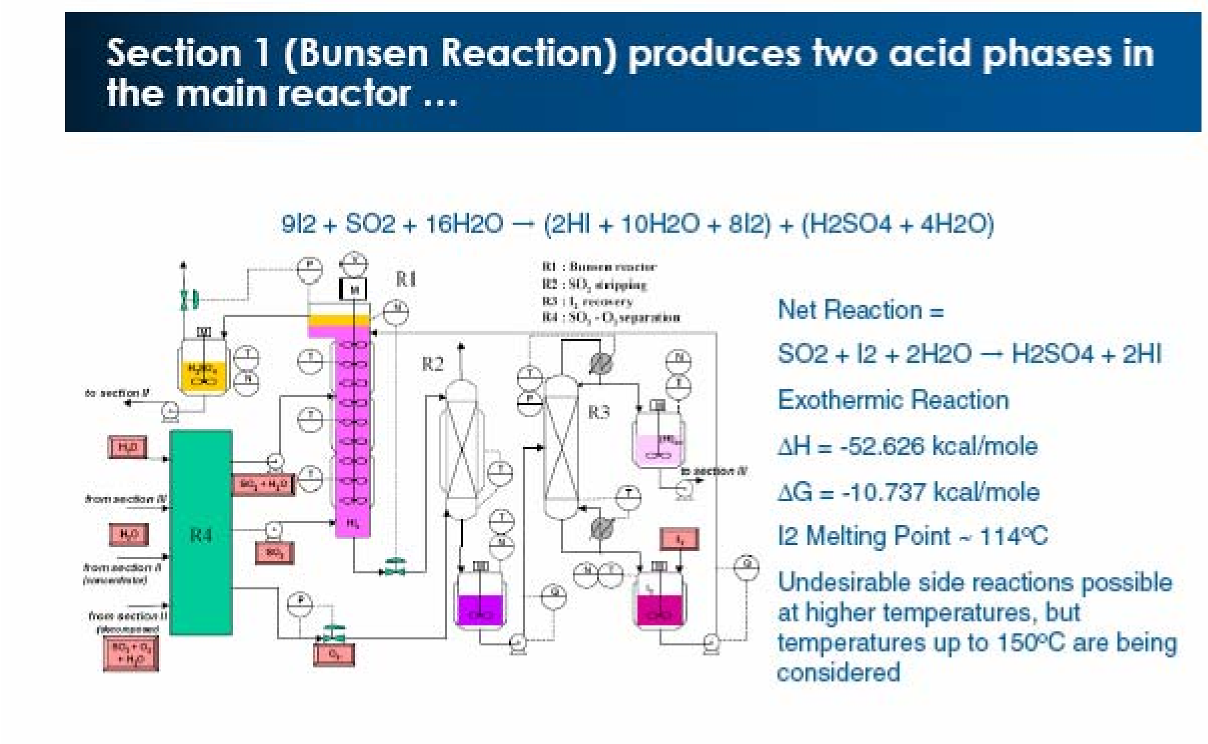

FIG.3. CEA has constructed a Bunsen reaction device in France

Figure 4 shows the schematics of the sulfuric acid decomposition device constructed by Sandia at New Mexico.

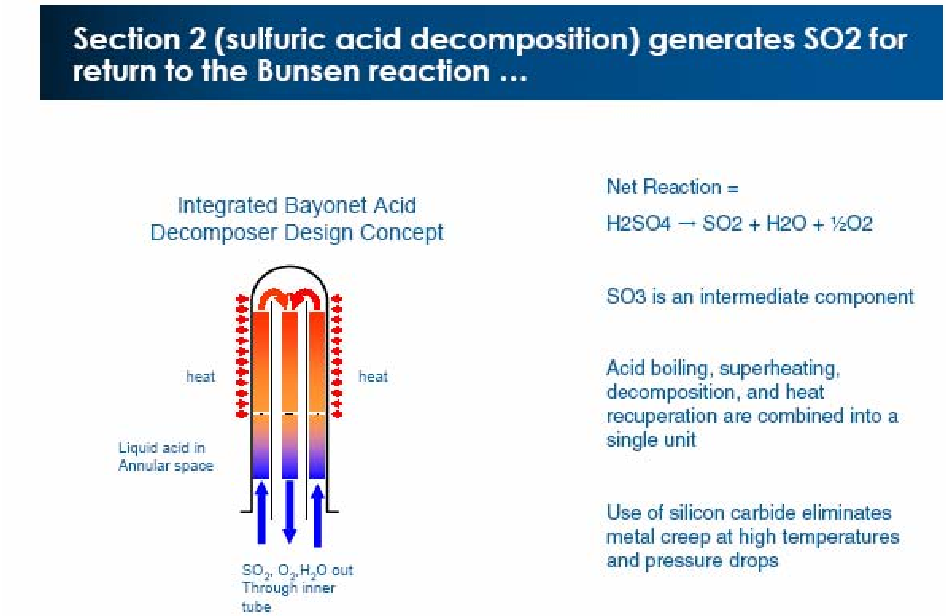

FIG. 4. SNL has constructed a sulfuric acid decomposition device in New Mexico

Figure 5 shows the schematics of the HI decomposition device constructed by General Atomics at California.

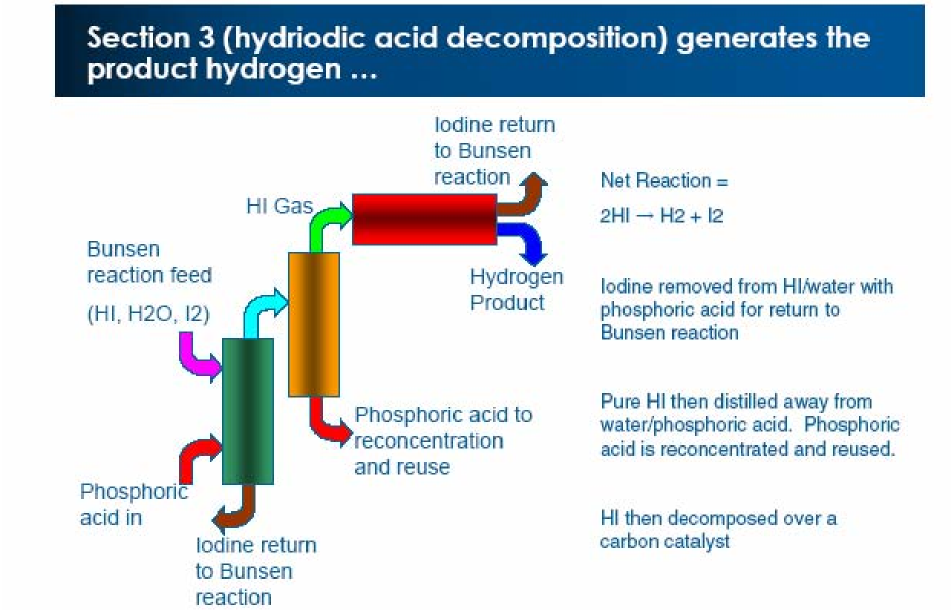

FIG. 5. GA has constructed a hydriodic acid decomposition device in California

Figure 6 shows a three dimensional view of the integrated skid containing the three sections mentioned above. This will allow independent operation during startup and troubleshooting.

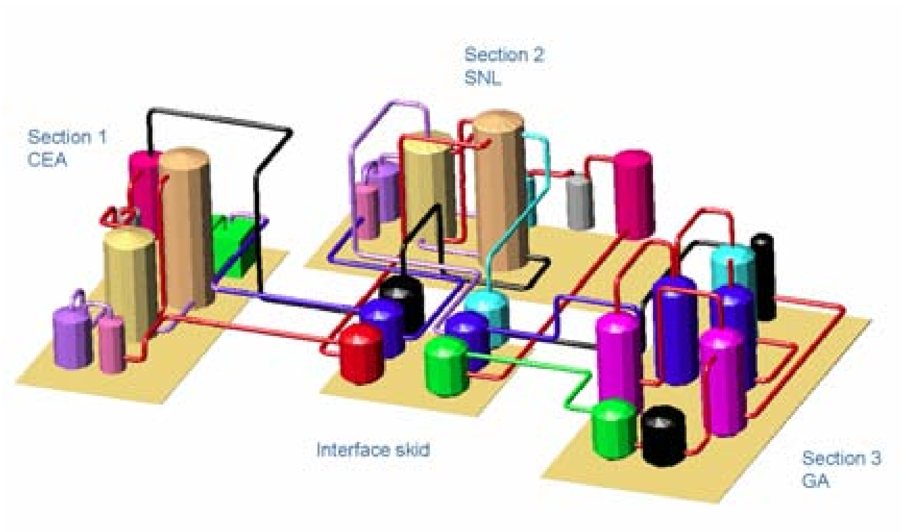

FIG. 6. An interface skid will allow for independent operation during start-up and troubleshooting

6. Summary

The progress of the work schedule on the project till date is indicated as below:.

- The sulfur-Iodine Engineering demonstration loop construction is in work and on schedule
- Individual skid testing and initial integration work through 2007
- Fully integrated experimentation and operation through 2008
- Potential scale up to 1000 liters per hour in 2009
- Representatives from CEA and SNL will work long-term at the GA site on the project
- Organizations from other countries interested in participating

Verification tests performed for development of an integral type reactor

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Abstract. SMART is an integral type reactor with innovative design features aimed at achieving a highly enhanced safety and improved economics. The SMART design is based on proven reactor design technologies with the use of new advanced design features. Most of the design features implemented into the SMART have been proven, however the advanced design features implemented into the SMART should be proven by testing. Various thermal hydraulic experiments have been carried out and also planned to assure the fundamental behavior of major concepts of the SMART and to prove the performance of the systems with new innovative technologies. This paper describes the thermal hydraulic test program for the SMART development and briefly discusses the typical test results.

1. Introduction

Small and Medium sized Reactors are currently under development worldwide not only for electricity generation, but also for sea water desalination. SMART [1-2] is an integral type reactor with a sensible mixture of new innovative design features and proven technologies aimed at achieving highly enhanced safety and improved economics. In the beginning stage of the SMART development, top-level requirements for safety and economics were imposed for the SMART design features. To meet the requirements, highly advanced design features enhancing the safety, reliability, performance, and operability are introduced in the SMART design. Advanced design features require tests to confirm the performance of the design and to produce data for the design code verification.

The safety of the SMART design is assessed for more than 1500 design based events of 21 different types. The computer code used for the analysis is MARS/SMR [3-4], which is a best-estimate thermal-hydraulic system analysis code based on a two-fluid model for two-phase flows. This code is a modified version of MARS for the SMART safety and performance analyses. A number of SMART specific models reflecting the unique design features of the SMART, such as a helical tube SG, pressurizer, and critical flow with non-condensable gas have been addressed in the code.

The SMART design is based on proven reactor design technologies with the use of new advanced technologies. Most of the design features implemented into the SMART have been proven, however the advanced design features implemented into the SMART should be proven by testing. Various thermal hydraulic experiments are being carried out and also planned to prove the performance of the systems with new innovative technologies. Upon the completion of the basic design phase, various comprehensive tests have been conducted.

This paper describes the thermal hydraulic test program for the SMART development and briefly discusses the typical test results.

2. Test program

2.1. VISTA integral effect test

The VISTA facility is designed to simulate the primary and secondary systems as well as the major safety-related systems. Its scaled ratio with respect to the SMART is 1/1 in height and 1/96 in volume. The reactor core is simulated by an electrical heater with the capacity of 818.75kW. Unlike the integrated arrangements of the SMART, the VISTA primary components including a reactor vessel, a main coolant pump (MCP), a helical-coiled steam generator (SG), and a pressurizer are connected by pipes with each other for an easy installation of the instrumentation and a simple maintenance. The secondary system having a single train is simply designed to remove the primary heat source.

Besides these major systems a make-up water system and a chilled water system are installed to control the feed water supply and its temperature. The schematic diagram of the VISTA facility is shown in Fig. 1.

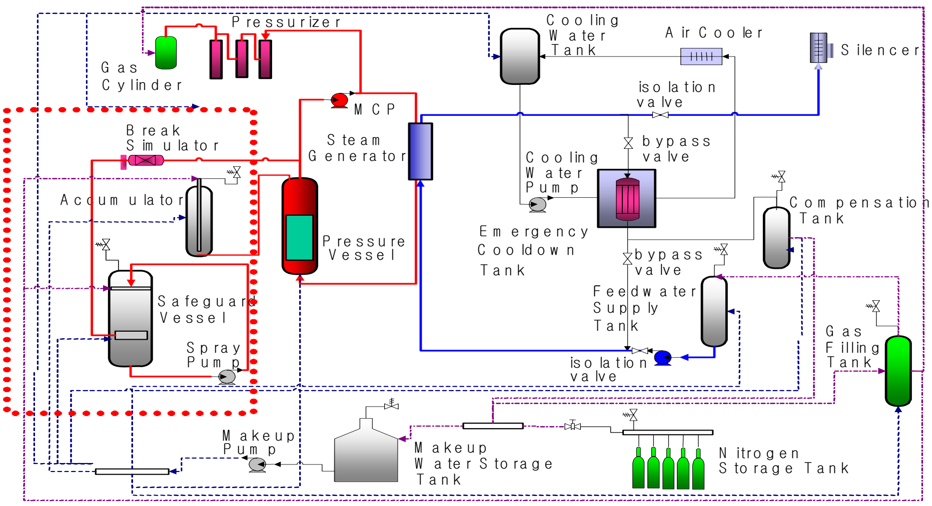

FIG. 1. Schematic diagram of the VISTA facility

2.2. Test results

Using the thermal-hydraulic integral test facility, VISTA, several performance tests were carried out [5-6]. It was found that the VISTA facility had the capability to correctly simulate the thermal-hydraulic conditions in the SMART within an acceptable tolerance. The effects of step/ramp power changes on the performance of the VISTA facility were investigated.

The thermal-hydraulic behavior of the VISTA facility during the PRHR system was also investigated for a limited number of cases. In the PRHR transient tests, the natural circulation flow rate through the PRHRS loop reached around 12 percent in the early stages of the PRHR operation. The PRHRS accomplished well its functions in removing the transferred heat from the primary side in the SG as long as the HX is submerged in the ECT. Figure 2 shows that MARS code calculation provided reasonable prediction of natural circulation process that happens in reactor during transients.

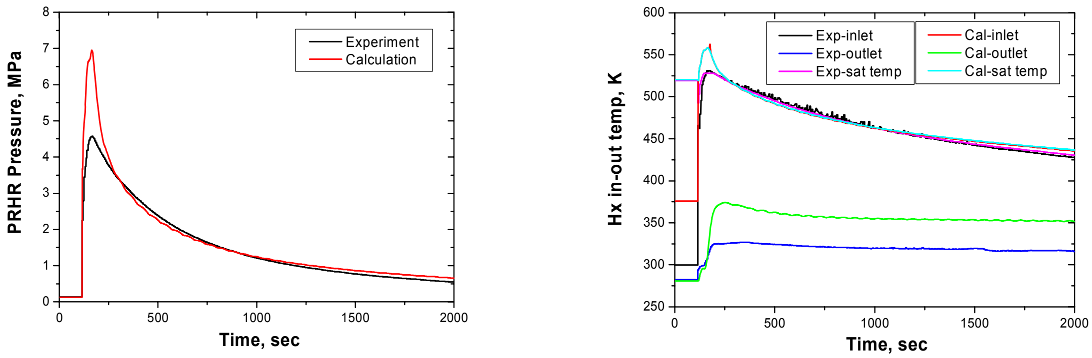

FIG. 2. Typical thermal hydraulic behavior versus MARS code calculation

Up to now various test series were carried out such as

– Comprehensive performance tests for major components
– PRHRS and SG performance tests
– Reactor trip/cool down and natural circulation tests
– Reactor heat up and power variation test
– Safety-related design basis accident tests (Non-LOCA)

The VISTA facility was used to verify performance and safety of the integral type reactor SMART. Several design basis accidents, such as increase or decrease of feed water flow, loss of coolant flow, control rod withdrawal, and a limited case of loss of coolant accident (LOCA) on the line to the gas cylinder are under investigation in order to understand the thermal-hydraulic responses and finally to verify the system design of the SMART.

2.3. Separate effect tests

Various fundamental thermal hydraulic experiments were carried out to assure the key technology of the advanced safety systems during the design development. For verification purpose of SMART technology, various separate effect tests on the major component and system were identified, which are including as follow,

– Flow distribution in core test
– Two-phase critical flow test with non-condensable gases
– Critical heat flux test
– Wet thermal insulation performance test
– PRHRS condensing heat exchanger test
– Major components(MCP,CEDM and SG) performance test

Some of these tests are introduced.

2.3.1. Flow distribution in core flow test

The COFLOW shown in Fig. 3 is an experimental facility to investigate the flow distributions of the core flow channels and the steam generators of the SMART. It was constructed based on the linear scaling law. The flow distribution of the core flow channels is one of the very important factors affecting the thermal margin in the core design.

FIG. 3. COFLOW facility

Four groups of core flow channels were taken into account for the core flow distribution. The core flow was found to increase in the central region for the low flow conditions comparable to the natural circulation condition. Several operation conditions were considered by varying the speed of the MCPs. Also the asymmetric operating conditions such as a one pump operation at a high and a low speed were considered.

2.3.2. Two phase critical flow test

A non-condensable gas two-phase critical flow test facility (CFTL) was constructed to simulate the pipe break accident of the SMART as shown in Fig. 4. The major components of the non-condensable gas two-phase critical flow test facility are the pressure vessel, the test section, the suppression tank, and the nitrogen gas supply system. A series of two-phase critical flow tests with a non-condensable gas was performed using a test section with an inner diameter of 20.0 mm to ascertain the effects of a non-condensable gas such as nitrogen gas in a critical flow at high-pressure conditions. The critical flow data is produced to simulate the discharge of the coolant with a non-condensable gas through a broken pipe during the small break loss of coolant accident. The produced experimental data is used to validate the existing two-phase critical flow model with a non-condensable gas and to develop a new model to be included in the TASS and MARS code [3-4].

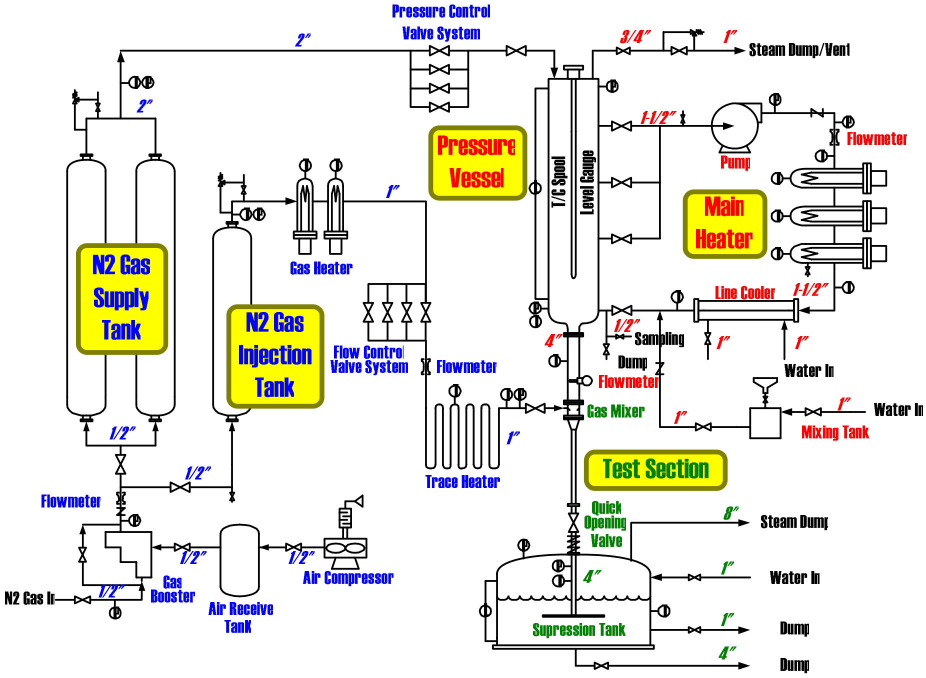

FIG. 4. Schematic diagram of the critical flow test facility

The test conditions were the stagnation pressures of 4.0, 7.0, 10.0 MPa, water subcoolings of 0.0, 20.0, 50°C, and nitrogen gas flow rates of 0.0 ~ 0.22 kg/s. Based on the experimental data, an empirical correlation of the non-dimensional critical mass flux is developed, which can be expressed with a function of a non-dimensional volume flow rate of the non-condensable gas. Figure 5 shows the prediction results of the critical mass flux using the developed empirical correlation.

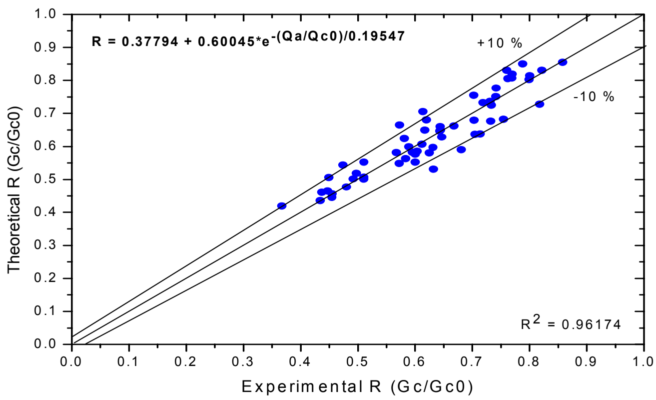

FIG. 5. Prediction results of the critical mass flux

2.3.3. Critical heat flux tests

In the reactor core with low a power density, the critical heat flux (CHF) is the most important parameter that restricts the thermal power capability of the reactor. A series of CHF experiments have been conducted in RCS loop facility. The RCS Loop was constructed to obtain the CHF data under high pressure conditions [7].

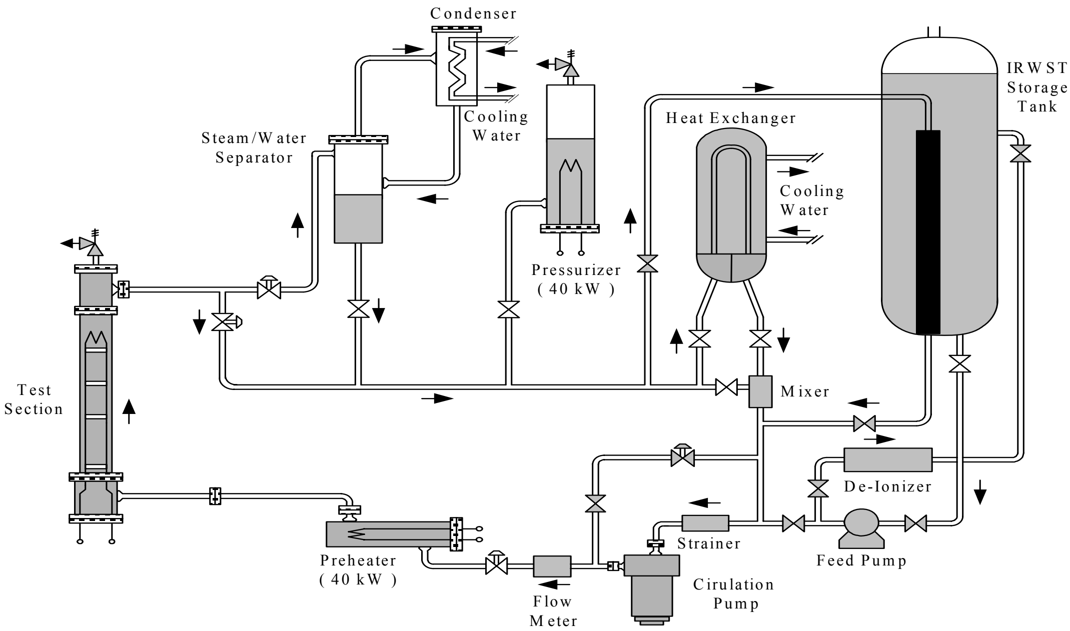

FIG. 6. Schematic diagram of the critical heat flux test facility

The principal operating conditions of the loop are

- operating pressure 0.5 - 16 MPa
- test section flow rate 0.03 - 3 kg/s
- maximum water temperature 620 K
- working fluid de-ionized water
- available heating power of test section 970 kW.

Figure 6 shows the simplified flow diagram of the RCS loop facility. It basically consists of a main circulating pump, preheater, CHF test section, steam/water separator, pressurizer and a cooler. The loop is filled with de-ionized water. Water is circulated around the main loop by a canned motor centrifugal pump. The flow rate of the test section inlet is controlled by the adjustments of the motor speed of the circulating pump and the flow control valve. Figure 7 shows a comparison of calculated versus experimental CHF data. The calculated CHF agree well with experimental data.

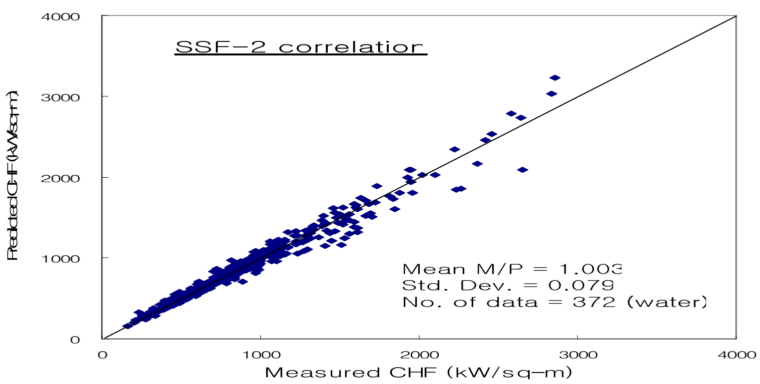

FIG. 7. Comparison of calculative versus experimental CHF

3. Conclusions

SMART design combines firmly established commercial reactor design technologies with the new advanced technologies focusing on an enhancement of the safety and an improvement of the economics. The enhancement of safety is realized by incorporating inherent safety improving features and reliable passive safety systems. The improvement in the economics is achieved through a system simplification, component modularization, construction time reduction, and increased plant availability.

The new advanced design technologies implemented into the SMART were proven by experience, testing or analysis. The equipments were designed and qualified according to the applicable industrial standards. For the verification of the new advanced technologies adopted in SMART design, comprehensive fundamental thermal-hydraulic experiments were carried out during the design development stage. In addition, the thermal hydraulic tests were conducted to support key technology and design verification of SMART development. According to the performance tests carried out by using the VISTA facility, it was found that the VISTA facility had the capability to correctly simulate the thermal-hydraulic conditions in the SMART.

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Hydrogen production and delivery analysis in U.S. markets: Cost, energy and greenhouse gas emissions

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Abstract. This paper describes a combined hydrogen production and delivery analysis model. The model is capable of assessing the cost of various options for hydrogen production and distribution to U.S. markets. The production technologies considered are steam methane reforming, coal gasification and nuclear heat from HTGR to SI water splitting process. The model is also capable of assessing the energy use and greenhouse gas emissions associated with various production-delivery pathways.

1. Introduction

The combined model includes three separate tools: the Hydrogen Delivery Scenario Analysis Model (HDSAM), developed as part of the US Department of Energy's hydrogen analysis project (H2A) to analyze alternative distribution options, an H2A-developed model of central hydrogen production, and another tool (based on the GREET model) for estimating energy use and greenhouse emissions. Together they compute the levelized cost (i.e., cost plus a predefined return on investment) of producing and delivering hydrogen to different markets. Like all H2A-developed tools, the combined model applies a common set of financial assumptions and runs in a Microsoft Excel environment. However, unlike other H2A tools, the model links a number of separate H2A-developed modules, and incorporates a graphical user interface to assist in selecting and analyzing alternative scenarios and estimating the cost of individual components within each scenario.

Three central hydrogen production technologies and six delivery options (defined as combinations of two markets and three delivery modes) are considered. The considered technologies for hydrogen production are natural gas steam methane reforming (NG SMR), coal gasification, and nuclear thermo-chemical water splitting. The delivery modes include pipelines, liquid hydrogen trucks and gaseous hydrogen trucks. Delivery can be to an urban market, a rural market or a combined urban/rural market. The level of hydrogen vehicle penetration in a given market can be specified in the range of 1 to 100%.

2. Results and discussion

2.1. Hydrogen production and delivery cost

For centralized hydrogen production, unit cost ($/kg) is dependent on scale (Fig. 1). Although scale effects are most pronounced for plant sizes below 100 tonnes per day (tpd), production cost continues to decline in the range of 200-650 tpd as well (Fig. 2). Similarly, for most delivery modes and markets, delivery cost depends on scale (Fig. 3). Thus, the cost to produce and deliver a kilogram of hydrogen to rural markets at high market penetration is typically less than at low penetration, and delivered cost to urban markets is lower than to rural markets. Cost drops rapidly with increasing scale for all market types and sizes, but less so for production via natural gas SMR and delivery via high-pressure compressed gas trucks. Cost for delivery also drops with increasing market size up to 100 tpd. Scale matters for pipeline and liquid truck delivery; less so for high-pressure compressed gas trucks. Thus, the latter may be attractive for smaller markets. However, since high-pressure compressed gas trucks are not generally available at present, further analysis is needed to verify the highly uncertain cost assumptions underlying this finding.

The distance between a centralized hydrogen production plant and the market it serves could also change relative costs. It should be noted that all results shown assume a 100 km distance.

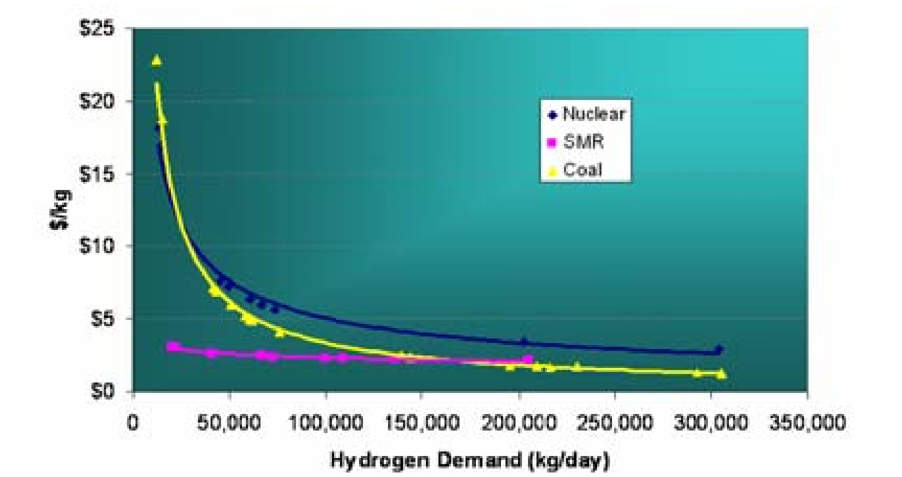

FIG. 1. Nuclear- and coal-based hydrogen production cost, 0-300 tpd production rate

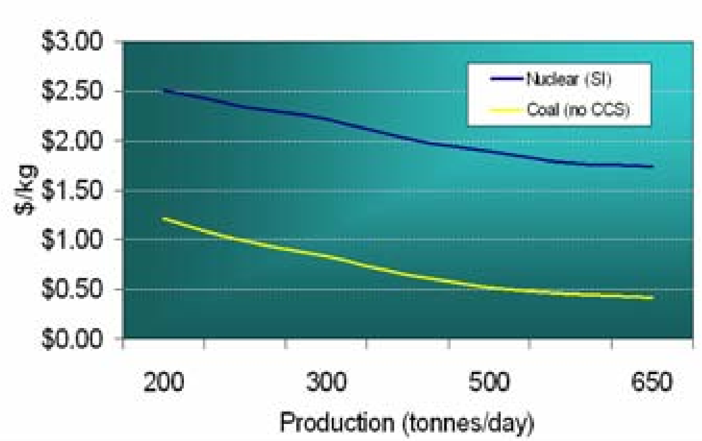

FIG. 2. Nuclear- and coal-based hydrogen production cost, 200-650 tpd production

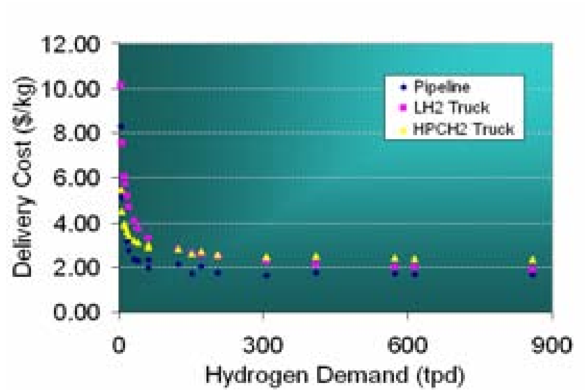

FIG. 3. Hydrogen delivery cost, 10-850 tpd

Model results show that capital cost represents the largest share of production cost. However, there are important differences among technologies. As shown in Fig. 4, the capital cost to produce hydrogen by the nuclear route is nearly $1.25/kg higher than by coal-based units without carbon capture and sequestration (CCS). Operating and maintenance costs also account for a much larger share of production cost for hydrogen from nuclear- than from coal-based processes. Much of this difference is due to labor assumptions.

Using H2A default assumptions for coal and uranium prices and process efficiencies, fuel accounts for \$0.33 of the unit-cost of hydrogen produced from coal versus \$0.01 for hydrogen from nuclear processes.

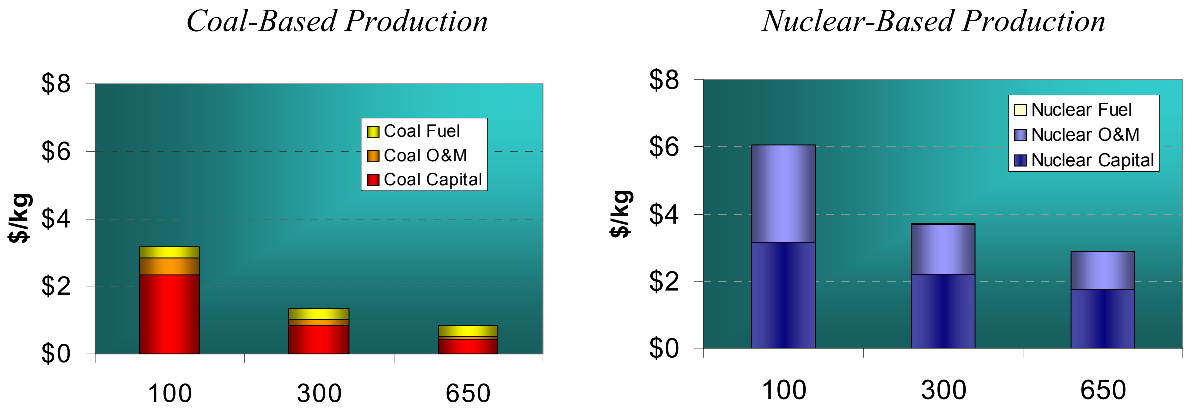

FIG. 4. Capital, operating and maintenance, and fuel cost breakdown for coal vs. nuclear production of hydrogen by production rate (tpd)

As compared with operating and energy costs, capital cost dominates virtually all distribution modes. When examined by individual component, storage and conditioning account for the bulk of this cost. With the exception of liquid truck delivery, where liquefaction is very energy-intensive, energy accounts for the smallest share of delivery cost (Fig. 5) and displays no scale effects.

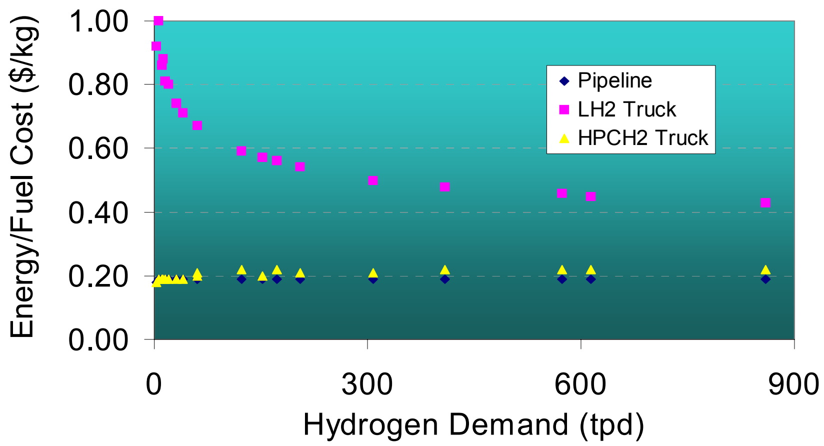

FIG. 5. Unit-cost of energy for hydrogen delivery by mode and scale (in tpd)

2.2. Energy use and greenhouse gas emissions

Greenhouse gas (GHG) emissions reflect the energy efficiency and carbon content of each component in a production-delivery pathway. Coal- and natural gas-based production pathways (without CO_2 sequestration) have high energy consumption and significant GHG emissions. Hydrogen production via nuclear thermo-chemical cycles is the most favorable from an energy use and GHG emissions perspective. Although per-unit energy use (i.e., per kg of delivered H_2) declines slightly with increasing production or delivery rate, energy use is more a function of production technology and delivery mode. Because of the high energy intensity of hydrogen liquefaction, gaseous hydrogen truck and pipeline delivery have much lower energy use and GHG emissions than liquid hydrogen truck delivery (where the liquefier accounts for most of the energy and GHG emissions).

2.3. Hydrogen production costs with carbon taxes or sequestration

Given H2A default assumptions for fuel prices, process efficiencies and labor costs, nuclear-based hydrogen is likely to be more expensive to produce than coal-based hydrogen. As shown in Fig. 6, carbon taxes and caps can narrow the gap, particularly at large scale.

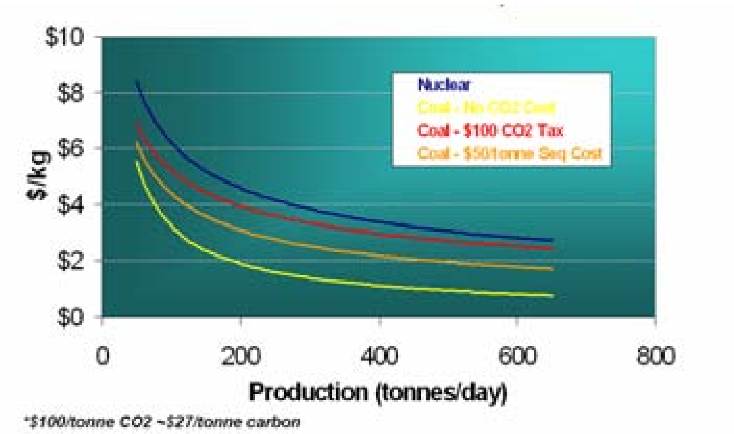

FIG. 6. Unit costs for producing hydrogen from coal-based plants by carbon strategy as compared with nuclear-based plants

3. Conclusions

This paper summarizes analyses conducted with a US DOE-developed set of models known as H2A. Models of hydrogen production via SMR, coal gasification and nuclear thermo-chemical water splitting were combined with a delivery model to estimate the unit-cost of delivered hydrogen to a variety of U.S. markets. Estimates were also developed for associated energy use and greenhouse gas emissions. Findings include:

- SMR is the least-cost production option at current natural gas prices and for initial hydrogen vehicle penetration rates. However, at high production rates, SMR may not be the least-cost option.
- Unlike coal and nuclear technologies, the cost of natural gas feedstock is the largest contributor to SMR production cost.
- Coal- and nuclear-based hydrogen production have significant penalties at small production rates (and benefits at large rates).
- Nuclear production of hydrogen is likely to have large economies of scale. But because fixed O&M costs are uncertain, the magnitude of these effects may be understated.
- For smaller urban markets, compressed gas delivery appears most economic, although cost inputs for high-pressure gas trucks are uncertain.
- For larger urban markets, pipeline delivery is least costly.
- Liquefier and pipeline capital costs are a hurdle, particularly for small markets.

Acknowledgements

This work was supported by the U.S. Department of Energy's Office of Hydrogen, Fuel Cells and Infrastructure Technologies. We gratefully acknowledge the assistance of other members of the H2A team, most notably Matt Ringer of the National Renewable Energy Laboratory and Daryl Brown of Pacific Northwest National Laboratory, as well as a number of industry experts who provided valuable inputs and model review.

Status of PBMR process heat plant project

W. Kriel, R. Greyvenstein, M. Correia, G. Claassen

Pebble Bed Modular Reactor (Pty) Ltd.

Abstract. Conventional nuclear power plants only supply energy in a portion of the electricity sector, while the transportation and industrial energy sectors remain to rely exclusively on fossil fuels for its energy needs. However, the transportation and industrial sectors are vast consumers of energy and jointly contribute to approximately 66% of global CO_2 emissions. Industry concerns for escalating cost of natural gas and petroleum, energy security and environmental acceptability are driving interest in using nuclear energy as primary energy source for transportation and industrial applications. An opportunity exists to introduce nuclear process heat into the world's energy market, but to succeed any technology must be available commercially in the needed timeframe, be demonstrably safe in order to be located close to the process plant, be economical, match the process energy needs and must produce the required temperatures. The Pebble Bed Modular Reactor (PBMR), under development in South Africa, fits each of these requirements.

The PBMR is an advanced helium-cooled, graphite-moderated High Temperature Gas-cooled Reactor (HTGR). A 400 MWt (165 MWe) Demonstration Power Plant (DPP) for the production of electricity is being developed in South Africa for its national utility Eskom. The DPP project is envisioned to form the platform to launch future commercial PBMR products, notably including a variety of process heat applications for the transport and industrial sectors.

PBMR Company has partnered with the Shaw Group, Westinghouse and others to develop and pilot its nuclear process heat technology. The team proposes that the first demonstration facility involve a consortium of industrial clients and is currently working to that end. One of these collaborative projects includes the Westinghouse-led consortium that was awarded the principal contract for the initial phase of pre-conceptual engineering services and planning for the Next Generation Nuclear Plant (NGNP) by the U.S. Department of Energy (DOE). This initial 12-month phase of the NGNP is the U.S. government's first step in deploying a commercial scale HTGR prototype plant for the generation of hydrogen and/or electricity.

Promising process heat applications identified for other PBMR process heat plant work include steam methane reforming, oil sands recovery, hydrogen production, co-generation for petrochemical industries and desalination. This paper reflects current status of the PBMR Process Heat Plant project.

1. Introduction

Global concern for diversification of energy supply to reduce exposure to increasing cost of natural gas and petroleum, together with incentives to reduce CO_2 emissions, are leading to increased interest in using nuclear energy to "leverage" existing hydrocarbon reserves. High Temperature Gas-cooled Reactor technology is presently an option for economically providing large amounts of process heat in the 900°C range without emitting CO_2. An opportunity exists to introduce nuclear process heat into the world's energy market, but to succeed any technology 1) must come soon; 2) must be safe, in order to be located close to process plants; 3) must be economical; 4) must have the right size; and 5) must produce the right temperature. The PBMR technology fits these five requirements. A variety of process applications require heat in the 900°C temperature range.

The process heat from a PBMR HTGR can be used to 1) generate steam for recovery and upgrading of bitumen from oil sands deposits, 2) reform methane to produce syngas (to be used as feedstock to produce hydrogen, ammonia, methanol), 3) to produce hydrogen and oxygen through water splitting, which is particularly well suited for coal-to-liquids and coal-to-gas processes to maximise carbon efficiencies and minimise CO_2 emissions. PBMR technology is also well suited to generate process steam through co-generation for the petrochemical industry and other markets.

The PBMR Company has partnered with Westinghouse and the Shaw Group to develop and pilot the nuclear process heat technology. The team proposes that the first demonstration facility involve a consortium of industrial clients and is working to that end.

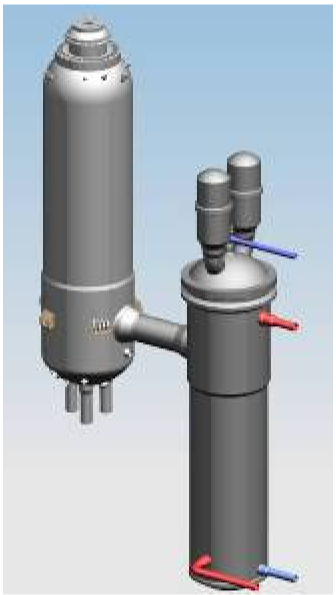

FIG. 1. Typical PBMR process heat plant heat delivery

High Temperature Gas-Cooled Reactor (HTGR) technology, such as is employed in a PBMR plant, delivers thermal energy at a temperature and at a rate suitable for various process applications. The heat source considered for process applications is helium from a 400MWt-500 MWt Pebble Bed Modular Reactor (PBMR) at a delivery temperature up to 950ºC and a return temperature in the range of 350ºC, see Fig. 1. It is assumed that hot helium is delivered at high pressure at the process battery limits, cooled in process reactors and/or heat exchangers, and returned to the heat source. Market studies have shown that the 400 MWt-500 MWt power range is favorable for various process applications, especially steam-methane reforming and oil sands. Existing steam methane reforming and oil sands plants are in the 400 MWt-500 MWt power range.

The key elements completed for the PBMR Process Heat Plant project include:

- Identification of relevant markets and representative applications
- Development of practical PBMR heat delivery configurations
- Identification of technology development requirements and associated risks
- Economic evaluation of representative PBMR process heat applications
- Identification of implementation requirements and market windows

2. Markets and applications

Various process applications which represent a good match to the temperature and quantity of heat output from a PBMR reactor were reviewed. Applications were evaluated based on likely market sizes, expected economics, technology development requirements and other criteria. These process technologies were also reviewed for their ability to use large amounts of hydrogen and oxygen which could be produced from a nuclear water-splitting system.

The results of this analysis determined several attractive near term markets including steam for oil sands recovery and refinery applications, steam methane reforming and water-splitting processes which can provide major improvements for coal-to-liquids technologies.

3. PBMR heat delivery configurations

The PBMR Demonstration Power Plant (DPP), to be built in South Africa on the existing Koeberg site, is comprised of a single 400 MWt reactor with a reactor outlet temperature of 900°C and a nominal net electrical output of 165 MWe. The configuration of the PBMR Process Heat Plant (PHP) and the requirements associated with the Intermediate Heat Exchanger (IHX) will depend on the specific process heat application, see Fig. 1 for typical process heat plant. Paper [1] qualitatively compares several possible cycle configurations. PBMR can provide process heat up to 950°C, based on development and qualification of an acceptable IHX design. Optimisation studies will determine the appropriate process parameters for each application that will satisfy the process energy needs whilst operating within PBMR reactor and component design constraints. Find below a number of configurations for interfacing the reactor to various thermal process applications that were developed for some of the leading applications.

Figure 2 shows a possible configuration for generating high pressure steam for oil sands production applications. The high pressure steam generator is located on the primary helium loop as the only heat exchanger driven by the reactor.

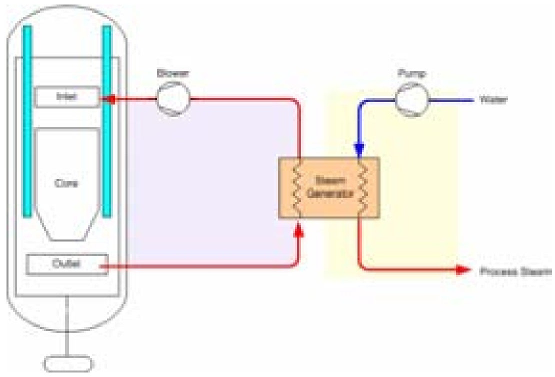

FIG. 2. PBMR PHP configuration for steam generation

Figure 3 below, shows a possible configuration for heat delivery to a Steam Methane Reforming (SMR) system. Two heat exchangers are placed on the primary helium loop with the reactor. The first drives an intermediate helium loop to the reformer, while the second is a steam generator. This configuration was chosen based on preliminary screening efforts but may be re-evaluated once the costs of heat exchangers and the need for an intermediate helium loop to isolate the reformer from the primary helium loop are investigated further.

Figure 4 illustrates a possible configuration used for the Hybrid Sulfur (HyS) water-splitting process, which utilises both heat and electric power from the nuclear source. Heat is delivered through an intermediate helium loop to the process coupling heat exchangers, the largest of which is a high temperature decomposition reactor. Remaining heat is used to generate power using a steam generator and steam turbo-generator plant based on standard Rankine cycle power plant technology. For large scale applications, steam output from a group of reactors can be combined to improve the efficiency and economics of the power generation unit.

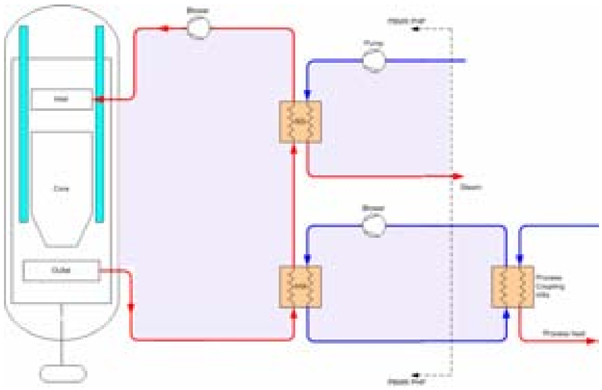

FIG. 3. Configuration for steam methane reforming

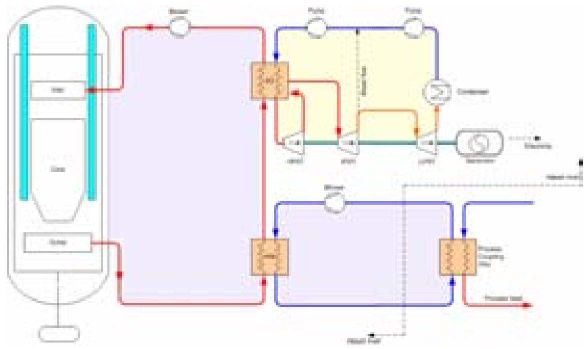

FIG. 4. PBMR PHP configuration for hybrid sulfur process (water splitting)

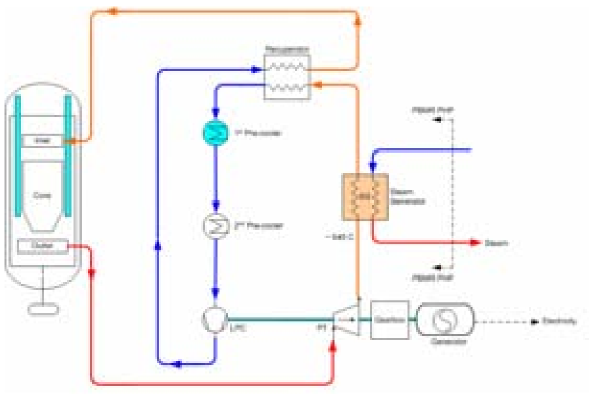

FIG. 5. PBMR PHP configuration for process steam and electricity cogeneration

Figure 5 illustrates a possible configuration for co-generating process steam and electricity used for the petrochemical and oil sands industry. A topping Brayton cycle, adapting direct-cycle turbo-generator plant designs already developed for the PBMR demonstration power plant, is used to utilise the high-temperature capabilities of the reactor when generating lower temperature process steam [3].

4. Technology development requirements and risks

Each potential market opportunity for process heat applications has specific technology development requirements that must be addressed prior to full scale demonstration (see also paper [5]. See the paper of Kriel [6] for an overview of technology development requirements and risks.

5. Economic evaluation of representative applications

Indicative financial models were used to provide conservative estimates of the revenue streams required to provide an attractive rate of return to a potential operator. A consistent assumption set included the following:

- Overnight capital costs derived from estimates for the PBMR DPP by removing power-plant equipment and adding back equipment cost estimates for each application
- Nuclear licensing, site permitting and other owner's capital costs were based on the North American environment
- Project financing on the basis of 75% debt financing with 9.9% construction loan interest, with 20% contingency.
- Cash flow models included capital recovery, operating & maintenance, fuel costs based on PBMR fuel estimates assuming localised supply, feedstock costs etc
- General inflation assumed at 2.5% with 0.5% price escalation on nuclear fuel and feedstocks, 2% annual escalation on natural gas prices.

The results of analyses developed to evaluate opportunities offered by likely power and process applications are described in the sections below.

5.1.1. Electrical power plant economics

In order to calibrate the evaluations performed in an energy industry context, a levelised cost comparison of the PBMR power plant against fossil-fuel and other nuclear alternatives was conducted. The results indicate that the levelised cost of power from a mature, commercial design PBMR electric plant is likely to be very close to an advanced light water reactor. However, the smaller capital requirement, ability to stage construction, and potentially lower risks associated with regulatory requirements will make the PBMR electric plant easier to finance without major public support.

Conclusions of this economic analysis gave an initial indication of the likely competitiveness of a PHP against gas and coal energy sources, and highlighted further advantages of the PBMR design:

- The total power cost resulting from installing a new PBMR electric plant or ALWR plants is predicted to be less than the variable cost of continuing to operate existing gas fired combined cycles at gas prices of $7/MMBtu or higher.
- PBMR electric plant and ALWRs should be economically competitive with conventional and advanced coal-based power plant designs for coal prices above $1.5/MMBtu (without CO_2 credits).

- The PBMR's modular nature and lower expected nuclear licensing risk should allow staged construction schedules that reduce owner risk profiles and risk intensities, improving the potential financeability of PBMR power projects. ALWR projects will need major government and public risk sharing to support financings and will continue to be vulnerable to changes in nuclear safety requirements for generation III reactor designs that may change after construction is started.

5.1.2. Basis for cash flow modeling of process heat applications

Financial models were developed for each process application. The projected capital cost, operation and maintenance costs, performance and availability of each case were estimated in January 2006 US dollars. The cash flow model represents current dollar expenditures and revenues over a 20 year analysis period. Conservative assumptions, consistent with the power generation benchmark but based on project financing assumptions typically applied in the petro-chemical industry, were used for capital structure, financing costs, economic environment assumptions and differential inflationary increases for fuel costs, O&M and capital, including:

- Project implementation schedule leading to commercial operation in 2016
- Plant operates 8000 hours per year
- No credits for avoiding CO_2 emissions

PBMR estimated the capital and operating costs based on the electrical demonstration project with adaptations for the process heat delivery plant, including the interface heat exchangers, helium piping and circulator. Shaw developed conceptual designs for both the Steam Methane Reforming and Oil Sands SAGD applications. These designs included material/energy balances, equipment sizing, capital and operating costs. Capital costs were assembled using assumptions consistent with similar projects, including conservative assumptions regarding owner's costs, project development and financing, obtaining nuclear licenses, interconnections, cost escalation, construction interest and project contingencies. A financial model was developed for each process application to determine the required revenue streams to provide an attractive rate of return. The costs of providing steam or synthesis gas from conventional gas-based technology were calculated to relate expected revenue to projected gas prices. Financing would require development of acceptable risk management arrangements to isolate lenders from risks they are not normally exposed to.

5.1.3. Oil sands steam production

A preliminary review of project economics for a steam-only PBMR oil sands application was completed. Using conservative assumptions and costs, it appears that a profitable application would result from a contract to provide steam to an oil sands producer for a price comparable to the cost of generating steam from natural gas at $6.0-6.5 US per MMBtu. Adding the benefit of CO_2 credits can reduce the breakeven gas price as shown in Fig. 6.

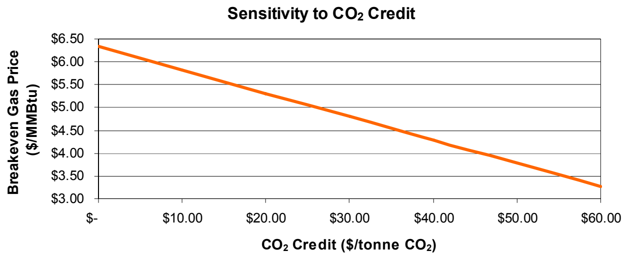

FIG. 6. Sensitivity of breakeven gas price to CO_2 credits for oil sands steam production

Initial conclusions of this analysis are that at current gas prices and in the absence of CO_2 emission credits, a PBMR facility producing high pressure steam could be profitable immediately. As CO_2 credits and mature plant economics are implemented, more dramatic savings are possible over the use of natural gas. The conclusion is that the PBMR steam plant application has the potential to increase the economic value of oil sands deposits by reducing total cost of production and avoiding consumption of natural gas.

5.1.4. Steam methane reforming

A preliminary review of project economics for SMR PBMR applications was completed using provisional estimates and conservative financial assumptions for the costs of an intermediate helium heat delivery system, a convective reformer and balance of plant. Results indicate that such an application for an initial plant could be profitable if syngas could be sold at a price equivalent to that produced from a conventional facility with natural gas available in the range of $7 per MMBtu. Relative costs of syngas production over a range of methane prices are presented in Fig. 7 below.

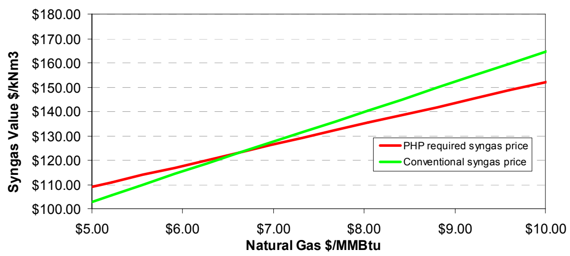

FIG. 7. Relative cost of Syngas from conventional and PBMR-based facilities

As CO_2 credits are implemented, the breakeven cost of a PHP syngas plant would also drop as shown in Fig. 8. Using these assumptions, at a $20/ton CO_2 credit, the breakeven marginal price of gas drops to about $4.5/MMBtu which would provide dramatic savings over natural gas firing and would likely be economic relative to other advanced techniques for SMR. Again, the profit potential in this application confirms the economic benefit of displacing fossil fuel combustion with process heat form the PBMR source.

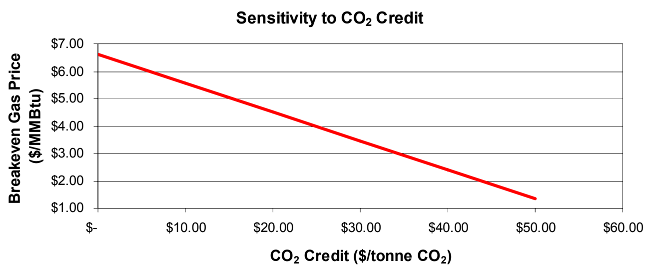

FIG. 8. Sensitivity of PBMR PHP Syngas plant breakeven gas price to CO_2 credits

5.1.5. Hybrid sulfur process (water splitting)

The economics of water splitting are more speculative given the early state of conceptual design and cost estimating for the HyS process. However, the potential value of water splitting is amplified by the high cost and low efficiency of converting coal to hydrogen.

Based on very preliminary cost and performance assumptions, the cost of hydrogen from a PBMR based water splitting plant would not be competitive with SMR at current or projected near term gas prices. However, when integrated with a coal-to-liquids or coal-methane conversion plant design, the co-production of hydrogen and oxygen could potentially double the output of these facilities and eliminate CO_2 emissions. This would potentially generate value from three major areas – capital cost savings, reduced coal and operating costs, and credits for eliminating CO_2 emissions.

5.2. Implementation requirements and market windows

The time to market is constrained by nuclear regulation, technology development, and the economics associated with gas supply, production of transportation fuels and other refining applications.

A key question in how fast the PBMR technology can move into the process heat market is the amount of time between demonstration projects and commitments to proceed with commercial projects. The following projections assume that several commercial PHP projects are "pre-developed" and waiting for release pending initial successful operation of the electric demonstration project. This may be somewhat optimistic, although there are examples of new energy technology, such as combustion turbines, that entered the market very quickly based on the "near-commercial" nature of demonstration projects.

The critical path to a PBMR PHP first process application could include the following steps:

- Completion of South African nuclear regulatory acceptance -- 2009
- Technology certification in the application country (e.g. US., Canada) -- 2012
- Project-specific licensing (Engineering and design in parallel, possible early release of lead time items) -- 2013
- Procurement, fabrication, delivery, installation and startup -- 2016

To support a schedule leading to the completion and operation of a demonstration plant by 2016, any technology development would have to be completed in time to obtain nuclear regulatory approval (if required) and to support ordering commercial equipment by 2013. This appears to be feasible for the steam-only oil sands application, and possibly for steam methane reforming applications, but is predicated on early collaboration with prospective customers in the respective industries. The schedule for water splitting technology development is more speculative and could extend beyond that time frame unless a very aggressive technology development schedule is adopted.

See the paper of Kriel [6] for an overview of potential markets, including oil sands, SMR, and water splitting.

6. Conclusions

The economic assessments of particular market opportunities for process heat applications of the PBMR have confirmed that the high initial capital costs of nuclear process heat applications can be offset by increasing fossil fuel (particularly gas) prices, combined with possible credits from avoided CO_2 byproduct, to produce viable business for nuclear process heat applications. Using the assumptions stated, for steam methane reforming, an initial PBMR PHP can economically replace a natural gas heat source at a current gas price of slightly under $7/MMBtu. For nuclear supplied steam for oil sands SAGD, the breakeven natural gas price is about $6.3/MMBtu. The potential returns identified in these process heat applications both illustrate the economic value to be created in displacing the combustion of natural gas with the PBMR heat source.

Even with conservatively low forecasts for growth in long term gas prices, there is a commercial interest in hedging against their volatility and rapid increase. Also, commitments to major reductions in CO_2 emissions will enhance interest in nuclear energy since it appears to be the only reliable option that can be implemented economically on a large scale. Longer term technology development for nuclear water splitting technology is already supported by several government programs and international research organisations. Opportunities to accelerate commercial applications brought about by early market entry of the PBMR should be considered.

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NUCLEAR SEAWATER DESALINATION AND OTHER APPLICATIONS

SESSION 5 (PARALLEL SESSION)

Chairpersons

P.K. Tewari
India

S. Nisan
France

An overview of global activities in nuclear desalination

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Abstract. The global activities in the field of nuclear desalination have been summarized. The IAEA activities on nuclear desalination in some of the Member States have been presented. It is noted that increasing number of Member States consider nuclear desalination as a viable option to meet the requirement of fresh water. Various activities representing the latest in research and development in desalination technologies, economics, analysis of transport cost for desalinated seawater, and update of software and tools have been carried out. It can be concluded that nuclear desalination will play an important role in the future if some problems associated inherently with nuclear energy are solved. In this paper, the current trends and activities being pursued by some Member States on nuclear desalination have been highlighted as an integral part of the IAEA effort to harness nuclear energy for the benefits of mankind. Activities and final results obtained by the representatives of the participating Member States as part of the IAEA coordinated research project on "Economics Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies" which is finalized recently, have been presented.

1. Introduction

Under the IAEA inter-regional technical co-operation (TC) framework, several international collaboration activities, a number of technical co-operation projects have assessed the feasibility of nuclear desalination projects. There were projects between China and Morocco, the Republic of Korea and Indonesia, France and Tunisia and in Pakistan. Other TC national projects for UAE, Algeria and Jordan to perform techno-economic feasibility studies of nuclear desalination plants are currently being considered. Member States like Argentina, Peoples Republic of China, Egypt, France, India, Republic of Korea, Pakistan, Russian Federation, Syrian Arab Republic and the USA have just completed various activities including:

Evaluation of economic aspects and investigated the competitiveness of nuclear desalination under particular site-specific conditions in case studies.

Identified innovative techniques leading to further cost reduction of nuclear desalination systems.

Refined economic assessment methods and tools.

In particular, they have done research in the following areas:

Collection and analysis of economic and performance data of various existing nuclear desalination installations.

Determination of economic and technical site-specific conditions and conducting national case studies.

Updating and validating the IAEA's desalination cost evaluation software DEEP, through benchmarking, integration of data from operating plants and inclusion of additional desalination/coupling options (e.g. HTRs and other reactors utilizing waste heat for desalination).

Development of a consistent, international approach for economic evaluation of nuclear desalination options, through the analysis of the results of the site-specific case studies.

2. Nuclear desalination activities

The world energy requirements are presently met from oil, coal, gas, hydro, nuclear and renewable energies in that order as shown in Table I.

Table I. Percentage of world energy use

Fuel	Percentage (%)	Present trends
Oil	39	Short-term: Building of additional plants continues
Coal	25	Building of additional plants continues
Gas	22	Short-term – Building of additional plants continues; gas turbine combined cycle plants considered the cheapest of fossil fuelled plants.
Hydro	7	Building of dams continues, where possible
Nuclear	6	More or less stagnant in developed countries, with a hope for renewed interest; high rate of expansion in emerging countries.
Renewable energies	1	Gradual expansion; continued efforts to reduce costs.

Nuclear power is a proven technology, which has provided more than 16% of world electricity supply in over 30 countries. More than ten thousand reactor-years of operating experience have been accumulated over the past 5 decades. There are many reasons which favour a possible revival of the nuclear power production in the years to come. It is thus expected that this revival would also lead to an increased role of nuclear energy in non-electrical energy services, which, at the moment, are almost entirely dominated by fossil energy sources. Among various utilization of nuclear energy for non-electrical products, using it for the production of freshwater from seawater (nuclear desalination) has been drawing broad interest in the IAEA Member States as a result of acute water shortage issues in many arid and semi-arid zones worldwide. With technical co-ordination or support of the IAEA, several demonstration programs of nuclear desalination are in progress in several Member States to confirm its technical and economical viability under country-specific conditions. Over 175 reactor-years of operating experience on nuclear desalination have already been accumulated worldwide. All nuclear reactor types can provide the energy required by the various desalination processes. In this regard, it has been shown that Small and Medium Reactors (SMRs) offer the largest potential as coupling options to nuclear desalination systems in developing countries. The development of innovative reactor concepts and fuel cycles with enhanced safety features as well as their attractive economics are expected to improve the public acceptance and further the prospects of nuclear desalination.

The coupling with nuclear system is not difficult technically but needs some consideration in (a) avoiding cross-contamination by radioactivity, (b) providing backup heat or power sources in case the nuclear system is not in operation (e.g. for refuelling and maintenance), (c) incorporation of certain design features, minimising the impact of the thermal desalination system's coupling to the nuclear reactors. Japan has over 150 reactor-years of nuclear powered desalination experience. Kazakhstan had accumulated 26 reactor-years before shutting down the Aktau fast reactor (BN-350) at the end of its lifetime in 1999. In India, a low temperature (LT) desalination plant using waste heat of nuclear research reactor has been operating since 2004. Table II gives the reactor type, location, desalination process and status.

Table II. Reactor types and desalination processes

Reactor Type	Location	Desalination Process	Status
LMFR	Kazakhstan (Aktau)	MED, MSF	In service till 1999
	Japan (Ohi, Takahama, Ikata, Genkai)	MED, MSF, RO	In service with operating experience of over 150 reactor-years.
PWRs	Rep. of Korea Argentina, etc.	MED RO	Integral SMRs of the PWR type; under design or to be constructed
	Russia	MED, RO	Under consideration (Barge mounted floating unit with the KLT-40)
	USA (Diabolo Canyon)	RO	Operating
BWR	Japan (Kashiwazaki-Kariva)	MSF	Never in service following testing in 1980s, due to alternative freshwater sources; dismantled in 1999.
	India (Kalpakkam)	MSF/RO	Under commissioning
HWR	India (Trombay)	LT-MED	In service since 2004
	Pakistan (KANUPP)	MED	Existing CANDU modified to be coupled to an MED plant (under construction)
NHR-200	China	MED	Dedicated heat only integral PWR; under design
HTRs	France, The Netherlands, South Africa	MED, RO	ANTARES, multipurpose reactor, GT-MHR and PBMR; under development and design

In many Member States, studies for evaluating the techno-economic feasibility of nuclear desalination have been completed:

Argentina has identified a site for its small reactor (CAREM), which could be used for desalination. A related initiative on safety aspects of nuclear desalination addresses practical improvements and implementation and shares advances around the world.

China has implemented and completed the feasibility study of.nuclear desalination project, using NHR-200 type of nuclear reactor, at an identified coastal Chinese site. A test system is being set up at INET (Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing) for validating the thermal-hydraulic parameters of a multi-effect distillation process.

Egypt has completed a feasibility study for a nuclear co-generation plant (electricity and water) at El-Dabaa. Construction of a pre-heat RO test facility at El Dabaa has been completed. The data generated will be shared with interested Member States.

France has recently concluded several international collaborations: one with Libya designed to undertake a techno-economic feasibility study for a specific Libyan site and the adaptation of the Libyan experimental reactor at Tajoura into a nuclear desalination demonstration plant using both MED and RO processes in a hybrid combination. The other collaboration is with

Morocco (The AMANE project) for a techno-economic feasibility study of Agadir and Laayoun sites. Under a bilateral collaboration signed between India and France, it has also been agreed that the two partners will collaborate on the development of advanced calculation models, which will then be validated at Indian nuclear installations (the experimental reactor CIRUS and the Kalpakkam plant, with hybrid MSF-RO systems).

Israel continues to regularly provide technical and economic information on low cost desalination technologies and their application to large-scale desalination plants.

Japan continues with its operation of nuclear desalination facilities co-located inside many nuclear power plants.

The Republic of Korea is proceeding with its SMART (System-integrated Modular Advanced Reactor) concept. The project is designed to produce 40 000 m^3/day of potable water.

Morocco continues the process of establishing an adequate legal and institutional legislative and regulatory nuclear framework while staying abreast of technical developments in general and nuclear desalination.

Tunisia has completed its techno-economic feasibility study, in collaboration with France, for the la Skhira site in the southeast part of the country. The final report, presented in March 2005 was very favourably received by the Tunisian authorities who have already announced their willingness to go for the nuclear desalination option.

USA will include in its Generation IV roadmap initiative a detailed discussion of potential nuclear energy products in recognition of the important role that future nuclear energy systems can play in producing fresh water.

Further R&D activities are also underway in Indonesia and Saudi Arabia. In addition, interest has been expressed by Algeria, Brazil, Islamic Republic of Iran, Iraq, Italy, Jordan, Lebanon, Philippines, Syrian Arab Republic and UAE in the potential for nuclear desalination in their countries or regions.

Several nuclear desalination demonstration projects are being implemented. For example:

India is building a demonstration plant at Kalpakkam using a 6300 m^3/day hybrid desalination system (MSF-RO) connected to an existing PHWR. The RO plant, with a production capacity of 1800 m^3/day, was set up in 2002 and is since operating. The MSF plant (4500 m^3/day) is to be commissioned in 2008. Already the CIRUS research reactor, providing waste-heat to a LT-MED plant, has been operating since 2004. It is also planned to couple the forthcoming AHWR with a desalination plant.

Libyan Arab Jamahiriya is considering, in collaboration with France, to use the Tajoura experimental reactor for nuclear desalination demonstration plant with a hybrid MED-RO system. The MED plant, of about 1000 m^3/day production capacity, will be manufactured locally.

Pakistan is constructing a 4800 m^3/day MED thermal desalination plant coupled to a PHWR at Karachi. It is expected to be commissioned in 2008.

The Republic of Korea is exploring a possibility of using a co-generating integral type reactor SMART combined with a multi-effect distillation (MED) plant producing 40 000 m^3/day of fresh water. The basic design of 330 MWth SMART is completed. In parallel with out-pile tests, a one-fifth scale pilot plant SMART-P is being planned to construct along with a MED unit by 2008.

The Russian Federation continues its R&D activities in the use of small reactors for nuclear desalination and has invited partners to participate in an international nuclear desalination project based on a nuclear floating power unit (FPU) equipped with two KLT-40s reactors. The co-generation plant, foreseen for construction in 2007, will be sited at the shipyard in Severodvinsk, Arkhangelsk region in the western North Sea area where the FPU is being manufactured.

3. Economics of nuclear desalination

Any nuclear reactor, capable of providing electrical and/or thermal energy can be coupled to an appropriate desalination process. The reactors can operate as dedicated (single purpose) systems, producing only desalted water or as co-generation (dual purpose) systems, producing both water and electricity. Single purpose nuclear desalination systems are considered more suitable for remote isolated regions. The fundamental role of the economic evaluation of any engineering project is to enable coherent and just comparisons with alternative options, to prepare the financing details for the implementation of the project, to fix tariffs and finally to furnish a clear choice of options to decision makers. The deployment of nuclear energy in most of the emerging and developing countries (DCs) continues to be rather stagnant (except in China and India) for numerous and very complex reasons. Among these the most important one is the considerable difficulties that such countries encounter in finding adequate financing of the nuclear projects [1]. Two main factors appear to be the root cause of this problem: the relatively high investment cost of nuclear reactors and the associated uncertainties and risks [2] and relatively longer construction lead times, which have varied in the past from 6 to 14 years in some countries. A construction lead-time of about 6 years is considered normal for a first of a kind reactor. Delays beyond this period are in particular related to the additional investment that a given country has to make: construction of roads and adequate transport, development of large enough ports to receive heavy material, development of infrastructures, preparation of the site including facilities for the personnel etc. For a construction period of 8 years and 7% discount rate these additional investments may represent from 30 to 40% of the total investment cost.

New developments in nuclear desalination are remarkable as many Member States have consistently progressed almost simultaneously in the three technical fields: the development of improved or new generation nuclear reactors, the improvements in desalination technologies and the adoption of several cost reduction strategies. These developments have been discussed in detail in the recent IAEA publication on the “Status of Nuclear Desalination in Member States”. An interesting feature of this development is that many Member States, normally not considered as exporting countries, have begun to develop their own nuclear reactors. This is, for example, the case for Argentina, which is developing the CAREM reactor. CAREM is a small sized integral PWR. The construction of the prototype, providing 100 MWth (27 MWe) is to begin in 2007. China is pursuing the development of the dedicated heat only reactor NHR-200 providing relatively low-temperature heat for an MED process, with some electricity production to meet the local electricity needs. India is going along with a consistent evolutionary approach to develop its advanced PHWRs. The republic of Korea continues with its programme to develop the System-integrated Modular Advanced Reactor (SMART), which is a small sized (330 MWth) integral type PWR, containing all major primary components in a single pressurized vessel. A nuclear desalination project designed to produce 40 000 m3/day of potable water at one of the Korean sites is foreseen. Among the other countries, several developments are in progress:

Continuation of the R&D by ANSALDO (ITALY) and WESTINGHOUSE (USA) on the development of the medium sized PWR, the AP-600.

Certification of the GT-MHR by General Atomics (USA) and continuation of further developments.

Construction of the PBMR by PBMR PtY in South Africa.

Development of the new generation HTR, the ANTARES reactor, by FRAMATOME, a joint subsidiary of SIEMENS (Germany) and AREVA (France), designed to respond to a multiplicity of non-electric applications such as hydrogen production, industrial heat applications and desalination.

Russia has acquired considerable experience in designing of cogeneration plants and nuclear desalination complexes based on floating power units (FPU) with advanced marine light water reactors. Analogues of such reactors are successfully operating on Russian nuclear ships and are serviced by a specially established infrastructure. Presently, construction of a nuclear power plant based on FPU with KLT-40S reactors has been started in Severodvinsk, Arkhangelskaya Region, Russia. Development of the reactor design for new icebreaker is continued. One of the long-range tasks of Russian nuclear desalination projects is development of a FPU for nuclear desalination complexes based on an advanced reactor with inherent safety, capable for long-term operation without refueling at the site.

4. Advances in desalination technologies

Desalination technologies have, on the whole, shown continued progress over the past decades [3] with emphasis on cost reduction strategies through technological innovations.

4.1. Thermal processes

Thermal desalination process produces distilled quality water. New developments in the thermal processes can be summarized as follows:

High Gain Output Ratio (GOR)

Choice of high performance materials, development of high heat transfer alloys for the tubes, increasing use of non-metallic evaporator materials.

Improvement in corrosion resistance (e.g. utilization of anti-scaling organic products).

Improvements in availability and thermodynamic efficiencies, due to the incorporation of on-line cleaning procedures.

Modular construction, with improvements in fabrication procedures, reducing construction lead times.

Development of efficient and more precise process control systems and procedures.

4.2. Membrane based technologies

Reverse Osmosis (RO) systems are the rapidly expanding ones in today's desalination markets. Membrane based systems have become the corner stone of the strategies for water recycling and recuperation. Among the notable advances in membrane desalination are:

Increase of salt rejection efficiency (from 98 to 99.8 %).

Increase in permeate flux.

Enhanced chlorine tolerance.

Reduction of the costs of cleaning and pre-treatment requirements.

Development of longer life membranes.

Membrane based pretreatment

Efficient energy recovery devices

5. Cost reduction strategies

Energy cost represents a substantial fraction of the total desalination costs. Although desalination processes have been, and continue to be, considerably improved, there is a strong incentive to further reduce desalination costs. Several approaches are currently under investigation:

5.1. Utilization of waste heat from nuclear reactors

5.1.1. Utilization of waste heat from high temperature, gas cooled reactors

Commonly used desalination processes are the multistage flash (MSF), multi-effect distillation (MED) and the reverse osmosis (RO). In all these cases, part of the useful energy is drawn from nuclear power station to produce the desalted water. If the desalting capacity is high, this energy loss could be very significant.

An alternative, providing virtually free heat to be used with the MED process, is based on the utilization of gas-cooled, high temperature reactors. Thus, for example, in the two such reactors currently being developed (the GT-MHR and the PBMR), circulating helium, which has to be compressed in two successive stages, cools the reactor core. For thermodynamic reasons, these compression stages require pre-cooling of the helium to about 26 °C through the use of the pre-cooler and intercooler helium-water heat exchangers. Considerable thermal power (about 300 MWth) is thus dissipated in the pre-cooler and the intercooler. This thermal power is then evacuated to the heat sink.

Depending upon the specific designs, the temperature ranges of the water in these exchangers could be between 80 and 130°C. This is an ideal range for desalination with the MED plant, which can be coupled between a mixer (of the flows from the pre-cooler and the intercooler) and the switch- cooling unit, evacuating the heat to the heat sink, (sea or river).

5.1.2. Utilization of waste heat from the condensers of PWRs and CANDUs (the ROph process)

The net electrical efficiencies of the power conversion systems in most PWRs and CANDUs are of the order of 30 to 33%. This means that nearly two thirds of the net thermal power, produced in the reactors, is evacuated to the heat sink via the condensers. The relatively hot seawater from condenser outlet can be fed to an innovative variant of the RO process, with preheating now known as the ROph process. In hybrid systems, it is also possible to use the cooling seawater return stream from the thermal desalination component as feed to the RO component.

It is observed that ROph can lead to a desalination cost reduction of about 14 % as compared to the desalination cost of a conventional RO system. This reduction is independent of the power source.

5.1.3. Utilization of waste heat from the Indian PHWRs

5.1.3.1. The research reactor CIRUS

Nuclear research reactors produce significant quantities of waste heat. A scheme was developed at BARC (India) to integrate a desalination unit such that the technology of utilizing reactor waste heat for desalination of sea water by a low temperature evaporation (LTE) process can be demonstrated [4]. This process is schematically shown in Fig. 1. The LTE desalination unit was then coupled to the CIRUS reactor. The nuclear research reactor (CIRUS) has a capacity of 40 MW(th) using metallic natural uranium fuel, heavy water (D_2O) moderator, demineralized light water coolant and seawater as the secondary coolant. An intermediate heat exchanger (IHE) has been incorporated between the nuclear reactor (CIRUS) and the desalination plant to ensure no radioactive contamination and high protection of desalted water.

The integrated system has since then been successfully operated and has clearly demonstrated the technical fesibility of the coupling to nuclear research reactor. The product water from the plant meets the make up water requirement of CIRUS. The data from this plant will be useful for the design of larger size LT-MED seawater desalination plants for the production of demineralized water and process water. This type of plant is envisaged to be coupled to Advanced Heavy Water Reactor (AHWR) utilising low grade/waste heat from AHWR and produce 500 m^3/day distilled quality water from seawater to meet the demineralized water makeup requirement of the reactor.

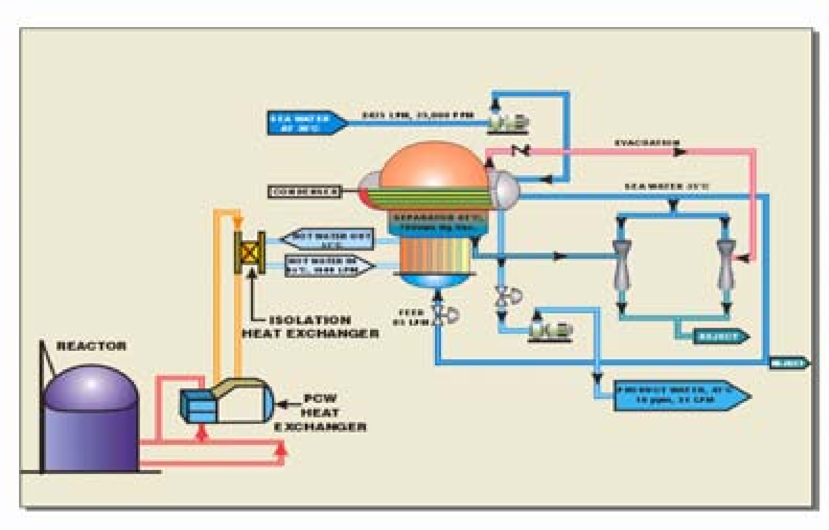

FIG. 1. LTE system coupled to CIRUS reactor

5.1.3.2. Waste heat utilization from the 500 MWe PHWR

In the 500 MWe Indian PHWR, the heavy-water moderator is cooled from 80 to 55°C by process water, which in turn is cooled from 55 to 35 °C by seawater that enters at 32°C and comes out at 42°C. About 100 MWth is thus available as waste heat for seawater desalination. The details have been worked out using 55°C process water temperature to avoid any changes in the moderator system. The coupling scheme is presented in Fig. 2. The nuclear desalination system produces about 1000 m^3/day of desalted pure water, which is about 25 % more than the total makeup demineralized (DM) water requirements of the 500 MWe PHWR. It is more economical to use this water as make up DM water as the thermal energy cost for the LT-MED plant is zero, since it only uses waste heat. Direct production of distilled water eliminates the need for demineralizers and regeneration chemicals. The raw water, otherwise used as feed for the DM plant, can be made available for other purposes e.g. drinking.

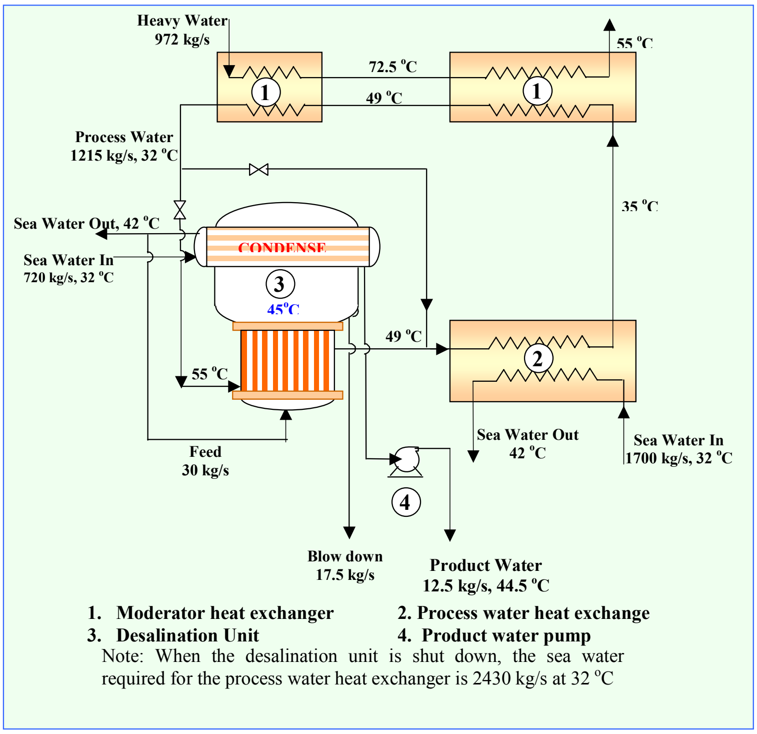

FIG. 2. PHWR500 coupling scheme, utilizing waste heat.

5.2. Utilization of hybrid systems

A relatively new trend in cogeneration of power and water using desalination involves the coupling of a hybrid seawater desalination plant with a steam-producing power plant. A hybrid desalination plant consists of a combination of thermal and membrane desalination unit. Hybrid system has several advantages such as a shared and smaller seawater intake system, utilization of higher feed-water temperature to the RO plant for improved performance, possibility to blend RO and thermal plant product water to obtain a range of product water grades (distilled and drinking quality). It has the ability to use seasonal surplus of idle power and diversify steam/power allocations and potential to decrease fuel costs by using the less energy consuming RO plant. Other advantages of a hybrid desalination system are:

The ability to blend and dilute discharged concentrate with power plant cooling water.
Combined seawater pre-treatment and product post-treatment systems.

Hybrid desalination systems appear very promising for seawater desalination. Hybrid system leads to cost savings due to smaller seawater and reject disposal system, the advantages of pre-heating the feed to the RO plant, and blending of the product streams of RO and thermal desalination plants. Other cost savings result from reduction in water post-treatment needs and overall increase in plant reliability. The reduced need in pumping water directly from the sea to the RO plant due to partial feed supply from the thermal desalination plant can reduce overall cost of the supply and discharge system by about 25% for a 2:1 ratio RO to thermal desalination product water capacity. The intake and discharge systems amount to about 7% for both thermal and RO plants' total direct capital costs [5]. Pre-heating the feed to the RO by blending fresh seawater with warm cooling seawater discharge from the thermal desalination plant increases the overall flux through the membranes on one hand (by about 2-3% per $1^{o}C$), and an increase in product water (permeate) salinity (by about 1.25% per $1^{o}C$). Thus, careful attention must be given to the ratio of feed seawater blending to achieve desired product quality and not to exceed the membrane manufacturer's set limit of $45^{o}C$ for RO membrane performance. This temperature limit ($45^{o}C$) is especially significant during summer months, when inlet seawater temperature is expected to increase relative to the average year-round seawater temperature.

The cost savings due to a reduction in membrane surface area requirements (higher flux) and related RO plant infrastructure amount to about 10% of initial capital cost. The reduction in membrane surface area can reduce the number of membranes required by over 10% and, thus, reduce overall membrane replacement costs by a similar amount. By blending RO plant product water with product water of thermal desalination plant, membrane life can be increased. Membrane replacement can be delayed by up to 7 years in some cases by allowing product water from the RO plant to have higher salinity due to the possibility of blending this poorer quality water with the high purity product water (<10 ppm TDS) of thermal desalination plant. Thus, the TDS concentration of product water from the RO plant can readily be allowed to exceed the acceptable 500 ppm limit. Increase in membrane life from 5 years (the expected lifetime) to 10 years can decrease membrane replacement significantly.

6. Conclusion

It may be concluded that nuclear desalination systems are not only technically feasible but economically attractive options in varying site conditions and with a variety of nuclear reactor concepts. Several approaches have been proposed and studied in participating countries to reduce the cost of nuclear desalination. The first of these is the use of waste heat from nuclear reactors for desalination. Thus for example, the waste heat rejected by the PWRs to the heat sink through their condensers can be profitably used to preheat the feed-water for RO systems (the ROph process) resulting in from 7 to 15% cost reductions as compared to traditional RO systems. Similarly, the waste heat from the pre-cooler and intercooler exchangers of the new generation HTRs, such as the GT-MHR and the PBMR, can lead to significant cost reductions in MED systems coupled to such reactors. Utilization of nuclear waste heat from nuclear research reactor (CIRUS) has been successfully demonstrated for seawater desalination. Another approach to cost reduction would be the use of hybrid thermal/RO systems leading to a considerably enhanced flexibility of the combined system to meet the varying water demands and in which the overall cost of the system is significantly lower. Yet another approach to increase the overall efficiency of the desalination systems would be to extract strategic and valuable materials from the concentrated brine rejected by the desalination plants. This would simultaneously render nuclear desalination systems relatively more environment friendly since no discharges would be made directly to the sea. Through numerous discussions during the Coordinated Research Project (CRP) meetings and the studies carried out by the participating Member States, the software package DEEP (version 3) has been considerably improved. The results of the CRP demonstrate that the methodology used in the DEEP software may become an international and consistent approach for desalination cost evaluation of both fossil and nuclear energy based systems. However, more work is required to benchmark and validate DEEP results. Nuclear desalination costs are strongly influenced by such parameters as the interest and discount rates, the total plant availability, the power costs, the specific water plant base costs etc. In general, it can be stated that RO costs would be in the range of 0.5 to 0.9 $\$/m^3$. Desalination costs from thermal systems such as the MED would be slightly higher being in the range of 0.6 to 0.96 $\$/m^3$. It should be recalled that the product water salinity by thermal desalination plants is much lower (about 30 ppm) as compared to 300 to 500 ppm from RO plants. The real choice of one over the other would thus be a complex problem, depending upon the specific industrial, agricultural and potable water needs of the countries.

The water transport costs are an essential part of the global picture. Judging from the results of two reported studies it can be stated that they would be in the range of 0.1 to 0.2 $cents/m^3/km$. These costs should be added to the above production costs to obtain the real cost of desalted water.

The foremost challenge facing nuclear desalination is that the countries suffering from scarcity of water are, generally speaking, not the holders of nuclear technology and of the infrastructure for product water distribution. The utilization of nuclear energy in those countries will require infrastructure building and other institutional arrangements for financing, liability, safeguards and security. It will also require preparation for the fuel cycle including upstream and downstream. The concept of multi-national or international fuel cycle centres, as is proposed by the IAEA, could be used to assure a supply of nuclear material to legitimate would-be users with the control of sensitive parts of the nuclear fuel cycle.

Acknowledgement

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The contribution of the AAEA in desalination projects in the Arab countries

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Abstract. In the late nineties, because of the wide interest in the Arab world, as well as the rest of the world, about the dual use of nuclear power in seawater desalination and electricity generation, the Arab Atomic Energy Agency (AAEA) has established a permanent project in the field of nuclear desalination.. The objective was to define and develop the preliminary steps and methods necessary to help in establishing nuclear desalination plants in Arab region. Nine Arab states participated in this project; Egypt, Libya, Tunisia, Lebanon, Jordan, Syria, Saudi Arabia, Morocco and Iraq. A principal committee and many technical groups have been formed to address the following issues.

- Selecting a reference site, which will be suitable for construction of the plant.
- Identification of the reactor type, size and characteristics.
- Identification of the desalination process, which goes along with the model plant.
- Defining the infrastructure requirements for the reference site.
- Feasibility study.
- Safety and licensing

The specific functions and progress of the activities of these groups are presented in this paper. Brief status of nuclear desalination in some Arab countries namely Egypt, Libya, Morocco, Tunisia, Algeria and Gulf States have been also presented.

1. Background

The scarcity of water resources and the increase in needs of fresh water in Arab countries, especially in the regions of Arabian Gulf and North Africa, put a big pressure on the decision makers to find proper ways and solutions for this strategic problem. One of the imminent solutions to overcome this problem is to install desalination plants using fossil fuel.

Therefore, many desalination plants have been installed and the number of these plants and their capacity is growing, mainly in the Arabian Gulf states, due to the population increase and the economical growth. Some Arab countries in North Africa have expressed their interest in using nuclear power for seawater desalination and electricity generation.

In the late nineties, and because of the wide interest in the Arab world, as well as the rest of the world, about the dual use of nuclear power in seawater desalination and electricity generation, the Arab Atomic Energy Agency (AAEA) has established a permanent project in parallel with IAEA coordinated research project in the field of nuclear desalination. The main aim of this project is to put forward the basic studies of a model nuclear desalination plant; its suitable site, desalination process, reactor type and characteristics that go along with the needs and capabilities of the Arab countries that showed interest in using this technology.

Hitherto, no water desalination project has been implemented in the Arab countries using nuclear power, but the preliminary study has been made and it is now available for decision makers in the Arab states who expressed their interest about the subject. The AAEA, in general, contribute effectively in developing the human resources capable of understanding the different aspects of nuclear technology and its application in the Arab region.

2. Overview

The rapid increase in population and an increase in living standards in the Arab countries led to a greater demand for fresh water and electricity. Accordingly, the Arab world has a leading role in the desalination industry, contributing about 60% of total world production. Studies indicate that population in the Arab world will double by the year 2030. At that time, domestic and industrial water demand will be 360 million m³ per day; meanwhile, electrical power consumption will be 4.5 trillion kWh per day. Most desalination today uses fossil fuels, which are depleting, and also contribute, to increased levels of greenhouse gases. These facts make the nuclear energy option very real and promising for both seawater desalination and electricity generation. Total world capacity of desalinated potable water is approaching 37 million m^3/day, in some 17,500 plants. Half of these are in the Arab region. The largest produces 454,000 m^3/day.

The major technology in use is the multi-stage flash (MSF) distillation process using steam, but reverse osmosis (RO) driven by electric pumps is increasingly significant. With brackish water, RO is much more cost-effective, though MSF gives purer water than RO. A minority of plants uses multi-effect distillation (MED) or vapour compression (VC). MSF-RO hybrid plants exploit the best features of each technology for different quality products.

Desalination processes are highly power intensive. Thus, different types of energies are used to bridge the gap between these processes and the general increased demand in production. Reverse osmosis needs about 6 kWh of electricity per cubic meter of water (depending on its salt content), while MSF and MED require heat at 70-130°C and use 25-100 kWh/m^3. A variety of low-temperature heat sources may be used, including solar energy. The choice of process generally depends on the relative economic values of fresh water and particular fuels. Small and medium sized nuclear reactors (SMR) are suitable for desalination, often with cogeneration of electricity using low-pressure steam from the turbine and hot seawater feed from the final cooling system. The main opportunities for nuclear plants have been identified as the 80,000-100,000 m^3/day and 200,000-500,000 m^3/day ranges.

The feasibility of integrated nuclear desalination plants has been proven with over 175 reactor-years of experience, chiefly in Kazakhstan, India and Japan.

The BN-350 fast reactor at Aktau, in Kazakhstan, successfully produced up to 135 MWe of electricity and 80,000 m^3/day of potable water over some 27 years, about 60% of its power being used for heat and desalination. The plant established the feasibility and reliability of such cogeneration plants.

In Japan, some ten desalination facilities linked to pressurized water reactors operating for electricity production have yielded 1000-3000 m^3/day each of potable water, and over 150 reactor-years of experience have accrued. MSF was initially employed, but MED and RO have been found more efficient there. The water is used for the reactors cooling systems.

India has been engaged in desalination research since the 1970s and in 2002 set up a demonstration plant coupled to twin 170 MWe nuclear power reactors (PHWR) at the Madras Atomic Power Station, Kalpakkam, in southeast India. This Nuclear Desalination Demonstration Project is a hybrid reverse osmosis / multi-stage flash plant, the RO with 1800 m^3/day capacity and the higher-quality MSF 4500 m^3/day. Much relevant experience comes from nuclear plants in Russia, Eastern Europe and Canada where district heating is a by-product.

Large-scale deployment of nuclear desalination on a commercial basis will depend primarily on economic factors. The International Atomic Energy Agency (IAEA) is fostering research and collaboration on the issue, and more than 20 countries are involved.

In 1998, the IAEA initiated a Coordinated Research Project (CRP) on Optimization of the Coupling of Nuclear Reactors and Desalination Systems with participation of institutes from nine Member States three of which are Arab states; Egypt, Morocco and Tunisia. The CRP was initiated as a step forward for facilitating an early deployment in developing countries, where nuclear desalination is being considered as an option to cope with fresh water deficit as well as energy in the coming future.

The CRP has enabled the IAEA and participating institutes to accumulate relevant information on the latest research and development in the field of nuclear desalination and share it with interested Member States. The CRP has produced optimum coupling configurations of nuclear and desalination systems, evaluated their performance and identified technical features, which may require further assessment for detailed specifications of large scale nuclear desalination plants.

In the mean time AAEA launched a long term project with conjunction of IAEA CRP of nuclear desalination and with participation of 9 Arab countries.

3. The AAEA project on nuclear desalination

In late nineties the AAEA established a coordinated project on nuclear desalination. Nine Arab states participated in this project; Egypt, Libya, Tunisia, Lebanon, Jordan, Syria, Saudi Arabia, Morocco and Iraq. The first meeting of the participants, the IAEA representative and three international experts were convened in Cairo, Egypt between 21 and 25 March 1999. The objective was to define and develop the preliminary steps and methods necessary to help in establishing a nuclear desalination plants in Arab region. However a principal committee and many technical groups have been formed to address the following issues:

- Selecting a reference site, which will be suitable for construction of the plant.
- Identification of the reactor type, size and characteristics.
- Identification of the desalination process, which goes along with the model plant.
- Defining the infrastructure requirements for the reference site.
- Feasibility study.
- Safety and licensing

In order to carry out the above tasks, the following technical groups with specific functions have been initiated:

Siting studies group

The aim of this technical group is to study the parameters of different available qualified or studied sites and decide to adopt one or two model sites with specific characteristics to be used afterward in choosing the appropriate reactor. The selection criteria of the suitable site in Arab region for a nuclear desalination plant include geological, meteorological, cooling water supply discharge, transport infrastructure, population, electric grid, water network capacity, environmental impact and airport movement. The technical group has determined the specification and characteristics of a virtual site and suggested its name, ARAFRA, and it is a virtual city located somewhere in coastal area in north Africa with population of 600000 and the daily average consumption of water for each person is 0.33 m^3/day. Some qualified sites are already studied and determined such as: Dabaa-Egypt, TanTan-Morocco, Rabigh-Saudi Arabia, Oran-Algeria, Ganush-Tunisia and Sirt-Libya.

Reactor technology group

This technical group task is to investigate and select the type and characteristics of the reactor to be considered for this purpose. The reactor must be selected from proven or evolutionary reactors available and the technical group relied on the IAEA Options Identification Program (OIP) and other documents i.e. Site requirements Document (SRD) and User Requirements Document (URD). Furthermore, other advanced evolutionary reactor design or generation proposed from countries like Canada, China, Argentina, Korea, Japan or Russia have to be considered in order to select a suitable design for the model site. The reactors which have been studied by the group are: PWRs; AP-600 and QP-300, HWRs; CANDU-6 and PWR-220, GCRs; PBMR, and other designs; SIR, ISIS and ATS-150. The group outlined in details the specifications of these reactor types; their safety, performance, design, fuel cycle, waste management and national requirements. A special emphasis was given to the electricity demands considering both the used desalination system and electrical energy that the site area need.

Safety and licensing group

This group task is to review the status of the regulatory structure available in the Arab States and proceed with the development of proposals for establishing a model approach for safety, regulatory and licensing rules, regulations and procedure to be applied for nuclear desalination. This should be consistent with international standards and practices as far as it is possible.

Desalination technology and coupling schemes group

All available desalination technologies including those mentioned in IAEA- North African Study Report have been considered and studied by this group in order to select a suitable desalination process and technology that can be adopted for the model plant in the selected site. All coupling methodology has been considered as to determine the appropriate coupling scheme. The group suggested that the plant should produce 300-450 MWe electricity and 100,000-150,000 m^3/day water. It suggested also that the MSF-RO process is most convenient because of low energy consumption and low cost. The high capacity MSF process may be considered depending on the circumstances or the two processes can be used together.

Feasibility study group

The technical group assessed the economics of the model plant considering the requirements imposed by the chosen site characteristics and available capabilities within the region. IAEA documents are always used as a reference guide. The study included: the capital cost, operation and maintenance costs, energy supply cost and costs of storage, transportation and distribution of water.

The outcome of the studies carried out by the different technical groups has been submitted to the principal committee and thus to the directorate of AAEA. And the principal committee also has reviewed the IAEA desalination activities carried out for North African countries under RAF TC project. Many meetings and activities were held since the beginning of the project namely:

Periodical meeting of different technical groups
Workshop on computer program DEEP
Workshop on Integrated Reactor Evaluation program
Continuing the cooperation with IAEA in organizing SMR and URD workshops

In fact, the AAEA project for nuclear desalination is inactive for the past 3 years, but after the positive global opinion drift towards the nuclear energy, many countries, among them Arab countries, reconsidered using nuclear energy especially in desalination and electricity production. Therefore the AAEA project has gained momentum and hence the project is reactivated.

Below we outline the status of nuclear desalination in some Arab countries:

Egypt has carried out a feasibility study of a cogeneration plant for electricity and potable water at El-Dabaa, on the Mediterranean coast.

Libya confirmed its interest in nuclear desalination and availability of a qualified site for international utilization for nuclear desalination demonstration.

Morocco has completed a pre-project study with China, at Tan-Tan on the Atlantic coast, using a 10 MWt NHR-10 Chinese reactor which produces 8000 m^3/day of potable water by distillation (MED), after completion of the pre-project study with China in October 1998.

Tunisia is looking at the feasibility of a cogeneration (electricity-desalination) plant in the southeast of the country in order to fill the water deficit in the southern part of the country, treating slightly saline groundwater.

Algeria is considering a 150,000 m^3/day MSF desalination plant for its second-largest town, Oran (though nuclear power is not a prime contender for this).

Yemen is in process of studying the feasibility of installing a nuclear plant of dual use.

The Gulf Arab sates are moving ahead with plans to explore development of nuclear energy plants exclusively for desalination and electricity generation. The states are planning to seek help from IAEA.

Most these countries have requested technical assistance from IAEA and AAEA under their technical cooperation projects on nuclear power and desalination. Here safety and reliability are key requirements.

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Nuclear desalination activities and prospects in the Arab countries

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Abstract. From the early days of nuclear energy, it was realized that it could be utilized to overcome two of the challenges to the development of humankind, namely sustainable supply of electricity and water. Several Arab countries were interested in the concepts of Nuclear Desalination and Agro-industrial Complexes in the 1960s, and participated actively in national and international activities on Nuclear Desalination since the interest was renewed in the beginning of the 1990s. This was motivated by acute shortage of freshwater and/or lack of primary energy resources.

This paper presents a review of the overall Arab nuclear desalination activities, including, feasibility studies and R&D activities. The results of recent studies are presented regarding: quantification of seawater desalination market in the Arab countries and preliminary economic assessment of potable water production by various combinations of energy sources and desalination processes.

Key words: Arab, Feasibility Studies, Activities; Demonstration; Desalination; Development; History; Issues; Nuclear; Research; Seawater

1. Introduction

From the early days of nuclear energy, it was realized that it could be utilized to overcome two of the challenges to the development of mankind, namely sustainable supply of electricity and water. As early as in the 1960s, the IAEA surveyed the feasibility of using nuclear reactors for seawater desalination, and has since published a number of reports on the technical and economic aspects of the subject [1-5] and sponsored an international conference on nuclear desalination in 1968 [6]. These studies have drawn attention to the economical advantages of co-generation (combining water and power production into a single system).

An extension of the nuclear desalination concept was the integration of large food-producing centers and selected industries with nuclear power and desalting complex in nonproductive arid regions of the world to solve their socioeconomic problems. In 1967, a generalized study of the technological and economical feasibility of agro-industrial complexes was made at Oak Ridge National Laboratory (ORNL). The investigation indicated that seawater desalting on a large scale is expected to be accomplished most economically in dual-purpose plants, which also generate power on a large scale [7].

Several Arab countries were interested in the concepts of Nuclear Desalination and Agro-industrial Complexes, [8-13]. The Middle East Study [8-10] was initiated in June 1968 to explore the technical and economic feasibility of using nuclear-powered dual-purpose plants to provide large amounts of fresh water and electricity in agro-industrial complexes (energy centers) for development of arid regions of the Middle East. The region studied included Egypt, Israel, Jordan, Lebanon, and Syria.

Egypt was interested in agro-industrial complexes as early as 1964, when it issued specifications for a dual purpose NPP to be built about 30 km west of Alexandria along the northern coast at Sidi Kreir. The plant consisted of a 150 MW nuclear power station and a 20,000 m^3/d desalting unit to supply desalted water to an agricultural pilot area of about

10,000 acres. The primary objectives of this project were firstly to ascertain the economic feasibility of the method, and secondly to establish suitable farming techniques and cropping patterns, and ultimately to determine the conditions for the use of desalination as an economic and reliable means of water supply for future agricultural development in this area [11]. Although the nuclear power project has not been realized due to difficulties in securing financing after the 1967 War with Israel, studies of the pilot agricultural scheme were continued.

In accordance with the increasing demand for fresh water and power generation, a contract was signed in the late 1970's between Libya and ATOMENERGOEXPORT (former USSR) to design and construct a dual-purpose nuclear power plant for electric generation and seawater desalination. A Soviet design WWER-440, with thermal power of 1,375 MW, was proposed. The contract envisaged the construction of two units of 440 MW(e) with total power production of about 840 MW(e) and desalinated seawater production of about 80,000 m^3/d. The plant was supposed to be constructed in the Gulf of Sirt, but realization was never materialized.

However, the main interest during the 1960s and 1970s was directed towards the use of nuclear energy for electricity generation, district heating, and industrial process heat. Therefore, as of 1977, IAEA nuclear desalination activities came to a halt until 1989 when interest in nuclear desalination was renewed, as indicated by the adoption of a number of resolutions on the subject in the IAEA General Conferences. Again, several Arab countries, particularly the North African Countries showed interest in Nuclear Desalination and participated actively in national and international activities on the subject.

This paper reviews the overall Arab nuclear desalination activities since 1990, including, feasibility studies and R&D activities, and the prospects for utilizing Nuclear Power for electricity generation and seawater desalination in selected Arab Countries[1].

2. General aspects of the arab countries

The Arab countries extend from the Atlantic Ocean in the West to the Persian Gulf in the East with a total area of about 14 million square kilometers, of which only 0.7 million square kilometers are cultivated. Most of the Arab Countries lie within the temperate zone, and the bio-climate varies from arid to extremely arid, as shown in Fig. 1. Rainfall in most parts of the Arab Countries is marginal and insufficient to cover current demand of fresh water that is aggravated by high population growth rate and limited water resources.

[1] The Arab Countries are: Algeria, Bahrain, Comoros, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, UAE, Yemen.

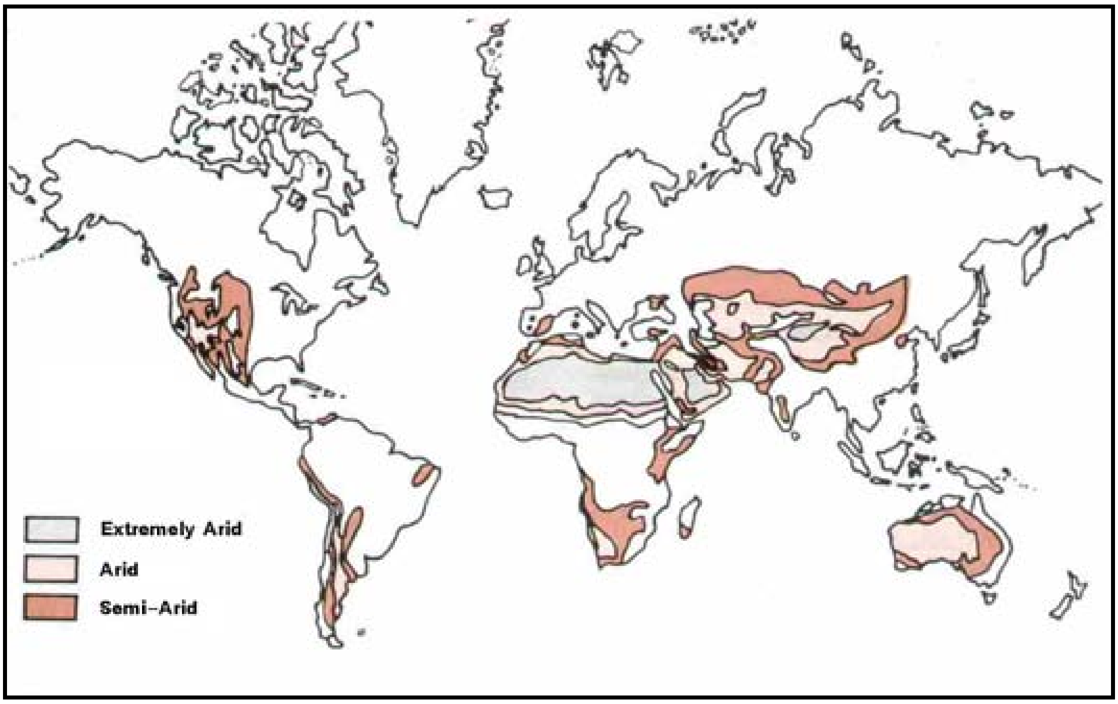

FIG. 1. World Arid Regions

2.1. Population

The population of the Arab countries increased from 168 millions in 1980 to 333 millions in 2005 with an average annual growth rate of 2.8%, as shown in Table 1. Individual annual growth rates varied during the same period from 0.9% in Lebanon to 5.4% in Qatar. It seems certain that population of the Arab countries will continue to increase at fairly high growth rate, despite apparent success of some countries to reduce the population growth rate. Assuming population growth rates that are 80% of the current growth rates up to the year 2030, the total population of the Arab countries, not including Palestine, could be as high as 500 millions, as indicated in Table II i.e. about 170 millions more than the 2005 population. Egypt will remain the most populous Arab country in 2030 with a population of 115 millions followed by Sudan, Algeria and Morocco with populations of 66, 47 and 46 millions, respectively. This, together with the increasing urbanization, industrialization, developmental needs, and the rising living standards, will increase the demand on both electricity and water.

2.2. Fresh water resources

Countries can be divided into three categories based on per capita annual share of fresh water resources or specific water consumption (SWC), namely:

Water Abundant Countries where SWC > 1667 m^3/capita/year;
Water Stressed Countries where 1000 < SWC < 1667 m^3/capita/year, and
Water Scarce Countries where SWC < 1000 m^3/capita/year

It is clear from Table III that most of the Arab Countries are water-scarce countries. Only Iraq, Sudan and Syria, where SWC is larger than 1000 m^3/capita/year, are classified as water stressed countries. However, due to increase in population, these countries will become water-scarce countries before 2030.

Table I. Development of Arab population, (1980-2005)

Country	1980	1985	1990	1995	2000	2005	Average annual growth rate, %
Algeria	18.806	22.008	25.093	28.083	30.409	32.550	2.22
Bahrain	0.348	0.424	0.500	0.573	0.634	0.689	2.77
Comoros	0.33	0.38	0.43	0.50	0.58	0.671	2.84
Djibouti	0.279	0.297	0.366	0.409	0.431	0.477	2.17
Egypt	42.634	50.052	56.694	63.322	70.492	77.542	2.42
Iraq	13.233	15.694	18.135	19.557	22.676	26.085	2.75
Jordan	2.163	2.628	3.262	4.202	4.999	5.766	4.00
Kuwait	1.370	1.733	2.142	1.621	1.974	2.334	2.16
Lebanon	3.086	3.088	3.147	3.335	3.578	3.827	0.87
Libya	3.065	3.675	4.140	4.654	5.115	5.767	2.56
Mauritania	1.550	1.747	1.984	2.342	2.668	3.087	2.80
Morocco	19.487	21.857	24.686	27.447	30.122	32.737	2.10
Oman	1.175	1.482	1.773	2.131	2.533	3.002	3.82
Palestine	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Qatar	0.231	0.345	0.481	0.613	0.744	0.864	5.43
Saudi Arabia	9.999	13.330	16.061	19.967	23.153	26.451	3.97
Somalia	5.791	6.446	6.675	6.291	7.253	8.594	1.59
Sudan	19.064	23.454	26.627	30.567	35.080	40.210	3.03
Syria	8.774	10.481	12.436	14.310	16.306	18.459	3.02
Tunisia	6.443	7.362	8.207	8.973	9.564	10.077	1.81
UAE	1.000	1.570	1.951	2.176	2.369	2.564	3.84
Yemen	9.133	10.540	12.416	14.859	17.479	20.723	3.33
Total	**167.963**	**198.588**	**227.207**	**255.928**	**288.158**	**332.732**	**2.77**

Source: United States Energy Information Administration, *International Energy Annual 2004.* Data for 2005 was estimated by the Author based on 2005 growth rates.

The largest sources of surface water in the Arab World are rivers Nile, Tigris and Euphrates that provide significant resources in Egypt, Sudan, Syria and Iraq. These rivers are shared by several countries. Tension over water rights could escalate to outright conflicts, driven by population growth and rising demand for water. Surface waters also include smaller rivers in Algeria, Morocco, Tunisia, Syria and Lebanon, as well as, rain water intercepted by dams or cisterns. These however, are limited and/or polluted due to uncontrolled urban growth. Groundwater resources play an important role in providing freshwater in the Arab Countries. However, most of these resources are fossil and available at great depth. In several Arab Countries, large- scale extractions in coastal areas have led to a sharp decline of in water levels followed by seawater intrusion [14-15]. Over-extraction and pollution have reduced the availability of potable water drastically.

To augment shortages in fresh water resources, several Arab countries utilized desalination technologies to various degrees. Desalination plants were introduced into the Arab world as early as 1907 when a land marine type desalination plant was built in Saudi Arabia [16]. Various sizes and technologies have since been employed by the Arab countries to satisfy their increasing demand for fresh water for both municipal and industrial purposes. The IDA world-wide inventory of desalting plants [17], indicated that the total Arab Countries capacity of plants capable of producing more than 100 m^3/day of freshwater per unit (delivered or under construction as of 31 December 1999) was about 16 million m^3/day as indicated in Table IV.

Table II. Projections of Arab population, (1980-2005)

Country	2005	2010	2015	2020	2025	2030	Growth rate, %
Algeria	32.550	35.544	38.812	42.381	46.278	46.793	1.46
Bahrain	0.689	0.769	0.858	0.957	1.068	1.083	1.83
Comoros	0.671	0.751	0.840	0.940	1.052	1.067	1.87
Djibouti	0.477	0.520	0.566	0.617	0.672	0.680	1.43
Egypt	77.542	85.350	93.943	103.402	113.813	115.197	1.60
Iraq	26.085	29.086	32.432	36.162	40.322	40.880	1.81
Jordan	5.766	6.750	7.902	9.249	10.827	11.045	2.63
Kuwait	2.334	2.543	2.770	3.017	3.286	3.322	1.42
Lebanon	3.827	3.962	4.101	4.245	4.393	4.413	0.57
Libya	5.767	6.383	7.064	7.817	8.651	8.763	1.69
Mauritania	3.087	3.448	3.851	4.302	4.804	4.872	1.84
Morocco	32.737	35.577	38.662	42.016	45.659	46.140	1.38
Oman	3.002	3.491	4.059	4.719	5.486	5.592	2.52
Palestine	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Qatar	0.864	1.069	1.322	1.635	2.022	2.077	3.57
Saudi Arabia	26.451	30.925	36.155	42.269	49.418	50.406	2.61
Somalia	8.594	9.155	9.753	10.390	11.068	11.157	1.05
Sudan	40.210	45.326	51.093	57.594	64.922	65.911	2.00
Syria	18.459	20.799	23.436	26.407	29.754	30.206	1.99
Tunisia	10.077	10.826	11.631	12.495	13.424	13.546	1.19
UAE	2.564	2.982	3.468	4.034	4.693	4.783	2.53
Yemen	20.723	23.637	26.959	30.749	35.072	35.660	2.19
Total	**322.480**	**358.890**	**399.676**	**445.397**	**496.687**	**503.589**	**1.80**

Table III. Freshwater withdrawal, by country and sector (2006 update)

Country	Total freshwater withdrawal	Per capita withdrawal	Domestic use	Indust. use	Agri. use	Domestic use	Indust. use	Agri. use
	(km^3/yr)	(m^3/p/yr)	(%)	(%)	(%)	m^3/p/yr	m^3/p/yr	m^3/p/yr
Algeria	6.07	185	22	13	65	41	24	120
Bahrain	0.30	411	40	3	57	163	12	233
Comoros	0.01	13	48	5	47	6	1	6
Djibouti	0.02	25	84	0	16	21	0	4
Egypt	68.30	923	8	6	86	70	55	793
Iraq	42.70	1,482	3	5	92	47	68	1367
Jordan	1.01	177	21	4	75	37	8	133
Kuwait	0.44	164	45	2	52	73	3	86
Lebanon	1.38	385	33	1	67	126	2	257
Libya	4.27	730	14	3	83	102	22	606
Mauritania	1.70	554	9	3	88	49	16	489
Morocco	12.60	400	10	3	87	40	12	348
Oman	1.36	529	7	2	90	38	11	476
Qatar	0.29	358	24	3	72	86	10	257
Saudi Arabia	17.32	705	10	1	89	69	8	628
Somalia	3.29	400	0	0	100	2	0	398

Sudan	37.32	1,030	3	1	97	27	7	996
Syria	19.95	1,048	3	2	95	34	19	994
Tunisia	2.64	261	14	4	82	37	10	214
UAE	2.30	511	23	9	68	118	44	349
Yemen	6.63	316	4	1	95	13	2	301

Source: Pacific Institute web site: www.Worldwater.org

Table IV. Desalination inventory in the Arab countries

Country	Process: Capacity m^3/day					Total	No. of units
	MSF	***MED***	***VC***	***RO***	***ED***		
Algeria	125222	955	33525	83964	19976	263624	174
Bahrain	581420	1135	47264	140526	13914	784259	156
Comoros	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Djibouti	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Egypt	33652	2577	12350	139133	33385	221624	230
Iraq	10824	1175	0	232051	88563	332613	207
Jordan	0	0	1100	7726	1537	10363	N/A
Kuwait	1468750	11672	150	166472	5093	1652137	178
Lebanon	520	0	14670	3200	0	18390	N/A
Libya	462575	6456	71489	138430	69264	748214	431
Mauritania	3000	0	1654	0	0	4654	N/A
Morocco	7002	0	8064	0	1404	16470	N/A
Oman	329927	4200	14019	28837	896	377879	102
Qatar	782901	3642	21334	13811	0	821688	94
Saudi Arabia	3486985	17870	75512	1751191	97776	5429334	2074
Somalia	0	0	120	288	0	408	N/A
Sudan	226	750	900	0	0	1876	N/A
Syria	0	0	0	6983	1983	8966	N/A
Tunisia	336	240	4820	58615	0	64011	64
UAE	4468769	9346	474505	174553	5102	5132275	382
Yemen	2400	61506	250	7411	3330	74897	66
TOTAL	**11764509**	**121524**	**781726**	**2953191**	**342223**	**15963155**	**-**

Source: IDA Worldwide Desalting Plants Inventory, CD-PAM 2000, Prepared and Published by Wangnick Consulting, 2000. [Reference 17].

2.3. Primary energy resources

The availability of energy is a prerequisite of any socio-economic development in all countries, developing and developed alike. One of the most important conditions for sustainable development is the proper management and development of primary energy resources. The only significant primary energy resources in the Arab World are crude oil, natural gas. Limited hydropower exists in some Arabic countries such as: Morocco, Egypt, Syria and Iraq, but it is nearly fully utilized. There is a potential for solar and wind energies but the technology for large-scale electricity production is not yet economic.

Table V shows the development of the Arab proved crude oil reserves, as well as, the production in 2005. Comparison between reserves and consumption in 2005 reveals that reveals that oil will be depleted completely in most of the Arab countries within the next two decades unless new discoveries are made. The oil exporting Arab countries: Iraq, Kuwait, Libya, Qatar, Saudi Arabia and UAE have large reserves that can keep production at the current level for a minimum of 40 years (Qatar) and a maximum of 155 years (Iraq). As oil is depleted worldwide, pressure will increase on these countries to increase their crude oil production, and hence, their reserves will be depleted faster.

The situation regarding natural gas is better as shown in Table VI. The largest reserves exist in Qatar (26 trillion cubic meters) followed by Saudi Arabia (7 trillion cubic meters).

Table V. Arab proved crude oil reserves, January 1, 1980 - January 1, 2005 estimates (million metric tons)

Region/Country	**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**Production in 2005**	**Life, years**
Algeria	1064	1134	1132	1132	1158	1485	90.4	16
Bahrain	33	23	15	29	20	17	2.4	7
Comoros	0	0	0	0	0	0	0.0	0
Djibouti	0	0	0	0	0	0	0.0	0
Egypt	427	441	620	449	406	510	35.6	14
Iraq	4185	5993	13459	13459	15177	15512	99.8	155
Jordan	0	0	1	0	0	0	0.0	-
Kuwait	9459	12797	13397	13310	13296	13985	126.0	108
Lebanon	0	0	0	0	0	0	0.0	0
Libya	3127	2808	3008	3008	3841	4551	76.3	62
Mauritania	0	0	0	0	0	0	0.0	0
Morocco	0	0	0	0	0	0	0.2	-
Oman	327	477	580	659	721	751	37.7	20
Qatar	498	447	600	493	486	1996	49.5	40
Saudi Arabia	23055	23626	35171	35669	36173	35378	517.2	68
Somalia	0	0	0	0	0	0	0.0	0
Sudan	0	0	0	40	35	76	16.8	5
Syria	291	212	237	343	343	343	22.8	15
Tunisia	293	197	228	54	40	40	3.9	10
UAE	3932	4344	12915	12915	12948	12889	132.6	97
Yemen	N/A	N/A	524	524	524	524	20.3	26

Source: United States Energy Information Administration, *International Energy Annual 2004*. Data for 2005 was estimated by the Author based on 2005 growth rates.

To preserve the crude oil reserves, natural gas production and utilization has increased in the producing countries except Iraq, which produces a fraction of its natural gas resources. But this resource is a fossil resource and unless new discoveries are made it will be depleted in most of the Arab countries in about 50 years.

2.4. Electricity demand

Survey of the Arab countries electricity generation over the period 1980 to 2005 (Table VII) indicated that the electricity generation increased from 90 TWh in 1980 to 536 TWh in 2005 with an average annual growth rate of about 7.4%. If the electricity demand continues to grow at the same rate, net Arab electricity consumption will be about 3200 TWh in 2030. The total installed electricity generating capacity in the Arab countries increased from 27 GWe in 1980 to 104 GWe in 2004, according to US Energy Information Agency. The total installed could be as high as 500 GWe in 2030.

Demand for energy and electricity continues to grow in the Arab World, and this must be satisfied in order to maintain economic growth. Also, in view of the unavoidable decline in the per capita share of the more or less constant natural fresh water resources in the Arab countries, seawater desalination is expected to play an increasing role in mitigating future deficit in potable water supply. Because of the limited fossil fuel energy resources and the almost fully utilized hydro energy, Several Arab countries have been considering for sometime utilization of nuclear energy for electricity generation and seawater desalination.

Table VI. Arab dry natural gas production, 1980-2005, (billion cubic meters)

Country	**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**NG Reserves in 2005**	**NG Life, years**
Algeria	11.661	38.587	50.702	58.215	83.405	79.761	4554	57
Bahrain	2.837	4.653	5.816	6.503	8.587	9.901	92	9
Comoros	0.000	0.000	0.000	0.000	0.000	0.000	0	0
Djibouti	0.000	0.000	0.000	0.000	0.000	0.000	0	0
Egypt	0.851	4.965	8.115	12.454	18.336	35.444	1660	51
Iraq	1.759	0.653	4.199	3.176	3.156	2.790	3121	1780
Jordan	0.000	0.000	0.130	0.291	0.291	0.311	6	20
Kuwait	6.923	3.972	5.249	5.982	9.619	10.360	1575	162
Lebanon	0.000	0.000	0.000	0.000	0.000	0.000	0	0
Libya	5.107	5.107	6.214	6.353	6.012	11.835	1475	183
Mauritania	0.000	0.000	0.000	0.000	0.000	0.000	0	0
Morocco	0.070	0.085	0.057	0.020	0.050	0.050	1	24
Oman	0.794	1.560	2.809	4.178	9.128	18.761	831	48
Qatar	5.221	5.419	7.831	13.527	29.158	48.959	25819	658
Saudi Arabia	9.476	20.315	30.557	38.115	49.909	71.968	6668	101
Somalia	0.000	0.000	0.000	0.000	0.000	0.000	6	0
Sudan	0.000	0.000	0.000	0.000	0.000	0.000	85	0
Syria	0.482	0.142	2.922	2.946	6.112	7.374	241	34
Tunisia	0.361	0.397	0.340	0.331	1.884	2.520	78	32
UAE	5.675	13.732	22.131	31.382	38.456	47.935	6018	130
Yemen	0.000	0.000	0.000	0.000	0.000	0.000	479	0

Source: United States Energy Information Administration, *International Energy Annual 2004.* Data for 2005 was estimated by the Author based on 2005 growth rates.

3. Motivations for nuclear desalination

The reasons which led some Arab countries to consider the nuclear desalination option are basically the following:

— Steadily increasing demand for energy and electricity, caused by population growth, urbanization, industrialization, and the desire and intention to improve the conditions and the standard of living of the people;
— Inadequate and insufficient known national primary energy resources to supply on a medium and long term the increasing demand for energy and electricity; also limited potable water resources, which will require the addition of new sources of supply, in particular for remote areas.
— The desire to save the depletable fossil energy resources, particularly crude oil and natural gas for future generations, and utilization of these resources as irreplaceable raw material in petrochemical industries.
— Perception of nuclear power as a convenient, economically competitive and viable source of energy which, if introduced in the country, would not only complement the traditional energy sources, but would also promote technological development and serve as an incentive for social and economic progress.

Table VII. Arab total net electricity consumption, 1980-2004

Region/Country	1980	1985	1990	1995	2000	2005	Annual growth rate, %
Algeria	6.224	10.722	13.987	16.548	22.143	28.872	6.3
Bahrain	1.445	2.568	3.051	4.032	5.505	7.737	6.9
Comoros	0.008	0.013	0.014	0.014	0.018	0.018	3.0
Djibouti	0.102	0.143	0.156	0.161	0.167	0.190	2.5
Egypt	16.978	30.039	38.509	48.993	66.968	89.088	6.9
Iraq	9.984	18.381	19.270	25.378	27.916	30.006	4.5
Jordan	0.932	2.159	3.187	5.515	6.492	9.621	9.8
Kuwait	8.201	13.716	18.017	20.741	28.720	40.502	6.6
Lebanon	2.670	3.730	2.645	5.130	8.275	9.766	5.3
Libya	4.209	10.315	14.687	15.736	13.546	19.737	6.4
Mauritania	0.083	0.096	0.124	0.135	0.144	0.175	3.0
Morocco	4.577	6.140	8.555	11.464	14.027	20.302	6.1
Oman	0.833	2.534	4.672	5.647	7.965	13.899	11.9
Qatar	2.117	3.452	4.212	5.224	7.985	12.658	7.4
Saudi Arabia	19.020	41.209	60.356	90.997	110.317	155.854	8.8
Somalia	0.105	0.193	0.229	0.238	0.246	0.252	3.6
Sudan	0.896	1.176	1.369	1.674	2.197	4.281	6.5
Syria	3.401	8.235	7.725	13.492	22.195	29.277	9.0
Tunisia	2.438	3.714	4.834	6.471	9.268	11.100	6.3
UAE	5.484	10.652	14.932	21.839	34.919	48.975	9.2
Yemen	0.438	0.795	1.454	2.071	2.983	4.017	9.3
Total	90.146	169.982	221.984	301.500	391.995	536.327	7.4

Source: United States Energy Information Administration, *International Energy Annual 2004.* Data for 2005 was estimated by the Author based on 2005 growth rates.

These reasons have not only retained their validity, but have also been reinforced by the developments, which have been taking place. Currently, energy and electricity demand continues to grow faster than population in the Arab countries, and it is recognized that no economic development can be achieved without satisfying this demand.

4. Nuclear desalination activitities in the Arab countries

In 1991 five North African Countries (NACs): Algeria, Egypt, Libya, Morocco and Tunisia submitted a request to the IAEA for assistance in carrying out a feasibility study on seawater desalination by using nuclear energy at selected sites. The study analyzed the electricity and potable water demands and the available energy and water resources in NACs [14].

The scope included the selection of representative sites, analysis of various combinations of energy sources and desalination processes appropriate for each site, economic factors, financial aspects, local participation, infrastructure requirements, and institutional and environmental aspects. The main conclusions of the study were [14]:

- Nuclear power could play an important role in meeting the expanding regional needs for energy that can be supplied to the grid in the form of electricity, or to desalination plants as heat and/or electricity. There are no technical impediments to the use of nuclear reactors for the supply of energy to the desalination plants.

TableVIII. Most economic cases of nuclear and fossil options [14]

Plant size (1000 m^3/d)	Location	Economic couplings [(1)]				
		Nuclear	Water cost $/$m^3$	Fossil	Water cost $/$m^3$	Average $/$m^3$
720	Tripoli	GT-MHR/RO[(2)]	0.73	GT/Hybrid	0.70	0.715
240	El-Dabaa	CANDU-6/RO	0.80	CC/RO	0.78	0.790
120	Oran	GT-MHR/RO[(2)]	0.79	CC/RO[(3)]	0.83	0.810
60	Zarzis	CAREM-	0.87	CC/RO	0.89	0.880
24	Laayoune	- [(4)]	-	Diesel/RO	1.04	-

[(1)] Base case: 8% interest rate, 2% oil price escalation and US$15.5/bbl oil price including cost of transportation.

[(2)] Warm condenser cooling water is used as feed water to the RO system

[(3)] GT/MED will give a slightly lower cost of US$0.82/$m^3$. However, this combination was chosen to facilitate comparison with other combinations in the Table.

[(4)] All selected reactors for this site were heat only reactors.

Based on the selected energy source/desalination process combination for the five representative sites, the cost of desalted water for the most economic fossil and nuclear driven desalination processes (Table VIII) were in the same range. Sensitivity analyses indicated that higher fuel price and/or lower interest rate will make the nuclear option more economic. The most economic desalination process was RO plants with preheated feed water (i.e. utilizing the cooling water of the steam power plant's condenser as a feed water to the RO system).

This was followed by a number of related activities in several Arab countries (Egypt, Morocco, Saudi Arabia, Tunisia and United Arab Emirates) with and without technical assistance from the IAEA. These are briefly reviewed below.

4.1. Nuclear desalination activities in Egypt.

Egypt carried out two feasibility studies in the period 1995-2001. The first investigated in the period 1995-1997 the prospects of constructing nuclear desalination plants of different capacities in three sites along its Mediterranean Coast [18]. The results of this study is shown in Table IX.

Table IX. Summary of levelized water costs in three potential sites in Egypt [18]

ENERGY SOURCE	POWER (MWe)	COST OF DESALTED WATER IN VARIOUS SITES US$/m^3					
		Site I (172 000 m^3/d)		Site ll (108 000m^3/d)		Site III (87 000 m^3/d)	
		MED	RO	MED	RO	MED	RO
I-Nuclear							
NP-300	300	1.140	0.840	1.172	0.876	1.376	0.901
CAN DU-3	450	1.113	0.779	1.203	0.814	1.270	0.839
AP-600	600	1.026	0.765	1.070	0.784	1.100	0.796
CANDU-6	660	1.087	0.750	1.133	0.768	1.165	0.780
II-Fossil							
Combined Cycle	350	0.900	0.784	0.908	0.770	0.930	0.784
Steam Turbine	600	1.042	0.795	1.055	0.813	1.069	0.832

Bold numbers are the most economic nuclear and fossil coupling options

The second was a more detailed feasibility study focused on the construction of a nuclear power and desalination complex on Dabaa site, and was carried out with IAEA technical assistance in the period 1999-2001. The Feasibility Study concluded that [19]:

1. Installing a Nuclear Power Plant in Egypt, at the El-Dabaa site, to produce electricity and potable water, is technically feasible, economically convenient and financially viable.
2. The Egyptian grid could accommodate without stability problems the addition of any nuclear (or otherwise) unit in the currently available power range. However, because the largest unit connected to the grid is currently 625 MW (Kuraimat), it is more suitable to have the first nuclear unit in the range 600-1000 MW.
3. For assurance of potable water supply under all operating conditions, the plant should consist of two identical units, and utilize a unit size of the order of 600 MW(e) appears to be the preferable choice. The installed seawater desalination capacity should be 150,000 m^3/day.
4. Launching a Nuclear Power Program with this project will benefit the country. There are several major suppliers interested and willing to provide the plant.

The Feasibility study recommended the initiation of the of Bid Invitation Specifications preparation.
The results of the economic evaluation for both studies confirmed the economic competitiveness of the nuclear option as obtained in previous studies [14, 20, 21].

The Egyptian Ministry of Electricity and Energy (MEE) carried out a comparative study of the various strategies and options for electricity generation in Egypt with technical assistance from the International Atomic Energy Agency (IAEA) utilizing the DECADES Tool. The main objective of the study was to determine the optimal electricity generation mix up to the year 2020, including nuclear and renewable (solar and wind) energies [22].

The assessment of alternative nuclear options indicated that [22]:

— Both BOOT Plants and Integrated Solar-thermal units were not competitive under any of the three nuclear variants considered.
— The most competitive nuclear option is Nuclear-100 MW, which does not seem to be affected significantly by changes in interest/discount rate due to its short construction time. However, this reactor does not exist anywhere and the data used in the analysis has to be validated by experience.
— Large WCRs above 1000 MW seem to be more competitive than Medium sized WCRs (~600 MW).
— The nuclear share in the expansion plan decreases with increasing the interest rate. As a result, the natural gas consumption increases with increasing interest rate and thus, the total emissions are increased.

In view of the possible role of RO desalination technology in any future Egyptian nuclear desalination program and the need to validate the concept of RO feed water preheating,

Table X.. Summary of levelized electricity and water costs [19]

Plant Type	WCR-1000 low cost	WCR-1000 high cost	WCR-650 low cost	WCR-650 high cost	SPP-325	SPP-650	CC-500	ISC-150
Levelized Electricity Cost, mills/kWh								
- Capital Cost	26	35	31	39	15	13	14	31
- O&M Cost	7	7	8	8	1	1	2	7
- Fuel Cost	5	5	5	5	42	42	36	30
- Electricity Generation Cost	38	47	44	52	58	56	52	68
Levelized Water Cost, US$/m^3 LT-MED								
- Capital Cost	0.44	0.44	0.44	0.44	0.49	0.46	0.45	0.48
- O&M Cost	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
- Fuel Cost	0.33	0.33	0.32	0.35	0.47	0.43	0.40	0.51
- Water Production Cost	0.90	0.90	0.89	0.92	1.09	1.02	0.98	1.12
Levelized Water Cost, US$/m^3 RO								
- Capital Cost	0.26	0.26	0.26	0.26	0.32	0.32	0.31	0.32
- O&M Cost	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
- Fuel Cost	0.16	0.19	0.18	0.20	0.30	0.30	0.25	0.38
- Water Production Cost	0.59	0.62	0.61	0.63	0.79	0.79	0.73	0.87

Nuclear Power Plants Authority (NPPA) has decided to construct an experimental RO facility at its site in EI-Dabaa, with the following objectives [23]:

1. *Overall:* to investigate experimentally whether the projected performance and economic improvements of preheated feedwater can be realized in actual operation. The intent is to simulate as closely as possible performance characteristics that would be expected to occur in commercial large-scale RO seawater desalination plant.
2. *Short-term (3 years):* to study the effect of feedwater temperature and pressure on RO membrane performance characteristics over a range of temperatures (20-45 C) and pressures (55-69 bar). The intent is to gather data on all aspects of system operation, utilizing membranes from three different manufacturers, so that sufficient data analysis is possible to determine if the performance and economic benefits suggested by the analytical models can in fact be demonstrated by experiments, and to determine the possible differences in results due to materials and type.
3. *Long-term:* to study the effect of feed water temperature and pressure on RO membrane performance characteristics *as* a function of time. The intent is to select one of the membranes used during the short-term program for extended study to investigate possible reduction in membrane lifetime due to effects such as increased fouling or membrane compaction

The construction of the facility was delayed for reasons beyond the control of NPPA, and the facility is expected to be operational in April 2007. NPPA is committed to making the results of the experimental program available to the international nuclear desalination community.

NPPA cooperated with the IAEA through technical cooperation project (EGY/04/046) to upgrade the capabilities of El-Dabaa basic training simulator through the inclusion of a nuclear desalination simulation module and to build up NPPA capabilities in modeling and simulation of Nuclear Desalination Plants. NPPA staff is carrying out programming to simulate the nuclear power plant using APROS. The IAEA contracted CEA of France to develop the desalination module. The coupling between the nuclear and desalination modules was carried out by NPPA.

4.2. Nuclear desalination activities in Morocco.

Morocco carried out, in cooperation with China in 1997-1998, a pre-project study of a nuclear desalination demonstration plant with a 10 MW (th) Chinese Nuclear Heating Reactor (NHR-10) to be built in Tan-Tan [24]. The plant was designed to have a production capacity of 8,000 m^3/d of potable water through an MED process. The production capacity of the demonstration plant was chosen so that it will reinforce the current supply in Tan-Tan and provide sufficient water for its growing population expected to reach 70,000 inhabitants by the year 2010. The study aimed also at establishing a database for reliable extrapolation of the water production costs for a commercial nuclear desalination plant for producing 140,000 m^3/d of potable water using a 200MW(th) NHR [25]. The project was suspended in 2000, pending the results of another project initiated with IAEA in 1998 on the introduction of small and medium reactors (SMR) for power production.

Morocco also investigated within an IAEA coordinated research project [23, 26], the coupling options for the two candidate sites of Agadir and Laayoune. DEEP[2] was used for economic evaluation of three nuclear power reactors and a combined cycle plant in the range of 600

[2] IAEA Desalination Economic Evaluation Program.

MWe coupled with desalination processes: MED, MSF, RO (contiguous and stand alone) and hybrid (MSF-RO and MED-RO). The study considered two scenarios for each site. The first scenario assumed that nuclear desalination would provide only part of the water demand. The second scenario assumed that all of the water demand would be met by nuclear desalination. Table XI summarizes the results of the evaluation for the two sites.

For both sites, the costs of desalted water produced by nuclear and fossil energies are in the same range. The most economic configuration appears to be contiguous RO coupled with a PWR and an adequate amount of electricity to the grid. The installation of a 600-MW(e) PWR in Agadir could produce more than 300,000 m^3/day of desalted water at competitive cost and an average of 517 MW(e) to the grid. In the case of Laayoune, these figures are 72,000 m^3/day and 517 MW(e) respectively.

Table XI. Summary of water cost for Agadir and Laayoun [23]

Desalination process		**Desalted water cost, $/m^3**			
		PWR	**PHWR**	**CC**	**GTMHR**
Agadir site					
MED	Scenario-1	0.62	0.63	0.64	N/A
	Scenario-2	0.74	0.77	0.88	N/A
MSF	Scenario-1	0.88	0.90	0.91	N/A
	Scenario-2	1.41	1.47	1.69	N/A
S-RO	Scenario-1	0.57	0.58	0.58	0.58
	Scenario-2	0.66	0.68	0.74	0.68
C-RO	Scenario-1	0.56	0.56	0.57	N/A
	Scenario-2	0.63	0.65	0.71	N/A
MED-RO	Scenario-1	0.58	0.58	0.59	N/A
	Scenario-2	0.72	0.74	0.82	N/A
MSF-RO	Scenario-1	0.62	0.59	0.63	N/A
	Scenario-2	1.02	1.05	1.17	N/A
Laayoune site					
MED	Scenario-1	0.89	0.91	0.94	N/A
	Scenario-2	0.80	0.83	0.92	N/A
MSF	Scenario-1	1.33	1.50	1.55	N/A
	Scenario-2	1.44	1.50	1.70	N/A
S-RO	Scenario-1	0.81	0.82	0.85	0.81
	Scenario-2	0.75	0.77	0.83	0.77
C-RO	Scenario-1	0.75	0.76	0.79	N/A
	Scenario-2	0.69	0.70	0.77	N/A
MED-RO	Scenario-1	0.80	0.82	0.88	N/A
	Scenario-2	0.73	0.74	0.81	N/A
MSF-RO	Scenario-1	0.92	0.94	1.02	N/A
	Scenario-2	0.82	0.84	0.92	N/A

An investigation of utilizing uranium produced as a by-product in an advanced high temperature reactor used for nuclear desalination was published in 2005 [26]. The study indicated that while the investment cost for the nuclear plant would be more than double that for gas fired plant, and would take a longer time to build, the nuclear option would cost less per year (more than 50%). The economic comparison of the two options is shown in Table

XII. The nuclear option is more environmentally benign and would secure energy independence for the country.

4.3. Nuclear desalination activities in Saudi Arabia.

Saudi Arabia is a large arid country without any rivers. The average rainfall is less than 102 mm and surface water resources are scarce. The best way of obtaining freshwater in Saudi Arabia is through efficient use of the sea and ground water resources. However, these resources are highly saline and cannot be used directly without desalination. Therefore, Saudi Arabia depends heavily on seawater desalination as a source of freshwater. Nearly 50% of the seawater desalination plants worldwide are located in Saudi Arabia.

Despite the large Petroleum reserves, Saudi Arabia was interested in nuclear desalination as early as the 1970s [12-13]. Studies carried out in the 1980s concluded that nuclear power generation is a favorable option to meet the fast growing energy demand in the country [28], and that the most suitable reactor for electricity generation and seawater desalination is CANDU type reactor [29]. In 1997, a study carried out at King Saud University [30] concluded that the electric and thermal power produced from CANDU-80 might be used for desalination plants of the RO, MSF, or MED type in Saudi Arabia. The study recommended coupling this reactor with a hybrid RO-MSF desalination plant.

Table XII. Comparison of advanced HTR and gas-fired power plant coupled with MED desalination [26]

	Nuclear plant+MED	**Dual cycle gas plant+MED**
Electrical output, MWe	280	300
MED water output, m^3/d	25000	25000
Power plant expected life, years	40	20-25
MED life, years	20-25	20-25
Power plant cost, euros	400 M	165 M
MED plant cost, euros	20 M	20 M
Yearly cost of power plant, euros	52 M	76 M
At gas cost of:	-	US $ 3.5/ M BTU
Cost of kWh produced, eurocent	ab. 2.7	ab 3.1
Yearly cost of MED plant, euros	3.75 M	6.25 M
Cost of water produced, euro/m^3	0.5	0.8
Total investment, euros	790 M	289 M
Amortization 5%, years	25	20
Total Yearly cost, euros	56 M	82.5 M
Advantage over gas	After 19 years	-

An economic evaluation study was carried out utilizing DEEP [31] for several energy options, namely:

- Pressurized Water Reactor, PWR (600 MWe)
- Small Pressurized Water Reactor, SPWR (160 MWth)
- Pressurized Heavy Water Reactor, PHWR (450 MWe)
- Heat Reactor, HR (200 MWth)
- Gas Turbine, GT (125 MWe or 175 MWe)

The above energy sources were compared for the desalination technologies MSF, MED, RO and hybrid MED-RO. The calculations were made for two interest rates zero (the current practice by the Government) and 8%. The results are shown in Table XIII. As can be seen in the Table, for the zero interest case, the HR with MED, GT with MED and GT with MED-Ro give very comparable minimum levelized water costs. For the 8% interest/discount rate, the GT with MED gives minimum levelized water cost followed by PWR with RO, GT with RO and then PHWR with RO.

Table XIII. Results of the economic evaluation of the eastern region cases [31]

Case name	Energy source	Desalination method	Interest and discount rates	Levelized electricity cost S/kwh	Desalination plant size M^3/d	Net saleable electricity Mwe	Levelized water cost $\$/m^3$
ECF	PHWR	MSF	YES	0.054	1,915,000	1,224	1.34
ECM	PHWR	MED	YES	0.054	1,915,000	852	0.80
ECR	PHWR	RO	YES	0.054	1,915,000	14	0.75
EGF	GT	MSF	YES	0.067	1,915,000	0	0.97
EGM	GT	MED	YES	0.067	1,915,000	0	0.60
EGR	GT	RO	YES	0.057	1,560,000	83	0.74
EGRO	GT	MED-RO	YES	0.067	1,532,000	1,116	0.65
EHF	HR	MSF	YES	N/A	1,915,000	0	0.94
EHM	HR	MED	NO	N/A	1,915,000	0	0.60
ECMN	PHWR	MED	NO	0.028	1,915,000	863	0.45
ECRN	PHWR	RO	NO	0.028	1,915,000	27	0.41
EGMN	GT	MED	NO	0.068	1,915,000	0	0.38
EGRN	GT	RO	NO	0.068	1,560,000	83	0.59
EGRON	GT	MED-RO	NO	0.068	1,915,000	1,116	0.39
EHFN	HR	MSF	NO	N/A	1,560,000	0	0.49
EHMN	HR	MED	NO	N/A	1,915,000	0	0.37
EPFN	PWR	MSF	NO	0.029	1,560,000	1,007	0.67
EPMN	PWR	MED	NO	0.029	1,915,000	735	0.46
EPF	PWR	MSF	YES	0.1573	1,719,528	1431	1.29
EPM	PWR	MED	YES	0.1704	1,719,528	735	0.78
EPR	PWR	RO	YES	0.1558	1,747,046	774	0.73
EPRO	PWR	MED-RO	YES	0.1549	1,402,103	732	0.80
ESF	SPWR	MSF	YES	0.7019	1,719,528	0	1.82
ESM	SPWR	MED	YES	0.7698	1,314,889	0	0.98
ESR	SPWR	RO	YES	3.1949	1,747,046	16	0.96
ESRO	SPWR	MED-RO	YES	1.1641	1,462,357	96	1.08

4.4. Nuclear desalination activities in Tunisia.

In 2002, the Tunisian National Center for Nuclear Desalination and Technologies (CNSTN) and the French Atomic Energy Commission (CEA) signed a contract within the IAEA interregional cooperation programme to carry out nuclear desalination feasibility study for the Skhira site in the south of Tunisia. The main objectives of the study were [23]:

- Pre-dimensioning of the nuclear reactor and desalination processes, compatible with Tunisian electricity needs and required water production capacity at the Skhira site.
- Coupling of the selected nuclear reactor to desalination processes and system optimization.
- Economic evaluation of the integrated systems elaborated above.
- Safety verification studies of coupled systems.

The study concluded that an integrated desalination system based on a 600 MWe plant would provide to the grid from 591 to 375 MWe, depending upon the desalination process used, and the required capacity.

For the purpose of the economic study, five types of solutions were considered for this power range, two are fossil power plants (Super Steam Boiler and Gas turbine combined cycle) and three nuclear power plants, namely:

- An innovative reactor of the type SCOR-600, currently being studied at CEA, DER/SERI/LFEA.
- Two modules of the GT-MHR whose conceptual design studies are being carried out by a consortium comprising FRAMATOME (France), GENERAL ATOMICS (USA), MITSUBISHI (Japan) AND MINNATOM (Russian federation).
- A 900 MWe PWR of the type operating in France, in case by 2020, the Tunisian grid is interconnected to the European grid and could thus support reactors of higher power.

The results for the base case (i.e. Discount rate=8% & Fossil fuel price=25 \$/bbl) are shown in Table XIV. Careful inspection of the table indicates that:

- Whatever the desalination process, production capacity or the discount rate, the desalination costs by the two nuclear options PWR900 and SCOR600 are almost the same, since the relative difference between their costs does not exceed 2 to 4%.
- For the two desalination processes (MED and RO) the desalination costs by nuclear systems are significantly lower than corresponding costs by CC600 or SSB600. Thus for example, the desalination cost by SCOR600 +MED is respectively 25 and 33 % lower than that by CC600 +MED and SSB600 +MED systems.
- In similar conditions with the RO process, SCOR 600+RO gives desalination costs, which are respectively 21 and 29% lower than those by the fossil energy based systems.
- ROph systems appear to be the cheapest. With SCOR600 + ROph, the desalination cost is respectively 16 and 19% lower compared to SCOR600 +MED and SCOR600 +RO.
- The GTMHR+MED system produces only about 43500 m^3/day. However, the desalination cost by GT-MHR+MED is still 3% lower than SCOR600 +MED. This advantage does not exist for GT-MHR+RO (48000 m^3/day), since its desalination cost is higher than the GT-MHR+MED system.

Table XIV. Comparison of desalination costs for fossil and nuclear options [23]
(Base scenario: Discount rate=8% & Fossil fuel price=25 $/bbl)

Parameters	Units	SSB-600		CC-600		PWR-900			SCOR-600			GT-MHR	
Total power	MWe	600		600		951			600			571 (with 2 modules)	
Desalination process		MED	RO	MED	RO	MED	RO	RO_{ph}	MED	RO	RO_{ph}	MED	RO
Year of operation		2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020
Production	m^3/d	157155	152867	157155	152867	152123	152867	150461	157155	152867	150461		
Construction cost of desalination unit	M$	167.1.	161.8	171.4	161.8	182.9	161.8	115.2	183.8	161.8	115.2	-	162
Specific investment cost	$\$/m^3/d$	952	1047	977	1047	1042	752	1047	1047	1047	752	-	1048
Seawater desalination cost	**$\$/m^3$**	**0.85**	**0.83**	**0.76**	**0.75**	**0.58**	**0.59**	**0.48**	**0.57**	**0.59**	**0.48**	**-**	**0.59**
Production	m^3/d	49111	54595	49111	54595	47538	54595	50154	49111	54595	50154	43538	54595
Construction cost of desalination unit	M$	58.5	67	60.2	67	63.3	67	42.8	63.7	67	42.8	70.3	67.1
Specific investment cost	M$/y	1030	1179	1060	1179	1114	1178	818	1098	1179	818	1238	1180
Seawater desalination cost	**$\$/m^3$**	**0.88**	**0.87**	**0.78**	**0.79**	**0.60**	**0.63**	**0.50**	**0.60**	**0.63**	**0.50**	**0.58**	**0.63**

4.5. Nuclear desalination activities in United Arab Emirates.

Though the United Arab Emirates (UAE) has vast reserves of fossil fuel, the country showed interest in introducing nuclear power for electricity generation and seawater desalination. The main motivations are:

- Preparing the ideal conditions for the future when fossil fuel resources are depleted.
- Conservation of oil resources for the next generation and for other important applications such as the transport and petrochemical industry.

The Department of Energy and Renewable Energy of the Ministry of Electricity and Water approached the IAEA for technical assistance in carrying out a technical and economic feasibility study of nuclear power and water desalination plant for the United Arab Emirates. An IAEA Expert Mission[3] was carried out in June 2005 to prepare the detailed work plan for the technical and economic pre-feasibility study (PFS) of the nuclear power and water desalination plant in UAE.

The outcome of this study has not been reported.

5. Utilization of SMRs in the Arab countries

The review in the above sections indicates that most of the reactors considered in the various Arab studies are Small and Medium Reactors (SMRs). SMRs are by definition, the power reactors less than 600 MW(e). Applying this definition, more than half of the operating reactors would qualify as SMRs.

SMRs are perceived by several countries, particularly developing countries with weak infrastructure and limited financial capabilities, as a convenient, economically competitive and viable source of energy which, when introduced would not only complement the traditional energy sources, but would also promote technological development, serve as an incentive for social and economic progress, and secure potable water needs [32].

5.1. Rationale for the development of SMRs

The incentive for the development of SMRs has a two fold origins. In some cases the R&D efforts have been the result of economic considerations:

- SMRs could open up additional energy market sectors (e.g. heat production), not accessible to large reactors, also offering valuable contribution to CO_2 emissions reduction;

- SMRs can provide a better response to slow grow rates of energy demand.

- SMRs fit better into small electricity distribution grids and are good candidates for the replacement of older (usually small) fossils fueled plants.

In other cases SMRs have been or are being developed based on the users requirements, mostly in relation to safety and public acceptance issues. Common points in the requirements issued in different countries are:

[3] The author was one of the experts contracted by the IAEA to carry out this mission

— A simple and more rugged design:
— Increased safety margins leading to, for example, longer grace periods, i.e. longer times before operator actions are needed;
— Lower core damage risks.
— Small (if any) accident consequences for the population.

5.2. Main technological features

Common to SMRs developments the pursuit of passive safety systems based on the premise that such systems are easier to implement in plants smaller than the current large nuclear power plants (NPPs). In addition, there is no new design which does not lay emphasis on simplification and the benefits that it is expected to produce. Examples of such simplifications include [33]:

— Elimination of external primary system re-circulation loops and pumps (integrated design);
— Reduction of large bore primary piping;
— Elimination of safety-grade coolant make-up systems;
— Increased in-vessel heat storage capacity;
— Application of passive emergency cooling;
— Application of passive residual heat removal systems;
— Location of reactor pressure vessel (RPV) penetrations in the upper part of the vessel;
— Incorporation of large pressurizes (internal or external);
— Minimization of the number of seismic structures, simplification of the building concept and use of seismic isolation.
— Elimination of emergency diesels.
— Modularization of design to allow a higher degree of off-site manufactures and reduced construction time.

6. Possible areas of cooperation among Arab countries

One of the important characteristics of the post World War II is the tendency of individual states, developed or developing to agglomerate in larger entities for political, economical or cultural reasons, in order to optimize the utilization of their resources and protect their common interests. The European Union is a successful example of such regional cooperation.

The Arab countries share a common land without any natural barriers as well as common language, culture and national feelings. They are all members of the Arab league, the main organ for coordination between the Arab countries. Therefore, links already exist to support cooperation activities. The present level of cooperation between Arab countries, as indicated by the inter-trade figures, is quit low. However, there is a room for improving the level of regional cooperation between the Arab countries.

Regional cooperation, particularly in satisfying the Arab countries' needs for electricity and water, include but not limited to the following advantages:

— Reduction and possibly elimination of short and medium term needs for installation of new power plants through unification of their national power systems[4]. This will allow

[4] Plans already exist to establish a Unified Arab Electrical Grid that will be connected to Europe through Turkey an Spain as well as to the African interior.

utilization of the existing reserves in each country due to difference in peak loading among the Arab countries.

— Standardization of power plants will facilitate local participation and manufacturing on the country and regional levels, as well as, enlarging the market for local industry, hence, improving the feasibility of local manufacturing. This will lead to minimization of foreign currency components in future projects.
— A more efficient utilization the Arab countries limited highly qualified and skilled manpower, as well as minimizing the cost of developing further manpower capabilities.

The field of nuclear desalination is new to all the Arab countries, therefore, a new cooperative approach might possibly be applied easier than in other fields where practices already established. Regional cooperation in the field of nuclear desalination should be viewed as part of a wider regional cooperation in the fields of energy, water and industry.

From the viewpoint of nuclear desalination, the prime areas of regional cooperation are:

- **Legal framework**: This constitutes a highly country-specific area, where every country has to develop its own legal structure. Nevertheless, mutual consultation could be of benefit in facilitating the smooth development of joint undertakings. The Arab countries have the opportunity of building-up their regulatory structures adopting a joint approach and establishing similar or even the same rules and procedures.
- **Manpower development**: Development of an adequate manpower infrastructure requires a long time and major efforts. If these efforts can be shared, it would benefit all. Cooperative approaches can be applied both to desalination plants and to nuclear reactors. In addition to sharing resources and experiences, regional training centers equipped with sophisticated training facilities such as simulators, could be of substantial benefit to all.
- **Regional participation**: This aims at maximizing regional share not only in manufacturing process, but also in all other activities that can be evaluated by money such as: construction, erection, commissioning, operation and maintenance. Regional manufacturing should be considered from the regional point of view, because this would effectively increase the size of the potential market. Standardization is another area that improves regional participation. The benefits of joint approach are not limited to nuclear reactors; they could also be applied to desalination plants. Sharing of experience, mutual assistance, reduction of engineering effort and costs through repeated projects, do open-up the possibility of reducing costs of product water. There is also room for transfer of knowledge, skills and experience in the areas of construction, erection, commissioning, operation and maintenance, which would ultimately result in mutual benefits to all countries of the region, even if not directly involved in particular project. The need for substantial regional manufacture means that the Arab countries should start developing specific QA/QC codes of practice for the region, which should be acceptable, and if possible mandatory within the region, in order to escape from the current fragmentary situation.
- **Acquisition and financing**: The acquisition process of complex technology installations is time consuming, costly and require expertise which usually not fully available in developing countries. Regional cooperation through participation in the acquisition phase of projects, at least in the development of bid invitation specifications and in evaluation of bids, would increase local capabilities, tend to avoid the repetition of mistakes, and promote a trend towards standardization. Regarding financing, taking into account that

very large investments are required, sharing of the financial load and eventually the benefits, might very well facilitate solving this problem.

- **Research and development**: Regional cooperation in this area could take various forms such as: sharing the experience and consultations, coordinated research programmes utilizing existing R&D institutes in each country or the establishment of a joint R&D Institute. Other forms of cooperation could be through the enhancement of the role of the Arab Atomic Energy Authority (AAEA), which provides a good forum for advancing peaceful uses of nuclear energy in the Arab World.

7. Conclusions

- Most of the Arab Countries lie within the temperate zone, and the bio-climate varies from arid to extremely arid. Most of the Arab Countries are water-scarce countries. Only Iraq, Sudan and Syria, are classified as water stressed countries. However, due to increase in population, these countries will become water-scarce countries before 2030. To augment shortages in fresh water resources, several Arab countries utilized desalination technologies to various degrees.
- The only significant primary energy resources in the Arab World are crude oil, natural gas. Limited hydropower exists in some Arabic countries such as: Morocco, Egypt, Syria and Iraq, but it is nearly fully utilized. There is a potential for solar and wind energies but the technology for large-scale electricity production is not yet economic.
- Survey of the Arab countries electricity generation over the period 1980 to 2005 indicated that the electricity generation increased from 90 TWh in 1980 to 536 TWh in 2005 with an average annual growth rate of about 7.4%. If the electricity demand continues to grow at the same rate, net Arab electricity consumption will be about 3200 TWh in 2030.
- Because of the limited fossil fuel energy resources and the almost fully utilized hydro energy, Several Arab countries have been considering for sometime utilization of nuclear energy for electricity generation and seawater desalination.
- Several Arab countries were interested in the concepts of Nuclear Desalination and Agro-industrial Complexes, as early as the 1960s. From the beginning of the 1990s the North African Countries (Algeria, Egypt, Libya, Morocco and Tunisia), as well as Saudi Arabia and United Arab Emirates participated actively in the IAEA nuclear desalination activities and carried out feasibility studies and other national activities.
- These studies indicated that nuclear power could play an important role in meeting the expanding needs for energy that can be supplied to the grid in the form of electricity, or to desalination plants as heat and/or electricity. There are no technical or economic impediments to the use of nuclear reactors for the supply of energy to the desalination plants.
- Most of the reactors considered in the various Arab studies are Small and Medium Reactors (SMRs). They are perceived as a convenient, economically competitive and viable source of energy which, when introduced would not only complement the traditional energy sources, but would also promote technological development, serve as an incentive for social and economic progress, and secure potable water needs.
- Common to SMRs developments the pursuit of passive safety systems based on the premise that such systems are easier to implement in plants smaller than the current large nuclear power plants (NPPs).
- The Arab countries share a common land without any natural barriers as well as common language, culture and national feelings. They are all members of the Arab league, the main organ for coordination between the Arab countries. Therefore, links already exist to

support cooperation activities. Regional cooperation, particularly in satisfying the Arab countries' needs for electricity and water, has many advantages.

- From the viewpoint of nuclear desalination, the prime areas of regional cooperation are: Legal Framework, Manpower Development, Regional Participation, Acquisition and Financing, and Research and Development.

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Desalination and water reuse- A technology for the future

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Abstract. The paper discusses the role of desalination in meeting the worldwide increasing water demand. The technical details of key commercial desalination processes and the current industrial trends are presented. Advantages of hybrid desalination systems are particularly highlighted. Potential for technology improvement and resulting cost reduction aspects are looked in to.

1. Introduction

Large -scale extraction of ground water is resulting in rapid depletion of the aquifers. The only available choice, to meet the future water demand is seawater desalination. Desalination will create sustainable development of extra water resources. It will help minimize regional and international conflicts over sharing of water. It will offer commercial opportunity of 80 billion dollars plus, in the next 10-20 years.

The market drivers for desalination are increasing water demand, decreasing unit cost of desalination through technology improvement and environmental constraints increasing the cost of traditional water sources.

2. Desalination worldwide inventory

Worldwide there are 15,233 desalting units with total capacity of 32,400,000 m^3/d. Over the last two years the increase averaged 10.5% / year. The Middle East is still the dominant market. The major contributors to desalting capacity are;
(i) Saudi Arabia 22.4%
(ii) UAE 20.4%
(iii) USA 12.0%
(iv) Kuwait 8.4%

Figure 1 shows the worldwide desalination capacity region wise.

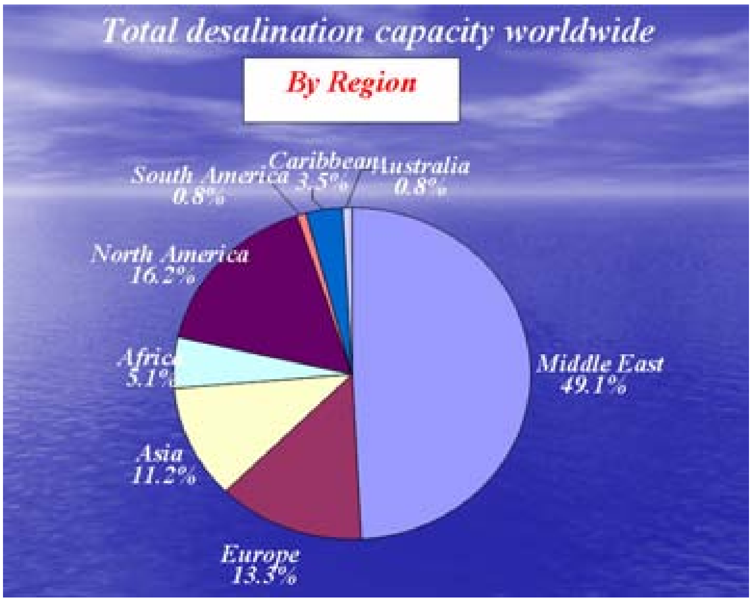

FIG. 1. Desalination capacity region wise.

The distribution of desalination plants source wise is shown in Fig. 2.

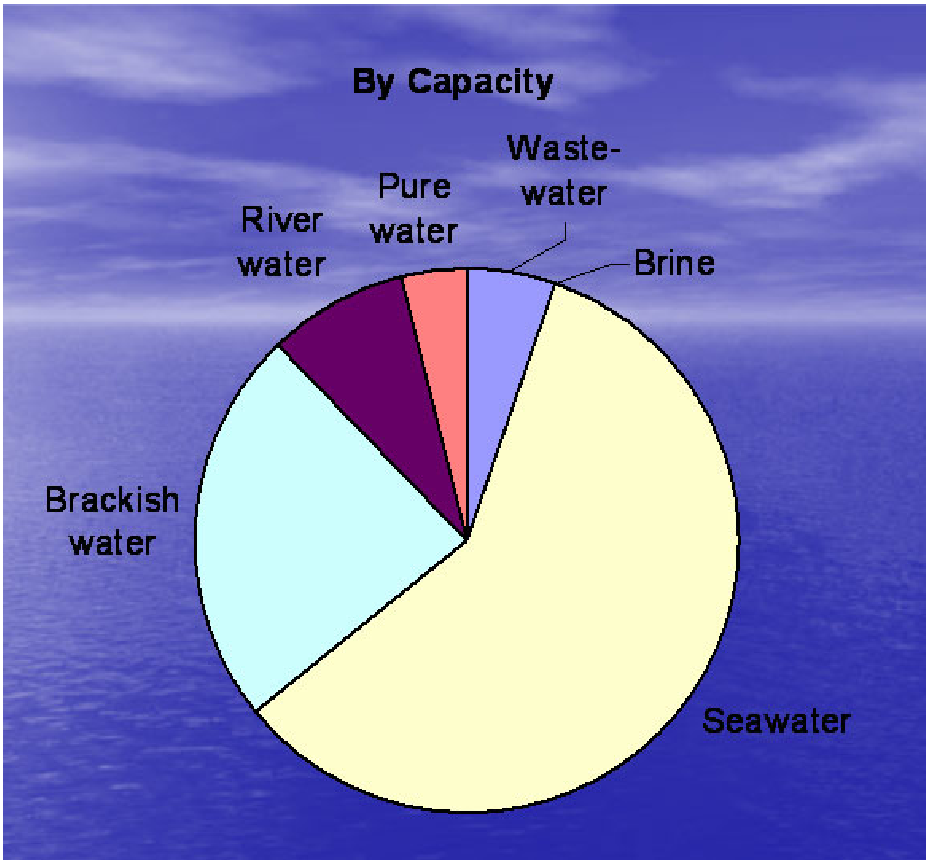

FIG. 2. Total desalination capacity worldwide by the source water

Out of all the desalination processes MSF and RO processes are the major contributor as shown below:

(a) For all plants installed and contracted

— MSF represents 43.5%

— RO represents 43.5%

(b) For seawater as a feed

— MSF represents 66.3%

— RO represents 22.4%

MED and Hybrids coming strong

3. Salient characteristics of desalination processes.

The typical energy requirements (heat and electricity) for the common desalination processes are indicated in Table I. The overall energy requirement for the MSF process are largest followed by MED and RO.

Table I. Energy requirements (steam/electricity)

Product	Process live steam (ton product /ton steam)	Electricity KWh /ton product
Multi Stage Flash	8	4
Vapour Compression	n/a	8
Multi Effect Distillation	12	2
Reverse Osmosis:		
with energy recovery	n/a	3.5 – 5.5
without energy recovery	n/a	8.5

The salient features of these processes are as below:

Multi Stage Flash (MSF)

(a) Raw seawater total dissolved solids (TDS) : 35-47,000 mg/L

(b) Maximum brine temperature : 112^{o} C

(c) Performance ratio : 8

(d) Electrical power : 3-4 kWh/m^3

(e) Scale inhibitors used for scale control

(f) Recycle type plant

(g) Dual purpose plant

Multi Effect Distillation (MED)

(a) Raw seawater total dissolved solids (TDS): 35-47,000 mg/L

(b) Maximum brine temperature: 76^{o} C

(c) Performance ratio: 12

(d) Electrical power: 2 kWh/m^3

(e) Scale inhibitors used for scale control

(f) Dual purpose plant

Reverse Osmosis (RO)

(a) Raw seawater total dissolved solids (TDS) : 35-47,000 mg/L

(b) Feed pressure: 1000 psia (70 bars)

(c) Conversion factor: 35%-50%

(d) Membrane life: 5 years

(e) Electrical energy consumption: 4.5 kWh/m^3

4. Some typical innovative case studies.

Three typical examples are presented in the paper aiming towards cost reduction.

(i) Fujairah's 100 MGD MSF-RO plant
(ii) Sharjah's NF-MSF plant
(iii) Desalination, Aquifer storage and Recovery (DASR)

(i). Advantages of simple hybrid MSF-RO power system at Fujairah

(a) A common, considerably small seawater intake can be used as RO plant utilizes the warmer cooling water return from the MSF plant.
(b) Product waters from the RO and MSF plants are blended to obtain suitable product water quality.
(c) A single stage RO process can be used as the product water blending reduces the demand of high quality from RO plant.
(d) Increased recovery ratio of RO plant due to operation at elevated temperature.
(e) The RO membrane life can be extended

The water cost from the 100 MGD Fujairah's combined MSF-RO hybrid plant is reported to be around $ 0.80 per cubic meter taking the above advantages.

(ii). Advantages of Sharjah's NF-MSF plant

A typical flow sheet of NF-MSF hybrid plant is shown in Fig. 3.

NF preferentially removes scaling ions which allows higher top brine temperature for MSF approaching 120 deg C. This results in higher flash ranges leading to increased water production. Adoption of NF in Sharjah has resulted in increase in capacity of MSF plant from 5 MGD to 7.2 MGD. The overall capital and operating costs of the MSF plant is therefore reduced. A comparison of costs from Sharjah's RO vs NF-MSF plants indicate the RO plant costs around $0.598/cu.m., where as the cost from NF-MSF is projected to be 0.479/cu.m.

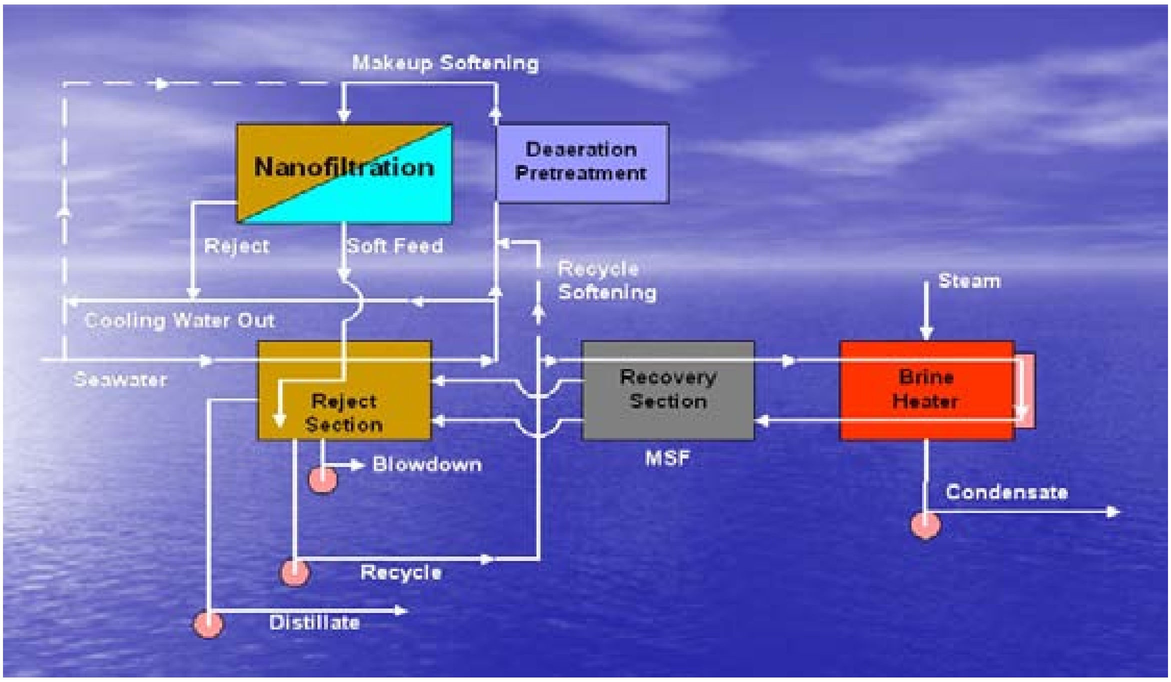

FIG. 3. Nanofiltration NF with multistage MSF flash process

(iii) Desalination and aquifer storage and recovery

Water can be stored while electricity can not be stored. Electricity demands drop to 30-40% of the peak during winter months in Gulf area. Over 50% of power generation capacity is idle in winter months. This idle power can be used to produce water from membrane processes and stored in aquifers. The stored water can be withdrawn in summer months spending little power. This is known as desalination, aquifer storage and recovery (DASR). Figure 4 shows the schematics of DASR

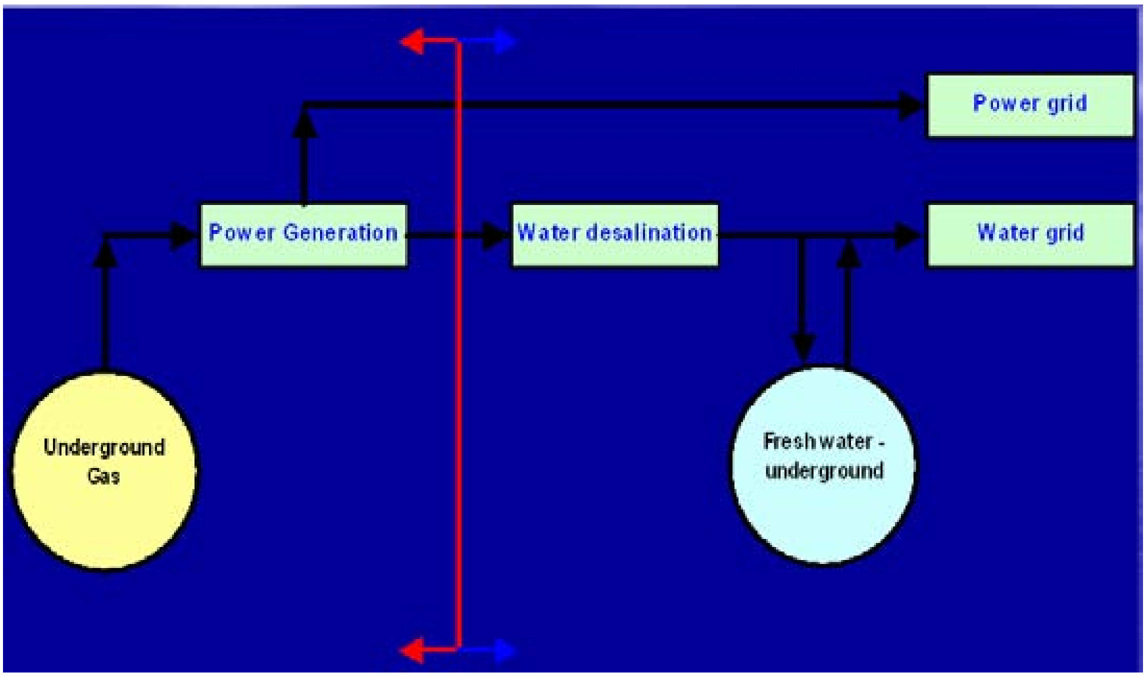

FIG. 4. GAS to power, power to seawater Desalination and Storage/Aquifer Storage and Recovery (DASR)

5. Potential improvements

The significant increase in recent years in fuel-energy (oil $ 75-95/ barrel; natural gas $ 9-11/MMBTU) and material cost (steel, copper, nickel and concrete) has a dramatic impact on capital and operation cost of desalination and power. The challenge is to minimize energy consumption and reduce volume and weight of desalination plants. The following are the commercial development in this direction, likely to come in future years

- Larger capacities of MSF, MED and RO plants reducing the capital investment per cubic meter plant capacity due to economy of scale.
- Introduction of UF/NF for seawater pretreatment as against the conventional methods used presently.
- Wide scale adoption of NF-MSF and NF-MED and NF-RO plants

Since nuclear energy is nearly carbon free generation and is long-term sustainable solution and potentially completive with fossil fuels it is necessary to consider as a choice for desalination projects. Particularly in cases when power and heat for desalination is generated from using heavy crude oil or coal, which requires significant cost for pollution control and is an inefficient generation solution, resulting in significant increase of the penalty for CO_2 emission and greenhouse impact.

Suggested programme for developing Sinai desert community using nuclear energy

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Abstract. In Egypt, the sea lies beside the desert and this is clear in Sinai peninsula. The development of Sinai community needs large amounts of water and energy. It is suggested that the nuclear energy utilization for this purpose is convenient. Three nuclear dual purpose power plants are to be constructed to supply the whole peninsula with water and electricity. Two of these plants will be constructed in the north on the mediterranean sea and the third in the south on the red sea shore. The main features of these plants are defined due to the previously conducted studies. The suggested capacity of each plant may reach 400 MW electricity and 250 million gallons per day of desalted water. The steam is bleeded from steam turbines to heat the brine at 120°C giving the flexibility to use the back pressure scheme if required. The reactor is PWR type using uranium dioxide fuel with enrichment 3.4 and multiplication factor 1.09. The thermal efficiency is 29% and the load factor is 70%.

1. Introduction

With raising costs and decreasing supply of energy, the nuclear energy becomes more competitive. In Egypt, where the sea lies beside the desert in most cases, the nuclear desalination seems to be the proper solution of the problem of the population and development of the arid and semi-arid zones. The use of dual-purpose nuclear plants for power production and water desalination may achieve substantial energy savings in the cost of desalted water. In the MSF (multi-stage flash) applications, the steam extracted from a steam turbine is used to heat the brine [1,2]. The water cost in a dual-purpose plant is strongly affected by the method of desalination as well as the water to power ratio [3]. The studies based on the second law of thermodynamics show that about 60% of thermal energy required for MSF plants may be saved in case of dual-purpose plants using steam turbines [4].

2. Sinai geography

The Sinai Peninsula lies in the northeast of Egypt. In spite of its political and economic importance, the development of its community is very slow. Although it is surrounded by seawater almost from all sides, the water supplies for agriculture and human uses are not enough. Most of the area of Sinai is still unpopulated and even the populated areas suffers from decrease of water and energy. The economic activities are restricted to weak agriculture in the north and the tourism in the south. Enough water and energy will be the real support of development. The map of Sinai is shown in Fig. 1.

FIG. 1. The Map of Sinai peninsula

3. Plan of development

It is convenient to utilize the nuclear energy in Sinai for peace and progress. It is suggested to construct three dual-purpose nuclear plants to solve the problem of water and energy needs. Two of these plants may be constructed in the north on the Mediterranean sea shore. The third is needed in the south for tourist activities. In the north, the lands can be cultivated for agriculture and it is possible to construct an agro- industrial complex in the near area of each plant [5]. In the south and middle of Sinai, the main source of income is tourism. It is suggested to construct the third dual-purpose plant on the Red Sea shore to supply the tourist resorts and small villages with the required amounts of water and electricity. The choice of the exact sites of these plants needs an independent study.

4. The plants features

The preliminary main features of the suggested nuclear dual-purpose plants are defined due to the needs of the community and the economics of power and water production. Many studies have been conducted to choose the size and site of proposed nuclear plant for Egypt [6-8]. These studies are rather old and the prices of energy, nowadays, are much higher. It is convenient to choose medium size reactors for these dual purposes plants. These reactors satisfy the needs of the community and are rather better in operation and safety. The MSF-VTE (multi-stage flash-vertical tube evaporator) is used in the desalination unit with rate of production of 250 mgd (million gallons per day). This unit is connected to PWR reactor utilizing high pressure steam to generate 400 MW(e) from total thermal power of 1950 MW operating at 70% load factor. The nuclear fuel is uranium dioxide with 3.4% enrichment and multiplication factor 1.09.

The steam is extracted from the turbine at a temperature suitable to heat the brine. Two schemes may be used to extract the steam from the turbines. These schemes are the back pressure and the extraction condensing schemes. These schemes are shown on Fig. 2 and 3. The choice of operation scheme depends on required load factor and water to power ratio [9]. The use of back-pressure scheme results in high load factor and then, the plant is used in the base load of electrical network. The extraction condensing scheme increases the flexibility of the water and power production of the plant. The back pressure scheme is more advantageous from the economic point of view. This scheme is more suitable since the total production is needed.

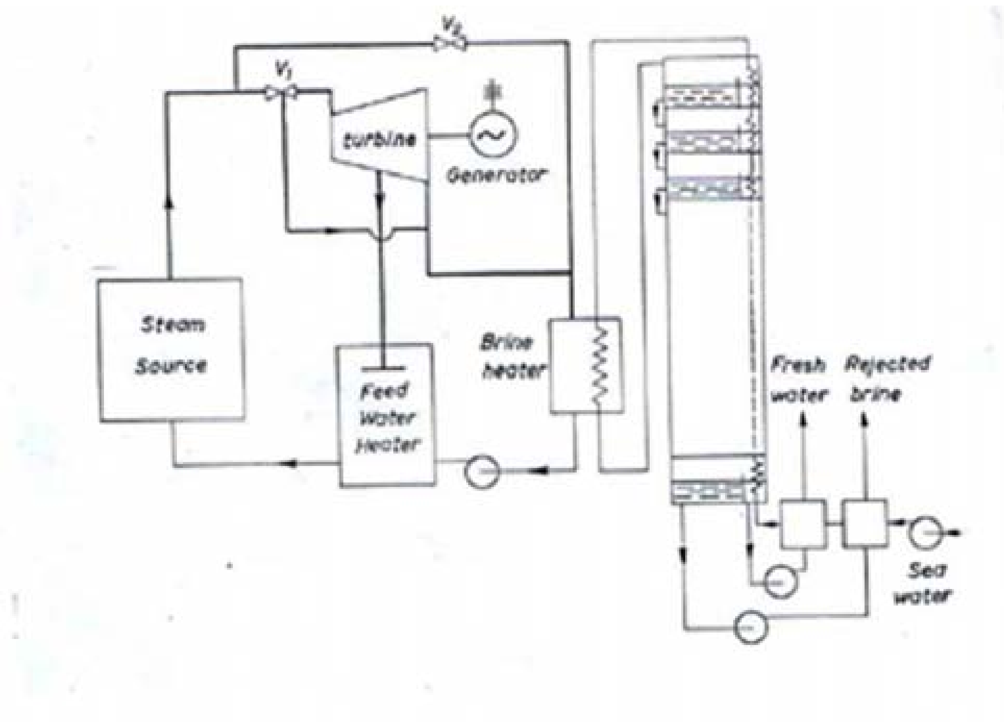

FIG. 2. Back preesure scheme

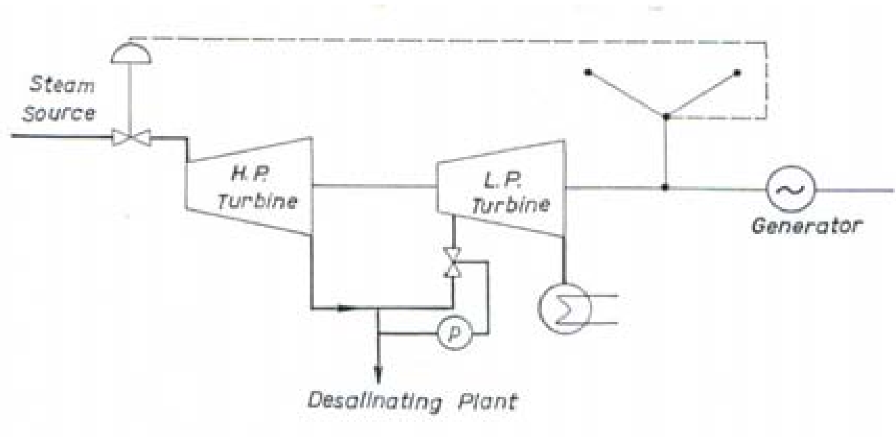

FIG. 3. The extraction condensing scheme

5. The training of manpower

The introduction of new technology especially nuclear power technology necessitates adequate efforts for manpower preparation. The economic and technical consequences of well-trained personnel may contribute in the success of the program. In order to have successful training, local participation should play important role. The chosen staff should be trained in the fields of both the desalination and nuclear power technologies.

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Prospect on desalination by nuclear energy in Indonesia

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Abstract. Indonesia is suffering from lack of clean water, especially in major cities during the dry season. Water resources are contaminated by volcanic sources, salt-water intrusions, industrial waste, and domestic sewage discharges. The problem is exacerbated by inadequate infrastructure and ill-management of clean water supply/storage and waste control. The demand for clean water supplies has increased significantly in the recent years and is likely to increase by 200% in the next 15 years. In an effort to meet the current and future water and energy demands, Indonesia is now planning to utilise nuclear power for producing fresh water through desalination process. Feasibility and option studies have been carried out by Indonesian National Nuclear Energy Agency, locally called Badan Tenaga Atom Nasional or 'BATAN' since 1995, and also in collaboration with Korean Atomic Energy & Research Institute (KAERI) since 2002. The study concluded that it would be technically feasible to build desalination plants on selected sites pending further economic assessments.[3] BATAN has mobilised a small project team to develop and prototype a small scale Mechanical Vapour Compression system to study and establish vital parameters that will affect system performance, water chemistry, corrosion, scaling, evaporation, condensation, and choice of materials. A concept design has been completed and a mock-up plant is currently being constructed albeit at snail-pace due to limited project funding and resources. The current status and future plans are elaborated in this paper.

FIG. 1. Map of Indonesia

1. Introduction

Water resources in Indonesia are rainwater, groundwater and surface water. The amount of available water in Indonesia varies significantly depending on the location and seasons (wet or dry season). Indonesia is a huge archipelagic country, as shown in Fig. 1, extending 5,120 km from east to west and 1,760 km from north to south encompassing as many as 18,000 islands of which about 6,000 are inhabited by 215 million people. About 60% of the inhabited regions receive plenty of annual precipitations in the range of 2,000 mm to 3,500 mm, whereas some areas see greater than 5,000 mm and some less than 1,000 mm. In addition to these generous rainfalls, Indonesia is endowed with no less than 5,590 rivers flowing over 5,500 billion tons of water per year (or 5,500 km³/year). As such, Indonesia may appear to have an abundant supply of water and be free from water shortage problems. In reality, however, Indonesia is suffering from clean water shortages due to ever-increasing demand for water to support growing population, developing industry and agriculture as shown in Table I. This is exacerbated by lack of land/water management and natural environmental impacts, such as climate changes, land degradation and water pollutions. A good example of a man-induced environmental impact is over-pumping of groundwater in Jakarta, which has caused seawater intrusion into the groundwater supply. As a result, more people consume bottled water at high costs.

Table I. Water inventory in Indonesia: Surface water and ground water [1,2]

Island(s)	Area	Population	Water resource	Water demand		Water resource	
	Million-km^2	Million	(mill.m^3/yr.)	(mill.m^3/yr.)		(Thousand m^3/yr.)	
				2000	2015	Per-km^2	Per-capita
Java	0.133	113.6	187,000	83,378	164,672	1,406	1.6
Lesser Sunda	0.086	10.8	60,000	13,827	42,274	698	5.5
Celebes	0.187	13.5	247,000	25,555	77,305	1,321	18.3
Sumatra	0.471	40.1	738,000	25,298	49,583	1,567	18.4
Borneo	0.535	10.2	1,008,000	8,204	23,093	1,884	98.8
Mollucas+ Papua	0.492	3.9	981,000	589	1,886	1,994	251.5
Indonesia	**1.905**	**192.2**	**3,221,000**	**156,850**	**358,813**	**1,690**	**16.8**

In an effort to meet the current and future energy demands, Indonesia initiated and carried out Nuclear Power Plant (NPP) programs in the early 1990s, although they had been suspended following the epidemic economic crisis in Asia in 1997. Nevertheless, other activities, such as IAEA Extra Budgetary Programs, have continued in order to develop the knowledge and operational experiences on the existing three Indonesian research reactors, thereby building grass-root knowledge on NPP for future constructions. The Presidential Decree Number 5 (Year 2006) on National Energy Policy specified a target of achieving great than 5% energy mix from new and renewable energies by 2025 using biomass, nuclear, hydro, solar and wind. Indonesia is now planning to construct a nuclear power plant in Muria area (Ujung Lemah Abang, Ujung Watu and Ujung Grenggengan) by 2016. Other plans include the continuation of feasibility studies and evaluation of desalination plants for Muria.

2. Plan for desalination in Indonesia

There are about 12,500 desalination plants in the world, half of which are located in the Middle East. The total worldwide desalination capacity is approaching 30 million m^3/day, with the single largest unit producing 454,000 m^3/day. Most of the desalination plants today use fossil fuels. The Multi-Stage Flash (MSF) distillation process using steam is the most commonly adopted technology today. Reverse Osmosis (RO) driven by electric pumps is becoming popular because of its energy efficiency, i.e. 6 kWh/m^3 as opposed to 25 to 200 kWh/m^3 consumed by MSF. However, the water quality is inferior to MSF distillation. There are also other types of desalination, such as Multi-Effect-Distillation (MED) or Vapor Compression (VC). MSF-RO hybrid plants exploit the best features of each technology. The choice of the process generally depends on the relative economic values of fresh water, product quality and fuel costs. To put it in the context, a typical nuclear power plant is capable of desalinating 80,000 to 500,000 m^3/day with no greenhouse emission, thereby making it an attractive proposition.

Single-effect desalination processes are suitable for remote and small population areas. They are based on various types of Mechanical Vapour Compression (MVC) techniques, comprising mechanical compression, steam jet ejector, solute-water vapour absorption, and solid-water vapour adsorption. The single effect MVC desalination process is most attractive among various single-stage desalination processes. The MVC system, driven by electric power, is compact and confined, and does not require external heating source. As such, it is suitable for remote population areas with access to power grid lines. Operating at low temperatures around 70°C, as opposed to 140°C for MSF, this system is less prone to thermal losses, scaling and corrosion. Only limited literature studies on MVC modelling and analyses have been made.

3. Mechanical vapour compression desalination

The MVC desalination process design is based on the material balance, energy balance, heat transfer for evaporator/condenser and preheater, and specific power consumption that was reported elsewhere [4]. The main parameters considered are thermo physics, thermodynamics and heat exchange process for the whole system. Operating temperatures and salt concentration are also taken into account during the design because they affect the power consumption and unit cost of the product.

A prototype is being developed at BATAN, as shown in Fig. 2. It comprises 5 main functional parts: (a) mechanical vapour compressor, (b) evaporator/condenser heat exchangers, (c) preheaters, (d) pumps, and (e) containment tank (vacuum chamber) [4].

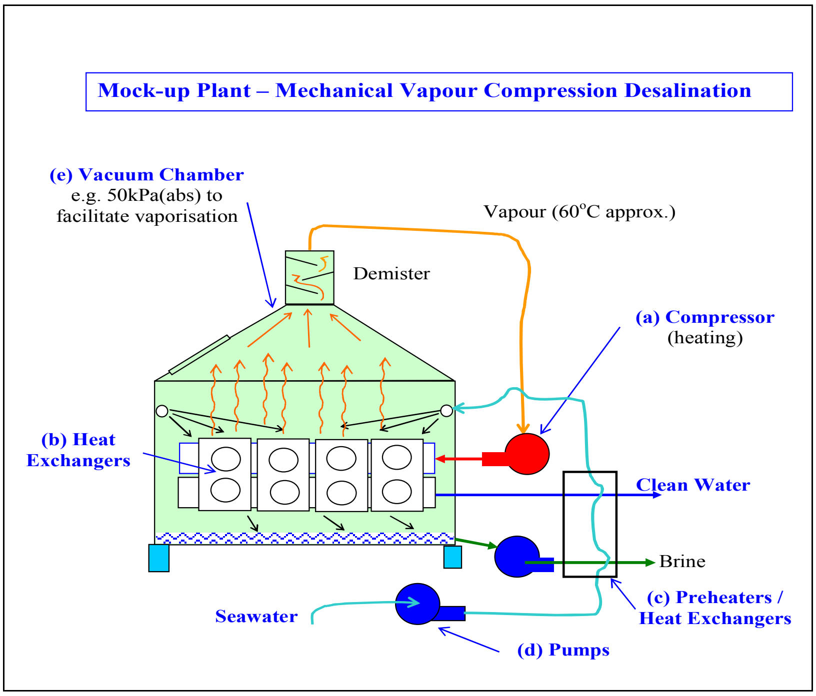


FIG. 2. Process diagram for MVC

Seawater at around 25°C is pumped into the preheaters where it is heated by using waste heat from the desalination process. The preheated seawater flows into the sprayer rails and sprays onto the main heat exchangers for evaporation. Skin temperatures of the heat exchanger are kept around 80 to 100^{o}C depending on the compressor used. The containment is maintained at negative pressures or partial vacuum (approx. -50kPa gauge) to aid evaporation at low temperatures. The mixture of water vapour (gas) and mist (liquid) naturally rises to the top and extracted into the compressor via the demister. The demister, placed atop, filters out liquid mist and allows desalinated water vapour to pass through to the compressor. The vapour is then superheated by compression and pumped to the heat exchangers to provide heating required for evaporation (previous process) and, in exchange, cooled and condensed into liquid water or the final product. It finally passes through the preheater to transfer its residual heat/energy to warm up seawater intake at the beginning of the process. Brine also passes through the preheater to contribute its waste heat for the desalination process.

4. Design description

4.1. Preheater

The Preheater is designed to maximize energy utilization by recycling waste heat back into production. Following the evaporation process, hot brine and desalinated water are discharged via heat exchanger core tubes while cold seawater intake passes over them to warm up by the discharging fluids. For optimum performance, the brine side of the heat exchanger needs to be 10 times larger than the fresh waterside. As shown in Fig. 3, the heat exchanger has 2 separate chambers, one for the brine cooling (121 tubes x 1.8 m long) and the other for the fresh water cooling (19 tubes x 1.8 m long). The tube material is stainless steel, grade 304, 16 mm outside diameter and 1.2 mm shell thickness. The tube bundles are cased by a stainless steel pipe (324 mm inner diameter and 4 mm thick) and ported with flange connections to flow working fluids. Standard pipe and tube sizes are used to facilitate procurement and manufacture.

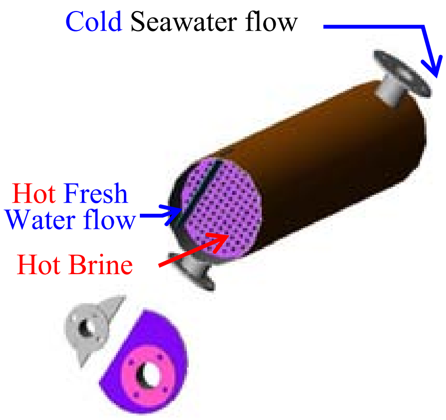


FIG. 3. Preheater

4.2. Heat exchanger - Evaporator/condenser

The required surface area for evaporation and condensing has been calculated to be 23.8 m^2, or a total length of 345 m of stainless steel (grade 304) tubes with 16mm outer diameter and 1.2 mm thick. Heat transfer coefficients for evaporation and boiling are 4.15 $kWh/m^{2o}C$ and 4.32 $kWh/m^{2o}C$, respectively. Boiling and evaporation coefficient are 4 $kWh/m^{2o}C$, and condensation coefficient is 53 $kWh/m^{2o}C$.

The heat exchanger design is shown in Figure 4. It consists of 4 modules, each comprising 29 tubes with effective length of 1.7 m × 2 (2 passes). The modules are flange connected to the inlet and outlet headers. This system allows future expansion if so desired.

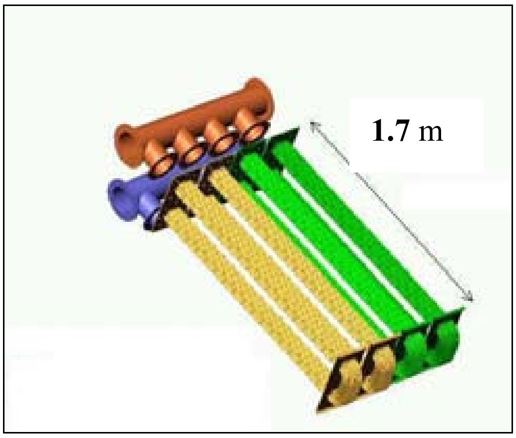
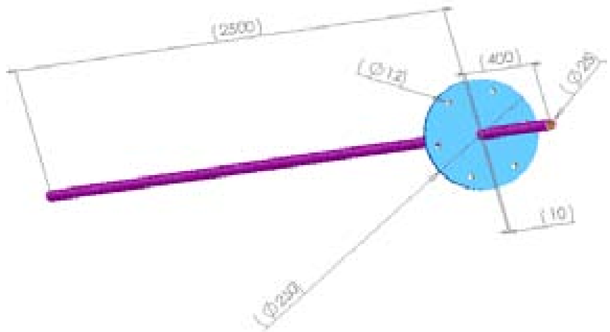


FIG. 4. Heat exchanger: Evaporator/condenser

4.3. Sprayer

Two stainless steel spray rails (ϕ25mm tube with series of holes along the 2.5 m length) are inserted into the containment tank. As shown in Fig. 5, they are flange connected to the tank with a view to facilitating replacement with different rails to experiment various spray nozzle designs that would yield optimum atomization and evaporation. The objective is to create thin film on the heat exchanger tube surfaces for maximum evaporation of pure water with minimum mix of mist (liquid).



Plan View: As installed into Containment

FIG. 5. Sprayer assembly

4.4. Containment

The containment tank, Figure 6, provides partial vacuum (-50 kPa gauge) to aid evaporation of seawater injected onto the heat exchangers. The conical roof of the tank is designed to facilitate vapour flows into the demister placed on top. The tank assembly has been designed to conform to ASME VIII Pressure Vessel Code to ensure safe operation under vacuum (or external pressure). It has not yet been fabricated but will be made of stainless steel (5 mm thick shell and 25mm thick flat base) to form 3.3m diameter and 2.5m tall containment. The heat exchangers are placed on the tank base. The tank shell is lifted in one piece, lowered onto the flanged base, and fastened (bolted and sealed) to contain the system. It has viewing ports, fluid inlet/outlet ports, vacuum/vent ports, and many service ports for insertion of various spray rails for experiment and other applications.

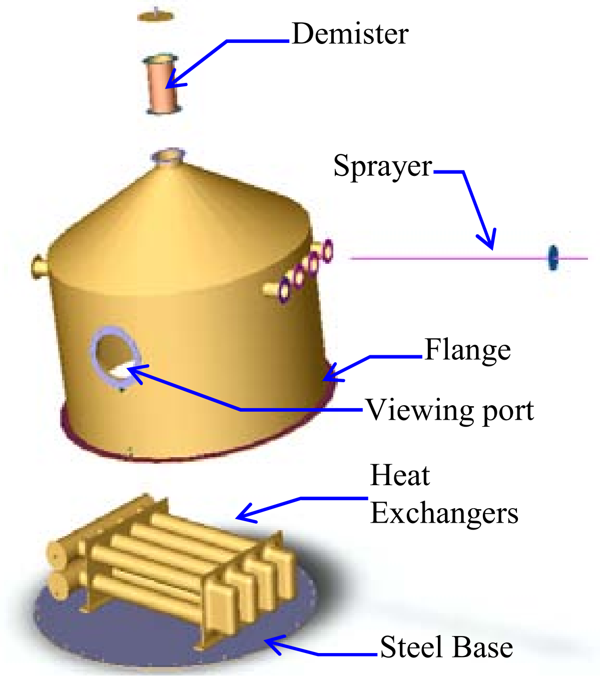


FIG. 6. Containment tank

4.5. Demister

The demister, Figure 7, is flange connected to the containment tank to form a chimney. Its function is to segregate unwanted water mist from the vapour. Demister materials are yet to be determined after some trials. Ideally, they should have the following properties; low water absorption, resist 70^{o}C, low flow restriction, high efficient mist filtration, cheap, no flooding, high capacity and compact. The demister housing has been designed to facilitate experiments with various demister materials. It has a perforated metal base to contain demister material while allowing the vapour to pass through and coalescing mist/liquid to drain back into the tank. The assembly is made of stainless steel ϕ300mm, 3mm thick shell and 500mm tall. Flanges are provided at both ends to facilitate removal and replacement of demister materials.

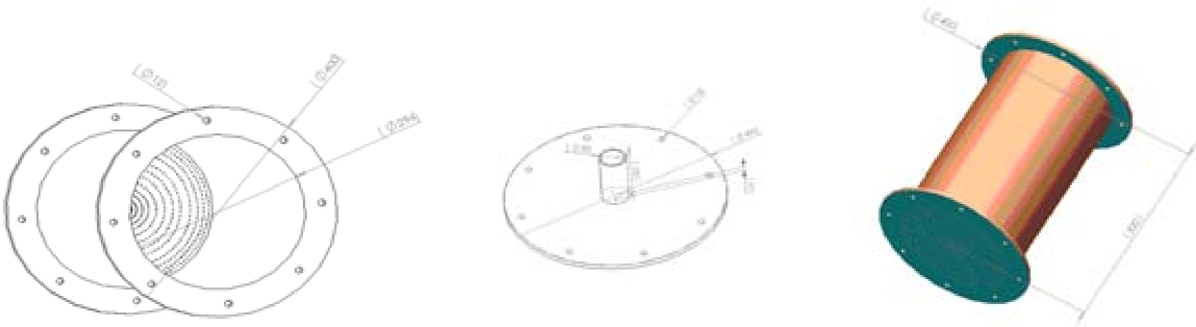


FIG. 7. Demister assembly

5. Results and discussion

A small scale MVC desalination plant has been designed to produce 0.5 m^3/day (~6 mL/s). Power consumption is estimated to be 322 kWh/m^3. Desalination efficiencies have been studied in terms of heat exchanger capacities and fresh water production rates, see Fig. 8. The capacity of the main heat exchanger is found to be dominating the system performance and directly affects the product throughput. That is, any increase in heat exchanger size is realized by a greater gain in fresh water production. Increase in brine preheater size also shows great return up to a certain desalination throughput, 0.1 kg/s, after which, the net gain is significantly retarded although continues to increase. On the other hand, little performance gain is observed when the fresh water preheater capacity is increased. This is yet to be tested to validate the design upon completion of system construction. Effects of demister densities have been studied. Although it did not change flow patterns, power consumption increased from 300 to 500 kWh/m^3 as the demister density was changed from 200 to 930 kg/m^3.

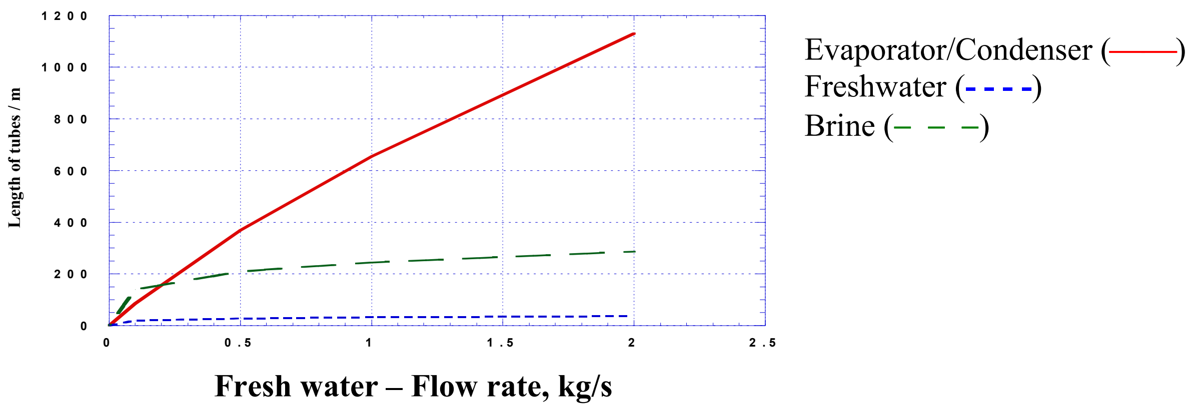


FIG. 8. Effect of heat exchanger size on desalination rate

6. Conclusion

Following the completion of the concept design, the project has proceeded with prototype construction. The mock-up plant is currently under construction in parts. It is difficult to estimate completion dates due to limited project funds and resources. Nevertheless, research activities and procurement of system components continue whenever opportunities arise. Further studies and experiments will be carried out when the mock-up plant construction is completed.

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Conceptual design of a desalination plant using the PBMR as heat source

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Abstract. The world is becoming increasingly aware of critical limitations in the availability of fresh water for agricultural, industrial and domestic uses. Because of the growing population, many regions are faced with increased fresh water demands that greatly exceed the capability of existing supply infrastructure. Less than one percent of water on earth is available for human use. It is forecasted that about two thirds of the world's population will face shortages of clean water by 2025. Interest in desalination for fresh water production has grown during the past decade. About 34 million m^3/day of desalted water is currently produced by approximately 12,500 plants set up in various parts of the world which is increasing by an annual average of 1 million m^3/day. However, these plants largely use fossil energy sources. Nuclear energy provides an alternative energy source for desalination. One of these nuclear plants is the Pebble Bed Modular Reactor (PBMR) being developed in South Africa. The PBMR Demonstration Power Plant (DPP) to be constructed in South Africa is a 400 MWt High Temperature Gas-cooled Reactor (HTGR) power plant producing 165 MWe of electricity, using a direct single-shaft Brayton cycle. The PBMR rejects approximately 220 MWt to the environment through its inter-cooler and pre-cooler at a water temperature of approximately 70°C. This waste heat can be utilized for desalination processes like Multi Effect Distillation (MED) and Reverse Osmosis (RO) with pre-heating. This paper will report on the opportunities of using PBMR technology to address water scarcity concerns. The focus of the paper is to present conceptual designs and layouts of PBMR coupled desalination plants and will include a description of the challenges and integration options of coupling desalination technologies with the PBMR DPP and will include economic evaluations of the integrated PBMR desalination plant options.

1. Introduction

The supply of fresh water and energy is fundamental to quality of life. Fresh water is needed in agriculture, as drinking water and as process water in various industries [1]. Because of the growing population, many regions are faced with increased fresh water demands that greatly exceed the capability of existing supply infrastructures. The problem is compounded by increases in both pollution and salinity of fresh water resources. Development of adequate water resources, their conservation and their preservation have thus become a very important worldwide challenge. Nearly three quarters of the earth's surface are covered with water. However, 97.5 percent of this amount is represented by the oceans, which are highly saline and unfit for human consumption. Of the remaining 2.5 percent, a major portion is locked up in the ice caps. On balance, less than one percent is available for human use. According to forecasts, about two thirds of the world's population will experience shortages of clean fresh water by 2025 [2].

Approximately 34 million m^3/day of desalted water is currently being produced annually in various parts of the world. These plants largely use fossil energy sources. Interest in using nuclear energy for producing potable water has been growing worldwide over the past ten years. This has been motivated by a wide variety of drivers such as economic competitiveness, energy supply diversification, conservation of limited fossil fuel resources, environmental protection and spin-off effects of nuclear technology in industrial development [2].

The PBMR, under development in South Africa, is an advanced helium-cooled graphite moderated high-temperature gas-cooled nuclear reactor. The heat of the PBMR can be used to produce electricity or alternatively be applied to a variety of process applications. The 165 MWe PBMR DPP, to be built for the South African utility Eskom on its existing Koeberg Nuclear Site, is well suited for coupling with a desalination plant. The PBMR DPP rejects ~220 MW of waste heat through the pre-cooler and inter-cooler at ~70°C. This waste heat is ideally suited for some desalination processes and can be used without negatively impacting on the power output and efficiency of the nuclear power generating plant. The PBMR DPP could therefore be coupled to a desalination plant to produce clean fresh water for the Western Cape region, which suffers from water scarcity.

This paper discusses the opportunities of using PBMR technology to address water scarcity concerns by coupling the PBMR DPP to a desalination plant. Conceptual designs and layouts of PBMR DPP coupled desalination plants is presented together with a description of the challenges, integration options and a high level economic evaluation of the integrated desalination plant options.

2. PBMR

The PBMR DPP will be built in South Africa in the Western Cape on the existing Koeberg Nuclear Site. Construction is scheduled to start during 2008 with commissioning scheduled for 2012/13.

The PBMR DPP utilizes a direct recuperative Brayton cycle with helium as working fluid. PBMR fuel is based on a proven, high-quality German fuel design consisting of low enriched uranium triple-coated isotropic (LEU-TRISO) particles contained in a molded graphite sphere. The PBMR DPP has a thermal power rating of 400 MWt and produces ~165 MWe of electricity to the grid.

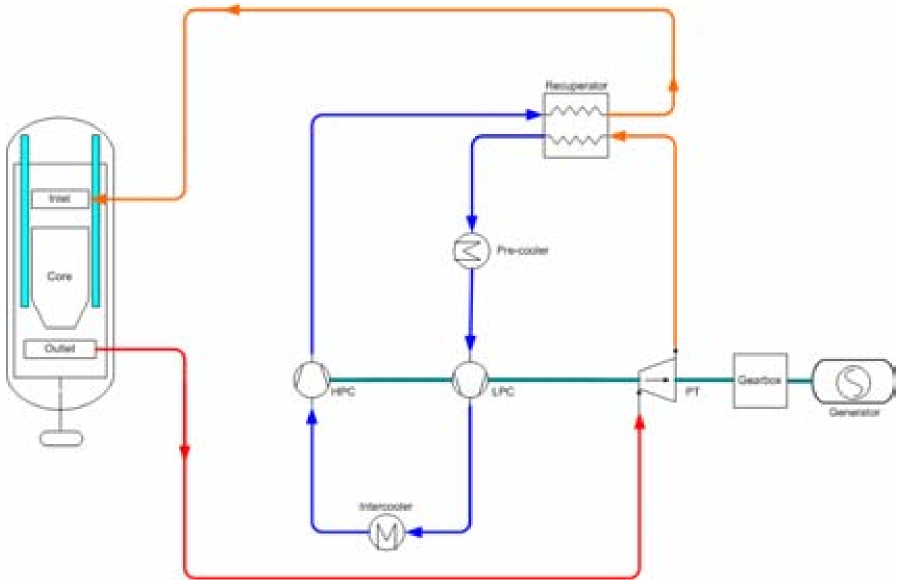

FIG. 1. Schematic representation of the PBMR DPP power conversion unit

The Brayton cycle utilizes a pre-cooler and inter-cooler to cool the helium before entering the low-pressure compressor (LPC) and the high-pressure compressor (HPC) respectively. Figure 1 shows a schematic layout of the PBMR DPP power conversion unit. The secondary side of both the pre-cooler and inter-cooler use demineralized water as secondary heat transport medium. The pre-cooler and inter-cooler combined reject ~220 MWt of waste heat at a water temperature of ~70°C. This is an advantage of high temperature gas-cooled reactors using a Brayton cycle over power plants using conventional light water reactors, since the conventional nuclear plants reject waste heat at lower temperatures of ~35°C.

The PBMR DPP makes use of a closed, intermediate loop between the secondary side of the pre-cooler and inter-cooler and the ultimate heat sink. Figure 2 shows a schematic of a typical single PBMR DPP cooler circuit. The waste heat rejected by the pre-cooler and inter-cooler is ideally suited for some desalination processes.

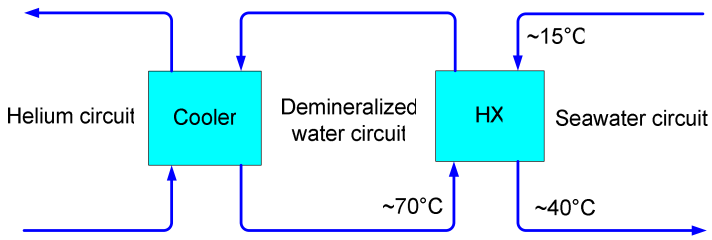

FIG. 2. Typical conditions for a PBMR DPP cooler circuit

3. Desalination technologies: A brief overview

Currently, a number of commercially proven large-scale desalination techniques exist. The different techniques can be classified according to the process of saline separation namely thermal evaporation and membrane filtration. Presently two large-scale thermal evaporation technologies and one large-scale filtration technology exist: multistage flash distillation (MSF), multi effect distillation (MED) and reverse osmosis (RO). Thermal evaporation desalination has been used for approximately 50 years. Starting in the 1950s with MSF followed by MED that was introduced in the 1960s but did not gain wide acceptance until the early 1990s. In the early 1970s, RO started to gain momentum [3]. RO is based on membrane filtration rather than thermal evaporation and is more energy efficient compared to the evaporation based processes. However, RO consumes electricity rather than heat. Currently RO is the fastest growing desalination technology worldwide. Nuclear desalination plants have been in operation for more than 20 years in Japan and Kazakhstan. Nuclear reactor operating experience for desalination exceeds 150 reactor-years with an exceptional safety record as of 2000 [6].

3.1. Multistage Flash Distillation

MSF has been one of the leading desalination processes, because of operational simplicity, proven performance and availability of standard designs and equipment. It is advantageous in large capacity ranges where thermal energy is available in the form of low-pressure steam.

Figure 3 shows a schematic representation of a MSF process. In the MSF process, the seawater feed is first sent to a chemical pre-treatment system. The seawater feed passes through tubes in each evaporation stage where it is progressively heated. Final seawater heating occurs in the brine heater by the heat source. Subsequently, the heated brine flows through nozzles into the first stage, which is maintained at a pressure slightly lower than the saturation pressure of the incoming stream. As a result, a small fraction of the brine flashes forming pure steam. The heat to flash the vapor comes from cooling of the remaining brine flow, which lowers the brine temperature. The produced vapor condenses on the outside of the condensing brine tubes and is collected in a distillate tray. The heat transferred by the condensation warms the incoming seawater feed as it passes through that stage. The remaining brine passes successively through all the stages at progressively lower pressures, where the process is repeated. The hot distillate flows from stage to stage and cools itself by flashing a portion into steam which is re-condensed on the outside of the tube bundles.

The capital cost of MSF plants varies from \$1,000 to \$3,000 per m^3/day installed capacity and MSF plants have reached a mature and reliable stage of development. Unit sizes up to 60,000 m^3/day have been built [2].

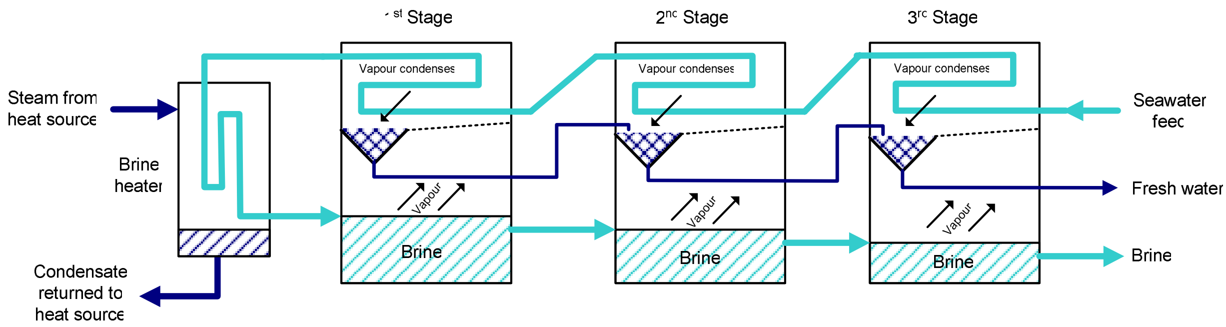

FIG. 3. Schematic representation of a MSF process

3.2. Multi Effect Distillation

Figure 4 presents a flow diagram of a MED process. In each effect, heat is transferred from the condensing water vapor on one side of the tube bundles to the evaporating brine on the other side of the tubes. This process is repeated successively in each of the effects at progressively lower pressure and temperature, driven by the water vapor from the preceding effect.

In the last effect at the lowest pressure and temperature the water vapor condenses in the heat rejection heat exchanger, which is cooled by incoming brine. The condensed distillate is collected from each effect. As a heat source, low-pressure saturated steam is generally supplied by steam boilers or dual-purpose plants (co-generation of electricity and steam). MED plants have a much more efficient evaporation heat transfer process than MSF plants. Due to the thin film evaporation of brine on one side of the tubes and the condensation of vapour on the other side, high heat transfer coefficients are achieved. Consequently, the number of effects for a given temperature difference between heat source and cooling water sink can be increased in comparison to MSF plants, thus decreasing the specific heat consumption. The pre-treatment of seawater for MED plants is similar to that in MSF plants. Some low temperature horizontal tube designs need a more stringent filtration of the seawater feed, as a result of the small nominal diameters of the brine distribution devices, which do not permit the presence of relatively large suspended particles in seawater.

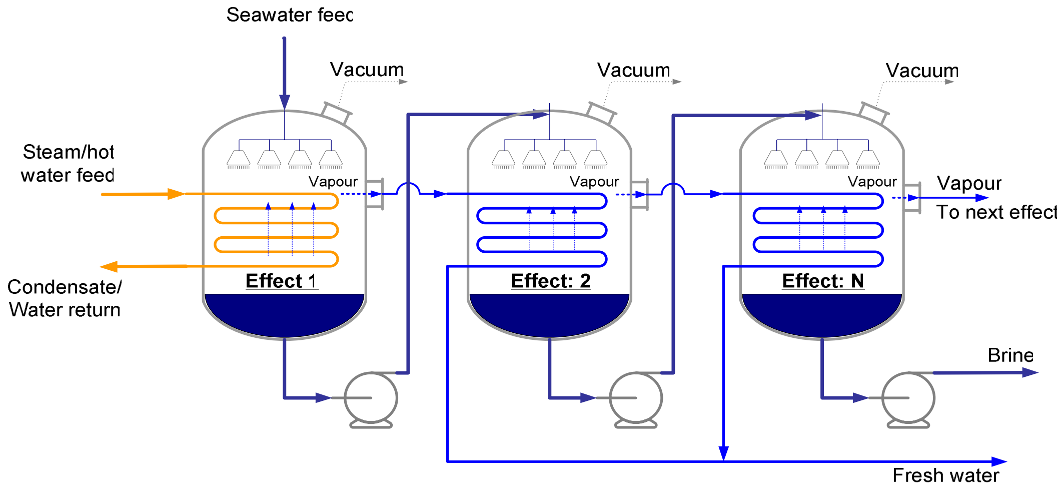

FIG. 4. Schematic representation of a MED process

The MED process produces water with approximately 5-25 parts per million (ppm) total dissolved solids (TDS) from 35,000 to 45,000 ppm TDS of seawater. The energy efficiency of the MED plant can be increased by increasing the number of effects. The Gain Output Ratio (GOR) for a MED process is theoretically equal to the number of effects, but practically somewhat less, because of heat losses. Alternatively the MED process can also operate with a low temperature feed water temperature of up to 70°C. This process is called the Low Temperature (LT)-MED process and holds a number of advantages over the High Temperature (HT)-MED process [2]. The lower operating temperatures reduce operational problems caused by scaling and corrosion and limit the amount of expensive materials required.

According to current trends and expectations, MED may likely be one of the dominating processes for thermal desalination in the small and medium capacity ranges. Current MED capital costs vary from $900 to $2,000 per m^3/day capacity [2].

3.3. Reverse Osmosis

RO is a membrane separation process in which pure water passes from the high-pressure seawater side of a semi-permeable membrane to the low pressure permeates, or “pure” water, side of the membrane. Figure 5 shows a schematic representation of a typical RO process. In order to overcome the natural osmotic process, the seawater side of the system has to be pressurized to create a sufficiently high net driving pressure across the membrane. In practice, the seawater can be pressurized to pressures as high as 70-80 bar. RO systems require stringent feed water pre-treatment in order to protect the membranes from effects such as scaling and fouling, including biological fouling. The extent of pre-treatment requirements depends on a variety of factors, such as seawater composition and temperature, seawater intake, membrane materials and recovery ratio.

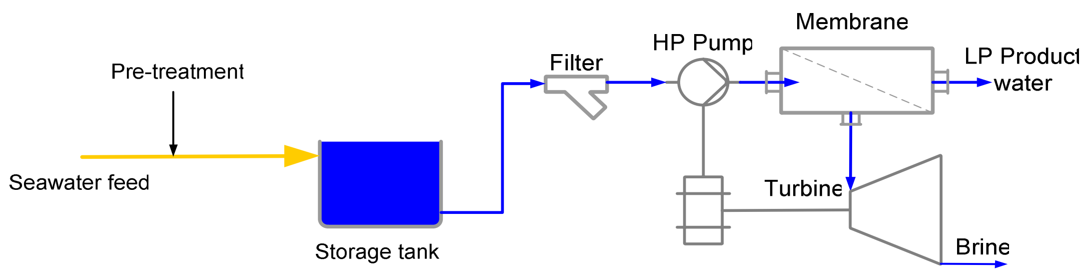

FIG. 5. Schematic representation of a RO process

The performance of an RO plant is evaluated in terms of the recovery factor, the permeate flux and the percent salt rejection. The recovery factor is the ratio of permeate flow rate to seawater feed flow rate. The permeate flux is the flow rate of permeate water across a unit of membrane area. A typical RO desalination plant consists of a pretreatment section, a high-pressure pump, RO modules and a post-treatment section. RO normally uses only electrical energy, and the largest power consumer is the high-pressure pump, which delivers flow at a head of 70-80 bar. In large capacity RO desalination plants, it is possible to recover around 30-40 percent of the energy from high pressure reject brine by energy recovery systems such as pelton wheels and hydro turbines. The energy consumption in seawater RO plants using energy recovery units is around 4-6 kWe·h/m^3 of product water [2].

Elevated feed water temperatures yield both high flux and high salt passage. Using the waste heat discharged from a power plant or thermal desalination plant to pre-heat the RO feed water may be economically attractive as long as the upper temperature limit of the membrane is not exceeded. The capital costs of RO plants vary from \$900 to \$1,700 per m^3/day capacity [2].

4. Desalination with the PBMR DPP

The MSF process is advantageous where thermal energy in the form of low-pressure steam at 100-110°C is available [2]. It has a proven performance, design and equipment record and can deliver product water with high levels of purity. However, considering that the MSF process ideally requires heat at 100-110°C this process will not be ideally compatible with the low temperature waste heat rejected by the PBMR DPP. LT-MED and RO with pre-heating presents compatible desalination technologies for coupling with the PBMR DPP and will subsequently be evaluated as possible desalination options.

4.1. MED for the PBMR DPP

The newer, MED process has several process advantages that are increasing its application around the world. MED plants use approximately 33 percent of the electrical power required by an equivalent MSF system, and can also operate at lower temperatures (e.g. 65°C versus 110°C) than MSF systems. The lower operating temperatures reduce operational problems caused by scaling and corrosion. Seawater intake water requirements can be up to 50 percent smaller than that of a similarly sized MSF installation. The capital, operating and energy cost advantages of MED over the MSF are well known. Until recently, the size of commercial MED units was generally limited to small and mid-size plants. New installations have however demonstrated that the MED's economic advantages can be exploited in larger plants as individual units are produced with rated capacities of up to 22,700 m^3/day [4]. The LT-MED process produces high levels of product water purity between 5-25 ppm TDS from seawater containing 35,000 to 45,000 ppm TDS [4].

Figure 6 presents a schematic of a PBMR DPP coupled MED plant utilizing the intermediate cooling water circuit as heat source. The water in the intermediate circuit enters the first effect of the MED plant at approximately 65°C. The layout shown by the figure provides operation flexibility since the ultimate heat rejection heat exchanger is not replaced by the MED brine heater. Whenever the desalination plant needs to undergo maintenance the brine heater can be bypassed resulting in the ultimate heat rejection heat exchanger rejecting all the waste heat from the PBMR DPP. The MED plant can also be sized to utilize only a fraction of the total waste heat rejected by the PBMR DPP, since the ultimate heat rejection heat exchanger will reject the excess waste heat not utilized by the desalination plant. If a higher feed water temperature to the MED plant is preferred, the configuration shown by Fig. 6 can be slightly altered to only utilize the water rejected by the pre-cooler, which is at a slightly higher temperature (70°C). However, this would result in a reduced amount of waste heat available for desalination, since the pre-cooler only rejects ~121 MWt.

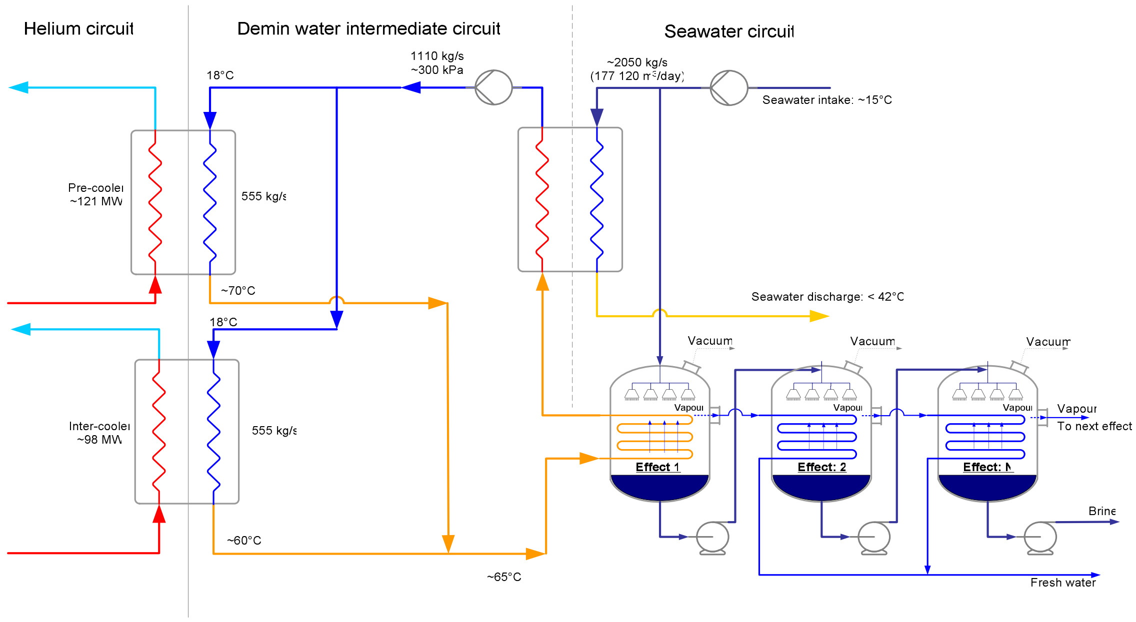

FIG. 6. Schematic of LT-MED plant coupled with the PBMR DPP heat rejection system

A MED plant with a conservative GOR of 2.0 coupled to the PBMR DPP as shown by Fig. 6, will be able to produce

$$Output = \frac{GOR \times WasteHeat[MWt] \times 3600[\sec/hr] \times 24[hr/day]}{h_{fg}[MJ/kg] \times \rho_{water}[kg/m^3]}$$

$$Output = \frac{2 \times 220[MWt] \times 3600[\sec/hr] \times 24[hr/day]}{2.4[MJ/kg] \times 1000[kg/m^3]} = 15,840 m^3/day$$

of clean water [7]. Table I shows the influence of an increase in GOR versus product water output.

Table I GOR versus product water output

GOR	Product Water Output (m^3/day)
2	15,840
3	23,760
4	31,680
5	39,600

Assuming that water in South Africa will be sold at an average price of $0.57/$m^3$ (assuming a 6 percent increase over the next 6 years from current levels of $0.4/$m^3$ [5]), a MED plant coupled to the PBMR DPP producing 15,000 m^3/day (95 percent plant availability), could produce product water revenues of approximately $8,550/day. This could be compared to electricity revenues of $95,040/day assuming an electricity price of $24/MWh (assuming a 6 percent increase over the next 6 years from current levels of $17/MWh). A LT-MED desalination plant could therefore add approximately 9 percent to the PBMR DPP revenues.

If a capital cost of $1,450 per m^3/day capacity [2] is assumed, the cost of a 15,000 m^3/day PBMR DPP coupled MED plant is estimated at $21.75 million. Considering the above-mentioned economic parameters a straight payback period of 7 years could be achieved.

The output of the LT-MED plant can be increased (as shown by Table I) by increasing the number of effects (heat exchanger area). This would increase the revenues generated by the MED plant albeit at increased capital cost.

4.2. RO for the PBMR DPP

RO membrane systems are the fastest growing segment of the desalination market. This growth can be attributed to technology advances over the past ten years that have improved membrane performance and reduced manufacturing costs.

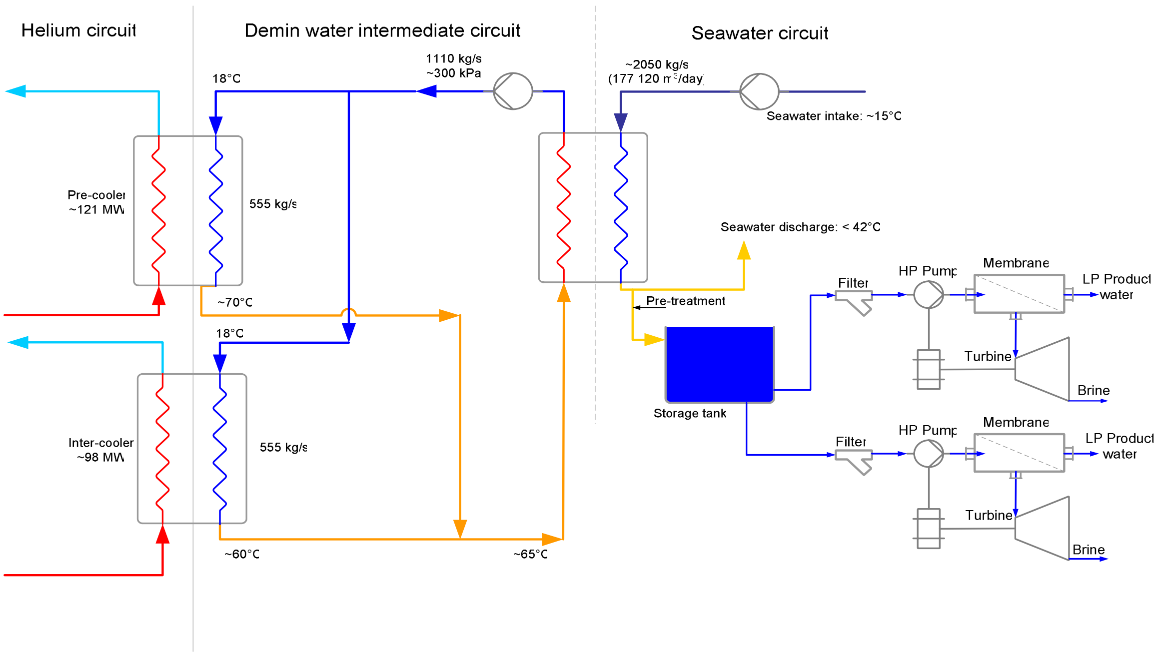

FIG. 7. Schematic of RO plant coupled with the PBMR DPP heat rejection system

Figure 7 presents a schematic of a PBMR DPP coupled RO plant. The ultimate heat rejection heat exchanger of the PBMR DPP provides the RO plant with pre-heated seawater feed at ~40°C. Since the RO plant requires mainly electrical energy to drive its high pressure pumps the PBMR DPP will provide the RO plant with the required electrical energy from the grid. The net electricity generated by the PBMR DPP will therefore be less, depending on the size of the RO plant. The RO plant could consist of a number of modules as shown by the figure. Additional modules can be added as the fresh water demand escalates. Considering that the PBMR DPP rejects ~2050 kg/s of seawater at a temperature of < 42°C and assuming a recovery ratio of 40 percent for the RO plant a maximum of 70,848 m^3/day could be produced by a multi-module RO plant. The plant layout shown by FIG. 7 allows the RO plant to undergo maintenance at any stage without affecting the operation of the PBMR DPP, since the seawater discharged by the PBMR DPP ultimate heat rejection system can be routed to the ocean instead of the RO plant.

A PBMR DPP coupled RO desalination plant producing 15,000 m^3/day (similar to the MED plant evaluated previously) of clean, fresh water would require approximately 3.8 MWe on a continuous basis.

Assuming a water cost of \$0.57/m^3 in South Africa, a revenue of \$8,550/day could be generated by the RO plant. The associated electricity cost would be \$2,189/day. The capital cost of the plant would be in the order of \$19.5 million if a capital cost of \$1,300 per m^3/day capacity [2] is assumed. The desalination plant would result in net revenues of \$6,361/day, which would result in a straight payback period of 8.4 years.

5. Challenges

The feasibility of the different desalination options for coupling with the PBMR DPP remains to be assessed in terms of the site specific seawater quality, which will affect the pre-treatment requirements of the deslination options. A trade-off economic evaluation needs to be performed for the MED and RO options in order to determine the best suited option for the specific application in terms of economic performance.

A further challenge is to assess the fresh water market that exsits in surrounding areas of the Koeberg Nuclear Site. The market will have a significant influence on the choice of the desalination option. MED produces high quality, low salt content water fit for industrial applications. In order to produce acceptable drinking water from a MED plant, minerals will have to be added to the product water The low salt content product water produced by the MED plant can also be blended with existing drinking water sources to produce acceptable drinking water quality. RO produces lower quality product water fit for human use.

6. Summary

The possibility to address water scarcity concerns by using desalination technologies in conjunction with the PBMR was investigated in this paper.

MED and RO are mature and proven desalination technologies. These technologies present feasible options for a PBMR DPP coupled desalination plant. The waste heat rejected by the PBMR DPP is ideally suited for a LT-MED process or a RO process in which the feed water is preheated to increase the efficiency of the process. A desalination plant coupled to the PBMR DPP could deliver 15,000 m^3/day of clean, fresh water serving between 55,000 and 300,000 people in the Western Cape region.

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Feasibility study for nuclear desalination plant construction in Madura island

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Abstract. During 2005-2006 BATAN performed a technical cooperation project of TC-INS/4/034 under the arrangement of the International Atomic Energy Agency (IAEA) as assistance to carry out a Feasibility Study for Nuclear Desalination Plant Construction in Madura Island. The objectives of the study is to conduct a feasibility study for preparation and introduction of nuclear desalination. The activities that have been done during 2005-2006 are : Study on Human Resources Development on Industrialization in Madura, The Projection of Water Supply and Demand up to year 2020 In Madura Island, Workshop on Public Information & Education of Nuclear Desalination.

Keywords: Feasibility Study for Nuclear Desalination Plant Construction in Madura Island

1. Introduction

The Madura Island belongs to the East Java Province, geographically being separated from the Java Mainland by the Surabaya Strait. It is inhabited by 3.1 millions people in four administrative regions as of 2000 and their main occupation is agriculture producing rice, tobacco and corn, and salt industries. It has big potential of industrial development if the energy and fresh water demands are met. If the Suramadu Bridge connecting Surabaya and Kamal/Madura will be realized, the industries and tourism development in the Island, mainly in the Bangkalan area will be greatly stimulated.

Power supply on the Island has depended on the Java Island through transmission lines across the Surabaya Strait. Surrounding the Island, potential energy resources are believed to exist in terms of hydrocarbon basins containing oil and gas. Unfortunately these are not in sufficient quantity and mostly delivered to the industries in the Java Island. Concerning the water resources, the Madura Island mainly depends on rainfall, not very countable, and some limited groundwater resources. The development of the Madura Island largely depends on the availability of power and water. Stable supply of power and fresh water is the key element to make it happen.

Considering a realistic approach of providing the area of interest on the Island with both electricity and fresh water simultaneously by a co-generating power plant on the Island, which is independent of the risk of supply interruption due to unpredictable accidents across the Strait, the National Nuclear Energy Agency (BATAN) has conducted Feasibility Study for Nuclear Desalination Plant Construction in Madura Island under IAEA Program TC-INS/4/034. The study was conducted in the year 2005-2006 and it covered Study on Human Resources Development on Industrialization in Madura, The Projection of Water Supply and Demand up to year 2020 In Madura Island, Workshop on Public Information & Education of

Nuclear Desalination. The proposed project will offer a practical and realistic option to provide the Madurese with sufficient power and potable water for the public and to support industrialization and tourism in the Madura Region.

2. Study on human resources development on industrialization in Madura

This study aims at arriving at rich description about human resources readiness toward industrialization by 1) determining the direction of industrialization development, 2) discovering supporting as well as interfering factors, 3) identifying alternative solution to the problems, 3) analyzing human resources capacity in terms of Human Development Index, 4) recognizing labor development strategy, 5) noticing the role of education in developing human resources, 6) formulating human resources development agenda. Some supporting factors associated with the industrial development scenario in Madura are Suramadu Bridge, and the availability of facilities and infrastructure. In addition, there are some interfering factors to be considered such as low perception of the local community on the importance of industrialization as well as the shortage of electricity and water intake. The alternative solutions to the obstacles above are to promote socialization program on the importance of industrialization for the advancement of Madura region by all related stakeholders while considering the use of NPP-SMART and desalination over water and electricity problems. The industrialization development scenario in Madura is shown in Fig. 1. Labor development strategy policy can be carried through; 1) improving accessibility to Madura to speed up the flow of outside investment, production as well as business; 2) promoting local labor force; 3) improving the prevailing economics activities; 4) improving local government capacity to attract outside investors based on its comparative and competitive superiority; 5) promoting qualified capacity toward local human resources.

Seen from their positive aspect, Maduranese are known as people who have strong motivation, religious obedience, and honesty. However, for some reason they also embody such negative aspects as unpunctuality, inefficiency, uncooperativeness, quick–tempered and narrow-minded. They are migratory people and this becomes their tradition. A majority of Maduranese dominantly work in the informal sector especially trade. The role of religious leaders is very dominant in directing the manpower development program.

Generally the values of Life Expectancy Index (LEI), Educational Index (EI), and Human Development Index (HDI) are considered lower than that of East Java. Nevertheless, Maduranese’s Purchasing Power Parity Index (PPI) seems to be so high that they have strong purchasing power. With regard to industrial scenario, Maduranese’s HDI value is still relatively low due to its human resources quality that it turns into serious threat in competing with other people of different areas in the formal sector. Nevertheless, because of its prevailing self-identity such as spirit, persistent will power, and high work ethos, Maduranese still has competing power in informal sector. The Human Resources Based on HDI Analysis in Madura and Some Other Areas of East Java in 2004 is shown in Table I [1].

Table I. Human resources based on HDI analysis in Madura and some other areas of East Java [1]

Regency	LEI	EI	PPI	HDI
Gresik	74,33	78,53	61,44	71,44
Mojokerto	74,83	76,58	61,51	70,98
Surabaya	73,88	85,35	53,35	70,86
Sidoarjo	74,17	85,09	56,93	72,06
Lamongan	74,05	70,66	56,15	66,95
Bangkalan	62,33	59,84	56,89	59,69
Sampang	55,92	48,87	57,18	53,86
Pamekasan	65,75	64,78	57,11	62,55
Sumenep	62,00	59,23	53,69	58,31
Averages MADURA	61,50	58,18	56,60	58,60
Averages (East Java)	70,33	70,92	52,21	64,49

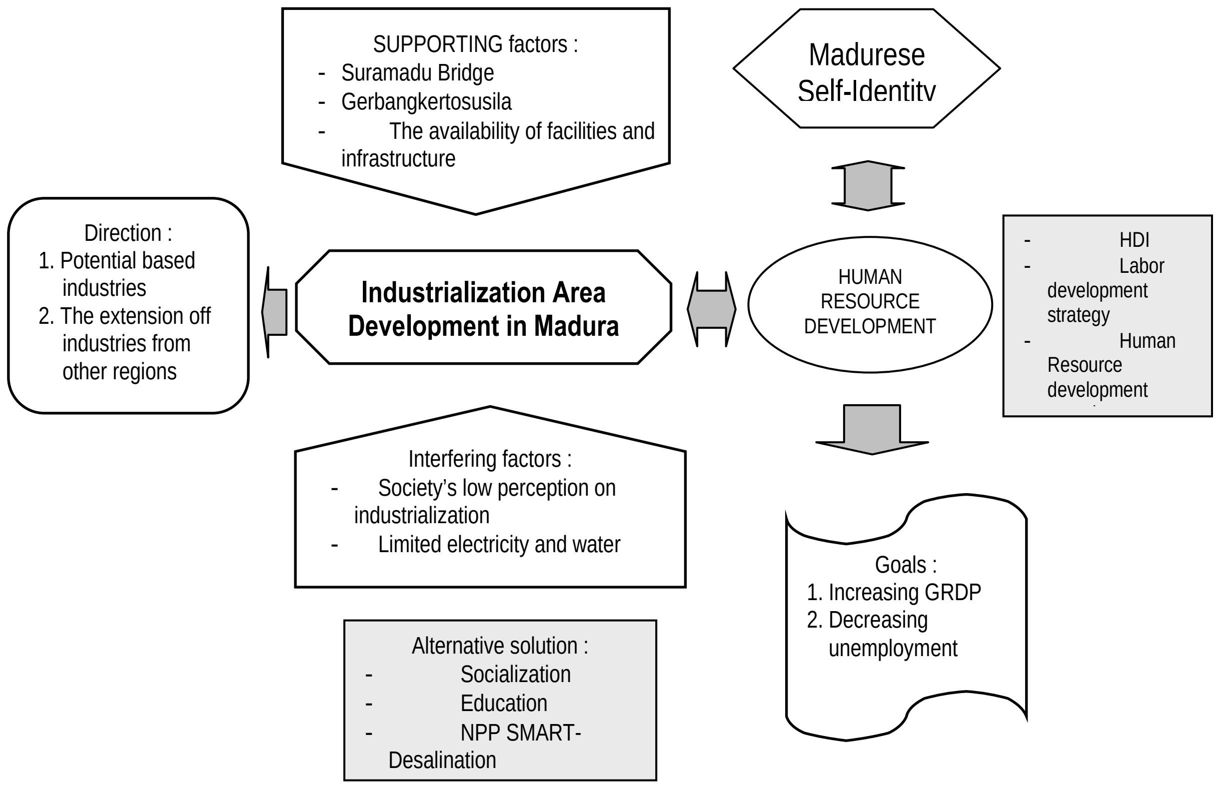

FIG. 1. Industrialization development scenario in Madura [1]

3. The Projection of water supply and demand up to year 2020 in Madura Island

Madura recognized with dry area, the rate of rainfall per year about 1408 – 1825 mm. This condition cause water availability is limited, especially in the hilly area of the middle side of the island. In dry season there are queuing people to get water. This phenomenon describes the difficulties to get water for their life. Whereas life activities need water in the rate of 60 liters/person/day in the rural areas and 120 liters/person/day in the urban areas. In 2004, potable water demand in madura islands is 257,766.91 m³/day, meanwhile the potable water supplied by water Municipality Company is 26,577.25 m^3/day and the potable water supplied by individual system is 118,270.53 m^3/day [2], it means there is potable water deficit about 112,909.13 m^3/day. In the future, potable water supply deficit will reduce to 75,196.48 m^3/day.

Due to the condition, development of water supply program should be extended to help people easier to get water. This is one of strategic program to support people health and economic development. Besides that, the government has agreed with international commitment called Millennium Development Goals (MDG) where one of its agenda is about water supply and sanitation sector and the government has also given target the supply of the water become 80% in the urban area and 60% in the rural area [2]. Supporting the water supply target, an assessment of water supply and demand has to be conducted. Madura Island was served by Municipality Water Company (PDAM) of each regency by using water resources from the wells, springs and surfaces water. The only water treatment installation unit is in Burneh district with the optimal capacity of 90 L/second.

Besides that, water supply was served by society consist of individual system and communal system. Individual system is water supply is done by a resident individually, while communal system done by gathering of resident of potable water user (hippam) organize potable water in the rural area by exploiting water resources existing in the rural area. Generally individual water supply uses dug-well, surface water, and rainfall storage. Bangkalan has five hippam serving more or less 6,700 residents. Another regency that has hippam only is Sumenep regency. The amount of hippam is as much of 27 groups [2]. These serve about 25,280 residents. The water is supplied by Municipality Water Company use pipe line to serve rural resident.

The production of potable water from PDAM in Madura Island is 61,870.22 m^3/day. The average of potable water production in each PDAM is shown in Table II.

Table II. The PDAM production average and its using in Madura 2004 [2].

Regency	Production (m^3/day)	Water using (m^3/day)	Water losses (%)
Bangkalan	17,272.20	6,946.77	59.67
Sampang	17,857.92	6,213.58	65.20
Pamekasan	10,328.80	6,989.76	32.32
Sumenep	16,599.63	6,427.14	60.00
Total	61,870.22	26,577.25	57.04

The production of potable water is from 14 springs, 51 boreholes, and one water treatment installation unit with the total capacity is 4,310 L/sec. The potable water is distributed to the customer in the served areas consist of the regency capital and district town. PDAM customer consist of domestic, government institutions, social, trading and industry.

3.1. Water supply projection

Water supply projection up to year 2020 are based on : (1) water supply by PDAM year 2004, (2) PDAM plan to reduce water loses up to 25%, (3) PDAM program to use water resources maximally and (4) assumption of projection of non pipe line MDG target. The potable water supply projection in madura is shown in Table III.

Table III. Potable water supply projection in Madura up to 2020 (m^3/day) [2]

Explanation	Projection			
	2004	2010	2015	2020
Bangkalan				
Water Supplied by PDAM	6,946,77	12,954,15	39,528,00	39,528,00
Water Supplied by individual	28,076,90	28,076,90	28,076,90	28,076,90
system	35,023,67	41,031,05	67,604,90	67,604,90
Total				
Sampang	6,213,58	13,393,44	27,540,00	27,540,00
Water Supplied by PDAM	28,114,91	28,114,91	28,114,91	28,114,91
Water Supplied by individual	34,328,49	41,508,35	55,654,91	55,654,91
system				
Total	6,989,76	7,746,60	23,544,00	23,544,00
Pamekasan	26,281,19	26,281,19	26,281,19	26,281,19
Water Supplied by PDAM	35,270,95	34,027,79	49,825,19	49,825,19
Water Supplied by individual				
system	6,427,14	12,449,72	30,780,00	30,780,00
Total	35,807,53	35,807,53	35,807,53	35,807,53
Sumenep	42,234,67	48,257,25	66,587,53	66,587,53
Water Supplied by PDAM				
Water Supplied by individual	**114,857,78**	**164,824,44**	**239,672,53**	**239,672,53**
system				
Total				
Grand Total				

3.2. Water demand projection

The projection of potable water demand is based on population in each regent, which growth rate was applied to predict future populations. By the assumption of water demand per person 120 L/day in the urban area and 60 L/day in the rural area, so in the year 2004 the domestic potable water demand is 215,273.94 m^3/day. In the future water demand will increase by increasing population. The increase is 6.20 % of water demand in the year 2004, but in 2015 and 2020 increase up to 11.69 % and 19.84 % continually. The highest potable water demand is Sumenep regency, and then followed by Bangkalan, Sampang and the lowest is Pamekasan Regency. The projection of potable water demand in each regency is shown in Table IV.

Table IV. The projection of population and potable water demands in Regencies

Explanations	Projection			
	2004	2010	2015	2020
Bangkalan				
Population (people)	791,647	840,798	884,081	948,446
Growth Rate (%)	1,01	1,01	1,01	1,01
Water Demand (m³/day)	62,611,87	65,898,22	71,278,36	75,857,94
o Domestic	50,856,97	54,014,57	56,795,55	60,930,09
o Non Domestic	11,654,90	11,883,65	14,482,81	14,927,85
– Institutional	5,546,98	5,401,45	5,247,51	6,043,06
– Public Facilities	4,836,50	5,131,84	5,395,54	5,788,75
– Trading and Industry	1,271,42	1,350,36	2,839,76	3,046,50
Sampang				
Population (people)	756,509	803,909	845,670	907,804
Growth Rate (%)	1,018	1,018	1,018	1,018
Water Demand (m³/day)	61,949,82	65,750,18	70,317,52	75,483,74
o Domestic	51,518,30	54,746,21	57,590,11	61,821,46
o Non Domestic	10,431,53	11,003,97	12,727,41	13,662,28
– Institutional	4,467,42	4,708,17	4,952,75	5,316,64
– Public Facilities	4,933,75	5,200,88	5,471,06	5,801,03
– Trading and Industry	1,030,36	1,094,92	2,303,60	2,544,85
Pamekasan				
Population (people)	719,081	763,796	803,235	861,893
Growth Rate (%)	1,012	1,012	1,012	1,012
Water Demand (m³/day)	57,246,26	60,784,92	65,263,07	70,029,05
o Domestic	47,964,25	50,951,32	53,582,17	57,495,13
o Non Domestic	9,282,01	9,833,60	11,680,90	12,533,92
– Institutional	4,467,16	4,738,47	4,983,14	5,347,04
– Public Facilities	3,615,75	3,821,35	4,018,66	4,312,13
– Trading and Industry	1,199,10	1,273,78	2,679,10	2,874,75
Sumenep				
Population (people)	1,005,053	1,067,264	1,122,038	1,203,477
Growth Rate (%)	1,006	1,006	1,006	1,006
Water Demand (m³/day)	75,958,96	80,606,93	86,556,20	92,848,57
o Domestic	64,934,43	68,953,78	72,492,64	77,754,25
o Non Domestic	11,024,53	11,653,15	14,063,56	15,084,32
– Institutional	4,620,42	4,895,71	5,146,97	5,520,55
– Public Facilities	4,780,75	5,033,60	5,291,96	5,676,06
– Trading and Industry	1,623,36	1,723,84	3,624,63	3,887,71

3.3. Water supply deficit

The potable water demands cannot be fulfilled by PDAM because the production of potable water is only 61,870.22 m³/day. Beside the water need is supplied by PDAM by using pipeline system, the publics also get the water supplies from individual system/non pipeline system. According to Public Work Department individual system can supply potable water to 50 % the publics in the towns and 56 % the publics in the rural [2]. By this assumption, individual system can supply water about 118,280.53 m³/day. By adding water supply from this system, the water demand still cannot fulfill. There is water supply deficit about 112,909.13 m³/day in 2004. The deficit of potable water supply will decrease in the future, if the water resource more explore maximized by PDAM. Prediction of water deficit in the future is shown in Table V.

Table V. Potable water supply deficit in Madura in 2004 up to 2020 (m^3/day) [2]

Explanation	Projection			
	2004	2010	2015	2020
Bangkalan				
Water Demand	62,611,87	66,438,37	71,278,36	76,467,65
Water Supplied by PDAM	6,946,77	12,954,15	39,528	39,528,00
Water Supplied by individual	28,076,90	28,076,90	28,076,90	28,076,90
system	27,588,20	25,407,32	3,673,46	8,862,75
Water deficit				
Sampang	61,949,82	65,750,18	70,317,52	75,483,74
Water Demand	6,213,58	13,393,44	27,540,00	27,540,00
Water Supplied by PDAM	28,114,91	28,114,91	28,114,91	28,114,91
Water Supplied by individual	27,621,33	24,241,83	14,662,61	19,828,83
system				
Water deficit				
	57,246,26	60,784,92	65,263,07	70,029,05
Pamekasan	6,989,76	7,746,60	23,544,00	23,544,00
Water Demand	26,281,19	26,281,19	26,281,19	26,281,19
Water Supplied by PDAM	23,975,31	26,757,13	15,437,88	20,203,86
Water Supplied by individual				
system				
Water deficit	75,958,96	80,606,93	86,556,20	92,838,57
	6,427,14	12,449,72	30,780,00	30,780,00
Sumenep	35,807,53	35,807,53	35,807,53	35,807,53
Water Demand	33,724,29	32,349,68	19,968,67	26,251,04
Water Supplied by PDAM				
Water Supplied by individual	**112,909,1**	**108,755,9**	**53,742,62**	**75,196,48**
system	**3**	**6**		
Water deficit				
Total Deficit				

The highest water deficit is in Sumenep Regency and then followed by Pamekasan, Bangkalan and Sampang respectively. Even though there are many wells in regencies but these are not used to supply potable water. Those wells are used for irrigations, which is really needed by the people for food production.

4. Workshop and seminar

4.1. National workshop on public information on nuclear desalination

The workshop has been done on November 28-30, 2005 in Pamekasan – Madura. The workshop is the workshop divided into six sessions and the end of the session is round table discussion. In round table discussion have topic Critical Problem and development of a follow up action plan for increased Public Information (PI) and understanding and responsibilities of concerned parties. The follow up actions related to the workshop were identified: Batan should continues to give information and education to the public at four regions in Madura; Batan is invited to give presentation regarding nuclear desalination program at Moslem institution in Sumenep; All the participants who attend in the workshop agreed that the nuclear desalination program should be realized soon; Department of information and communication at four regions (Sumenep, Pamekasan, Sampang, Bangkalan) will support Batan to conduct the public information in Madura; In the near future Batan will conduct study about electricity demand in Madura in each sector (domestic, industrial, transportation, etc); Batan will form “Public Information Team Work in Madura in the near future.

4.2. Nuclear science and technology seminar in Sumenep Regency on September 13, 2006

The seminar was held in Moslem Leader office in Lenteng -Sumenep – Madura on September 13, 2006. The seminar was attended by 100 persons; consists of NGO (Nahdlatul Ulama), some Moslem Leaders, Local Government, Students and University of Wiraraja. The results of the seminar are followings:

(a) The participants need more information in detail regarding the implementation of nuclear desalination in Madura.
(b) The participants are support the implementation of nuclear desalination in Madura.
(c) The participants needs detail information about benefit and unbeneficial of implementation nuclear desalination.
(d) Public information and education should be performed cooperation with NGO.
(e) The decision of implementation nuclear desalination should be taken by Madura people, not government.

4.3. Workshop on public information & education of nuclear desalination on Nov. 28- 29, 2006 in Sumenep Regency- Madura.

In accordance with Technical Cooperation (TC) program through BATAN – IAEA INS/4/034, one of the activities should be performed by Batan is “Workshop on Public Information & Education on Nuclear Desalination”. The workshop was conducted on November 28-29, 2006 and the workshop was organized by Wiraraja University and supported by BATAN and IAEA.

Under the project framework, there is the need to increase public understanding and awareness on possible introduction of nuclear desalination in the country. The proposed workshop is aimed to provide information and education to the public and concerned community groups, and share experience on nuclear desalination as well as to provide information on technical, safety and economic aspects and public awareness for decision makers.

In this workshop have more than 70 participants from four (4) regencies (Pamekasan, Sumenep, Sampang and Bangkalan) was satisfactory as a whole (although details unknown): engineers, University, NGO's, Religious/Moslem Leaders, Teachers, Pers, Government Officials and mostly mid-aged people, but also some younger and senior people. Besides that participants who delivered presentation of the technical paper are Wiraraja University (UNIJA) Sumenep, JAIF (IAEA's Experts), one from Egypt (IAEA's Expert) and colleagues from Batan. The results of the workshop are followings:

(a) BATAN is recommended that it continue its activities on deepening the project preparation and the communication with the community, with maximum use of its accumulated experience and resources to coordinate developing further infrastructures needed for the nuclear desalination project in Madura. It is also recommended that BATAN consider transferring its accumulated expertise to its younger staff for long-term activities on relevant subjects, which are not limited to Madura.
(b) It is recommendable to recruit more professionals (including PI communicators) from the region. That will work effectively in obtaining understanding of the religious (and academic) leaders, information penetration in the region, etc. PI communicators should be provided with training opportunities by external experience. If necessary, an external expert might be recruited as an assistant or a co-communicator for the personnel from the region.
(c) BATAN is advised to disseminate fair and objective information including benefits to the local communities such as spin-off effects of industrial development and HRD.
(d) PI is an activity to be continuously implemented by coordination with the central and local governments. BATAN should take note that most of PI methodologies are applicable to any other nuclear projects but specific contents and priorities of activities depend on specific projects.

5. Conclusions

(a) The supporting factors in Madura's industrialization development scenario include the Suramadu bridge, the extension of Gerbang Kertasusila into Germa Kertasusila, and the availability of facility as well as its water and electricity supplies; whereas, other interfering factors are society's low perception on the importance of industrialization and the limited water and electricity supplies.
(b) The human resources development is still inappropriate (Life Expectancy Index = 61, 5; Educational Index = 58.18; Purchasing Power Parity Index = 56.22; Human Development Index = 58.60) and considered below the average of East Java (Life Expectancy Index= 70, 33; Educational Index = 70.92; Purchasing Power Parity Index = 52.21; Human Development Index = 64.49).
(c) The development agenda, in order to improve the quality of Madurese' education, should consider the following aspects such as 1) curriculum development for Madurese human resources, 2) management development, 3) facilities and human resources training.
(d) In 2004, potable water demand in Madura Islands is 257,766.91 m^3/day, meanwhile the potable water supplied by PDAM is 26,577.25 m^3/day and the potable water supplied by individual system is 118,270.53 m^3/day, it means there is potable water deficit about 112,909.13 m^3/day. In the future, potable water supply deficit will reduce to 75,196.48 m^3/day.
(e) BATAN is advised to disseminate fair and objective information including benefits to the local communities such as spin-off effects of industrial development and HRD.

(f) PI is an activity to be continuously implemented by coordination with the central and local governments. BATAN should take note that most of PI methodologies are applicable to any other nuclear projects but specific contents and priorities of activities depend on specific projects.

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The economic prospects of nuclear desalination in Yemen

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Abstract

Yemen as a developing country has limited fresh water resources (annually: 125 m^3 Per Capita). Based on 2004 census, Yemen has a high annual population growth rate in excess of (3.0%) and at the same time it has a sea which is lining more than half of its borders making many of its cities and villages coast near-by lands. Yemen is making efforts to combat this scarcity of water with a number of strategies where desalination is one under consideration and without doubt would have remarkable results if implemented.

Yemen's oil exports (the only Energy-fuel it produces for now, as gas has not yet produced power) contributes to 70% of the government revenues. The country's long-term energy policies plan to limit energy oil-dependent technologies, therefore, in electricity generation, it is seeking fuel alternatives such as gas, solar and wind energy (for villages), and Nuclear Power.

The country has established the National Atomic Energy Commission in 1999 and has adopted a number of IAEA TC projects since then contributing to peaceful applications in industry, medicine, agriculture and science. A ground water study is among these projects. The Nuclear-electricity option desire was recently declared by the President of Yemen which is expected to solve the electricity shortage for both urban need and industry within the scope of sustainable development, and at the same time reserve the main source of wealth of the country (oil), if such an option will find its way into the energy mix of the country in the near future, Nuclear CHP will be the optimum choice taking advantage of the 2/3 of thermal energy which is lost in Nuclear Power Plants.

In this paper the economic prospects of Nuclear Desalination in Yemen will be discussed.

Non-electrical applications with Gen-IV reactor systems

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Abstract. The paper deals with the development work on hydrogen production by high temperature electrolysis carried out jointly at Idaho National Laboratory (INL) and Ceramatec, Inc. It presents the test results of the 25-cell and 60 cell electrolytic stacks conducted for 1000 hrs. It discusses the plans for future work on the integrated laboratory scale unit being set up at INL.

1. Introduction

While the thermochemical water splitting of water for producing hydrogen requires future generation Gen IV reactors, the high temperature electrolytic production of hydrogen is possible using even present day reactors. As shown in Fig 1., the nuclear hydrogen initiative includes the HTE process in the temperature range starting from 300 deg C and onwards. The efficiency of HTE process however improves at further higher temperatures. Experimental results of HTE in the above temperature ranges will provide useful information in the near term.

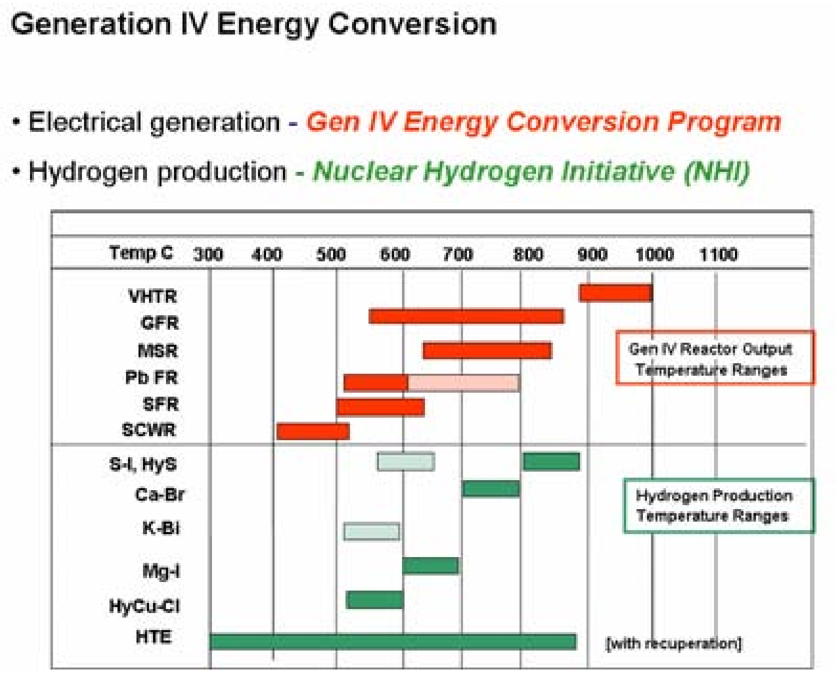

FIG. 1. Hydrogen production temperature ranges and Gen IV conversion programme

2. High temperature electrolysis

Figure 2. presents a simple schematic of the high temperature electrolysis process based on a VHTR. Figure 3 shows the electrode materials and also the electrode reactions.

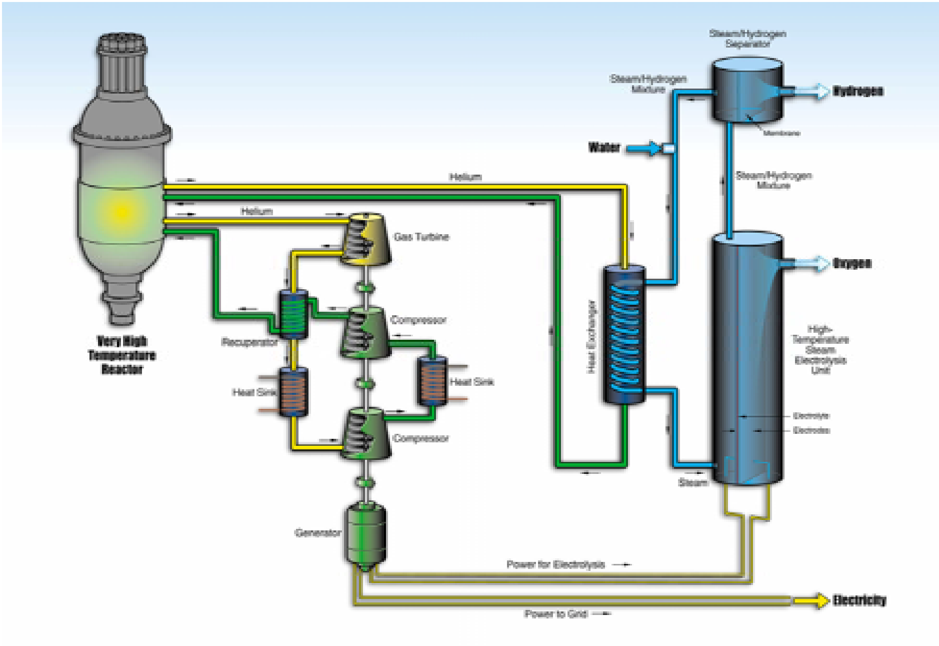

FIG. 2. High temperature electrolysis plant

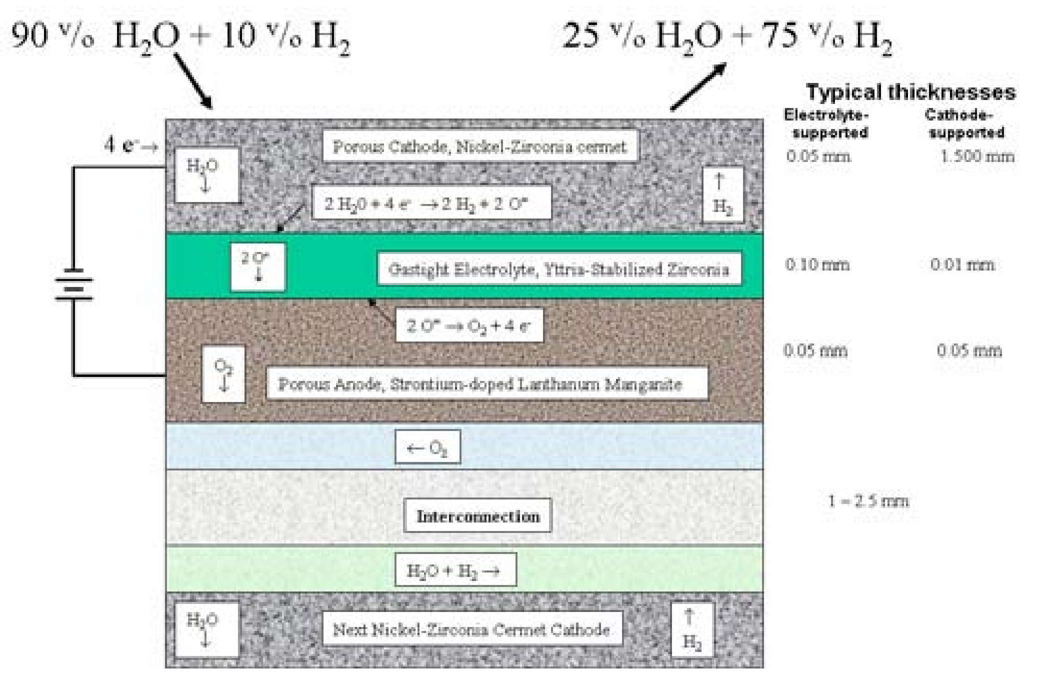

FIG. 3. The electrode materials and reactions

Figure 4. shows the photographs of the 25-cell and 2×60 cell electrolytic stacks used for the demonstration tests. The 25-cell produces 160 NL/h and the 2×60 cell stack (half module) produces 800 NL/h of hydrogen.

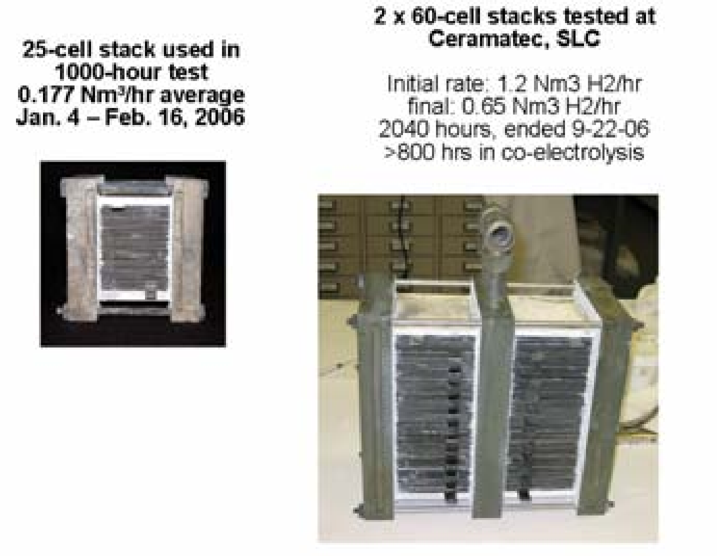

FIG. 4. 25-cell and 2×60 cell stacks

Figure 5. shows the integrated laboratory scale experiment unit of 5000NL/h capacity being built at INL for further studies..

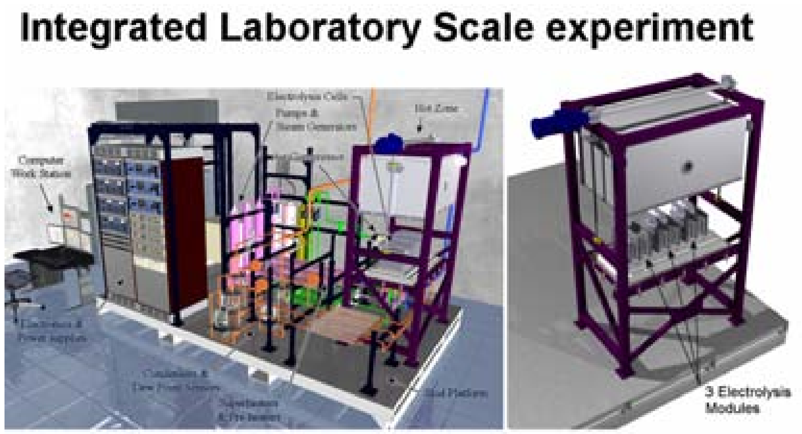

FIG. 5. Integrated laboratory scale experiment at INL

3. Conclusions

- Conventional electrolysis is available today
- High temperature electrolysis is under development and will be more efficient
- HTE Experimental results from 25-cell stack and 2×60-cell half-module, fabricated by Ceramatec,
  - Hydrogen production rates in excess of 160 normal liters/hour were maintained with a 25-cell solid-oxide electrolysis stack for 1000 hours
  - Hydrogen production greater than 800 normal liters/hour are now being achieved in the half-module test
  - An Integrated Laboratory Scale experiment is now being built, which will produce about 5,000 normal liters/hour
- In the near-term hydrogen from nuclear energy will be used to upgrade crude and later to synthesize conventional gasoline and diesel fuel from renewable carbon sources
- In the long-term pure hydrogen from nuclear energy will power vehicles directly through fuel cells

Overview of the safety aspects of nuclear desalination coupling

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Abstract. In the frame of non-electric applications of Nuclear Power Plants (NPP) Seawater Desalination appears to be the one with most rapidly increasing interest. The aspects related to the safety of a Nuclear Desalination Plant (NDP) design deserve special attention and they have been analysed with different scopes and viewpoints, in compliance with IAEA guidelines. It is widely accepted that the general safety approach for Nuclear Facilities is valid and this approach must be reflected in the Safety Analysis Report of the NDP. This paper reflects an overview of the work performed on this field within Nuclear Engineering Department, INVAP (Argentina) starting with the basis on which a safety analysis must be performed including recommendations on the way to report it following IAEA Standards, and reaches the comparison of engineered safety features considered in the coupling analysis and the rationale to select one for a specific project. The conceptual engineering developed for two Isolation Systems based on different engineered safety features, not only gives a better idea of the feasibility of detecting initiating events and the effectiveness of the protection action, but shows the complexity of the systems implied, costs and operation requirements, as well. This approach is intended to complement the design assessment of a NDP coupling in the early stages of the project and to give support to the Regulatory Bodies on the licensing process.

1. Introduction

Needless to say that the world is quickly becoming aware of its shortage of fresh water and the use of nuclear reactors for seawater desalination is expected in this energy market in a share similar to the existing share of the electricity market.

Although it is widely accepted that coupling a Desalination Plant (DP) to a Nuclear Power Plant (NPP) does not pose any significant additional hazard, it must clearly be considered as a major modification of the design. The co-generation plant, as a nuclear installation, should be designed in such a way to withstand a large variety of abnormal situations that may result, eventually, in an accidental condition.

The goal of this work is to present an overview of our contribution to the safety approach for Nuclear Desalination thermal coupling. It includes the most commonly accepted technique used for the deterministic analysis of NDP and the generic issues that should be included in a NDP SAR. Finally, it includes a discussion on the conceptual design of Coupling Systems based on two engineered safety features, showing that their design is derived by safety guidelines, and not imposed as a dogma.

2. Brief description of NPP-DP coupling

The safety approach will be performed taking as a reference the coupling between a small Nuclear Power Plant (100 MWth) and a generic Multi-Effect-Distillation plant (MED) with a production of 20.000 m^3/day. The main component in the coupling is the evaporator using steam taken from the turbine.

A generic Pressurised Water Reactor (PWR) of the Advanced Type, with an Integrated Primary Coolant Loop and once through Steam Generators, producing superheated steam corresponds to the NPP defined for coupling. The Thermal-Cycle (Turbo-group) would be quite standard for a Small Size NPP, with a single turbine having several extractions and the final heat sink (through seawater) uses different exchange surfaces for condensing and sub-cooling.

In this "straightforward" coupling design (i.e. without engineered safety features) a leak in the evaporator would imply the convection of water from the BoP to the DP.

3. Nuclear safety approach

A set of terms commonly used when dealing with nuclear safety is presented before starting with the main concepts required for the Safety Analysis Report.

3.1. Commonly used terms

Postulated Initiating Events (PIE): Those events giving rise to a sequence leading to accidental conditions. These may be equipment failure, human errors and internal or external events.
Accidental Sequence. It is the evolution of the Plant condition starting from a PIE, and according to a possible sequence of failures.

Envelope Safety Case: Given a certain effect under analysis (any safety relevant parameter as Fuel Elements thermal limits or off-site contamination release) the accidental sequence with the most severe consequences may be identified, and taken as an envelope safety case for performing a deeper analysis of the Plant design.

Design Basis Accident (DBA): Those accidents that the nuclear facility can withstand with its safety systems without exceeding the design limits.

Critical Group: It is the group of people that has the higher probability of being exposed to the eventually contaminated effluents of the nuclear installation by any way in an accident situation. Similarly the "consumer group" concept appears. It can be defined like the group of people affected by the use of water produced in the Nuclear Desalination Plant (NDP), for any purpose (drinking water, agricultural uses, etc.)

Defence-in-Depth concept: In nuclear industry this concept is singled out amongst the fundamental principles since it underlies the safety technology of nuclear power. The concept is centred on several levels of protection providing a graded protection against a variety of PIEs. The graded (envelope) protection should ensure the achievement of safety goals.

The implementation of the defence in depth concept is mainly carried out through deterministic analysis (which may be supplemented with probabilistic studies) and application of sound engineering practices based on research and operational experience.

The levels of defence in depth, which shall be considered in the design, are:

(a) Prevention of deviations from normal operation and of failures;
(b) Control (detection and interception) of such deviations and failures in order to prevent anticipated operational occurrences from escalating into accident conditions;
(c) Control of the consequences of the resulting accident conditions derived from design basis accidents in the unlikely event that the escalation of certain anticipated operational occurrences is not arrested by a preceding level;
(d) Control of severe conditions including prevention of accident progression and mitigation of the consequences of a severe accident;
(e) Mitigation of radiological consequences of significant releases of radiation materials.

Although the level (e) above is not directly covered by the design, it has been included here for completeness of the defence in depth concept.

3.2. Proposal for the NDP SAR

For nearly all of the existing NPPs the Safety Analysis Report approving its operation is based on a deterministic safety approach, in which the Plant design is analyzed against a list of PIE limited to DBA, and developing sequences applying the single-failure criterion to the systems and conservative assumptions.

Within this approach, the coupling of a Desalination System to a NPP implies verifying that there is no possible influence or effect on the NPP systems of events taking place in the Desalination Plant, so, no modification at all would be needed in the NPP SAR.

On the other hand, it is clearly convenient to present the SAR related to the addition of a DP as an appendix possible to be presented as a self-standing document. It should be clearly stated that the submission of this SAR (namely the DP SAR) does not imply a revision of the NPP SAR.

However, an up-dated style safety analysis, i.e. probabilistic, could be applied to the DP coupling. According to this approach, PIEs should be analyzed, grouped in envelope cases, and their consequences assessed in terms of harm to the public (effective dose). For every accidental enveloping sequence the chance of occurrence should be calculated (probabilistic) out of the failure probability of components and equipment.

A "map" of accidents in terms of Probabilities of occurrence vs. Effective Dose, could be built, and their acceptability according to regulations and guidelines should be verified. E.g. for the case of Argentine Regulatory Body the Criterion Curve, Fig. 1, once applied to all safety cases defines the acceptability of a design.

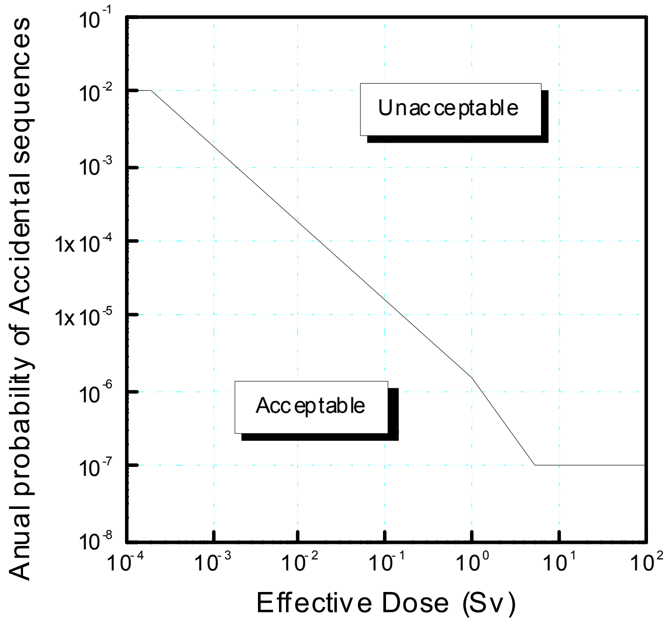

FIG. 1. Criterion curve

On the design stage of a coupling, this map would reveal the technical need of additional engineered safety features such as a barrier between potentially radioactive material and product water (PW hereafter) featuring a pressure reversal or the monitoring of PW to prevent the radioactive material from reaching the distribution grid.

4. Specific contents of the SAR for a nuclear desalination plant

The index of the "NRC Standard format and content of Safety Analysis Reports for NPP", [1] is adopted as a guide for the DP-SAR intending only to provide a uniform format for presenting the information. The content needed to be included on each of the issues is extremely dependent on the Desalination technology and the coupling design. It must be clearly understood that contents described in the following section is just a preliminary maximised list of issues to consider following the standard format index. Comments are given only on those chapters deserving more detail in the contents than the one implied explicitly in the title. For more details see reference [2].

4.1. Chapters according to NPP standard format index

Chapter 1: Introduction and General Description of the Facility

Chapter 2: ***Site Characteristics***. In the analysis corresponding to this appendix, the "consumers group" must be identified as compared to the "critical group" in case they are different groups.

Chapter 3: Design of Structures, Components, Equipment and Systems

Chapter 4: ***Reactor.*** This chapter is not applicable for the DP SAR.

Chapter 5: ***Reactor Coolant System and Connected Systems***. In this chapter the coupled DP and its connected systems should be presented. It is clearly understood that the DP is, in no way, a system connected to the Reactor Coolant System, and therefore the chapter title should be changed to **"*Desalination System and Connected Systems".*** The safety classification of DP systems and subsystems deserves some further analysis. There should be a careful analysis on the limits of the scope of supply around components, measuring sensors, actuators, and I&C connections and control-logics. It seems clearly recommendable to retain the safety-graded systems or components in hands of an experienced Nuclear Vendor.

Chapter 6: ***Engineered Safety Features***. A description and analysis of the Engineered Safety Features specially designed for the DP must be included here. Section 6 of this report presents two Engineered Safety Features based on different process variables to detect the need of isolating the NDP from the Potable Water distribution grid.

Chapter 7: Instrumentation and Control
Chapter 8: Electric Power
Chapter 9: Auxiliary Systems
Chapter 10: Steam and Power Conversion System

*Chapter 11****: Radioactive Waste Management.*** Not applicable, since no radioactive waste is produced.

Chapter 12: ***Radiation Protection.*** The change in the radioactive background of seawater intake due to the NPP under normal conditions must be taken into account.

Chapter 13: Conduct of Operations

Chapter 14: Initial Test Program

Chapter 15: ***Safety Analysis.*** Within this chapter a list of PIEs and their consequences must be presented, classified and grouped, and the envelope safety cases must be identified and assessed. Section 5 of this report presents a conceptual Safety Analysis for a NDP SAR.

Chapter 16: Technical Specifications
Chapter 17: Quality Assurance

4.2. Additional chapters according to other SAR format index

Based on INVAP´s experience as a nuclear vendor, the best way to ensure a smooth licensing process is to provide chapters as self-standing as reasonable, and to avoid including issues of different kind or importance within the same chapter (avoid the "cut and paste collage"). Therefore, although not part of the NRC standard format, the inclusion of the following chapters should be considered.

Chapter (*): ***Safety Objectives and Engineering Design Requirements.*** Starting from safety objectives, the derivation of general Safety Design Requirements may be explained, and their development into specific Engineered Safety Features. The Defence-in-Depth philosophy may also be introduced here.

Chapter (*): ***Environmental Assessment.*** This chapter may be considered as a section within chapter 2 considering not only the impact of the brine discharge, but also the changes in the water reservoir and the benefits on human activities, life quality and water stress.

Chapter (*): ***Decommissioning***. Specific provisions may be needed in the DP design for ensuring easy decommissioning of potentially contaminated components.

5. Conceptual safety analysis of a NDP, the safety case

In this Section, a methodology to perform the NDP safety analysis is suggested and outlined.
Safety objectives: the NDP coupling should be designed ensuring that its inclusion does not result in any adverse effect on the safety of the NPP and/or any hazards of a different nature or higher probability than those stated or implied in the NPP SAR.

The first objective is readily complied with by all the projects of co-generation NDP [3].

For the second objective it is assumed that the inclusion of the DP may change the definition of the critical group potentially affected by the release during accidental situations. In this scenario the relevant issue is the possibility of transferring radioactive material to the PW. Therefore, the only relevant safety function related to coupling is the confinement of radioactive material, and the Accidental Sequences to be analysed are those threatening the loss of barriers.

5.1 Construction of the accidental sequence

Considering only the sequence of events leading to the transfer of radioactive contamination of PW, it would imply at least the following events:

- The main Heat Exchanger (evaporator) breaks allowing the irruption of water from the BoP of the NPP into the Desalination System.
- The Steam Generator fails and the primary coolant enters the BoP loop.

— The Nuclear Fuel matrix and cladding fail and the primary coolant water is immediately contaminated with fission products.

A less severe PW contamination case (that might be admissible in a probabilistic approach, but not in this deterministic one) would be given by only the first event, considering that the allowable radioactivty level for BoP water is higher than the one for drinking water.

5.2. Defence in depth barriers

The main features to assess for the fulfillment of safety functions is summarized in Table I.

Table I. Defence-in-depth barriers

Level	Main characteristics	Safety features
1.	Conservative design and inherent safety features	Fuel matrix (pellet) + Fuel rod cladding NPP Steam Generator tube walls DP Heat Exchanger tube walls A system for isolating the DP from the PW distribution grid
2.	Operation control and response to abnormal operation	Automatic regulation of the DP around the nominal operating point Alarms and/or triggering of DP automatic actions

5.3. Safety cases

Summarizing previous section, for the reference “straightforward” design (with no engineered safety features) the accidental sequences giving rise to the Safety Cases are:

— Nuclear Fuel matrix and cladding failure, followed by the Steam Generator failure (leak mode), in turn followed by the Main Heat Exchanger failure (leak or rupture mode). This sequence is highly unlikely because of detection means in the NPP and may produce a severe contamination.
— A simple Main Heat Exchanger failure (leak). This sequence is quite likely and produces a weak contamination of water within the DP.

6. Engineered safety features

Following the “Top down Approach” recommended by IAEA, the Safety Objectives have to be translated into general safety design requirements under the light of defence in depth principle. Considering the safety case of the reference design, these requirements would be:

— The provision of multiple barriers between potentially radioactive material and PW.
— The provision of features preventing the radioactive material from reaching the PW even in case of any credible sequence of failures, i.e. in the safety case mentioned previously.

Both requirements could be condensed engineering a design feature consisting of a physical barrier whose integrity can be monitored. In what follows two relevant Engineered Safety Features that comply with this requirement, namely Water Monitoring and Pressure Reversal, are analysed for the reference NDP showing advantages and disadvantages.

6.1. Water monitoring

The radioactivity monitoring of PW has been proposed as the key safety feature in several documents [4–6] and [7]. It has to be assumed that for the coupling system the accidental sequences (i.e. the safety case loosing barriers between the BoP and the DP process) should be detected by the radioactivity monitoring function.

This isolation system (IS) would compare a set of monitoring sensors signals against pre-set allowable levels. The system should trigger the trip of the DP and the isolation towards the distribution grid (namely isolation trip).

Even using updated technology (2006), continuous on-line monitoring of PW is not a viable means of detecting radioactive contamination on the acceptable limits. The hold-up time for sampling and batch monitoring for PW can hardly be reduced below 60 minutes resulting in massive consequences on the storage capability required by the DP. See [8].

A very preliminary costing (in U$S) of the components needed to comply with a safety graded monitoring for the reference NDP produces 50.000, - for the Monitoring modules using detectors within Marinelli devices, 10.000, - for the I&C of automatic sampling, while 800.000, - are needed for the Process System achieving the hold up time by huge tanks (about 800 m^3 each). For the reference DP the total would imply some 5% of the DP overnight investment and the impact would be bigger for smaller plants.

It should be pointed out that this impact is related with monitoring as a safety feature able of detecting leaks in the thermal coupling. If PW monitoring is taken strictly as a surveillance task with periodical manual operation, then its economical cost is negligible.

6.2. Pressure reversal

A different engineered safety feature for ND coupling is the provision of a barrier in which the pressure on the NPP side is lower than in the DP side, namely a “pressure reversal”. A loss of integrity in the barrier would simply imply a leak of water towards the NPP and contamination would not spread. The monitoring of the pressure configuration allows ensuring the safety feature by detecting the Accidental Sequence comparing the measured ΔP in the barrier against settings of the Isolation System (IS), and triggering a trip of the DP or of the Intermediate Loop (IL).

The simplicity of this safety feature makes it attractive, and the use of redundancy in sensors, signaling chains, voting logic, processors and actuators allows reaching virtually any specified reliability.

Although the safety feature is the pressure difference in the Main Heat Exchanger, it may be convenient to implement a simpler logic based on absolute pressure as shown in [9].

A very preliminary costing (in U$S) of the components needed to comply with a safety graded pressure monitoring produces 7.000, - for the safety related instrumentation, 27000, - for the Process Systems (accounting only for the changes respect to a straightforward design of the coupling) and an additional 1.5 factor taken for erection, assembling and commissioning. The total estimation of this Isolation System renders 34000 U$S.

An additional analysis was performed on how an IL, the main feature of this IS, affects the NDP efficiency, and to verify if it may threaten the viability, [10]. The first finding is that the loss is extremely case sensitive. For example, depending on the IL scheme and thermodynamic conditions, it may produce no loss of thermal efficiency, adding only a small electrical consumption (less than 0.4 kW-h/m^3). But if the steam quality (in temperature and pressure) of the BoP is too close to the MED first effect, the IL may imply a relevant loss of efficiency. Similarly, if the distance between plants is too big, the design of the IL has to be carefully optimized in order to keep the thermal efficiency. So, it can be concluded that the engineering of an IL featuring PR although technologically simple is strictly Plant Specific and not necessarily convenient for all cases.

7. Conclusions

A very rough overview of the safety approach adequate to Nuclear Desalination Coupling was presented covering different aspects, starting from the contents of the Safety Analysis Report of the DP, the outline of a safety analysis and the derivation of specific design requirements from the Safety Objectives. Finally the comparison of two Isolation Systems based on different engineered safety features was presented.

This work is intended to summarise the findings achieved during INVAP work contributing safety aspects of Nuclear Desalination. Among others:

- The commonly accepted techniques (including the "top down approach") used for deterministic safety analysis of NPP can be applied to NDP,
- The SAR of the DP can be presented as a self-standing appendix, acting as a complement of the NPP SAR.
- The development of Engineered Safety Features for the thermal coupling of Nuclear Desalination Plants is an issue technically solvable within Safety Guidelines.
- There is not a unique/universal Isolation System. The development of optimal Isolation Systems providing an Engineered Safety Feature requires safety expertise (the safety analysis and engineering cannot be saved).
- The impact of the design solution regarding Isolation Systems and Engineered Safety Features (in terms of efficiency and safety categorization) should be considered during the first stages of a NDP project when drafting user requirements, in order not to put in risk the project viability.

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A U.S. nuclear desalination study

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Abstract. Recent dramatic increases in water shortages across the globe necessitate exploring innovative and practical methods for increasing the world's ever-depleting water and energy supplies. In the U.S., States such as California, Florida and Texas are examples of regions experiencing local and sometimes severe water shortages. One proposed solution to alleviate water shortage, which is gaining popularity around the world, is to desalt seawater and produce potable water, i.e., via *seawater desalination*.

There is a growing interest in cogeneration of water and power in arid and semi-arid regions around the world. Cogeneration may be achieved by coupling a power plant to a desalination plant in order to extract available waste heat and power to drive thermal as well as membrane-based desalination systems. The attractiveness of hybridizing membrane and thermal desalination plants for the production of freshwater from seawater is seen advantageous. Costs of water produced by co-located desalination/power plant complexes has been shown to be as low as 0.50 USD per cubic meter. The option of the unique coupling of green house gas-friendly nuclear power plants to desalination systems (i.e., *nuclear desalination*) is specifically explored.

1. Introduction

The need for freshwater, high purity water, and other grades of water for various domestic, industrial, and agricultural applications is ever increasing in the U.S. Population growth and continuous economic and technological growth are the main drivers for the increased demand in water. Indeed, it is predicted that more than 60 billion additional cubic meters of water will be needed in the U.S. for municipal and light industrial uses by the year 2020. Cogeneration of water and power could offer a major portion of the additional water needed in addition to providing much needed energy for maintaining sustainable development and growth.

According to the Desalination and Water Purification Technology Roadmap, Jan 2003, US Bureau of Reclamation and Sandia National Labs, desalination and water purification technologies will contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply to the United Sates by 2020. The future goals suggested for water cost from desalination and water purification technologies are;

Near term objectives (by 2008): overall 20% improvement in capital cost, operating cost, energy efficiency, and cost of zero liquid discharge.

Long term objectives (by 2020): overall 80% improvement in the above areas.

This paper presents a case study of economic evaluation of various desalination processes utilizing fossil energy sources under US conditions. Desalination plants based on RO, MED and their hybrids of 100000 to 300000 m^3/d capacities are considered in the study.

The results are compared for the same capacity plants when the energy source is a Gen-III type nuclear reactor AP1000.

2. Hybrid thermal-membrane systems

The desalination systems of choice in this study are the membrane RO and LT-MED (low temperature MED, with steam supply at 0.4 bar and 70°C) systems and a combination (or hybrid) of the two. The choice was based mainly on investment and operational costs, where energy requirements and costs are of paramount importance. Capital investment and energy requirements (and hence costs) are typically the lowest for RO membrane and MED plants.

The schematics of the classical MED-RO hybrid desalination plant is shown in Fig. 1.

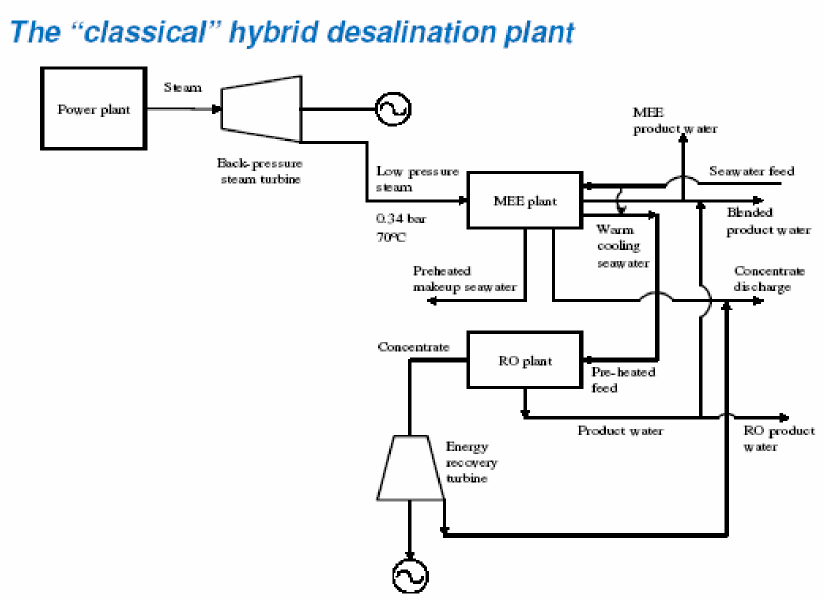

FIG. 1. The classical hybrid desalination plant

The hybrid thermal-membrane systems have several advantages. These are:

- Shared and typically smaller intake system.
- Higher temperature feed water to RO system for improved performance. Costs savings: 10% in initial capital costs due to fewer membranes needed. Lower pumping costs.
- Option to blend RO and thermal water products for a range of products. Cost savings: membrane replacement costs can be reduced by 50% and more.
- Ability to use seasonal surplus of idle power and diversify steam/power.
- Potential decrease in fuel costs by using RO.
- Blending of discharged concentrate with power plant cooling water.
- Combined pretreatment and post-treatment systems.

3. Results and discussion

The input data for cost calculations and the cost results of the 100000, 200000 and 300000 m^3/d RO, MED and their hybrids using fossil energy sources is presented in Tables I to V. The economic comparison of similar plants using energy from nuclear reactor AP-1000 is shown in Table VI.

3.1. RO plant cost calculations

The RO plant option for the coastal and inland sites in this study offers a plant that consumes the least amount of energy per freshwater produced. This low energy consumption is made even lower by the use of an energy recovery turbine (ERT) through which the concentrate stream is fed and some of the overall process pumping energy is recovered. Seawater RO plant is the system of choice for the potential coastal Texas site.

A typical large-scale RO system is composed of several sub-units known as trains. A typical RO seawater large train size is in the range of 10 000 to 20 000 m^3/day product capacity. In this current study, the train size was chosen as 14 000 m^3/day, based on common-day design experience. A train of this size will contain a total of 1344 membrane elements (modules) housed in 168, 8-element pressure vessels. This design was recently chosen for the Tampa Bay cogeneration project in Florida. The required system feed pressure and, hence, power consumption was calculated using the commonly used membrane process design software from Hydranautics. (www.membranes.com). The software was used to calculate required system pressure, resultant product salinity, and power consumption (with and without ERT) using specific input parameters (see Table I).

Table I. Default input data for seawater RO plant cost calculations

Seawater feed temperature (^{o}C)	25
Feed-water salinity (ppm)	27500
Recovery ratio (%)	50
Cost of electricity ($/kW.h)	0.04*
Interest/discount rate (%)	7
Plant economic life (years)	20.00
Amortization factor	0.09
Plant availability (%)	90
Specific electric consumption (kWh/m^3)	2.37*
Specific chemical cost ($/$m^3$)	0.04
Membrane cost ($/element)	650
Longevity of membrane elements (years)	5
Specific labour costs ($/worker/year)	50 000

Table II. RO results

Production capacity (m^3d): 1	100000	200000	300000
Initial capital investment ($):	1.044E+08	1.901E+08	2.699E+08
Annual costs ($/y):			
Direct costs:	9.850E+06	1.794E+07	2.548E+07
Indirect costs:	3.940E+06	7.176E+06	1.019E+07
O&M (+spare parts):	1.970E+05	3.588E+05	5.095E+05
Membrane replacement:	1.204E+06	2.407E+06	3.611E+06
Chemicals:	1.622E+06	3.244E+06	4.867E+06

Power:	3.845E+06	7.689E+06	1.153E+067
Labour:	7.000E+05	9.899E+05	1.212E+06
Total annual costs:	2.136E+07	3.981E+07	5.740E+07
Unit product cost in terms of production ($/m^3):	0.585	0.545	0.524
Unit product cost in terms of capacity ($/m^3/d):	213.58	199.03	191.34

The water cost can be seen to be around $0.50/m^3 range for the large size RO plants

3.2. MED plant cost calculations

The LT-MED plant offers a high performance ratio (PR) and a low operating temperature, requiring only low-grade steam as the main driving force for the thermal evaporative desalination process. The largest available unit size of a MED system is around 20 000 m^3/day of freshwater production capacity, which is smaller than the largest available MSF units (around 50 000 m^3/day capacity). However, a 20 000 m^3/day MED plant with a PR of 10, using 0.34 bar steam with a direct capital investment of around $1200/m^3/day is a more efficient and a more cost effective choice than the a MSF plant with the same capacity and PR, an initial capital investment of more than $1400/m^3/day, and higher grade steam requirement (3 bar and 109^{o}C).

Table III. Input data for LT-MED plant cost calculations

Seawater feed temperature (^{o}C)	25
Feed-water salinity (ppm)	27500
Performance ratio	10
Cost of electricity ($/kW.h)	0.04
Interest rate (%)	7
Plant economic life (years)	20
Amortization factor	0.09
Plant availability (%)	90
Specific electric consumption (kWh/m^3)	1.40*
Specific chemical cost ($/m^3)	0.04
Fuel cost ($/GJ)	0.45**
Specific stem requirements (kg/m^3 of product water)	100
Specific labour costs ($/worker/year)	50000

Table IV. Economic analysis for LT-MED

Production capacity (m^3/d):	100000	200000	300000
Initial capital investment ($):	1.200E+08	2.197E+08	3.130E+08
Annual costs ($/y):			
Direct costs:	1.132E+07	2.074E+07	2.954E+07
Indirect costs:	4.529E+06	8.295E+06	1.182E+07
O&M (+parts):	2.265E+05	4.147E+05	5.909E+05
Chemicals:	1.622E+06	3.244E+06	4.867E+06
Power costs:	2.271E+06	4.542E+06	6.813E+06
Steam costs:	4.248E+06	8.497E+06	1.275E+07
Labour:	7.000E+05	9.899E+05	1.212E+06
Total annual costs:	2.492E+07	4.672E+07	6.759E+07
Unit product cost in terms of production ($/$m^3$):	0.683	0.640	0.617
Unit product cost in terms of capacity ($/$m^3$/d):	249.20	233.60	225.30

The total annual cost and unit product cost for the LT-MED plant are naturally higher than those for the RO plant due to higher capital investment costs and the additional significant cost of the low-grade steam.

3.3. Hybrid cases cost calculations

Table V. Economic comparison of desalination options

Annual costs ($/Year)	Hybrid RO+MEE	Stand-alone RO (w/savings*)	Hybrid (w/o savings)	Stand-alone RO (w/o savings)
Direct costs:	1.908E+07	1.109E+07	2.059E+07	1.261E+07
Indirect costs:	7.630E+06	4.437E+06	8.235E+06	5.042E+06
O&M (+parts):	3.815E+05	2.219E+05	4.118E+05	2.521E+05
Membrane replacements costs:	6.404E+05	6.404E+05	1.601E+06	1.601E+06
Chemicals:	3.244E+06	2.158E+06	3.244E+06	2.158E+06
Power costs:	6.635E+06	5.113E+06	6.635E+06	5.113E+06
Steam costs:	2.846E+06	N/A	2.846E+06	N/A
Labor costs:	9.899E+05	8.073E+05	9.899E+05	8.073E+05
Total annual costs ($/Year)	4.144E+07	2.447E+07	4.455E+07	2.758E+07

Unit product cost in terms of production ($/m^3)	*0.568*	*0.504*	*0.610*	*0.568*
Unit product cost in terms of capacity ($/m^3/d)	207.21	183.99	222.76	207.37

In addition to providing a range of water products of various qualities and operational flexibility, the hybrid RO/LT-MED plant option offers water costs that are very close to those of the stand-alone RO seawater plant.

3.4. Economics of nuclear desalination with AP1000 like rector

Table VI. Economics of nuclear desalination with AP1000-like reactor

Desalination plant type	Unit product cost ($/m^3)			Total electrical power consumption (MW(e))			Total thermal power consumption (MW(t))		
	Plant capacity (m^3/d): 100000	200000	300000	Plant capacity (m^3/d): 100000	200000	300000	Plant capacity (m^3/d): 100000	200000	300000
Brackish water RO	0.267	0.247	0.237	2.79	5.58	8.37	n/a	n/a	n/a
Seawater RO	0.585	0.545	0.524	9.88	19.8	29.6	n/a	n/a	n/a
LT-MEE	0.683	0.640	0.617	5.83	11.7	17.5	269	539	808
Hybrid RO/LT-MEE	0.608	0.568	0.546	8.54	17.0	25.6	88.9	181	269

The main advantage of a nuclear power plant coupled to a desalination plant over a fossil-fuel fired plant is the low cost of fuel. However, some additional capital investment may be needed for a nuclear cogeneration plant due to the required isolation loop coupling a thermal or a hybrid plant to the power plant.

4. Main conclusions of case study

- The most economical choice for a coupled desalination plant for the inland site is the brackish water RO plant. However, capital investment costs could be significantly higher (some 43% higher) if deep well discharge is chosen as the concentrate disposal method rather than blending of the concentrate with the power plant cooling water discharge stream.
- In addition to providing a range of water products of various qualities and operational flexibility, the hybrid RO/LT-MED plant option offers water costs that are very close to those of the stand-alone RO seawater plant.
- The overall energy consumption for the hybrid plant (on the basis of total equivalent MWe and assuming a 30% power plant thermal efficiency) is, on average, 60% lower than for the stand-alone LT-MED plant.
- The main advantage of a nuclear power plant coupled to a desalination plant over a fossil-fuel fired plant is the low cost of fuel. However, some additional capital

investment may be needed for a nuclear cogeneration plant due to the required isolation loop coupling a thermal or a hybrid plant to the power plant.

- The safety and environmental considerations of a nuclear desalination complex do not pose significant economic or health risks. Some provisions need to be made in order ensure that when the desalination plant as a heat sink is shut down or operated in partial load, there will be a backup heat sink available to accept rejected heat from the power plant and prevent power plant shutdown.
- There is a need to perform a detailed socio-economic study that will assess the true amount of water to be produced by desalination methods.

Design considerations in secondary cycle system for coupling existing Nuclear Power Plant (NPP) to nuclear desalination demonstration plant

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Abstract. This paper brings out the design basis and operational philosophy for supplying nuclear steam from existing NPP to Desalination plant. The process engineering has been carried out to ensure operation of NPP is not affected under any situation.

1. Introduction

Madras Atomic Power Station (MAPS-1, 2) is a Pressurised Heavy Water Reactor (PHWR) type twin unit of 220 MWe rating NPP located 88 Km south of Chennai on the coast of Bay of Bengal. A Nuclear Desalination Demonstration Plant (NDDP) of 6300 m^3/day (4500 m^3/day by Multi stage flash (MSF) and 1800 m^3/day by Reverse Osmosis (RO)) is set up adjacent to MAPS-1, 2 NPP. The requirements of MSF desalination plant from MAPS-1, 2 are:

(1) Heating steam: 21 t/h of LP steam at 3.0 kg/cm^2(a) for heating brine and 0.5t/h of HP steam at 40 kg/cm^2(a) for vacuum ejectors.
(2) Sea water – 1750 m^3/h from cooling water outfall.
(3) Power supply 2.0 MWe.

The product water can be used as process water input to MAPS-1, 2 and as domestic water supply to nearby villages.

2. Brief description of MAPS

The reactor building (RB) houses the reactor, boilers and associated auxiliaries. The service building (SB) connected to RB via air lock houses the new fuel storage room, spent fuel storage bay and related maintenance shops/laboratories. The turbine building (TB) houses the TG set, conventional steam/condensate system, electrical equipments and main control room. An adjoining wing houses the water treatment plant and Diesel Generators (DG) sets. The cooling water (CW) pump house behind the TB houses the CW pumps. Fresh water for process cooling, fire water, domestic water etc. is drawn from Palar river 20 km away. A 220 KV switch yard exports power to the southern national grid.

3. MAPS secondary cycle system

Steam Generator (SG) supplies at maximum continuous rating (MCR) of 1330 t/h of saturated steam at 41kg/cm^2(a) to Turbine generator. Steam after expansion in High Pressure (HP) Turbine passes through Moisture separator reheater (MSR), where moisture (12%) is removed and steam reheated. Thereafter steam expands in Low Pressure (LP) turbine and condenses in surface type condenser. The condensate is then pumped back to SG through different stages of LP feed heaters (three nos.), deaerator and HP heaters (two nos.). The steam for heating is extracted from stages of HP and LP turbine cylinders.

4. Present status of NDDP

The Sea Water Reverse Osmosis (SWRO) plant is commissioned and producing desalinated water with about 500 ppm dissolved solid. It augments the raw water requirements of MAPS during summer.

The Multi Stage Flash (MSF) plant is under fabrication and is expected to be commissioned by this year end. The steam supply and condensate return system has been erected and is ready for hook up to MSF plant.

5. Design considerations for providing steam to NDDP

LP steam has been tapped from cold reheat line at the exhaust of HP turbine (refer attached Heat Balance diagram and LP steam supply schematic). This location has been considered appropriate from following considerations

(a) Thermal efficiency:

The NDDP requires LP steam at 3.0 kg/cm^2(a). The following locations were considered

(i) Main steam header.
(ii) HP turbine outlet before moisture separator reheater (MSR) called Cold Reheat line.
(iii) Suitable existing extraction line.

Main steam header pressure is at 41.0 kg/cm^2(a), hence tapping from this location would require dropping pressure to 3.0 kg/cm^2(a). This would be highly uneconomical and hence not considered.

Cold Reheat line pressure is 6.0 kg/cm^2(a). This requires very less pressure reduction. The steam at this location has expanded in HP turbine generating about 40% of power hence same is most economical.

Tapping from LP turbine extraction line was not considered advisable as same would affect existing plant operation.

(b) Availability of steam at varying power levels:

Main steam header pressure varies from 41kg/cm^2(a) at 100% load to 50kg/ cm^2(a) at no load. Cold Reheat line pressure varies from 6.0 kg/cm^2(a) at 100% load to 2.64 kg/ cm^2(a) at 40% load. Hence tapping from cold reheat line is most appropriate on this aspect.

(c) Safety:

Tapping from Main steam Header is safest as during any load throw off there is no chance of water induction to Turbine.

Cold Reheat line tapping is also considered safe as during any load throw off water induction to Turbine is only possible after flooding of cold reheat line, MSR and hot reheat line.

At the LP steam tapping location the steam has a moisture content of 11.2% (refer Heat Balance Diagram of MAPS – Fig.-1) and hence a moisture separator is provided. Moisture separator is located in Turbine building close to tapping point. Moisture separator is located on lower elevation to steam tap off point and its drain is also connected to existing Moisture separator drain tank at lower elevation. This ensures moisture drain by gravity. LP steam produces steam in an intermediate loop, which in turn is used for Brine heating. This arrangement will prevent Tritium activity, if any, to pass to the product water. The intermediate loop also prevents salt ingress in return condensate line incase of brine heater tube leakage.

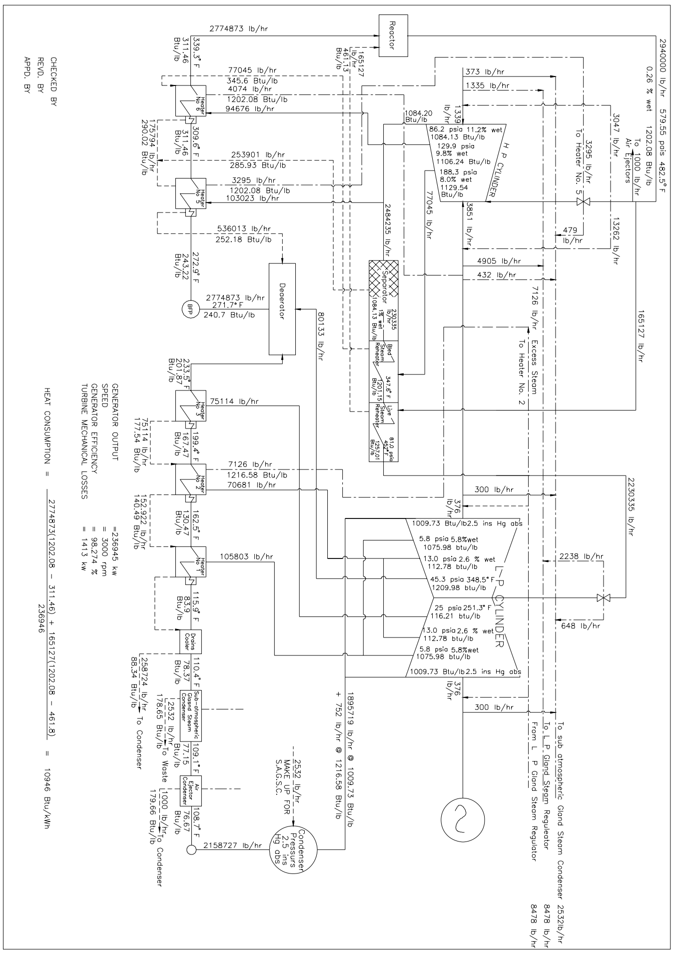

FIG. 1. Heat balance diagram of MAPS

To prevent back flow of steam/moisture to turbine, an air operated non return valve (NRV) upstream of moisture separator and motor operated isolation valves upstream and downstream of moisture separator has been provided. The NRV and isolation valves close automatically on turbine trip. The LP steam supply schematic is shown in Fig.-2.

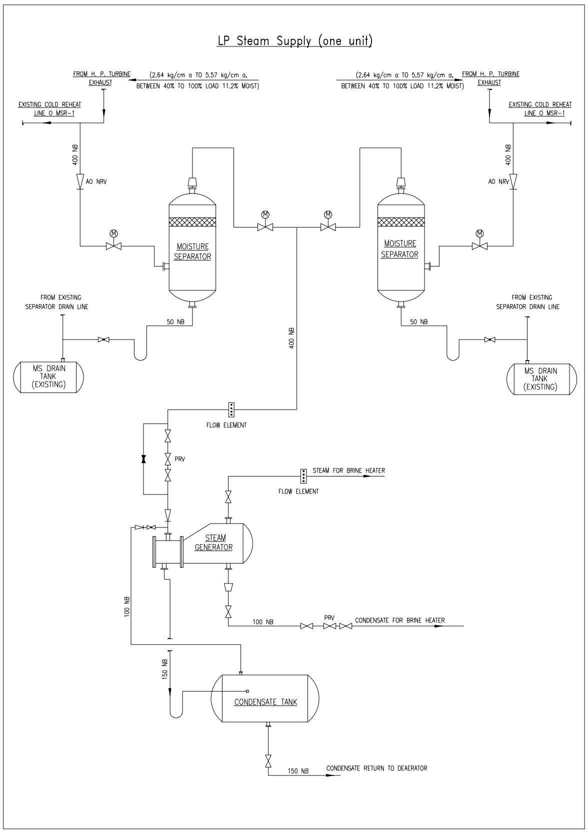

FIG. 2. Schematic of the LP steam supply

HP steam has been tapped from Main steam header to hogging ejector. The pressure in main steam header meets the requirement of steam for desalination plant vacuum ejectors. A motor operated isolation valve and a normal NRV is provided to prevent back flow of steam. The motor operated valve is manually operated and shall be closed when NDDP is shutdown. HP steam produces steam in an intermediate loop, which in turn is used for vacuum ejectors. This arrangement will prevent Tritium activity, if any, to pass to the product water. The HP steam supply schematic is shown in Fig.-3.

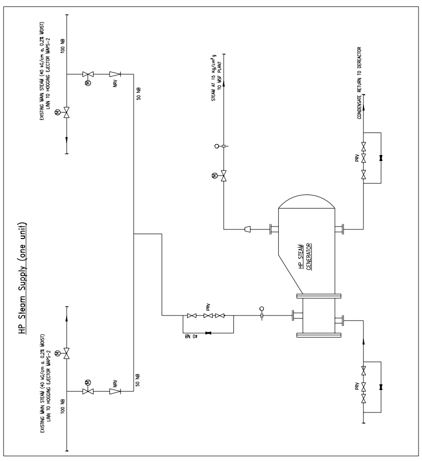

FIG. 3. Schematic of the HP steam supply

6. Design considerations for condensate return from MSF desalination plant:

Condensate is collected in common condensate tank in NDDP. Condensate is pumped back to MAPS. Condensate return pump head is designed for return connected to Deaerator. The return condensate could be connected to Condenser or Deaerator. The return condensate temperature is 120^{o}C. Hence for better efficiency the condensate was connected to Deaerator. The saving on this account is worked out to be about 0.26 MWe.

7. Control philosophy for supply of steam and return of condensate

Provision of supply of steam and condensate return has been made from both units of MAPS so that even if one unit is not available the NDDP can be operated through the other unit. MAPS control room (CR) controls the operation of LP and HP steam supply valves and condensate return valves. As per the operating status of unit-1 & unit-2, MAPS can decide which unit shall supply steam and hence receive the return condensate.

Flow measuring instruments are provided to record quantity of steam supplied and condensate returned. On line conductivity meter has been provided in the condensate return line. Any leakage in brine heater and LP steam generator shall be detected through the conductivity meters and condensate return shall be stopped immediately.

8. Civil changes in turbine building

The following changes/considerations were considered for steam supply to NDDP in Turbine Building:

(a) A Moisture Separator (MS) has been provided in LP steam supply system. This was to be located close to steam tap off point to avoid long piping carrying wet steam. The MS was located suitably as per available space in mezzanine floor. As the MS is retrofitted it was anchored to floor by cinch anchoring. The suitability of floor to take extra loading was checked by civil group.

(b) The dry steam outlet from MS was very close to operating floor and hence an opening was made in the operating floor. The design of the opening was carried out in consultation with civil group and suitable reinforcement provided.

(c) The steam piping was supported from existing beam/columns of turbine building and wherever required additional reinforcements were provided.

9. Piping layout

The steam and condensate piping layout was prepared in consultation with MAPS engineers and as per site requirements to avoid any clash with existing piping/equipments. The piping layout outside Turbine building required provision of suitable additional civil columns/beams.

10. Cost of supplying steam to NDDP

The loss of power generation due to supply of steam to NDDP was worked out considering various tapping points. The most optimum location (considering thermal efficiency, turbine safety and availability) in the HP turbine exhaust has been chosen for which the loss of power generation works out to be the least i.e.3.0 MWe. The cost of heating steam considering MAPS tariff of Rs. 1.82 per kWh works out to Rs 1.31 lakhs/d (~ \$ 3000/d) for producing 4500 m^3/d desalinated water that is \$ 0.66/m^3.

11. Conclusions

The following conclusions are drawn while executing the design of coupling NPP with retrofit desalination plant:

(i) Considerable thought and evaluation needs to be given to locate the steam tap off point for supplying nuclear steam to desalination plant. The major aspects are thermal efficiency, availability at various power levels and safety.
(ii) Suitable control and instrumentation needs to be provided to isolate the NPP and desalination plant in case of trip of either of the plant.
(iii) Additional loading in existing buildings needs to be reviewed and suitable changes carried out.
(iv) The cost of nuclear steam is the major operating component of the final cost of desalinated water. Any NPP before considering coupling with desalination plant has to carryout a cost analysis of existing raw water supply cost vis-a-vis final cost of desalinated water.

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CANDU™ plants for oil sands applications

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Abstract. This paper reviews the opportunity for nuclear power to become a major energy source for oil sands projects. The application of nuclear technology will significantly lower the environmental impact of bitumen production since it is an energy source that does not produce green gas emissions. It will also either reduce the depletion rate of Canadian natural gas reserves or allow for its alternate use. Studies have been undertaken to assess the feasibility of using a CANDU nuclear plant as the energy source for extraction and processing of bitumen from the Athabasca oil sands in Western Canada. A single 700 MW class reactor unit can supply the thermal energy requirements of an in-situ extraction facility for the production of up to 215,000 barrels of bitumen per day, while displacing 3 Megatonnes/year of CO_2 emissions. Alternatively a next generation ACR-1000 reactor could provide enough thermal energy to produce 333,000 barrels of bitumen per day while displacing 4.6 Mt/year of CO_2 emissions.

1. Introduction

Alberta's oil sands deposits are the second largest oil deposit in the world, containing approximately 174 billion barrels (bbl) of oil (28 billion m^3) of economically recoverable oil, and have emerged as the fastest growing, soon to be dominant, source of crude oil in Canada. The oil sands industry currently produces close to half of the nation's petroleum needs, and has the potential to account for more than sixty percent of Western Canadian crude production by the year 2010.

Traditional open-pit mining has been used by the industry for many years to remove oil sands from shallow deposits. About 20% of the deposit (35 billion bbl) is believed to be surface recoverable and most of the projects in place have exploited this more easily accessible resource. However, most of the reserve is located deep underground. To increase production capacity, the industry is looking for new technology to exploit bitumen from the deep deposits. Among them, Steam Assisted Gravity Drainage (SAGD) appears to be the most promising approach, which uses steam to remove bitumen from underground reservoirs. This in-situ recovery process has been put into commercial operation by major oil companies.

Overall, for both extraction methodologies, a significant amount of energy is required to extract bitumen and upgrade it to synthetic crude oil as the feedstock for oil refineries. For the SAGD process high pressure steam is needed and is injected into underground wells. For open-pit mining there is a requirement for a large quantity of hot water (at 40 ~ 75ºC) and relatively small amount of steam as the thermal energy source. Both extracting methods need relatively small amounts of electricity to operate the process equipment. The product of both processes is bitumen that needs to be upgraded in order to achieve a quality comparable to crude oils extracted using conventional methods. This upgrading process requires large amounts of hydrogen. Currently, the industry uses natural gas as the prime energy source for bitumen extraction and upgrading. As oil sands production continues to expand, the energy required for production becomes a great challenge with regard to economic sustainability, environmental impact and security of supply. With this background, the opportunity for nuclear reactors to provide an economical, reliable and virtually zero-emission source of energy for the oil sands becomes very important.

2. Application of CANDU reactors for steam assisted gravity drainage

2.1. Generic SAGD process

A typical SAGD application involves twin horizontal wells drilled in parallel, with one a few meters above the other, as shown in Fig. 1. The upper well is called the injection well and the lower one the production well. Medium pressure steam is injected into the underground deposit area through the injection well, to heat the reservoir of bitumen-sand mixture by conduction. The heating reduces the viscosity of the bitumen, increases its mobility, and establishes pressure communication between the two wells along their length, so that a flow of fluids (mixture of bitumen and condensed water) can occur. These are then collected through the production well. Establishment of pressure communicaiton between the two wells can take 2 to 3 months. The produced water mixture is transported to a central facility, where the bitumen is separated and the condensate is collected, treated, and sent back to the boilers.

The required steam injection pressure depends on the circumstances of the oil field and the life cycle of the well, and varies from 2 to 6 MPa. At the initial stages of production (two to three months), each well requires steam at higher pressure than that required during normal operation. Each barrel of bitumen requires 2~3 barrels of steam (steam volume is corrected to 4°C and 1 bar - cold water equivalent), as the quality of the deposit changes with location and time.

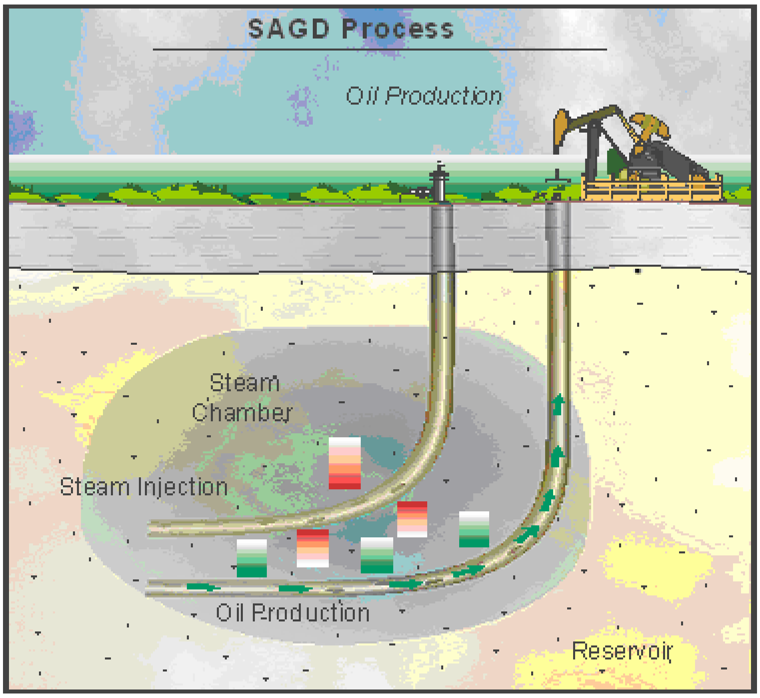

FIG. 1. SAGD process

2.2. CANDU plant configuration for SAGD application

In order to provide the required energy to Oil Sands applications from a CANDU plant, the Balance of Plant (BOP) has to be modified while the Nuclear Steam Plant (NSP) remains as the generic design. Current CANDU 6 reactors have a net electrical power output of approximately 700 MWe and a thermal power output corresponding to 2062 MW_{th}. Next Generation ACR-1000 reactors are designed for a thermal output of 3180 MW_{th}.

The fundamental product of a CANDU nuclear power plant is steam from the SGs (steam generators). Depending on the circumstance of each specific project, a CANDU plant can be adapted to provide steam only, or a mixture of steam and electricity for various steam/electricity ratios.

For SAGD application, intermediate heat exchangers, called reboilers, are introduced into the system. This "3-cycle" option prevents any possibility of radioactive contamination of the oil sands resource. The reboilers use the main steam generated by SGs as a heating source to produce the required process steam for SAGD use. Figure 2 shows a simplified configuration of a CANDU plant for SAGD applications. Depending on a customer's steam requirement, a CANDU plant can be modified to be an electricity/steam cogeneration plant, or be a dedicated steam generation plant. Accordingly, the steam turbine/generator system is either reduced in capacity or removed from the system. The CANDU plants are flexible enough to meet the various electricity/steam ratio in customers' requirements.

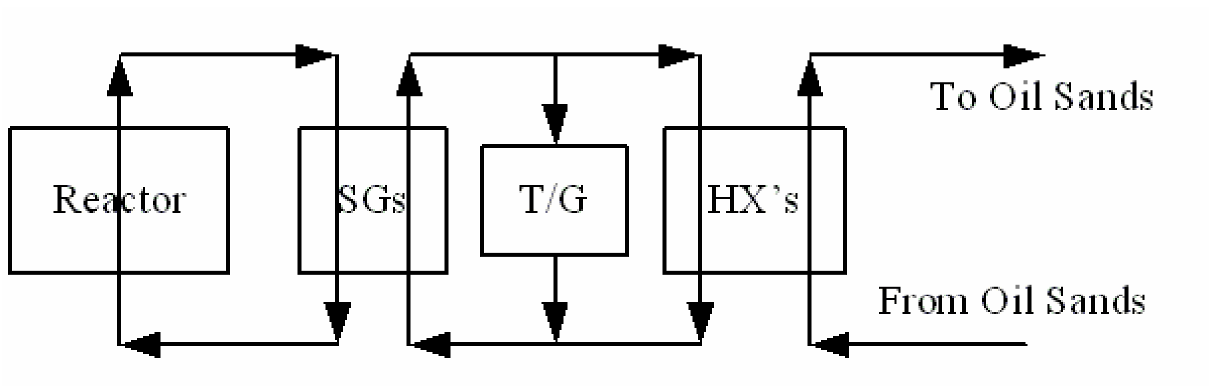

FIG. 2. A simplified configuration of a CANDU SAGD application

With the steam-only option, the steam generated from the reactor is totally dedicated to supply steam to oil sands processes, and no electricity is generated. Hence, the turbine island (shown in block form in Fig. 2) is totally eliminated from the plant, and replaced by facilities dedicated to steam and feedwater supplies.

The steam/electricity option splits main steam from SGs into two streams: one is dedicated to supply steam to oil sands and the other is channelled to generate electricity. As a result, the turbine capacity becomes smaller than that of a standard CANDU plant.

The steam-only option for a CANDU 6 plant can supply enough steam (85,500 m^3/day) to produce approximately 215,000 bbl/day of bitumen assuming a steam to oil ratio (SOR) of 2.5 and water returned from the oil facility at 170ºC. A CANDU 6 reactor that provides 150 MWe of electricity, can still provide enough steam to produce 153,000 bbl/day of bitumen (an ACR-1000, generating 150 MW of electricity produces enough steam for 263,000 bbl/day of bitumen production). For the steam/electricity mix option, the steam supply capacity depends on the electricity output and can be tailored to different steam/electricity ratios, with some limitations.

2.2.1. Steam and electricity generation

For this option (see Fig. 3), the main steam from the CANDU 6 steam generators is divided into two streams. One stream supplies the steam turbine to generate electricity while the other supplies reboilers to generate process steam.

There are a number of reboilers to take the required heat load, and each of them is associated with a drain cooler. The reboilers get heating steam from the main steam header (not shown) through an individual steam line. Inside the reboilers the main steam releases latent heat to the process water as the steam condenses. This condensate enters the associated drain cooler and is used to preheat the process water and is cooled down further in order to meet the SG feedwater temperature requirement. The drain water is collected in drain tanks, then pressurized by feedwater pumps, and sent back to the SGs.

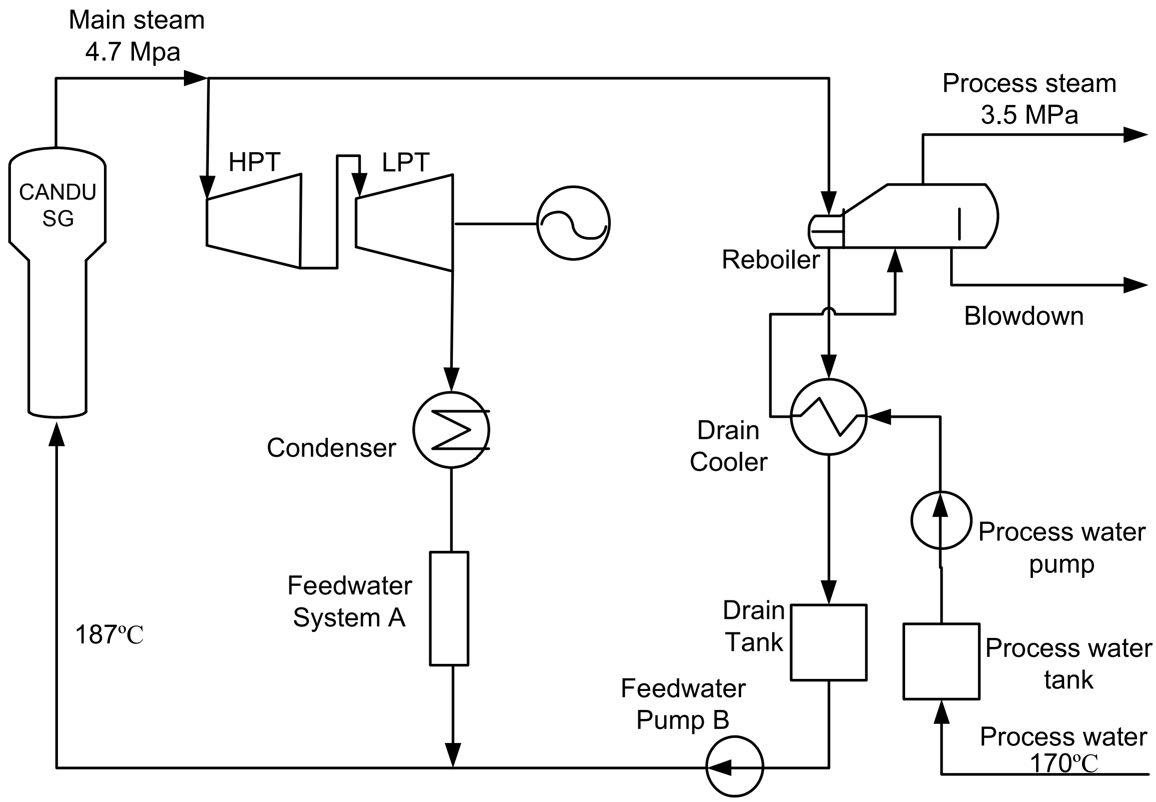

FIG. 3. Overall design concept for a CANDU 6 SAGD application (steam and electricity generation[1])

The process water returned from the oil facility is collected in the process water tank. The process water pumps draw water from the process water tank, and pressurize the water to meet the reboiler feedwater pressure requirement. A process water header (not shown) is located at the outlet of the process water pumps, from where the water is fed to each drain cooler. The water is preheated inside the drain coolers, and then enters the associated reboilers where it becomes process steam. The process steam is collected in a process steam header and transimitted to the SAGD wells. This steam then releases its latent heat, which is used to reduce the viscosity of bitumen, so that it becomes mobile and the steam becomes condensate. The condensate mixes with bitumen and is driven by pressure out of the recovery well. The condensate gets separated from the bitumen and cleaned in the SAGD facilities, to distilled water purity levels before being sent back to the nuclear plant as process water to feed the reboilers.

The remainder of the main steam goes to the turbine to produce electricity, is condensed in a condenser and becomes feedwater to the SGs, as in a generic CANDU plant. The two streams of condensate, one from the reboilers and one from the CANDU main steam condenser are mixed and become feedwater for the SGs.

2.2.2. Steam generation only

In this option, all the main steam from the SGs is used by reboilers to produce process steam and there is no turbine/generator or associated auxiliary systems in the plant design. The overall design concept for an ACR-1000 in this application is shown in Fig. 4. The condensate from the reboilers provides the total feedwater supply for the SGs. Not having a turbine generator in the nuclear plant does introduce some complications with respect to the electricity supply.

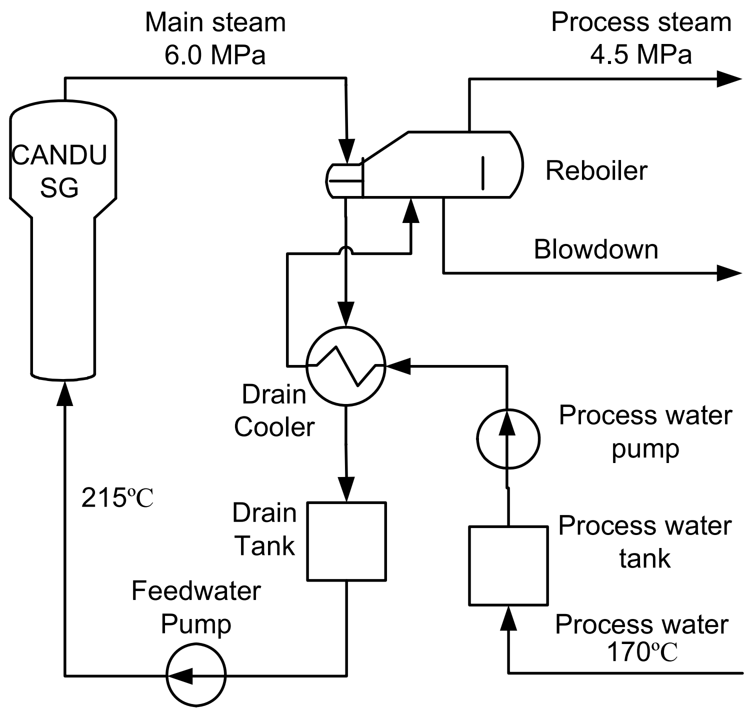

FIG. 4. Overall design concept for ACR-1000 SAGD application (steam only)[2]

In this option the nuclear plant gets all of the electrical power that it needs for plant loads from the electrical grid and a back-up source of station service power is required. At least two independent and diverse connections to the transmission system will be required. The back-up power will be provided by a large combustion turbine generator (CTG). The expectation is that the gas turbine will be operated for approximately 15 days throughout the year at those times that the grid is at its greatest risk of failure, for example during lightening or ice storms.

3. Application of a CANDU reactor for open-pit mining operations

3.1. The generic open-pit mining process

Figure 5 illustrates how the bitumen extraction process works in the open-pit mining process. Trees and overburden (soil) are first removed. The oil sands are then excavated and transported to crushers, then mixed with water for slurring, transported and conditioned in a pipeline and sent to a bitumen-extraction facility. The bitumen is separated as froth, which are a mixture of bitumen, water and a small portion of solids. The froth is further treated in a froth treatment plant, which produces bitumen.

Unlike the SAGD process, which requires only a small amount of electricity and large amounts of high pressure steam, the open pit mining process requires large amounts of hot water and steam at two different pressures, around 1 MPa and 2 MPa as well as electricity. The steam is used in the extraction process and in froth treatment.

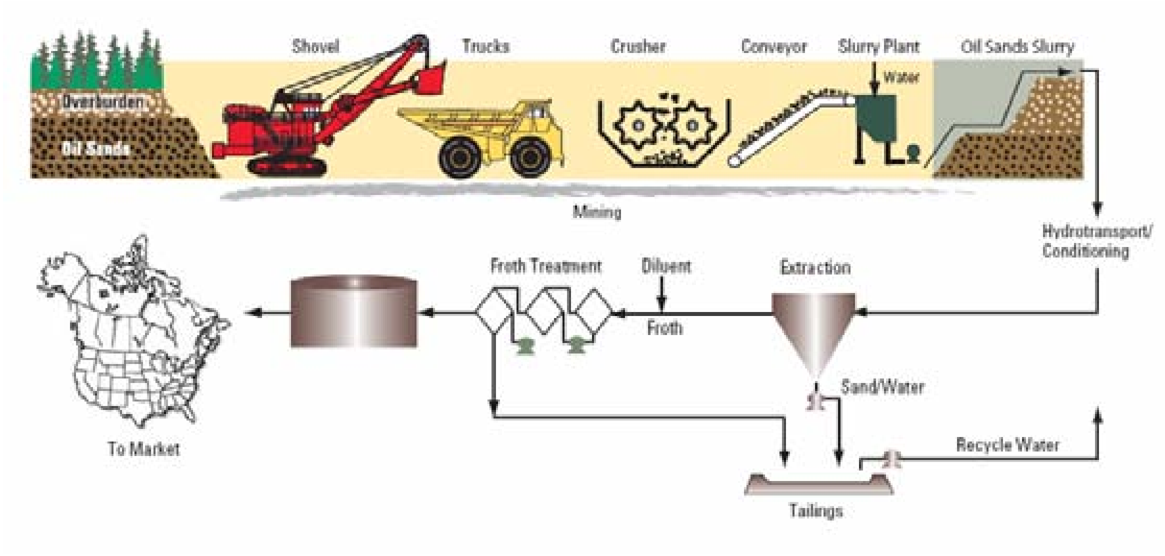

FIG. 5. Overall process diagram for Bitumen extraction using open pit mining [1]

3.2. Open-pit mining applications

Figure 6 shows a simplified flow sheet of a CANDU 6 cogeneration plant for energy supply to a mining facility. Part of the main steam from the SGs is used as the heat source for kettle reboiler 1 to generate process steam at 2 MPa. The condensate is returned to the CANDU SG feedwater system. The remaining portion of the main steam supplies the turbine system. Extraction steam from the high pressure (HP) turbine is the heat source for reboiler 2 to generate process steam at 1 MPa. The condensate returns to the SG feedwater system. Extraction steam from the LP- turbine is supplied to the water heater to produce process hot water. This condensate is also returned to the SG feedwater system. Since the feedwater to the water heaters from the bitumen extraction plant is at a low temperature (from 8 to 23˚C), it is used as a part of the condenser cooling water (CCW) before being sent to the water heaters for further heating. This utilizes thermal energy that otherwise would be lost through the CCW, and boosts the overall system's thermal efficiency. As an outcome, electricity generation can be increased while supplying the same thermal power to oil sands facilities. Adopting this approach also significantly reduces the need for cooling water.

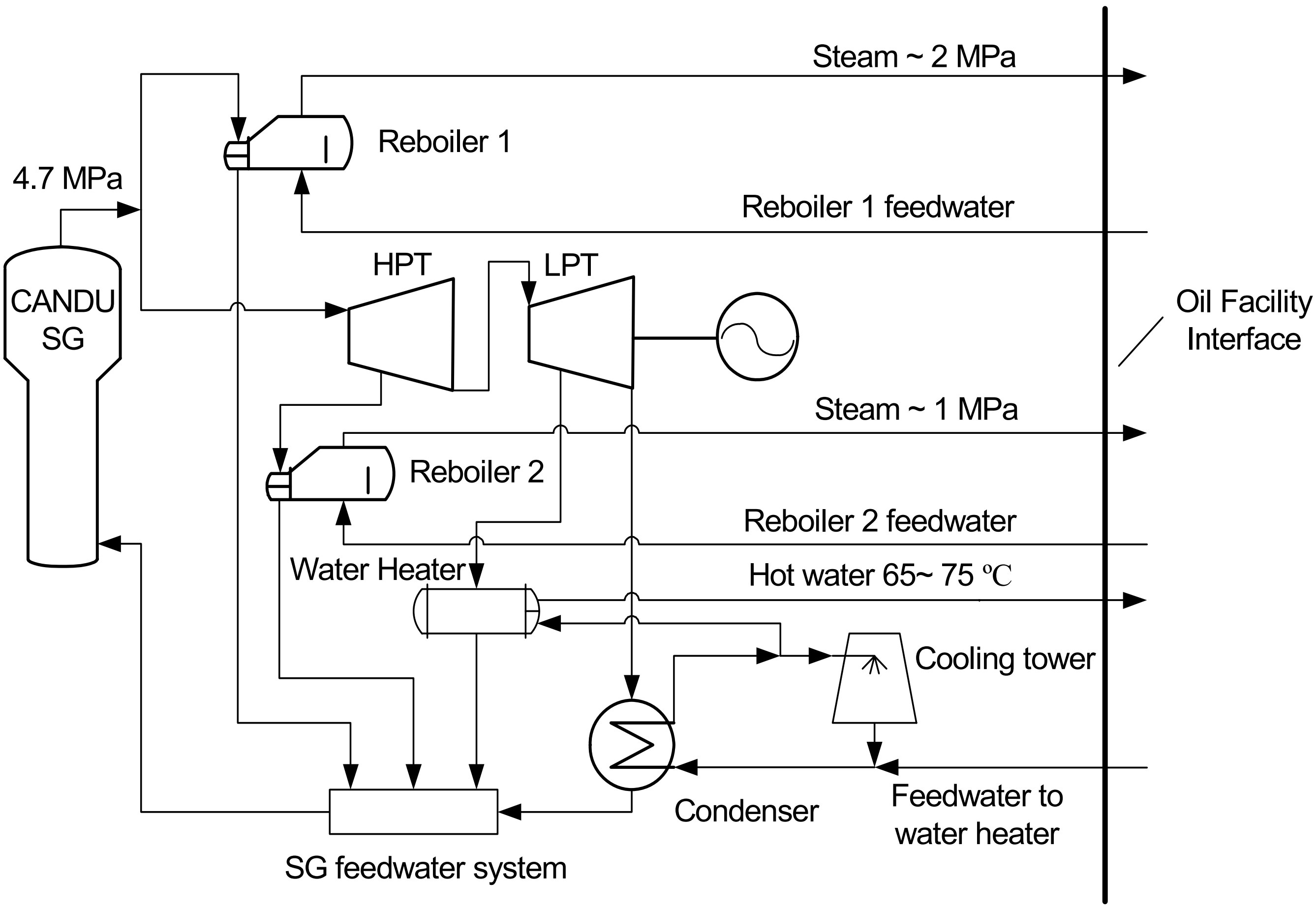

FIG. 6. Simplified flow sheet of a CANDU 6 cogeneration plant (mining application)

Unlike the SAGD process, the open-pit mining process is subject to large seasonal variations in thermal requirements. Automatic extraction turbines, instead of condensing turbines used in a generic CANDU plant, will be used to accommodate the various extraction steam flow rates induced by the fluctuations in the thermal power demand. This is a proven technology which is widely used in cogeneration power plants. As a result, the electricity output from the CANDU cogeneration plant varies seasonally. Assuming the thermal load for a manageable size of an extraction plant with 300,000 bbl/day of bitumen production, a system simulation was performed for typical year-round weather conditions in Northern Alberta for this configuration. For average weather conditions, the thermal power demand is 1552 MWt. A CANDU 6 plant is able to provide the required thermal power while generating 327 MWe (gross) electricity, resulting in an energy utilization efficiency of 91.1%.

Using a CANDU plant for providing the energy requirements of an open-pit mining process is the most efficient use of a nuclear reactor in the oil sands because of the ability to to recover the majority of the condenser heat load, which is otherwise lost to the cooling source, to produce the hot water.

4. Economics of CANDU reactors in the oil sands

Currently oil sands facilities use natural gas as the prime source of energy for their bitumen extraction and upgrading processes. The volatility of natural gas prices over the last several years (300% price increase in the last 4 years) has forced oil companies to look seriously at alternative sources of energy that are both sustainable and predictably priced. Nuclear energy has only a marginal dependence on fuel cost, compared to natural gas, and is a reliable source of inflation-proof energy supply. Currently, no other energy source with feasible economics and acceptable environmental impact has been identified. We have carried out an economic analysis of the cost of nuclear steam supply compared to that of natural gas and the results are shown in Fig. 7. The cost of nuclear steam is dependent on reactor type and size, the number of units and project specifics. In 2005, the average cost of natural gas was $8.33 (Can)/GJ and it was as high as $14/GJ (incidently, off the scale in Fig. 7) at points during the winter. As the figure shows, nuclear power is an economically competitive energy source for oil sands projects.

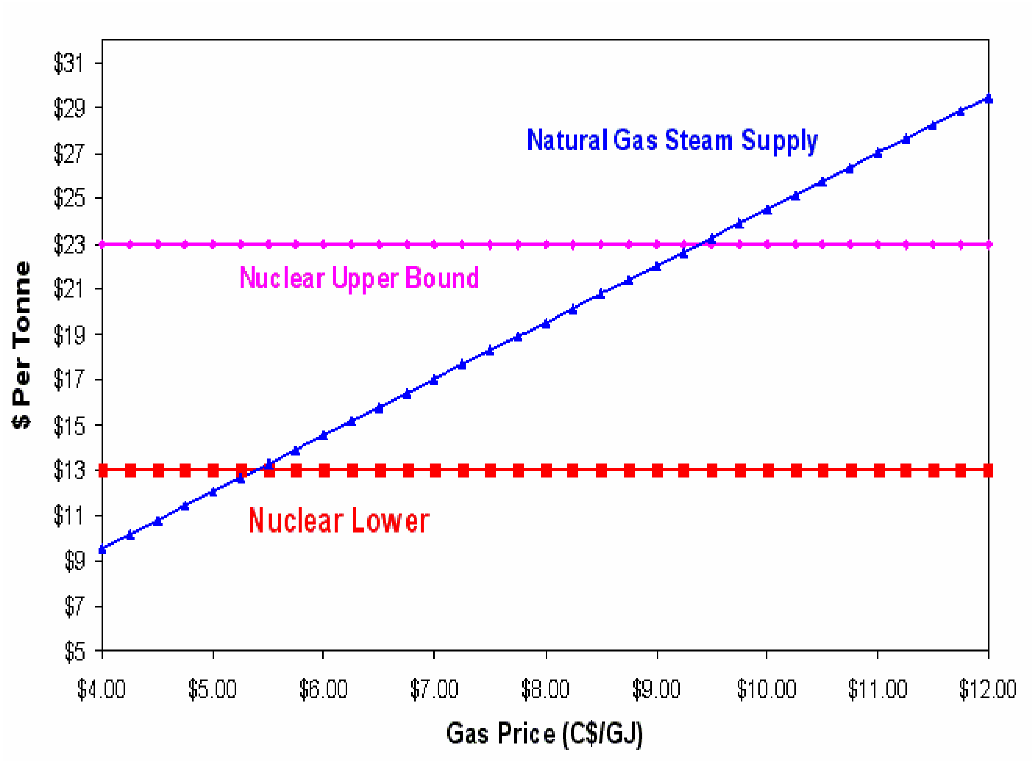

FIG. 7. Cost comparison between natural gas and nuclear power for steam generation

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Fuel ethanol production using nuclear-plant steam

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Abstract. In the United States, the production of fuel ethanol from corn for cars and light trucks has increased from about 6 billion liters per year in 2000 to 19 billion liters per year in 2006. A third of the world's liquid fuel demands could ultimately be obtained from biomass. The production of fuel ethanol from biomass requires large quantities of steam. For a large ethanol plant producing 380 million liters of fuel ethanol from corn per year, about 80 MW(t) of 1-MPa (~180ºC) steam is required. Within several decades, the steam demand for ethanol plants in the United States is projected to be tens of gigawatts, with the worldwide demand being several times larger. This market may become the largest market for cogeneration of steam from nuclear electric power plants. There are strong incentives to use steam from nuclear power plants to meet this requirement. The cost of low-pressure steam from nuclear power plants is less than that of natural gas, which is now used to make steam in corn-to-ethanol plants. Steam from nuclear power plants reduces greenhouse gases compared with steam produced from fossil fuels. While ethanol is now produced from sugarcane and corn, the next-generation ethanol plants will use more abundant cellulose feedstocks. It is planned that these plants will burn the lignin in the cellulosic feedstocks to provide the required steam. Lignin is the primary non-sugar-based component in cellulosic biomass that can not be converted to ethanol. Low-cost steam from nuclear plants creates the option of converting the lignin to other liquid fuels and thus increase the liquid fuel production per unit of biomass. Because liquid fuel production from biomass is ultimately limited by the availability of biomass, steam from nuclear plants can ultimately increase the total liquid fuels produced from biomass.

1. Introduction

In the United States, the production of fuel ethanol from corn for cars and light trucks has increased from about 1.6 billion gallons per year ($6 \cdot 10^9$ L/y) in 2000 to 5 billion gallons per year ($1.9 \cdot 10^{10}$ L/y) in 2006. It is projected by 2030 that up to 30% of the liquid fuels consumed in the United States could be made from biomass [1, 2] with an ultimate production capability twice as large. Long-term studies [3] indicate that biofuels could provide about 30% of the global demand in an environmentally acceptable way without impacting food production. Rapid expansion of liquid fuels production from biomass is predicted for many other parts of the world as well. Sugarcane and corn are the primary feed stocks today, but future plants are expected to also use abundant cellulose. The rapid growth in biomass-to-ethanol plants is a result of three factors: new biotechnologies that are dramatically improving the economics; increased concern about global warming, which generates renewed interest in renewable liquid fuels; and the high cost of oil.

The production of fuel ethanol from biomass requires large quantities of steam. For a large ethanol plant producing 100 million gallons of fuel ethanol from corn per year ($3.8 \cdot 10^8$ L/y), about 80 MW(t) of 150-psi (1 MPa; ~180ºC) steam is required. Within several decades, the steam demand for ethanol plants in the United States is projected to be tens of gigawatts, with the worldwide demand being several times larger. These changes open up a new large market for nuclear cogeneration of steam for (1) electricity and (2) process plants that convert biomass to liquid fuels. The technologies and changes are described herein.

2. Ethanol: The fuel

As a liquid fuel, ethanol has long-term advantages. If produced from biomass, it can be a renewable greenhouse-free liquid fuel. Green plants use solar energy and carbon dioxide from the atmosphere to produce the biomass, which is then converted to ethanol. The burning of the ethanol returns the carbon dioxide to the atmosphere. The environmental hazards of ethanol are less than those of gasoline or other traditional fuels because ethanol is quickly degraded to carbon dioxide and water in the environment by various bacteria.

Ethanol is increasingly being used as a transport fuel in three different ways. First, ethanol has an octane rating of 113–115 and therefore is used as an octane enhancer. It is replacing MTBE, a hydroscopic octane enhancer that has caused significant groundwater contamination and has major legal liabilities associated with its use. Second, ethanol is used to meet the minimum oxygen-content requirements for gasoline. Some oxygen is required in gasoline to minimize carbon monoxide pollution from vehicles and pollutants that produce ozone. Last, ethanol is a fuel, both when mixed with gasoline and when used alone. However, the values of ethanol as an octane enhancer and as a means of achieving minimum oxygen requirements for the fuel are significantly higher than its fuel value. If ethanol became widely available, engine performance and efficiency could be improved by taking advantage of the very high octane rating it offers.

3. The revolution in fuel ethanol production

The potential benefits of fuel ethanol have long been understood; however, it is the development of new biotechnologies that are beginning to make this option a technically and economically viable option in large parts of the world. There are four biomass feed stocks, each requires a somewhat different technology.

Monomeric sugars. Traditional fermentation can directly convert simple sugars such as those from sugar cane and sugar beets into alcohol. This is the primary method that has been used to produce alcohol for human consumption for thousands of years. However, the availability of these feed stocks is limited because they are also used for food. Today most of the fuel ethanol from simple sugars is made from sugarcane in Brazil, where the combination of land, labor, and climate provides favorable economic conditions.

Starch. Starch is a biopolymer of glucose, a monomeric sugar. It is the primary component of corn and other grains. Starch cannot be directly fermented to alcohol. An enzyme is required to break it down into simple sugars. The simple sugars can then be fermented to alcohol. While brewers learned long ago how to use natural enzymes to achieve this conversion, only in the last several decades has modern industrial enzyme technology developed methods to make inexpensive enzymes to allow economic production of fuel ethanol. Those technical developments have made possible the new fuel ethanol industry in the United States based on corn. The availability of starch is an order of magnitude larger than that of monomeric sugars but is also constrained because starch is a food for humans and many farm animals.

Cellulose. Cellulose is the most common form of biomass and is also a biopolymer of glucose. It is structured to be difficult to break down and thus serves as a defense mechanism for plants, because only some animals can digest cellulose.

Hemi cellulose. Hemi cellulose is the fourth sugar biopolymer. However, unlike the other sugars, it is a highly branched chain of five- and six-carbon sugars. It is the second most common form of biomass. Like cellulose, only some animals have the capability to digest it.

Cellulose-rich feed stocks contain 40–60% cellulose, 20–40% hemi cellulose, and 10–25% lignin. Lignin is a non-sugar biopolymer which will be discussed later. Like starch, cellulose and hemi cellulose can be broken down into their sugars with appropriate enzymes. However, much more sophisticated enzymes are required to break down these biopolymers [4]. In the last decade, the development of low-cost enzymes to break down these biopolymers to monomeric sugars now makes it appear possible to economically convert these feed stocks to ethanol. The first pilot plants are now in operation, and industrial facilities are expected to follow. The available cellulosic biomass is an order of magnitude larger than the available supplies of starch and is sufficient to meet a significant fraction of the world's liquid fuel demands. New technologies are expected to significantly increase cellulose yields as an energy crop [5]. The large projected growth in fuel ethanol production is based on the commercialization of this technology.

4. Benefits of using nuclear energy to supply steam

Biomass is not a free energy source. Large quantities of energy are required to grow biomass and convert it into ethanol. The non-solar-energy input to grow the biomass (e.g. corn) and convert it to ethanol is typically about 70 to 80% of the energy value of the ethanol [6]. About half of this energy is in the form of low-temperature, low-pressure (1-MPa; 150-psi) steam [7]. The fermentation of sugars yields a mixture of water and alcohol. With corn, the mixture is typically >13% alcohol by volume. Above ~15%, the alcohol is toxic to the yeast. The alcohol content depends upon the type of biomass and other factors. Distillation, an energy-intensive process, is required to separate the ethanol from the water. Smaller quantities of steam are required to sterilize the feed before fermentation and drying of various secondary products. A typical flow sheet for the conversion of corn to ethanol and animal food is shown in Fig. 1. Today different sources of energy are used to provide the steam.

Monomeric sugars. In Brazil sugarcane in Brazil is the primary feedstock to produce ethanol from simple sugars. The sugar cane is squeezed to separate the sugar water from the cellulose-rich cane called bagasse. The bagasse is burned to provide the energy for the ethanol plant.

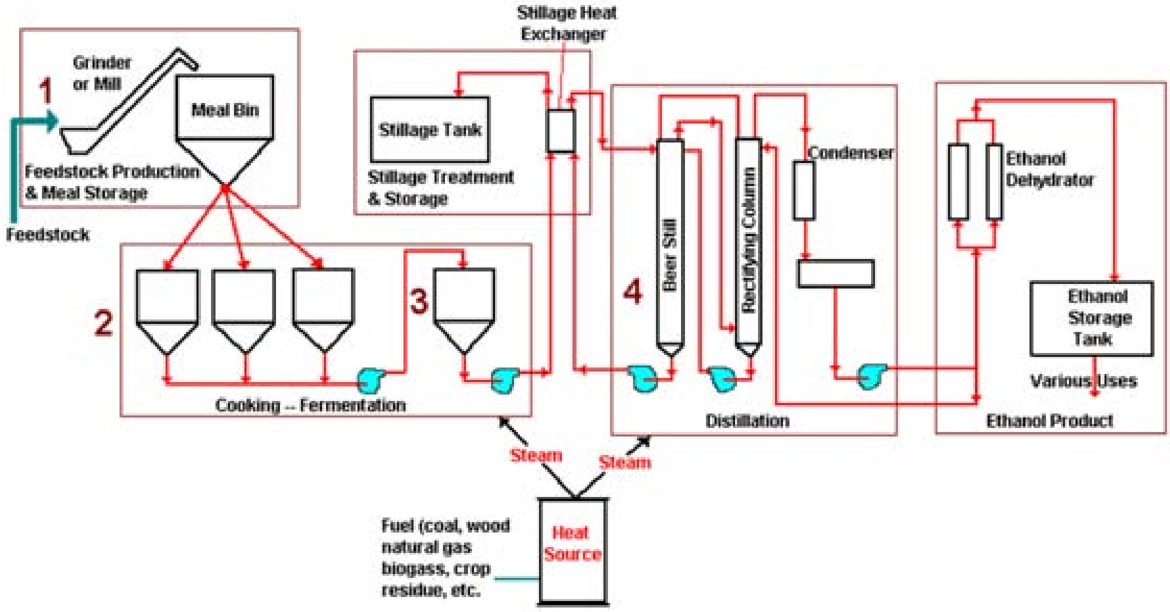

FIG. 1. Flow sheet for conversion of corn to fuel ethanol and animal food.

Starch. In the United States corn is the primary starch that is converted to ethanol. Corn contains starch in the form of carbohydrates and proteins. In the corn-to-ethanol process, the fermentation step converts the carbohydrates to ethanol, which uses about two-thirds of the corn kernel. The non fermentable components, which consist primarily of proteins and the other by-products of fermentation, become animal food or are converted to other useful products. Because of the value of the protein as an animal food, these by-products are not burnt to produce energy to operate the plant. In most cases, natural gas is used to provide the energy to operate the plant.

Cellulose and hemicellulose. The current plans to convert these materials to ethanol assume that the lignin associated with the cellulose and hemicellulose will be burnt to provide energy.

Nuclear power plants excel in the production of steam. That capability enables them to cogenerate electricity and steam, with the steam used to operate ethanol plants. For ethanol production, steam would be provided by the reactor. In the ethanol plant, the steam would be condensed, and warm water would be returned to the nuclear power plant. Almost all of the heat would come from condensing the steam. Modern steam systems would allow more than a kilometer of separation between the reactor and the ethanol plant. Ethanol plants would have to be located beyond any security perimeter because such plants require easy access by grain trucks, trains, or barges. The separation required to avoid security concerns would be more than necessary to ensure safety against fires and other accidents in the ethanol plant.

There are multiple incentives to use steam from nuclear power plants, as outlined in the following subsections.

4.1. Economics

After the cost of biomass, energy is the second largest cost in the production of fuel ethanol. For the production of ethanol from corn (starch) in the United States, the energy to make the steam is provided by natural gas. Steam from existing nuclear power plants in the Corn Belt and along the Mississippi River can potentially be supplied at significantly lower costs than steam from fossil fuels.

The price of nuclear plant steam can be estimated from the price of electricity. A nuclear power plant produces steam that can be sold or used to produce electricity. The utility will demand at least the same revenue from the sale of steam as from the sale of electricity. A rough estimate of the price of steam can be calculated from the wholesale price of electricity, as clarified in the following example. The price of electricity varies across the country; thus, this example will use the recent average market price for wholesale electricity in Minnesota which is \$53.89/MWh(e). Minnesota is a major producer of fuel ethanol in the United States and has nuclear reactors at Monticello and Prairie Island. The efficiency of nuclear power plants is ~33%; that is, if one less kWh of electricity is produced, 3 kWh of steam become available. However, nuclear reactors produce high-temperature steam whereas ethanol plants require only relatively low-temperature steam. In converting high-temperature steam to electricity, 40% of the electricity is obtained by the time the steam pressure is 150 psi (1 MPa) and suitable for ethanol production, with the remaining 60% of the electricity produced in the low pressure turbines. Using this information, a rough estimate can be made of the corresponding price of steam from a nuclear plant given the price of electricity:

$$\$53.89/\text{MWh(electricity)} \cdot 0.33 \cdot 0.6 = \$10.67/\text{MWh(steam)} = \$3.13 \text{ per million Btu.}$$

This cost represents less than half the price of natural gas in the United States. Similar economics apply to the cogeneration of low-temperature steam almost everywhere in the world. There is also the potential for additional savings. The price of electricity is lower at night than during the day. If some of the steam demand (such as for by-product drying) can be shifted to the nighttime, steam costs may be one-half or one-third as much.

4.2. Greenhouse impacts

The energy value of the fossil fuels required to grow corn and convert it to ethanol is 70 to 80 % the energy value of the ethanol. Using steam from nuclear plants would reduce in half the fossil fuel consumption and thus reduce in half the greenhouse gas releases in the production of ethanol from corn.

4.3. Full use of biomass

Recent U.S. studies [1] indicate that biomass (primarily cellulose) could provide 30% of the liquid fuel demand by 2030. The primary limitation is the availability of biomass. If steam from nuclear plants can displace bagasse (primary cellulose) from sugarcane-to-ethanol plants or lignin from cellulose-to-ethanol plants as the energy source for ethanol plant operations, more liquid fuels can be produced per unit of biomass.

5. Limitations

5.1. Biomass transportation

Biomass is bulky, heavy, and expensive to transport. As a consequence, ethanol plants are located where biomass is available or where the by-products can be sold. This limits the potential sale of steam from nuclear plants to those plants near large sources of biomass or to river locations where low-cost barge transport may allow long-distance transport of biomass. In the United States today, most of the nuclear plants that can economically provide steam for this application are in the Corn Belt or along the Mississippi River or other waterways where cheap barge transport is available (Fig. 2).

The size of ethanol plants has grown rapidly. New large ethanol plants require ~100 MW(t) of steam. Plant size is increasing but will ultimately be limited by biomass transport costs. Except for river sites, this will likely limit the market for steam from most nuclear sites to a few hundred megawatts. These logistic constraints imply a major market for cogeneration of steam from nuclear reactors for ethanol production. However, construction of large nuclear reactors dedicated to ethanol production is less likely. Instead, ethanol production represents a market for cogeneration of electricity and steam.

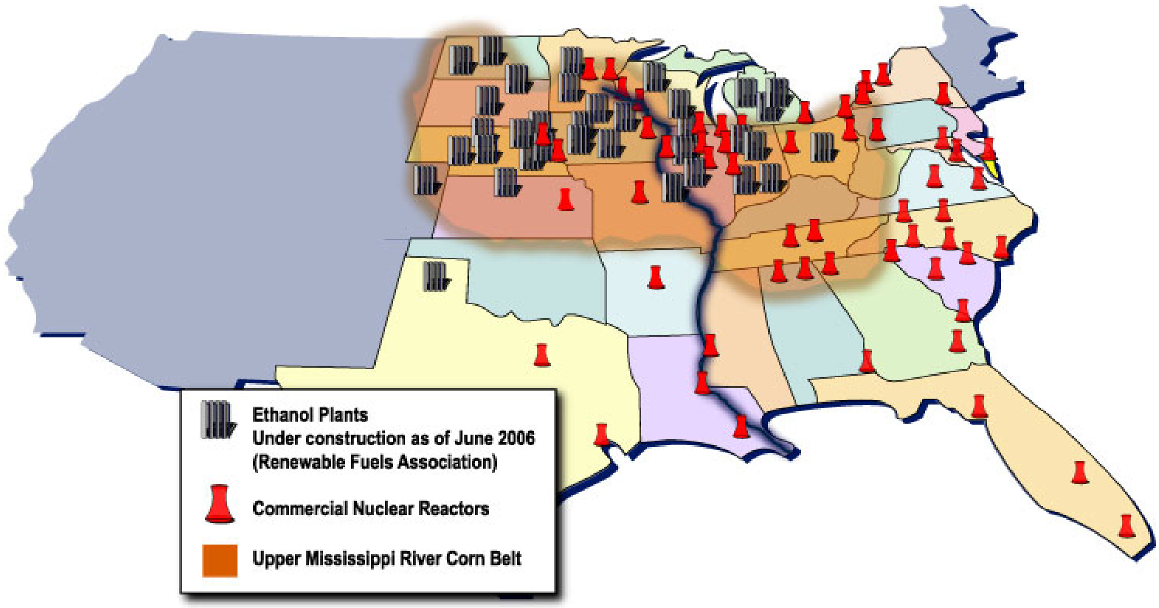

FIG. 2. Ethanol plants under construction, existing nuclear power plants, and the corn belt.

5.2. Institutional

The idea of using nuclear power plants to co-produce electricity and heat is not new. Since the beginning of the development of nuclear energy [8], steam has been used for district heating (45 reactors), desalting (10 reactors), and industrial purposes (25 reactors). Canadian nuclear power plants have been used to produce electricity and steam, with the steam used for the isotopic separation of heavy water and other industrial purposes. This included the use of steam from the Bruce Nuclear Power Station in Canada for about a decade for the production of ethanol. Plants in Switzerland and Russia produce both electricity and district heat. In the United States, a two-unit nuclear plant was partially built at Midland, Michigan, to produce electricity and steam for the Dow Chemical Company. However, applications have been limited. One reason is that the prices of fossil fuels have been low. Equally important, very few markets exist for large quantities of steam. It is not usually worth the effort to modify a nuclear power plant producing 1500 to 4500 MW of steam to produce a few megawatts of heat.

The development of fuel-ethanol production from corn in the last 5 years is now creating a new potential market for large quantities of steam from nuclear power reactors. The size of corn-ethanol plants is rapidly increasing, as is the corresponding steam demand per plant. The plants that produce ethanol from corn operate continuously, resulting in a steady-state demand for steam. In the production of ethanol, the primary cost is corn, followed by the cost of energy—thus, the economic incentive to consider steam from nuclear power plants. Finally, the demand for steam is located in rural areas where nuclear power plants already exist. This represents a new market that did not previously exist. Only with the development of large corn-to-ethanol plants and the coming development of cellulose-to-ethanol plants does a market now exist. The new market, with its own specific constraints, will require the development of appropriate business structures to combine nuclear steam with ethanol production.

5.3. Cellulose-to-Ethanol

The new corn-to-ethanol market in the United States may enable up to 30 existing reactors to sell steam for ethanol production. However, this is a small market limited to a few countries compared with the future global cellulose-to-ethanol market. To enter the latter market, chemical processes must be developed to convert lignin into liquid fuels [4, 9] or other uses [10]. Lignin is a complex biopolymer made by plants from various phenyl alanines that is not consumed in a cellulose-to-ethanol plant. For this type of plant, plans are to burn the lignin to produce steam. With high fossil-fuel prices, lignin is the low-cost energy source for such plants—unless nuclear steam is available.

There are multiple ways to convert lignin to liquid fuels [4, 9]. The Fisher-Tropsch process, which is used to convert other carbon-based materials to liquid fuels, can be used. However, this process is typically used on a much larger scale of operations. Lignin provides a low-sulfur, highly uniform feed that should improve the economics of smaller-scale plants. However, this potential has not been fully examined. Research is also under way to convert this biopolymer to high-octane (>100 octane number) gasoline additives and other useful compounds by various catalysts. The need is to accelerate this work—something that will happen with the recognition that steam from nuclear power plants could provide a low-cost alternative energy source to operate ethanol plants and free lignin for other uses.

6. Conclusions

Markets determine the demand for steam from nuclear power plants. An ongoing revolution in biotechnology is driving down the cost of producing ethanol from biomass. Biomass-to-ethanol plants require very large quantities of low-temperature steam. The growth of the ethanol from biomass market may soon create a major market for cogeneration of steam from nuclear power plants. The ultimate size of this market is measured in hundreds of gigawatts of thermal energy and thus may become the dominant cogeneration market for nuclear heat. The corn-to-ethanol plants provide the near-term market for nuclear steam for nuclear power plants located where corn is grown. In the longer term, there is potentially a larger market for steam to cellulose-to-ethanol plants. However, this market also requires development of the technology for conversion of lignin to fuels or other products.

Acknowledgements

The views expressed herein are the views of the authors and not necessarily the views of Oak Ridge National Laboratory or the U.S. Department of Energy.

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ROUND TABLE DISCUSSION ON CHALLENGES IN THE INTRODUCTION OF NUCLEAR HEAT APPLICATIONS

(SESSION 6) (PLENARY):

Chairpersons

I. Khamis
IAEA

SESSION 6. PANEL DISCUSSION

Panelists: M. Ogawa, M. Petri, A. Eltayeb, S.J. Herring, S.M. Ghurbal,
H .Al Thani, I. Othman

Rapportier: R.S.Faibish

The panel consisted equally of members from developing countries and OECD countries. It was noted that representatives from the developing countries (Libya, Sudan, Syria, and the UAE) focused on one big issue that is their countries are witnessing increasing power and water demands in the present and coming years due to increasing population, industrialization and economic development. These countries are considering the introduction of nuclear power and desalination for their future energy and water security in the near and long terms. The OECD countries were represented by panelists from the US and Japan. They shared the information on the other promising heat applications of nuclear power. The focus of the panel was to highlight the challenges to the introduction of nuclear power and its use for non-electric applications particularly in the developing countries and suggest solutions/ actions.

General issues

For nuclear desalination to be attractive in any given country, two factors must be in place simultaneously: a lack of water and the ability to use nuclear energy for desalination. In most regions, only one of the two is present. Both are present for example in China, the Republic of Korea and, even more so, in India and Pakistan. These regions already account for almost half the world's population and thus represent potential long- term market for nuclear desalination. The market will expand further to the extent that regions with high projected water needs, such as the Middle East and North Africa, increase their nuclear expertise and capabilities. Many of the countries in these regions already have large-scale desalination plants based on fossil sources.

Most of the countries, suffering from scarcity of water, are generally not the holders of nuclear technology, do not generally have nuclear power plants, and do not have a nuclear power infrastructure. The utilization of nuclear energy in these countries will require infrastructure building and institutional arrangements for such things as financing, liability, safeguards, safety, and security and will also require addressing the acquisition of fresh fuel and the management of spent fuel.

As a greenhouse-gas-free alternative, the U.S., Japan, and other nations are exploring ways to produce hydrogen from water by means of electrolytic, thermochemical, and hybrid processes. Most of the work has concentrated on high-temperature processes such as high-temperature steam electrolysis and the sulfur–iodine and calcium-bromine cycles. These processes require higher temperatures (>750^{o}C) than can be achieved by water-cooled reactors. Advanced reactors such as the very high temperature gas cooled reactor (VHTGR) can generate heat at these temperatures, but will require many years for commercial deployment. Meanwhile research work on hydrogen storage, distribution and its use in FCVs is continuing. Another important high temperature application of nuclear power is in the production of synthetic fuels and other hydrocarbons in a nuclear-chemical complex, as an alternate clean fuel source.

Nuclear power production is now a mature technology. Its role in combined heat and power application such as mentioned above is significant indeed. Unfortunately, existing nuclear power plants have been branded as “cash cows” for most utilities worldwide. A remarkable change in the view of the capital markets in the last few years on nuclear being not that capital intensive is quite encouraging. Economic competitiveness appears to be no more an issue. A large number of reactors are now planned in many developing countries due to their increasing energy demand as a result of high economic growth, but which have meagre fossil fuel resources.

However lack of confidence in the political stability, nuclear regulatory policies and financial aspects in many countries interested in nuclear technology has been a negative factor. To overcome this, partnership of utilities / large industrials will be welcome. The role of governments in recognizing the social benefits and in reducing various risks is also desirable.

Nuclear heat applications including desalination have been considered for long time, but not much has succeeded. Effective and practical measures to climate change/ green house gas reduction need to be taken, taking advantage of it being a clean energy source. Nuclear technology and its related institutions should advance and address to the real world as other technologies and environmental institutions do. Practical application would be possible based on exchange of experiences and further international collaboration.

Specific issues

Specific issues were raised by the panelists from the developing countries especially from Middle East and North Africa for the introduction of nuclear power/ desalination or other heat applications in their regions. These are as follows;

Although, no nuclear reactors have been so far utilized for electricity production in the Middle East region, dual use and other applications of nuclear reactors have been now suggested. As energy source, oil and gas reserves in the Middle East make more than 70% of world resources this may be one of the reasons for not giving priority to nuclear energy as an option. The socio-economic aspects of nuclear applications are favourable when compared and judged against conventional, non-nuclear competitors on cost, reliability, safety, simplicity and sustainability. When considering these applications, nuclear energy has priority not only in energy supply, but also in health, industry and agriculture.

Developing countries need skilled and trained human recourses to operate nuclear installations. In this respect the IAEA can support capacity building and enhance the knowledge in non -electrical applications. The IAEA support may include but not limited to energy options, health and safety risks of alternatives energy systems, local, regional and global environmental issues. In conclusion, it is time to benefit from nuclear power in the region of the Middle East and start serious joint nuclear projects. The Middle East countries got all reasons for success in achieving these objectives.

Seawater desalination is the sustainable solution for the supply of potable water. In view of the impact of conventional fuel prices, its depleting nature and the concern over the global warming, using nuclear energy for seawater desalination gained wide interest and is being considered as an appropriate solution including in North African countries. Countries, which are enjoying good wealth from oil revenue, need to consider the energy mix plan in their national strategy in order to maintain socio-economic development.

The need for introduction of nuclear power technology for seawater desalination and electricity generation in developing countries faces some challenges. Among these challenges that can generally be envisaged are:

- The public perception (negative due to safety concern),
- Political will (both sides, vendor and recipient countries),
- Infrastructure requirement for nuclear power project such as, regulatory bodies, qualified manpower, grid size, basic supporting industry etc. The IAEA role in training, guidance, etc is desirable.
- Financial barrier.
- International community concern about safety and proliferation.

In fact these challenges differ from one country to another depending on its economic situation, available infrastructure and others.

Open floor discussion

Many points were raised during the open floor discussion wherein the participants took active interest. The challenges and the solutions suggested during this discussion are as follows:

Challenges to the introduction of nuclear power

- System integration/ requirements of nuclear power plants
- Safety/ radiological issues
- Feed stocks: Transport and location
- Region- specific needs
- Building infrastructure
- Initial investments and general financial issues
- Public acceptance
- Political will
- Regulatory institutions and guidance
- Socio-economic and environmental concerns

Some issues on nuclear hydrogen production

- Distribution and storage
- Analysis tools and predictive modelling needs
- Understanding real market needs
- Safety and risk analysis

Suggested solutions/ actions for combined heat and power (CHP) applications

- Share information experiences in nuclear infrastructure planning and building possibly through IAEA
- Educate the public to alleviate concerns also with leadership of IAEA
- Utilize existing and develop additional required analysis tools in planning and implementation of nuclear applications: clearly identify opportunities, markets, customers, suppliers and understand short and long term needs
- Move quickly to demonstration projects of non-electric nuclear energy applications with IAEA leadership
- Engage potential investors/financiers in planning to make things happen (eg World Bank)
- Develop the regulatory infrastructure as soon as possible

IAEA's role

IAEA has reflected the new trend of rising expectation of nuclear power deployment particularly in developing countries, in its programme by putting emphasis on assistance to those countries, which are planning to introduce nuclear power or intend to extend its capacity. These include support to infrastructure building, technical cooperation for new projects on specific request from interested Member States, workshops and conferences. The Agency's increased scope of interest includes activities on non-electric applications of nuclear power. IAEA support covers wide spectrum of areas including infrastructure building, legal & regulatory frame- work, institutional issues, human resource development, site evaluation and others. A number of IAEA workshops in some of these areas were held in 2007 and many documents were published. Some of the relevant documents/ working materials are:

- IAEA-TECDOC-1513, Basic Infrastructure for a Nuclear Power Project.
- IAEA-TECDOC-1522, Potential for Sharing Nuclear Power Infrastructure between countries.
- IAEA-TECDOC-1555, Managing the First Nuclear Power Plant Project.
- IAEA-TECDOC (in preparation), Improving Prospects for Financing Nuclear Power Plants.
- Workshop on Steps for Conducting Assessment of Nuclear Power Plant Technology with Water cooled Reactors
- Workshop on Milestones for Nuclear Power Infrastructure and Issues for Improving Financing of Nuclear Power Projects Development
- Workshop on Common User Criteria for Development and Deployment of Nuclear Power Plants in Developing Countries.

Member States introducing their first nuclear power/ heat application project will benefit from the available information.

HTTR Workshop

Chairpersons

R. Hino
JAEA

HTTR WORKSHOP (Organized by JAEA)

Operation of the high-temperature engineering test reactor

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Summary. A High Temperature Gas-cooled Reactor (HTGR) is particularly attractive because of its capability of producing high temperature helium gas and its inherent safety characteristics. Hence, the High Temperature Engineering Test Reactor (HTTR) was successfully constructed at the Oarai Research Establishment of the Japan Atomic Energy Agency. The HTTR achieved the full power of 30MW and reactor outlet coolant temperature of about 850ºC on December 7, 2001. After several operation cycles, the HTTR achieved the reactor outlet coolant temperature of 950ºC on April 19, 2004. It is the highest coolant temperature outside reactor pressure vessel in the world. This is one of the major milestones in HTGR development of high temperature nuclear process heat application. Extensive tests are planned in the HTTR and a process heat application system will be coupled to the HTTR, where hydrogen will be produced directly from the nuclear energy. This paper gives an overview of the HTTR Project focusing on the latest results from the HTTR test and the future test plan using the HTTR.

Fuel researches in the HTTR project

Shohei Ueta

Nuclear Science and Energy Directorate
Nuclear Applied Heat Technology Division
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Abstract. For the establishment of the HTGR fuel technologies in Japan, the fuel fabrication process on mass production scale, the fuel performance during the HTTR high temperature test operation with 850/950ºC of outlet coolant temperatures and the future plan for post-irradiation examination of the HTTR fuel are presented. R&D work for HTTR was started from 1960's. The first- and second-loading fuel has been fabricated with low as-fabricated failure fraction. During the HTTR normal operation, fractional release of fission gas ^{88}Kr was lower than 1×10^{-8} at full power and it was confirmed that high quality fuel was successfully fabricated by mass-production. Post irradiation examination (PIE)s of the first loading fuel will be carried out to confirm fuel behavior under real-HTGR condition.

For upgrading technologies for the Very High Temperature gas-cooled Reactor (VHTR) fuel, present status and future R&D plan for advanced HTGR fuels are presented. As the JAEA's activity, R&D for future HTGR fuel includes the following topics; burn up extension for SiC-coated fuel particle and the development of ZrC-coated fuel particle as advanced fuel. JAEA has experienced two irradiation tests to extend the burn up with SiC coated fuel particles. Based on these experiences, the new R&D programmes with the new designed SiC-coated fuel particle are being planned with irradiation tests / PIEs under the possible international cooperation. The model development is on going with the benchmarking work in the framework of an IAEA CRP. Also, R&D on ZrC-CFP to develop the advanced VHTR fuel is presented. The new over-100g-scale coater by bromide process has been constructed at JAEA Oarai. Coating tests with surrogate particles are being carried out and the stoichiometric ZrC layer has been obtained. Irradiation test with ZrC coated particle and fuel performance modeling will be carried out under I-NERI between US and Japan.

Development and validation of analysis method for reactor performance and safety characteristics of HTGR

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Summary. The High Temperature engineering Test Reactor (HTTR) is a graphite-moderated and a gas-cooled reactor with a thermal power of 30 MW and a reactor outlet coolant temperature of 950 °C (SAITO, 1994). Safety demonstration tests using the HTTR are in progress to verify its inherent safety features and improve the safety technology and design methodology for High-Temperature Gas-cooled Reactors (HTGRs). The reactivity insertion test is one of the safety demonstration tests for the HTTR. This test simulates the rapid increase in the reactor power by withdrawing the control rod without operating the reactor power control system. In addition, the loss of coolant flow tests has been conducted to simulate the rapid decrease in the reactor power by tripping one, two or all out of three gas circulators. The experimental results have revealed the inherent safety features of HTGRs, such as the negative reactivity feedback effect. The numerical analysis code, which was named ACCORD, was developed to analyze the reactor dynamics including the flow behavior in the HTTR core. We used a conventional method, namely, a one-dimensional flow channel model and reactor kinetics model with a single temperature coefficient, taking into account the temperature changes in the core. However, a slight difference between the analytical and experimental results was observed. Therefore, we have modified this code to use a model with four parallel channels and twenty temperature coefficients in the core. Furthermore, we added another analytical model of the core for calculating the heat conduction between the fuel channels and the core in the case of the loss of coolant flow tests.

This paper describes the validation results for the newly developed code using the experimental results of the reactivity insertion test as well as the loss of coolant flow tests by tripping one or two out of three gas circulators. Finally, the pre-analytical result of the loss of coolant flow test by tripping all gas circulators is also discussed. The reactor power decreases to decay heat level from the maximum reactor power of 30 MW due to the negative reactivity feedback effect of the core. Although the reactor power becomes critical again, the peak power value is merely 2 MW. It was confirmed that by using the developed code, it is possible to not only analyze the reactor core dynamics but also simulate the core dynamics during the abnormal events postulated in the HTGR safety analysis.

Study on safety related issues of the cogeneration VHTR

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Abstract. Environmental issues are being increasingly taken up by the international community. One of the top-priority issues is the global warming which stems largely from the release of carbon dioxide gas from the industrial usage of fossil resources and vehicles exhaust gases. Hydrogen is considered to be the solution for these issues, since it doesn't release carbon dioxide gas on combustion and it can be produced by water which can be found all over the world.

Japan Atomic Energy Agency (JAEA) has been conducting R&D for hydrogen production utilizing nuclear heat to contribute the hydrogen society in near future. Design studies of hydrogen cogeneration high temperature gas cooled reactor (GTHTR300C), the commercial hydrogen production system utilizing nuclear heat from Very High Temperature Reactor (VHTR), have been carried out.

Since the hydrogen production system in GTHTR300C is required to achieve economic competitiveness against other conventional hydrogen production process attracting a great deal of interest from non-nuclear industries, it should be designed and constructed as non-nuclear grade. The necessary requirement for the non-nuclear grade hydrogen production system is to keep the reactor operation despite the operational condition of the hydrogen production system. In GTHTR300C, intermediate heat exchanger (IHX) for hydrogen production system is installed upstream of the gas turbine system directory and operational sequence using control valves are proposed so that the nuclear reactor can operate normally during the thermal load disturbance of hydrogen production system.

This presentation shows summary of the GTHTR300C, operational sequence during the thermal load disturbance of hydrogen production and calculation results of the loss of hydrogen production thermal load. It was confirmed that the reactor can keep its operational condition during loss of hydrogen production thermal load by operational sequence.

Visit to HTTR Facilities (Organized by JAEA)

The Japan Atomic Energy Agency (JAEA) organized a technical visit, for participants, to the High Temperature Engineering Test Reactor (HTTR). The HTTR is being utilized mainly to demonstrate high-temperature nuclear heat utilization i.e. hydrogen production using high temperature nuclear reactor. The visit was limited to the hydrogen production plant but not to the High Temperature Engineering Test Reactor itself. The demonstration test plan is constructed as a hydrogen production system by steam reforming of methane and coupled to the High-Temperature Engineering Test Reactor (HTTR). The test facility is a 1/30-scale of the HTTR-H2 and simulates key components downstream from an intermediate heat exchanger of the HTTR. The main objective of the simulation tests is the establishment and demonstration of control technology, focusing on the mitigation of a thermal disturbance to the reactor by a steam generator and on the controllability of the pressure difference between the helium and process gases at the reaction tube in a steam reformer.

POSTER PAPERS

Economic evaluation of seawater desalination in Cuba using DEEP

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DEEP is a Desalination Economic Evaluation Programme developed by the International Atomic Energy Agency (IAEA) [1]. The version 3 of DEEP (DEEP-3.0) was acquired and implemented in the country as a result of the cooperation between the IAEA and Cuba. The above-mentioned programme has been used in the national project "Feasibility of seawater desalination in Cuba", which will be implemented in the 2005 – 2007 triennium. This project is aimed at analyzing different technologies of seawater desalination so as to determine the most feasible technology for Cuba from the technical and economic viewpoints.

DEEP was used in the economic evaluation of different desalination plants with reverse osmosis (RO) technology. Real data obtained from the RO plant performance such as required capacity, modular unit size, seawater pump efficiency, feed salinity, and design flux as well as data of the RO plant costs was used. The selected energy source was grid electricity (stand-alone RO). The results obtained from the modeling of the desalination plant located at the Cayo Largo Island (at the Southern portion of Cuba) are shown. The RO plant, which uses Italian technology, has a capacity of 1000 m^3/day.

The paper presents the results of the sensitivity analyses by changing the interest rate, total capacity of the desalination plant, feed salinity, feed temperature and purchased electricity cost.

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Technical and economic consideration for water desalination by reverse osmosis

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Abstract. In August 2006, light crude oil exceeded US $73 per barrel and it expected to reach US $100 per barrel by the end of this year as a result of regional conflicts.Some experts argue that the world is heading towards a global energy crisis due to a decline in the availability of cheap oil and recommend a decreasing dependency on fossil fuel. This has led to increasing interest in alternate power/fuel research such as, hydrogen fuel, solar energy, and wind energy. To date, only hydroelectricity and nuclear power have been significant alternatives to fossil fuel. On the other hand, fresh water resources are limited, while, the world population has increassed rapidly; hence considering seawater desalination is of prime importantance. Seawater desalination is energy intensive process, therefore, energy utilization is a vital aspect. There is continued research and development of seawater desalination by reverse osmosis (RO) technique due to its lower energy consumption. Therefore, this study will focus on the effect of preheating feed water reverse osmosis unit by using heat discarded from nuclear power plants to obtain the lowest possible cost per cubic meter of fresh water.

A seawater membrane FT30SW-2540 included in a test rig is used to perform the study. Product flow rate and salt rejection are the key performance parameters. These are mainly influenced by variable parameters such as feed pressure, feed temperature. The results show that the permeate flux increases by increasing the feed pressure and/or increase in the feed temperature. For the same system productivity, the increase in the feed water temperature leads to reduced applied feed pressure. The membrane water permeability coefficient K_w is determined experimentally by the test rig measured parameters and compared with the projected manufacturer system analysis programme (ROSA) for the same operating conditions. Besides, it is correlated and presented with the different operating parameters.

For the above case the results show that; an increase in the feed water temperature by one degree centigrade is associated with a reduction in applied feed pressure by 0.7 % to 1.35 % ,shown in Table (I), a decrease in the membrane salt rejection of almost 1.4%, an increase of permeate flux from 1.11 % to 2.58 %, and a decrease of the specific energy consumption by an average value of 0.29 kWh/1000 gal, according to the feed salt concentration and feed pressure. The results show that an increase in feed salt concentration of one gram per liter decreases permeate flux by an average value of 2.41% to 2.8 %, decreases the membrane salt rejection percentage by 0.06 to 0.16, decreases the membrane water permeability coefficient by 1.23%, and increases the specific energy consumption by an average value of 5.073 kWh/1000 gal, according to the feed temperature. In addition, the membrane FT30SW-2540 water permeability coefficient is experimentally determined, compared with manufacturer, and correlated as a function of feed salt concentration, feed temperature, and feed pressure.

1. Introduction

RO membrane permits only fresh water to pass through, separating salt, at a higher feed pressure than the osmotic pressure of seawater by means of a high-pressure pump. The RO system design tends to save the pumping power as well as increasing the system productivity. The experts and the system designer's have two different opinions with regard to the RO feed preheating systems. The first group believes that the RO feed preheating increases the system productivity and/ or saves the process power consumption. Meanwhile, the second group believes that RO feed preheating neither increases the system productivity, nor increases the salt passage. In this respect, the author carried out an extensive work in which the criteria of the feed preheating of the seawater RO system optimal operation is extensively studied using the leading RO element [1]. Moreover, a proposal of RO system rehabilitation is presented and analyzed [2]. It is worth mention that aforementioned work is carried out through the RO system projection to determine the permeability coefficients for water of the used membranes. In the present work, the conformation of the projected permeability coefficient for water is carried out experimentally to realize and confirm the aforementioned work in the field of co-generative systems study area. An experimental setup of small seawater RO system is equipped with appropriate measuring instruments to measure the operating parameters, such as feed pressure, flow rate, temperature, and salt concentration, and system productivity. The corresponding projections are also performed.

2. The experimental loop

A small reverse osmosis unit is used to carry out this work. This experimental loop was constructed at the Heat Transfer and Desalination Laboratory, Reactor Department, Nuclear Research Center, Egyptian Atomic Energy Authority. Dissolved NaCl in tap water was prepared as the synthetic feed water, with similar concentrations as seawater for use in this experiment. A new membrane of a FILMTEC model FT30SW2540 membrane is installed to avoid the uncertainty of the membrane fouling. In such case the fouling factor is assumed equal to unity (FF = 1). The experimental rig front and side views are shown in Fig. 1. The rig is equipped with accurate measuring instruments such as the digital pressure gauge, temperature controller, and conductivity meter to measure the operating parameters. It is worth to mention that this small experimental rig can be helpful to obtain results for explaining the performance of the unit, which gives the insight of the best operation and control of the large RO units.

(a) Rig side view **(b) Rig front view**

FIG. 1. RO experimental rig.

3. Membrane performance

The membrane performance is affected by different operating parameters, which contribute in assigning the membrane flux and membrane salt rejection, such as applied feed pressure, feed temperature, and feed salt concentration.

3.1. The feed temperature

In the present study, the membrane FT30 SW 2540 was considered [3]. Therefore, the membrane water permeability coefficient, (K_w) is determined from the Reverse Osmosis System Analysis program (ROSA) [4] at different operating feed temperature, feed salt concentration, and constant permeate flow. Figure 2a depicts the membrane water permeability coefficient for water, (K_w) variations with the feed temperature at different feed-brine concentrations. This figure shows that K_w slightly decreases by increasing the temperature. It increases by decreasing the feed-brine concentration.

Figure 2b depicts the effect of feed temperature on the applied feed pressure for different feed salt concentration, and constant permeate flow. It is clear from Fig. 2b that the applied feed pressure decreases by the increase of the feed temperature for all feed salt concentrations. The results from running ROSA program clarifies that, for the membrane integrity point of view, any increase of feed temperature (T_f) by one degree centigrade, must corresponded to a decrease of the feed pressure (P_f) with a percentage of 1.35% to 0.7% according to the feed salt concentration of water, to maintain the same membrane permeate flux, shown in Table I.

Table I. Effect of feed temperature on the applied feed pressure, for different feed salt concentrations.

Feed concentration, mg/l	Value of feed temperature raise. °C	Value of feed pressure decrease, psi	% Of decrease in feed pressure, psi /degree °C
15,000	(20 – 40)	(497 – 363)	1.348
20,000	(20 – 40)	(576 – 441)	1.171
25,000	(20 – 40)	(657 – 521)	1.035
30,000	(20 – 40)	(740 – 603)	0.925
35,000	(20 – 40)	(825 – 689)	0.830
40,000	(20 – 40)	(914 – 777)	0.749
45,000	(20 – 40)	(1007 –867)	0.695

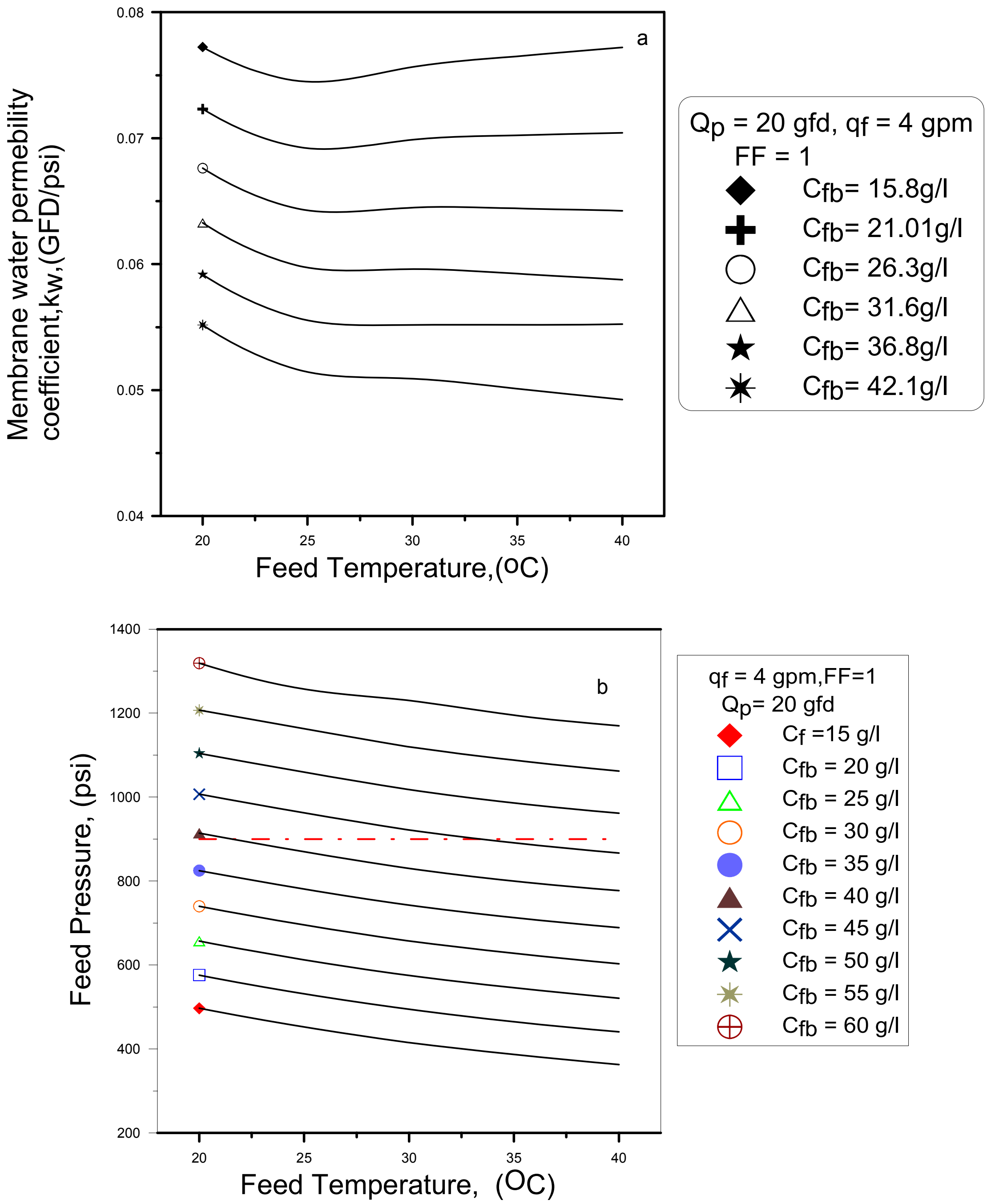

FIG. 2. Effect of feed temperature on FT30SW2540 permeability coefficient and feed pressure for different feed concentrations.

Figure 3 depicts the effect of feed temperature on the permeate flux, salt rejection, and the permeator product recovery together at different feed salt concentrations and different feed pressures. It is worth mentioning that the broken lines in this figure indicate the manufacturer membrane operating productivity flux limitation.

It is clear from Fig. 3a and d that the permeate flux increases by the increase of feed temperature for the decrease of feed salt concentration (at constant feed pressure (600 psi[1])), and for the increase of feed pressure. The obtained results from the experimental work show

[1] 1 kg/cm^2 = 14.73 psi

that; an increase of feed temperature of one degree centigrade, leads to an increase of 2.58%, 2.39%, 2.19%, 1.25%, and 1.11% of permeate flux, corresponding to feed salt concentrations of 25 g/L, 30 g/L, 35 g/L, 40 g/L, and 45 g/L respectively, at feed pressure of 600 psi. Meanwhile, an increase by feed temperature of one degree centigrade, results in an increase of 1.43%, 1.95%, and 1.78% of permeate flux, corresponding to feed pressures of 600 psi, 700 psi, and 800 psi respectively, at feed salt concentration of 40 g/L.

It is clear from Fig. 3b and e that the permeator salt rejection decreases by the increase of the feed temperature, for different feed salt concentrations and feed pressure respectively. The obtained results from the experimental work demonstrates that; an increase of feed temperature of one degree centigrade, results in an average decrease for salt rejection of 1.4% at the feed pressure of 800 psi. Meanwhile, the salt rejection decreases by the increase of the feed salt concentrations, and the decrease of feed pressure.

Figs. 3c and 3f illustrate the effect of feed temperature on the permeator recovery, for different feed salt concentrations and feed pressure respectively. Figure 3c illustrates that the permeator recovery increases by the increase of the feed temperature, and remarkably increase by the decrease of the feed salt concentrations.

Meanwhile, the permeator recovery increases by the increase of the feed temperature and feed pressure.

3.2. The feed pressure

Figure 4 depicts the effect of feed pressure on the permeate flux, salt rejection, and the permeator product recovery; together at different feed salt concentrations and constant feed temperature (T_f = 25°C). It is worth mentioning that the broken lines in this figure indicate the manufacturer membrane operating limitations.

Figure 4a illustrates the effect of feed pressure on the permeate flux at different feed salt concentrations. It is clear from the Figure that the permeate flux increases by the increase of the feed pressure and by the decrease of the feed salt concentration. The same trend is indistinguishably observed in Fig. 4c, which depicts the permeator recovery variations with the feed pressure. Furthermore, the permeator salt rejection remarkably increases as the feed pressure increase, as shown in Fig. 4b.

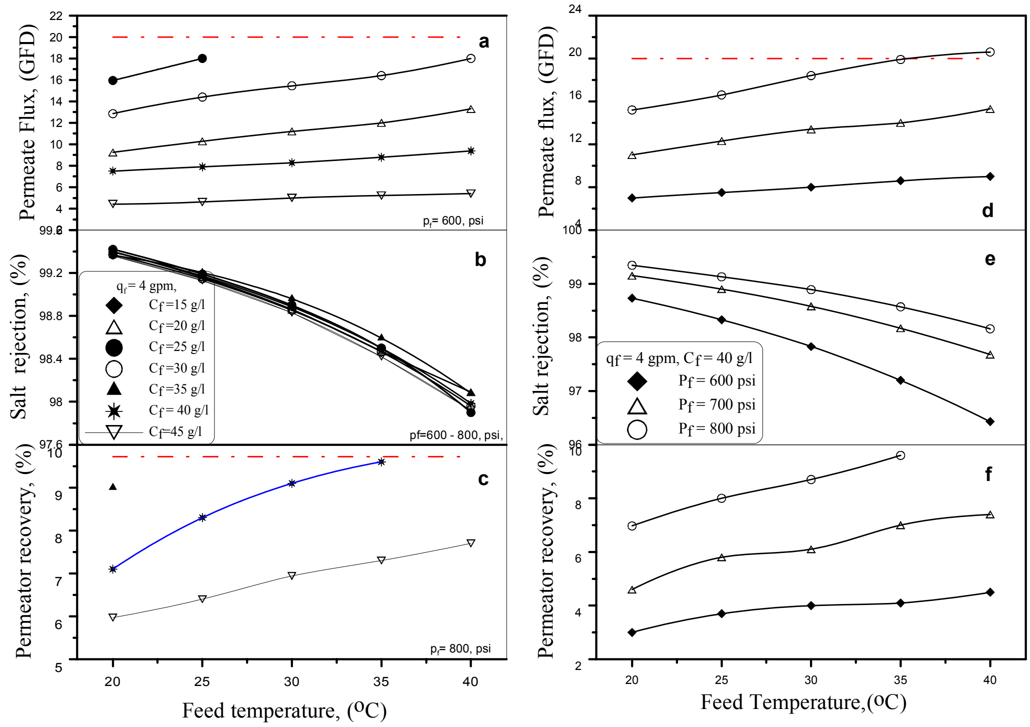

FIG. 3. Effects of feed temperature on permeate flux[2], salt rejection, and recovery.

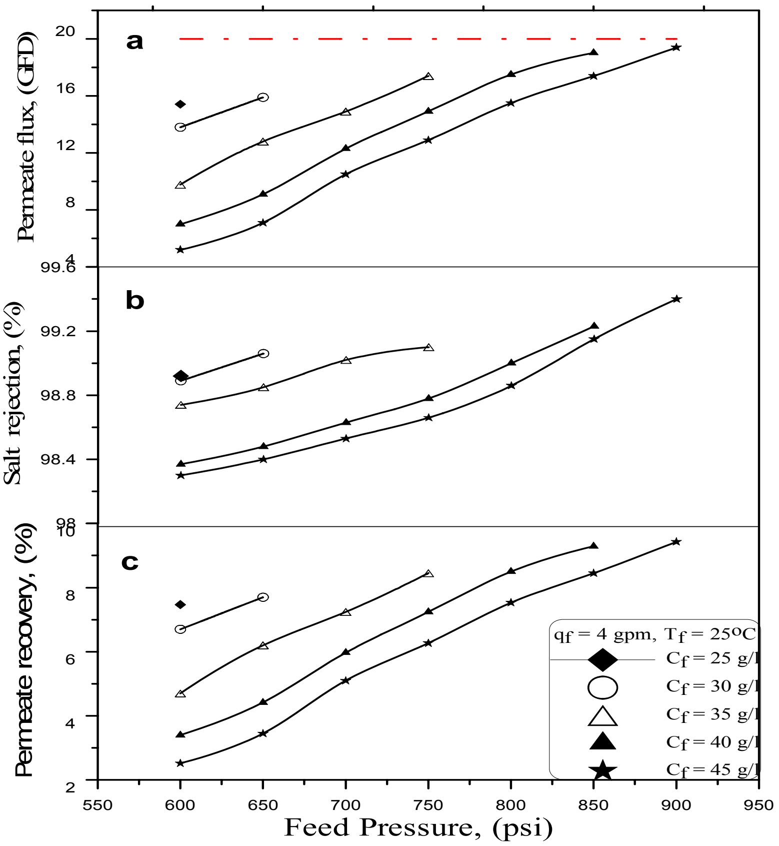

FIG. 4. Effect of feed pressure on permeate flux, salt rejection, and permeator recovery.

[2] 1000 igallon = 4.5 m^3

3.3. The feed salt concentration.

Figure 5 depicts the effect of feed salt concentrations on the permeate flux, salt rejection, and the permeator product recovery; together for different feed temperature and constant feed pressure (600 psi). The broken lines in the figure indicate the manufacturer maximum operating permeate flux.

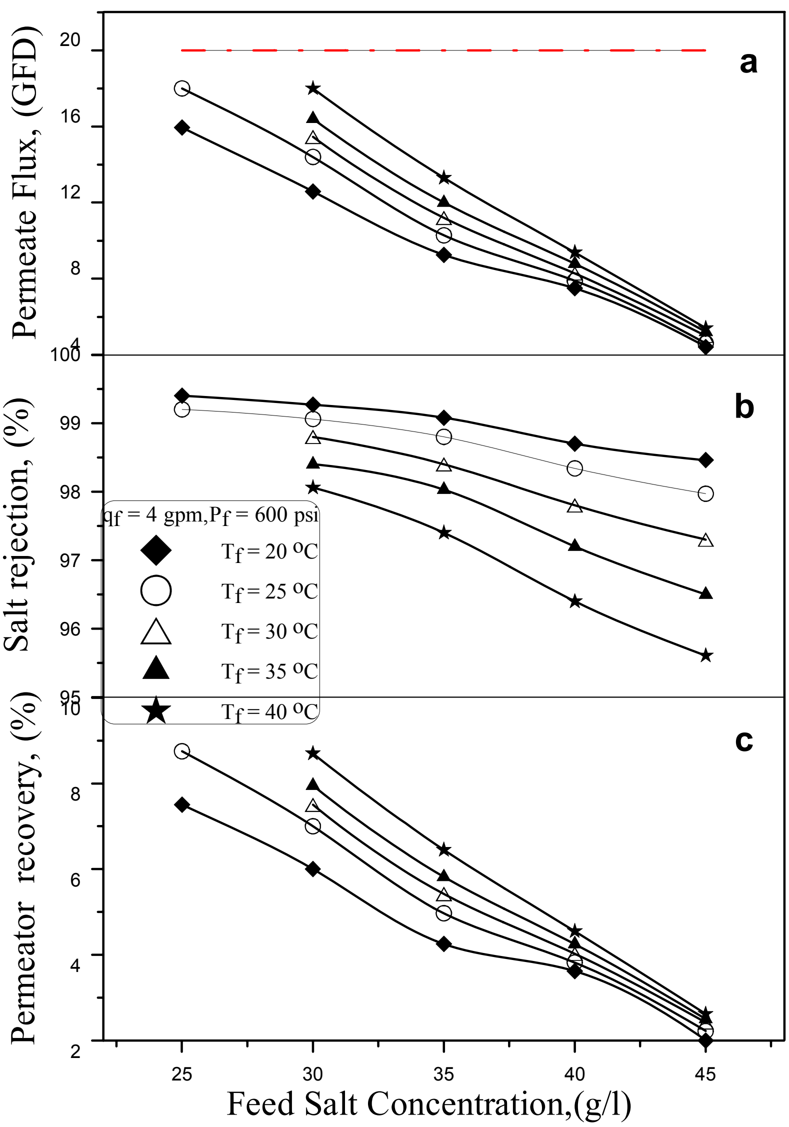

FIG. 5. Effect of feed salt concentrations on permeate flux, salt rejection and recovery

Figure 5a illustrates the effect of feed salt concentration on the permeate flux at different feed temperature. It is clear from Fig. 5a that the permeate flux decreases by the increase of the feed salt concentration and by the decrease of the feed temperature. Any increase in (C_f) value with one g/L decreases the permeate flux by an average value of 2.41% to 2.8 % according to the feed temperature, for a constant feed pressure (P_f = 600 psi). The same trend is indistinguishably observed in Fig. 5c, which depicts the permeator recovery variations with the feed concentrations.

Figure 5b depicts that the effect of feed salt concentration on the permeator salt rejection at different feed temperature. It is clear from the experimental work that the salt rejection percentage of the permeator decreases by the increase of the feed salt concentrations and by the increase of the feed temperature. The average decrease in the salt rejection percentage of the permeator is 0.06 to 0.16, according to the feed temperature.

Figure 6 depicts the effect of feed salt concentration on the membrane water permeability coefficient K_w at different feed temperature. It is clearly observed from this figure that as the membrane water permeability coefficient K_w considerably decrease by the feed salt concentration increase with an average decrease value of 1.23% per one gram per liter feed salt concentration increase.

Figures 6a and 6b illustrate the effect of feed salt concentration on the membrane water permeability coefficient K_w at different feed temperature obtained from the experimental data and from the Reverse Osmosis System Analysis program (ROSA [4]) respectively, at different feed temperature. These figures show that the permeability coefficient K_w decreases by the increase of the feed salt concentration. Meanwhile, it is slightly decrease by the increase of the feed temperature. It is observed from these figures, that the permeability coefficient of a feed temperature at 20°C has slightly elevated value than the rest of the feed temperatures. This may attribute to the effect of temperature correction factor, which has a value less than unity at this feed temperature. The relationship between K_w, feed temperature, feed pressure and feed salt concentration obtained from the experimental data is correlated as in the following equation;

$$K_w = (0.4675 - 0.136761*\beta*\pi_{fb})*(0.3702 - 0.179744*T_f)$$

Where; K_w = permeability coefficient, gfd[3]/psi

β= concentration polarization factor

π_{fb} = average feed-brine osmotic pressure, psi

T_f = feed temperature, °C

This equation demonstrates that the membrane permeability coefficient for water K_w decreases by increase of feed temperature and increases of feed salt concentration.

Figure 7 shows the comparisons of water permeability coefficients variations of experimental data and ROSA 6 program [4], with the feed salt concentration at each individual feed water temperature. Figs. 7a, b, c, d, and e depict the differences of the membrane permeability coefficient for water obtained from experimental data and ROSA 6 programs, at different feed salt concentrations. It is observed from Figs. 7a, b, c, d, and e that the variations of experimental data and ROSA 6 program at the feed salt concentration of 42 g/L is slightly deviated for the experimental data from ROSA 6 program, which may attributed to the limitation of the flow meter in this range of low permeate flow rate. The rest feed salt concentrations ranges between the experimental data and ROSA 6 program, have tiny differences. The membrane permeability coefficient for water K_w obtained from ROSA 6 program is deviated from that obtained experimentally by a value less than 5.48 %.

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[3] 1 m^3/m^2.d = 21 gfd

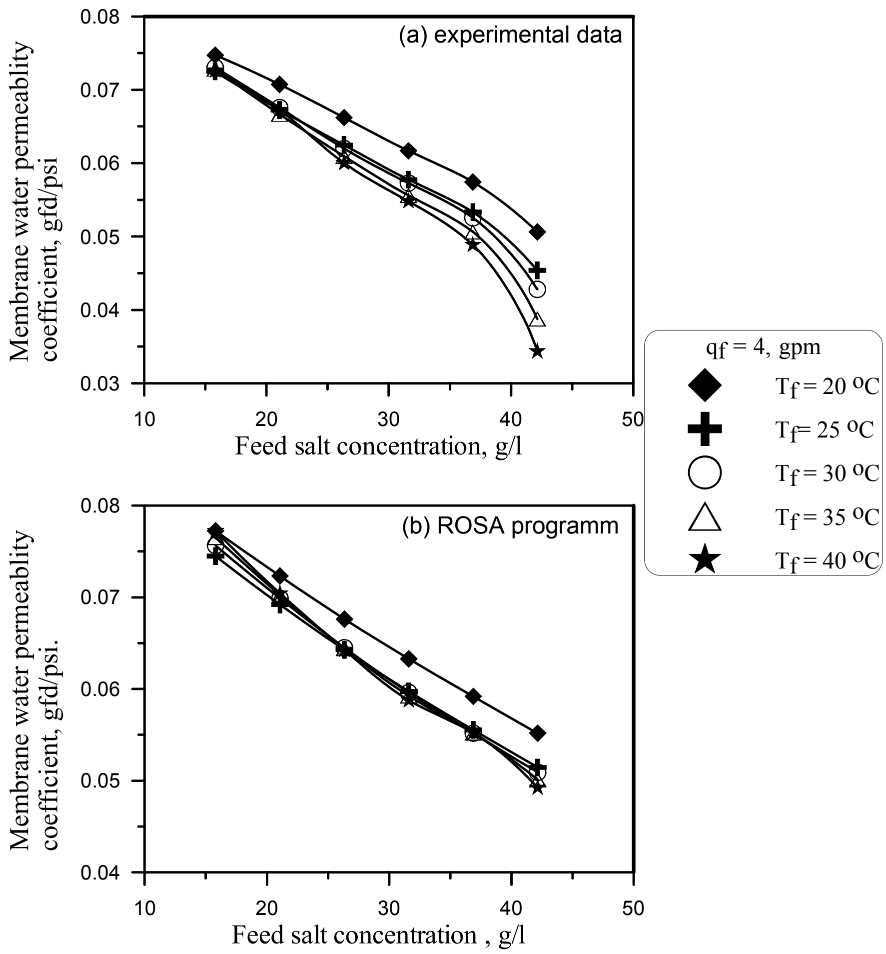

FIG. 6. The variations of the permeator water permeability coefficient with the feed salt concentration.

4. Effect of operating parameters on water unit costs

Desalinated water cost is one of the main parameters used in selecting specific desalination technology. Capital and operating costs are the two main parameters used in cost estimates for any desalting process. Unit product cost is affected by several design and operational variables: Salinity and quality of feed water, plant capacity, site conditions, qualified labor, energy, and plant life and amortization. From an operational and economical point of view, one of the most important design features of RO seawater plant is the feed pump energy consumption per unit volume of permeate produced (i.e. specific energy consumption). Figure 8 depicts the effect of feed temperature on the specific power consumption for different feed salt concentration and constant feed pressure. It is clear from this figure that the specific energy consumption decreases as the feed temperature increases for different feed salt concentration almost by an average value (0.29 kWh/1000 gal per 1^{o}C). Meanwhile, it is considerably increases by the increase of the feed salt concentration by an average value of (5.073 kWh/1000 gal per 1^{o}C).

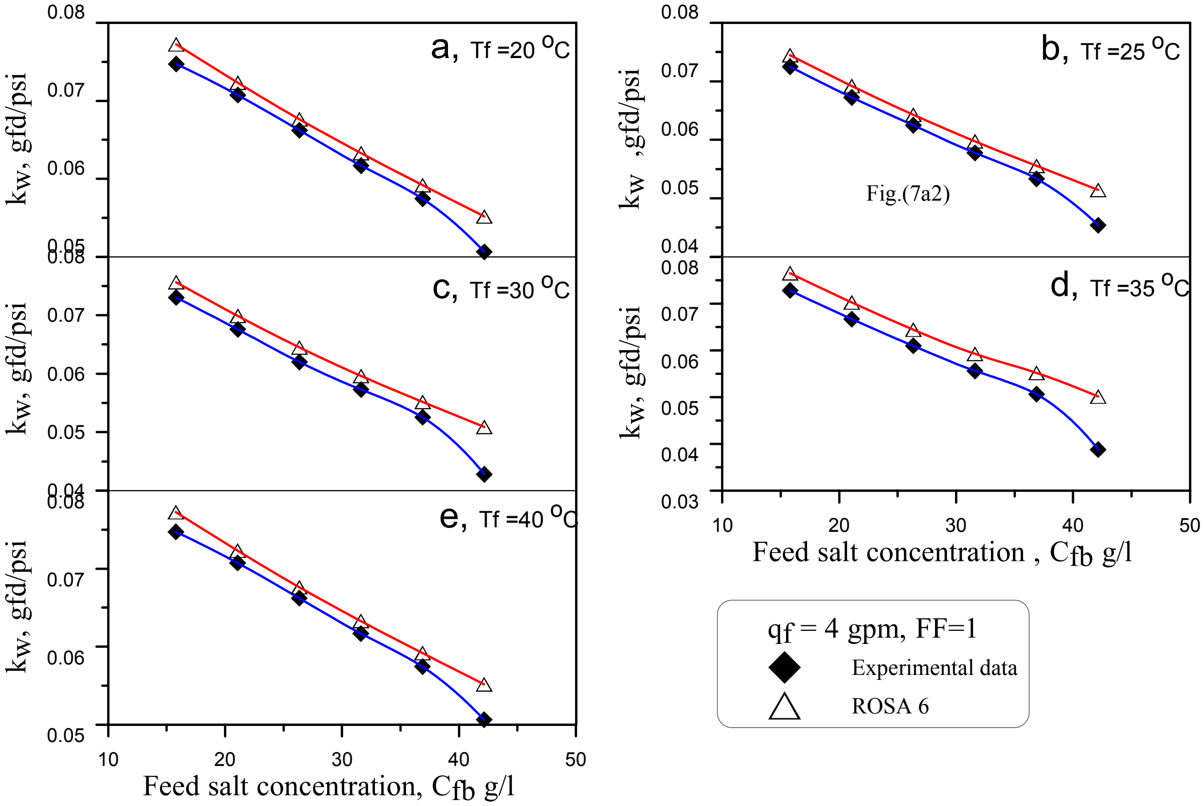

FIG. 7. Comparison between the permeator permeability coefficients obtained from experimental data and ROSA6 program.

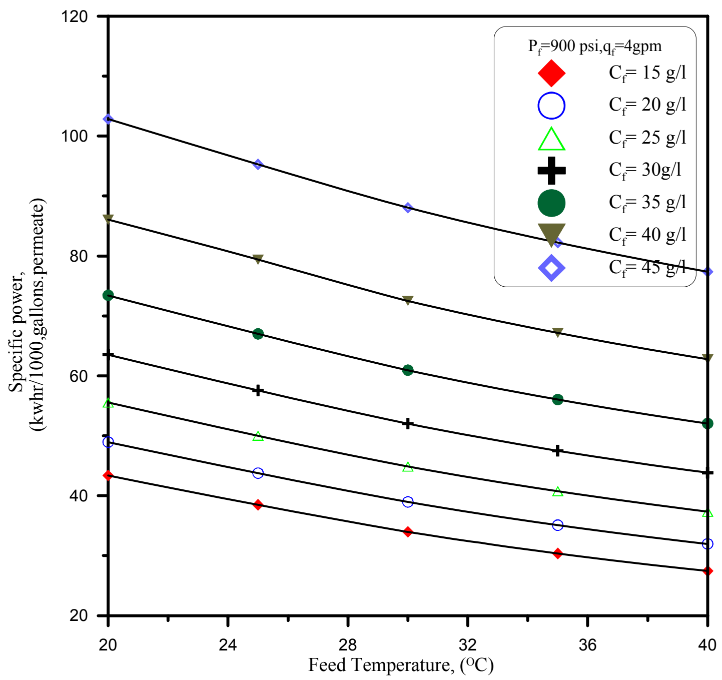

FIG. 8. Effect of the feed temperature and salt concentration on the permeate specific energy consumption.

on the product specific power consumption. It is clear from this Fig. 8a that the specific energy consumption decreases as the feed temperature increases almost by an average value of 0.29 kWh/1000 gal per one-degree centigrade. Meanwhile, it considerably increases by the increase of the feed salt concentration by an average value of 5.073 kWh/1000 gal per one-degree centigrade. The recent result confirmed with the author findings [2, 5].

5. Conclusions

1. An increase of one degree centigrade of the feed water temperature leads to:
   a. A reduction of applied feed pressure from 0.7 % to 1.35 % according to the feed salt concentration, to maintain the same membrane permeate flux.
   b. An increase of permeates flux from 1.11 % to 2.58 % according to the feed salt concentration and feed pressure.
   c. A decrease in the membrane salt rejection of almost 1.4%
   d. A decrease of the specific energy consumption by an average value of 0.29 kWh/1000 gal, at the same feed salt concentration.
2. An increase in feed salt concentration of one gram per liter (C_f) leads to:
   a. A decrease of the permeate flux value equal to from flux by an average value of 2.41% to 2.8 % according to the feed temperature.
   b. An average decrease of the permeator salt rejection percentage of 0.06 to 0.16, according to the feed temperature.
   c. A decrease in the membrane water permeability coefficient with an average value of 1.23%
   d. An increase in the specific energy consumption of an average value of 5.073 kWh/1000 gal.
3. The membrane FT30SW-2540 water permeability coefficient is experimentally determined and correlated as a function of feed salt concentration, feed temperature, and feed pressure.
4. Extensive studies are needed for different membrane types for different manufacturers to explore membranes characteristics and adaptation for co-generative systems.

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An overview of El-Dabaa RO experimental facility

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Abstract. Egypt has been considering for a number of years the introduction of nuclear energy for electricity generation and seawater desalination. Based on the findings and recommendations of previous IAEA studies, the fact that Egypt does not posses any nuclear power plant, and the existing financial limitations, Nuclear Power Plants Authority (NPPA) decided to construct an experimental Reverse Osmosis (RO) facility at its site in El-Dabaa to validate the concept of feedwater preheating. This concept was introduced in 1994 and has been adopted and investigated by the IAEA in all subsequent studies. These studies have shown that there is a potentially significant economic and performance benefit through the combined effects of feedwater preheating and system design optimization. However, these conclusions have been drawn from analyses and preliminary design studies without any experimental validation.

Construction of the RO experimental facility started in mid 2000 and was expected to be completed in one year. However, for reasons beyond the control of NPPA was delayed then stopped completely. Construction was restarted in July 2005 and is progressing well. The facility was expected to be operational in the first quarter of 2006. The results of this experimental work could have a strong influence on how the international nuclear desalination community perceives the value/benefit of feed water preheating, and hence there is a common international interest in this project.

This paper gives a full description of the test facility, its design basis and the planned experimental programme, as well as the status of the project.

Keywords: Reverse Osmosis, Experimental, Research, Heating, Performance, Nuclear, Desalination, Egypt, Membranes.

1. Background

In view of the limited Egyptian resources of both primary energy and fresh water, Egypt has been considering for a number of years the introduction of nuclear energy for electricity generation and seawater desalination. In this regard, the Nuclear Power Plants Authority (NPPA) participated actively in a number of national and international studies to investigate the prospects of using nuclear energy for the simultaneous production of electricity and potable water [1-3]. These studies concluded that:

- In general, there are no technical impediments to the use of nuclear reactors for the supply of energy to desalination plants;
- The costs of electricity and desalted water for the most economic fossil and nuclear driven power/desalination plants were in the same range;
- Nuclear reactors which offer the best prospects for near term commercial deployment are: PWRs, PHWRs and NHRs;

— The most economic desalination process seems to be contiguous RO plants with preheated feed water.

In response to the increasing interest in nuclear desalination, the IAEA has performed a two-year Options Identifications Programme (OIP). The OIP identified three possible approaches to the demonstration of nuclear desalination technology, namely [3]:

— Demonstration through the design and construction of a nuclear desalination facility.
— Demonstration of nuclear desalination as an addition to an existing NPP.
— Demonstration based on simulation of nuclear desalination.

The OIP recommended also a number of intermediate steps to reduce unknowns and risks aiming at gradual, partial and progressive confidence building. The recommended intermediate steps for RO were [3]:

⇒ Small scale preheated seawater desalination with RO;
⇒ Small scale RO integrated with NPP;
⇒ Large scale RO integrated with a fossil-fueled power plant.

Based on the above findings and recommendations, the fact that Egypt does not posses any nuclear power plants, and the existing financial limitations, NPPA decided to construct an experimental RO facility at its site in El-Dabaa to validate the concept of feed water preheating. The results of this experimental work could have a strong influence on how the international nuclear desalination community perceives the value/benefit of feed water preheating, and hence there is a common international interest in this project. Therefore, NPPA proposed in January 1998 the research project "Investigation of feed water preheating on RO performance" as part of the IAEA coordinated research project "Optimization of the coupling of nuclear reactors and desalination systems". In May 1998, the IAEA agreed to fund the project and a research contract was conclude with NPPA.

2. Justifications

Although the proportional relationship between feed water temperature and membrane permeability is well known, the idea of utilizing the condenser's cooling water as a source of feed for RO systems did not appear until early 1994 [4,5]. This concept was adopted and investigated by the IAEA in all subsequent studies [2,3,6]. These and other studies [1-7] have shown that there is a potentially significant economic and performance benefit through the combined effects of feed water preheating and system design optimization. These conclusions have been drawn from analyses and preliminary design studies without any experimental validation.

Experimental validation is of extreme importance in the confidence building process, particularly when other experts [8] argue that elevated temperatures may result in higher product water salinity, more rapid membrane fouling, greater membrane compaction, reduction in membrane lifetime and that saving in total water cost by elevating temperature from 15~18 C to 30 degC would be in the range of 3% only.

3. Objectives

In view of the possible role of RO desalination technology in any future Egyptian nuclear desalination program and the need to validate the concept of RO feedwater preheating, NPPA has decided to carry out this research project, with the following objectives in mind:

I. *Overall*: to investigate experimentally whether the projected performance and economic improvements of preheated feedwater can be realized in actual operation. The intent is to simulate as closely as possible performance characteristics that would be expected to occur in commercial large-scale RO seawater desalination plant.

II. *Short-term (~ 3 years)*: to study the effect of feedwater temperature and pressure on RO membrane performance characteristics over a range of temperatures (20-45 degC) and pressures (55-69 bar). The intent is to gather data on all aspects of system operation, utilizing membranes from three different manufacturers, so that sufficient data analysis is possible to determine if the performance and economic benefits suggested by the analytical models can in fact be demonstrated by experiments, and to determine the possible differences in results due to materials and type.

III. *Long-term*: to study the effect of feedwater temperature and pressure on RO membrane performance characteristics as a function of time. The intent is to select one of the membranes used during the short-term program for extended study to investigate possible reduction in membrane lifetime due to effects such as increased fouling or membrane compaction.

4. Design of experimental unit

In order to design a trouble-free, efficient and flexible test facility, NPPA carried out a detailed screening and qualifying process of potential project consultants. Subsequently one of the most reputable and experienced desalination consulting firms in the Arab World, the Consulting Engineering Company (CEC), was selected to design the test facility, prepare technical specifications, supervise construction and commissioning, and supervise training of personnel. The IAEA provided technical assistance to review the preliminary Design Report submitted by CEC. The cooperation between NPPA, CEC and IAEA resulted in successful completion of the design. Major design parameters are outlined below.

4.1. Number and size of membranes

To determine the minimum number of membranes needed to ensure statistical relevance of the results, a statistical analysis was carried out to determine sample size for any one type of membranes tested. The analysis indicated that a sample size of five membranes in parallel is optimal. The bases of the analysis were as follows [9]:

- Membranes manufactured follow the normal distribution.
- Standard deviation 10% of the mean value.
- Sample size was varied from 1 to 9.
- Different levels of confidence were selected (35, 50, 64, 73, and 88) whereby results at each were obtained.
- Level of confidence was calculated for each sample size.
- Relevance tolerance was set at 5% (this could be changed whereby a stricter criterion would enlarge the sample required and vice versa).
- Confidence interval divided by the mean was plotted against sample size. Sample sizes selected for plotting were: 1, 2, 3, 4, 4, 6, 7, 8, 9 and 100.

The study indicated: a sample size of 5 is optimum at selected level of confidence of 73%. It also showed that the choice of sample size is important since sensitivity will vary with sample number significantly. This analysis stands for the membrane as "individual" Accordingly 5 membranes will be tested in parallel.

The size of the experimental unit will be equal to the number of parallel membranes multiplied by the capacity by the particular membrane to be tested. Because the objective of the experimental facility is to investigate membranes performance, rather than the production of potable water, it is important for economic reasons to have the smallest capacity capable of representing performance characteristics under investigation.

Commercial membranes are produced in various sizes; the most common of which are the 4" and the 8" diameter membranes. From the economic and practical point of view, the 4" membrane seems to be a more attractive choice for the following reasons:

The cost of the experimental facility is likely to be reduced significantly. Although the cost of membranes would be reduced, that is likely to be one of the least significant impacts. More significant is the reduction in feed flow required, and hence a reduction in the size of high pressure feed pumps, storage tanks, piping, membrane cleaning system, etc. In general, it can be said that the entire facility would be reduced in size. In addition, significant reductions could be expected in O&M (operating and maintenance) costs for a system based on 4" membranes.

More flexibility is likely in the selection of membrane configurations and in the number of membranes used in the experimental facility.

Reconfiguration of the experimental facility to allow changeover from one membrane type to another is likely to be easier with smaller diameter membranes.

However, the primary risk introduced by the use of smaller diameter membranes is the potential that the performance characteristics of the 4" membranes may not be representative of the performance characteristics of 8" membranes under operating conditions expected during the experimental program.

In order to assess this risk, a number of "membrane equivalency comparisons" of the performance characteristics of 4" and 8" membranes have been made using the ROSA code. For a fixed feed flow and recovery, the highest feed pressure occurs at the lowest temperature. For any given feedwater TDS, an iterative analyses is required to establish the specific feed flow and recovery that will correspond to the maximum allowed operating pressure (69 bar), without violating minimum brine flow requirements. Feed flow and recovery were then held constant in each case, and the membrane performance characteristics were calculated over the temperature range 20-45^{o}C, the results are shown in Figs. 1 and 2 below.

As can be seen from Fig. 1, the feedwater pressure as a function of temperature is essentially identical for the 4" and 8" membranes. The permeate TDS for the 4" and 8" membranes, as shown in Fig. 2, is not identical, albeit, very close. Other parameters of interest in the comparison of the 4" and 8" membranes are shown in Table I.

The conclusion that can be drawn from these results is that the 4" membrane provides a very close equivalence to the 8" membrane in its essential performance characteristics. It has virtually the same pressure profile with temperature and a very similar permeate TDS profile with temperature. Of even more significance, it has a nearly identical flux through the membrane surface, as would need to be the case in order to expect equivalent performance characteristics.

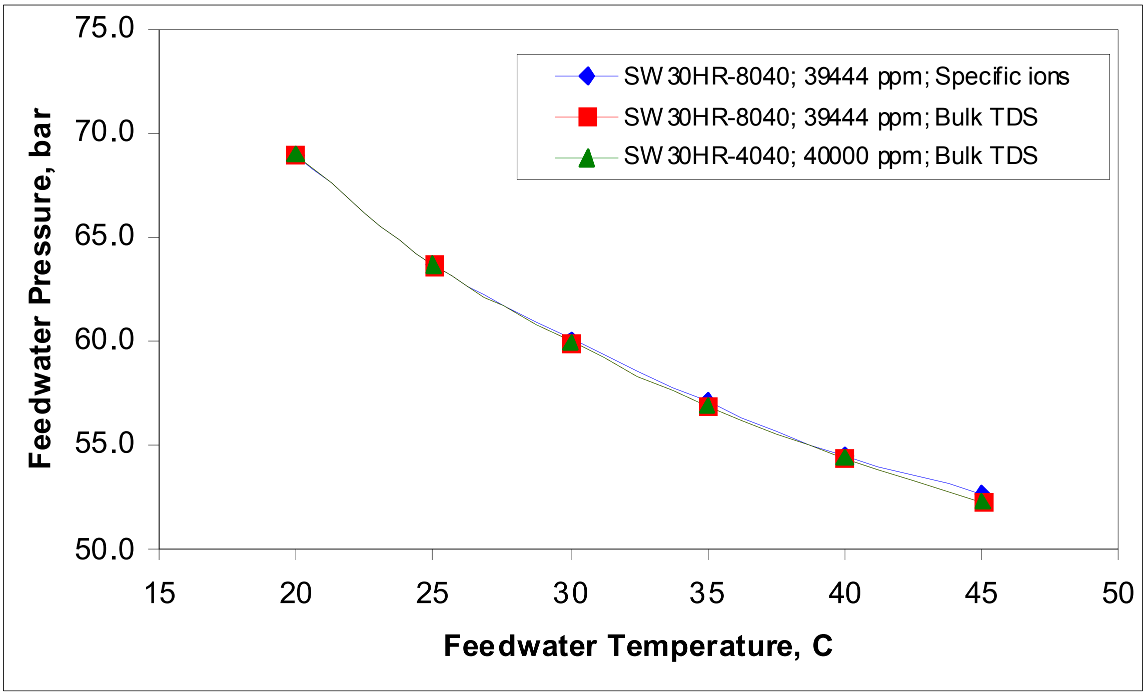

FIG. 1. Comparison of feedwater pressure versus temperature

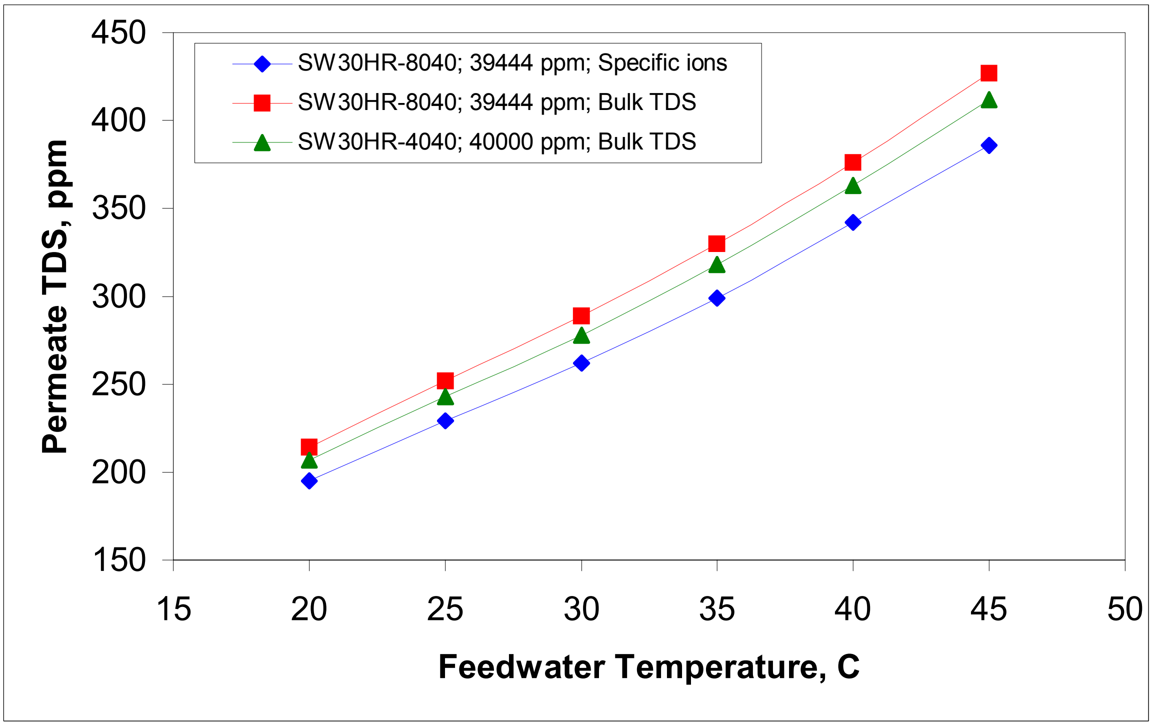

FIG. 2. Comparison of permeate tds versus feedwater temperature

However, the feedwater flow rate and the daily energy consumption are significantly less for the 4" membrane, as shown in Table I. Therefore, the experimental program can be carried out with 4" membranes without adverse impact on its representation of essential performance characteristics. Moreover, potentially significant savings in program capital and O&M costs can be realized.

4.2. Unit capacity

Different commercial membranes have different performance characteristics. In particular, they have different nominal permeate flows and conversions at some standard test conditions, as shown in Table II. Because the high-pressure pump should accommodate the different commercial membranes to be tested, it will be based on the highest anticipated feed flow.

The short term experimental program shall be based on the three 4" spiral wound membranes manufactured by Filmtec, Fluid Systems and Hydranautics. The rational for this selection is:

— The capability to operate at high feed water temperature (45 ^{o}C).
— Similar permeates flows and recovery ratios. Thus, limiting the operational range of the HP pump will facilitate the pump selection.
— Similar dimensions and materials. This should facilitate racking requirements and changing from one commercial membrane to another as well as direct comparison of performance.

Table I: Comparison between 4" and 8" membrane characteristics

Membrane	Feed Flow	Average Flux	Energy Consumed*
	m^3/h	$L/m^2/h$	kWh/d
SW30HR-8040	4.18	19.3	256.4
SW30HR-4040	1.146	19.6	70.4

*Based on ROSA calculation at 20?C without energy recovery

Table II. Performance characteristics of some commercial membranes

Manufacturer		Dupont	Filmtec	Fluid Systems	Hydranautics	Toyobo
Type		Hollow Fiber	Spiral Wound	Spiral Wound	Spiral Wound	Hollow Fiber
Model		6410	SW30HR-4040	TFC 1820SS	SWC1-4040	HR3155
Material		Aramid HF	Thin Film Composite	Composite Polyamide	Composite Polyamide	CTA
Dimensions						
- Diameter	mm	154	99	102	100	104
- Length	mm	587	1016	1016	1016	400
Permeate Flow	m^3/d	2.46	3.8	4.2	4.2	0.4
Salt Rejection	%	99.2	99.4	99.3	99.6	99.4
Test Conditions	ppm	35000	35000	32800	32000	35000

- Salinity	bar	69	55.2	55.2	55.2	55.2
- Pressure	%	30	**8**	**7**	**10**	30
- Recovery	^{o}C	25	25	25	25	25
- Temperature						

Although Dupont membranes allow lower feedwater temperature, they constitute about 40% of the worldwide RO membranes. Therefore, Dupont membranes should be tested at a later stage.

Based on information provided in Table II and the results of the statistical analysis, the nominal size of the experimental unit will be about 21 m^3/d (for a facility consisting of two units, the nominal permeate capacity would be 42 m^3/d)

4.3. Method of heating feedwater [9]

To simulate the power plants condenser cooling water, the feedwater has to be heated. This shall be done utilizing a fresh water/sea water heat exchanger. The freshwater will be heated by an electric heater selected for the following advantages:

- Easy installation and maintenance.
- No on-site fuel combustion leading to clean, fume-free and easy operation.
- No fuel delivery and storage problems.

At start-up, the required energy to raise the temperature of seawater from ambient temperature (assumed to be 20 ^{o}C) to 45 ^{o}C was found to be 104,500 kJ/m^3. At steady state and at continuous operation, the permeate and brine heat content will be utilized to pre-heat the seawater through heat exchangers.

4.4. Performance requirements

The experimental facility is designed to study the following performance parameters for each of the three commercial membranes:

- Feed temperature.
- Operating pressure
- Feed flow.
- Recovery Ratio.
- Permeate salinity.
- Product capacity.
- Membrane deterioration.
- Salt rejection.

4.5. Plant protection interlocks

The experimental facility is fitted with comprehensive instrumentation and automatic control equipment necessary for safe and efficient operation, the details of which are provided in reference [9].

5. Configuration of the test facility

The test facility consists of two identical units, as shown in Fig. 3: one unit operating at ambient seawater temperature and the other with preheated feed water at 25, 30, 35, 40 and 45°C, as called for by the experimental sequence. This configuration is considered practical with 4” membranes, and has the benefit of giving direct comparison of performance characteristics for the preheated and no-preheated cases at all values of preheat temperature. The test facility consists of the following main components:

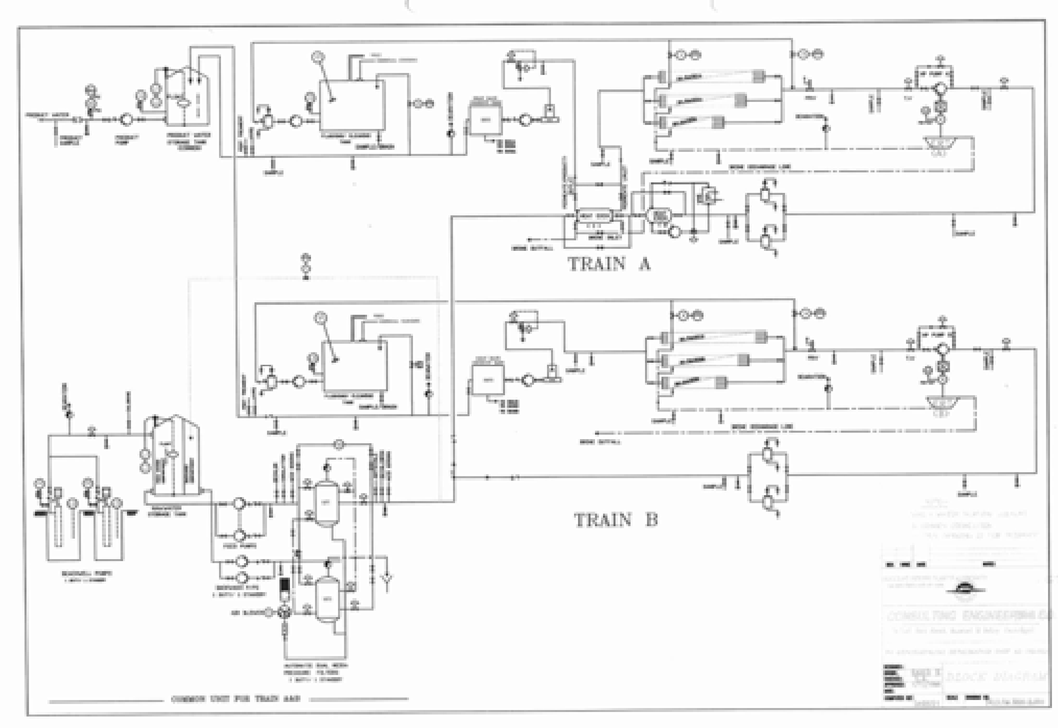

FIG. 3. Block diagram of the experimental facility

(a) Beach wells and pumps

To ensure clean feed water with minimum pretreatment requirements and lower operational costs, beach wells will be used for the feed water rather than open seawater intake. Although the required feed capacity is small, two beach wells will be used (one working and one standby) in order to ensure wells reliability and durability. The beach well pumps shall be operated intermittently in cases of unit’s lower capacity. As for the filter feed pump, it shall be provided with variable speed motor or hydraulic coupling to cater for the required capacity variation.

(b) Pretreatment system

The pretreatment system is designed to allow for the various pretreatment requirements for the different commercial membranes to be tested. This includes the various chemicals and dosing points recommended by the manufacturers.

(c) Water heating system (for one unit only)

Direct heating of the raw seawater is not recommended due to scale formation problems. Therefore, the feed water will be heated by freshwater/seawater heat exchanger. The hot fresh water shall be obtained from an electric water heater. To reduce fuel consumption during continuous operation, the hot brine and permeate shall be used to preheat the feed water, utilizing permeate/seawater and brine/seawater heat exchangers. This will give the following advantages:

* Reduction of fuel consumption in the water heater.
* Reduction in permeates temperature.
* Reduction in the brine temperature before disposal, which will be advantageous from the environmental point of view.

(d) High Pressure Pump with Energy Recovery and Hydraulic Coupling
The experiments involve different types of membranes, requiring different operating pressures and feed flows. Therefore, the high-pressure pump is coupled with a hydraulic coupling to obtain the required pressure-flow. For fine-tuning, throttling and back pressure valves are provided. To recover the brine kinetic energy, energy recovery turbine (ERT) is provided.

(e) *Other systems* common to commercial RO are also included, such as:

- Cleaning/flushing system
- Post-treatment system
- Chemical treatment system
- Raw and product water tanks
- Etc.

6. The experimental program

The specific approach to application of RO technology that this experimental program is intended to investigate is based on several important principles. These include:

Operations at temperatures above ambient seawater temperature results in increased permeate production relative to that same plant operated at seawater temperatures.

Operation at the highest pressure allowed by the membrane design limitations results in the most efficient operation. Permeate production is maximized, and design configurations can be establish which allow such operation without exceeding permeate TDS limits.

Operation at high pressure results in unit energy consumption being minimized. Although power consumption is increased to pump feed water to higher pressures, energy consumed per cubic meter of permeate produced is reduced.

The experimental program is intended to generate data that can be used to validate these performance characteristics. It is assumed that test runs for the experimental program do not begin until the experimental unit has completed all its commissioning trials and has demonstrated the ability to maintain a stable operating state.

6.1. Test sequence and timing

The planned sequence and timing of testing (Steps 1-5 below) is provided below. Actual test sequencing and timing will need to be adjusted as experience is gained throughout the experimental program. In the discussion that follows, Train B is taken to be the unit that operates at ambient seawater temperature. Train A is the unit in which the RO membrane feedwater will be preheated.

Step 1
The traditional approach to RO system design is to minimize the feed pressure, consistent with the required permeate flow. In the first phase of testing, a set of "reference" operating profiles would be established consistent with this approach. These tests would hold feed flow and recovery constant while feed pressure was allowed to drop with increasing temperature.

Step 2
The goal of this step is to collect data for operation at the maximum operating pressure and a fixed feed flow for all values of RO feedwater preheat. Data collected from this step should give an indication of the performance benefits achieved due to feedwater preheat. The tests performed in this step hold feed flow and pressure fixed, allowing recovery to vary with temperature.

Step 3
In order to assess the impact of feed pressure, it is necessary collect data at various feed pressures below the maximum allowed membrane pressure. In this step, data is collected at the first of these reduced pressure plateaus.

Step 4
The lowest operating pressure normally used in large seawater RO systems is on the order of 55 bar. Data is collected during this step to represent operation at that pressure.

Step 5
Having completed data collection at a feed pressure of 55 bar, the system should be returned to a steady state operating condition. This steady state operating condition is one for which:

Feed flow and recovery ratio for both Trains A and B remain fixed at values that allow operation with a feed pressure of 69 bar.

Train B operates with a feed temperature at ambient seawater temperature.
Train A operates with a feed temperature of 45^{o}C.

6.2. Test cycle

On the assumption operating parameters, including feed temperature, can be changed and a stable plant condition reached within a time period of 12 hours, the above test sequence should take on the order of 24 days to complete. Having completed one full test cycle (Steps 1-4) and returned the plant to maximum pressure and temperature operating conditions (Step 5), operation should continue for the balance of the month (approximately 6-7 days).

Following one full month of operation (including testing), the next test cycle (Steps 1-5) should be carried out. This pattern should be repeated for the duration of the current test phase. In accordance with the current schedule, the experimental program is to consist of 3 phases, each phase taking approximately one year and consisting of testing with one of the three membranes being evaluated. Following this schedule will provide a series of data sets taken at monthly intervals over the duration of a year, for each membrane type. This test cycle is illustrated in Fig. 4, which shows one complete monthly test cycle. This cycle is repeated each month for the full year of testing.

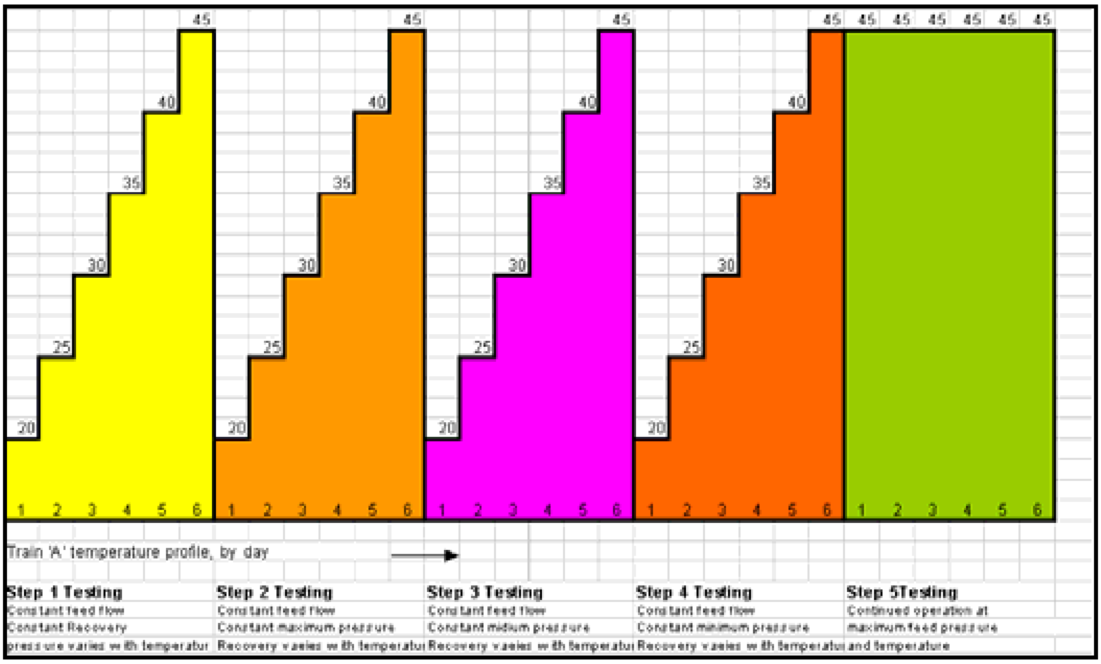

FIG. 4. One-month test cycle

6.3. Data collection

At each test plateau a complete set of data should be taken, consisting of:

Feed water temperature.
Feed water TDS (based on conductivity and water analysis).
Feed water SDI, before and after pretreatment.
Feed water flow rate.
Feed water pressure
Permeate flow rate.
Permeate TDS
Permeate pressure
Permeate temperature
Brine flow rate
Brine pressure
Brine temperature
Brine TDS
Chemicals used for feed water pretreatment
Electrical consumption
Other process parameters as per the Design Report by CEC.

6.4. Data analysis

Data analysis requirements will be established, to some extent, by the nature of the data taken and its indication of membrane performance characteristics. As a minimum, essential membrane performance characteristics should be derived from the data.

7. Status of the project

The work plan for the duration of the research project included the following activities:
(i) Design of Experimental Unit
(ii) Development of Detailed Experimental Program
(iii) Preparation of Technical Specifications
(iv) Call for Bids, Bid Evaluation and Contracting
(v) Construction and Commissioning of the experimental Facility
(vi) Carrying Out the Experimental Program.

The duration of the experimental program was expected to be 3 years divided into three Phases (I-III). Each Phase is based on a particular membrane make, with a matrix of fixed operational conditions such as:

- Feedwater Temperature
- Feed Pressure
- Chemical dosing and type
- Operating time
- Etc.

The experimental program was developed with IAEA technical assistance in September 1998, the design of the experimental facility was completed in December 1998, and preparation of the technical specifications and tender documents was completed in May 1999. It was envisaged that the experimental program could start at the beginning of January 2000. However, delays were encountered, in the following activities:

1. Contracting: bid evaluation took longer than expected, because there were many details that needed clarifications from the bidders. Finally, when the financial envelopes were opened, it was found that the prices of the successful bidders exceeded the allocated budget. Bidding process was repeated and contract concluded with a main contractor at the beginning of July 2000.
2. Construction: The construction work started in January 2001 due to delays in submitting the final drawings and designs. The situation was further complicated by devaluation of the Egyptian pound (currently US$ 1= LE 6.4 compared to US$ 1= LE 3.4 in 2000). This lead to difficulties in importing the equipment and increase in prices. In addition, some problems occurred during the execution phase between NPPA and the Contractor, which lead to stopping the civil work several times and financial problems between the main contractor and the Electro-mechanical sub-contractor. As a result the construction of the experimental facility was not completed.
3. Resumption of works: In June 2005 the remaining construction and installation activities were assigned to another main contractor and work was resumed with reasonable schedule. It is expected that the experimental facility will be operational in the first quarter of 2006.

The current status of the project as of December 2005 is summarized below.

1- Design and Engineering	Completed
2- Civil Work	Completed
3- Beach Wells	Completed
4- Electrical Power Supply Infrastructure	Completed
5- Procurement	Completed
6- Installation of Electro-mechanical Equipment	In progress
7- Commissioning	Pending

NPPA remains committed to making the results of the experimental program available to the nuclear desalination community.

8. Conclusions

1. NPPA is constructing a comprehensive RO experimental facility at its site in El-Dabaa. The construction of the facility was delayed for reasons beyond the control of NPPA.
2. Construction and installation works were resumed in June 2005 and the facility is expected to be operational in the first quarter of 2006.
3. NPPA remains committed to making the results of the experimental program available to the international nuclear desalination community.

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Desalination of seawater utilizing waste heat from nuclear plants using membrane distillation

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Abstract. In this work, an approach to conduct desalination at lower temperature (preferably at around 65°C) is developed utilizing waste heat rejected from nuclear power plants. The designed desalination plant uses warm saline water generated from nuclear plants. Desalination is carried out using newly developed approach of vacuum enhanced direct contact membrane distillation which gives very high permeate flux. This technique also reduces temperature polarization effect and reduces mass transfer resistance offered by the membrane. The products are fresh desalinated water and concentrated brine, which could be further used in production of common table salt or can act as a raw material for chlor-alkali industry. The designed process has a very high efficiency with the salt rejection of as high as 99.4 %. It has many merits pertaining to use of waste low-grade heat of nuclear plants, desalination at lower temperature and pressure, reduction in temperature of rejected water within permissible limits to water bodies etc and the operation temperature is far lower than those in other distillation techniques resulting lesser scaling and corrosion problem.

1. Introduction

Drinking water shortage is expected to be the biggest problem of the century due to unsustainable consumption rates and population growth. Pollution of fresh water resources by industrial wastes has heightened the problem. Only about 0.014% of the world's water resource is directly available to human being and other living organisms [1]. Desalination is a reliable technology which could potentially meet this potable water shortage. Many desalination techniques are used for large-scale desalination. Multi-Stage Flash (MSF), Reverse Osmosis (RO), Vapour Compression and Multi-Effect Distillation (MED) are the most popular ones widely used today.

Energy is indisputably the most significant contributor to the cost of desalination. It was estimated that the production of 1 million m^3/day requires 10 million tons of oil per year [1]. Most of the desalination plants like those in Middle-East use petroleum fuel to run distillation processes like MSF & MED. Increasing fossil fuel price and climatic changes have discouraged the use of fossil fuel directly for desalination, and if economically viable, alternatives are extensively used.

Many studies have been carried out to harness low-grade heat source like solar energy, waste thermal heat etc [2]. Attempts have been made to use heat from nuclear power plant by using techniques like vapour compression (VC) and low-pressure MED processes. Conventional mass transfer equipments exibit high mass-transfer resistance and require lot of moving parts and huge distillation columns which increases operation and maintenance cost of the plant.

Nuclear energy systems provide energy security and do not emit green house gases and air borne particulates which are a major cause of climatic changes. Process heat generated from

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huge thermal operation units like nuclear power plant, thermal power plant and oil refineries too have a huge potential for providing energy for desalination as these processes generate lot of waste energy.

Typical nuclear power plants reject about 2/3rd of its process energy as waste heat. Waste heat generated is rejected into nearby water bodies causing threat to aquatic life. Waste heat of these processes appears in form of low-grade heat (at lower temperature) and is carried away by the cooling water. Thus, this waste heat could not be directly used for distillation. Some nuclear power stations use cooling ponds for reducing temperature of the rejected process water to minimize its effect on our environment.

A new approach utilizing waste heat emitted from the nuclear reactor is proposed in the current work. The design could be used over existing nuclear plant itself and so do not involve modification of the established nuclear reactor units and can be easily incorporated in existing nuclear plants. The desalination unit uses newly developed membrane distillation techniques called Vacuum-Enhanced Direct contact membrane distillation. With the advent of this technology, membrane distillation can give permeate flux to as high as about 40 $kg/m^2/hr$. Also, the quality of permeate obtained is very high with salt rejection of about 99.4% [3].

2. Theory

2.1. Membrane distillation

Membrane distillation is not a new process. It was first observed in 1960 and is very much similar to pervaporation. It has long been investigated in small scale laboratory studies and has the potential to become a viable tool for water desalination [3]. A pilot plant investigating the potential of membrane distillation was setup in Kaisui, Japan which gave a good performance over the time [4]. Membrane distillation combines simultaneous mass and heat transfer through a hydrophobic micro-porous membrane to achieve separation. Mass transfer is carried out by evaporation of a volatile solute or a volatile solvent (water) by elevating its temperature. The driving force for mass transfer in the process is vapour pressure difference across the membrane. Due to increased vapour pressure of the desalination side, net permeate flux is in the direction of higher to lower osmotic pressure side.

Direct contact membrane distillation (DCMD) is one of four basic configurations of membrane distillation [5-7]. In this configuration, a feed solution at elevated temperature is in contact with one side of the membrane and colder water is in direct contact with the opposite side of the membrane as given in Fig 1. It is mainly the temperature difference between the liquids, and to some extent their solute concentration, that induces the vapour pressure gradient for mass transfer. The permeate flux could be further increased by using vacuum over the lower osmotic pressure side.

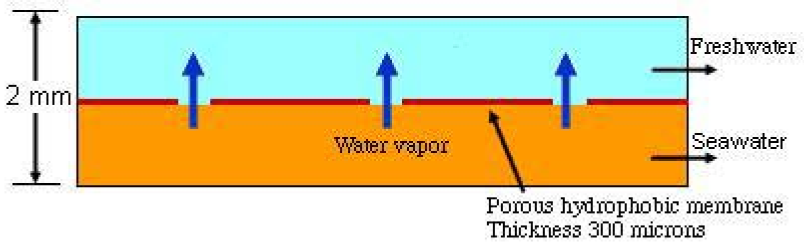

FIG. 1.Direct-contact membrane distillation

In vacuum enhanced direct-contact membrane distillation, the chemical activity of the potable water side is further reduced by application of vacuum and thus drastically increasing the permeate flux. The amount of vacuum, which should be used depends upon the liquid entry pressure of water (LEPW) [3] and also depends on the physical and chemical characteristics of the hydrophobic membrane being used for the process.

2.2. Separation candle

Desalination is carried out by separation candles, which have a spiral-wound membrane element made out of hydrophobic micro-porous membrane. This configuration maintains the simplicity of fabricating flat membranes while increasing remarkably the membrane area per unit separator volume to as high as 328 m^2/m^3 while decreasing pressure drop and heat losses [8]. The assembly consists of a sandwich of four sheets wrapped around a central core of a perforated collecting tube. The four sheets consist of a top sheet of an open separator grid for feed channel, the membrane, a porous felt backing for permeate (fresh water) and the membrane as shown in Fig 2. Alternatively, hollow-tube configuration could be used which is much easier to fabricate. The arrangement with hot water flowing in the porous felt ensures adequate turbulence to reduce any effect of temperature and concentration polarization.

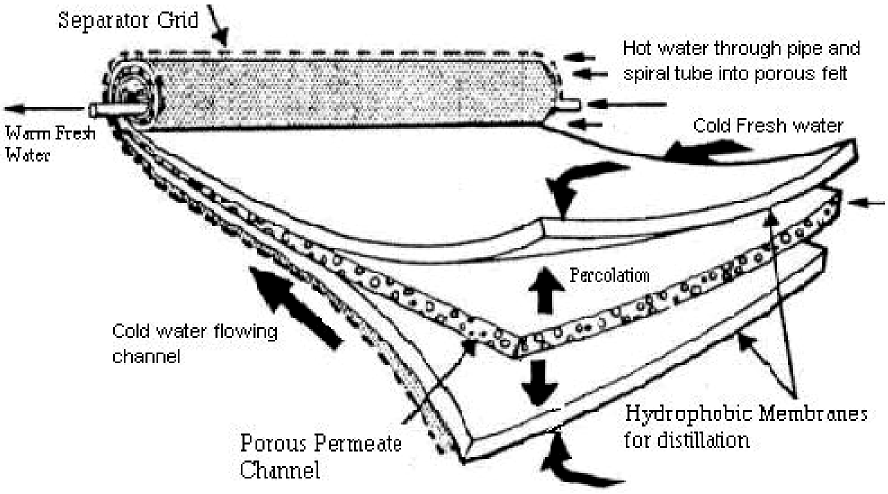

FIG. 2. Spiral-wound element

3. Process design

In this process, saline water coming from water bodies like sea is taken as raw material. Some pre-treatment pertaining to removal of suspended particles is required before feeding to heat exchangers. Water requirement is trivial for a nuclear establishment, as it is needed to complete the work cycle (Carnot cycle) for electricity generation. Saline water acts as a sink for this Carnot cycle. The incoming saline water is heated by heat exchangers associated with these work cycles. In conventional nuclear plants, generated warm water is left open to cool down to near ambient temperature to avoid environmental problems like fall in dissolved oxygen by warm temperature. This incurs capital investment over building of such cooling pools and loss of potential heat energy present in it.

System has a long train of membrane distillation candles having hydrophobic membrane with porous support sandwiched between them. After passing through the heat exchangers, the temperature of the saline water increases 15°~20° C. Warm water then moves into a train of membrane distillation candles. Water vapour from warm saline water passes through the hydrophobic membrane and condenses on the side of desalinated cooler water. The cooler potable water side is at pressure lower (vacuum) than atmospheric pressure. Vacuum level highly influences the permeate flux value. The extent of vacuum is determined by the Liquid Entry Pressure of Water (LEPW). LEPW is the property of the configuration and the pore size of the membrane.

Inside the candle, the porous felt is sandwiched between two hydrophobic membranes along with a separator grid. Turbulence created by random pattern of the felt reduces polarization effects. Pressure drop would be created by the felt and if polarization effects are not so prominent then a regular channel membrane grid could be used. The separation process will give potable water and concentrated brine as products. Fig 3 gives an outline of the process.

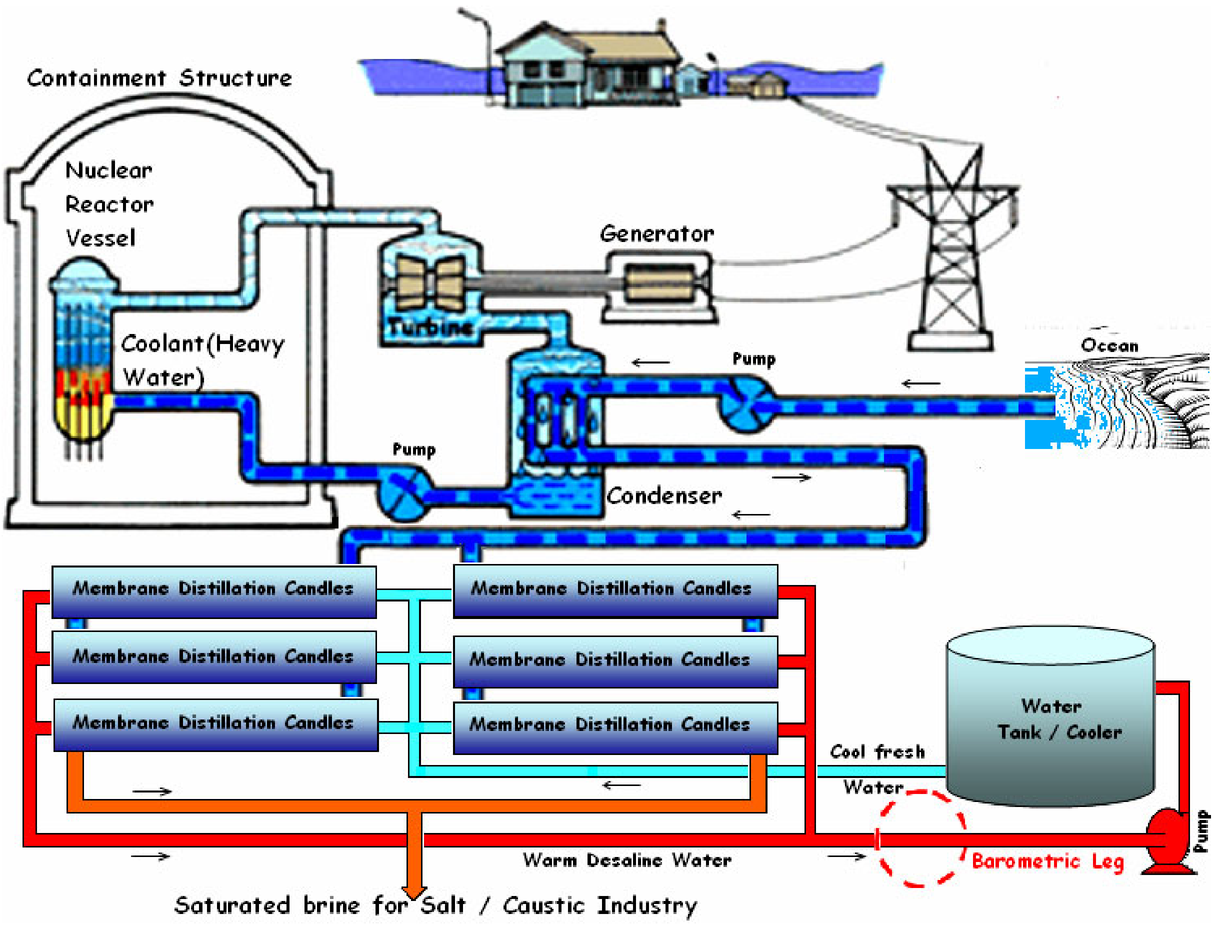

FIG. 3. Outline of the process

Air-gap membrane distillation is much more efficient in terms of heat energy utilization as it could even extract latent heat of vaporization of water vapour coming from warm saline water side [9].

Effluent generated in form of concentrated brine could be either dumped back into the water body by checking its temperature and/or could be used for common salt production. Concentrated brine could also be used for extraction of valuable minerals and salts like vanadium, uranium etc [10-11].

Potable water which comes out in form of warm desalinated water is send to a large storage tank where its temperature falls to ambient temperature value by convective losses. Cooler desalinated water is re-circulated to the candle train.

Vacuum in the system is achieved by using a vacuum system in conjugation with a barometric leg. One of the most interesting features of barometric leg is that it reduces load over the vacuum pump system in two ways:

— By condensing vapours formed in vacuum line.
— By creating a low pressure system based on Torricelli's principle.

Figure 4 gives a brief outline of a simple barometric leg. It contains a leg or column filled with water whose level is set according to the required vacuum. Colder water is sprinkled to lower the temperature of the leg. Vacuum line used for creating lower pressure in the potable water side is made to enter tangentially. Much of the water vapour condenses into tiny droplets and collects into the column. Uncondensed portion is taken to vacuum pump system. Vacuum in the barometric leg is maintained by its water level, which is controlled by a pump at its base.

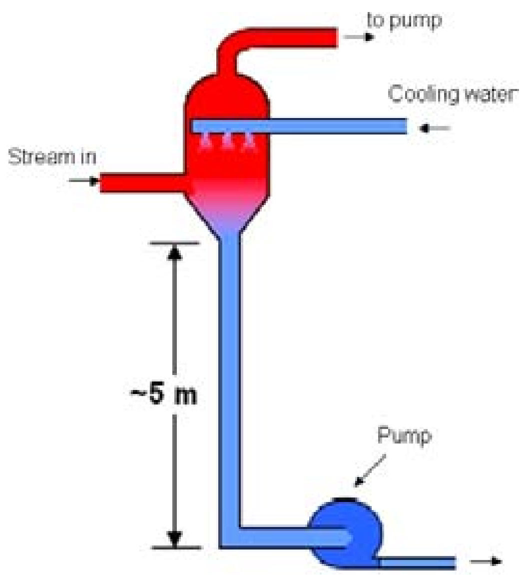

FIG. 4. Barometric leg

4. Discussion

The designed process is capable of utilizing waste heat from nuclear power plants and thus can acts as an excellent system for water desalination. The process uses saline water with temperature lower than 65°C. Operation at temperature lower than 70°C has an added advantage that corrosion and scaling problems are very less. Scaling and corrosion problems appear above about 70°C. Operation at near atmospheric pressures minimizes rupturing of membranes and makes the process more reliable and economical than other membrane processes like reverse osmosis.

Typical life of hydrophobic membranes is about 3 years. Membranes sometimes get wetted and loose their hydrophobic character and could be easily reactivated by drying [12]. Thus, membrane candles could also be designed with drying capability so that hydrophobic membranes could be reactivated in very short time.

Another remarkable property of the process is the quality of potable water obtained from it. Salt rejection of as high as 99.4% could be achieved with it. In the whole process, much amount of heat is lost from the warmed saline water and so the effluent disposed do not cause much threat to aquatic life. As the process does not require extensive pre-treatment and mammoth distillation columns like flash chambers, much of the operation and maintenance cost also reduces.

Process has some drawbacks too. Present cost of hydrophobic membranes is very high and their availability is limited too with very few commercial producers. Also, membranes are very sensitive towards pressure spikes. Special care should be taken to avoid generation of any pressure spikes in the system. With proper design and control system, the problem could be eradicated. The system cannot work with water containing surfactants and other surface tension reducing agents as they wet the membranes. The process should be used with water, which is free from such impurities and should be pre-treated if any such impurities are present. Bio-fouling would also occur but due to high chemical stability of material of the membrane, in situ bleaching process could be used.

5. Conclusion

Desalination seems to be very attractive solution for increasing water demand. The above proposed process design opens a whole new world of possibility of utilization of waste nuclear heat which would have been difficult to tap with convectional desalination techniques. Using waste nuclear heat would be beneficial in terms of both environmental and economic factor.

Achieving distillation at low temperature by membrane distillation and obtaining high flux is the key factor, which increases its economic feasibility. Capital investment over the membrane would reduce in the coming time with better fabrication techniques and large-scale production.

Acknowledgements

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Nuclear power demand in Mongolia

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Abstract. The paper addresses the nuclear power demand in Mongolia. In particular, air pollution from the thermal electric power plant and uranium resources, which is the fuel of nuclear power plant in Mongolia is described.

1. Introduction

Nuclear power provides nearly 17 % of the world's total annual electricity generation. In 2006 there were 445 nuclear power plants (NPPs) operating in 31 countries. Approximately 30 percent of total energy produced is electric energy and the rest 70 percent is heat energy. In Asia, nuclear energy is an increasingly important source of power. As for Mongolia, heat energy consists 80 percent of the total energy output. The demand for nuclear energy is growing steadily for it will contribute to environment protection, reduce fossil fuel expenses and shall ensure full satisfaction of the market demand. The recent studies prove that the energy demand in major cities like Ulaanbaatar, Darkhan and Erdenet shall grow by 4 percent on average annually. In the Aimags (provinces) the heat/ power demand shall increase by 5.5 percent per year. Since the currently existing electric power plants shall fail to meet the increasing energy need, creation of new reliable energy sources shall be inevitable. Our studies confirm that the nuclear power plant is the only way out of the energy crises likely in the near future. In framework of the Master plan on energy system development until 2015, a program reflecting the expected demand of heat and electric power and the guidelines of further development has suggested Mongolia's need for nuclear power station.

Mongolia located on the northern plateau of Central Asia, is landlocked country, bounded on the north by Russia and on the east, south and west by China. Mongolia is one of the highest countries in the world, with an average elevation of 1,580m (5,180 ft). About 81% of the country is higher than 1,000m (3,280 ft) above sea level. The highest mountain is Tavan bogd Mountain in Bayan Ulgii Province at 4,370m (14,350 ft) and the lowest point is Khukh Lake in the east at 560m (1,820ft). Mongolia is the seventh largest country in Asia and 18th largest in the world. The climate is harsh, with extremes of both heat and cold. Mongolia is sparsely populated, with a little over 2.6 million inhabitants.

2. Thermal electric power plant in Mongolia

Mongolian Central Electricity Supply system is illustrated in Fig.1. The Ulaanbaatar Fourth Thermal Power Plant (TPP-4) is the largest in Mongolia. The first unit started to operate in 1983. The installed capacity of TPP is 540 MW.

Mongolian National Statistical Office collects data on electric power and thermal power generations from each power stations, each month and estimates account for electricity capacity once in a year (Table I; Fig. 2) [5]. In this section of electricity gross power generation and imports of electricity, station internal use, other losses in transmission and distribution, consumption are covered and reported by physical units as well as classified by economic activities.

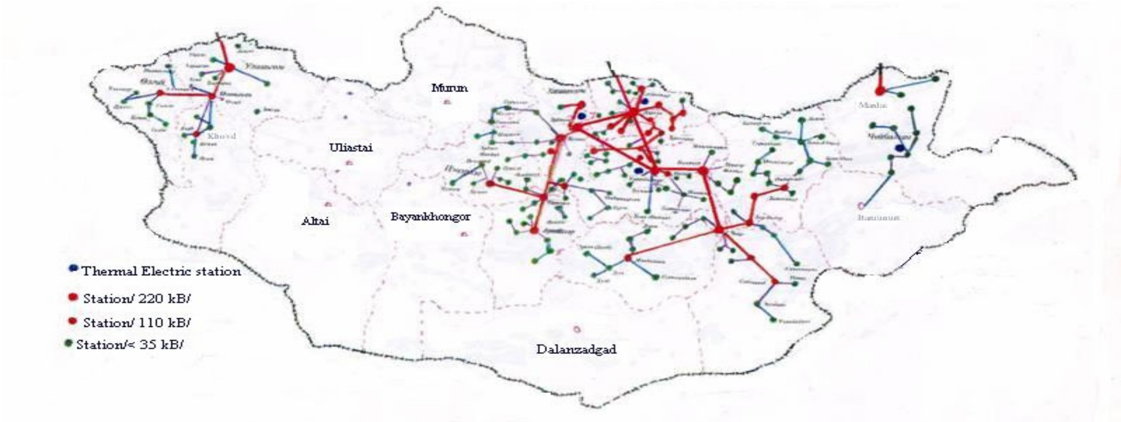

FIG. 1. Central electricity supply of Mongolia

Table I. Balance sheet of electricity in Mongolia

GW.h

	2002	2003	2004	2005
Resources-Total	**3 279.0**	**3309.0**	**3 474.3**	**3 586.4**
Cross generation	3111.7	3137.7	3303.4	3418.9
Import	167.3	171.3	170.8	167.5
Distribution	3279.0	3309.0	3374.3	3586.4
Consumption	2031.7	2194.6	2357.0	2534.0
Of which:				
Industry & Construction	1260.1	1361.1	1458.8	1569.1
Transport & Communication	84.7	91.5	98.5	105.8
Agriculture	22.0	23.8	25.6	27.5
Household and Communal housing	487.1	526.1	567.6	609.3
Other	177.8	192.1	206.5	222.3
Losses in transmission and distribution	582.8	489.2	480.4	419.7
Electric station internal use	649.0	618.4	628.8	620.8
Export	15.5	6.7	8.2	11.9
Electricity produced per capita, kW.h	1265.4	1260.3	1311.6	1341.9

3. Air pollution from thermal electric power plant

During the last 50 years, the average annual temperature in Mongolia has increased approximately by 0.7°C. The main sources of environment pollution in Ulaanbaatar city are TPP-4 (Fig.3), over 90 thousands Mongolian national gers using brown coal and vehicle combustion exhaust (70000 cars 3500 taxis and 2500 buses).

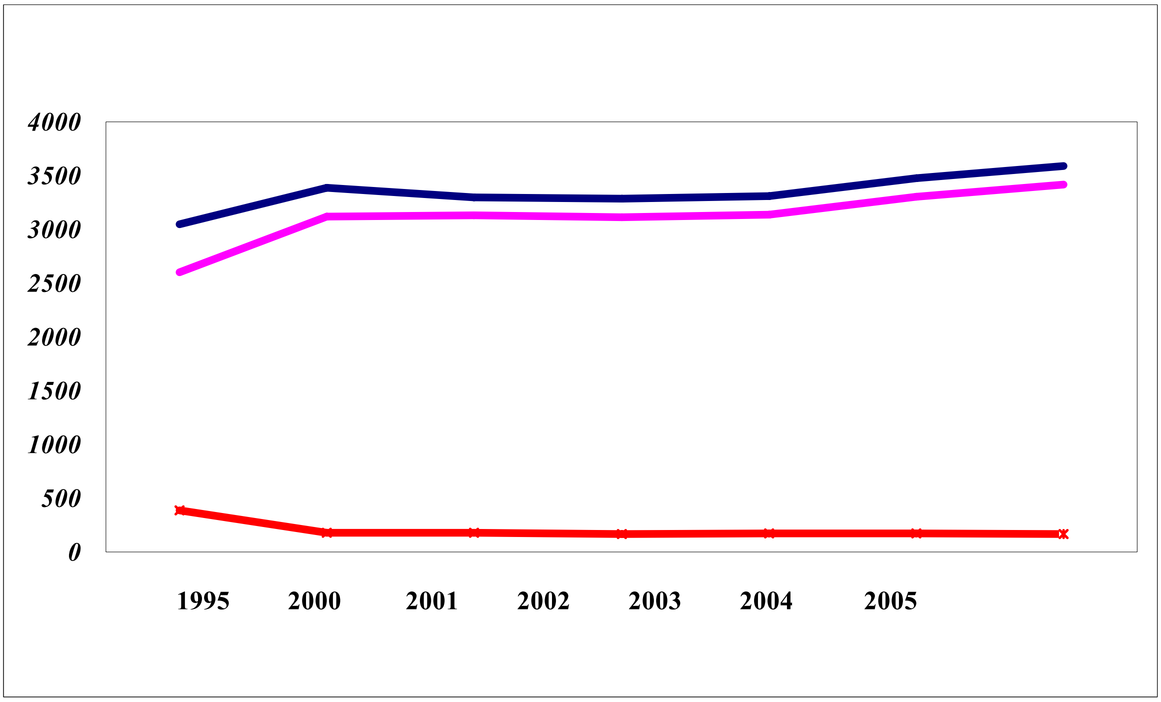

FIG. 2. Electricity generation & consumption, import, GW.h

FIG. 3. Fourth thermal power plant in Ulaanbaatar, Mongolia

One of the peculiarities of Mongolian climate is that, in winter it gets very cold, and persistent temperature inversion dramatically increases environmental pollution. Especially contents of fly ashes and other pollutants in the environment of Ulaanbaatar exceed the permissible level.

The main fuel of the TPP-4 is brown coal of the Baganuur and Shivee-Ovoo coal mines. Radioactivity in brown coal is relatively concentrated. A year usage of coal is about 2.4 million tones. According to the last 20 years research, the TPP had used 38.511 million tones of coal and given into the environment with flue gas 283233 tones of ash, 40124 tones of CO, 219325 tones of SO_2, 4.752 million tones NO_2.

The ashes content of fly ashes falls into the ground surface, and the flue gases distributes in the different layers of air. The concentrations of the ashes are determined by estimation and several measurements [3]. The flue gases are a cause for environmental pollution. For the Baganuur coal with mean ash content of A^{p}=10-19% of TPP - 4 with 540 MW the flue gases contain approximately of 1289 g/sec of ashes. In 1983-2004 the ashes formed during coal combustion at the TPP- 4 reach 5,455.9 tons or 14.16% of total burned coal. During this period, approximately 283,233 thousand tons of fly ashes were emitted into the air (see Fig. 4).

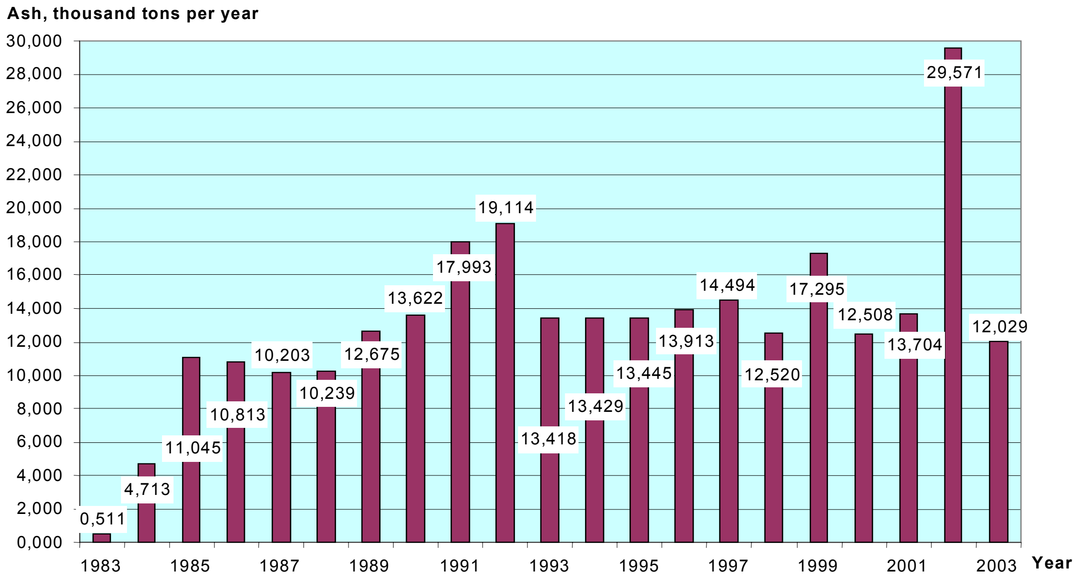

FIG. 4. Fly ash

Activity concentrations of natural radionuclides and gross beta activity

In the selection of samples for the analyses of soil, relatively equal platforms were chosen: equal places by the size of 1 m^2 at a depth 5 cm from surface soil. Table II lists that directions of the TPP-4 where surface soil samples were taken. The results of determinations of activity concentration of natural radionuclides and gross beta activity by high resolution gamma-ray spectrometry and beta radiometry BC-4 in soil at 8 directions and distances from the TPP-4 are shown by following table II.

4. Nuclear power is needed in Mongolia

Mongolian scientists have suggested that a nuclear power station is needed in Mongolia. The Mongolian physicists have for many years been proposing to establish such station. But some specialists of Mongolia have been paying their attention in coal stations, which pollute air and require large expenses.

Table II. Activity concentrations of natural radionuclides in surface soil, which different directions from TPP-4 of Ulanbaatar (SW-Southwest, NW-Northwest, NE-Northeast, SE-Southeast)

N	Direction	Activity concentration, Bq/kg						Gross β activity, Bq/kg
		^{40}K		^{238}U		^{232}Th		
		Mean	Range	Mean	Range	Mean	Range	
10	South	857	281-1880	16	4-35	29	13-50	399±23
8	SW	396	79-988	68	14-130	27	15-37	410±29
6	West	761	352-1419	25	20-30	25	11-32	444±34
6	NW	799	503-976	15	2-40	26	19-33	466±42
4	North	949	356-1343	7	3-14	39	23-59	484±36
9	NE	493	116-780	25	2-41	33	17-74	456±25
7	East	1453	412-6162	107	50-212	53	34-73	596±33
11	SE	1318	630-1965	66	17-109	29	14-38	503±31
Average results								
Near TPP-4 (61 point)		931	79-6162	45	2-212	32	11-74	461±31
Ulan Bator (40 points)		880	712-1100	33	21-42	39	21-41	285±4
Mongolia (19 provinces)		835	320-1330	28	14-49	32	11-55	-
World		370	100-1000	25	10-50	25	7-50	-

Launching a nuclear power station in Mongolia is one of the main duties for Mongolian current nuclear physicists. It has been reflected in the Mongolian Energy Program that an atomic power station will be installed. Mongolian physicists hope that the goal would be reached by 2015, and have been making their researches in the direction.

Nuclear power is cost competitive with other forms of electricity generation, except where there is direct access to low-cost fossil fuels. Fuel costs for nuclear plants are a minor proportion of total generating costs, though capital costs are greater than those for coal-fired plants. Nuclear power is one of the cleanest methods of producing electricity because it does not produce greenhouse gas.

Power demand in Mongolia

- Electricity demand in the CES system is expected to grow at an average rate of 4.5 % per annum.
- Heat demand in major cities covered by the CES system is expected to grow at an average rate of 4 % per annum.
- Electricity and heat demands in Aimag’s centers are expected to grow at an average rate of 5.5 % per annum.

Average growth rates: total demand 5.3 % per year
Peak demand 5.0 % per year
Electricity demand projections for Aimag centers show
Average growth rates: for total generation
(5.3 %- 6 %) per year

Heat demand projections for major cities in the CES system (Table III)
Average growth rates for heat energy and peak demand are about 4 % per year. For the Aimag centers the average growth rate is slightly higher at around 5 % per year.

Table III. Heat demand projections for major cities in the CES system

	2010	2015
Ulaanbaatar		
Total Demand (GW.h)	7987	10350
Max. Demand (MW)	2095	2683
Darkhan		
Total Demand (GW.h)	1254	1598
Max. Demand (MW)	314	396
Erdenet		
Total Demand (GW.h)	2137	2761
Max. Demand (MW)	546	697
Baganuur		
Total Demand (GW.h)	545	710
Max. Demand (MW)	136.2	175.5

We have carried out thorough studies of almost 30 nuclear power plants of the world and based on the findings we have selected a number of nuclear power plants with the most fitting parameters for the conditions of Mongolia. For example, the CANDU-3 reactor was selected as the most acceptable option. This nuclear power plant with heavy water coolant and moderator was developed in Canada in 1986. The CANDU-3 power plant is deemed as most appropriate for it is provided with an inactive security system. The capacity of the plant is 400 MW electric energy and 1370 MW of heat energy. Thus a similar power plant could be built in a location close to Zavkhan, Gobi-Altai and Bayankhongor aimags. Such a size nuclear power plant costs US$ 1028 million. In case of erecting of a twin power plant the price shall drop to US$ 1710 million. This sum includes the necessary expenses commencing with the optimal location survey and identification as well as the expenses of the works until putting the plant into operation.

5. Uranium in Mongolia

Canada is the world's leading supplier of uranium. Mongolia is set to emerge as Southeast Asia’s number 1 uranium explorer.

Uranium can be found almost everywhere in soil and rock, in rivers and oceans. Traces of uranium are even found in food and human tissue.

High-grade ore body –20%	200,000 ppm U
Low-grade ore body –0.1%	1,000 ppm U
Granite	4 ppm U
Sedimentary rock	2 ppm U
Average in earth’s continental crust	2.8 ppm U
Seawater	0.003 ppm U

Uranium deposits are found all over the world. The largest deposits of uranium are found in Australia, Kazakhstan and Canada. High-grade deposits are only found in Canada.

Table IV. Reserve and resources of uranium in Mongolia

/Thousand ton/

Metalogenic province Mineralization district	Ore joining [o.j] Ore field [o.f] Lifers [l]	U form ation	Total rese-rve & reso-urces	From which				
				Reserve		Resources		
				C1	C2	P1	P2	P3
I.Mongol Priargun	I.1.1 Dornod o.j.	3	70	31	20	6	13	
1.North	I.1.2 Ugtam o.j.	3	5				5	
Choibalsan	I.1.3 Turgen o.j.	3	5				5	
	I.1.4 Engershand o.j.	3	5				5	
	I.1.5 Sumiin nuur l.	2	5				5	5
	I.2.1 Uliisaikhan uul o.j	3	15				10	5
	I.2.2 Batnorov o.j.	3	12				7	
2.Berkh	I.3.1 Bor-Undur o.j.	3	5				5	
	I.3.2 Khongor o.j.	3	7				7	
3.Dorno Gobi	I.3.3 Ulaannuur o.j	3	15				15	
	I.3.4 Shivee o.j.	3	3				3	
	I.3.5 Choir l	2	90				54	20
	I.3.6 Nyalga l	2	12				6	6
	I.3.7 Tavansuveet l	2	20		8	8	20	
	I.4.1 Mushgia khudag o.j.	3	16				6	10
	I.4.2 Ulzii uul o.j.	3	20				10	10
4.Dund Gobi	I.4.3 Ongiin gol l.	2	115				50	65
	I.5.1 Matad o.j.	3	5				5	
	I.5.2 Ulzii o.j.	2	25				15	10
5.Outside of field	I.5.3 Choibalsan l.	2	5				5	
	I.5.4 Gurvansaikhan l.,o.f.	2	15				10	5
II.Gobi Tamsag	II.1 Sainshand o.f.	2	30			3	12	15
	II.2 North Sainshand l.	2	30				7	23
	II.3 Zuunbayan l.	2	50				20	30
	II.4 Undurshil l.	2	50				20	30
	II.5 Tamsag l.	2	60				10	50
	II.6 Ail o.f.	3	10				5	5
	II.7 Outside other field		270					270
III. Kentii – Daur	III.1 Tuv o.f.	4	30			4	10	16
	III.2 Janchivlan o.j.	4	10				10	
	III.3 Chuluut o.j.	1	30				10	20
	III.4 Outside other field		80					80
IV. Northern Mongolia	IV.1 Buteeliin nuruu o.f.	7	15				5	10
	IV.2 Khuvsgul o.f.	8	20					20
	IV.3 Ar gol o.f.	6	30				5	25
	IV.4 Tsagaan shivee o.f.	6	35					35
	IV.5 Mongol Altai o.f.	5	50				5	45
	IV.6 Dundgorkhi o.j.	5	5				5	
	IV.7 Tashaat deluu o.j.	5	5				5	
	IV.8 Bayankhongor o.f.	8	40					40
	IV.9 Tuba o.f.	6	30					30

	IV.10 Khangai o.f.	6	15					15
	IV.11 Kharaatsag uul o.f.	6	5					5
	IV.12 Nuuriin khotgoruud	2	100					100
	Total		1470	31	28	21	390	1000
	Percent		100	2.1	1.9	1.4	27	68

The following data shows known conventional resources of uranium. Australia-28 %, Kazakhstan-16 %, Canada-12 %, South Africa-7 %, Brazil-6 %, Namiba-6 %, Niger-6 %, Russian Federation-5 %, United States-3 %, Mongolia-2 %, Ukraine-2 %, Uzbekstan-2%.
The world's power reactors, with combined capacity of some 370 GWe, require about 68,000 tones of uranium from mines (or the equivalent from stockpiles) each year. The annual uranium demand will grow only slightly to 2010. Uranium is an extremely concentrated and efficient fuel, much more so than coal or oil.

Energy source	Electricity produced
1 kg of firewood	1 kWh (kilowatt hour)
1 kg of coal	3 kWh
1 kg of oil	4 kWh
1 kg of uranium	50,000 kWh

Mongolia is rich in mineral resources that are being increasingly exploited by a variety of joint venture and Western companies, including the exploration and ongoing development of new and existing uranium deposits.

Soviet and Mongolian geologists began exploring for uranium in Mongolia in the 1940's. From 1967 to 1988 more systematic exploration for uranium was undertaken, and four major uranium deposits were defined in Mongolia, the Priargun, Gobi-Tamtsag, Hentei-Daur and Northern Mongolia uranium provinces (Table IV). Uranium deposits of economic value were discovered in the Dornod, Gurvanbulag, Mardai areas of eastern Mongolia and the Kharaat area of southern Mongolia.

6. Conclusion

- It is deemed that developing of nuclear energy industry is a strategic necessity, which shall ensure ecologically safe energy source and the general development of national sustainable economy.
- It is understood that construction of small and medium reactor (nuclear power plant) shall be most rationale.
- The problems of environmental pollutions from thermal power plants (TPP) in winter are greater than any other seasons. Therefore, reaching the maximum value, samples taken in winter are useful for comparing with the permissible values with a purpose of monitoring contaminations.
- Environmental pollution is maximum at 20xH or 4-5 kilometers (height of a chimney H=250 meters) from the TPP-4
- Radioactive contamination in surface of soil is greater in the left directions [^{40}K: 1453 (412-6162) Bq/kg; ^{238}U: 107 (50-212) Bq/kg; ^{232}Th: 53 (34-73) Bq/kg; β: 596±33 Bq/kg] of the TPP-4 than the right directions [^{40}K: 761 (352-1419) Bq/kg ; ^{238}U: 25 (20-30) Bq/kg; ^{232}Th: 25 (11-32) Bq/kg; β: 444±34 Bq/kg]. It is because wind directions in Ulaanbaatar are usually from right to left.

— Mongolia is set to emerge as Southeast Asia's number 1 uranium explorer.

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Implementation of nuclear seawater desalination in Algeria

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Abstract. This paper deals with the programme of nuclear desalination of seawater in Algeria. It starts by giving actual data about the needs of Algeria of fresh water up to the year 2025 and presents the strategies, which are adopted to satisfy these needs by various techniques including nuclear desalination of seawater. Finally the application of nuclear seawater desalination is presented in more details.

1. Introduction

Water scarcity is a major developmental issue in Algeria. Arid and semi-arid zones cover large parts of the country; droughts are recurrent and rainfall is insufficient to meet the current demand for fresh water. The country's population is over 30 million and is expected to reach 43.5 million in the year 2025. Increased urbanisation, economic growth and an ever expanding infrastructure needs related to rising living standards put more and more pressure on available scarce fresh water resources. The situation is compounded by the vulnerability of the limited available water resources to incremental salinity and pollution.

Water desalination has been considered as one possible solution for providing fresh water. As Algeria has adequate reserves of fossil fuel, this source of energy can be used for this purpose. The use of fossil fuel - oil and gas- for seawater desalination does not seem to be cost-effective because it is non- renewable and is expected to be depleted in a few decades.

In response to these needs, the Algerian Government contemplated the feasibility of nuclear desalination as a source of low cost potable water. Algeria participated in the IAEA's Regional Project for North Africa RAF/4/010, which focused on analyzing the electricity and potable water demand and the available energy and water resources in the participating countries, and the follow up project RAF/4/013.

As the need for fresh water and electricity supply is rapidly increasing in Algeria, the Algerian Government plans to carry out a comprehensive study to assess the potential of a nuclear power plant for producing energy as well as for water desalination.

2. Problems of water in Algeria

2.1 Water resources

Algeria is one of the countries in the world with water resources that are well below the threshold adopted by the World Bank (under 1000 m^3 per person per year). The situation is aggravated by the fact that there is a uneven spatial distribution of the water, seasonal and inter-annual irregularities of the rainfall (principal periods of dryness in the Mediterranean basin are summarized in Table I), filling up of the reservoirs with sediment, vast losses of water due to the aging of the municipal distribution networks, bad management of the resources, pollution, insufficient infrastructure, and a lack of maintenance. The shortage of water affects both the potable water supplies for the population and the supply of irrigation water for the farmers [1].

In 2003, the total quantity available of the resources varies from 4900 to 5660 Hm^3 /year according to the assumed climatic situation. As indicated in Fig 1, this volume is entirely made up of surface water collected in dams (and of retained collinaires) and of underground water. The recycling of wastewater practically does not exist, because the collection and the purification of wastewater are limited to some agglomerations only. Seawater desalination plants were not established yet [4].

Table I. Principal periods of dryness in the Mediterranean basin [6]

Country	Greece	Italy	France	Cyprus
Periods	1982 - 1983 1988 - 1990	1982 - 1983	1988 -1990	1989 – 1991 1995 - 1998
Country	**Morocco**	**Algeria**	**Tunisia**	**Spain**
Periods	1990 - 1995	1970 – 1971 1977 – 1978 1981 – 1984 1987 -1990 1993 - 2000	1982 – 1983 1985 – 1989 1993 - 1995	1982 – 1983 1990 - 1995

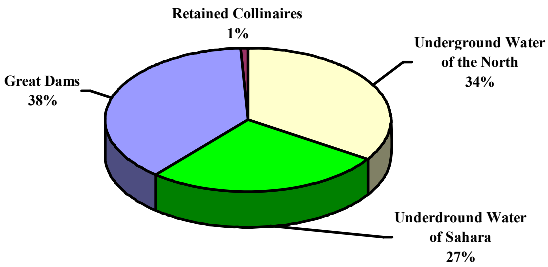

FIG. 1. Distribution of the water resources in 2003[4]

2.2. Water demand in Algeria

In 2003, the total water demand is estimated from a total of 6800 Hm^3/year up to 7700 Hm^3/year depending on the prevalent climatic conditions. Most of the demand comes from the agricultural sector. Almost all the remainder is for the potable and industrial water supply where network losses play a major role [4]. The distribution of the demand for 2003 is shown in Fig 2.

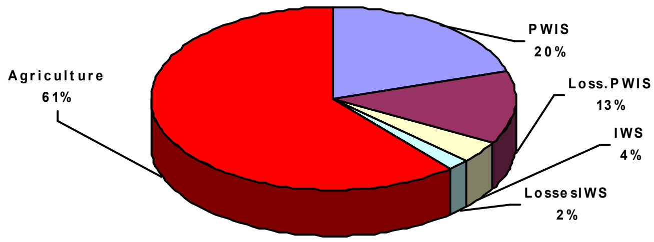

FIG. 2. Distribution of the demand in 2003 [4]

2.3. *Water needs in Algeria*

The needs are calculated using the given total demand as a preliminary and taking into account the losses estimated in (%); it is calculated in the following way:

Need = Total Demand / (100% - Losses)

According to the DAEP (Direction de l'Alimentation en Eau Potable) and ADE (Algérienne Des Eaux), there are not confirmed information on the distribution and the scale of the losses. It is currently practised, in an exemplary way in Tlemcen (Algeria), as a study of this problem within the framework of the project financed by KfW (Kreditanstalt Für Wiederaulfbau) for Tlemcen. In 2003, the order of magnitude of the losses is quantified as being of 45%. These losses should be reduced to approximately 25% by 2020. Table II indicates the corresponding values of the need on five yearly basis [4].

Table II. Corresponding values of the need for the fixed horizons (calculated) [4].

	2001	2005	2010	2015	2020
Potable and Industrial Water Needs (Hm^3/year)	3830	3870	3940	3990	4080

2.4. *Conclusion*

From Table III, we can arrive to following conclusions:

Table III. Comparison between supply and demand in 2003 [4].

	Average Year (Hm^3)	Dry Year (Hm^3)
Total Supply	5613	4824
Total Demand	6823	7668
Deficit	-1210	-2844

Under climate effects, the situation of year 2003 is characterized by a significant deficit of 1210 Hm^3 corresponding at 18% of the demand, for an average year. For a dry year, it rises to almost 2850 Hm^3, which constitutes more than one third of the demand (37%).

The water resources, of a total of 5600 Hm^3, come from two thirds of subsoil water (61%) and a third of surface water (39%).

3. Strategies adopted in Algeria

3.1. Introduction

Taking into account the existing fresh water resources and the total water demand, required to meet the various water's needs for the fixed time horizons, the Algerian Government adopted a strategy to deal with the problem of water at these horizons. This strategy is implemented jointly by two ministries: the ministry for the water resources and the ministry of energy and the mines. The strategy fixed for each ministry is developed hereafter.

3.2. Implementation of the strategy by the Ministry for the Water Resource

The current situation of the potable and industrial water supply and of the irrigation in the north of the country is very alarming. It is due to the unequal distribution of the resources and the distribution, the major risk of significant deficits in the event of prolonged dryness and finally the irrigation very limited in the north of the country.

This situation should improve in the future thanks to the conventional resources, which will be mobilized by the new dams in construction and/or in project, as well as the rehabilitation of the adductions network. However, serious uncertainties remain nevertheless on the level of: pluviometry, the realization of the projects, physical losses, the overexploitation of underground waters, the quality of surface water and finally water distribution.

The Ministry for the Water Resources (MRE) is in charge of part of the strategy adopted by the Algerian Government: in order to ensure the necessary water resources to the extension of the irrigation, this ministry started the transfer of part of the water reserves from coastal zone dams towards the Tellian Atlas zone, and the surplus will then in turn be transferred towards the High Plains. The deficit of the coastal zone will have to be made up by the desalination of seawater and the conservation of water; this last option being a priority. In addition, the resorting to the non-conventional resources to make up the short-term deficit was carried out by the installation of 21 units of desalination in opposite process osmosis of low capacities in the coastal zone. The total capacity installed is of 57,500 m^3/day. These units are distributed as follows: 14 units installed in the Centre, the remainder in the East and West of the Mediterranean coast.

3.3. Implementation of the strategy by the Ministry for Energy and Mines

The pluviometric risks recorded in particular these last years have unfortunately reduced the impact awaited of the agreed investments by the Algerian State. Thus, there is a need to imagine, as of today and for the future, complementary solutions and sometimes of substitution.

As regards governmental strategy relating to the water resources in the short and medium term, the Ministry for Energy and Mines registers its program by putting in place the non-conventional resources along the coast. This program is translated, in the short term, by the installation of 13 seawater desalination units with a total capacity of 2,260,000 m^3/day by the horizon 2009. The Joint Company of Algerian right named 'Algerian Energy Company', created by SONATRACH[†] and SONELGAZ[*] in May 2001, is in charge to carry out this program. Table IV gives a status summary of the 13 seawater desalination units projected.

[†] Société nationale de recherche, exploration, transport et commercialisation des hydrocarbures

Table IV. Statement of the 13 seawater desalination units projected [5].

N	Project	Localization	Capacity (m^3/day)	In Production	Process
1	Kahrama	Industrial zone of Arzew	90,00	3rd quarter 2005	MSF
2	Hamma Water Desalination	Hamma, Algiers	200,000	4t quarter 2007	RO
3	Aguas de Skikda	Industrial Zone of Skikda	100,000	4t quarter 2007	RO
4	Béni Saf Water Company	Béni Saf, Ain Temouchent	200,000	3rd quarter 2008	RO
5	Alger Est	Cap Djinet	100,000	3rd quarter 2009	RO
6	Alger Ouest	Fouka	120,000	2nd quarter 2009	RO
7	Mostaganem	Mostaganem	200,000	1st quarter 2009	RO
8	Tlemcen	Honaine	200,000	1st quarter 2009	RO
9	Tlemcen	Souk El Tarf	200,000	4t quarter 2009	RO
10	El Tarf	Echott, El Tarf	50,000	4t quarter 2009	RO
11	Oran	Macta	500,000	4t quarter 2009	RO
12	Ténès	Ténès	200,000	4t quarter 2009	RO
13	Tipaza	Oued Sebt	100,000	4t quarter 2009	RO

The program, presented in Table IV, makes it possible to secure for a few years the Algerian coastal band and to reinforce the position of the Ministry for the Water Resources as regards to non-conventional resources.

In the short term, AEC is always interested by desalination of seawater by means of the nuclear energy. To this end, a study is started this year under the supervision of the Ministry for Energy and the Mines with the assistance of the IAEA. The Atomic Energy Commission of Algeria (COMENA) is a major actor in this study, because of its expertise in the nuclear engineering field.

Medium-term projection consists to introduce the nuclear seawater desalination to the horizon 2017-2020.

3.4. *Conclusion*

Algeria has more than 1200 km of coast, the sea is practically non-polluting and inexhaustible source of water. The majority of the population (70%), the industrial parks and hotels, regarded as large water consumers, are located near the sea. The recourse to the seawater

* Société nationale de l'électricité et du gaz

desalination, like non conventional resource, is in fact a solution which will be in the long term like a source of substitution at very competitive prices, thanks to the fast development of new techniques of desalination, to cover the totality of the requirements of domestic an industrial water of the country coastal areas. In fact, the water cost price is lowered by the reduction of the transport cost.

4. Nuclear desalination in Algeria

The desalination of seawater by means of the nuclear energy was introduced in Algeria in 1991 through regional project RAF/4/010 nuclear desalination as source of low cost potable water' initiated by the International Atomic Energy Agency for the five countries of North Africa (Morocco, Algeria, Tunisia, Libya and Egypt) following their request. This project was related to the study of pre-feasibility of desalination of seawater by means of the nuclear energy, because of the water resources limitation in these countries. This project made it possible to establish for each country taking part in it, with the assistance of the IAEA:

- An analysis of the water supply and demand
- An analysis of the energy supply and demand
- A definition of potential nuclear site
- An evaluation of the industrial capacity
- And an implementation of the nuclear desalination program

The continuity of this study was ensured by another regional project RAF/4/013 always initiated by the Agency on behalf of the five countries of North Africa.

In accordance with the conclusions of the Workshop organized at the time of the “3rd Regional Meeting on Nuclear Desalination as a Source of Low Cost Potable Water” organized in Algiers (September 9-11, 1991), Algeria projected a study of pre-feasibility for the realization of a desalination unit using nuclear and fossil energies. Table V and Fig 3 summarize the Main Parameters of the HR-200 Nuclear Desalination System

Table V. Main Parameters of the HR-200 Nuclear Desalination System [10].

Parameter	Value
Energy Plant	
Reactor Power, MW (th)	200
Electricity Output, MW (e)	15
Outlet Temperature at the Steam Generator, (°C)	141
Desalination Plants	
Process	MED
Steam Pressure at First Effect of Desalination Plant, (MPa)	0,12
Steam Temperature at First Effect of Desalination Plant, (°C	104,8
Seawater Temperature, (°C)	25
GOR	16
Output of Fresh Water, (m^3/day)	120,000

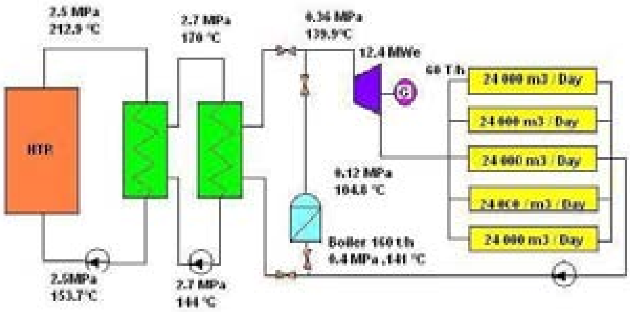

FIG. 3. Nuclear desalination plant capacity 5x 24000 m^3/day; Reactor HR-200, 200 MWth [10]

The results of this study of pre-feasibility for the realization of a unit of desalination functioning in cogeneration mode (nuclear and fossil energy) are illustrated by Table VI and Fig. 4.

Table VI. Results of the pre-feasibility of realisation of seawater nuclear desalination unit [10]

Specific Water Costs	Foreign US $	Local Current US $
Fixed Charge	0,375	0,444
Fuel	0,103	0,007
Decommissioning	0,020	0,020
Spare Parts, Consumables, Maintenance	0,035	0,049
Insurance	0,053	0,053
Chemicals	0,010	0,030
Personnel	0,024	0,052
Specific Water Costs:		
Foreign Portion	0,620	
Local Portion	0,655	
Total Water Costs per m^3	**1,275 US $/ m^3**	

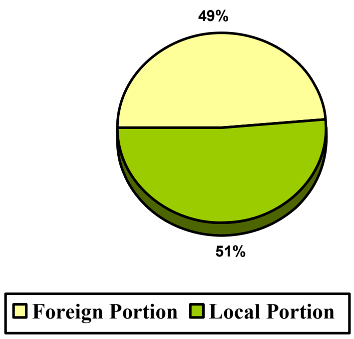

FIG. 4. Total water cost (1,275 US $ / m^3)

In 2005, the Ministry for Energy and Mines introduced to the agency, a biennial project ALG 2005013 entitled "Techno-economic study of pre-feasibility of the desalination of seawater by means of the nuclear energy". The strategic objective of this study is the elaboration of a document for the decision makers, with the assistance of the IAEA, for the introduction of nuclear desalination by 2017-2025.

The co-operation with the IAEA will be translated in the following way:

- Technical assistance
- Expertise
- Formation
- Scientific visits
- Acquisition of tools for analysis and simulation

The principal stages of this study, which will be starting in 2007, were defined. All the tasks related to these stages were described in details by taking into account: the financial impact and the repercussions of the anticipated results. Table VII presents the work plan for the project:

Table VII. Work plan for the project ALG2005013

Activity	Start	End
1)Collection of data on Electricity and Water requirements for 2025-2030		
2)Selection Criteria's of Reactor Technology and Desalination	Q1/2007	Q3/2007
3)Site and Infrastructure Studies		
Pre-dimensioning Study of the Nuclear Desalination Plant	Q2/2007	Q3/2007
Coupling Study of the Desalination Unit with a Nuclear Reactor	Q3/2007	Q4/2007
Safety's Study of Nuclear Desalination Plant, Socio-Environment Impact Studies	Q1/2008	Q2/2008
Economic Study of Nuclear Desalination Plant	Q3//2008	Q4/2008
Preparation of Project Report at the Developed Information	Q4/2008	Q4/2008

5. Conclusions

Progress achieved in the techniques of desalination, had a very positive influence on the costs related to the fresh water production. These costs have decreased a lot during the last ten years.

Historical successes of the experiments undertaken in the field of nuclear desalination in the Kazakhstan and Japan proved the feasibility of this approach. So, nuclear desalination is on the way to become a reality.

In this context, nuclear desalination seems a very competitive solution, compared to the systems based on fossil energy sources not only for the simultaneous production of electricity and potable water, but also for the minimization of the emission of greenhouse gases.

The energy strategy adopted by Algeria, is allowing the diversification of the energy sources: nuclear and renewable in addition to existing fossil ones.

This strategy, in the medium and long term, will meet the increasing demand for water by means of the non-conventional resources such as the nuclear desalination, which could be a solution in the coastal areas of the country. This will meet mainly the domestic and industrial needs and sometimes even the agricultural needs in these areas.

This strategy must be enhanced by a policy of 1) water economy, 2) waste water treatment for agricultural purpose, and 3) rational exploitation of the underground water resources.
The nuclear may play a major role as source of energy for the seawater desalination and by preserving the environment.

This represents the major axes of the strategy of Algeria for water in order to ensure a durable development and to ensure for a long term sustainability of the water resources.

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CONCLUSIONS

SESSION 7 (PLENARY)

Chairpersons

I. Khamis
IAEA

CONCLUSIONS

Summary of Session 1 (Plenary)
Outlook for Nuclear Power and the Future of Process Heat Application

Chairpersons: L. Awerbuch, IDA
T. Dujardin, OECD/NEA

Five papers were presented in this session by representatives from OECD/NEA, IAEA, JAEA, FZJ Jülich and the IDA.

The OECD/NEA paper dealt with the World Energy Outlook from present till 2030. The projected two scenarios include the Reference Scenario with present trends and an Alternate Policy Scenario in which technologies to help curb emission growth are likely to be implemented widely with consequent impact on different energy sources.

In the Reference Scenario (RS), global demand will grow by more than half over the next quarter of a century, with coal use rising most in absolute terms. World oil demand will grow by just over half between 2004 and 2030. Most of the increase in oil demand will come from developing countries, where economic growth -the main driver of oil demand- is most rapid. Oil remains by far the most heavily traded fuel, but trade in natural gas will expand faster. World electricity demand will double between 2004 and 2030. Most of the additional demand for electricity is expected to be met by coal, which remains the world's largest source of electricity up to 2030.

In the Alternative Policy Scenario (APS), global savings in energy related CO_2 emissions, improved end-use efficiency of electricity & fossil fuels accounts for two-thirds of avoided emissions in 2030. More favourable policies on nuclear could significantly accelerate the growth in global capacity especially in OECD countries. Electricity supply investments are lower than in Reference Scenario, but renewables and nuclear investment are higher. Over a quarter of global electricity comes from renewable energy sources in 2030 in APS. A dozen policies in the US, EU & China account for around 40% of the global emissions reduction in 2030 in the Alternative Policy Scenario. The share of nuclear power drops much less than in the Reference Scenario, helping to curb emissions growth

Nuclear energy main features are: mature technology, nearly carbon-free electricity generation source, stable cost and low marginal cost, geopolitical distribution of uranium resources and domestic source of energy. Today, nuclear power plants generate 16% of world electricity. There are 442 nuclear reactors operating in 33 countries. The existing power plants are very competitive; their load factors have remained very high. Upgrading of plant capacities in many cases have also taken place. A number of older reactors are scheduled for life- time extension as it is found economical. Nuclear power production is now a mature technology. Gas-fired electricity is no longer the cheapest form of generation; gas prices assumed to remain between 6 and $9 per Mbtu and even more.

Unfortunately, existing nuclear power plants have been branded as "cash cows" for most utilities worldwide. Decisions to build new plants "future cash cows" were thus difficult to make. A remarkable change in the view of the capital markets in the last two years on nuclear being not that capital intensive is quite encouraging. Economic competitiveness is no more an issue. A large number of reactors are planned in many developing countries with increasing energy demand and having meagre fossil sources. Capital markets expect new construction in some countries of Europe too. Resources to invest in new NPP are available.

However lack of confidence in the political stability, nuclear regulatory policies and financial aspects in many countries interested in nuclear technology was a negative factor. To overcome this, partnership of utilities/large industrials ('the Finnish solution') are welcome. The role of governments in recognizing the social benefits and in reducing the risks is also desirable.

The concluding remarks outlined by the author on Energy Policy are:
"There are no ideal or magic solutions to avoid the unclean, uncertain and expensive energy in near future as the present trends indicate. All energy technologies will be therefore needed in the years to come. As far nuclear is concerned, uranium resources are available for exploitation of nuclear energy and advanced nuclear technologies are developed/ are under development. From a sustainable development perspective, nuclear energy has a major role to play in terms of reduction of CO_2 emissions, security of energy supply and diversification of supply and price stability."

The paper also discussed the OECD/NEA activities on non-electric applications. These primarily include; information exchange meetings on nuclear production of hydrogen, isotope production, R&D activities and exchange of information with the VHTR system project and processes applicable to systems other than VHTR.

The IAEA paper indicated that growing awareness of the need for environmental protection together with recognition of energy supply security that nuclear power is offering, has lead in many parts of the world to renewed discussion about the nuclear power option to meet increasing energy and electricity demands, particularly in developing countries. The IAEA has reflected this new trend of rising expectation in its programme by putting emphasis on assistance to those countries, which are planning to introduce nuclear power or intend to extend its capacity. More recently the Department of Nuclear Energy of IAEA has increased its scope of interest and included new activities on Non-electric Application of Nuclear Energy.

The IAEA programme is based on three pillars: Science and Technology; Safety and Security; and Verification. IAEA and the nuclear community would have three priorities: First to ensure protection when nuclear energy is used to produce electricity, for district heating, desalination or hydrogen production, it is used safely, securely, and with minimal proliferation risk. Second, to ensure continued technological innovation for improved economic viability, enhanced safety, security and proliferation resistance. Third, to ensure that the needs of developing countries are taken into account.

The paper from JAEA reported that JAIF Committees on Nuclear Heat Application were established as early as in 1969. A number of useful publications were made covering the subject of industrial uses of nuclear heat, uses of LWR and HTR heat and contribution towards global environment protection.

The paper first discussed about the operating nuclear desalination plants in a number of Japanese reactor sites. The salient details the VHTR applications and utilization systems were then presented. The objectives of this study were:

- Propose promising VHTR applications and utilization systems

- Estimate possible fossil energy savings and CO_2 reduction
- Identify technological gaps for practical use

An outline of the VHTR deployment scenario, the scenario for FCVs and scenario for a "Hydrogen Town" were put forward.

In author's opinion, nuclear heat applications have been considered for long time, but not much has succeeded. Effective and practical measures to gain the advantages of aspects of climate change/green house gas reduction need to be taken now. Nuclear technology and its related institutions should advance and address to the real world as other technologies and environmental institutions do. Practical application would be possible based on exchange of experiences and further international collaboration.

The paper from FZJ Jülich dealt with present role of nuclear energy in power generation and suggested combined heat and power (CHP) and nuclear process heat (NPH) as other forms of nuclear energy utilization. The strong points of nuclear CHP are;.more independence of energy imports, increase in efficiency by ~ 15 %, reduced heat waste and CO_2 emissions, adaptation to industrial needs (modular size) and good social acceptance.

The operating experiences of the industrial heat supply in Canada, Germany and Switzerland, the district heating in European countries and of nuclear desalination in Kazakhstan and Japan were presented by the author. The prospects of nuclear production of synthetic crude oil, heat supply for SMR process and a nuclear refinery for production of hydrocarbons and liquid fuels were also indicated.

In conclusion the author pointed out the following;

Nuclear energy is a clean, safe, and powerful greenhouse gas emission-free option to help meet the world's demand for energy. It has a still unexploited potential of producing, in the CHP mode, process heat and steam in a broad temperature range. There is experience with nuclear in the heat and steam market in the low temperature range. An extension appears possible on a short term in the areas of desalination, district heating, and tertiary oil recovery.

In the higher/temperature heat/steam range, a significant potential for nuclear is given in the petro-chemical industries including the production process of liquid fuels for the transportation sector. It still needs, however, a broader deployment of respective nuclear heat sources. The VHTR represents a highly promising, near-term option of a Gen IV type nuclear reactor of the future.

The IDA paper gave a detailed account of the current status of desalination technology, future developments and prospects of nuclear energy as a source for future large-scale desalination on a sustainable basis. The details of the commonly operated desalination processes, MSF, MED, RO and hybrid plants including the capital costs and the energy consumption and their efficiencies were discussed. The salient aspects of the paper are as follows:

Worldwide Desalination Inventory Report includes a total of 17,348 desalting units with a total capacity of 37,750,000 m^3/d or 8.3 billion imperial gallons per day, installed or contracted as on July 2006. Desalination is already used in 125 countries around the world. Desalination has decisively proven during last 30 years its reliability to deliver large quantities of fresh water from the sea. Unlike oil, fresh water has no viable substitute. The sea is the unlimited source to create new fresh water through desalination. The future requires effective integration of energy resources to produce power and desalinated water economically with proper consideration for the environment.

The significant increase in fuel-energy and material cost has a dramatic impact on capital and operational cost of desalination and power plants. Impact of US$ 60-75 per barrel oil and high demand for raw materials, steel, copper, nickel has dramatically increased pressure to develop novel solutions which can minimize fossil energy consumption and reduce capital expenditure of desalination plants. All of this leads to renewed global interest in the nuclear energy.

In an era of high energy and material cost, an integrated use of technology can compensate the impact on rising cost. As desalination and water reuse expansion in the world continues at a rapid pace, these innovations must be integrated into the next generation of water facilities. Desalination provides hope to the world community that we can provide water, the essence of life, at a reasonable cost, solving the scarcity of existing water supplies, avoiding regional and territorial conflicts, and providing the water resource for sustainable development.

Since nuclear energy is nearly carbon free generation and is long-term sustainable solution and potentially competitive with fossil fuels it is necessary to consider as a choice for desalination projects. Particularly in cases when power and heat for desalination is generated from using heavy crude oil or coal, which requires significant cost for pollution control and is an inefficient generation solution, resulting in significant increase of the penalty for CO_2 emission and greenhouse impact.

Summary of Session 2
Nuclear Energy for Non-electric applications: Technology & Safety

Chairpersons: S.Shiozawa, JAEA
A.Omoto, IAEA

The Session 3 dealt with nuclear energy for non-electric applications: technology and safety. There were a total of 10 papers in this session. Some papers introduced the status of the national or international projects concerning the nuclear energy for non-electric applications. Some of the papers stressed needs for the nuclear applications, and suggested possible global markets in general and also local markets specific to desalination and district heat.

Although there was not much discussion on the needs and markets of the nuclear energy for the other promising non-electric applications, it was generally well recognized in the conference deliberations.

Some papers also introduced the status of technology development and future plans dealing with technical issues. Those are mainly concerning the economy or improvement of thermal efficiency. The economic competitiveness of the many nuclear application was found to be not so obvious compared to the conventional fossil applications.

In addition to this, issues related to the importance of materials of construction were brought out by the participants. In conceptual design, issues of materials are left behind, but it is thought to be critical for commercialization. Thus, the issues of materials need a better look and may be discussed more in a global sense.

It seems that the technical issues would be solved in the near future provided the R&D plan is executed as expected. However it is not clear that those will be fully funded as proposed. Also it is not desirable that each country takes up the same technical issues.

Therefore, a certain international cooperation is thought to be necessary in an effective way. The Agency can work to foster the necessary international cooperation by holding information exchange meetings and/or cooperative R&D such as CRP.

Several interesting ideas were given on the heat application systems, which include the alternative of current exiting ideas. However, it seems that those ideas are not systematically organized even in one country. There are too many ideas and some of them were already evaluated to be not worthwhile. It may be a good idea to have a seminar to discuss and argue on the new idea on the heat applications in the Agency.

Regarding safety for the non-electric applications, many speakers summarized the general and technical issues on the safety. It seems that the technical issues would be solved in a proper way. An interesting question was raised from the audience whether the heat application systems can be categorized to be non- nuclear grade, because the application system is a part of nuclear system, as it works as a cooling system of the reactor, for example. For this question, a Japanese paper gave one of the possible solutions, which was developed for the HTTR - IS process demonstration plant, where the IS process is to be connected to an actual reactor of the HTTR. The idea how the application system can be treated as non-nuclear system was introduced in the paper.

Therefore the common standards and evaluation methodology shall be developed in a global manner. The Agency may make a significant contribution to develop and authorize such a global safety standards.

The safety aspects of non-electric applications using low temperature heat such as desalination, district heating and a few industrial process heat applications have been the subject matter of intense study and many useful reports were published. There is already over 1000 reactor years of accumulated experience of safe operation of such systems.

With regard to combined nuclear and chemical facilities, apart from their own specific categories of hazards, a qualitatively new class of events will have to be taken into account which is characterized by interacting influences. Arising problems to be covered by a decent overall safety concept are the question of safety of the nuclear plant in case of a flammable gas cloud explosion, or the tolerable contamination of the product. In addition, there are the comparatively more frequently expected situations of thermodynamic feedback in case of a loss of heat source (nuclear) or heat sink (chemical).

The risk analysis of a nuclear hydrogen production plant by coupling of the nuclear reactor and the chemical plant, with higher temperature & pressure and corrosive environment and also having explosive contents, is an important issue. The risk can be reduced by the enhanced safety of the VHTR as well as the separation of the reactor and the chemical plant. Release of any radioactivity such as tritium from nuclear fission that can contaminate the product hydrogen also need to be monitored.

The siting of nuclear heat application systems from a public acceptance point of view is also a subject matter of great importance. In general, nuclear reactor must be built near the heat demands district, because the distance of the heat transport is limited due to the heat loss considerations. This is a tough question to be solved and the Agency should take a leading role for the public acceptance.

Summary of Session 3

Economics and Demand for Non-Electric Applications

Chairpersons: L. Brey, USA
M. Megahed, Egypt

This session featured nine papers from six Member States and the IAEA. Most of the author's focus centered on the economic and financial aspects of seawater desalination. In many cases, the tool utilized in the economic analyses was the IAEA's Desalination Economic Evaluation Program (DEEP) software code, which provides an economic basis for comparing different fossil and nuclear energy sources coupled to various desalination systems. The salient feature of this code and the pertinent information from the corresponding Coordinated Research Programme on *"Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies"* was the subject of a presentation by the IAEA.

Specific site related studies were presented by the Member States for possible desalination plants in Tunisia, Brazil, Indonesia and for various regions throughout the Mediterranean and Arabian Gulf. Many of these featured co-generation applications of electricity production and seawater desalination. For Tunisia, combinations of nuclear and fossil (at 70 to 120 $/bbl fuel cost) energy sources were considered coupled with RO and MED/RO hybrid desalination systems for an output of up to 192,000 m^3/day. Results from this study indicated the nuclear co-generation/desalination plants exhibited costs lower than fossil fired systems with the GT-MHR/RO plant being the lowest cost system.

Economic results for a co-generation plant located in Northern Brazil indicated that the nuclear plant, with its high capital cost, was less competitive than a natural gas fuelled plant, However, with a long term trends of lower capital and operating costs for nuclear coupled with the trend of rising natural gas cost, the nuclear co-generation plant becomes attractive.

A representative of Indonesia's BATAN supplied the results of an economic and financial study for setting up a co-generation plant utilizing the South Korea's SMART modular reactor coupled to a MED desalination system on Madura Island. Again the IAEA's DEEP software was utilized as the economic software to investigate this plant with an output of 40,000 m^3/day. The resulting calculations showed the SMART/MED plant to be both feasible and beneficial.

The economics associated with desalination utilizing different co-generation energy sources and desalination methods was addressed in a paper authored by technical experts from France and Germany. Of special consideration was the effective credit or penalty associated with green house gas emissions from the burning of fossil fuels. Sensitivity studies utilizing different values for fossil fuel prices, interest, discount rates, etc. were considered for these different systems in order to provide techno-economic options for decision makers in considering the appropriate plant type for specific sites.

A comparative economic analysis for the siting of desalination plants in three distinct world regions was provided by the Nuclear Power Institute of China. This study also used the IAEA DEEP software for comparing a number of nuclear and fossil energy sources, including the seawater desalination pool shell type reactor (SDPSR). The results showed the SDPSR to be competitive with other nuclear technology and fossil fuelled plants for water production in Region 1 (Southern Europe) and Region 2 (SE Asia and N. Africa).

Authors from Japan, France and the USA addressed the Power Credit (PC) economic modelling approach for evaluation of joint product production utilizing nuclear energy. This approach, utilized within both Generation IV and in the IAEA's DEEP process for economics of nuclear desalination, was described in detail with focus on the calculation of levelized unit costs for non-electricity products and jointly produced outputs such as electricity with fresh water, hydrogen, heat or actinide incineration services.

Economic and environmental aspects of applying China's PSNR200 nuclear heating reactor to provide 1.5MPa steam as an energy source for industrial applications in the Shanghai area were explored. When compared to a coal fired plant to produce the same quantity of energy, an annual reduction in CO_2 emission of 675,000 tonnes was possible. Factoring this environmental benefit into the economic analysis (with the recent trade price of 25US$/ton of CO_2 between England and China) results in total annual revenue of 406.27 million RMB (8 RMB = 1 US$) for an internal rate of return of 22.58%.

The industrial activities of Japan relative to non-electric applications of nuclear power, specifically the HTGR, were considered. Recent areas of focus in Japan include the following: Development of fuel cell vehicles to utilize hydrogen production via nuclear energy; use of steam and/or hydrogen and electricity via nuclear power to replace aging fossil fired chemical complexes to limit carbon based gas emissions, and the proposed establishment of "Hydrogen Towns" in selected areas of Japan which are aimed at utilization of hydrogen as the energy of the future.

Summary of Session 5: High-Temperature Applications

Chairpersons: **S.J. Herring, United States of America**
A.I. Miller, Canada

This session had 18 presentations, interestingly equally from OECD countries and the emerging countries. The session provided an exceptional opportunity for sharing of technical information between countries – especially with countries with little opportunity for such sharing. Extensive new interest from many countries in producing hydrogen using nuclear power, especially using the SI process was clearly noted.

The majority of the papers dealt with thermochemical water splitting SI process for hydrogen production using heat and electricity from the HTGRs. These papers covered modeling & analysis, experimental study & developmental work, bench scale & engineering demonstration loop and national projects and experiences. A few papers concerned with electrolytic and hybrid processes utilizing heat and electricity from water cooled reactor, super critical water cooled reactor and fast breeder reactor. One paper highlighted the role of high temperature reactors in synthetic fuel production. Technical details of existing high temperature reactors and the ones under consideration or development were presented along with the details of various proposed applications. The economic and financial aspects were also considered in some cases.

The theme of the conference that it is possible to do much more than produce electricity from nuclear reactors was convincing and broadly expressed. The case for nuclear heat for synthetic fuels was strongly made and the possibilities reviewed were directed toward real problems, e.g. supplying water, making synfuels and ameliorating the GHG-climate crisis.

Coal gasification/liquefaction as a relatively cleaner fossil fuel source is an area of active interest. Production of synfuels and other hydrocarbons using nuclear heat is another area of greater promise. CO_2 can be used as feedstock together with water, nuclear heat and electricity for producing synthetic hydrocarbons, which may be better energy carrier than hydrogen. This can also act as CO_2 sink reducing its emission to the environment. Preliminary estimates indicate that synfuels could be produced at prices comparable or even lower than fossil fuels. Further work on integrated nuclear-chemical complex is desirable to gain vital experience in this area.

Most of the work on hydrogen production has concentrated on high-temperature processes such as high temperature steam electrolysis (HTE) and the sulphur–iodine (SI) and calcium-bromine cycles. These processes require higher temperatures (>750^{o}C). Advanced reactors such as the very high temperature gas cooled reactor (VHTGR) can generate heat at these temperatures, but will require several years before they are commercially deployed. There are estimates that for SI or even for HTE process, the hydrogen cost can be brought to \$2/kg levels, if O_2 credit is also taken in to account. If the natural gas price ranges between \$6-8 /MMBTU and CO_2 sequestering costs are also included, hydrogen by steam methane reforming (SMR) would cost more than nuclear hydrogen.

A greater appreciation is emerging of the economic and financial aspects of hydrogen production. It was particularly noted that the ability to switch between two possible product streams – e.g. electricity and hydrogen; heating and desalination may further improve economics.

Several papers reported on interesting new experimental results and momentum toward and enthusiasm for experimental demonstrations was clearly evident. This is appropriate since, for example, materials issues as we go to higher temperatures with aggressive chemicals are not fully solved.

Training is seen as a key topic for spreading nuclear to new countries and new markets. For the non-electric applications, the wealth of work done in the 70s and 80s in Europe, especially in Germany, should be recaptured while this is still possible, even to the extent of involving retirees. It is well known how General Atomics draw on the experience of people from the earlier “hydrogen age” who are still employed. This was noted as hugely valuable to current work. However, much of the European work has no new generation of specialists to maintain knowledge of previous work.

Summary of Session 5

Nuclear Seawater Desalination and other applications

Chairpersons: P.K.Tewari, India
S. Nisan, France

The session covered in all fourteen papers from eight countries and three international organizations. Presentations included two regional and three national studies. Two specific studies were presented on applications other than desalination namely oil shale sands and ethanol production.

In the first part of the session, the nuclear desalination activities of IAEA Member States both with past and existing nuclear desalination systems were summarized by IAEA. Currently, a number of Member States are involved in techno-economic site- specific studies while some are pursuing nuclear desalination demonstration projects.

The role of Arab Atomic Energy Agency (AAEA) in promoting nuclear desalination in Member Arab states was outlined by its representative. AAEA is now coordinating a project to define and develop steps for deploying nuclear desalination systems. Nine Arab countries are participating in the project which involves working groups dealing with:

- Specifications and characteristics of a virtual site
- Safety and licensing
- Desalination technologies and coupling schemes
- Techno-economic feasibility studies

In the subsequent presentation, the history of nuclear desalination activities in the Arab World was presented, first giving the balance of water and energy demands and of the available resources. The presenter gave several arguments in favour of nuclear desalination systems, based on the probable use of Small and Medium-sized Reactors (SMRS). The paper concluded by discussing the various reasons and socio-economic factors, which could lead to a broader pan-Arab collaboration.

The next presentation from IDA, discussed the market drivers for power and desalination. Tremendous increases have been reported in power and water demands worldwide. The primary conditions to meet these demands in a sustainable manner would be to first meet the challenges regarding further cost reductions, environmental sustainability and public acceptance of nuclear desalination systems. In future, the single most important requisite for desalination market expansion would be the privatization of the desalination market.

Some facts and figures for nuclear desalination systems for the development of the Sinai region were presented in the next paper. A paper on the development of a small sized MVC plant development for a remote island site in Indonesia was then presented.

In the following paper, the first results of a demonstration nuclear desalination system based on the utilization of a PBMR to be constructed at Koeberg site in South Africa around 2012 were presented.

Another paper from Indonesia explained why the nuclear desalination system comprising two SMART reactor units coupled to MED, were considered necessary for the Madura Island. This presentation included analysis of complex factors such as the introduction of a sophisticated nuclear desalination system in a relatively undeveloped area with little qualified manpower and deep rooted rural background.

In the last paper of the first part of the session, representative from Argentina discussed the contents of an eventual safety report for a nuclear desalination system, the safety approach that should be used to meet the double safety objective of desalted water free from any radioactivity without any impact on the operation and safety of the coupled nuclear reactor. It was shown, how the incorporation of certain engineered features could meet these objectives.

In the second part of the session the US representative from Idaho National Laboratory gave a presentation on the use of generation IV power conversion systems in the context of the hydrogen initiative. The paper outlined various methods by which nuclear reactors could provide the energy for the production of transportation fuels while the carbon source for these fuels is extracted from the atmosphere using biomass.

It was shown that this approach could be a sustainable method for the continued use of hydrogen fuels. High temperature electrolysis is proving to be a flexible product of H_2 and/or synthesis gas. At the moment there is no clear economic advantage of one particular method of hydrogen production over the other.

In the second paper from Argonne National Laboratory USA, the future of desalination in the US, were presented for the water stressed regions are California, Texas and Florida. In this context, two objectives have been identified:

- A short- term objective aiming to achieve a 20% improvement in costs and energy efficiency.
- A long- term objective to achieve up to 80 % improvements, to be realized around 2030.

It was shown how optimized hybrid systems using RO and MED could lead to considerable flexibility of water quality for various applications. It was observed that the costs of such hybrid systems could be of the same order as that of a stand- alone RO system.

In the next presentation some interesting facts and figures about water demands and use in Yemen were presented. In this country, 90% of the available water is used for agriculture.

A paper from Canada presented the work on extraction of oil from oil sands in the Alberta region, using the SAGD process. This process is very energy intensive. At present, natural gas-fired plants are used as energy source, which could be replaced by nuclear reactors producing steam and electricity or dedicated reactors producing only high temperature steam.

The last presentation of the session was from Germany on the fuel ethanol production using nuclear plants. A typical example is the production of ethanol from corn. Other biomass forms could be sugar or starch and cellulose, from which sugar with enzymes would be produced to enable ethanol production. The processes are energy intensive and could use massive quantities of steam, ideally provided by nuclear reactors. The ultimate requirement of the market is measured in hundreds of Giga Watts of nuclear heat.

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Session 1	L. Awerbuch T. Dujardin	IDA OECD/NEA
Session 2	S. Shiozawa A. Omoto	JAEA IAEA
Session 3	L. Brey M. Megahed	USA Egypt
Session 4	S.J. Herring A.I. Miller	USA Canada
Session 5	P.K. Tewari S. Nisan	India France
Session 6 Panel Discussion	I. Khamis	IAEA
HTTR Workshop	R. Hino	JAEA
Session 7 Conclusion	I. Khamis	IAEA

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