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Basic Principles

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Opportunities for Cogeneration with Nuclear Energy

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Energy and its resources play a crucial role in economic development, energy security and wealth generation. Every State should make efforts to balance energy need and availability, and hence investigate various options — one of which is cogeneration.

Cogeneration, also referred to as combined heat and power, is the simultaneous sequential production of electrical and thermal energy (heat) from a single fuel. Since the 1990s, cogeneration has become an attractive and practical proposition for a wide range of thermal applications, including district heating and cooling applications. It is now important to extend this to the area of nuclear energy applications by expanding electricity generation from nuclear power plants to cover heat generation for cogeneration applications. As a result, the benefits of nuclear energy will be more recognized in various sectors other than power generation. In addition, there are technical advantages with cogeneration, as the systems will be more efficient and cost effective and less harmful to the environment than alternative sources of energy.

The IAEA wishes to thank the contributors to the drafting and review of this publication, in particular I. Dincer (Canada). The IAEA officer responsible for this publication was I. Khamis of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Energy plays a vital role in the economic development of a country and in the well-being of the inhabitants. However, the future of the energy sector depends on moving from oil based sources, which emit large quantities of greenhouse gases (GHGs), to energy sources which are more reliable and cost effective and less harmful to the environment. The growing investment in nuclear energy is one such source which is less harmful to the environment compared to fossil fuels.

It is important to look for ways to improve and enhance nuclear power. One advantage of using nuclear power plants is their integration with other systems and the generation of multiple outputs. The process, or waste, heat generated by nuclear power plants can be used in other processes, such as district heating, process heat, desalination and hydrogen production. The use of nuclear power plants in cogeneration systems provides many economic, environmental and efficiency related benefits. However, not every power plant can be used for the same application, and it will depend on the technology, type of reactor and fuel, and temperature of the cogeneration system.[1] Potential plants include the following:

— Light water reactors (LWRs);
— Heavy water reactors (HWRs);
— Small modular reactors (SMRs);
— Liquid metal fast reactors (LMFRs);
— High temperature gas reactors (HTGRs);
— Supercritical water reactors (SCWRs);
— Gas cooled fast reactors (GFRs);
— Molten salt reactors (MSRs);
— Modular helium reactors (MHR).

1.1.1. Definition

Cogeneration is a way to use a single source of energy efficiently to produce power and useful thermal energy. The Carnot cycle shows that to produce a specific amount of power, a heat engine needs to work between a hot source of energy and a cold environment. Therefore, there is always a considerable amount of heat to be released to the cold source. The idea of cogeneration is to use this rejected heat for the second, or bottoming, production plant to increase the efficiency. Figure 1 illustrates a basic cogeneration process which works at three different temperature levels. The temperature difference between hot source (T_H) and the cold source (T_{C1}) results in producing work (W) as a basic heat engine. Since much energy is lost to the environment in power plants, it is possible to make use of this energy to produce another useful output such as heating, cooling, and the production of hydrogen or fresh water. Heat can be recovered and used for cogeneration purposes (Q) between T_{C1} and T_{C2}.

In power cycles, the temperature of the exhaust flow (or working fluid), which transfers the heat to the surrounding environment, is usually high. Hence, using an intermediate temperature of a second working fluid can recover the heat losses and increase the efficiency. Examples of such cycles include combined cycle plants and combined heat and power (CHP) systems. Food, car and steel production processes emit vast amounts of heat to the environment which can be recovered. These heat sources can be used to produce other products.

The benefit of using nuclear based cogeneration is that the nuclear fuel is used in a more efficient and environmentally friendly manner. Energy and exergy analyses presented in this publication show that the performance of a nuclear power plant can be increased by 5–10% if it is used in a cogeneration mode. Nuclear based cogeneration applications can also lead to a drastic reduction in the environmental impact of up to 35%.

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[1] For further information, see www.iaea.org/NuclearPower/NEA_Cogeneration/index.html

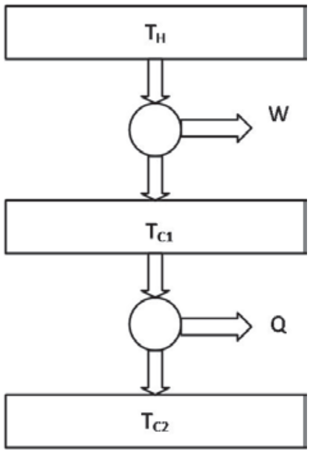


FIG. 1. The cogeneration process.

1.2. OBJECTIVE

The objective of this publication is to provide support to Member States considering nuclear cogeneration as a viable option to achieve increased savings in, and to gain public acceptance of, nuclear power. This publication is based on the experiences, best practices and expectations for the future of nuclear power technology. It explores the technical issues, the available solutions and the economic implications of cogeneration with nuclear power.

1.3. SCOPE

The scope of this publication is diverse, including fundamental aspects, practical systems and applications, economic factors and case studies. This publication presents a comprehensive overview of nuclear energy based cogeneration for increased efficiency, cost effectiveness and sustainability, and less harm to the environment. This publication is aimed at users from academia to industry and from government agencies to public institutions as well as local and international organizations, and includes researchers, scientists, engineers and policy makers. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

The fundamental aspects of cogeneration are explored in Section 2. Nuclear energy based cogeneration and its applications are examined in Sections 3 and 4, respectively. Safety considerations are laid out in Section 5. Sections 6 and 7 describe the economic evaluations, and the comparative environmental impact and sustainability assessments, respectively. Section 8 presents some case studies, and Section 9 concludes and offers examples of future areas of study.

2. FUNDAMENTAL ASPECTS OF COGENERATION

2.1. USERS OF COGENERATION

Cogeneration for heat and electricity production is gaining increasing importance all over the world because of the growing environmental impact of energy consumption. The energy paradigm is shifting from ‘providing more energy’ for people to ‘better energy use’ without impeding human comfort or wealth. Cogeneration can help this energy transition. Global primary energy consumption need not grow (it could even eventually decline), while the final energy use might still increase. That can be partially achieved by retrofitting existing power plants to increase their energy efficiency by adopting cogeneration production.

Cogeneration systems may rely on networks other than electric grids, such as heat and steam networks or gas pipelines. Depending on the optimal final utilization of heat, these networks could either end up being large and extended or small and local, built either separately or connected in clusters. This energy sharing between different users of the same production cluster offers many possibilities in demand management and cost minimization. The energy bundling will ultimately profit from advanced smart metering innovations as well as new instrumentation and control technology deployed for smart grids management. The major types of cogeneration system include:

— Steam turbine cogeneration;
— Gas turbine cogeneration;
— Reciprocating engine cogeneration;
— Fuel cell based cogeneration;
— Nuclear based cogeneration.

2.1.1. User requirements

The fundamental aspect of cogeneration is that if both power and heat are produced using a single source as prime mover, there is a market for both in order to meet the demand. Although industrial and residential energy customers use energy sources in different ways, it is mainly as electrical power and heat. However, the demand varies depending on the location and season. This coherency between demand and offer provides a worldwide market for cogeneration systems. There are different categories of cogeneration plant and different types of user.

2.1.2. Power generation industries

In this category, cogeneration is a power–power cycle in which the bottoming cycle uses the rejected heat of the upcoming cycle to produce as much power as possible. One such example is combined cycle power generation systems which utilize waste heat from a gas turbine in a heat recovery steam generator to produce steam and to generate electricity in the Rankine steam cycle. Users in this category seek the highest efficiency, with continuous and almost steady loads. Since efficient power plants work at high temperatures, the prime movers in such plants are usually gas turbines, which can deliver a large mass of high temperature flue gas at their exhausts. Combined cycle power plants are categorized according to the pressure level. The greater the pressure level, the greater the cycle efficiency. However, the investment cost increases as a consequence.

2.1.3. Industrial users

There are many options in industrial applications which can be categorized as a cogeneration system. If a process releases a large amount of heat, this heat can be a source of energy for a bottoming cycle to reproduce heat, power, hydrogen or fresh water. Users in such industries wish to reduce their energy costs without compromising the security and efficiency of the original cycle. Power, heat and cooling are the common products in such industries, even though this source of energy may be used in another process in the main plant.

Oil, gas and refinery plants need a large amount of power. In such cases, a power generation site is constructed and, according to the plant, the rejected heat of the power cycle can be used in the main plant or as a cogeneration cycle to produce heat or power. Secure, reliable and economic power generation are the most important requirements.

2.1.4. Residential users and the building sector

Residential users and the building sector are the most sophisticated energy consumers, since their load does not follow a specific trend. These users look for the most economical method to fulfil all their energy demands.

Moreover, the supply needs to be secure, reliable and easy to maintain. Such a system has to work with various users with different demands. It is important to note that no steady load is available.

User needs not only depend on the size and the application of the building but also on the main energy carrier and the local climate. The method selected to size and design the cogeneration plant depends on the function of the building, and can include systems such as heat based, electrical based, cooling based or multifunctional hybrid designs.

The present trend in many countries is to find compensation schemes or incentives to reduce individual energy consumption in buildings, for example through large scale renovation, such as investing in housing insulation. However, the savings through energy reduction need to justify the investment in the renovation. Here, cogeneration can help large scale renovations by reducing upfront costs.

2.2. POTENTIAL BENEFITS

The importance of the combined production of heat and power or cogeneration results from the more efficient use of fuel, and corresponding reductions in the emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). It can often be misleading to compare the efficiency of cogeneration — at around 85% — with the efficiency of power generation facilities (i.e. condensing power plants) — at around 40%. A better comparison would be to take the weighted average of the efficiency of power and heat production and to compare it with the efficiency of cogeneration. The importance of cogeneration can be seen in the comparison between a cogeneration plant and conventional plant to produce electricity and heat. Rosen [1] reports that:

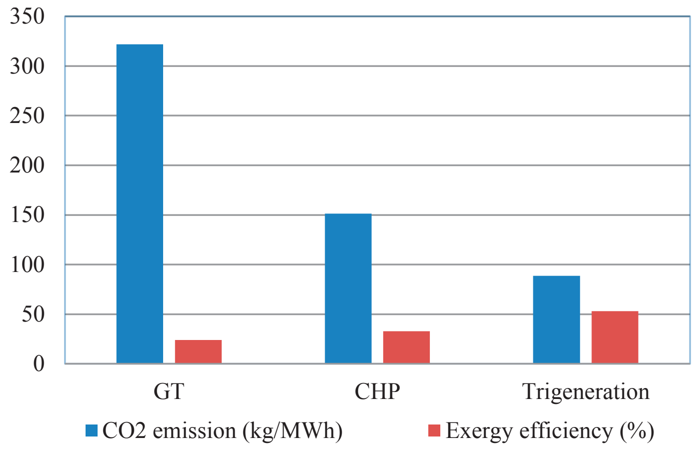
> “Thermal plants, such as fossil-fuel and nuclear power plants, form the basis of most cogeneration systems. In thermal power plants, an energy resource (normally a fossil or nuclear fuel) is converted to heat in the form of steam or hot gases. The heat is then converted to mechanical energy (in the form of a rotating shaft), which in turn is converted to electricity. A portion, normally 20% to 45%, of the heat is converted to electricity, and the remainder is rejected to the environment as a waste.
>
> …….
>
> “Cogeneration can be applied to plants of varying sizes, ranging from those for single buildings to utility-scale facilities.”

Since cogeneration plants have more than one output, they are more efficient than separate power generation systems. Among power generation systems, thermal and nuclear power plants are good candidates for cogeneration applications to produce the second useful output that could be heating, cooling or hydrogen. Nuclear power plants produce a large amount of both electricity and heat. Some of the generated electricity can be used for fresh water production using reverse osmosis (RO) desalination, and the heat could be used for hydrogen production, using thermochemical cycles (i.e. copper–chloride cycles). Another benefit of cogeneration systems is the reduced amounts of GHGs they emit, which leads to less harmful gases with a single prime mover. Figure 2 shows the advantage of CHP and trigeneration systems, which both emit less CO_2 compared to a gas turbine power plant, and CHP is also more efficient.

2.3. ECONOMIC ASSESSMENT OF COGENERATION SYSTEMS

The economic assessment of cogeneration systems examines the following:

— Economic parameters (e.g. interest rates);
— Sources of financing (e.g. private, public and loans);
— Costs and benefits;
— Cost of environmental impact.



Note: CHP — combined heat and power; GT — gas turbine.

FIG. 2. Comparison of exergy efficiency and environmental impact of three different types of plant.

The different tools used in the economic assessment include the following:

- Exergoeconomic approach;
- Payback period;
- Sensitivity analysis.

2.3.1. Economic parameters

The real time value of initial investment depends on the real interest rate on investment and loans. High inflation rates and unstable economic policies greatly affect the financial aspects of the project. The long period of construction, operation lifetime, and maintenance and overhaul shutdown time needs to be considered in the economic assessment. Taxes, fuel price variations, labour and professional wages are additional considerations.

2.3.2. Sources of financing

The are different sources of financing include the following:

- Self or private financing;
- Loans;
- Leasing;
- Third party;
- Facility management.

2.3.3. Costs and benefits

Cost and earnings flows are categorized as follows:

- Initial investment (e.g. equipment purchase cost and installation);
- Operation and maintenance costs;
- Fuel costs;
- Sale or purchase of energy;
- Cost of environmental impact.

In many cases, cogeneration units reduce the energy costs and make systems more efficient and environmentally friendly. Such a cost reduction is considered a win (benefit) in the economic analysis conducted.

2.3.4. Cost of environmental impact

Environmental impacts of a plant are inversely related to the plant efficiency. Any strategies which increase the plant efficiency will reduce emissions. Cogeneration plants can play an important role in greater efficiencies and lower emissions. The environmental assessment of a cogeneration plant is not only related to its current operation emission. Life cycle assessment estimates total environmental impacts of a plant from raw material to final state of the art technology which is installed (see Ref. [2] for more information on the environmental assessment and environmental impact associated cost for cogeneration plants). Estimates of the costs imposed on the economy of the plants for emissions are usually expressed in terms of US $ per kg or tonne of emissions (see Table 1).

TABLE 1. COST OF ENVIRONMENTAL IMPACT

Emission	Cost (US $/tonne)
Sulphur dioxide	1000
Nitrogen oxides	1000
Carbon dioxide	10–20
Methane	210
Particulates	2000

2.3.5. Exergoeconomic approach

Tsatsaronis [3] defines this approach as the following:

> "Exergoeconomics is the branch of engineering that appropriately combines, at the level of system components, thermodynamic evaluations based on an exergy analysis with economic principles, in order to provide the designer or operator of a system with information that is useful to the design and operation of a cost-effective system, but not obtainable by regular energy or exergy analysis and economic analysis."

Exergoeconomic analysis is a potential tool for cycle design procedure and payback period methods for decision making and marketing are common approaches. In general, customers look for the lowest payback period values. To design a more efficient cycle, a designer aims to reduce the overall lifetime costs of the plant, but which may lead to an increase in the investment cost. Cost of exergy flows are evaluated and losses are minimized as much as possible. The strategies and approaches are well developed and will be discussed later. The flow cost rate is identified for each stream in and out of the system, and a cost balance is written for each component.

2.3.6. Payback period

Customers do not need to know how efficient a cycle works on the basis of the exergoeconomic analysis. Instead, customers want to know which benefits can be achieved and their monetary value.

There are a number of analysis and assessment methods which evaluate the key benefits of the project or system. The traditional economic evaluation methods commonly recommended in the literature [4, 5] include:

- Payback method;
- Accounting rate of return method;
- Internal rate of return method;
- Net present value (NPV) method.

Among these methods, the NPV method is considered the most useful approach to evaluate investments. It assesses the difference between all the revenue the investment can be expected to achieve over its lifetime and all the costs involved, taking into account the rate of inflation and an appropriate discount rate for future costs and revenue. It can be challenging to calculate the NPV, since it is not always clear what the discount rate should be.

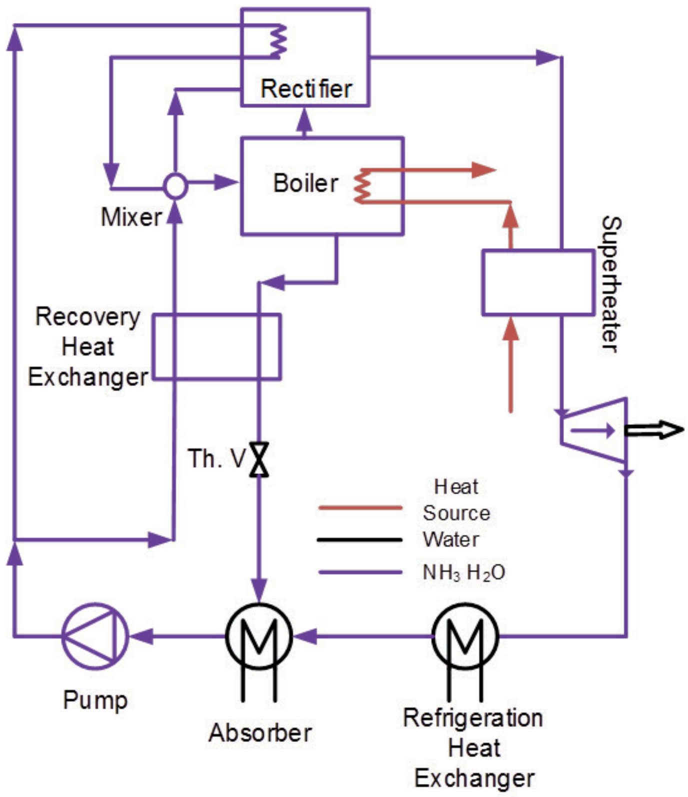
2.3.7. Sensitivity analysis

The data used in the evaluation are sensitive to assumptions and economic parameters such as the price of fuel, interest rates and the rate of taxes. Hence, the sensitivity analysis helps to determine the economic feasibility and expected profits of the project or system.

2.4. COGENERATION CONFIGURATION

Although there are many types of cogeneration configuration, they can be divided into prime movers (topping cycle) and bottoming cycles. The prime mover is usually for power production, and bottoming can be any possible cycle for the production of heating, power or cooling (see Fig. 3). Some examples of bottoming cycles with various products and potential sectors are provided in Table 2.

The performance of cogeneration plants are dominated by the prime movers. Different prime mover technologies can be categorized as renewable or conventional, depending on their energy resource or differences in the thermodynamics of the cycle. Solar, biomass and hydrogen are the most used renewable energies for cogeneration, since they provide a of hot stream. An example of a solar power, water cogeneration plant is illustrated in Fig. 4.

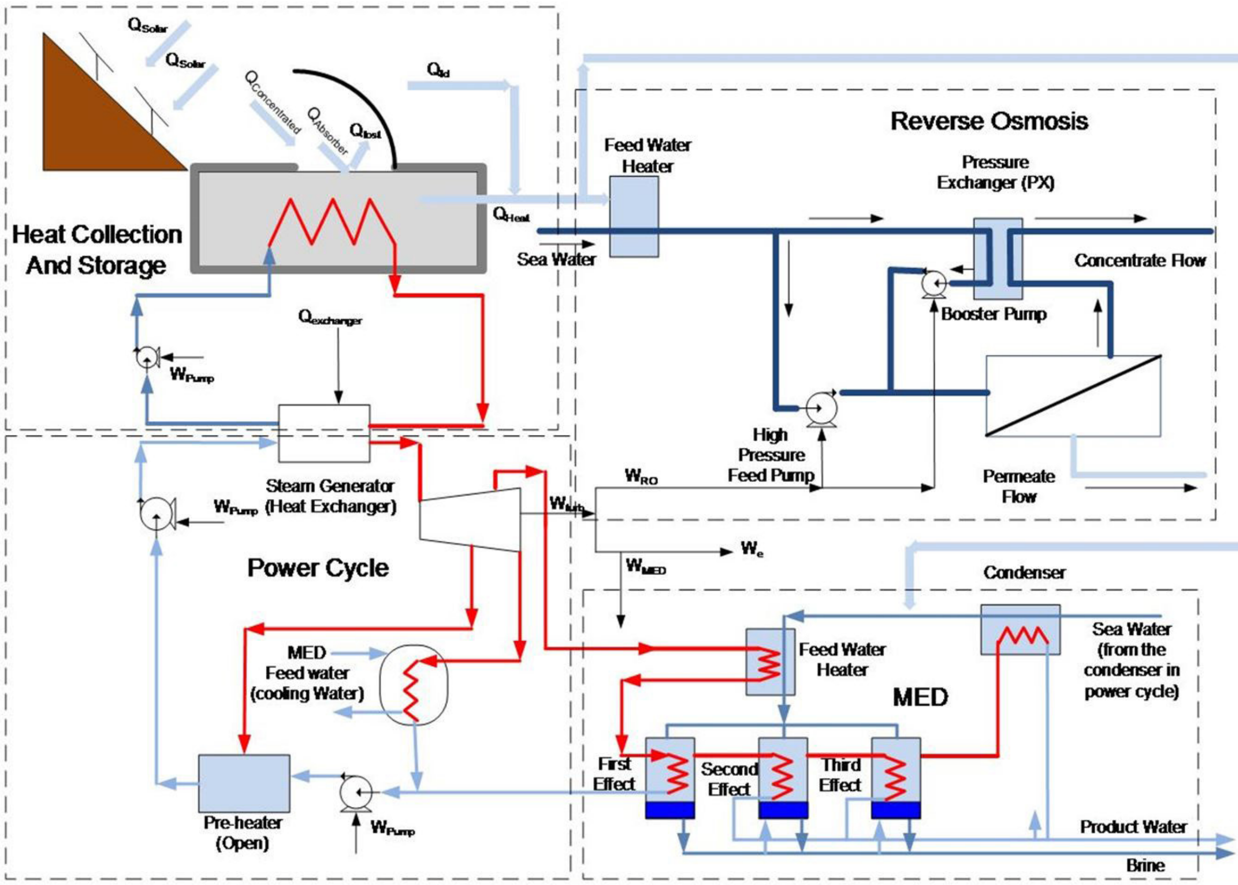


Note: Th. V — thermal vapour compressor.

FIG. 3. Water–ammonia system for cooling and power cogeneration.

TABLE 2. VARIOUS BOTTOMING CYCLE PRODUCTS AND SYSTEM EXAMPLES

Product	Example	System	Sector
Power	Combine cycle power plant	Gas turbine Steam turbine	Power generation
Heat	Combine heat and power generation	Gas turbine Heat recovery steam generator	Industry Construction
Cooling	Combined power and cooling generation	Gas turbine Adsorption chiller	Residential applications
Distillation	Gas turbine distillation Multi-effect distillation	Gas turbine multi-effect low temperature distillation	Industry Construction
Hydrogen	Nuclear power plant Hydrogen production site	Nuclear power plant Thermal water splitting	Residential applications
Fresh water	Nuclear based cogeneration	Nuclear power plant Multi-effect distillation desalination	Industry Construction



Source: See Ref. [6].

FIG. 4. A solar based integrated cogeneration system for electricity and fresh water production.

2.4.1. Nuclear based cogeneration for fresh water production

Dincer and Zamfirescu [7] report that:

"Desalination units need energy to separate salt from saline waters. The energy can be either heat for seawater distillation or mechanical energy to drive the pumps for pressurization of seawater across membranes using reverse osmosis (RO). The major source of heat energy comes from fossil fuels, including coal, oil and gas. Most of the large-size plants based on thermal and membrane processes are located near thermal power stations, which utilize fossil fuels to supply both steam and electrical power for desalination. However, the use of fossil fuel to produce freshwater has several side effects. As the combustion of fossil fuels emits greenhouse gases to the environment, it will lead to global warming, one of the main concerns of this century.

…….

"Over the long term it is not practical to establish a future desalting economy solely on fossil fuels because they have limited availability, whereas freshwater must continue to be available to sustain humankind. Long-term reliance on desalting should only occur if the availability of the energy supply is comparable to the required availability of the product. This criterion can be satisfied by nuclear energy."

A review on the history of the nuclear desalination and its future prospects can be found in Refs [8, 9]. Reference [10] reports that:

"Co-generation/desalination with a nuclear reactor requires careful consideration of how the desalination process is coupled to the power source. Safety, economic and operational factors are involved. The main safety concern is the prevention of radioactivity from migrating from the nuclear reactor to the desalination process, even under accident conditions. Yet another consideration is the ingress of salinity into the turbine circuit. In most of the couplings, this is prevented by an additional isolation loop."

Figure 5 shows the schematic of a nuclear based cogeneration plant for fresh water production. Saturated steam comes from the nuclear power plant, and a thermal vapour compressor (TVC) is used to produce fresh water using a multi-effect distillation (MED) desalination plant. The saturated vapour is used in the first effect of the

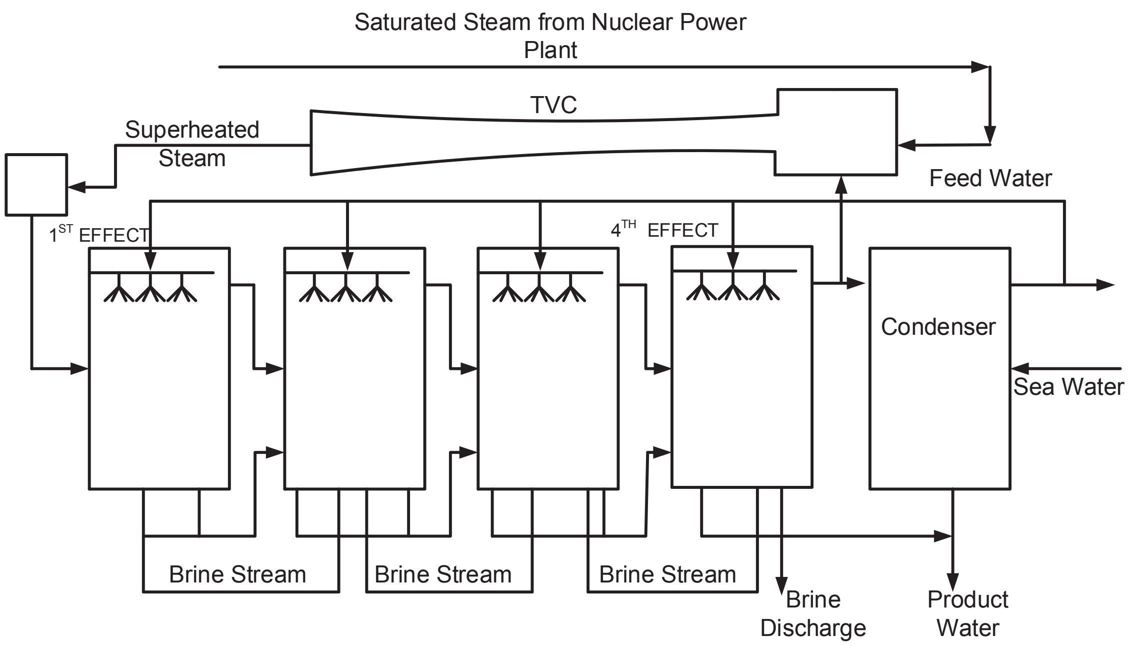


FIG. 5. Nuclear based cogeneration plant for power and fresh water production.

MED process as motive steam. The evaporation of the vapour, using four effects, produces the water to desalinate, with fresh water as the final product.

2.4.2. Nuclear based cogeneration for hydrogen production

Dincer and Zamfirescu [7] report that:

"Hydrogen is expected to play a significant role as energy carrier in the future. Hydrogen can be used as fuel in almost every application where fossil fuels are utilized today. In contrast to fossil fuel, its combustion is without harmful emissions, disregarding NO_x emissions that can be effectively controlled. In addition, hydrogen can be transformed into useful forms of energy more efficiently than fossil fuels. Hydrogen is as safe as other common fuels, despite its common perception. Hydrogen is not an energy source and hence it does not exist in its elemental form.

"Therefore, hydrogen must be produced from water, the most abundant source of hydrogen, or from other sources. However, splitting of water for hydrogen production necessitates energy that is higher than the energy that can be obtained from the produced hydrogen. Therefore, hydrogen is considered an energy carrier for a suitable form of energy like electricity. It is commonly accepted that hydrogen is one of the promising energy carriers and that the demand for it will increase greatly in the near future, for it can be utilized as a clean fuel in diverse energy end use sectors, including the conversion to electricity with no CO_2 emission."

Figure 6 illustrates nuclear based cogeneration for hydrogen production. The thermal efficiency of this production process is considered as the ratio of the lower heating value of the produced hydrogen to the energy input into the system from all sources. The production process could vary from electrolysis to steam reforming (see (a) in Fig. 6). Cogeneration for hydrogen production using electrolysis is considered a candidate for integration with nuclear energy because it may be combined with either existing nuclear electrical generating plants or with new, highly efficient nuclear plants (see (b) in Fig. 6).

The Pickering Nuclear Generating Station (PNGS) has been in operation since 1971 and is located in Ontario, Canada. The plant is operated by Ontario Power Generation, a provincial electricity company. The net electrical output of the plant is approximately 500 MW and is a good representative of recent nuclear technologies. For detailed information on the PNGS system description and analyses, Dincer and Rosen [2, 11] highlight the importance of transforming a nuclear power plant into cogeneration and multigenerational systems.

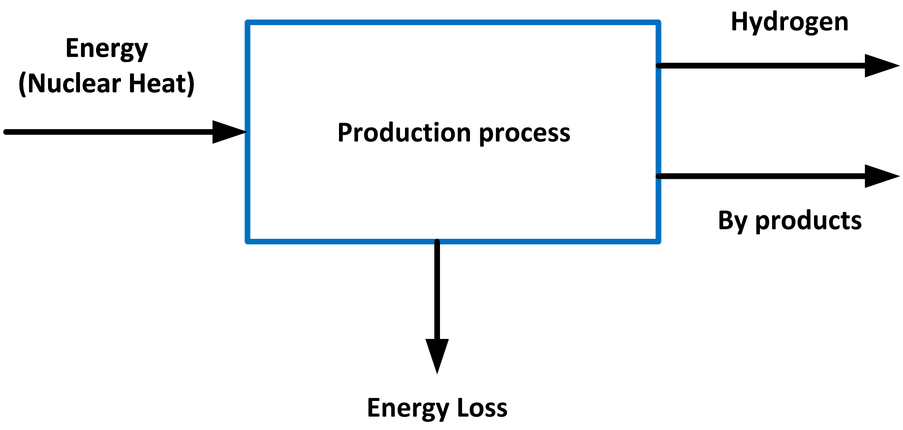
2.5. CONCLUSION

Cogeneration is sequential generation of two different forms of useful energy using a single primary energy source. Most cogeneration plants generate electricity and heating or cooling, although there are several systems for fresh water and hydrogen. The major advantages of cogeneration plants include the following:

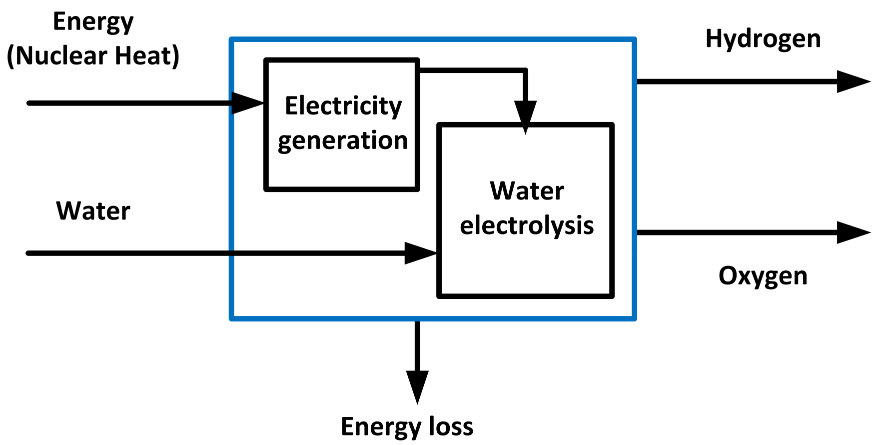
- Lower primary energy consumption;
- Reduced energy bills;
- No transmission and distribution losses;
- Reduced burden on governments for power generation;
- Less pollution.

One of the most important factors of cogeneration systems is their environmental benefits. The most major benefits include the following:

- Increased energy efficiency, leading to fewer emissions;
- Less contribution to acid rain phenomena;
- Significant reduction in GHG emissions;
- Reduction in unwanted solid wastes.



(a) Nuclear based cogeneration for hydrogen production: General concept



(b) Nuclear based cogeneration for hydrogen production: Using electrolysis

FIG. 6. Nuclear based cogeneration for hydrogen production.

3. COGENERATION WITH NUCLEAR POWER PLANTS

3.1. INTRODUCTION

Among power generation options, nuclear power plants have higher thermal efficiency and lower environmental impacts. The main benefits of nuclear energy include the following:

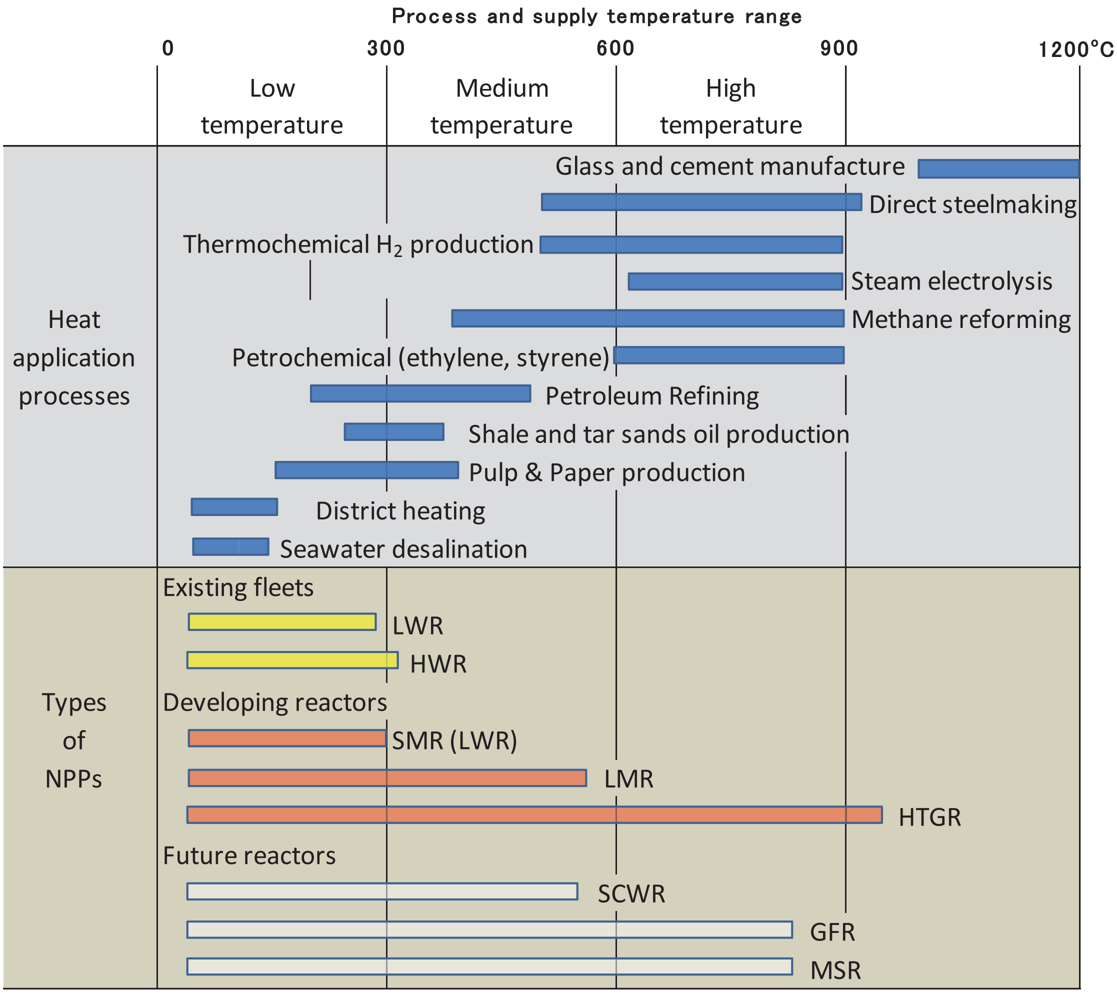
(a) They have very low life cycle GHG emissions.
(b) A small amount of matter can create a large amount of energy.
(c) A single power plant generates much energy.
(d) Nuclear power plants require little space compared to thermal and gas turbine power plants for the same power output.
(e) An abundance of nuclear fuel means plants can continue for hundreds of years.
(f) The output thermal efficiency of nuclear power plants is higher compared to steam and gas turbine power plants, and the cost of electricity per kW·h produced by nuclear power plants is less expensive.

Although nuclear based cogeneration systems have several advantages, some challenges include the following:

— Nuclear plants are more expensive to build and maintain than thermal power plants.
— The waste products are harmful and need to be carefully and safely stored for long periods of time.
— Since the fuel is radioactive, the reactor design is very costly and needs several levels of protection.

Figure 7 includes various heat application processes of interest for cogeneration with nuclear power. Applications such as water electrolysis for hydrogen production and RO for desalination are not included in this section because they do not necessarily require a nuclear power plant.

The temperature requirement for heat source varies widely according to the process. In the low temperature range are district heating of water or steam (80–150°C) and desalination of sea water (65–120°C) by thermal processes, such as multistage flash (MSF) and MED.



Note: GFR — gas cooled fast reactor; HTGR — high temperature gas reactor; HWR — heavy water reactor; LMR — liquid metal reactor; LWR — light water reactor; MSR — molten salt reactor; NPP — nuclear power plant; SCWR — supercritical water reactor; SMR — small modular reactor.

FIG. 7. Temperature ranges of heat application processes and types of nuclear power plant.

A large number of heat applications exist in the medium temperature range, although only a few major processes are identified in Fig. 7. Presently, the most significant application for nuclear cogeneration is the intensive supply of steam for bitumen extraction from oil sands in Alberta, Canada, where oil reserves are the world's second largest after Saudi Arabia. To extract bitumen from deep sand deposits, significant flows of high pressure steam (400°C) is required, using by in situ methods such as steam assisted gravity drainage. Further energy is required to upgrade bitumen to synthetic crude oil as ready feedstock for refineries. Currently, the industry uses natural gas as the prime energy source to produce crude oil from sand oil. A description of other steam heated processes applicable to nuclear cogeneration is given in Section 4.

The high temperature heat is typically demanded in petrochemical, steel and hydrogen production. The hydrogen produced has current and future applications in the following:

— Ammonia synthesis;
— Methanol synthesis;
— Heavy crude oil upgrade by hydrocracking;
— Fischer–Tropsch hydrocarbon synthesis;
— Methanation in long distance energy transport;
— Hydrogasification;
— Fuel for power generators and fuel cell vehicles.

Nuclear power plants support cogeneration in the processes identified above by meeting part or all of the consumption for heat and additional power. In comparison to single purpose generation, cogeneration with nuclear power could yield major benefits such as: reduced or zero fossil fuel energy uses; reduced or zero CO_2 emission; greater overall thermal efficiency through the utilization of low grade or waste heat from the nuclear power plants; and lower combined generation costs and environmental impacts.

3.2. TYPES OF NUCLEAR POWER PLANT SUITABLE FOR COGENERATION

Technically, any reactor type can be used for some form of cogeneration. Eight types are identified in Fig. 7, some of which have already been successfully deployed in cogeneration, while others offer strong potential to enter future cogeneration markets. The design parameters for these plants are given in Table 3.

In this section, the nuclear power plants are grouped into existing, developing and future reactors. Existing reactors are those which have been built (or have a licence to be built) for commercial purposes. Developing reactors are both evolutionary systems and those which are currently undergoing significant development, including engineering test reactors or demonstration reactors, with the prospect of commercial deployment in 10–20 years. Future reactors are the major technologies expected to be commercialized in the longer term.

3.2.1. Existing reactors for cogeneration

Existing reactors are based on LWRs and HWRs. As of June 2012, 433 commercial nuclear reactors were operational around the world, with a combined capacity of 371 GW(e). In total, 63 units (62 GW(e) in total) were under construction, of which 44 units were in Brazil, China, Indian and the Russian Federation. After a hiatus of more than thirty years, the United States Nuclear Regulatory Commission (NRC) resumed licensing new builds to utilities. Four reactor units were approved in the first quarter of 2012 and applications for over 20 other units were pending. The factors that contribute to the growing number of nuclear installations include the following:

— Increasing global demand for energy owing to population and economic expansion;
— Pressing issues with accelerated fossil fuel (e.g. resource depletion, climate change and price volatility);
— Desired diversification of supply for energy security.

Nuclear power has begun to enter new markets, particularly in the Middle East, where cogeneration with fossil fuel fired power plants is now widespread. The United Arab Emirates has placed an order for four reactors (5.6 GW(e) in total) with a vendor consortium from the Republic of Korea, with operation in 2017–2020. Saudi Arabia is planning to build as many as 16 reactor units by 2030.

TABLE 3. TECHNICAL PARAMETERS OF NUCLEAR POWER PLANTS SUITABLE FOR COGENERATION

Type	Neutron spectrum	Fuel cycles being used or studied	Coolant	Reactor outlet coolant temp. (°C)	Typical output (MW)
		Existing reactors			
Light water reactor	Thermal	UO_2 MOX	H_2O	280–325	600–1500
Heavy water reactor	Thermal	Natural UO_2 Low enriched	D_2O	310–319	700–1100
		Developing reactors			
Small modular reactor	Thermal	UO_2 MOX	H_2O	280–325	<300
Liquid metal fast reactor	Fast	MOX U–Pu nitrides MOX w/TRU	Na Pb Pb–Bi	SFR: 550 Pb or Pb–Bi: 500–800	20–1100
High temperature gas reactor	Thermal	UO_2 Th/U PuO_2 MOX U–TRU	He	750–950	50–300
		Future reactors			
Supercritical water reactor	Thermal Fast	UO_2 Th/U MOX	H_2O	430–625	700–1150
Gas cooled fast reactor	Fast	MOX U–TRU	He	850	280–1100
Molten salt reactor	Thermal	UO_2 Th/U	Li_2BeF_4 $NaF–ZrF_4$	750–1000	400–1200

Note: MOX — mixed oxide; SFR — sodium cooled fast reactor; TRU — transuranic.

Tables 4–6 list nuclear cogeneration plants constructed worldwide. Due to the limited temperature range of the existing types of reactor used, the majority of them are district heating and desalination systems, whose process operation temperatures are under 150°C, and the others are for the low temperature industrial and agriculture heat applications. The global nuclear desalination accumulated experience is 250 reactor years, whereas that of nuclear district heating is over 500 reactor years [10].

TABLE 4. NUCLEAR COGENERATION PLANTS: DESALINATION PURPOSES

Country and plant	Location	Start of operation: reactors (desal.)	Reactor type	Power (MW(e))	Water capacity (m^3/d)	Remarks
Japan						
Ohi-1,2	Fukui	1979 (1974–76)	PWR	2 × 1175	3900	MSF (1 × 1300 m^3/d) MED (2 × 1300 m^3/d)
Ohi-3,4	Fukui	1991–93 (1989)	PWR	2 × 1180	2600	RO (2 × 1300 m^3/d)
Ikata-1,2	Ehime	1977–82 (1976)	PWR	2 × 566	2000	MSF (2 × 1000 m^3/d)
Ikata-3,4	Ehime	1994 (1993)	PWR	890	2000	RO (2 × 1000 m^3/d)
Genkai-3,4	Fukuoka	1995–97 (1992)	PWR	2 × 1180	2000	MED (1 × 1000 m^3/d) RO (1 ×1000 m^3/d)
Takahama-3,4	Fukui	1985 (2003)	PWR	2 × 870	2000	MED/VC (2 × 1000 m^3/d)
Kashiwazaki	Nigata	1985 (not used)	BWR	1100	1000	MSF
Kazakhstan						
BN-350	Aktau	1973 (1963)	LMFR	150	8×10^4	MED, MSF
USA						
Diablo Canyon-1,2	San Louis Obisp	1985–86 (1985)	PWR	2 × 1100	2200	2 stage RO
India						
Kalapakkam-1,2	Tamil Nadu	1984–86	HWR	235	6300	Hybrid MSF/RO
Pakistan						
Karachi	Karachi	1972 (2010)	HWR/ CANDU	125	1600	MED

Source: Table 5.II of Ref. [10].
Note: BWR — boiling water reactor; CANDU — Canada deuterium–uranium; HWR — heavy water reactor; LMFR — liquid metal fast reactor; MED — multi-effect distillation; MSF — multistage flash; PWR — pressurized water reactor; RO — reverse osmosis; VC — vapour compression.

3.2.1.1. Light water reactors

Most of the operating LWRs in the world are Generation II systems that were built before 2000. The reactors currently being constructed or commercially offered are Generation III advanced systems, which incorporate improvements to fuel, cost reduction features such as design standardization, and better safety features. LWRs offer a ready means of cogeneration through new construction or by retrofitting operating nuclear power plants. This technical and commercial viability has been demonstrated at numerous operating plants in various countries for over 30 years.

TABLE 5. NUCLEAR COGENERATION PLANTS: DISTRICT HEATING PURPOSES

Country and plant	Location	Start of operation: reactors (heat)	Reactor type	Power (MW(e))	Heat output (MW(th))	Temp. (°C) at interface (feed/return)
Bulgaria						
Kozloduy-5,6	Kozloduy	1987 (1991)	PWR/WWER	2 × 953	2 × 20	150/70
Hungary						
Paks-2,3,4	Paks	1983 (1987)	PWR/WWER	3 × 433	3 × 30	130/70
Russian Federation						
Bilibino-1-4	Bilibino	1974 (1981)	RBMK/EGP	4 × 12	4 × 19	150/70
Novovoronezh-3,4	Novovoronezh	1972 (1973)	PWR/WWER	2 × 385	2 × 33	130/70
Balakovo-1–4	Balakovo	1986–93	PWR/WWER	4 × 950	4 × 200	130/70
Kalinin-1,2	Udomlya	1985–87	PWR/WWER	2 × 950	2 × 80	130/70
Kola-1–4	Apatit	1973–84	PWR/WWER	4 × 410	4 × 25	—[a]
Beloyarsk-3	Zarechny	1981	LMFR/BN-600	560	170	130/70
Leningrad-1–4	St. Petersburg	1974–81	RBMK	4 × 925	4 × 25	130/70
Kursk-1	Kursk	1977	RBMK	3 × 925	128	130/70
Kursk-2–4	Kursk	1979–86	RBMK	3 × 925	3 × 175	130/70
Smolensk-1,2	Desnogorsk	1983–90	RBMK	2 × 410	2 × 173	130/70
Slovakia						
Bohunice-3,4	Trnava	1985 (1987)	PWR/WWER	2 × 365	2 × 240	150/70
Switzerland						
Beznau-1,2	Dottingen	1969–71 (1983–84)	PWR	365 357	2 × 80	128/50
Ukraine						
Rovno-1,2	Rovno	1981–82 (1982)	PWR/WWER	950	2 × 58	130/70
Rovno-3	Rovno	1987 (1987)	PWR/WWER	2 × 950	233	130/70
South Ukraine-1,2	Yuzhnoukrainsk	1983–85 (1976)	PWR/WWER	950	2 × 151	150/70
South Ukraine-3	Yuzhnoukrainsk	1989 (1976)	PWR/WWER	950	232	150/70
Romania						
Cernavoda-1	Cernavoda	1996	HWR/ CANDU-6	660	47	150/70

Source: Table 5.IV of Ref. [10].

Note: CANDU — Canada deuterium–uranium; EGP — graphite steam power reactor; HWR — heavy water reactor; LMFR — liquid metal fast reactor; PWR — pressurized water reactor; RBMK — high power channel type reactor; WWER — water cooled water moderated reactor.

[a] —: data not available.

TABLE 6. NUCLEAR COGENERATION PLANTS: PROCESS HEAT PURPOSES

Country and plant	Location	Start of operation: reactors (heat)	Reactor type	Power (MW(e))	Heat output (MW(th))	Temp. (°C) at interface (feed/return)
Canada						
Bruce A	Bruce	1977–87 (1981)	HWR/ CANDU-6	4 × 848 4× 860	5350	—[a]
Germany						
Stade	Stade	1983	PWR	640	30	190/100
Switzerland						
Gösgen	Gösgen	1979	PWR	970	25	220/100
India						
RAPS	Kota	1975 (1980)	HWR	160	85	250

Source: Table 5.VI of Ref. [10].
Note: CANDU — Canada deuterium–uranium; HWR — heavy water reactor; PWR — pressurized water reactor.
[a] —: data not available.

Examples of Generation III systems include the following:

— AP1000 is an advanced pressurized water reactor (PWR) by Westinghouse.
— EPR is a European PWR by AREVA.
— ESBWR is an economic simplified boiling water reactor (BWR) by GE Hitachi.
— US-APWR is an advanced PWR by Mitsubishi Heavy Industries.
— APR-1400 is an advanced PWR by the Korea Electric Power Corporation.

Desalination has been cogenerated with LWR plants in Japan and the United States of America. In Japan, the heat and electricity of a nuclear plant is used to drive MED, MSF and RO desalination plants, with desalination capacities in the range of 1000–3000 m^3/d to cover the feedwater make-up and on-site potable water demands.

With regard to industrial heat cogeneration [12]:

“In Germany, the Stade NPP [nuclear power plant] PWR, 1892 MW(th), 640 MW(e) supplies steam for a salt refinery which is located at a distance 1.5 km since December 1983. The salt refinery requires 45 t/h process steam with 190°C at 1.05 MPa. This represents a thermal power of about 30 MW and is 1.6% of the thermal output of the NPP. The steam supply from Stade NPP is designed for 60 t/h, of which the remaining 15 t/h are used for space heating at the Schilling oil fired power station nearby, and for an adjacent tank storage facility. Since 1983, the steam supply by NPP Stade had very high time availability, and the operating experience with process steam extraction is very good.

“In Switzerland, the 970 MW(e) PWR of Gösgen provides process steam for a nearby cardboard factory since 1979. The process steam (1.37 MPa, 220°C) is generated in a tertiary steam cycle by live steam from the PWR. It is then piped over a distance of 1750 m to the cardboard factory. After condensation, it returns as 100°C hot water to the PWR. A maximum process steam extraction of 22.2 kg/s is possible which represents a thermal output of about 54 MW or about 2% of the total thermal power of the PWR.”

3.2.1.2. Heavy water reactors

Reference [12] also reports on the retrofitting of the Madras Atomic Power Station, in Kalpakkam, India, which was completed in 2008 to accommodate a desalination plant with a capacity of 6300 m^3/d. The hybrid desalination process combines MSF and RO. The MSF plant yields a performance ratio of 9 and produces 4500 m^3/d product water of 25 ppm total dissolved solids (TDS) from 35 000 ppm sea water. Around 1000 m^3/d will be used as demineralized water after passing it through a mixed bed polishing unit. The remaining 3500 m^3/d of water is mixed with 1800 m^3/d water produced from the RO plant (400 ppm TDS). The thermalelectric total energy requirement is about 1500 m^3/d per MW(e) for the MSF plant and 1800 m^3/d per MW(e) for the RO plant. This results in a total 4 MW(e) penalty to the nuclear power generation due to the retrofit.

In 2010, the world's latest nuclear cogenerating plant was commissioned by Pakistan. This is another project of retrofitting, this time to an MED unit to the Karachi nuclear power plant (KANUPP), a 125 MW(e) Canada deuterium–uranium (CANDU) HWR plant near Karachi. The completed desalination plant produces 1600 m^3/d. The same site had been running a 454 m^3/d RO plant for in-house water use.

The only, but significant, experience with HWR process heat cogeneration is the Bruce Nuclear Power Development (BNPD) park, in Canada, which has operated successfully for thirty years as the world's largest nuclear steam and electricity cogenerating station. Reference [12] reports that:

> "It includes eight CANDU nuclear reactors with a total output of over 7200 MW(e), the world's largest heavy water plant (HWP), and the Bruce Bulk Steam System (BBSS). The BBSS, capable of producing 5350 MW(th) of medium pressure process heating steam, was built to supply the HWPs from the four 848 MW(e) units of the Bruce A complex at BNPD. Each of the four 2400 MW(th) reactors can supply high pressure steam to a bank of 6 heat exchanger (24 in total) which produce medium pressure steam for the HWP and site services. The normal capacity is approximately 1680 kg/s of medium pressure steam from the reactors with 315 kg/s emergency backup available from oil fired boilers.
>
> "In order to meet HWP reliability criteria, the steam system is designed and operated to ensure a maximum steam supply interruption of just a few minutes in winter and 4 hours in summer. One of the 3 oil fired boilers is kept on hot standby and condensate pumps are supplied with uninterruptible power backed by gas turbine standby generators. During its entire 17 years of operation, the HWP has never suffered a loss of emergency steam.
>
> "Projected heavy water demand was less than originally forecast giving the BBSS significant long term steam spare capacity. Although the spare capacity is expected to be lower during the next few years because of extensive planned maintenance, the BBSS still provides access to nuclear heat energy sufficient to support substantial industrial development at the adjacent BEC. An industrial distribution supply system feeding the customers was constructed beyond the HWP in the form of a 5 km long, 0.91 m (36 inches) diameter steam line with a 0.46 m (18 inches) condensate return line. There are essentially three barriers between the steam the customer uses and the nuclear plants."

3.2.2. Developing reactors for cogeneration

With improved performance characteristics, mainly through inherent and passive nuclear reactor safety and higher outlet temperature, the next generations of nuclear power plants are expected to increase cogeneration application not only in the number of installations and but also in the temperature ranges to include medium and high temperature processes.

3.2.2.1. Small modular reactors

SMRs are limited to 300 MW(e) according to IAEA characterization. The developing LWRs within this range are not down sized existing reactors but modular systems being developed to reduce construction time and capital through shop fabrication and site assembly. Most SMRs have greatly enhanced safety, such as eliminating pipes or incorporating passive safety features through natural convection and radiation for decay heat removal during an emergency. Embracing passive and inherent safety approaches allow the kind of proximity usually demanded between heat source and heat application processes for economic reasons. These modular systems are suitable in remote sites without large grids in place. Where more capacity is required, several modules can be assembled in a single plant. The approach to economy of scale taken in current, large LWR is traded with one of modular construction. Examples of SMRs under current development include the following, reported by international experts in 2012:

— mPower is a PWR by Babcock & Wilcox [13].
— Westinghouse SMR is a PWR [14].
— NuScale is an integral PWR by NuScale Power [15].
— SMART — system integrated modular advanced reactor — is an integral PWR by the Korea Atomic Energy Research Institute (KAERI) [16].

The mPower is an integrated reactor system. The nuclear steam supply system for the reactor arrives at the site already assembled, and so requires very little site construction. Each reactor module produces around 125 MW(e) and can be linked together to form the equivalent of one large nuclear power plant. A letter of intent for design approval has been submitted by the vendor to the NRC.

The Westinghouse SMR is the 225 MW(e) version of the AP1000 PWR. It will be built underground in a silo 30 m deep and 30 m wide. All of the components are contained in a tall reactor pressure vessel housed in the silo. The SMR is installed on a site that is 30% of the area required by the larger counterpart AP1000. The construction process is expected to take about 18 months, compared to several years necessary for the AP1000. Westinghouse expects the first SMR to be generating electricity by 2020.

Reference [17] reports that NuScale envisions a containment fully immersed in a water filled, stainless steel lined concrete pool in the ground. The pool's size provides 30 days of core and containment cooling without water refill. After 30 days, the decay heat generation is sufficiently small so that natural convection heat transfer to air on the outside surface of the containment coupled to thermal radiation heat transfer is adequate to remove core decay heat. These passive safety systems can perform their function without external supply of water or power. Designed to be scalable, up to 12 factory fabricated, 45 MW(e) power modules can be built, delivered and installed to meet a power demand of up to 540 MW(e). NuScale hopes to have the plant in operation by 2020.

SMART is a 100 MW(e) cogeneration plant for thermal desalination and district heating. The design features eliminate loss of coolant events following a large pipe rupture. The design life is 60 years, with a three year refuelling cycle. The developer anticipates a demonstration plant to be in operation by 2017.

The above SMRs are all based on PWRs, and they share the design approach to integral reactor coolant system and passive means to cope with postulated design basis and beyond design basis accidents. Low enriched uranium oxide with zircaloy cladding and burnable poisons is used as fuel, and reactivity control by soluble boron is eliminated. The emphasis is on: enhanced safety, achieved via elimination of accident initiators and use of passive safety systems; and enhanced economics, pursued via system simplification, component modularization and factory construction. The ability for SMRs to support low temperature heat cogeneration applications is explored in Section 3.3.3.

3.2.2.2. Liquid metal fast reactors

Yan et al. [18] report that:

> "The objective of fast reactors is improved fuel sustainability through efficient irradiation efficiency of fertile uranium in the fast-neutron spectrum. To do so, highly enriched fissile uranium or plutonium is used as fuel and the reactor core must be sized more compact than that of a LWR. …
>
> "Sodium-cooled fast reactors (SFRs) have been designed in the range of medium size (150–1250 MWe)…. The reactor coolant outlet conditions are approximately 550°C and 0.5 MPa."

The Japan Atomic Energy Agency (JAEA) operates the experimental reactor JOYO (140 MW(th)) and the demonstration reactor MONJU (280 MW(e)) — both of which are sodium cooled. Super safe, small and simple (4S) is a nuclear battery system developed by Toshiba and the Central Research Institute of the Electric Power Industry. It is cooled by sodium and uses electromagnetic coolant pumps. It is designed to an outlet coolant temperature of 550°C. At this temperature, a number of cogeneration applications have been investigated, including steam supply and steam electrolysis through turbine steam extraction. Toshiba plans to sell 4S for different applications worldwide, including power generation at remote mines, desalination, steam for oil extraction, and hydrogen production.

In Kazakhstan, the Mangyshlak Atomic Energy Complex (MAEC) was operated on the eastern side of the Caspian Sea in 1973–99, supplying electricity, potable water and heat to the population and industries in Aktau. The complex consists of a LMFR nuclear power plant, a gas/oil fired thermal power plant, and a seawater desalination plant. The nuclear desalination capacity is around 80 000 m^3/d (see Sections 3.3.4 and 8.1 for more details).

3.2.2.3. High temperature gas reactors

Yan et al. [18] report that the HTGR, also known as VHTR (very high temperature reactor), is helium cooled and graphite moderated and uses a thermal neutron spectrum. The outlet coolant temperature is 950°C. It is recognized as the nearest term deployable advanced reactor.

> "Large reactors up to 2400 MWt have been designed and the largest operated is the 842 MWt FSV (Fort St. Vrain) in the United States. These larger systems were the design choices before the emphasis was shifted to fully passively-safe modular reactors of today's designs of under 600 MWt per reactor. In the case of the modular designs, multiple reactor modules can be added for incremental capacity increase or built jointly on the site….
>
> "In a 50-day test in 2010, JAEA operated the HTTR [High Temperature Engineering Test Reactor] (a 30 MWt HTGR test reactor) at high temperatures (>930°C) and full power. It plans to connect a thermochemical process to the HTTR to demonstrate nuclear hydrogen production around 2020."

In 2011, the United States Department of Energy and US industries completed a cost shared conceptual design effort for the next generation nuclear plant (NGNP) of 600 MW(th). Although the development programme has suffered delays, the design phase was originally scheduled for 2011 and startup in 2021. The plan included the dedication of 50 MW(th) heat to produce hydrogen using water splitting through high temperature steam electrolysis and a thermochemical sulphur–iodine process (see Fig. 8).

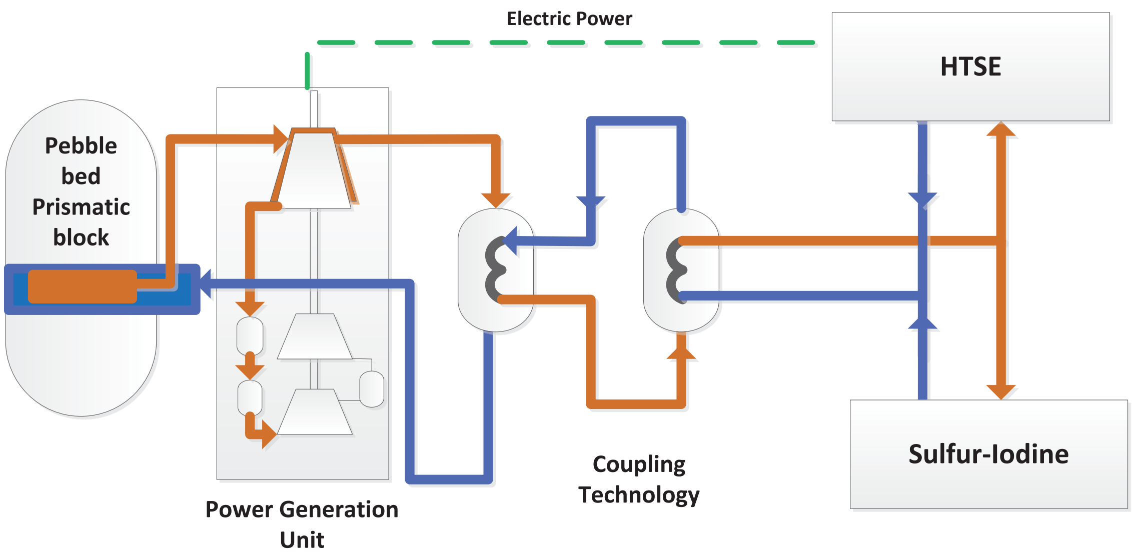
3.2.3. Future reactors for cogeneration

The future reactors discussed here include three Generation IV systems, which have yet to advance to such validation stages as engineering or demonstration reactors.

3.2.3.1. Supercritical water reactors

SCWRs use a supercritical light water coolant. Yan et al. [18] report that:

> "The low density of supercritical water requires additional moderator for a successful thermal-neutron spectrum. The SCWR connects to a direct cycle steam turbine much like the BWR but runs the high pressure single-phase coolant similar to the PWR. Although new in nuclear reactor, supercritical water already enters the fossil-fired power plants. The SCWR minimizes equipment count and commands greater operating temperature and pressure (up to 625°C and about 25 MPa, well above the thermodynamic critical point of 374°C and 22.1 MPa for water) than the Generation III+ LWRs. These features are expected to lower construction cost and raise thermal efficiency to estimated 45%, in comparison to about 33% for other LWRs. In addition to thermal-neutron spectrum, the SCWR due to the low density of the supercritical coolant may accept a fast-neutron spectrum core, which would demand further material research and development. The reactor systems such as Super-LWR or CAND-SCRW are being developed in Japan and Canada, respectively."



Note: HTSE — high temperature steam electrolysis.

FIG. 8. Next generation nuclear plant for hydrogen cogeneration.

In addition, the higher outlet coolant temperature allows more heat cogeneration applications, such as the medium temperature thermochemical hydrogen production processes (e.g. Cu–Cl cycles) currently under development in Canada and the United States of America [19].

3.2.3.2. Gas cooled fast reactors

Yan et al. [18] report that:

"The designs have been proposed for modular and larger systems rated between 600 and 2400 MWt. They use helium as coolant, which is neutron transparent as is preferable with fast-neutron spectrum, with reactor outlet temperature of 850°C. Helium is inert and benign with structural materials. Several fuel forms are being considered for their potential to operate at the high temperatures and to ensure excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds. Core configurations are being considered based on pin- or plate-based fuel assemblies or prismatic blocks. A commercial feasibility study by JAEA identified the coated particle fuel with mixed nitride kernel and TiN coating to be optimum".

At an outlet temperature as high as 850°C, GFRs can drive a direct, Brayton cycle, helium gas turbine for high efficiency power production, similar to HTGRs, and provide a wide range of possible routes for heat cogeneration. The limited development activities for GFRs have taken place in France and Japan.

3.2.3.3. Molten salt reactors

Yan et al. [18] report that two variants of MSR are characterized by fuel forms. The earlier proposed variant features a fuel coolant molten mixture of sodium, zirconium, and uranium or thorium fluorides.

"The homogenous liquid fuel allows various mixing of fuel and actinides for waste destruction. The flexibility with liquid fuel eliminates the need for fuel fabrication. The molten-salt fuel flows through graphite core channels, producing an epithermal to thermal spectrum.

"The more recent design, called AHTR (advanced high-temperature reactor) uses coated fuel particles with low-enriched uranium kernel, and a molten salt serves as coolant only. The fuel particles are dispersed in graphite matrix. The core is of thermal spectrum....

“The AHTR’s molten-salt coolant is a mixture of fluoride salts with melting point near 400°C and atmospheric boiling point around 1400°C. Various salts have been evaluated such as $^{7}Li_2BeF_4$ and NaF–ZrF_4. The reactor operates at low pressure (<0.5 MPa) with the core outlet coolant temperatures in a range of 700–1000°C. The reactor rating falls in the range of 900–2400 MWt. Heat is transferred from the primary coolant through a compact secondary molten-salt coolant to a third energy conversion loop for generation of electricity or directly hydrogen.”

3.3. TECHNOLOGY DESCRIPTION AND SYSTEM DESIGNS

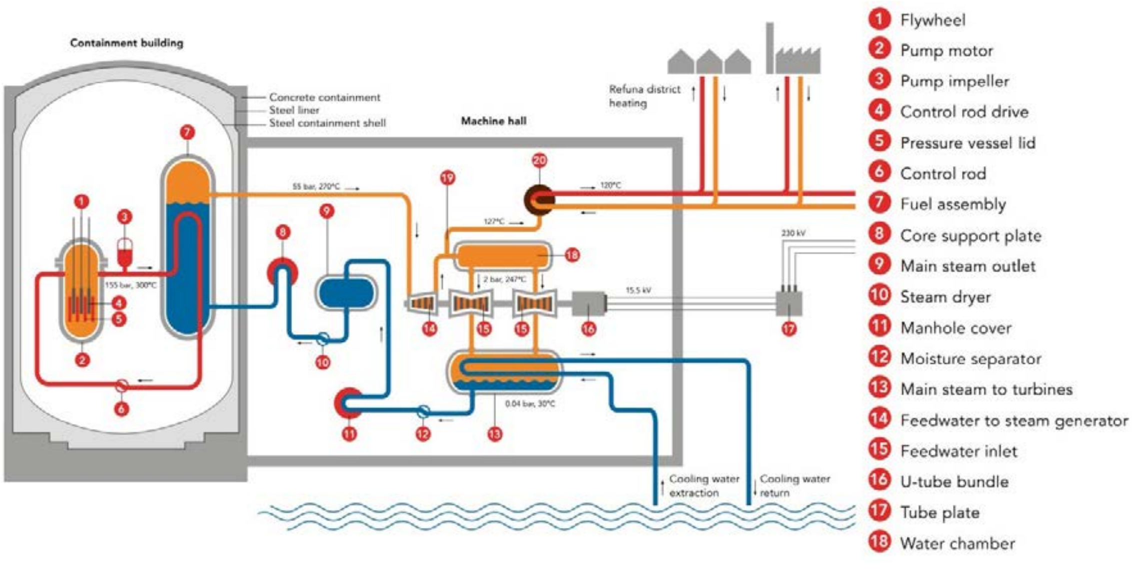
3.3.1. Light water reactors for district heating

Although a small number of dedicated nuclear district heating systems (not included in Tables 4–6) are operated in China and the Russian Federation, the majority of nuclear reactors deployed for district heating are cogeneration plants, which have been built in Bulgaria, the Czech Republic, Hungary, Romania, the Russian Federation, Slovakia and Switzerland. These plants have been operated safely and reliably for some 500 reactor years in total.

The construction of the twin plants (365 MW(e) PWR designs by Westinghouse) of the Beznau nuclear power plant, in Switzerland, commenced in 1965 and 1968, and commercial services started in 1969 and 1972. They began to supply nuclear district heating in 1983 and 1984, and have since operated reliably and successfully. The plants are cooled by the Aar River and the district heating system REFUNA, which provides 11 surrounding municipalities, which include 20 000 private, industrial and agricultural consumers. The peak district heat load is around 80 MW(th) from each reactor, reducing to 10 MW(e) power output per reactor when performing district heating.

The reactor produces and supplies steam to the power generation turbine in the secondary loop (see Fig. 9). Some steam (92°C) is extracted from the lower pressure turbine and directed to a heat exchanger to heat the circulating water returning from the district heating network. The water temperature is raised from 50°C to 85°C. The water is reheated to 125°C at 1.6 MPa in a second heat exchanger using the 130°C steam extracted from the back of the high pressure turbine. The water is supplied at 125°C in winter, while it is lowered to 85°C in summer by using only the low temperature heat exchanger.

The pressurized hot water is circulated in the third loop, and the pump station distributes the hot water to the consumers, which requires 35 km of main piping and an 85 km local distribution network. The heat loss is 1°C per 5 km in the main piping and 15% in the local network. Although this is relatively higher than individually customized oil heating, it is considered environmentally friendly by the municipalities.



Source: See Ref. [20].

FIG. 9. PWR for district heating cogeneration at the Beznau nuclear power plant, Switzerland.

The customers are covered by in-depth defense measures against a risk of radioactive contamination. Firstly, from the perspective of the customer, it is located in the fifth loop and provided with four layers of metal barriers in relation to the nuclear plant's primary system. Secondly, the fourth loop, which combines a smaller number of customers, is installed to separate the customer from the main heat transport (MHT) loop. Thirdly, the isolation valves are provided on the main transport loop to prevent, if necessary, any material exchanger between the reactor and the local distribution network. Finally, the water pressure of the main transport loop is kept at 0.28 MPa higher than the secondary steam so that no secondary steam can enter the MHT loop in case of accidental leak in the water heating heat exchanger tubes. Owing to these defense measures put in place, the safety of district heat cogeneration system was confirmed even in cases of simultaneous leaks in the reactor steam generator and the water heating heat exchangers.

Low grade nuclear heat can be cost attractive to consumers compared to alternative fuels. However, the final district heat cost can be affected by factors such as the distance of heat transport from the plant to the customers (as is the case with the Beznau plant). To be reliable, nuclear district heating systems could require a backup heat source when the main heat source becomes unavailable. This can be done by combining at least two nuclear power units or a nuclear and a fossil fuel fired unit to service the common district heating grids.

The design measures generally taken to prevent the transfer of radioactivity into the district heating network include one or more barriers to radioactive substances (e.g. in the form of a leaktight intermediate heat transfer loop at a pressure higher than that of the steam extracted from the turbine cycle of the nuclear plant). These loops are continuously monitored, and devices are provided to isolate potentially contaminated areas. These measures in the Beznau plants have proved to be effective. Similarly in the Paks nuclear power plant, in Hungary, which consists of four units of the water cooled water moderated reactor (WWER type) and supplies district heat to the hosting town, the secondary circuit steam leaving the steam generators is monitored by gamma detectors. The water pressure in the heat exchanger is kept higher than the steam pressure to prevent contamination of the hot water system circulated in the third loop. Similar technical requirements and constraints for cogeneration with LWR were considered in a recent project to develop a new PWR combined power and district heat plant, Loviisa 3.[2]

3.3.2. Light water reactors for desalination

All of some fifty commercial nuclear power plants in Japan are located on the coast to rely on sea water as the ultimate reactor heat sink [21]. At ten sites that have a limited access to fresh water, the power plants are equipped with seawater desalination cogeneration plants in order to provide high quality make-up to the boiler feedwater and for in situ potable water uses after appropriate treatment (including addition of minerals) [10]. These desalination plants have been in operation for more than 30 years with some 150 reactor years of continuous operating experience, and the combined capacity is approximately 14 000 m^3/d.

As indicated in Tables 4–6, individual plant capacities vary in the range of 1000–2600 m^3/d [10]. The technologies used are diversely (MSF, MED and RO). Although the MSF process was selected for earlier plants, MED or RO processes were chosen for the later plants because of their higher efficiency [10].

At the Ohi MSF plant, the heating steam is extracted from the nuclear plant steam turbine. The heating steam generates a second steam line in the steam converter (see Fig. 10), and the condensate of the heating steam is returned to the turbine cycle feedwater heater. The second steam line connects to the brine heater as the direct heat source for the desalination process.

The seawater temperature is in the range of 6–31°C. The salinity at the seawater intake is 35 g/L, while that of the product water is reduced to 10 mg/L. The product salinity is half of this level in other thermal desalination processes (e.g. at the MSF units of Itaka-1,2).

In general, the nuclear desalination cogeneration plants in Japan have successful operated for nearly forty years. None has encountered radioactive contamination of the product water. With regard to maintenance of the desalination plant, some piping was exchanged owing to corrosion by the high temperature brine. Although the capacities of the desalination plants are generally small, the operating data obtained are considered to be fully applicable to supporting the design and operation of larger scale nuclear desalination plants. The desalination plants have proven to be an effective means of supplying high quality make-up and potable water for the nuclear power plants.

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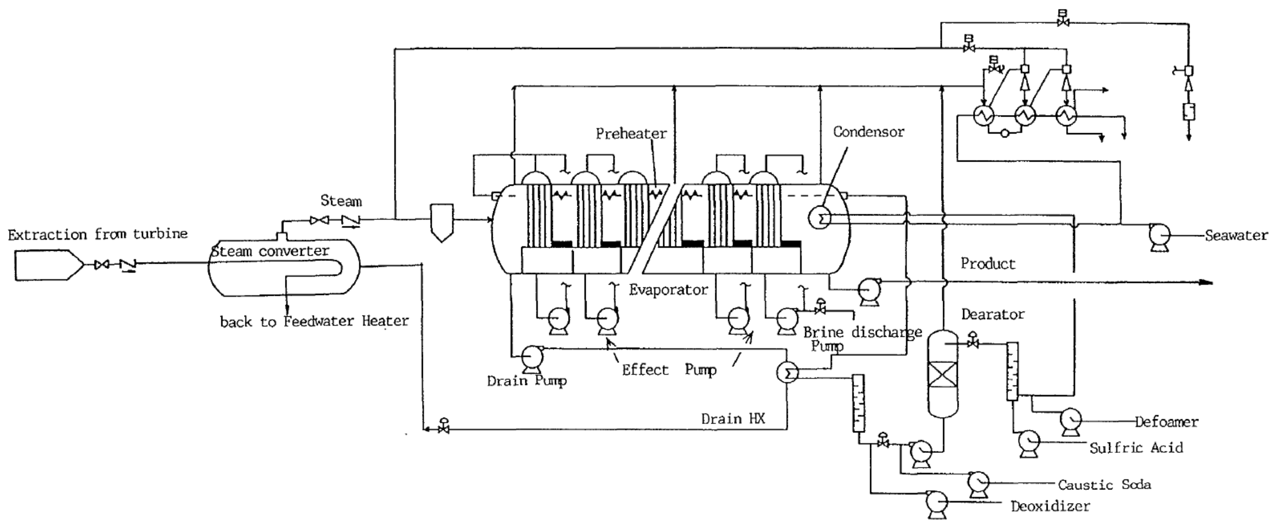
[2] For further information, see www.decentralized-energy.com/articles/print/volume-11/issue-3/features/carbon-free-nuclear.html



Source: Figure 8 of Ref. [12].

FIG. 10. Schematic of coupling from nuclear plant steam extraction to MSF desalination at the Ohi plant, Japan.

3.3.3. Small modular reactors for desalination and district heating

SMART is a 330 MW(th) integral PWR being developed as a multipurpose energy source (for electricity generation, seawater desalination or district heating) by KAERI together with domestic user and vendor industries [22, 23]. Unlike traditional, larger PWRs, SMART installs all major primary components, such as the core, steam generators, pressurizers, control element drive mechanisms and main coolant pumps, in a single steel pressure vessel. The integral arrangement of these innovative and advanced features enhance the safety, reliability, performance and operability of SMART, and have been well proven in the operation of existing commercial power reactors and in a technology validation programme conducted in 2012 (see Table 7 for the design parameters).

Although a small reactor lacks the economy of scale of a large reactor, alternative mechanisms to enhance economics include the elimination of large pipes and valves due to system simplification, reactor system modularization, component standardization, factory fabrication and easy site installation — all of which are expected to contribute to the reduction of construction cost.

SMART can cogenerate 90 MW(e) and 40 000 m^3/d of water. The desalination system consists of four MED units combined with a TVC. The MED-TVC unit operates at a maximum brine temperature of 65°C and a supplied seawater temperature of 33°C. The MED-TVC process coupled to SMART incorporates a falling film, a MED evaporation with horizontal tubes and a steam jet ejector. One significant advantage is its ability to use the energy pressure in steam. Thermal vapour compression is very effective when the steam is available at higher temperature and pressure conditions than required in the evaporator. The TVC compresses the low pressure waste steam, effectively reclaiming its available energy, and is achieved by using the ejector and with no moving parts.

The IAEA Desalination Economic Evaluation Program (DEEP) was used to assist in economic optimization of MED-TVC processes (for further information on DEEP, see Section 6.2.1). For 40 000 m^3/d, DEEP identifies that the lowest water production cost of US \$0.83/m^3 is at a maximum brine temperature (MBT) of 65°C, which yields a gained output ratio of 13. The electricity generation remains nearly constant at 90 MW(e) irrespective of the MBT range and approximately 10% of the thermal energy produced is consumed for the rated water production.

TABLE 7. SMART DESIGN PARAMETERS

Item	Specification
Reactor type	Integral PWR
Thermal power	330 MW(th)
Design lifetime	60 years
Electric power	100 MW(e) (80–90 MW(e) at cogeneration)
Cogeneration	Seawater desalination 40 000 m^3/d or district heat (628 GJ/h)
Fuel and reactor core	
Fuel type	UO_2 square fuel assembly
Enrichment	4.95wt%
Active fuel length	2.0 m
No. of fuel assemblies	57
Core power density	62.6 W/cc
Refuel interval	3 years
Reactivity control	
No. of control element banks	49
No. of control banks/material	49/Ag–In–Cd
Burnable poison material	Al_2O_3–B_4C, Gd_2O_3–UO_2
Reactor pressure vessel	
Overall length	9.8 m
Outer diameter	3.96 m
Average vessel thickness	19.8 mm
Vessel material	SA508 CL-3
Reactor coolant system	
Design pressure	17 MPa
Operating pressure	15 MPa
Core inlet temp.	270°C
Core outlet temp.	310°C
Steam generator	
Type	Once through with helically coiled tubes
No.	12
Design temp.	350°C
Design pressure	17 MPa

TABLE 7. SMART DESIGN PARAMETERS (cont.)

Item	Specification
Main coolant pump	
Type	Canned motor pump
No.	4
Flow rate	2006 m^3/h
Water head	17.5 m
Control element drive mechanism	
Type	Linear pulse motor driven
No.	49
Step length per pulse	4 mm
Make-up system	
No. of trains	2
Operating mode	Active
Secondary system	
Feedwater pressure	5.2 MPa
Feedwater temp.	180°C
Steam pressure	3.0MPa
Steam temp.	274°C
Degree of superheating	40°C

Source: See Ref. [10].

Alternatively, SMART may cogenerate electricity and district heating according to given variable ratios. Around 80 MW(e) and 630 GJ/h of heat can be delivered to the grids. The amount of delivered electricity and heat (~85°C hot water) is quite sufficient to meet the demands of a population of more than a 70 000 (~25 000 households), assuming a demand of 10 MW(e) and 100 GJ/h per 10 000 people.

3.3.4. Liquid metal fast reactors for desalination

The MAEC (1973–1999) is the largest commercial nuclear desalination plant ever to operate [10, 23]. Its history began in 1961 with the development of seawater desalination technology in the former Union of Soviet Socialist Republics and the construction of the first distillation test facility of up to 120 m^3/d on the eastern side of the Caspian Sea. Based on the experience gained, an MED unit with an output of 5000 m^3/d of product water was built in 1963. Cogenerating with a fossil fuel fired backpressure turbine, the unit provided water for Aktau, Kazakhstan, and its developing industries on the seashore.

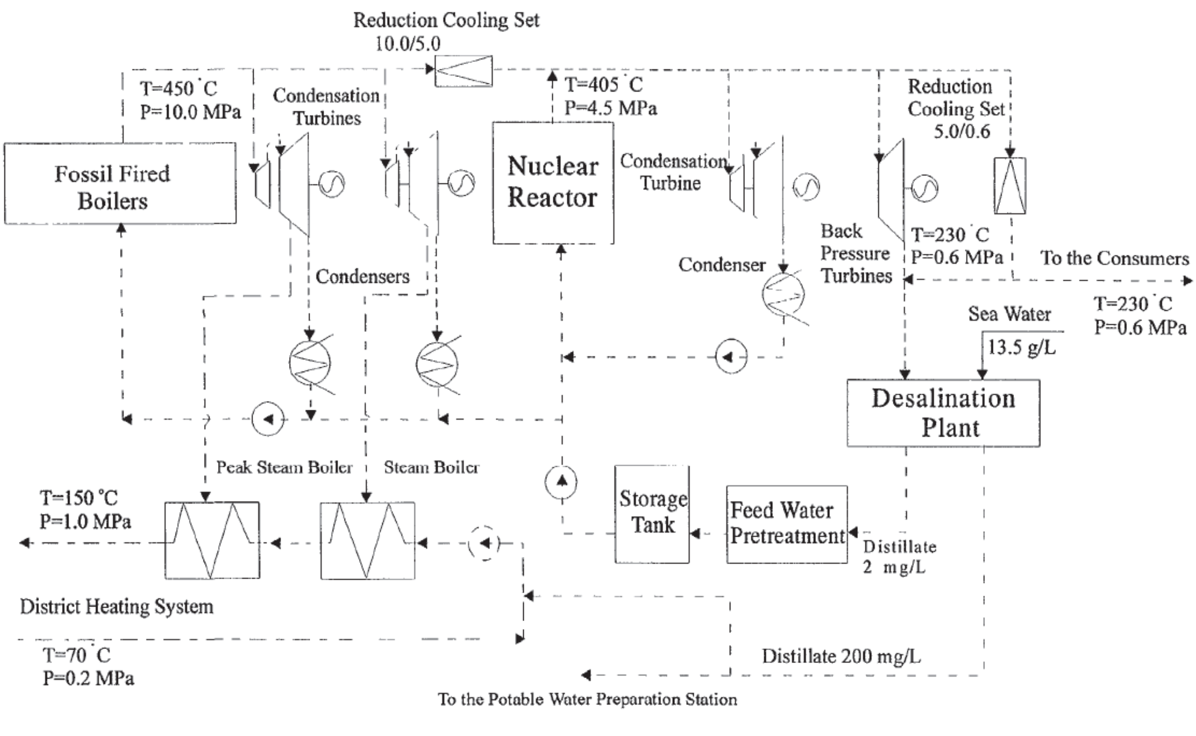
The MAEC comprised a 750 MW(th) sodium cooled LMFR BN-350, a gas/oil fired thermal power plant, three MED plants of five effects (each with a capacity of 12 000 m^3/d, coupled to three backpressure turbines of 50 MW(e) each) and a potable water preparation facility. The nuclear reactor was started up in 1973. By 1990, seven more MED plants of ten effects had been erected, with a capacity of 8000–14 500 m^3/d, which resulted in a total design capacity of 145 000 m^3/d. Although designed for 1000 MW(th), the BN-350 operated under 750 MW(th). It supplied up to 125 MW(e) to the electric grid and produced 80 000 m^3/d of potable water for municipal use.

Over 26 years, the MAEC accumulated more than 160 000 hours of power operation. The nuclear reactor was regularly shut down for 20 days, twice a year, for refuelling and scheduled maintenance, and was performed more than 55 times. The plant also encountered around 60 unplanned power reductions. In total, the average load factor achieved was 85%. The MAEC demonstrates the feasibility and reliability of a large LMFR cogeneration plant.

Steam rejected by the fossil fuel power plant and the nuclear power plant's steam generators is supplied in parallel to a condensation turbine and to the backpressure turbines (see Fig. 11). In these turbines, the temperature and pressure values of the stream are then reduced.

Muralev [24] reports on the MAEC and its reactor. The BN-350 is a loop type fast breeder reactor consisting of six primary sodium loops, which each have a pump and individually exchange heat with six secondary sodium loops via six sodium to sodium heat exchangers. Sodium leak was not encountered in either the primary or secondary loop, and cavitation damage in the pumps was insignificant. The steam generators were reconstructed after an initial few years of operation to eliminate failures of the steam generator tubes. The inlet/outlet temperatures of the primary sodium side in the heat exchanger are 437/288°C and those of the secondary size 260/420°C. The secondary loop generates a total steam flow of 1070 t/h at 405°C and 4.5 MPa in six steam generators with natural circulation.

The seawater intake channel is 2 km long and is used to remove silt from the sea water. The brine discharge channel feeds into an artificial shallow lake connected to the sea. The lake provides aeration of the brine and suspended particle cleanup. The desalination plant consists of three vertical tube MED units with five effects and seven units with ten effects. The exhaust steam of the backpressure turbines (0.6 MPa) is fed into the first effects of the MED. If more steam is available than is required for desalination, it is used to supply industrial district heat. Muralev [24] reports that pressure reducing and cooling devices were installed in order to provide redundant high grade steam taken from the fossil fuel or nuclear plant main steam lines to the desalination units during periods of low electrical power demand or in cases of backpressure turbine failures. Steam to the desalination plant was also supplied from the fossil fuel fired boilers of the thermal power station during reactor outages or when steam from the nuclear reactor was not sufficient for the required water production. Such switching between the heat sources happened regularly, and no problems arose. To meet daily peak demands of water, reservoirs were used for the distillated water and for the feedwater of the steam generators and boilers.



Source: Figure 1 of Ref. [24].

FIG. 11. Principle flow diagram of the MAEC, in Kazakhstan.

The desalination plant yielded two direct distillate products. The characteristics of which were independent of whether the nuclear or fossil fuel heat source had been used (see Ref. [25]). One distillate had lower residual salinity (TDS ≈ 2 mg/L) for the purpose of making up feedwater to the nuclear and fossil fuel plants' steam generators and industrial water uses. Since the distillate was already of high quality, it required only minor treatment. Compared with conventional methods, the cost of feedwater preparation was much lower.

The MAEC desalination plant demonstrated high reliability and flexibility on account of the multiple measures of steam supply redundancy from the fossil fuel and nuclear fired boilers. Furthermore, there is an independent source of electric power and water which can start up the complex, even when the complex is disconnected from the regional electric grid.

3.3.5. High temperature gas reactors for process steam supply

The HTGR is capable of cogenerating process steam at temperatures and pressures large enough to support a wide range of industrial heat process. The need to develop this potential is recognized in a European Vision Report of the Sustainable Nuclear Energy Technology Platform (SNETP) [26], in which recommendations are made to focus future nuclear research in the European Union on the three pillars of Generation II and III reactors, fast reactors for stretching uranium reserves and for minimizing wastes, and other uses than electricity generation, with the application of (very) high temperature reactors (V)HTRs for providing cogeneration capacity to industrial processes as a major element.

Following the recommendations of the Industrial Users Advisory Group, which comprises representatives of utility providers, heat users, chemical plant vendors, nuclear engineering companies and nuclear power plant vendors, the EUROPAIRS[3] R&D project commenced in 2009 with funding from the European Commission [27]. In cooperation between the nuclear industry, large energy and heat consuming industries, and academia, the project evaluated the potential of coupling HTGRs with industrial processes. Heat supply by means of an HTGR is seen as a viable energy alternative, especially in the production of hydrogen, methanol and synthetic fuels, thus reducing EU Member States' dependency on fossil fuels [28]. Angulo et al. [27] report that:

> "Nuclear pre-heating, i.e. the supply of medium temperature nuclear heat to a high-temperature fossil-fuel based industrial process, was found to be of potential interest, especially in high temperature sectors such as steel, glass and lime, although its feasibility has to be assessed in more detail."

The main goal was to establish a roadmap for the design of an HTGR for cogeneration of heat and electricity to be coupled to an industrial heat consuming plant. The first step was to identify the technical, industrial, economical, licensing and safety related boundary conditions for the viability of nuclear cogeneration systems connected to conventional industrial processes and, furthermore, find potential markets that could be supplied in the longer term. A final step was the development of the concept of a demonstrator plant. Process heat users express their requirements in terms of operating needs and constraints; whereas the nuclear industry provides the performance window of HTGR technologies to determine possible common operating windows and potential coupling schemes. EU Member States were found to be an attractive market because of their commercial experience of low temperature nuclear cogeneration and good industrial infrastructure (e.g. in terms of the availability of large and dense networks of industrial gas pipelines).

As reported in Angulo et al. [27], the first analytical results have led to a categorization of chemical processes into three classes according to temperature and the technology used:

(1) Steam class: Processes which need steam as heat transport and heating media in the range of 150–600°C, such as drying, district heating, desalination by MSF evaporation, distillation in a refinery, or power generation with a steam turbine;
(2) Chemical class: Processes in which heat is the driver of chemical reactions and is consumed as reaction enthalpy at constant temperature, taking place in the range of 600–900°C, such as the production of oil derivatives, or methane, biomass and coal derivatives;

[3] End User Requirement for Industrial Process Heat Applications with Innovative Nuclear Reactors for Sustainable Energy Supply.

(3) Mineral class: Processes in which heat is used to melt solids or to drive reactions between solids, usually taking place at temperatures above 1000°C.

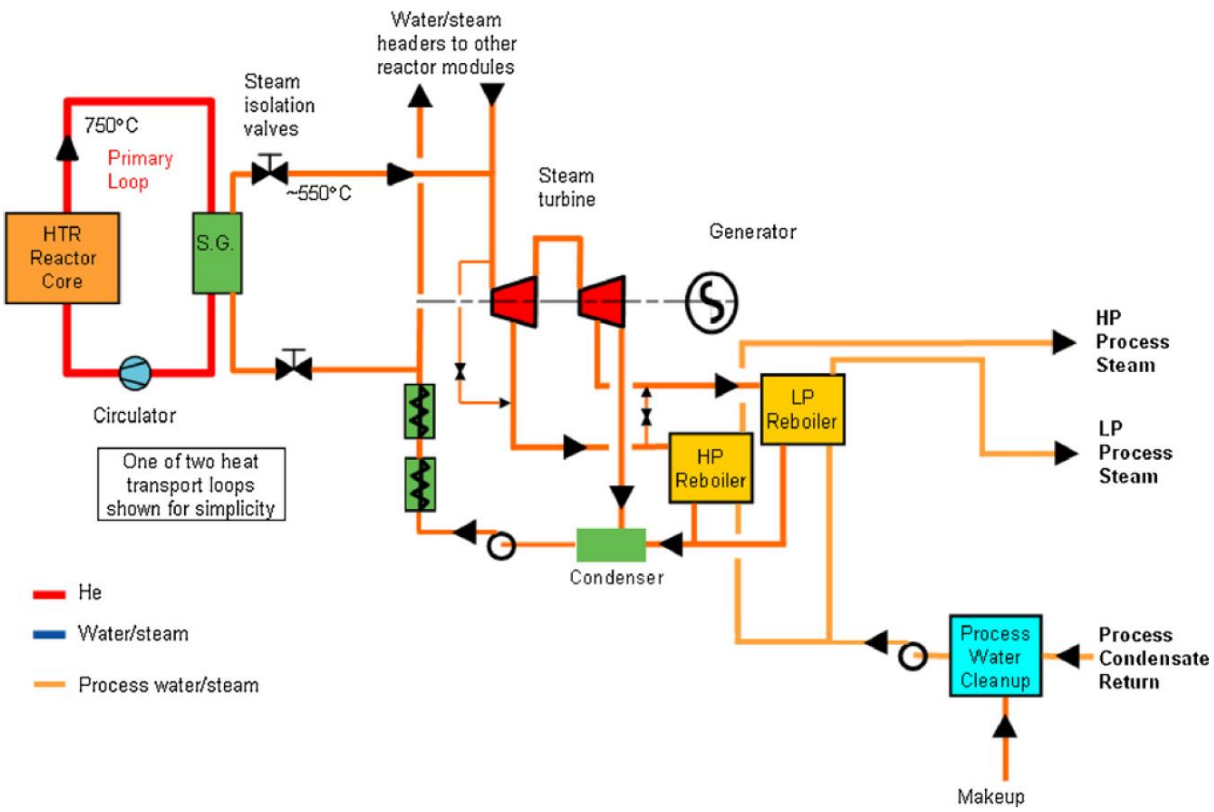
Figure 12 shows an example of a basic configuration of a prototype commercial process heat cogeneration facility, which is characterized by secondary steam production with a topping power conversion cycle and two options to extract process heat at different temperatures [27].

Hittner et al. [29] recommend the road towards the deployment of an HTGR cogeneration system be conducted in several steps, starting with the use of proven technologies before moving to the employment of more advanced technologies (e.g. higher temperatures and higher burnups):

(a) An appropriate first step is seen in an HTGR producing steam in a steam generator, to be coupled to existing industrial process heat applications up to 550°C, and without significant change in steam transport and industrial processes. All operational and licensing issues of the coupling will have to be addressed and solved at this stage. A successful demonstration will raise the interest in nuclear heat for industry, and may enable large scale deployment in the future.

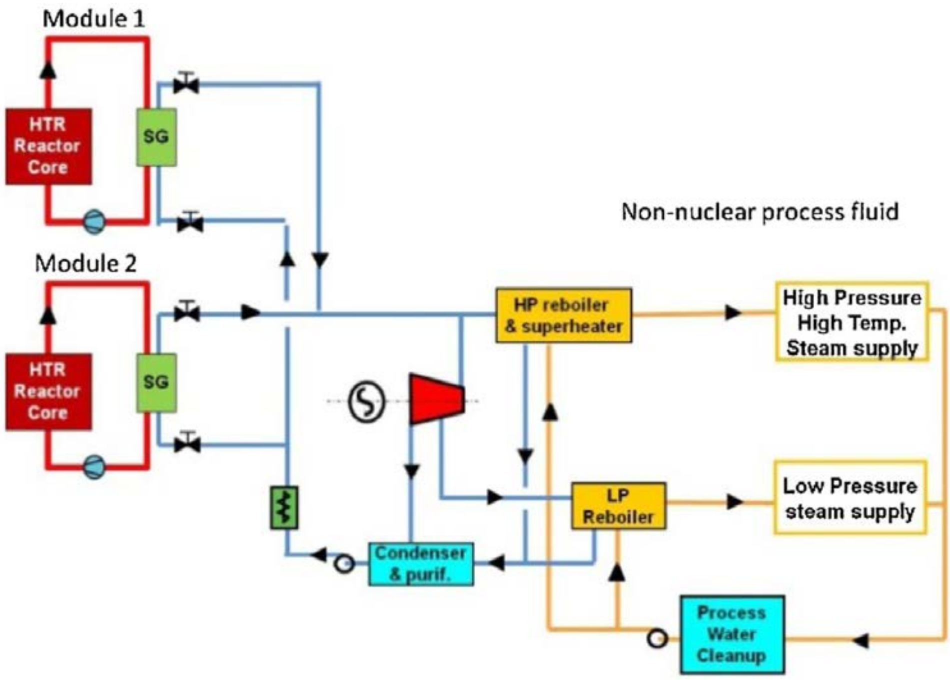
(b) Based on the same (HTGR) nuclear heat source, the next step could target an increased process heat temperature range of 550–700°C, where the heat will be exchanged in a gas to gas intermediate heat exchanger (IHX). Further development is needed for the IHX, the hot gas transport and the industrial application processes.

(c) A final step in the longer term is an advanced nuclear reactor providing process heat for higher temperature applications (above 700°C). This, however, requires extensive R&D on advanced materials and innovative fuel, and utilizing the feedback from the previous development steps.



Source: Figure 1 of Ref. [27].

FIG. 12. An example of a European nuclear cogeneration plant.



Source: Figure 3 of Ref. [27].

FIG. 13. A near term coupling scheme with a steam generator.

The perception that, in the first step, steam coupling would be the most appropriate scheme for a prototype (see Fig. 13) is based on the fact that only limited developments are needed with regard to the technology of heat transfer from the HTGR plant to the end users by means of dedicated steam generators [27]. Angulo et al. [27] report that "the most suitable power size an HTR shall be assessed depending on the core design (prismatic or pebble-bed) and number of primary loops."

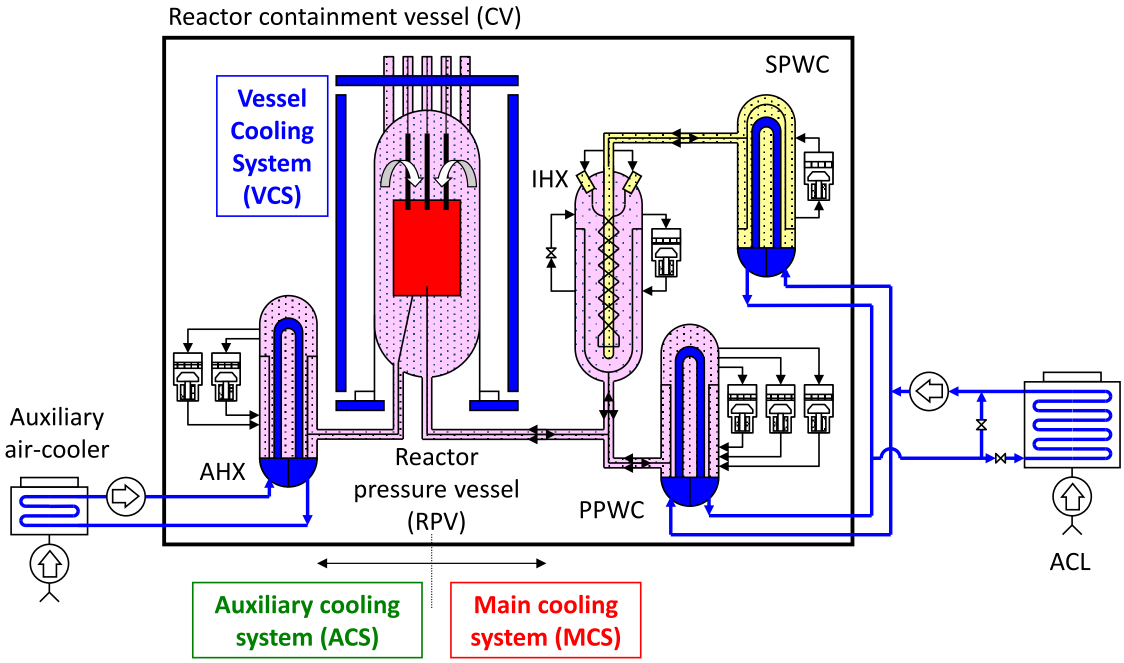
Hittner et al. [29] report that "Now the Nuclear Cogeneration Working Group…will initiate a Nuclear Cogeneration Industrial Initiative (NC2I) to concretize a large scale demonstration of the coupling of an HTR with industrial process heat applications." Meeting the conditions with regard to partnership, funding and political environment "requires an increased effort compared to the present budgets provided at European and national level for the development of base HTR technology. This increased effort could more easily reach a critical size if synergies are developed with international programmes involved in similar approaches."

In each of the steam generation schemes, a closed intermediate loop consisting of surface heat exchanger barriers (i.e. the nuclear reactor steam generator and the process reboilers) is provided to prevent material exchange between the nuclear primary system and the industrial process system. In addition to the dual physical barriers, the pressure in the intermediate loop is designed and monitored during operation to stay greater than both the primary pressure and the pressure in the process side. Its objective is prevention of material ingress into the intermediate loop in case of a tube leak in the steam generator or the reboiler.

3.3.6. High temperature gas reactors for hydrogen production[4]

The JAEA has developed and constructed a 30 MW(th) HTGR engineering test reactor called the HTTR, whose current operation is capable of an outlet coolant temperature of 950°C (see Fig. 14). Initial criticality was achieved in 1998, and full power operation at 850°C from 2001 and has been at 950°C since 2004. Inherent and passive safety design features of the HTTR have been demonstrated, including reactivity insertion and loss of coolant circulation without active control or emergency measures [32, 33].

[4] This section is based on Refs [30, 31].



Source: See Ref. [34].
Note: ACL — air cooler; AHX — auxiliary heat exchanger; IHX — intermediate heat exchanger; PPWC — primary pressurized water cooler; SPWC — secondary pressurized water cooler.

FIG. 14. Cooling system layout of the HTTR.

Based on the success of the HTTR, the JAEA has developed the basic design of a commercial series, including a power generation system GTHTR300 and its cogeneration system variants, named collectively GTHTR300C, which provide hydrogen production, process heat and desalination (see Table 8). The GTHTR300C employs the following:

— Fully passive reactor safety;
— High fuel burnup;
— Conventional steel reactor pressure vessel;
— Non-intercooled, direct Brayton cycle power conversion;
— Horizontal single shaft gas turbine;
— Electric generator;
— Modular system arrangement.

TABLE 8. MAJOR DESIGN SPECIFICATION OF THE HTGR REACTOR SYSTEMS BY THE JAEA

Specification	HTTR	GTHTR300	GTHTR300C
Reactor thermal power (MW(th))	30	600	600
Core coolant flow (kg/s)	12.4	439	322
Core outlet temp. (°C)	850/950	850	950
Core inlet temp. (°C)	395	587	594
Gas turbine inlet temp. (°C)	—[a]	850	850
Core coolant pressure (MPa)	4.0	6.9	5.1
Electricity generation (MW(e))	—[a]	280	202
Intermediate heat exchanger (MW(th))	10	—[a]	170

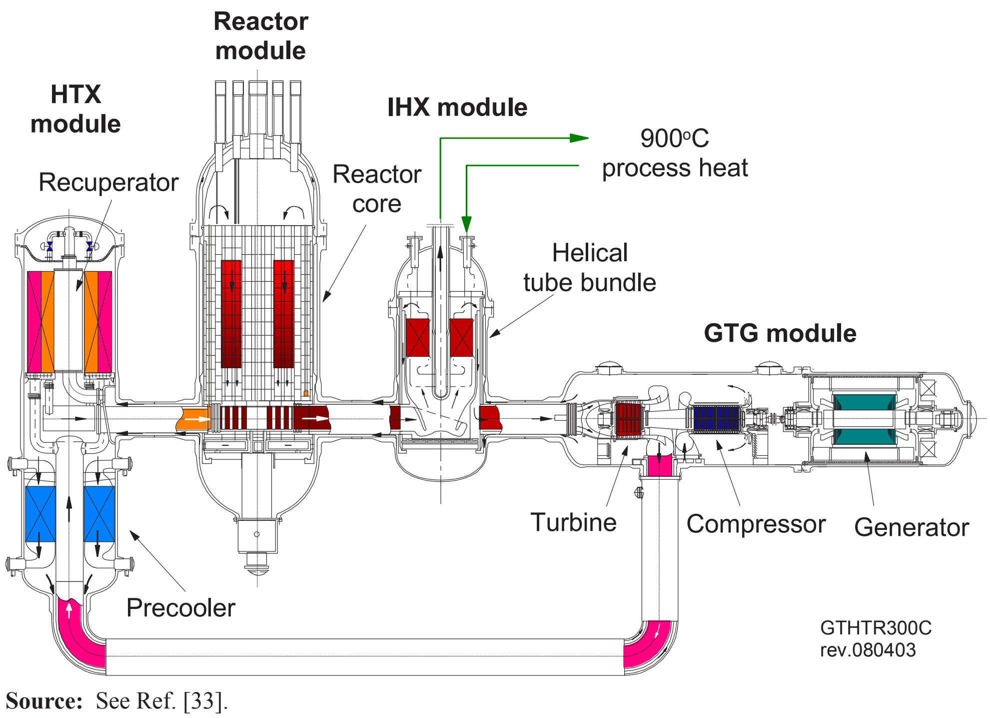
Source: See Refs [33–35].
[a] —: data not available.

The four modules of the GTHTR300C primary system comprise the reactor, gas turbine, heat exchanger and IHX (see Fig. 15). Figure 16 shows the cycle flow process of the GTHTR300C.

The reactor core of the GTHTR300C consists of 90 fuel columns arranged in an annular ring sandwiched by inner and outer graphite reflector columns. The resulting effective annular core has an inner and outer diameter of 3.6 m and 5.5 m, respectively, and a height of 8 m. The core average power density is 5.4 W/cm^3. Each fuel column is stacked of 8 fuel blocks, and each hexagonal fuel block contains 57 fuel rods. A fuel rod is composed of 12 fuel compacts supported on a graphite central rod. Approximately 1000 ceramic fuel particles 1 mm in diameter are bonded with a graphite matrix in a fuel compact. The uranium dioxide fuel kernel is coated in multiple layers of ceramics (TRISO coating), which consists of a low density pyrolytic carbon (PyC) layer, two high density PyC layers and a silicon carbide layer. The average uranium enrichment of the kernel is 14%. The fuel burnup is designed for up to 120 GW·d/t, and the refuelling interval is 18 months. The maximum fuel temperature is estimated at 1244°C in normal operation and at 1535°C in loss of coolant accident, which are both lower than the design temperature limit of 1600°C. The reactor outlet coolant flows into the IHX to generate very high temperature secondary helium to supply nuclear heat from the nuclear plant to the hydrogen production plant. Inlet and outlet helium temperatures are 950°C and 850°C, respectively. The 170 MW heat is transferred from primary to secondary helium in the IHX, and the secondary helium is heated up to 900°C.

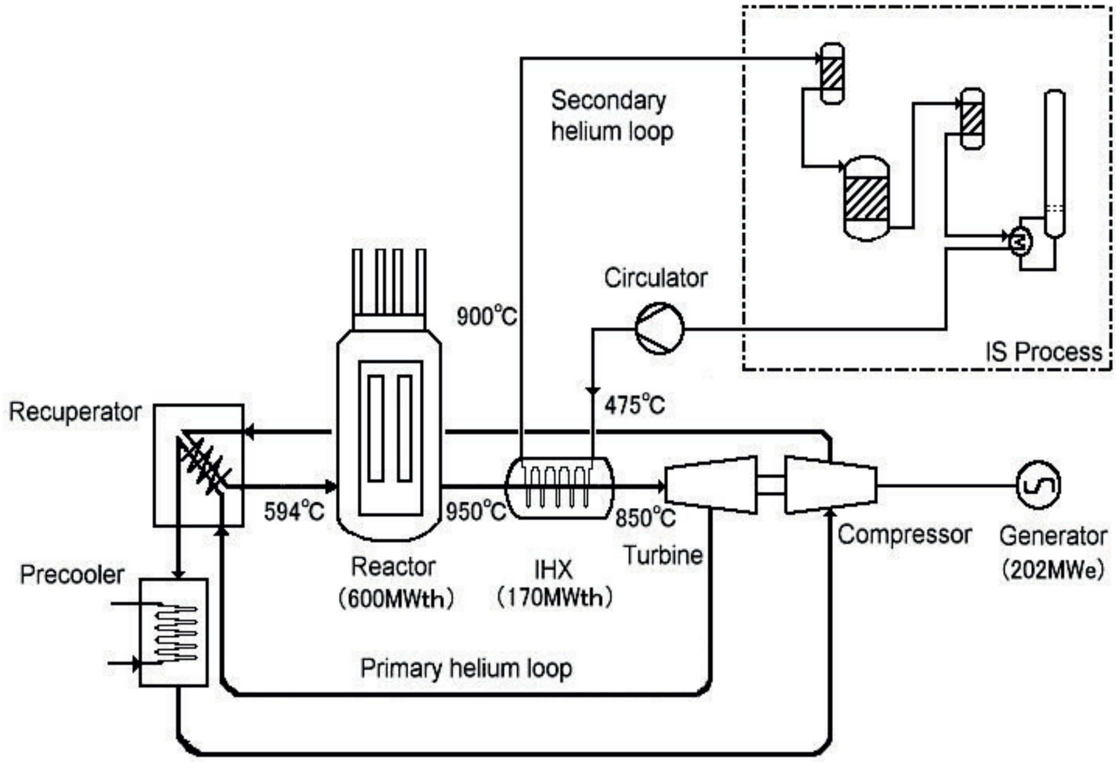
The GTHTR300C employs a gas turbine electricity generation system for power conversion. The gas turbine and a synchronous generator are placed in the gas turbine module. They are connected by a single rotor and supported by magnetic bearings. The gas turbine rotates at 3600 rpm. The recuperator recovers turbine exhaust heat. The performance of recuperator affects significantly electricity generating efficiency. A compact and highly effective plate heat exchanger operating in high pressure helium gas is employed. The precooler rejects the waste heat of the power generation cycle by cooling the helium gas to 28°C prior to the compressor. The overall compressor pressure ratio is 2.0. The compressor outlet helium is delivered to the recuperator for preheating to 594°C prior to entering the reactor core. The core outlet coolant is 950°C.

The design technology for the shell and tube type IHX of the GTHTR300C is essentially based on the IHX constructed and operated in the HTTR. Because the IHX operates at high temperatures (950°C), reduction of creep damage by primary stress is extremely critical to extending the design lifetime of the IHX heat exchanging tubes. The primary stress originates from the pressure load and the tube's own weight. The pressure load is reduced



Source: See Ref. [33].
Note: GTG — gas turbine generator; HTX — heat exchanger; IHX — intermediate heat exchanger.

FIG. 15. System layout of the GTHTR300C.



Source: See Ref. [33].
Note: IHX — intermediate heat exchanger; IS — iodine–sulphur.

FIG. 16. Cooling system of the GTHTR300C.

by minimizing the pressure difference between the primary and secondary helium. Similarly, in sizing the heat exchanging tube, both the weight and diameter of tube bundle should be minimized.

The hydrogen production system is coupled to the reactor via a high temperature intermediate heat transfer loop. The safety requirements are common for all types of reactor system, which are to protect people and the environment from harmful effects of ionizing radiation. The exposure of the public remains as low as reasonably achievable in operational states, and radiological risk is acceptably low in accident states. The defense in depth concept is employed to prevent accidental release of radioactive materials.

The GTHTR300C approaches to the safety of nuclear cogeneration through fully passive design measures [36]. Its nuclear reactor is designed coolable in accidents without requiring electric power or an operator. In a severe accident, such as a simultaneous loss of coolant and station blackout, the decay heat is removed from the inner core by conduction and convection to the reactor vessel. From here, it is transferred by radiation to the reactor cavity cooling system, which consists of a series of air cooling panels surrounding the reactor pressure vessel and removes decay heat under natural convection of the air to the stacks. The passive reactor safety means the reactor plant can be close to the industrial production process, reducing the costs of heat transport.

Based on the operating experience of the HTTR, the radioactivity of the primary coolant helium during reactor operation is so low that it can be released directly to the environment in the event of an accidental pipe rupture. With a large amount of helium entering the reactor confinement building, the pressure in the building rises and the pressure release panels open to blow the helium out to the atmosphere through the stacks to protect the confinement building from overpressure.

The stack panels close automatically upon the release of the pressure in the confinement building. The secondary helium pipes in the heat transfer loop penetrate the reactor confinement building. Failure of the heat transfer tubes in the IHX and the secondary helium pipe outside the reactor building can create a flow path to release helium coolant to the environment and to flow air into the reactor. The probability of this event is sufficiently low to exclude it from the design basis. However, multiple isolation valves are installed on the secondary helium piping near the penetration of reactor building to mitigate the consequences of the beyond design basis event.

The hydrogen production system coupled to the reactor should be a non-nuclear grade chemical plant to not add licensing, construction and maintenance costs owing to nuclear cogeneration. This would contribute to make nuclear hydrogen product cost competitive to hydrogen produced by the conventional fossil fuel system.

With the following requirements, a non-nuclear grade hydrogen production system in a cogeneration HTGR is achievable:

— The HTGR can continue safe operation independent of operational conditions of the hydrogen production system.
— The heat transfer loop, which provides hot helium gas from the IHX to the hydrogen production system, is not required to perform any nuclear safety function to prevent anticipated operational occurrences and accidents.
— Events originated in the hydrogen production plant do not affect to safe operation of the HTGR.

The functions of the heat transfer loop are primary helium cooling, pressure load control on the IHX heat exchanger tubes and impurity concentration control during normal operation. For further information on helium cooling and tritium contamination in hydrogen, see Refs [30, 31].

3.3.7. Modular helium reactors for multipurpose cogeneration

Since the 1970s, the majority of Russian HTGR designs have been for the cogeneration of heat and electricity (see Table 9). Recent research has focused on developing preconceptual system designs based on the MHR that can be tailored to enable a variety of cogeneration applications.[5]

TABLE 9. MAIN CHARACTERISTICS OF RUSSIAN HTGR BASED DESIGNS

Parameter	VGR-50	VG-400	VG-400GT	VGM	VGM-P	GT-MHR
Purpose: Electricity generation plus	Irradiation	Heat for producing ammonia	Domestic heating	Heat for technological processes	Heat for petroleum processing	n.a.[a]
Reactor design	Modular	Integrated	Integrated	Modular	Modular	Modular
Thermal power (MW)	136	1060	1060	200	215	600
No. of loops	1	4	4	1	1	1
Electric power (MW)	50	300	400	50	—[b]	290
Helium temp. (°C)						
At core entrance	296	350	350	300	300	490
At core exit	810	950	950	750–950	750	850
Helium pressure (MPa)	4	5	—[b]	5	6	7
Core type	Spherical fuel elements	Spherical fuel elements	Spherical fuel elements	Spherical fuel elements	Spherical fuel elements	Prismatic blocks

Source: Table 1 of Ref. [37].
[a] n.a.: not applicable.
[b] —: data not available.

[5] A description, in Russian, of the MHR-100 can be found at www.rosteplo.ru/Tech_stat/stat_shablon.php?id=2434

3.3.7.1. System configurations

The MHR-T plant is designed for safe and effective cogeneration of high grade heat for hydrogen production and electricity in a direct gas turbine cycle. The hydrogen production options under consideration are steam methane reforming and thermochemical (sulphur–iodine) water splitting. The MHR-T design has the following main components (see Table 10):

— High temperature helium cooled reactor of the gas turbine modular helium reactor (GT-MHR) type;
— High grade heat transport system with a heat exchanger for the hydrogen production plant;
— Power conversion unit (PCU) of a direct gas turbine cycle.

TABLE 10. MHR-T TECHNICAL CHARACTERISTICS

Parameter	MHR-T (+ steam methane reforming)	MHR-T (+ thermochemical water splitting)
Thermal power (MW)		
Reactor output	600	600
For hydrogen production	160	211
For electricity generation	435	384
Electric power (MW)	205	181
Helium temperature (°C)		
Core inlet	578	578
Core outlet	950	1000
Pressure (MPa)	7	7
Hydrogen output (t/h)	12.5	1.8

Source: See Refs [30, 37, 38].

The heat generated in the reactor core is supplied directly to the high temperature heat exchangers to be utilized in the hydrogen production process. The remaining heat is converted into electricity in the PCU with the direct gas turbine cycle (for further information, see Ref. [39]).

3.4. FEASIBILITY CONSIDERATIONS

The key aspects considered for a nuclear cogeneration plant are complementary to those required for a nuclear power plant (licensing, regulatory and operational aspects) or other industrial site [40]. These specific considerations will help to better define the overall layout and to determine the infrastructure required. One primary goal of the feasibility study is to identify problematic regulatory and environmental issues. A sound economic rationale should support the choice of selecting cogeneration, emphasizing its advantages. These issues should be addressed at an early stage of the project design in order to detect any hindrance needed to be lifted (for further information, see Ref. [41]).

3.4.1. Design requirements

3.4.1.1. General layout scheme

The general scheme comprises a nuclear power plant producing at least two products, one of which is usually electrical power. A transformation plant for the cogenerated product is installed at the same location. This industrial plant acts as a buffer between the nuclear power plant and the final users, and it alleviates the burden of following the time fluctuating load. Whenever the final product can be stored on site (water, gas or fuel), the reactor may run continuously in a steady state mode, delivering fixed and constant power. The storage capacity needs to satisfy demand in all circumstances. If there is insufficient storage for the final products (e.g. electricity and heat), then the nuclear power plant should be designed to allow operation in a load following mode, which implies some technical limitations. Under the assumption that all the electric power can always flow to the electric grid, then the nuclear power plant may still work in a continuous baseload mode, provided fast switching can be performed in between the electric production and the cogeneration production. This operational switching mode may even help the grid operator to sustain any external fluctuation either caused by the users or by some intermittent electrical sources. Cogeneration facilities may ultimately be a viable and flexible management option to ensure grid stability.

3.4.1.2. Coupling modes

The area containing the reactor and encompassing the whole primary circuit has to be physically separated from the cogeneration production. The cogeneration production area is a non-nuclear working place and, as an industrial facility, complies with regulations on the industrial product only. There is no direct connection between the final users and the nuclear power plant. The nuclear power plant and transformation plant are connected through an electrical feed line and a steam, or heat, transport line (see Fig. 17). The operating modes in between the two plants should be adapted depending on the cogenerated product and on the grid flexibility.

Flexible operation can be in two modes (see Table 11): baseload and load following. A baseload mode can operate at a fixed core thermal power, delivering either a 100% electrical output or a combination of electrical power and one cogenerated product (e.g. heat, steam, water, hydrogen or gas). The flexible operation can be arranged through a mass flow splitting in the secondary loop between the turbo-alternator and the cogeneration plant. With sufficient storage for the cogenerated product, the system will easily accommodate time dependent electrical variations. Fast switching will ensure grid stability. A second level of flexibility can be established by running the reactor in a load following mode by changing the core power according to the request from the electric grid operator. Although more challenging and more complex to deal with, the load following mode brings additional flexibility and offers a smooth and optimal drive of the cogeneration unit.

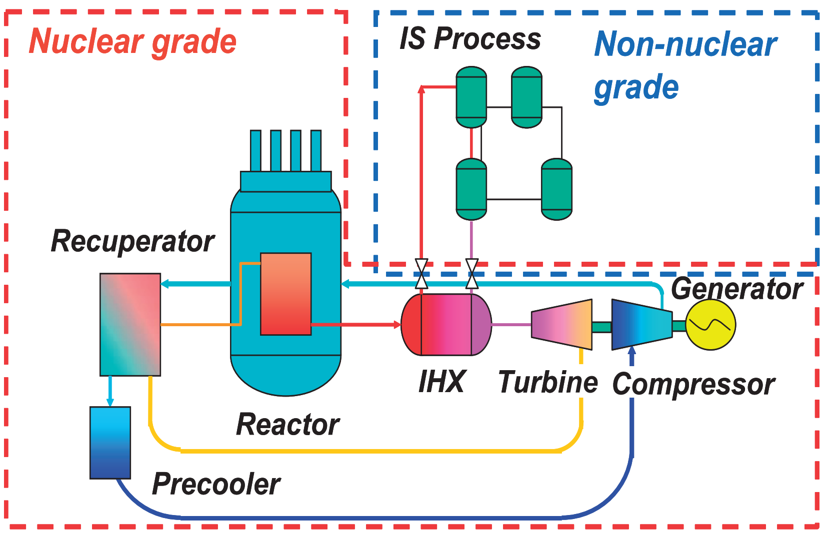


FIG. 17. Coupling scheme between the nuclear area and the cogeneration production area.

TABLE 11. COUPLING OPERATION MODES BETWEEN THE NUCLEAR POWER PLANT AND THE COGENERATION PLANT

Nuclear plant operation mode	Storage possible	Fast switching to electrical power	Cogeneration mode	Flexibility	Grid stability
Base load	Yes	Yes	Load following	Yes	Fast
	Yes	No	Continuous	Yes	No
	No	Yes	Load following	Yes	No
	No	No	Fixed	No	No
Load following	Yes	Yes	Load following	Yes	Fast
	Yes	No	Load following	Yes	Slow
	No	Yes	Load following	Yes	Fast
	No	No	Nuclear plant driven	Yes	Slow

3.4.1.3. Safety issues

In addition to the standard nuclear safety issues encountered in a nuclear plant and the common safety hazards of the industrial transformation plant, there is also the potential interaction of the two. Any single failure of one system should not weaken the safety of the other. In particular, the defense in depth will call for appropriate protective barriers against any radioactive transfer from the nuclear zone to the industrial zone: for example a pressure reversal scheme at a seawater desalination plant (see Fig. 18) [23, 42]. The higher pressure intermediate water loop will prevent any contaminant transfer from the reactor loop to the desalination plant loop, even in case of an accidental crack in the heat exchanger. This separate infrastructure provides a double physical barrier and acts as buffer zone. The loop is considered as part of the heat sink of the nuclear power plant and should be designed accordingly, enabling sufficient safety cooling capabilities in case of any failure at the cogeneration plant site.

3.4.2. Plant infrastructure

The dedicated infrastructure primarily includes an insulated heat transfer pipeline to connect the nuclear power plant to the industrial area. Required on-site infrastructure includes the following:

(a) To provide utilities: electrical power lines, water supply (industrial, domestic, sanitary and fire), water storage tanks, ventilation and cooling systems and eventually a steam distribution system if needed;

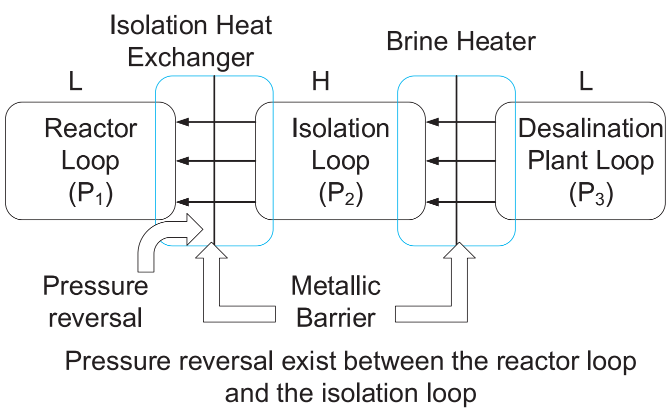


FIG. 18. A pressure reversal loop at a seawater desalination plant.

(b) To install exhausts: water discharge, heat discharge, air cooling and sanitary sewer;
(c) To ensure security: fence zone, entrances, monitoring and control, and a fire station;
(d) To provide access for people and materials: road construction, access for heavy components through rail or barge on a river, parking lots and the installation of telecommunications (secured on site and external).

3.4.3. Environmental impact

The co-location at the same site of the nuclear power plant and the cogeneration plant is not expected to add any impact to the environment when compared to having the same type of plant built at separate sites. On the contrary, running in a cogeneration mode will result in increased energy efficiency, reducing the overall GHG emissions for the same energy use. Moreover, locating the cogeneration plant close to the nuclear power plant will also help to share many conventional utilities and infrastructures and will consequently reduce both costs and land use.

3.4.4. Siting

The selection of a site begins before the licensing process. Because of the potential radiological impact on neighbouring populations in the event of a severe accident with a release of radioactivity, the nuclear power plant is usually located far from densely populated areas and near a large amount of water (e.g. close to the sea or a large river). The exclusion area is a few kilometres around the nuclear reactor, outside of which the cogeneration factory should be built. However, the supply of heat requires the industrial process be as close as possible to the nuclear power plant to reduce transmission line costs. Common guidelines include the following:

(a) If heat is transported in the form of hot water, the distance is not the main issue. Heat pipes can be designed to offer very low heat losses (<0.02%/km). Safety considerations should prevail.
(b) If heat is transported in the form of steam, transmission line costs rapidly increase with distance and steam pressure. The use of compressors in a steam system is generally not economical, so the transmission line length should be as short as possible (just beyond the exclusion zone boundary).

The specific requirements will be determined by factors such as the reactor type, the nature of the industrial process, the distance to the industrial facility, the distances from populous cities and the public perception of risks. The new generation of small reactors incorporating passive safety features might at least partly mitigate these siting issues [43]. The site survey should include a comprehensive study of subsurface geology and seismic conditions and a complete risk assessment of flooding in case of abnormal natural events. Criteria are similar for any new nuclear project proposed based upon local environmental regulations and national safety authority requirements.

3.4.5. Project evolution

The feasibility study is an essential phase of the project to trigger future investment. It is intended to convince owners, government entities and stakeholders of the technical, economic, social and financial soundness and the viability of the project. Consequently, a full cost and technical economic evaluation has to be carried out in which detailed technical and economic issues are addressed — in particular aspects specifically related to cogeneration.

3.4.5.1. Technical evaluation

The technical prerequisites include the following:

— General layout of the nuclear power plant, transfer line and cogeneration plant;
— All power levels output/input (electric and heat) for each facility;
— Heat transfer line design optimization (size, temperatures and losses);
— Basic design criteria for operational and interfaces control;

— Operational procedures and conditions (plant running modes, switching, power ramping up and down, and hot and cold shutdown);
— Emergency systems designs (residual heat removal, waste heat management and storage capabilities).

One goal undertaken in the technical feasibility would be to demonstrate the actual benefits expected from cogeneration in terms of energetic or exergetic efficiency as well as environmental GHG reduction. The selected technical solutions are either based on the industrial availability of mature technologies (e.g. district heating or seawater desalination) or on a convincing assessment of new technologies under development (e.g. second generation biofuels and hydrogen production).

3.4.5.2. Economic evaluation

The economic evaluation will be carefully scrutinized by investors on account of the high investment costs for both the nuclear power plant and the cogeneration infrastructure. Estimates of the following are required:

— Investment and financial costs (discount rate, interest rate, debt and equity, and phasing);
— Construction costs and time schedule;
— Uncertainties and risks of overruns.

The project will also have to consider the economic assets resulting from nuclear cogeneration production, such as:

— The economic value of the cogenerated product;
— The added value brought by the electric flexibility;
— The value of environmental and health benefits (including a significant reduction in GHG emissions);
— The value of long term social welfare (e.g. district heating or seawater desalination).

3.5. POTENTIAL OF COGENERATION IN EXISTING REACTORS[6]

3.5.1. Retrofit experience

In a coordinated research project with the IAEA, Pakistan connected a MED desalination demonstration plant to KANUPP, on the coast at Paradise Point [45]. The 137 MW(e) gross and 125 MW(e) net horizontal CANDU-PHW plant was constructed as a turnkey by Canadian General Electric and began commercial operation in 1972 (see Fig. 19).

Previously, a RO desalination plant of 454 m^3/d had been operated since 2000. The desalination plant uses extraction steam from one of the KANUPP feed heaters as the heat source for the desalination process. The existing intake structure of the power plant is used to pump sea water to the new desalination plant. The MED plan, which was commissioned in 2010, produces 1600 m^3/d potable water for domestic and industrial uses (see Table 12). The water produced serves the plant and the experience gained is expected to contribute to planning for large scale desalination plants along the arid coast of the country.

The reactor employs six steam generators, and the primary heavy water coolant transfers heat to produce the secondary light water steam. The saturated steam at the throttle valve is 3.85 MPa and is kept constant irrespective of load. It is supplied to a tandem turbine, which comprises one high pressure turbine and a double flow low pressure turbine. The feed water is regeneratively heated in five stages prior to returning to the steam generators. The choice of the dual purpose scheme is fairly restricted, as it has been basically designed only as a power plant. However, with the low water to power ratio, an extraction condensing scheme (pass-out turbine) would be both practical and economical.

[6] This section is based on Refs [22, 44].

TABLE 12. KANUPP MULTI-EFFECT DISTILLATION DESALINATION TECHNICAL PARAMETERS

Item	Specification
Plant capacity	1600 m^3/d
Process	MED (low temperature, horizontal tube, multi-effect, thin film evaporation)
Gain output ratio	6
Steam consumption	11.1 t/h saturated at 75°C
Electricity consumption (MED only)	66 kW(e)
Electricity consumption (MED feed pump)	55 kW(e) (500 m^3/h, head 30 m)
No. of effects	8 (2 vessels each housing 4 effects)
Seawater make-up preheating	2
Vacuum system	Hydro ejectors
Anti-scale systems	1
Anti-foam dosing systems	1
Acid cleaning skid	1
Remineralizing system (designed for full capacity of product desalination water)	1 (with $NaHCO_3$ and $CaCl_2$ injection and sterilization by NaClO)
Distillate total dissolved solids	<50 ppm
Potable water after remineralization and post-treatment	WHO standard, with 30 ppm Ca and < 250 ppm TDS

Note: MED — multi-effect distillation; TDS — total dissolved solids; WHO — World Health Organization.

FIG. 19. The KANUPP reactor coupled to the 1600 m^3/d MED desalination plant.

The steam take-off for the brine heater is at the crossover point between the moisture separator and the low pressure cylinders. Scale control techniques employed in the 1960s restricted the extraction steam for the brine heater to a maximum pressure of around 240 kPa. The steam conditions at the crossover point vary with power output: 100%, 220 kPa, 0.96% wet; 75%, 170 kPa; 50%, 130 kPa, 1.8% wet; and 25%, 70 kPa). The steam condition corresponding to 50% of the load is taken as the basis to design the heat transport coupling loop to the MED plant [45, 46].

The reactor steam generator powers steam turbine in the secondary loop. The heating steam for the MED plant is extracted at a rate of 7.7 kg/s from the steam turbine at 113°C and 157 kPa to make hot water (115 kg/s at 104°C) in a heat exchanger in a third closed coupling loop. The use of a closed pressurized water loop with a surface heat exchanger includes the following design advantages:

(a) A simplified operational requirement for the coupling loop water pump by freeing the pump from performing the loop pressure regulation. The pressure is regulated separately by a pressurizer, rather than the flash tank, thus eliminating the problem of pump cavitation. As a result, the pump control is simplified.
(b) The pump power consumption is reduced by 60%.
(c) The surface heat exchanger adds a third material exchanger barrier between the nuclear plant and the MED plant. As a result, two way pressure reversal is established. The pressure of the coupling is regulated to stay greater than both the side of the steam turbine loop and the side of the flash tank. Such pressure reversal prevents an exchange of material from the nuclear plant to the desalination plant and vice versa in the event of surface barrier failure.

3.6. NGNP INDUSTRY ALLIANCE

The NGNP Industry Alliance promotes the development and commercialization of HTGR technologies. A fundamental requirement for companies is the inherent safety of modular sized HTGRs, and that it is essentially impossible for any nuclear accident to impact the safety and investment protection of the industrial facility. Similarly, any accident that might occur at the industrial facility is not to impact the nuclear cogeneration facility.

Maintaining 100% availability of the end user's energy requirements favors multimodule plants, since nuclear units have to be shut down periodically for refuelling, maintenance and inspections. For example, supplying 2800 MW(th) of nuclear cogeneration capacity to an industrial facility could be accomplished with two 4 module HTGR plants (8 modules in total), with each module supplying 350 MW(th). To meet the availability requirements for energy supply, two additional 350 MW(th) natural gas fired units could be provided to address an unplanned outage of one nuclear module occurring during a scheduled outage (e.g. refuelling) of another. The capital costs of the natural gas fired units would be relatively small and could be recovered by using these units to provide electricity to the grid when they are not needed to backup the nuclear units.

As part of the NGNP conceptual design [47], the Plant Design Requirements Document [48] was prepared, which included requirements from prospective owner/operators and end users involved in the NGNP project. These requirements are summarized below for the NGNP plant with four 350 MW(th) reactor modules, tentative quantitative values provided in brackets { }.

(1) Deployment flexibility:
    (a) Structures, systems and components for electricity generation and process steam supply are to be tailored to the needs of the end user.
    (b) The design of the modular reactor is to permit the construction of reactor modules in series (sequential construction), including during progressive operation of previously constructed reactor modules, or in parallel (constructed as clusters).
(2) Performance:
    (a) Service life of at least 60 years.
    (b) Dispatch priorities in the following order: house load, end user process steam load, end user electric power load, and export to regional grid.
    (c) Operational basis to accommodate baseload operation, daily and weekly load following (all electric only), and steam load following with offsetting electricity generation.

(d) Accommodate all anticipated load changes and load manoeuvring events based on the plant duty cycle assessment.
(e) Step load rejection from 100% to house load without reactor trip.
(f) Cold shutdown to hot standby at full pressure and temperature (or vice versa) within 24 hours.

(3) Availability and reliability:
(a) Lifetime capacity factor for process steam only, based on rated delivery rate, is to be greater than 92%.
(b) Site reliability requirements are to be met with site specific optimum combination of conventional (fossil fuel) standby power systems.
(c) Independent operation capability is to be provided to operate reactor modules and associated turbine generators independently and at different power levels to other reactor modules and associated turbine generators in multimodule plants.
(d) Independent shutdown and startup capability are to be provided to shut down and start up individual modules and associated energy conversion and steam delivery systems with remaining modules in operation.

(4) Investment protection:
(a) Long outage event risk less than 10^{-3} per plant year for outages greater than six months.
(b) Frequency of events resulting in faulted plant conditions (i.e. plant unable to complete design lifetime) less than 10^{-4} per plant year.

(5) Public safety:
(a) The reactor modules are to meet all regulatory agency criteria without reliance on the operator, the control room and its contents, or any AC powered equipment for events within the design basis.
(b) The maximum accident dose per plant is be less than 10 mSv total effective dose equivalent and less than 50 mSv thyroid (United States Environmental Protection Agency, EPA, Protective Action Guides) at, or beyond, the exclusion area boundary, such that the emergency planning zone is coincident with the exclusion area boundary and that the normal, day to day activities of the offsite public are not disturbed by drills for sheltering or evacuation.
(c) Tritium release is to be less than the to be determined Bq/L in condensed process steam, liquid effluents or impacted ground water.
(d) Tritium concentrations in gaseous effluents and products are not to exceed the to be determined Bq/L.

(6) Operation and maintenance:
(a) Operation and maintenance personnel exposure is not to exceed 0.3 man Sv/GW(th)·a total effective dose equivalent in a refuelling year.
(b) Used fuel storage is to be sufficient for ten years of operation, plus one core. On-site fuel storage area is be reserved to accommodate storage of all used fuel and reflectors for plant design life.
(c) Low level solid waste is to be less than {15} solid m^3 per plant year, excluding replaceable reflectors and dry trash.
(d) Low level liquid waste is to be less than {5000} liquid m^3 per plant year.
(e) Design is to include provisions for replacement of equipment and components designed for less than plant design life.
(f) Staffing is to be optimized consistent with adapting state of the art automation systems, achieving availability requirements and lowest overall product costs.
(g) The plant is to be designed for on-line maintenance consistent with availability and economic requirements;

(7) Constructability:
(a) Modular design, manufacturing, assembly and construction techniques are to be applied to minimize costs, risks and schedule, and to accommodate sequential deployment of a multimodule plant.
(b) All modules and components are to be shippable by legal limit truck, or are to allow for field assembly and welding of shippable submodules or component sections.

(8) Commercial plant schedule:
(a) Less than {24} months allowance for procurement of long lead equipment and site preparation prior to start of site construction.

(b) Span from start of site construction work to full commercial operation of less than {36} months for the first module of a four module plant and less than {48} months for the fourth module of a four module plant.

A challenge is to set a provisional limit on the allowable tritium contamination in the product hydrogen or process steam. The international regulatory standards for allowable tritium contamination in air and drinking water vary remarkably: for drinking water, from a low of 100 mBq/g in France to 76 Bq/g in Australia. The EPA standard is 0.74 Bq/g. Traditional exposure pathway analysis for specific assumed release and transport scenarios appears inappropriate at this early stage of design definition. Consequently, the EPA drinking water standard of 0.74 Bq/g may be provisionally adopted as the goal for allowable tritium contamination in the product hydrogen or process steam at this stage. It is expected that a traditional exposure pathway analysis will demonstrate this 0.74 Bq/g limit on tritium contamination is conservative and can be relaxed by up to two orders of magnitude [49].

Regulatory licensing of a nuclear cogeneration system coupled to an industrial facility is a major challenge for both end user and public acceptance. As part of the NGNP prelicensing activities, the Idaho National Laboratory has prepared several white papers for the NRC (see Ref. [50]). The NRC prepared SECY-10-0034, Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs [51], to provide its perspective on this issue under item 4.4, Industrial Facilities Using Nuclear-Generated Process Heat:

> “The NRC staff has identified potential policy and licensing issues for those facilities used to provide process heat for industrial applications. The close coupling of the nuclear and process facilities raises concerns involving interface requirements and regulatory jurisdiction issues. Effects of the reactor on the commercial product of the industrial facility during normal operation must also be considered. For example, tritium could migrate to a hydrogen production facility and become a byproduct component of the hydrogen product. Resolution of these issues will require interfacing with other government agencies and may require Commission input to determine whether the design and ultimate use of the product is acceptable.
>
> “This issue is applicable to license applications for new, first-of-a-kind SMR designs, including the NGNP. However, the staff believes that resolution for this issue need not occur until after a license application is submitted because it concerns site-specific issues associated with the staff’s review of an operating license. Once a license application is received, the NRC staff will review the [sic] how the nuclear facility is connected to the industrial facility, consider the interrelationship between the staffs of both facility, consider white papers or topical reports concerning this issue that it receives from [Department of Energy] and potential SMR applicants, discuss design-specific proposals to address this matter, and review similar activities with nuclear and non-nuclear facilities. Should it be necessary, the staff will propose changes to existing regulatory guidance or new guidance concerning the effect of the industrial facility on the nuclear facility in a timeframe consistent with the licensing schedule.”

The only NRC historical licensing precedent for cogeneration relates to a dual unit PWR plant proposed for Midland, Michigan [50]. Construction permits were issued in 1972, but construction was halted and the plant was never completed. The plant furnished process steam (25%) and electricity (75%) to an adjacent industrial facility. The radioactivity content of the steam was required to comply with 10 CFR 20 [52]. Reference [50] states that:

> “Based on its review, the staff concluded that the power conversion system, including the provision to supply steam to the industrial facility, was in conformance with the regulatory criteria and design bases, could perform its designed functions, and was, therefore, acceptable.”
>
> Furthermore [50]:
>
> “[I]t is necessary to define two sets of regulatory boundaries to properly structure the possible HTGR licensing approaches and streamline the licensing process. First, there should be a clear understanding between the HTGR applicant and the NRC regarding those systems within the nuclear facility and under NRC regulatory jurisdiction (within the scope of the DC [design certification] and COL [Combined Operating Licence] applications) and those that fall outside NRC scope (industrial facility). Second, there should be a

clear understanding regarding what plant scope is to be addressed in an HTGR DC and what scope can be addressed in a site specific COL application.

"This paper defines the boundary between the nuclear facility (those systems and programes under the regulatory jurisdiction of the NRC) and the industrial facility (those systems and programes that fall outside of the regulatory jurisdiction of the NRC)."

3.7. CONCLUSION

From the end user perspective, the main challenges of nuclear cogeneration are safety, investment protection, regulatory licensing and maintaining 100% availability of the energy requirements. There also needs to be assurance that the industrial products have very low levels of radioactive contamination in line with the same products from fossil fuels. Public acceptance requires these end user challenges be addressed with a very high level of confidence.

Cogeneration with nuclear power can be performed in a range of heat processes at temperatures as high as 900°C, albeit only under 300°C in current practice. The cogenerating applications span over district heating, seawater desalination, industrial and agricultural processes. Some of the world's cogenerating reactors were originally built to produce power and were only later retrofitted to cogeneration (e.g. KANUPP in 2010). With the proven feasibility, more reactors which currently produce only electricity could be converted to cogeneration should heat users within the reach of the existing reactors be identified.

Having accumulated a combined operation period of more than 750 reactor years, these plants have demonstrated that there is no basic technical impediment to applying nuclear energy as a heat source for cogeneration. Furthermore, there have been no reports of radioactive contamination to either processes or products in any cogenerating reactor. In general, the prevention for potential radioactive contamination has been done by employing design measures such as closed intermediate loops thermodynamically coupling the process to the nuclear reactor with pressure gradients that act as material exchange barriers. However, the reactors need to be sited far from the residential customers receiving the district heating. The long pipe lines is a major construction cost and heat loss occurs when transporting heat over long distances.

Greater promise for nuclear cogeneration can be expected from the ongoing development of SMRs of 300 MW(e) or less. These SMRs are not scaled down versions of the existing fleet of large commercial reactors of 1000 MW(e) or more. Instead, they are developed to be passively safer while remaining cost competitive. Their improved safety and smaller capacity make them more suited to supplying users closer to them to save on heat transmission cost. They are also better suited as independent sources of electricity and heat.

The next generation reactors being developed by an international consortium are expected to enter markets after 2020.[7] These reactors, known as Generation-IV systems, feature increased safety, improved economics for electricity and new products such as hydrogen for transport applications, reduced nuclear wastes for disposal, and increased proliferation resistance. Their coolant temperatures are in the range of 540°C (LMFR) to 950°C (HTGR). The temperature range offers opportunities of cogeneration using more efficient and sustainable processes than traditional methods. Although most studies of Generation-IV cogeneration systems are related to the HTGR, some studies focus on SFRs (a review can be found in Ref. [31]).

4. COGENERATION APPLICATIONS

4.1. OVERVIEW OF COGENERATION APPLICATIONS (NON-ELECTRIC)

Most energy produced is consumed in heating, ventilating and air-conditioning and transport sectors. The world has so far relied on fossil fuels to meet the energy demand. However, with rising fossil fuel prices and the increasingly harmful environmental impacts caused by GHG emissions, there is a strong need to find alternatives to

[7] For further information, see www.gen-4.org/gif/jcms/c_9352/technology-roadmap

fossil fuels which fulfil key criteria such as efficiency, economic viability, commercial availability, environmentally friendliness and sustainability.

In the past, the use of nuclear energy for non-electric purposes was greatly hindered by the low price of fossil fuels and their abundance. Recent concerns with regard to rising fossil fuel prices, their availability in the long term and the harmful effects on the environment mean that the use of nuclear energy for non-electric purposes holds great potential for seawater desalination, district heating and cooling, and hydrogen production.

4.1.1. Seawater desalination

The provision of fresh water is a challenge for both developed and developing countries. For most developing countries in Africa, the Middle East and Asia, the shortage of fresh water is a great constraint on development. Fresh water can easily be supplied using seawater desalination technologies, as many of these countries have some sort of access to sea water. However, desalination technologies come at the expense of energy consumption, and countries with fossil fuels as their base energy carrier can face severe problems.

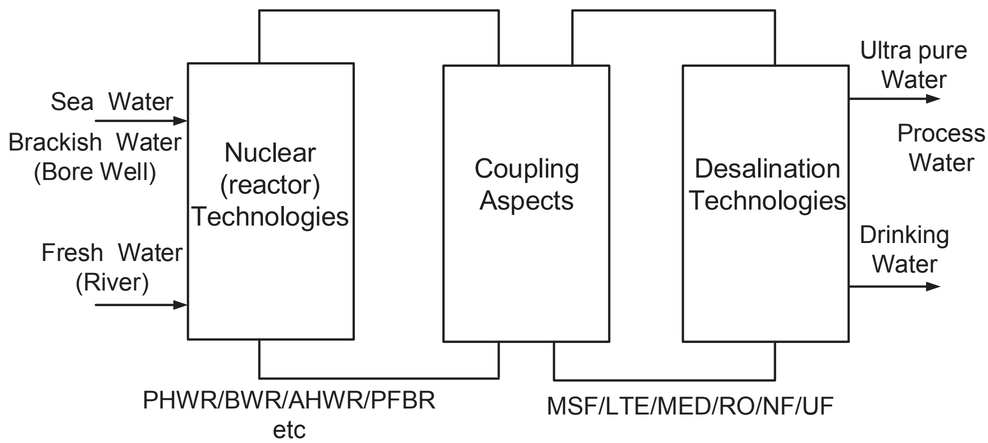
Nuclear desalination can meet a large part of water requirements for in-house and other applications, if demonstrated to be feasible and economically competitive, without any compromise in the product water quality through a properly designed coupling system between a nuclear reactor and a desalination plant (see Fig. 20).

Although global seawater desalination capacity doubles every decade, it is difficult to predict the market potential of nuclear desalination because its share is very small [46]:

> "An approximation of the market potential can be obtained by considering a 600 MW(e) nuclear reactor operating in the cogeneration mode and producing about 500 000 m^3 of water per day. For such water production about 20% of the electrical capacity of the plant will be used. The total existing world desalination capacity (~26 Mm^3/d) could therefore be powered by ~50 such reactors."

4.1.2. District heating and cooling

There is a large potential market for district heating and cooling applications. Global heating needs is currently estimated at above 20 000 TW(th) for residential and commercial use (see Section 4.3.1), and around 40% of the total energy consumed is used for heating purpose. The total heat consumption in the world is 62 000 TW(th). For Europe, North America and the countries of the former Soviet Union which face harsh winters, district heating estimates range from several hundred to several thousand reactors per region. The high estimates are also due to the historic use of centralized heating systems in both the domestic and industrial sector [46]. The opposite is true for countries in Africa, Asia, Latin America and the Middle East [46]. They have great potential for the supply



Note: AHWR — advanced heavy water reactor; BWR — boiling water reactor; LTE — low temperature evaporation; MED — multi-effect distillation; MSF — multistage flash; NF — nanofiltration; PHWR — pressurized heavy water reactor; PFBR — Prototype Fast Breeder Reactor; RO — reverse osmosis; UF — ultrafiltration.

FIG. 20. Design of coupling between nuclear reactor and desalination plant.

of district cooling for industrial and domestic purposes, using waste heat driven absorption refrigeration systems similar to the quadruple effect absorption refrigeration system researched by Ratlamwala et al. [53].

4.1.3. Hydrogen production

Hydrogen has great potential of becoming a leading energy carrier for a carbon free future. The major benefits are that there are no harmful byproducts when it is burned, it is abundant, and it can be stored on a large scale. Based on current hydrogen production technologies such as steam methane reforming and electrolysis, however, its generation is costly and it involves the emission of harmful gases [54]. This is changing with development of hydrogen production technologies that are cost effective and environmentally benign. One such field is nuclear hydrogen production technology, which benefits from large investments from Canada, Japan and the United States of America. Canada has increasingly focused on the Cu–Cl cycle, which can produce hydrogen using nuclear heat at around 550°C in an environmentally friendly and cost effective manner [55].

At present, global hydrogen production is approximately 50 Mt/year, of which only a very small amount is used in the energy sector [54]. By developing and improving fuel cells, the use of hydrogen as a source of energy could become ubiquitous.

4.2. SEAWATER DESALINATION

The first hybrid nuclear desalination plant that was coupled to a nuclear power plant in India was reported by the Bhabha Atomic Research Centre (BARC), India [12]. BARC has also successfully developed low temperature evaporation (LTE) desalination technology based on a boiling concept for utilization of waste heat from the nuclear research reactor CIRUS, in Trombay, India, and a 30 m^3/d capacity LTE was declared commissioned in 2004. A few of the existing large scale cogeneration systems and thermal desalination plants are provided in Table 13.

TABLE 13. EXISTING COGENERATION SYSTEMS AND THERMAL DESALINATION PLANTS

Plant type	Year	Capacity (m^3/d)	Total power (MW)	Location
MSF (first)	1978	37 850	71	Jeddah II, Saudi Arabia
MSF (largest)	1983	798 864	812	Al Jubail II, Saudi Arabia
MED (first)	1984	18 000	50	Ashdad, Israel
MED-TVC (largest)	2000	23 9736	50	Taweelah, UAE

Note: MED — multi-effect distillation; MSF — multistage flash; TVC — thermal vapour compressor.

The BARC has conducted R&D activities on both membrane and thermal based desalination technologies, including studies on desalination for cogeneration applications. As a part of the national programme to improve the quality of life by systematic induction of nuclear energy, BARC has researched technologies on:

— RO;
— MSF;
— LTE;
— Hybrid systems;
— Domestic water purification;
— Wastewater reuse.

In Aktau, Kazakhstan, ten units of MED plants were coupled to a 1000 MW(th) liquid metal cooled, fast breeder reactor (BN-350) to produce 14 500 m^3/d. It produced very high quality water with a TDS concentration of around 2–10 mg/L for industrial needs and potable quality by mixing with seawater. The complex also consisted of a gas or oil fuelled thermal power station along with the nuclear reactor connected to MSF desalination units, making a total capacity of about 80 000 m^3/d. The nuclear reactor was shut down in 1999 after around 26 years of successful operation.

4.2.1. Multistage flash desalination utilizing nuclear reactor waste heat

While the MSF proves to be the simplest and most reliable of the major desalination processes, a significant drawback is its higher energy consumption when compared to MED and RO. This disadvantage may be overcome by utilizing the waste heat of an HTGR (e.g. the GTHTR300). In the GTHTR300, the waste heat from the Brayton cycle power generation cycle is rejected to cooling water in a helium to water heat exchanger. The heat removed by the heat exchanger is 315 MW(th), which is available to the MSF process, even if the reactor generates thermodynamically peak electric power. The reactor helium coolant is cooled from 164°C to 28°C, while the water is heated from 25°C to 140°C. To limit scale deposition, the top brine temperature is set to 110°C, consistent with the typical upper limit for MSF in practice. A closed intermediate loop circulates the hot water to the brine heater of the MSF process. This loop is intended to provide two steel surface barriers between the nuclear plant and the desalination plant. In addition, the loop is operated at a higher pressure than either the nuclear plant circuit or the desalination plant circuit to prevent material exchange in the case of a barrier failure.

Using the highest permissible brine temperature should maximize the specific yield of water, or performance ratio. The higher the top brine temperature, the less heat is transferred in the brine heater. These two competing effects suggest the existence of an optimum top brine temperature. This is found to be near 85°C as indicated in Fig. 21. The maximum yield of water from a single train MSF is 38 627 m^3/d. Under this condition, the hot water enters the brine heater at 140°C and exits at 85°C.

Water production gains rapidly as the number of trains reaches three, then subsides thereafter. In the case of a single train optimized for peak water yield, only around 50% of the available nuclear waste heat is utilized. The balance is rejected to the cooling seawater downstream. With three MSF trains, however, the waste heat utilization is increased to 78%. The top brine temperatures are 110°C, 80°C and 50°C, while the inlet/outlet temperatures of the hot water are 140/110°C, 110/80°C and 80/50°C in the consecutive brine heaters. The water production in the case of three trains is 56 178 m^3/d, corresponding to an increase of 45% from the single train case.

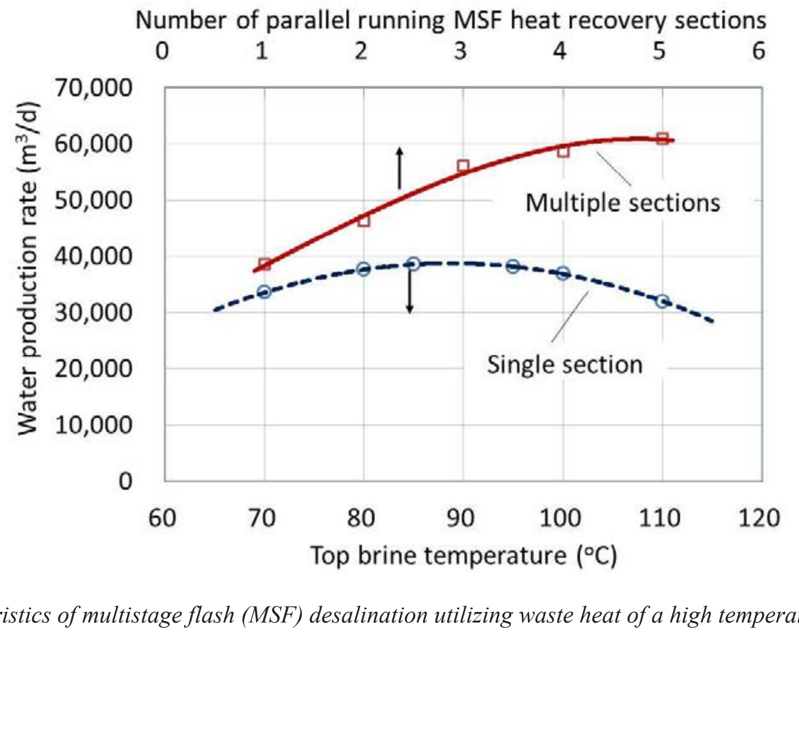


FIG. 21. Characteristics of multistage flash (MSF) desalination utilizing waste heat of a high temperature gas reactor.

Although the total number of flashing stages also increases with the number of trains, the size of the plant as a whole is primarily reflected in the gross water produced, rather than in any number of trains applied. The selection of the top brine temperature decides for the type of pretreatment and also for the once through or recirculation type of system design and thus reduces the consumptions of the pretreatment chemicals.

4.3. DISTRICT HEATING AND COOLING

4.3.1. Heat usage

The 25 000 TW·h of global heat demand is shared between residential users (40%), services (30%) and industry (30%). The majority (70%) is consumed as low temperature heat (<200°C), mainly in residential and service sectors but also in industry (e.g. drying). Only around 10% of the total heat is delivered to users through district heating networks as hot water or steam. However, this is expected to increase in the future for two reasons. First, small, local sources based on renewable energies (e.g. solar, biomass and geothermal) are increasing in many countries. Second, the network infrastructure is expanding, which will help to deliver long term competitive heat prices. If part of the financial return to the network operator is reinvested in the infrastructure, district heating will slowly, but steadily, displace the heat market. However, the main energy sources used today to produce heat are fossil fuels — primarily coal and gas. Although nuclear provides a sizeable contribution to the world electricity production (11%), the nuclear contribution to delivered heat is negligible. Less than 0.5% of transported heat in district heating comes from nuclear power plants.

4.3.2. District heating using nuclear energy

Currently, 53 nuclear reactors are running in a cogeneration mode with part of their energy distributed as heat power in a district heating network (see table 31 of Ref. [46]). Most of these reactors are located in the Russian Federation (28 reactors) or in Eastern Europe, and heat power output is in the range of 5–240 MW(th). The total distributed heat power is around 5000 MW, corresponding to an average energy withdrawal of less than 5%. In many cases, heat is used to feed nearby cities a few kilometres away from the plant. The MHT pipeline currently extends to 35 km (Beznau, Switzerland) or even up to 64 km (Kola, Russian Federation). Past experience of district heating systems using nuclear heat are detailed in Refs [22, 40].

Old district heating systems suffer from high heat losses in generation, transport, distribution and end use, hindering the rapid spread of nuclear based district heating systems. The lack of coordination between local and central decision making boards and national environmental and energy agencies has not helped the implementation of efficient and economical district heating networks. Nevertheless, new projects using nuclear cogeneration of heat and power are timely envisaged in the world (see Table 14).

4.3.2.1. Principle of nuclear cogeneration

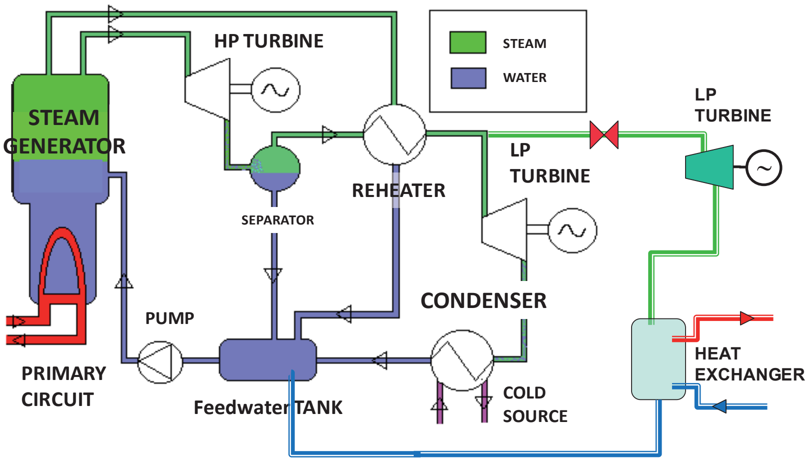
The process of extracting heat from nuclear energy is comparable to any CHP plant. The interaction of the two control–command systems (the nuclear power plant and the MHT) needs to have priority in the safe shut down of the plant in any accidental event. Radioactive contamination of the district heating system is prevented by physically isolating the primary loop of the reactor from the main transfer line. In a PWR, the secondary loop is already an isolated closed loop system, which serves as a barrier for contaminants. In a BWR, however, an additional water loop is required in between the heat exchanger/condenser at the turbine output and the MHT line.

For district heating applications, hot water, or steam, has to be supplied at temperatures below 200°C. If the desired output heat power is small compared to the nominal electrical power of the reactor, then bleeding from the low pressure turbine in the machine hall is usually sufficient to provide the required amount of heat. This bleeding can already be found in many reactors where hot steam is purposely extracted at temperatures between 60°C and 140°C to preheat cold water coming from the condenser prior to feeding the water tank (see Fig. 22). However, if the heat power requirement is important, then the extraction can be performed with a specifically designed low pressure turbine at the right temperature, fully utilizing the nuclear reactor heat. Anywhere between a pure electric

TABLE 14. NUCLEAR REACTOR PROJECTS CONSIDERING DISTRICT HEATING APPLICATIONS

Country, plant type or site	Location	Electrical output (MW(e))	Thermal output (MW(th))	Length of main pipe (km)
Bulgaria				
PWR/WWER	Belene	1000	400	60
China				
NHR-200	Daqing City	0	200	—[a]
Finland	Loviisa			
PWR/BWR		1200/1700	1000	80
Russian Federation				
RUTA	Obninsk	0	55	5
AST-500	Voronezh	0	500	—[a]
VK-300	Archangelsk	250	—[a]	—[a]
KLT-40	Severodvinsk (floating)	35	110	—[a]

Source: Table IX of Ref. [56].
Note: BWR — boiling water reactor; PWR — pressurized water reactor; WWER — water cooled water moderated reactor.
[a] —: data not available.



Source: Figure 1 of Ref. [44].
Note: HP — high pressure; LP — low pressure.

FIG. 22. Heat extraction in the secondary loop of a pressurized water reactor after the low pressure turbine.

power output (0% heat output) and 100% heat output can be achieved by simply diverting the correct quantity of steam in the corresponding branch. This flexibility can be used to adjust the output to match the demand of the district heating network.

4.3.2.2. Power and efficiency

Any heat extraction from the secondary loop circuit will induce a decrease in the electrical output of the nuclear power plant (see Fig. 22). Consequently, a trade-off has to be found between electrical efficiency (η_e) and heat output (Q).

However, given that pure electric efficiency (η_0) is typically around 33% for LWRs, overall energy efficiency (η) of the plant will be significantly enhanced in the cogeneration mode — the loss in the electric power output (P) being overcompensated by the gain in heat power. If Q_i is the total heat input in the primary circuit of the reactor, then the overall energy efficiency is given by:

$$\eta = \frac{P+Q}{Q_i} > \eta_0 = \frac{P_0}{Q_i} > \eta_e = \frac{P}{Q_i} \quad (1)$$

The loss in electrical efficiency depends the temperature at which the heat is extracted: the higher the temperature; the lower the electric efficiency. Furthermore, the extracted heat has a much higher heat value. The exergy (E) of a heat quantity Q delivered at a temperature T can be expressed as the maximum work that can be recovered using an ideal Carnot cycle and a cold sink at reference temperature T_0:

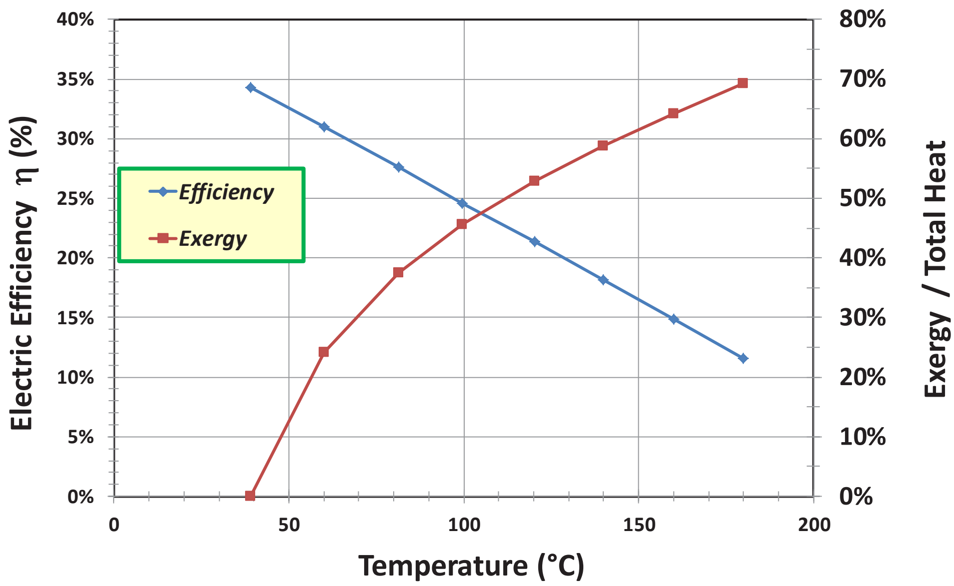
$$E = Q\left(1 - \frac{T_0}{T}\right) \quad (2)$$

To better illustrate this competition between electric efficiency and output heat, the case of a full use of heat is shown in Fig. 23. It is clear that an optimum operation point has to be found in the practical temperature range of interest for district heating in the range of 80–150°C. This optimum will depend on the demand profile or the geographical location and should result from a complete study including the foreseen heat distribution.

For a typical extracted temperature of T = 110°C, the corresponding figures are:

— Electrical efficiency: η_e = 23%;
— Exergy output: E/Q_i = 50%.

This means that the exergy corrected energy efficiency of the production plant operating in a full cogeneration mode, regardless of the subsequent heat losses in transport and distribution, will reach 73%. This enhanced energy use is a major achievement of nuclear cogeneration.



Source: See Ref. [44].

FIG. 23. Loss in the electric efficiency and increase of the exergetic value of heat as a function of the temperature of the extracted heat.

4.3.2.3. Heat transport

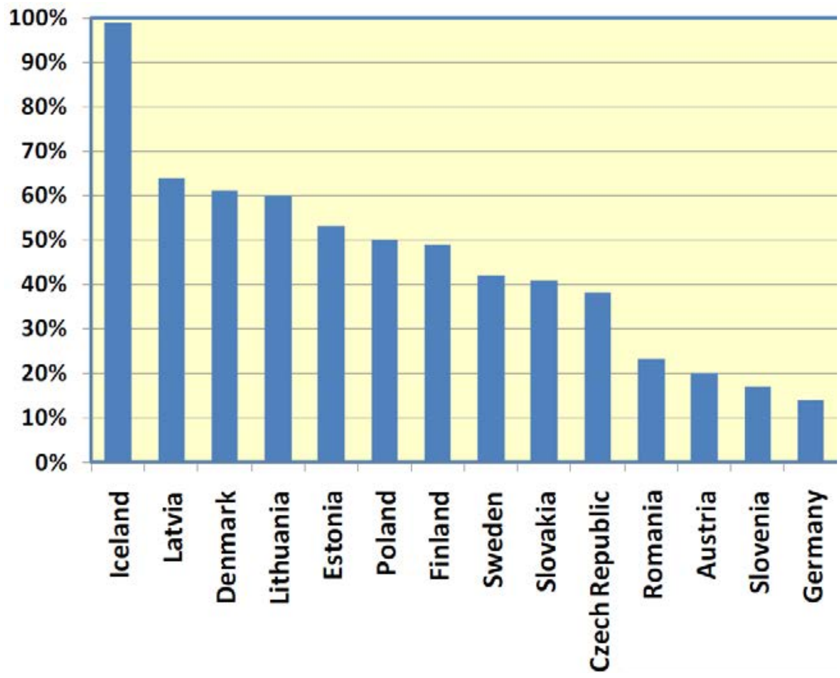
Nuclear power plants have so far been exclusively dedicated to electrical production. For safety reasons, they are sited far away from residential areas, which requires a long district heating network. However, the introduction of preinsulated pipes can drastically reduce heat losses. These pipes have an inner steel pipe insulated by polyurethane foam and an outer protecting jacket. While heat transport in the past was limited to a maximum distance of about 20 km for steam and 60 km for hot water, the new pipes mean that a 1000 MW MHT line can be built with a loss of less than 2% of the transported heat power for a 100 km double pipeline — a temperature decrease of −0.012 5°C/km [57].

Heat networks operate similarly to electrical networks. A large MHT line delivers to secondary pipelines and arrives at local distribution networks serving the final customers. District heating networks sector benefit from improved communication, controls and regulation. For example, sensors that detect leakages or hot spots can relay this information to the control room, improves maintenance. However, the construction of the MHT line is expensive, and it will determine the project's economic viability.

4.3.2.4. District heating network

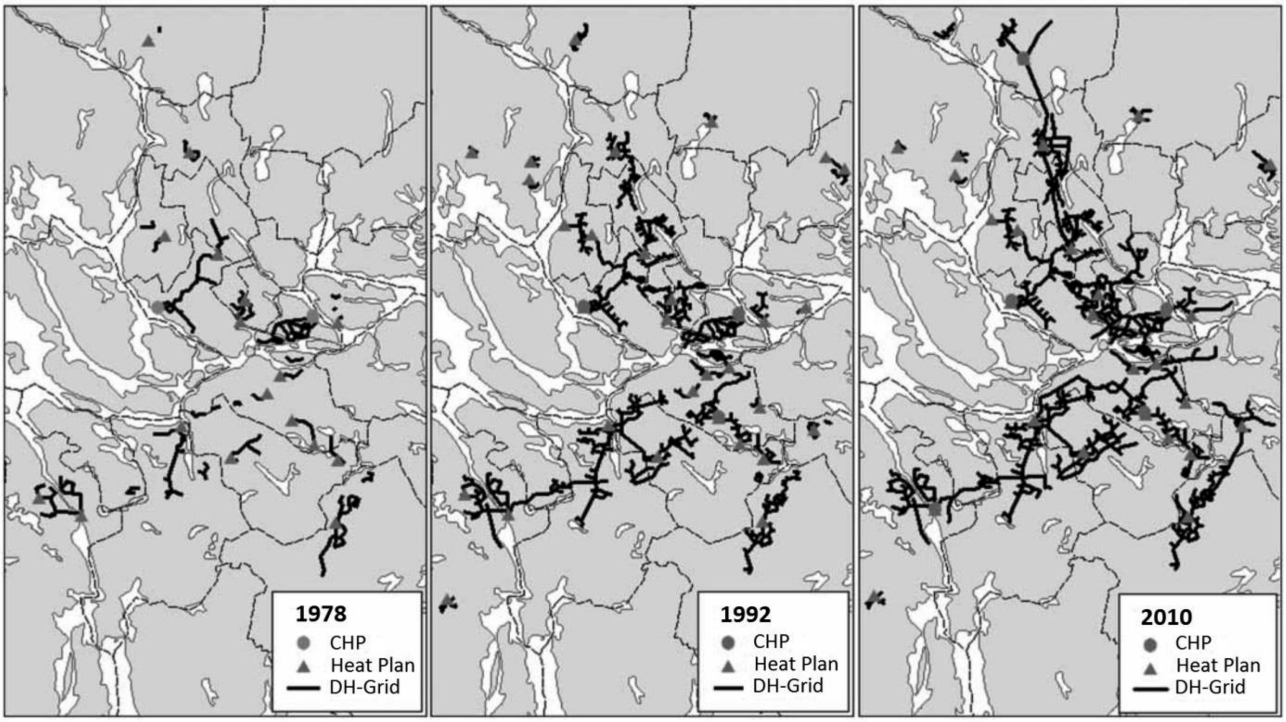
District heating networks can be found in most of the larger cities in Europe, essentially in the colder northern part. The percentage of citizens with access to district heating increases from south to north because of a colder climate (see Fig. 24). Its presence also depends on the population density (i.e. the heat demand density, including industry use) and the energy price (and availability), favouring areas with a high population density and low energy availability.

Rising energy prices is stoking demand for district heating. CHP plants combined with district heating is highly efficient and maintains heat prices at a reasonable level for the consumer. District heating networks can start small and fragmented, and then progressively grow and interconnect with time, obviating the need of a large initial investment [58]. Figure 25 shows the slow, steady expansion of district heating in Stockholm. The lifetime of a district heating network can be quite long, and most networks built in Europe between 1920 and 1930 still exist [58].



Source: See www.euroheat.org

FIG. 24. Percentage of the population with access to district heating (courtesy of H. Safa, French Alternative Energies and Atomic Energy Commission).



Source: See Ref. [59].
Note: CHP — combined heat and power; DH — district heating.

FIG. 25. The development of Stockholm district heating systems from 1978 to 2010.

4.3.2.5. Feasibility study

Traditionally, heat has always been considered a side product to the main electrical power production at a nuclear power plant. Steam bleeding from the low pressure turbine was generally considered enough thermal energy for local district heating applications. In 2009, a new nuclear power plant project in Finland introduced for the first time the option of implementing a true, full scale district heating application in the design phase of the project [58]. Another study conducted by Safa [44] in France shows that nuclear reactors currently in operation could be easily modified to efficiently supply large scale district heating networks. This opens up new perspectives in energy management and paves the way for future energy savings.

4.3.2.6. Plant modifications required

The plant modifications only affect the turbine hall, which is a non-radioactive zone in a PWR. Following the high pressure turbine and the reheater, a fraction — if not all — of the steam is directed to a new low pressure turbine. The pressure at the outlet of the new turbine is maintained at a higher level than standard atmospheric pressure. The expanded steam condenses in a large heat exchanger, which yields the corresponding heat to a ternary water circuit connected to the MHT line. Depending on the output temperature chosen, the condensed water can either be sent directly to the feedwater tank or reheated slightly. Control of the steam fraction diverted to the new turbine can ensure flexible operation to follow variations in heat demand. Overall, the plant modifications are moderate and most can be made without impeding plant operation.

4.3.3. Using present nuclear power plants for district heating

4.3.3.1. Main heat transport line

The main infrastructure in terms of both installation work and investment cost is the MHT line. The long distance, hot water pipeline serves a number of secondary water loops that exchange heat with local district heating networks in many different substations. The MHT line consists of a pair of pipes, one carrying the flow of hot water from the nuclear plant site to the city secondary station at a temperature of 100–120°C, and the other carrying the return water after heat utilization at temperatures of 40–70°C. To reduce environmental impacts, the MHT is generally buried underground, which also makes use of the thermal insulation properties of the soil.

The pipes can be either laid in a trench or in a tunnel. Digging a trench is less expensive than excavating a tunnel, but impractical in cities. Consequently, MHT pipes are generally laid in trenches where possible and in tunnels where ground civil work is more difficult. The movement of water causes friction along the inner surface of the pipe, so its velocity, and hence pressure, gradually decreases. Pumping stations along the MHT line compensates for this drop in pressure. Typically, one pumping station is installed approximately every 20 km, and its power consumption needs to be included in the overall cogeneration system. In the case of a Finnish project, the pumping power is estimated at 4% of the total transported heat power [60].

4.3.3.2. Nuclear power plant operation and coupling

A nuclear power plant can be coupled to a district heating system in a similar manner to a CHP plant. The multiple closed circuit loops between the primary coolant of the reactor core and the final user (at least five levels) excludes any possibility of radioactivity transfer. The change in heat demand will not affect the reactor operation if the secondary loop is designed as explained above. However, modifying the heat output will impact the generated electric power of the plant, which has to be compensated by the grid operator. This could be easily planned depending on the seasonal and the weather forecast.

4.3.3.3. Safety issues

Although the safety issues of nuclear cogeneration mode are basically the same as those for a nuclear facility, there are some specific safety aspects on the coupling of the plant to the district heating system. In a cogeneration mode, active cooling is ensured by the MHT system in replacement of the usual heat sink (sea, river or cooling tower). Any failure of this (e.g. pipeline rupture or heat exchanger defects) impacts the cooling performance of the nuclear part. In that event, priority is always given to the nuclear power plant, with an immediate switch back to a standard, 100% electric operation mode. With huge thermal capacity, however, the MHT line does offer an alternative heat sink to the nuclear power plant and, in that sense, a district heating cogeneration setup may even enhance the safety level of the nuclear power plant.

With regard to the reliability of heat production, the high availability of nuclear power plants (>80%) does not exclude the possibility of a potential loss of full power. Although this is more a concern for the heat system operator than a safety issue, the problem could be dealt with in two ways. First, more than one reactor generally operates at a nuclear site. If two reactors are properly equipped in the turbine hall, the second reactor can be switched on if the first one fails. The probability of both of them failing is extremely small. Second, backup boilers or CHP plants can be installed either at the nuclear site or at each secondary station location to provide the required heat in case of plant failure.

4.3.3.4. Cost of implementation

District heating systems are very capital intensive, with the investment cost much higher than the operating cost. The total cost can be divided into three parts: distribution, heat production and transport. Distribution costs are directly connected to the secondary district heating network and are independent of the heat source. They may vary with the number and density of customers, their geographical location and the history of the network. Heat production costs encompass all modifications to the nuclear power plant, including the control–command and the connection to the MHT system. Production costs determine the selling price from the producer (the nuclear power plant owner) to the MHT system operator. The construction cost of the MHT line represents the major part of the investment cost and can be as high as €10 million per kilometre. This level of investment is only suitable for large power heat loads. In order to be competitive in the heat market, nuclear cogeneration should aim at total heat cost below €50/MW·h considering that the average 2009 heat price in Europe was approximately €60/MW·h.[8]

[8] See www.euroheat.org

4.3.3.5. Savings in CO_2 emissions

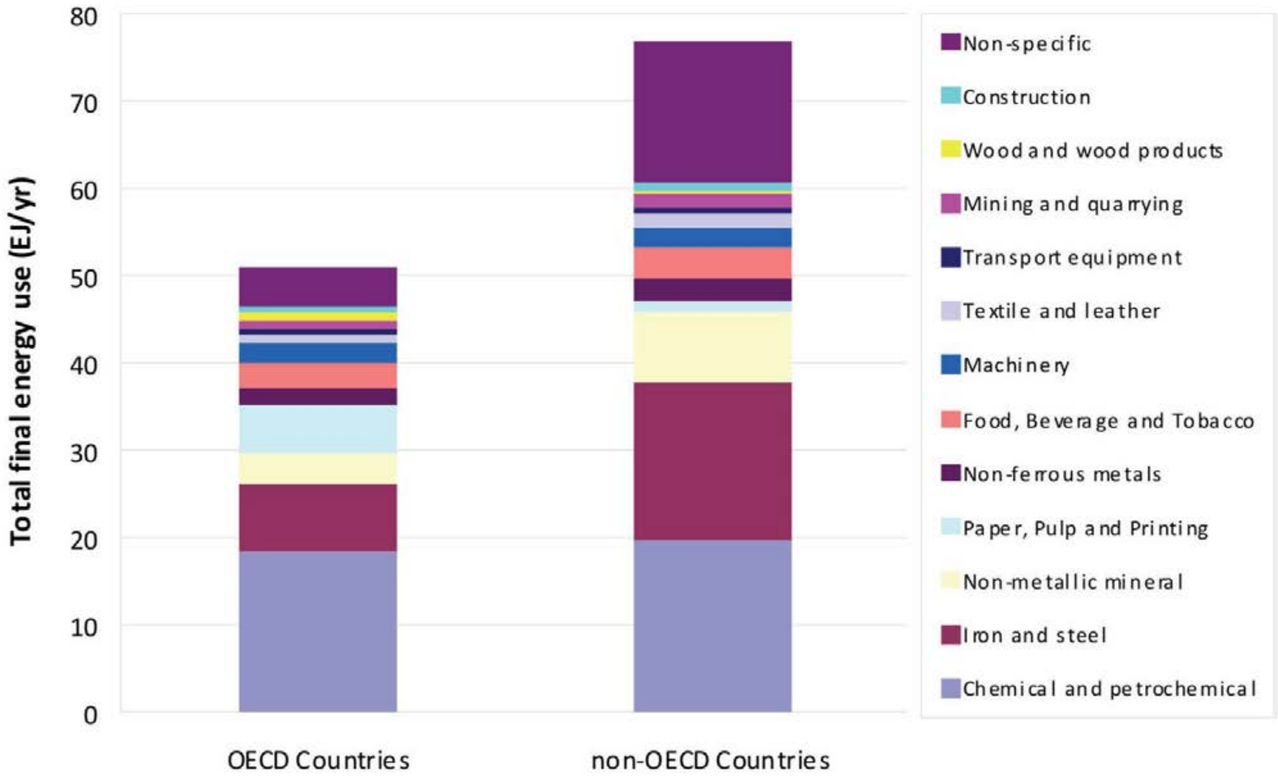
As nuclear is a carbon free energy source, large savings are expected from the recovery of heat from operating nuclear power plants. If a modified nuclear reactor delivers 10 TW(th) each year in addition to the electricity production, the estimated carbon emissions can be reduced by as much as 2 million tonnes of CO_2 per year.

4.4. HYDROGEN PRODUCTION

The large scale production of hydrogen using nuclear energy has been subjected to detailed theoretical and experimental studies. It is the focus of various R&D programmes to reduce fossil fuel consumption and to move towards an energy economy based on the environmentally benign energy carrier (see Ref. [18]). The GTGTR300C is a commercial hydrogen cogeneration plant design by the JAEA [33]. It employs a 600 MW(th) HTGR. For the hydrogen cogeneration, there is an IHX in serial between the reactor and the gas turbine (for further information on the plant description and safety issues for such an application, see Refs [18, 54, 61–63]).

4.5. OTHER INDUSTRIAL APPLICATIONS

The CHP operation mode has long been used as a means to optimize energy flows and to minimize losses, thereby improving energy (and fuel) efficiency and security, and reducing industrial CO_2 emissions. Around one third of the total final energy consumption is consumed by the industry sector. The share of industrial energy consumption in countries which are members of the Organisation for Economic Co-operation and Development (OECD) was around 40% (~51×10^{18} J). Figure 26 shows a breakdown of the total final industrial energy use according to different industry sectors.



Source: Figure 1 of Ref. [64].

Note: Data include feedstock use for petrochemicals, coke ovens and blast furnaces, and exclude the energy use of petroleum refineries.

FIG. 26. Sectoral breakdown of total final industrial energy use in OECD members and non-members in 2007.

Industries with a high and constant demand for steam and power and the need to handle considerable amounts of byproducts or waste fuels are ideally suited for cogeneration. The chemical and petrochemical sectors (and also iron and steel) are the most energy intensive, accounting for approximately 50% of the total final industrial energy use [64]. Together with food, pulp and paper sectors, they represent more than 80% of the total electric capacities at existing CHP installations [65]. Other sectors with a significant industrial energy share are the non-ferrous metals and non-metallic minerals industries. The United Nations Industrial Development Organization reports that only "a relatively small number of plants are involved worldwide in the energy-intensive bulk materials industry" [64]. Most widely spread in industrial CHP systems are combustion turbines. There are typically fuelled with natural gas; however, coal, wood and process byproducts are also extensively consumed, especially in large CHP systems, in industrial processes such as heating and drying, and in indirect applications such as the generation of steam, hot water or hot air [65].

Most industries carry a large potential for nuclear energy to cover a part of their heat/steam demand. In most cogeneration plants, be it fossil fuel or nuclear, the principal product is electricity. The amount of electricity that is produced from CHP has been increasing gradually and currently accounts for 10% of total global electricity production [65]. However, if heat or steam is to be provided at higher temperatures, some of the electricity production needs to be sacrificed.

Csik and Kupitz [43] report on the highly fragmented nature of the industrial heat market:

> "Regarding the power ranges of the heat sources required, similar patterns are found in most industrialized countries. In general, about half of the users require less [than] 10 MWth and another 40% between 10 and 50 MWth. There is a steady decrease in the number of users as the power requirements become higher. About 99% of the users are included in the 1 to 300 MWth range, which accounts for about 80% of the total energy consumed. Individual large users with energy intensive industrial processes cover the remaining portion of the industrial heat market with requirements up to 1000 MWth, and exceptionally even more."

Reference [46] reports that this last category "would be particularly disposed to nuclear applications." Industrial boiler systems are used for heating with hot water or steam in industrial process applications, and "As a customer can operate more than one boiler, it is the size of the boiler that would be most pertinent when deciding on the application of a nuclear boiler" [46].

Nuclear reactors are capable of supplying energy in the form of process heat and steam at low and high temperatures, depending on the industrial process to be coupled. High temperature nuclear heat applications comprise two fundamentally different techniques: the use of steam (up to 540°C); and the direct use of the heat transferred through a heat exchanger (up to 950°C). The simplest application for an SMR is the generation of high quality steam, and its small unit size can match the needs of the industry sector.

Nuclear reactors able to produce high quality process steam with typical parameters of 540°C and 18 MPa would meet the requirements that arise in a wide range of industrial processes. The petrochemical, chemical, metal, non-metallic mineral, food, and paper and pulp industries all have energy intensive processes which require both steam and electric power. The industrial energy supply is currently dominated by electricity (34%) and natural gas (31%).

Nuclear reactors that can generate very high coolant exit temperatures could be used to create new synthetic fuels to meet the future demand for transport fuels. Nuclear power can penetrate this market by assisting in steam methane reforming, coal gasification, oil extraction for the production of synthetic natural gas, methanol, ethanol and their derivatives and, ultimately, hydrogen fuel without emitting CO_2. Innovative applications are mainly being explored with gas cooled reactors because of their high temperature level [56].

4.5.1. Tertiary oil recovery

Verfondern [66] reports that:

> "One example with near-term prospects is the provision of high temperature heat/steam and electricity in 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. 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.…
>
> "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."

A case study of an ACR-700 nuclear plant and the coupling of nuclear process steam generation to a synthetic crude oil plant is explored in Ref. [30].

4.5.2. Fuel synthesis in the chemical and petrochemical industries

Verfondern [66] reports that a refinery with a throughput of 6–7 million tonnes per year of crude oil needs a steady supply of around 400 MW(th). Nuclear power might not be dedicated to a specific process in such a system owing to the complexity of the different chemical processes interactions, but rather cover the overall cogeneration of process steam, process heat and electricity. An additional approach will be hydrogen generation [66]:

> "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. Steam methane reforming is one of the essential process in petrochemical industry."

Verfondern [66] also finds that the coupling with nuclear as process heat source to 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.

4.5.3. Experience with nuclear industrial non-electric applications

4.5.3.1. Calder Hall Magnox reactor, United Kingdom

The Calder Hall plant comprises four Magnox reactors, each with a power of 196 MW(th) and 55 MW(e). Operated between 1956 and 2003, it was the first commercial electricity generating plant in the world. The steam generated was mainly used in a turbine for electricity production or as process heat in the nearby Windscale fuel works. The reactors were also used to sterilize hypodermic syringes and to produce radioactive cobalt, used in the treatment of cancer.

4.5.3.2. Halden Reactor Project, Norway

Although the Halden Reactor Project is not a power reactor, it is operated as an OECD project for nuclear fuels and materials investigations under a research category. It is a natural circulation BWR with a maximum power of 25 MW(th) (20 MW(th) nominal). The coolant is D_2O, and it flows as steam to two steam transformers, where its heat is transferred to a secondary circuit in which liquid (light) water flows to a steam generator. Steam is produced here in a tertiary circuit, which is either delivered as process steam at a rate of 30 t/h to a nearby paper mill for wood cooking or dumped in a river. Due to the reactor's research category, the process steam supply is regulated by an international research programme.

4.5.3.3. Gösgen nuclear power plant, Switzerland

Since December 1979, the Gösgen plant has extracted process steam as feed to a cardboard factory and other nearby heat consumers. In the turbine building, around 1% of the steam is diverted from the live steam system to heat a water/steam circuit that runs through a 1.8 km steam line to the cardboard factory. The line has a maximum capacity of 70 t/h of steam, operating at a pressure of around 1.2 MPa and a temperature in excess of 200°C. The quantity of heat transferred is equivalent to 45 MW(th). In 1996, the system was expanded to a small district heating network in nearby municipalities. In 2009, a separate water/steam circuit was built for another paper factory and was designed for a maximum throughput of 10 t/h of steam at a pressure of 1.5 MPa.

4.5.3.4. Bruce nuclear power plant, Canada

Comprising Bruce A and Bruce B with four units each, the Bruce plant is one of the largest in the world. Between 1973 and 1997, Bruce A delivered high pressure steam to a steam supply plant, from which medium pressure steam was distributed to the adjacent heavy water plant and also to a nearby industrial park and used as heat source for the D_2O production process. This plant eventually became the world's largest D_2O production plant, with a capacity of around 700 t/a and a total production of 16 000 t.

4.5.3.5. Stade nuclear power plant, Germany

Between 1983 and 2003, the Stade plant supplied a nearby salt refinery with 60 t/h of process steam at a pressure of 0.8 MPa and a temperature of 270°C. About 95% of the steam transported by pipeline over approximately 1.5 km returns in the form of condensate. After plant shutdown, the operation of the salt refinery was also shut down.

4.6. CONCLUSION

Many low temperature cogeneration applications can be found in seawater desalination, district heating, hydrogen production and industrial processes, representing a large potential for integration of nuclear energy cogeneration of heat and electricity.

The desalination technologies MSF, MED and RO are well established and have the potential for further improvement. Combined with a nuclear reactor, the desalination facility can focus solely on freshwater production or also be used for the cogeneration of electricity. The technical feasibility, reliability and safety of integrated nuclear desalination has been successfully demonstrated worldwide.

There are three main benefits of nuclear cogeneration with district heating. First, it significantly enhances the energy production and efficiency of power plants. Second, it provides a good investment for the future, ensuring a long term, stabile district heat price: once the MHT line is fully amortized, the remaining total heat cost will be significantly lower than any other energy source. Third, it has a much reduced carbon footprint and could make an essential contribution to the decarbonization of energy in the 21st century.

Hydrogen is a promising energy carrier of the future. Using electricity in conventional (low temperature) electrolyzers to produce hydrogen presents a near term option for distributed hydrogen generation. Several national and international collaborative R&D programmes are investigating different nuclear hydrogen production technologies and high temperature applications of nuclear energy.

5. SAFETY CONSIDERATIONS

5.1. SITE CONSIDERATIONS[9]

In addition to the typical siting of nuclear plants, close location to the load centres is desired. However, the trend is to choose remote, but accessible, locations to mitigate any consequences of an accident. Siting far from densely populated areas makes it easier to comply with regulatory requirements. Furthermore, plants need to be near a ready supply of cooling water.

[9] This section is based on Ref. [67].

The supply of steam to an industrial process generally requires the nuclear facility to be near the industrial plant. For the design and the site selection, the following apply:

— For a given steam delivery pressure, the unit energy cost of steam transmission increases with distance and decreases with transmission capacity and inlet pressure.
— Steam transmission costs decrease as the steam delivery pressure decreases.
— The use of compressors in steam transmission systems is generally not economical.
— Hot water can be delivered up to a distance of 150 km with a heat loss of 2%.

Building a nuclear facility near industrial plants, which might also be near populated areas, requires additional considerations. Some potential issues include the following:

— Requirements for additional safety features;
— Plans for the safe and orderly shutdown of the industrial process and the sheltering or evacuation of industrial facility staff in the event of an accident;
— Detailed plans for public notification, sheltering or evacuation in the event of accidents;
— Increased requirements for public education and programmes encouraging public acceptance.

The specific requirements will be determined by the reactor type, the nature of the industrial process, the distances from the industrial facility and population centres, and prevailing public attitudes. A new generation of smaller reactors with passive safety features might at least partly mitigate some of these issues.

5.1.1. Site considerations for a desalination plant

As described in Section 3, the site of a nuclear desalination plant should be near a seawater source (for a detailed account, see Ref. [10]). This will reduce the cost for the intake system and the cost for bringing raw sea water to the inside battery limits of the plant. For the smooth running of commercial plants, the availability of sea water needs to be ensured throughout the year and also under all conditions of high and low tides. This helps to reduce the cost of water disposal and to protect the environment. Types of possible seawater intake system and other related considerations include the following:

— Beach wells;
— Intakes through open channels;
— Intakes through gravity pipes;
— Intakes through suction;
— Seawater jetties.

The location of the intake point is based on seawater analyses and bathymetric surveys, which measure water depth with an echo signal. The seawater intake and reject disposal systems will depend on the type of system (once through or recirculation), the availability and seasonal variations of the source, and natural flow directions (see Fig. 27). Additional considerations for the location include coastal regulations, fishing and navigational activities in and around seawater source, and the availability of primary infrastructures (e.g. roads and transport, power sources, health centres, schools and markets).

Nuclear desalination plants also need the steam to be drawn from the nuclear power plant building to the coupling system. Secondary low and high pressure steam needs to be generated and then fed into the heating section (brine heater) of the MSF/MED based plants. A small quantity of high pressure steam is also required for the vacuum system. It reduces the cost of steam supply if the desalination plant is located near the nuclear power plant, and it also reduces the loss of steam temperature and pressure in transmission.

In addition to the raw sea water and steam supplies, the product water storage capacity and its distribution system is important for the site consideration. The storage tank is generally located inside the nuclear desalination plant battery limits. The size of intermediate storage tank usually accommodates a minimum production capacity of one hour.

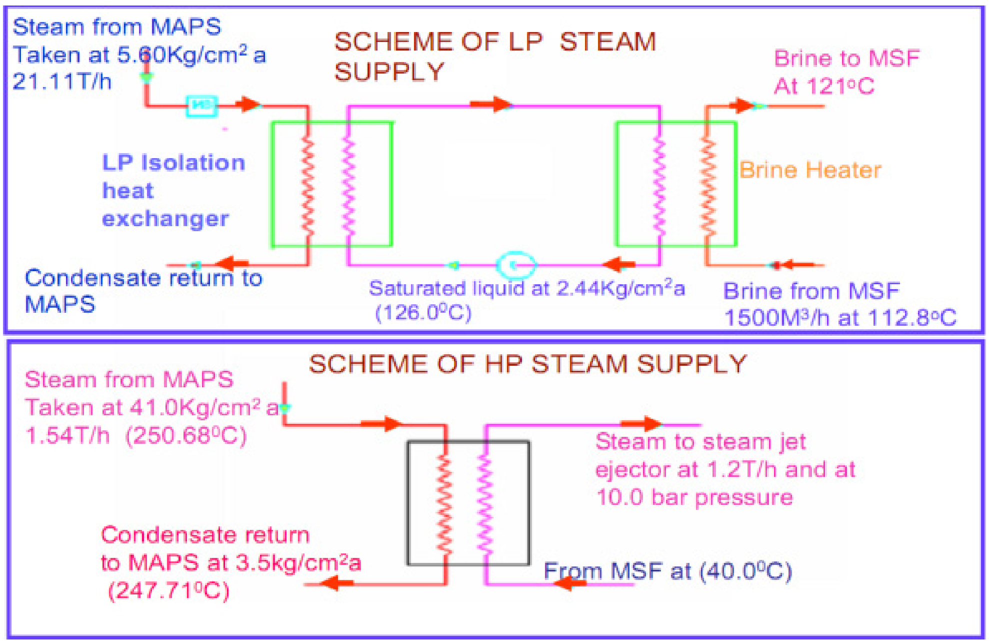
Reject disposal system   Multistage flash–reverse osmosis system

FIG. 27. Reject disposal at the nuclear desalination demonstration project, MAPS, Kalpakkam.

5.1.1.1. Madras Atomic Power Station

The nuclear desalination demonstration project site was selected next to Madras Atomic Power Station (MAPS) based on the above considerations. The coupling system for low and high pressure steam was installed inside the MAPS area to contain any possible leakage of primary steam. Steam requirements and quality are as follows (see Fig. 28):

(a) For the MSF process, steam at an absolute pressure of 0.25 MPa heats brine to a temperature of 121°C (the steam jet ejector is at 1.5 MPa).
(b) Steam is generated in the low and high pressure IHXs.
(c) Steam drawn from MAPS is in the primary circuit of the heat exchangers.



Note: HP — high pressure; LP — low pressure; MSF — multistage flash.

FIG. 28. The low and high pressure steam supply system to the nuclear desalination demonstration project, MAPS, Kalpakkam.

(d) Low pressure steam is extracted from the cold reheat line (i.e. outlet header of high pressure turbine before the moisture separator).
(e) High pressure steam is extracted at 4 MPa from the live steam header to hogging (or startup) ejector of MAPS.

5.2. SYSTEM COUPLING

As reported in Ref. [30], coupling a nuclear heat source to any industrial process heat application can be either be done with a heat transfer via an intermediate helium circuit from the reactor to the process heat plant, or with a heat transfer directly from a (nuclear grade) high temperature heat exchanging component in the primary circuit into the chemical process.

In operating HTGR plants such as Fort St. Vrain, in the United States of America, and the THTR-300, in Germany, the heat of the primary circuit is transferred directly to the steam generator for steam production. With the THTR-300, the nuclear steam reforming concept was based on a direct heat transfer to the process gas in the reformer tubes. Most new concepts of nuclear process heat applications, however, are based on the concept of an intermediate circuit, in which heat from the secondary helium is transferred in a process heat exchanger to the industrial process.

Heat exchangers play an important role in the cycles, since they connect reactors and pipelines to transport reactants and allow for heat input or recovery. The need of an IHX for the decoupling between the primary circuit and the heat utilization system is given for the following reasons [61]:

— Separation of the nuclear island from the chemical plant reduces the risk of any safety related interactions.
— Limitation or exclusion of radioactive contamination of the product (e.g. tritium).
— Control on corrosive process media for the exclusion of ingress into the primary circuit.
— Near conventional design of heat utilization system with ease of maintenance and repair.
— Flexibility in system design (e.g. in the choice of coolants for the intermediate circuit).

Verfondern [61] also notes that the “physical separation allows for the heat application facility to be conventionally designed, and repair works to be conducted under non-nuclear conditions.” The employment of an indirect cycle, however, has some disadvantages [30]:

— The requirement of an IHX as an additional component, which increases capital costs;
— The decrease of temperature potential of heat transferred to production facilities due to additional heat losses, which reduces plant efficiency.

Further information on the IHX for nuclear cogeneration for high temperature industrial applications can be found in Refs [30, 68].

5.3. PRESSURE REVERSAL

The system coupling in a nuclear desalination plant is an accepted safe practice for cogeneration. It is, however, important to use the pressure reversal technique as an engineered safety feature, consisting of a three loop concept, which provides a multiple barrier system for isolation between the nuclear plant and the desalination plant. Two possible engineering design features have been adopted to address possible leakage of radioactive material from the nuclear plant to the desalination plant. Referred to as the “High-Low-High configuration” and the “Low-High-Low configuration” [69], they have been used for the MSF plant coupling with MAPS, in Kalpakkam, and the LTE plant coupling with CIRUS, in Trombay. The regular monitoring of the intermediate loop with regard to conductivity, pH and tritium radioactivity are important, and these have been found working quite satisfactorily (for further information, see Ref. [69]).

5.4. MONITORING[10]

The limits for the discharge of radioactivity to the environment are normally specified by national regulatory bodies, and are often based on internationally agreed values. Brine and cooling water discharges and product water need to be analysed for possible radionuclide contamination. The radioactivity level allowed in the water and heat distribution circuits for other heat utilization applications will depend on the usage. The allowable limit, for example, in a district heating system may be higher than that in a system which produces drinking water.

For nuclear desalination, the aim is to comply with national and international drinking water standards based on state of the art technology. The value may be so low that continually monitoring the distribution stream at this value is not technically possible. In this case, radiation monitoring technology which measures closest to the limit can be used to determine whether to shut down the process before radiologically significant quantities of water have been released. Monitoring at other locations may also be considered, for example in an intermediate loop, where the concentration of contaminates may be higher during a malfunction.

While continual monitoring in the product stream may be difficult because of sensitivity limitations, supplemental periodic batch monitoring is usually possible for radionuclides with low detectability thresholds. Batch monitoring can require the product water to be collected in storage tanks or reservoirs prior to its release to the distribution system. The hold up time needs to be sufficient long to complete the monitoring. Although radiological limits for drinking water are available, advances in technology mean that existing limits might no longer be acceptable, and it may be necessary to re-evaluate proposed limits.

5.5. TRITIUM

The main sources for tritium in the reactor core are ternary fission and neutron captures on boron (control rods). In HTGRs, important sources are impurities (e.g. boron and lithium) in graphite (~35%), and activation of ^{3}He in the helium coolant (~15%). Due to tritium's small size, it can leak from the primary system through heat exchanging systems or the gas purification plant. The fluid in the process is not directly incorporated in the chemical process but rather used as a heat carrier only (process heating or turbine driving), so the tritium contamination of the industrial products may not be significant (i.e. below the sensitivity limit of the measurement): for example, if the steam of the tertiary circuit is used directly to produce hydrogen, which is a raw material for resins or synthetic fuel. In most cases, however, the steam is used for heating process products or driving turbines. Here the tritium migration to the industrial products should be negligible.

In a nuclear desalination plant, the pressure of brine in the brine heater is always kept around 25 kPa higher than the heating steam pressure entering to prevent any leakage of tritium in the recycled brine. Tritium in the streams tends to be at the background level, close to that of sea water, with concentrations measured in the steam and water of the thermal sections of the BN-350 plant not exceeding 6 Bq/kg (allowable level for drinking water is 30 kBq/kg).

Reference [30] reports that tritium, like most impurities in the helium coolant, is effectively removed from the circuit by the gas purification system. The degree of removal depends on how much of the coolant is bypassed through the purification system. Another measure of minimizing the escape of tritium (and other radionuclides) from the primary circuit is the operation of the secondary circuit at a higher pressure. An important sink for tritium in the HTGR are the graphite structures, where the tritium is bound by adsorption, chemisorption, and eventually diffusion into the inside of the graphite.

Reference [30] reports that "For HTGRs, what is most important is the capability of tritium to pass through metallic walls, penetrating the water/steam and/or product gas cycle." The permeation process depends greatly on material and surface effects as well as temperature and pressure conditions. The in situ formation of an oxide layer significantly reduces the tritium permeation rates. Furthermore [30]:

> "A drawback of protective oxide layers is their poor stability against temperature cycling. The controlled addition of water vapour may enhance the formation or repair of oxide layers. In this case, graphite corrosion may be carefully monitored. Pre-oxidation of the metals could also be an option."

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[10] This section is based on Ref. [33].

Reference [31] reports that the major contaminant of produced hydrogen is tritium because of its high diffusion permeability and relatively short half-life. Tritium is one of the most important dose forming nuclides, and different reactor types generate it at different rates. Tritium generation in HTGRs is around 19 GBq per year per 1 MW(th). IAEA Safety Standard Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [70], recommends a dose limit of 1 mSv/a for the public.

5.6. CONTROL AND OPERATION STRATEGIES

5.6.1. Control and operation strategies for a desalination plant

Instrumentation and control (I&C) systems are important for smooth operation, the ability to monitor process parameters, and performance evaluation of any plant. A desalination plant could be designed for manual, semi-automatic or fully automatic mode of operation. The I&C strategies adopted in a typical MSF desalination plant include the following:

— I&C components for intake and reject disposal systems;
— I&C components for steam and condensate systems;
— I&C components for balance systems;
— Details of various controls provision;
— Details of motorized valves and pneumatic control valves;
— Control room details and layout;
— Data acquisition system (DAS) details and logistics;
— Data for manual recordings not included in the DAS;
— Staff for recording manual, recordable data and data from DAS for quick assessment of plant performance.

The plant utilities and support systems required for MSF plant operation include the following:

— Normal power supplies to plant equipment and machinery;
— Emergency power supply systems;
— Compressed air systems;
— Service water supplies and availability at different plant locations;
— Communication systems;
— Emergency preparedness (e.g. firefighting and first aid);
— Transport systems for 24 hour operation;
— Administrative and canteen facilities.

The sample analysis of a typical MSF desalination plant is given in Table 15. A supervisory control and data acquisition system with sufficient screens to see the operating process parameters in a programmable logic controls interface are being designed and installed for recording purposes in all modern desalination plants.

TABLE 15. SAMPLE ANALYSIS OF A TYPICAL MULTISTAGE FLASH DESALINATION PLANT

Sample	Analysis
Raw sea water	Conductivity, pH, radioactivity, free Cl
De-aerator feed	pH
De-aerated feed	Dissolved oxygen, pH, $CaCO_3$, CO_2
Recirculating brine	Conductivity, pH, dissolved oxygen

TABLE 15. SAMPLE ANALYSIS OF A TYPICAL MULTISTAGE FLASH DESALINATION PLANT (cont.)

Sample	Analysis
Blowdown	Conductivity, pH, radioactivity
Product water	Conductivity, pH, radioactivity
Hydrochloric acid	% HCl
Caustic soda lye	% NaOH
Caustic soda solution	% NaOH
Brine heater condensate	Conductivity, pH, radioactivity
IHX condensate	Conductivity, pH, radioactivity
Blowdown from low pressure IHX	Conductivity
Blowdown from high pressure IHX	Conductivity
High pressure feedwater	Conductivity, pH
High pressure steam (condensed)	Radioactivity
Reject sea water	Radioactivity, pH, suspended solids, oil and grease, free Cl, biological oxygen demand, chemical oxygen demand

Note: IHX — intermediate heat exchanger.

5.6.2. Flexible operation

One major advantage of working in a cogeneration mode is the added flexibility offered to the electric grid. Whenever electricity production does not perfectly match demand on a given power grid, it usually translates into an overall frequency shift. To compensate for this mismatch, some controllable production sites could be asked by the grid operator to adjust their power accordingly. The primary, secondary and tertiary levels of frequency control correspond to three different speed controls. The primary is generally an automatic control implemented in the power plant control system and can act in a time frame of a few seconds. The secondary control can be either automatic or manual. Its time response is less than 15 minutes, and if required, it can cover a larger power range than the primary. The tertiary control is almost always manual. It basically covers a number of power units able to start or stop at will to recover lost margins due to secondary reserve solicitation. Tertiary control recovery can be very slow (hours), enabling the reserve capabilities needed for a secondary control operation to be brought back on-line progressively.

Although generally operated in a continuous baseload mode, nuclear units can be involved in the frequency control of the electric grid. This is mandatory whenever the nuclear share of electricity production is a significant part of the total electrical power. This is also the case if a large amount of intermittent renewables power (e.g. wind and solar) has been introduced in the electricity generation mix. Although achievable, power ramping of a nuclear power plant is bounded by technical limits and constraints. The thermomechanical stresses induced on the fuel cladding and some structural components in the core can limit operational range or reduce lifetime. Consequently, power ramping is limited to less than 5% per minute. In the case of a complete shutdown, power restarting procedures are long and are required to obey very strict procedures. Therefore, whenever a nuclear power plant contributes to a reserve capacity backup, its operational range is limited to 80% of its nominal power rating and the lowest acceptable output power level is kept above 20%.

Operating a nuclear power plant in a cogeneration mode can easily relieve all of these constraints while offering a full and fast adjustment of the electrical output power of the plant. The primary circuit of the nuclear power plant may always work in a continuous mode at a full thermal core power, delivering at any time part of the nominal electrical power to the grid together with a cogeneration production using the remaining available heat. In that way, flexibility is ensured by deriving part of the thermal production to the cogenerated product — be it heat, steam, desalinated water, hydrogen or synthetic gas. No additional thermal or mechanical stress is expected from this operation on the nuclear fuel as compared with any standard baseload plant operation.

5.7. RISK ASSESSMENT CONSIDERATIONS

5.7.1. Risk assessment considerations: A nuclear desalination plant

The hazards and safety measures at any desalination plant typically deals with electrical, thermal, chemical and high pressure handling systems and equipment. Personal safety gear, first aid and emergency contact numbers are important and need to be provided to the operating personnel. Like any nuclear installation, personal monitoring using thermoluminescent dosimeter badges in the coupling area of the isolation heat exchangers is to be practised at a nuclear desalination plant.

There are specific risk assessment considerations for a nuclear desalination plant in the case of retrofitting a nuclear power plant. Through redundancies in the system design using alarms, trips and standby provisions, safe long term or short term shutdowns are incorporated from the beginning of plant design (for further information, see Ref. [10]).

At the retrofitting of MAPS, in Kalpakkam, the intake seawater pipe lines were taken from the MAPS outfall rather than disturbing the main seawater intake system meant for reactor cooling. The rejects from the seawater RO and MSF plants were mixed before being disposed of in the sea, causing minimal effects to the environment and aquatic life.

At the LTE nuclear desalination plant attached to the 40 MW(th) CIRUS reactor, in Trombay, the risk assessment was carried out in terms of the possible changes in flow and temperature of the primary cooling water and seawater system before implementation of the project (see Table 16). The rise of the primary cooling water inlet temperature by 1.3°C does not have significant effect on the reactor system operations, as the desalination plant is designed for a 1 MW(th) load and the LTE plant capacity is enough to meet the make-up water requirement of the CIRUS reactor.

TABLE 16. CHANGES IN FLOWRATES AND TEMPERATURES OF PRIMARY COOLING WATER AND SEAWATER SYSTEMS AT 40 MW(th) OPERATION

Parameters	Case I: Existing CIRUS reactor	Case II: Proposed modifications	Case III: Non-availability of desalination unit
	Core		
Primary cooling water			
Flow (L/min)	17 700	17 700	17 700
Inlet temp. (°C)	45	46	47.3
Outlet temp. (°C)	76.2	77.2	78.5
	Heat exchangers		
Primary cooling water	3 540	3 285	3 285
Flow (L/min)	76.2	77.2	78.5
Inlet temp. (°C)	45	44.4	44.8
Outlet temp. (°C)			

TABLE 16. CHANGES IN FLOWRATES AND TEMPERATURES OF PRIMARY COOLING WATER AND SEAWATER SYSTEMS AT 40 MW(TH) OPERATION (cont.)

Parameters	Case I: Existing CIRUS reactor	Case II: Proposed modifications	Case III: Non-availability of desalination unit
Sea water			
Flow (L/min)	6 265	6 175	6 175
Inlet temp. (°C)	29	29	29
Outlet temp. (°C)	46.2	46	46.5
Intermediate heat exchanger			
Primary cooling water			
Flow (L/min)	—[a]	1 280	1 280
Inlet temp. (°C)		77.2	78.5
Outlet temp. (°C)		65.8	78.5
Seawater system			
Primary cooling water			
Flow (L/min)	33 600	35 150	35 150
Inlet temp. (°C)	29	29	29
Outlet temp. (°C)	45.7	45	45

Source: See Ref. [71].

[a] —: data not available.

5.7.2. Risk assessment considerations: Nuclear cogeneration

In general, risk assessment for nuclear cogeneration encompasses three different areas [72]:

(1) Deterministic and probabilistic risk assessments to support licensing of advanced reactor technologies that interface with industrial process facilities;
(2) Risks associated with development, deployment and commercialization of advanced reactor technologies;
(3) Assessments associated with the industrial process facility that could impact safety of the nuclear cogeneration facility.

With regard to the first area, the NGNP project has initiated prelicensing activities with the NRC to address the unique aspects of HTGR design and interfacing these reactors with industrial facilities. These prelicensing activities include preparation of a number of white papers for NRC review and comment, including a white paper focused on the approach for probabilistic risk assessment [73].

With regard to the second area, an overall process for assessing risk and driving risk mitigation for advanced reactor development and deployment was developed under a NGNP project [72]. The NGNP project had the goal of designing, licensing, constructing and operating a HTGR for the cogeneration of electricity and process energy for a range of industrial applications. Collins [72] reports that:

"The approach consists of the following functions and planning actions:

- Risk identification
- Risk quantification
- Risk handling strategy
- Residual risk workoff"

Risk types include both technical and programmatic risks, and risks are scored for probability of occurrence and severity of consequences [72].

The risk handling strategy includes the following elements [72]:

- Risk acceptance if the risk is acceptably low;
- Risk mitigation to identify specific steps or actions to reduce probabilities and consequences;
- Risk avoidance to identify design alternatives that completely eliminate the risk;
- Risk transfer to identify options for transferring the risk to a third party (typically applies more to programmatic risks).

Collins [72] reports that risks "are mitigated by applying a systematic approach to maturing the technology through research and development, modeling, testing, and design. Tasks needed to mature the technology and reduce project technical risks are developed and documented in a Technology Development Roadmap", also known as an engineering development plan (EDP).

An EDP was prepared as part of the conceptual design of the NGNP steam cycle cogeneration demonstration plant [74]. This EDP defines the base technology development, the analysis methods development, and the design verification and support programmes required to support conceptual design and licensing. The EDP contains plant specific design data needs (DDNs), summary descriptions of planned test programmes, and schedule and cost estimates for critical structures, systems and components (SSCs) that are not commercially available or are judged to be not fully qualified from previous operating HTGRs. It is possible that some DDNs might not be satisfied as the result of technology programme funding priorities. All DDNs include one or more fallback positions in the event the DDN is not satisfied. Typical fallback positions are to adopt more proven technologies or to include larger margins in the design.

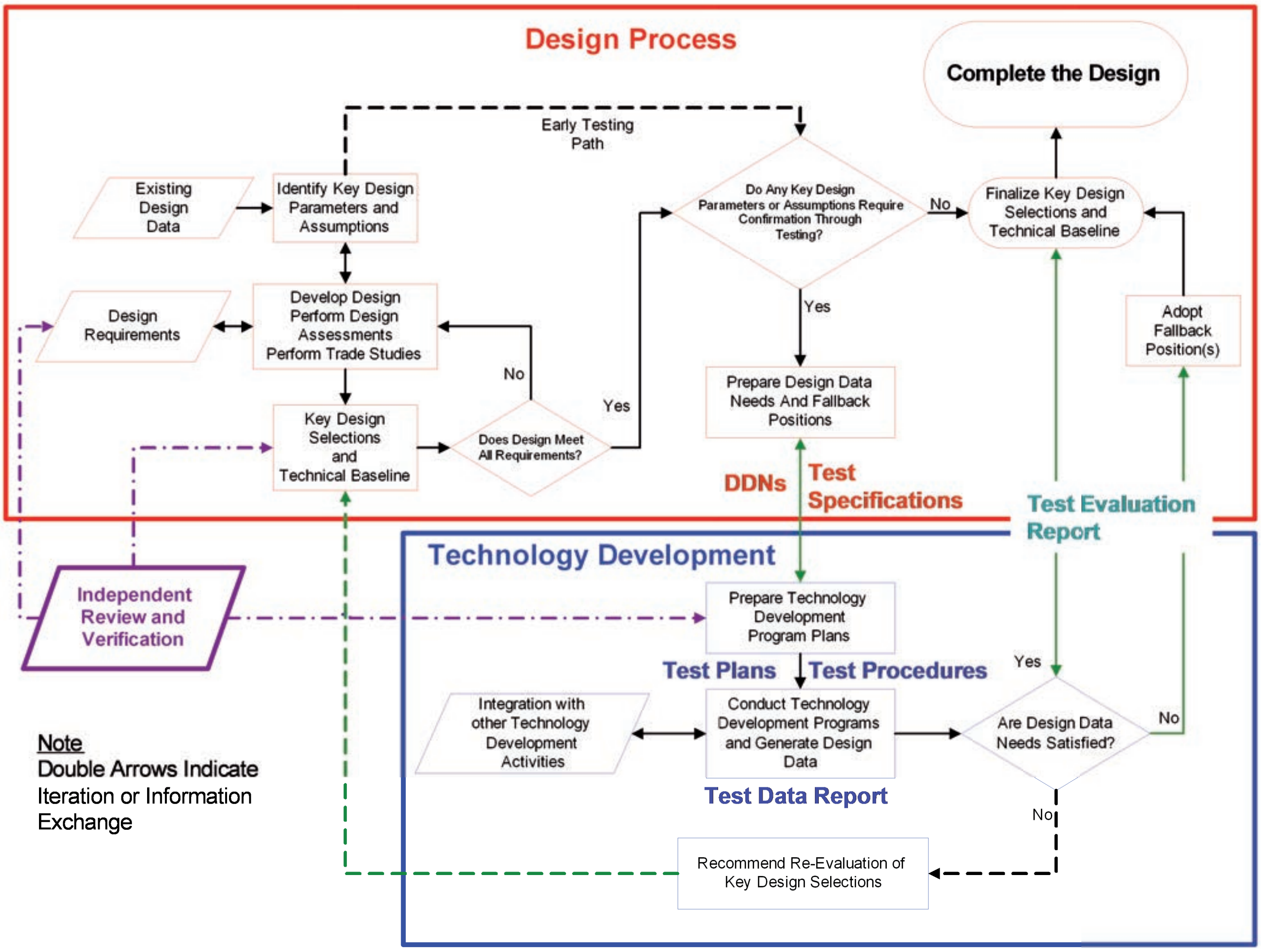
The approach for integrating design and technology development is illustrated in Fig. 29. This approach has been developed to maximize the benefit of the technology development programmes in terms of supporting plant design and licensing and to minimize the technical risk. The process begins by evaluating design requirements and reviewing existing design data from a variety of sources. Design assessments and trade studies are performed, eventually leading to key design selections and a technical baseline that meets all design requirements. At this point, a design has been developed that meets all requirements, but requires some technology development to confirm assumptions upon which the design is based. If necessary, the process also allows for a testing path to provide early confirmation of critical design assumptions (e.g. qualification of an advanced nuclear fuel). Further information on this can be found in Ref. [75].

With regard to the third area, an assessment was performed as part of the NGNP conceptual design to define the approach for including risks from the industrial process facility on the nuclear facility [47]. This approach included the following elements:

- Performance of a process hazards assessment of the industrial process facility;
- Preliminary screening evaluation of event sequences associated with process hazards;
- Detailed risk analysis of event sequences associated with process hazards and the impact of facility operations on the nuclear plant.

These elements should be included as part of the probabilistic risk assessment elements discussed above. As described in Ref. [47], the types of scenario that need to be considered in the definition of licensing basis events involving industrial process facilities include the following:

(a) Fires, deflagration explosions and detonation explosions that could occur at, or near, the industrial process facility, sending heat and blast waves that could challenge the nuclear plant SSCs supporting safety functions or render the control room or reactor building areas inhabitable. These could occur from releases of hydrogen or other combustible materials, source material used for the production of hydrogen (i.e. methane, propane and liquefied natural gas) depending on the process that is used. The results of the process hazards assessment and the review of the facility design help to focus the scenario development on those elements relevant to the design.



Note: DDNs — design data needs.

FIG. 29. Integration of the design process with technology development to reduce technical risk.

(b) Vapour clouds that could produce fuel air mixtures (hydrogen, methane or other combustible material) that could drift towards the nuclear plant and associated SSCs supporting safety functions and ignite near, or above, the reactor building. Even vapour clouds at significant elevations above the facility can produce blast waves that can impact the facility and damage structures.

(c) Hazardous chemical releases from the industrial process facility that could be toxic to reactor operators in the control room or near the reactor facilities. Such releases could have adverse impacts on the capability of the plant operators to safely operate or shutdown the facility.

(d) Propagation of hazardous materials, either combustible or toxic, from the production facility to the reactor building via leaks in the secondary and tertiary systems.

6. ECONOMIC EVALUATION

6.1. COSTING METHODOLOGY

The methodology used for evaluating the cogeneration costs of a nuclear power plant is the same as for a standard cogeneration plant using other energy sources, such as in modern CHP stations. The evaluation of the economic benefits from generating a second product in addition to electricity has to be compared to the market value of the product.

6.1.1. Methodology for allocating the cost of cogenerated products

As the main output of nuclear power plants is the generation of electric power, the cost of electricity generation will be used as reference. The levelized cost of electricity (LCOE) allows common based economical comparisons to be made between different fuels or technologies and is represented by c_0. If C_0 represents the total annual cost of a nuclear power plant (capital costs, operating costs, fuel costs, R&D costs and taxes) generating an annual production of electricity (E_0), the reference cost per unit of electrical energy produced is:

$$C_0 = c_0 E_0 \tag{3}$$

If the plant is modified to generate another product (e.g. heat, steam, hydrogen or water), its cost will increase. In addition, the corresponding modification may alter the initial electric output, resulting in a reduction in electricity generation. If the annual production of electricity in the cogeneration mode is E', then the annual cost of the plant in the cogenerating mode (C') is:

$$C' = c_0 E' + cH \tag{4}$$

where H is the annual production of the cogenerated product and c is the levelized cost of the cogenerated product (LCOH). The cost of the cogenerated product is:

$$cH = \left(C' - C_0\right) + c_0\left(E_0 - E'\right) = \Delta C + c_0 \Delta E \tag{5}$$

where ΔC is the increase in annual costs due to cogeneration and ΔE is the loss in electricity production due to cogeneration.

6.1.2. Nuclear power plant cost increase in a cogeneration mode

The annual cost increase (ΔC) depends on the final product generated. Therefore, any precise evaluation of the cost increase can only be made on a case by case basis, considering the overall economic, environmental and regulatory conditions. Safa [44] demonstrates that wasted heat could be advantageously recovered from a nuclear power plant to heat large cities — even when situated far from the plant. The actual cost at the delivery points (i.e. cities and industries) includes transport and distribution costs of the produced heat. These costs will ultimately represent a significant portion, especially over long distances.

6.1.3. Net present value of products

The levelized production cost of each product can be determined by discounting, at a fixed rate r, the actual production expenditures on a year by year basis over the plant lifetime (n). In the case of a pure electrical power plant, the levelized production cost of electricity (C_t) is:

$$C_t = \sum_{k=1}^{n} \frac{C_k}{\left(1+r\right)^k} \tag{6}$$

where C_k is the total plant expenditures for year k. All economic values are real monetary values time $t = 0$ (i.e. corrected for inflation). The total present value $\mathrm{PV_E}$ of the electricity production can be evaluated in the same manner:

$$\mathrm{PV_E} = \sum_{k=1}^{n} \frac{c_0 E_k}{\left(1+r\right)^k} = c_0 E_t \tag{7}$$

where E_k is the electricity production for year k and E_t is the total levelized electricity production. Thus, the LCOE (c_0) produced by the plant is:

$$c_0 = \frac{\sum_{k=1}^{n} \frac{C_k}{(1+r)^k}}{\sum_{k=1}^{n} \frac{E_k}{(1+r)^k}} \tag{8}$$

This can be simplified to:

$$c_0 = \frac{C_t}{E_t} \tag{9}$$

Consequently, the equations for the cogeneration costs still hold upon replacing each annual cost or production by its NPV, calculated according to Eq. (6). In particular, the LCOH (c) is:

$$c = \frac{\Delta C_t + c_0 \Delta E_t}{H_t} \tag{10}$$

where

ΔC_t is the increase in present value cost due to cogeneration;
ΔE_t is the loss in levelized electricity production due to cogeneration;

and H_t is the levelized amount of cogenerated product. Equations (9, 10) are considered the two main equations for establishing the actual cost of the generated products.

The LCOE (c_0) for a nuclear plant can be deduced from a costing accounting dividing the total discounted cost by the production yield as stated in Eq. (9). The total cost C_{tot} is the sum of capital, operation and maintenance, fuel, R&D and taxes:

$$C_{\text{tot}} = C_{\text{cap}} + C_{\text{O\&M}} + C_{\text{fuel}} + C_{\text{R\&D}} + C_{\text{tax}}$$

Capital costs include the overnight cost (see Ref. [74]), calculated as if the plant were built in one day, adding the interest financial overheads and risk premium during the construction time, the detailed design study, the commissioning and the project contingencies. The costs of dismantling the plant (usually 15% of the capital cost) is often added to this total investment cost upfront. Operation and maintenance costs are divided into fixed costs and variable costs (proportional to the electric output). Fuel costs include both the front end of the fuel cycle (uranium costs, conversion, enrichment and fuel fabrication) and the back end as well (reprocessing, storage and final disposal). The ultimate geological disposal for high level waste is also accounted for as provisions are taken from the electricity production to pay for the waste management. R&D and taxes on electricity greatly depend on different countries regulations and tax codes.

6.1.4. Economic performance criteria

Optimization of cogeneration performance is based on criteria such as the cost of products, return on investment (ROI) and exergy efficiency. Maximum flexibility of operation can help to achieve improved economic optimization which can react better to changes in regulations and thus minimize, the risks associated with implementing cogeneration.

6.1.4.1. Cost of products

The global optimization of the levelized cost depends on the selling price of the generated product and hence market conditions (e.g. demand profile, price at a given time and incentives). As a general rule, if g_0 is the average margin on electricity sales, then for positive overall profit, the average margin gain (g) for the cogenerated product sales is:

$$gH_t - g_0 \Delta E_t > 0 \tag{11}$$

$$\Rightarrow \quad g > g_0 \frac{\Delta E_t}{H_t} \tag{12}$$

6.1.4.2. Return on investment

The ROI can be calculated from the above as:

$$\mathrm{ROI} = r\left(\frac{gH_t - g_0 \Delta E_t}{\Delta C_t}\right) \tag{13}$$

If the additional cost (ΔC_t) is fixed, maximizing the ROI is strictly equivalent to maximizing the profit for a given discount rate (r). If not, the optimization maybe different — especially if the discount rates considered in the different economical options evaluated are not identical.

6.1.4.3. Exergy efficiency

The use of exergy helps to better assign a meaningful economic value to an energy based product. A variety of methods integrating exergy and economics have been developed, which has led to the new engineering field of thermoeconomics (see Section 7.3).

6.2. IAEA TOOLS FOR ECONOMIC EVALUATION

To address discrepancies in the economic analysis conducted by researchers and nuclear operators, the IAEA developed two standardized economic evaluation programs that analyse nuclear plants and their desalination and hydrogen generation systems.

6.2.1. Desalination Economic Evaluation Program

DEEP was developed by General Atomics for the IAEA and was later upgraded, based on user feedback, to provide more realistic results. The tool is based on a spreadsheet format to improve the software's familiarity to users. DEEP can perform comparative economic assessments of desalination plants using various power generation systems, such as MSF distillation, MED and RO. DEEP can also conduct economic analyses of nuclear, fossil fuel and renewable sources. The input data include the system configuration, power generation, water production capacity and various other cost factors (for a full description, see the DEEP 5 User Manual [76] and Ref. [77]).

6.2.1.1. Usage

DEEP is usually used for the following:

— Calculation of the LCOE and desalted water as a function of quantity, site specific parameters, energy source and desalination technology;

— Side by side comparison of a large number of design alternatives on a consistent basis with common assumptions;
— Quick identification of the lowest cost options for providing specified quantities of desalted water or power at a given location.

6.2.1.2. Models

DEEP includes models for nine power plants (three nuclear, five fossil fuelled and one renewable) and five desalination plants (two thermal, one electrical and two hybrid) [77]:

(a) Power plants:
  (i) Nuclear steam turbine: pressurized water reactor, pressurized heavy water reactor and small pressurized water reactor;
  (ii) Nuclear gas turbine: gas turbine modular helium reactor;
  (iii) Nuclear heat: heat reactor;
  (iv) Steam cycle (coal): split stream boiler;
  (v) Steam cycle (oil);
  (vi) Gas turbine: heat recovery steam generator;
  (vii) Combined cycle (steam turbine and gas turbine);
  (viii) Fossil heat: boiler;
  (ix) Renewable heat;
(b) Desalination plants:
  (i) Multi-effect distillation;
  (ii) Multistage flash;
  (iii) Reverse osmosis;
  (iv) Hybrid: multi-effect distillation + reverse osmosis;
  (v) Hybrid: multistage flash + reverse osmosis.

DEEP input variables are categorized as the following:

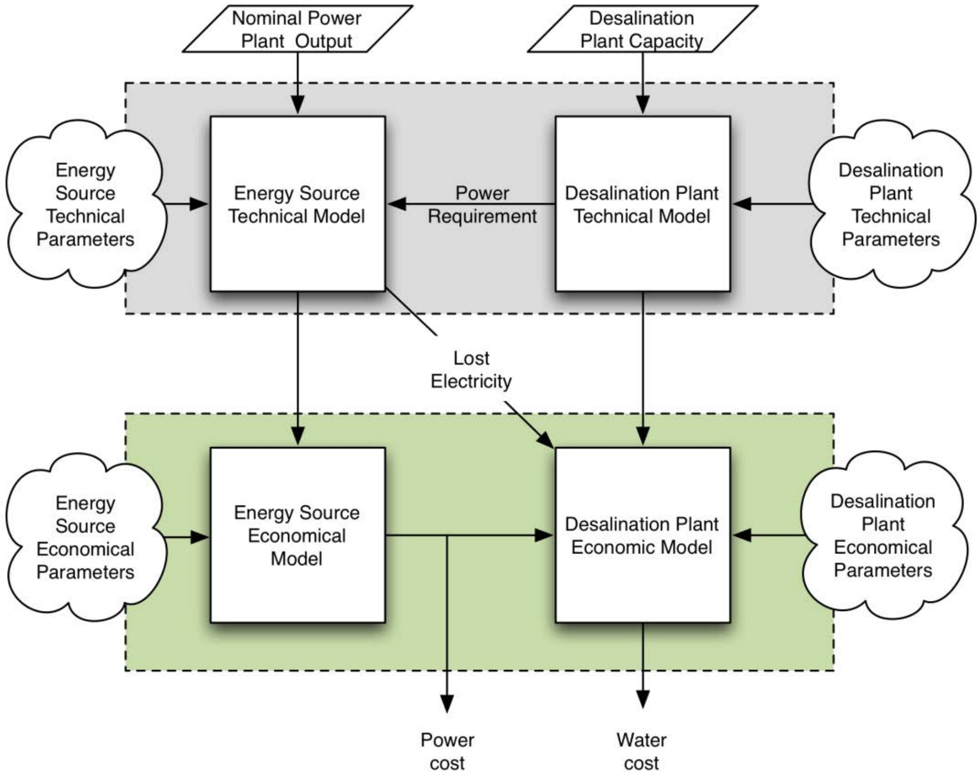
— User input data;
— Technical parameters;
— Cost parameters.

As outlined in Fig. 30 and described in the DEEP 5 User Manual [76]:

> "The benefits of the coupling of an energy source and a desalination plant are shown by using the 'power credit' method. This method is based on the comparison between the proposed dual purpose plant and an imaginary reference single purpose plant. The cost of electricity delivered to the desalination plant, is valued based on the cost of that product from alternative imaginary power plant. The cost of heat is taken to be the revenue that would have accrued from lost electricity generation (due to the delivery of heat). As a result, water is credited with all of the economic benefits associated with the plant being dual purpose. For dual purpose heat only plants that are coupled with a thermal desalination process, the levelized (heat) energy costs are calculated with the same procedure as for single purpose electricity only plants. An option for fossil fueled-backup heat is also available so that heat can be provided for desalination even if the power plant is unavailable."

6.2.2. Hydrogen Economic Evaluation Program

The Hydrogen Economic Evaluation Program (HEEP), a tool made freely available by the IAEA, is common cost assessment software for nuclear hydrogen. With similarities to DEEP, HEEP considers the source of energy, the distribution of hydrogen to end users, and its production and storage. The beta version was



Source: Figure 1 of Ref. [76].

FIG. 30. Modular representation of DEEP.

released in January 2010. The IAEA will maintain the software, facilitate its distribution and coordinate further development.

HEEP uses a discounted cash flow model that calculates the levelized cost of hydrogen, and comprises three modules:

— Preprocessing;
— Executing;
— Post-processing.

The graphical user interface provides user friendly features to the preprocessing and post-processing modules of HEEP. It is possible to model and analyse a number of combinations of heat sources, various hydrogen generating processes, and different methods to store and distribute it [78].

A wide range of plants using different hydrogen production processes can also be considered, such as electrolysis, high temperature electrolysis, and low and high temperature thermochemical cycles. It is also possible to conduct economic evaluations of plants operating on conventional processes using fossil fuels (for a full description, see Ref. [78]).

6.3. PROFITABILITY ANALYSIS

Feasibility analysis is performed to determine how a project will perform under a specific set of assumptions with regard to technology, market conditions and financial contingencies [79]. Financial viability is measured on the basis of accounting profits and projected cash flows indicating the operating profits generated year by year [79]. Cash flow methods include calculating the NPV at every step, the benefit to cost ratio and the payback period (i.e. the time required for the revenues to pay for the initial investment). Based on the equations in Section 6.1, the benefit to cost ratio for nuclear cogeneration is:

$$\frac{\mathrm{B}}{\mathrm{C}} = 1 + \frac{gH_t - g_0 \Delta E_t}{\Delta C_t} \tag{14}$$

The annual cash flow for every year k is calculated as:

$$A_k = (c+g)H_k - (c_0 + g_0)\Delta E_k - \Delta C_k \tag{15}$$

The NPV at time t is computed by discounting the annual cash flow:

$$\mathrm{NPV}(t) = \sum_{k=1}^{t} \frac{A_k}{(1+r)^k} \tag{16}$$

And the payback period is defined as the duration T of operation needed before the NPV is positive:

$$\mathrm{NPV}(T) = \sum_{k=1}^{T} \frac{A_k}{(1+r)^k} > 0 \tag{17}$$

6.4. FINANCING

Obtaining finance from the private sector for a nuclear power plant may prove difficult. Governments may ease the perceived risk by introducing loan guarantees. The main financial risks are overruns in construction costs and construction delays, which result in significantly higher costs than originally estimated. Considering all the risks, investors will pay very close attention to the rates of return on both debt and equity. The LCOE usually compensates debt and equity investors at their corresponding rates of return. The cost of equity is usually slightly higher than the cost of debt due to the increased risk taken by the investor.

In the case of cogeneration, however, the additional investment cost is generally lower than the total investment cost of the nuclear power plant. Therefore, the associated risk is also lower. An engineering, procurement and construction contract for the cogenerated product facility can be awarded to power companies offering state of the art technology. The cogeneration product system is a non-nuclear unit that could be handled by a conventional industry, providing there is a suitable interface with the nuclear power plant. Depending on the financing scheme and the size of the unit, the cogeneration production can be either run by the nuclear power plant owner or by a separate utility, which could buy the product from the nuclear power plant owner and sell it to consumers.

6.5. ECONOMIC CONSIDERATION OF THE ENVIRONMENTAL IMPACT

Implementing nuclear cogeneration provides products with almost no GHG emissions [80, 81]. If the products were to be generated by other means, especially using fossil fuels, their production would have a detrimental effect on the environment, with the economic value based on a price on GHG emissions. This price can take the form of emission permits, government incentives or a carbon tax. The dangers of global warming require an economic cost for carbon emissions to be set. This would immediately enhance the economic competiveness of nuclear power for electricity production. Savings in GHG emissions due to cogeneration can be expressed as:

$$P_{\mathrm{GHG}} = \gamma H_t \tag{18}$$

where

P_{GHG} is the price of the emission of one tonne of CO_2 equivalent GHGs;
γ is the quantity of GHGs emitted by standard fuels to produce the cogenerated product expressed in tonnes of CO_2 equivalent per unit of product;

and H_t is the levelized amount of cogenerated product. For the complete economic evaluation of cogeneration, this amount is added to the overall profit calculated from Eq. (10). The total economic benefit expressed in NPV is then:

$$\mathrm{B}_t = gH_t - g_0\Delta E_t + P_{\mathrm{GHG}}\gamma H_t \tag{19}$$

Under the assumption that nuclear power substitutes gas fuel for the production of the cogenerated product and that the carbon price is US \$20 per tonne of CO_2, savings can be made. An interesting value is the price for GHG emissions that would compensate the initial investment. Under the assumption that profit from selling the cogenerated product is zero, the economic benefit is the savings in GHG emissions. The reference price for GHG emissions is then:

$$P_{\mathrm{GHG}_{\mathrm{ref}}} = \frac{\Delta C_t}{\gamma H_t} \tag{20}$$

6.6. CONCLUSION

The economical evaluation of nuclear cogeneration is based on the cost of electricity generated by the same plant running in a pure electrical mode. Operating a reactor in a cogeneration mode clearly enhances the overall energy efficiency of the plant. In many cases, the value of the cogenerated product (heat, steam, water and hydrogen) appears to be competitive when compared to the cost of a standard fossil fuel based production. The comparison is even more favourable whenever an economical value is assigned to the reduction in CO_2 emissions.

7. ENVIRONMENTAL IMPACT AND SUSTAINABILITY ASSESSMENT

7.1. SUSTAINABLE DEVELOPMENT

After the United Nations Conference on the Human Environment, in Stockholm in 1972, people began to realize the adverse effects mass industrialization has on the environment. Hitherto, environmental problems and sustainable development had been regarded as two different issues. However, researchers now were starting to understand the need to link these two factors. The term sustainable development was used extensively at the United Nations World Commission on Environment and Development in 1987, outlined in the Brundtland Report [82], which integrated environmental issues with economic and social aspects. Sustainable development was the focus of further attention in the Rio Declaration on Environment and Development [83], which was the outcome of the United Nations Conference on Environment and Development in 1992.

The Brundtland Report [82] defines sustainable development as the following:

“1. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:
- the concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given; and

- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

Sustainability has been regarded as key to addressing environmental, economic and development problems around the world. Many organizations and researchers have explored sustainability so that it can be used as a benchmark for strategic planning.

The environmental and sustainability problems associated with the use of fossil fuels cannot be resolved by only changing the energy carrier. States have become more serious about resolving sustainability and environmental problems, and many concerned authorities have started integrating environmental and sustainability concerns into future energy planning [84]. To achieve sustainable development without harming the environment, nuclear fuel can be an alternative to fossil fuels.

7.2. ASSESSMENT METHODS

An energy system usually needs to accommodate the different expectations of governments and end users, and to address environmental and socioeconomic factors. Dincer and Rosen [2] report the following (see also Ref. [11]):

"• **Life cycle assessment.** LCA is an analytical tool used to assess the environmental burden of products at the various stages in a product's life cycle. In other words, LCA examines such products 'from cradle to grave.' The term 'product' is used in this context to mean both physical goods as well as services. LCA can be applied to help design an energy system and its subsystems to meet sustainability criteria through every stage of the life cycle. LCA, as an environmental accounting tool, is very important.

- **Environmental impact assessment (EIA).** EIA is an environmental tool used in assessing the potential environmental impact of a proposed activity. The derived information can assist in making a decision on whether or not the proposed activity will pose any adverse environmental impacts. The EIA process assesses the level of impact and provides recommendations to minimize such impacts on the environment.

- **Ecological footprints.** Ecological footprint analysis is an accounting tool enabling the estimation of resource consumption and waste assimilation requirements of a defined human population or economy in terms of corresponding productive land use.

- **Sustainable process index (SPI).** SPI is a measure of the sustainability of a process producing goods. The unit of measure is m^2 of land. It is calculated from the total land area required to supply raw materials, process energy (solar derived), provide infrastructure and production facilities, and dispose of wastes.

- **Material flux analysis (MFA).** MFA is a materials accounting tool that can be used to track the movement of elements of concern through a specified system boundary. The tool can be adapted further to perform a comparative study of alternatives for achieving environmentally sound options."

7.3. EXERGETIC ENVIRONMENTAL IMPACT AND SUSTAINABLE ASSESSMENT

A relatively new environmental and sustainable development assessment method based on exergy analysis is introduced in Refs [84, 85]. The parameters introduced include the following [84]:

— Environmental impact factor;
— Environmental impact coefficient;
— Environmental impact index;
— Environmental impact improvement index;

— Exergetic stability factor;
— Exergetic sustainability index.

The benefit of using these parameters is that they are based on an exergy analysis of the system and provide more realistic results as compared to an energy analysis. Sections 7.3.1–7.3.6 are based on the text and equations in Ref. [85].

7.3.1. Environmental impact factor

The environmental impact factor (f_{ei}) is the positive effect of the system on exergy based sustainability (i.e. supply more desired exergy output, decrease the irreversibility and minimize the waste exergy outputs during the systems operation). The reference value for this factor should be zero for better exergy based sustainability and is defined as:

$$f_{ei} = \frac{\dot{E}x_{dest,tot}}{\dot{E}x_{in}} \tag{21}$$

where $\dot{E}x_{dest,tot}$ is the total exergy destroyed by the system and $\dot{E}x_{in}$ is the total exergy carried by the fuel supplied to the system.

7.3.2. Environmental impact coefficient

The environmental impact coefficient (C_{ei}) is inversely proportional to the exergy efficiency (η_{ex}) of the system:

$$C_{ei} = \frac{1}{\eta_{ex}} \tag{22}$$

In the ideal case, its value should be one, indicating that the system is working under ideal conditions and with no exergy destruction.

7.3.3. Environmental impact index

The environmental impact index (θ_{ei}) indicates whether or not the system damages the environment on the account of its unusable waste exergy output and exergy destruction — the smaller the value, the better the system performance:

$$\theta_{ei} = f_{ei} C_{ei} \tag{23}$$

7.3.4. Environmental impact improvement index

The greater the value of environmental impact improvement index (θ_{eii}) the more beneficial is the system to the environment:

$$\theta_{eii} = \frac{1}{\theta_{ei}} \tag{24}$$

7.3.5. Exergetic stability factor

The exergetic stability factor (f_{es}) is a function of the desired output ($\dot{E}x_{tot,out}$), the total exergy destroyed ($\dot{E}x_{dest,tot}$) and the exergy carried by unused fuel ($\dot{E}x_{uf}$). The best value of this factor should be close to one:

$$f_{es} = \frac{\dot{E}x_{tot,out}}{\dot{E}x_{tot,out} + \dot{E}x_{dest,tot} + \dot{E}x_{uf}} \quad (25)$$

7.3.6. Exergetic sustainability index

The greater the value of the exergetic sustainability index (θ_{est}), the better is the performance of the system from an exergetic sustainability perspective:

$$\theta_{est} = f_{es}\theta_{eii} \quad (26)$$

8. CASE STUDY SUMMARIES

8.1. MANGYSHLAK ATOMIC ENERGY COMPLEX NUCLEAR DESALINATION PLANT

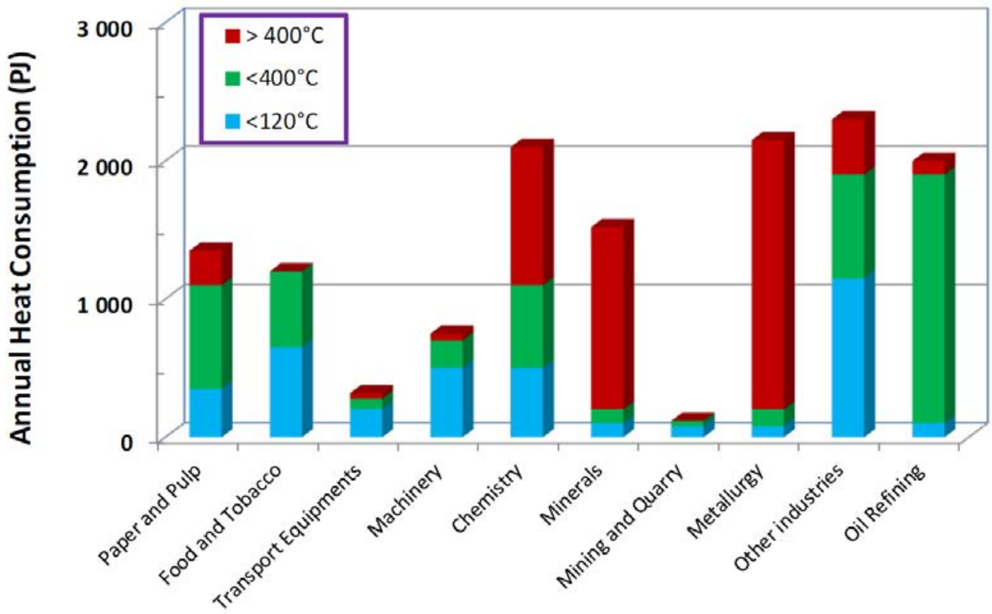
In the former Union of Soviet Socialist Republics, the construction of a desalination facility on the eastern side of the Caspian Sea led to the development of the desalination technology for sea water in 1961. The first distillation unit at the MAEC was capable of producing fresh water in the range of 70–120 m^3/d. In order to meet the rising freshwater demand of the city of Aktau (formerly Shevchenko) and its developing industries near the shore, a larger desalination plant consisting of two fossil fuel boilers, a backpressure turbine and a desalination unit (MED) was installed in 1963.

The expansion of the MAEC started with the construction of a power plant running on fossil fuel with a design capacity of 750 MW(th) followed by the nuclear reactor, three MED plants with the desalination capacity of 12 000 m^3/d coupled to three backpressure turbines each with a power generation capacity of 50 MW, and a potable water preparation facility. The nuclear power plant started generating electricity in 1973. By 1990, ten MED plants with a capacity of 8000–14 500 m^3/d had been installed, which led to the total design capacity of 145 000 m^3/d (for a detailed account, see appendix V of Ref. [86]).

8.2. DEVELOPMENT OF SMALL HTGR COGENERATION PLANTS IN DEVELOPING COUNTRIES

In recent years, many developing countries have shown a stronger commitment to introducing nuclear energy to address increasing energy demand, trade and security, and sustainability. Small nuclear reactor systems, such as HTGRs, are attractive to developing countries because they are less capital intensive to construct, simple and safe to operate, and adaptable to small electricity networks.

A project to build and operate a 50 MW(th) HTGR for electricity and heat cogeneration in a developing country is provided by the JAEA [87]. The plant is designed from the knowledge obtained from the development and construction of a similar reactor and associated plant technologies in Japan. In the design, the JAEA assumes construction to be in East Asia, with options of procuring equipment locally or importing them from Japan. The development roadmap is shown to commercialize the plant.



Source: Figure 1 of Ref. [88].

FIG. 31. Annual heat consumption in industries in Europe.

8.3. NUCLEAR BASED CRUDE OIL REFINERY

Crude oil refining is the industrial sector with the largest heat consumption in the temperature range of 350–550°C (see Fig. 31). It requires large amounts of energy, and most refineries require a dedicated production unit close by. New processes require more and more energy (i.e. removing sulphur and using heavier oils). Moreover, concerns about climate change mean industries are reducing their GHG emissions, which, for a refinery, means burning less gas. Therefore, a non-fossil fuel power plant might help to provide the energy needs of the refinery.

8.3.1. The refinery plant

Each refinery has some specific and rather complex inner organization with a variety of products (see figure 6 of Ref. [89] for a simplified flowchart). However, some major process units can be found in all modern facilities. The following main units account for over 90% of the total energy needs of the plant:

— Crude distillation unit;
— Vacuum distillation unit;
— Hydrotreating unit;
— Fluid catalytic cracker;
— Hydrocracker unit.

Safa and Borgard [88] report on the Gonfreville refinery, in France, which has a capacity of 15 Mt of crude oil per year (350 000 barrels per day). The energy consumption for each different process unit they estimated is summarized in Table 17.

TABLE 17. ESTIMATED HEAT DEMAND AND CORRESPONDING STEAM TEMPERATURES IN A REFINERY

Main unit	Heat demand (kW·h/t)	Temperature (°C)
Crude distillation unit	200	385
Vacuum distillation unit	90	390–450
Hydrotreater	170	280–430
Fluid catalytic cracker	20	20–540
Hydrocraker	30	290–400
Gasoline reformer	100	430–540
Coking	40	900
Wastewater cleaning	1	20–60

Source: Table 1 of Ref. [88].

8.3.2. Fast reactor technology

Fast reactors are being developed worldwide because of their ability to produce fissile material, ensuring long term sustainability for nuclear energy. Fast reactor technology can be considered as industrially available with 20 fast reactors, with around 400 reactor years of operating experience. They generally use liquid metal (sodium) as a primary coolant for the nuclear core. The high boiling point of sodium (880°C) allows a working temperature for the coolant of 550°C, conveniently matching the temperature required by most refineries. In addition, earlier experience in nuclear cogeneration using an SFR has proved to be effective, providing not only the main electrical power but also district heating. At the Phénix reactor, in France, a fraction of the steam at the reheater inlet is withdrawn and injected in the heating network of the centre of Marcoule [90].

8.3.3. A coupling scheme

An in-depth analysis of all safety related issues with regard to coupling a nuclear power plant to an industrial facility is mandatory. Being interconnected, the mutual effects between the reactor operation and the chemical units on site have to be clearly assessed, including how failures should be managed from each side. At the refinery plant, in addition to hot steam, gasoline desulfurization requires a significant amount of hydrogen gas. Currently, hydrogen is often produced in a dedicated methane reforming unit. In the future, however, it could also be generated through water electrolysis, using nuclear generated electrical power. Heat and electrical power delivered by the power reactor will feed transformation units to fulfil the electricity needs of the refinery (see Fig. 32).

8.3.4. Economic benefits

The replacement of a traditional gas burning plant with a nuclear reactor can result in large savings in liquid and gas fuels production. Safa and Borgard [88] report that an average refinery burns up to 10% of its output for its own energy consumption. This translates into a 1.5 Mt loss in the chemical process units for a 15 Mt throughput facility. The refinery could save over €1 billion a year by switching to a nuclear plant. At the same time, the refinery would also reduce annual GHG emissions by almost 4 Mt [88].

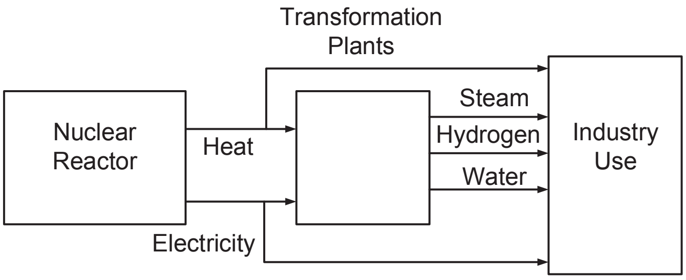


FIG. 32. General scheme for coupling a nuclear reactor to an industrial site.

8.3.5. Conclusion

Nuclear cogeneration has great potential in the crude oil refining sector. A medium size SFR is perfectly suited to providing all the energy needs of a large refinery, including steam, electricity, hydrogen and industrial water. The use of nuclear power yields savings in liquid fuels, increases profitability and also brings environmental benefits by reducing GHG emissions at the refinery.

9. CONCLUSION

Since 2000, there have been increasing efforts to enhance the use of nuclear power in various sectors beyond the utility sector through cogeneration for numerous applications, including district heating, heating and cooling, desalination, and hydrogen and fuels production.

The overview of nuclear energy based cogenerations systems in this publication will help researchers and governments around the world to understand better the potential of nuclear power plants for cogeneration. The main conclusions are as follows:

- LWRs and SMRs are suitable for use in district heating and desalination systems due to their working temperature in the range of 280–325°C.
- The working temperature of LMFRs, which is in the range of 500–800°C, makes them suitable for the production of fresh water using a desalination system in cogeneration mode.
- The high working temperatures of HTGRs (750–950°C), using helium as a coolant, makes them suitable for the production of hydrogen and process heat in cogeneration mode.
- The working temperature ranges of SCWRs (430–625°C), GFRs (850°C) and MSRs (750–1000°C) make them suitable for the production of hydrogen and process heat and desalination when they are used as cogeneration systems.
- Hot water can be delivered at a distance of up to about 150 km, with a heat loss of 2%.
- A medium size SFR is perfectly suited to providing all the energy needs of a large refinery, including steam, electricity, hydrogen and industrial water.

Future areas of research include the following:

(a) There is a strong need to conduct feasibility studies on nuclear power plants to investigate how they can be modified to better use nuclear fuels in cogeneration mode by recovering their waste and process heat.
(b) There is a need to find a working fluid with a high specific heat capacity and which can effectively carry the high energy content of heat rejected by nuclear power plants.
(c) The nuclear power plants current available cannot be coupled to thermochemical water splitting cycles for hydrogen production on account of their high temperature requirements. There is a need to develop new generations of nuclear power plants that address, expediting the shift to hydrogen.

(d) The feasibility of integrating cogeneration systems with nuclear power plants greatly depends on the nuclear power plant site. There is a need to identify new sites, keeping in mind the needs of the people living in the surrounding areas. In arid regions, for example, nuclear power plants should be developed along the sea coast to utilize cogeneration systems capable of producing fresh water.

(e) There is a demand for software which can analyse energy, exergy, cost and environmental factors for different cogeneration nuclear power plants. Software needs to be developed which can integrate thermodynamic, cost and environmental aspects of several cogeneration modes of nuclear power to assist researchers and governments selecting appropriate cogeneration nuclear power plants.

REFERENCES

[1] ROSEN, M.A., Energy, environmental, health and cost benefits of cogeneration from fossil fuels and nuclear energy using the electrical utility facilities of a province, Energy Sustain. Dev. **13** (2009) 43–51.

[2] DINCER, I., ROSEN, M.A., Exergy: Energy, Environment and Sustainable Development, 2nd ed., Elsevier, Oxford (2013).

[3] TSATSARONIS, G., Definitions and nomenclature in exergy analysis and exergoeconomics, Energy **32** (2007) 249–253.

[4] BARZEGAR AVVAL, H., AHMADI, P., GHAFFARIZADEH, A., SAIDI, M.H., Thermo-economic-environmental multiobjective optimization of a gas turbine power plant with preheater using evolutionary algorithm, Int. J. Energy Res. **35** (2011) 389–403.

[5] SAYYADI, H., SAFFARI, A., Thermoeconomic optimization of multi effect distillation desalination systems, Appl. Energy **87** (2010) 1122–1133.

[6] GHOBEITY, A., NOONE, C.J., PAPANICOLAS, C.N., MITSOS, A., Optimal time-invariant operation of a power and water cogeneration solar-thermal plant, Solar Energy **31** (2011) 2295–2320.

[7] DINCER, I., ZAMFIRESCU, C., Advanced Power Generation Systems, Elsevier, Amsterdam (2014).

[8] MEGAHED, M.M., Nuclear desalination: History and prospects, Desalination **135** (2001) 169–185.

[9] MISRA, B.M., Seawater desalination using nuclear heat/electricity: Prospects and challenges, Int. J. Desalination **205** (2007) 269–278.

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Introduction of Nuclear Desalination: A Guidebook, Technical Reports Series No. 400, IAEA, Vienna (2000).

[11] DINCER, I., ROSEN, M.A., Thermal Energy Storage: Systems and Applications, 2nd ed., Wiley, London (2011).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Heat Applications: Design Aspects and Operating Experience, IAEA-TECDOC-1056, IAEA, Vienna (1998).

[13] DOUG, L., "Generation power" (Proc. 18th Pacific Basin Nucl. Conf. (PBNC 2012), Busam, 2012).

[14] WESTINGHOUSE ELECTRIC, "SMR technology overview" (Proc. 18th Pacific Basin Nucl. Conf. (PBNC 2012), Busan, 2012).

[15] REYES, J.N., "Advanced passive safety systems for the NuScale energy facility" (Proc. 18th Pacific Basin Nucl. Conf. (PBNC 2012), Busan, 2012).

[16] KIM, H.R., "SMART: The first mover in SMR market" (Proc. 18th Pacific Basin Nucl. Conf. (PBNC 2012), Busan, 2012).

[17] GLOBAL WATER INTELLIGENCE, Desalination Markets 2010: Global Forecast and analysis, Media Analytics, Oxford (2010).

[18] YAN, X.L., KONISHI, S., HORI, M., HINO, R., "Nuclear hydrogen production: An overview", Nuclear Hydrogen Production: Handbook (YAN, X.L., HINO, R., Eds), CRC Press, Boca Raton, FL (2011) 47–81.

[19] SUPPIAH, S., "Development update on the Cu–Cl cycle" (10th Mtg GIF VHTR Hydrogen Production PMB, Oarai, 2012).

[20] AXPO, Nuclear Power Plant Beznau: Reliable, environmentally compatible electricity production, www.axpo.com/content/dam/axpo/switzerland/documents/about_us/151208_about_us_nuclear_kkb_brochure_e.pdf.res/151208_about_us_nuclear_kkb_brochure_e.pdf

[21] GOTO, T., KURODA, S., KAMATA, K., NAKATA, S., MINATO, A., "Operating experience gained with nuclear desalination plants by Japanese electric power companies", Nuclear Desalination of Sea Water (Proc. Symp. Taejon, 1997), IAEA, Vienna (1997) 367–378.

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Design Concepts of Nuclear Desalination Plants, IAEA-TECDOC-1326, IAEA, Vienna (2002).

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Aspects of Nuclear Plants Coupled with Seawater Desalination Units, IAEA-TECDOC-1235, IAEA, Vienna (2001).

[24] MURALEV, E.D., "Experience in the application of nuclear energy for desalination and industrial use in Kazakhstan", Nuclear Heat Applications: Design Aspects and Operating Experience, IAEA-TECDOC-1056, IAEA, Vienna (1998) 361–368.

[25] MURALEV, E.D., NAZARENKO, P.I., POPLAVSKIJ, V.M., KUZNETSOV, I.A., "Experience gained in the operation and maintenance of the nuclear desalination plant in Aktau, Kazakhstan", Nuclear Desalination of Sea Water (Proc. Symp. Taejon, 1997), IAEA, Vienna (1997) 355–365.

[26] EUROPEAN COMMISSION, The Sustainable Nuclear Energy Technology Platform Special Report: A Vision Report, EUR 22842, Office for Official Publications of the European Communities, Luxembourg (2007).

[27] ANGULO, C., et al., EUROPAIRS: The European project on coupling of high temperature reactors with industrial processes, Nuc. Eng. Des. **251** (2012) 30–37.

[28] HITTNER, D., et al., "A new impetus for developing industrial process heat applications of HTR in Europe", High Temperature Reactor Technology (Proc. 4th Int. Top. Mtg, Washington, DC, 2008), American Society of Mechanical Engineers (2008).

[29] HITTNER, D., BOGUSCH, E., FUTTERER, M., DE GROOT, S., DERUER, J., High and very high temperature reactor research for multipurpose energy applications, Nucl. Eng. Des. **241** (2011) 3490–3504.

[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Hydrogen Production Using Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.2, IAEA, Vienna (2013).
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Nuclear Power Process Heat Applications, IAEA-TECDOC-1682, IAEA, Vienna (2012).
[32] KATO, R., NISHIHARA, T., KUNITOMI, K., Design of the intermediate heat exchanger for the high temperature gas-cooled reactor cogeneration system, At. Energy Soc. Jpn. **6** (2007) 141–148.
[33] KUNITOMI, K., YAN, X., NISHIHARA, T., SAKABA, N., MOURI, T., JAEA's VHTR for hydrogen and electricity cogeneration: GTHTR300C, Nucl. Eng. Technol. **39** (2007) 9–20.
[34] JAPAN ATOMIC ENERGY RESEARCH INSTITUTE, Design of High Temperature Engineering Test Reactor (HTTR), JAERI 1332, JAERI (1994).
[35] YAN, X., KUNITOMI, K., NAKATA, T., SHIOZAWA, S., GTHTR300 design and development, Nucl. Eng. Des. **222** (2003) 247–262.
[36] NISHIHARA, T., OHASHI, K., MURAKAMI, T., KUNITOMI, K., Safety design philosophy of hydrogen cogeneration high temperature gas cooled reactor (GTHTR300C), AESJ Trans. At. Energy Soc. Jpn. **5** (2006) 325–333.
[37] MITENKOV, F.M., et al., High-temperature gas-cooled reactors: Energy source for industrial production of hydrogen, At. Energy **97** (2004) 829–840.
[38] RICHARDS, M., SHENOY, A., H2-MHR pre-conceptual design summary for hydrogen production, Nucl. Eng. Technol. **39** (2007) 1–8.
[39] OECD NUCLEAR ENERGY AGENCY, Nuclear Production of Hydrogen, Rep. No. 6805, Organisation for Economic Co-operation and Development, Paris (2010).
[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Managing the First Nuclear Power Plant Project, IAEA-TECDOC-1555, IAEA, Vienna (2007).
[41] SUMMERS, W.A., et al., Centralized Hydrogen Production from Nuclear Power: Infrastructure Analysis and Test-case Design Study, NERI Project 02-160, WSRC-TR-2004-00318, Savannah River National Library (2004).
[42] RAHA, A., RAO, I.S., SRIVASTAVA, V.K., TEWARI, P.K., "Safety analysis of hybrid nuclear desalination plant coupled to high temperature gas cooled reactor", Risk-based Technologies and Physics-of-Failure Methods (Proc. 2nd Int. Conf. Mumbai, 2010) (VARDE, P.V., SRIVIDYA, A., SANYASI RAO, V.V.S., PECHT, M.G.), Institute of Electrical and Electronics Engineers, Piscataway, NJ (2010).
[43] CSIK, B.J., KUPTIZ, J., Nuclear power applications: Supplying heat for homes and industries, Int. At. Energy Agency Bull. **39** (1997) 21–25.
[44] SAFA, H., Heat recovery from nuclear power plants, J. Electr. Power Energy Syst. **42** (2012) 553–559.
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Economics of Nuclear Desalination: New Developments and Site Specific Studies, IAEA-TECDOC-1561, IAEA, Vienna (2007).
[46] INTERNATIONAL ATOMIC ENERGY AGENCY, Market Potential for Non-electric Applications of Nuclear Energy, Technical Reports Series No. 410, IAEA, Vienna (2002).
[47] GENERAL ATOMICS, Conceptual Design Report: Steam Cycle Modular Helium Reactor (SC-MHR) Demonstration Plant, Rep. NGNP-R00016, Rev. 1, GA, San Diego, CA (2011).
[48] GENERAL ATOMICS, Plant Design Requirements Document: Steam Cycle Modular Helium Reactor (SC-MHR) Demonstration Plant, Rep. NGNP-S00212, Rev. 0, GA, San Diego, CA (2010).
[49] HANSON, D., NGNP Contamination Control Study, Rep. RGE-911117, Rev. 0, General Atomics, San Diego, CA (2008).
[50] IDAHO NATIONAL LABORATORY, NGNP Nuclear-Industrial Facility and Design Certification Boundaries, Rep. INL/EXT-11-21605, INL, Idaho Falls, ID (2011).
[51] NUCLEAR REGULATORY COMMISSION, Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs, Rep. SECY-10-0034, NRC, Washington, DC (2010).
[52] NUCLEAR REGULATORY COMMISSION, Standards for Protection Against Radiation, 10 CFR 20, US Govt Printing Office, Washington, DC.
[53] RATLAMWALA, T.A.H., DINCER, I., GADALLA, M.A., Performance analysis of a novel integrated geothermal-based system for multi-generation applications, Appl. Therm. Eng. **40** (2012) 71–79.
[54] INTERNATIONAL ATOMIC ENERGY AGENCY, Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications (Proc. Int. Conf. Oarai, 2007), IAEA, Vienna (2009).
[55] RATLAMWALA, T.A.H., DINCER, I., Energy and exergy analyses of a Cu–Cl cycle based integrated system for hydrogen production, Chem. Eng. Sci. **84** (2012) 564–573.
[56] MAJUMDAR, D., "Desalination and other non-electric applications of nuclear energy", Nuclear Reaction Data and Nuclear Reactors (Proc. Workshop, Trieste, 2002) (HERMAN, M., PAVER, N., Eds), ICTP Lecture Notes Series, Vol. 20, Abdus Salam International Centre for Theoretical Physics, Trieste (2002) 233–251.
[57] BEGROTH, N.M.S., "Large-scale combined heat and power (CHP) generation at Loviisa Nuclear Power Plant Unit 3", Nuclear Option in Countries with Small and Medium Electricity Grids (Proc. 8th Int. Conf. Dubrovnik, 2010), Croatian Nuclear Society, Zagreb (2010).

[58] ECOHEATCOOL, EUROHEAT & POWER, Possibilities with More District Heating in Europe: Final Report, Euroheat & Power (2006).
[59] MAGNUSSON, D., "Unbundling of district heating co-operations in Stockholm?", Critical Issues in Science and Technology Studies (Proc. 10th Ann. IAS-STS Conf. Graz, 2011), Institute for Advanced Studies on Science, Technology and Society, Graz (2011).
[60] PAANANEN, M., HENTTONEN, T., "Investigations of a long-distance 1000 MW heat transport system with APROS simulation software", Structural Mechanics in Reactor Technology (SMiRT 20, Proc. 20th Int. Conf. Espoo, 2009).
[61] VERFONDERN, K. (Ed.), Nuclear Energy for Hydrogen Production, Energy Technology, Vol. 58, Research Center Jülich, Jülich (2007).
[62] VERFONDERN, K., YAN, X., NISHIHARA, T., ALLELEIN, H.-J., Safety concept of nuclear cogeneration of hydrogen and electricity, Int. J. Hydro. Energy (2016).
[63] YAN, X., TACHIBANA, Y., OHASHI, H., SATO, H., TAZAWA, Y., KUNITOMI, K., A small modular reactor design for multiple energy applications: HTR50S, Nucl. Eng. Techn. **45** (2013) 401–414.
[64] UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, Global Industrial Energy Efficiency Benchmarking: An Energy Policy Tool, UNIDO, Vienna (2010).
[65] INTERNATIONAL ENERGY AGENCY, Tracking Industrial Energy Efficiency and CO_2 Emissions, OECD/IEA, Paris (2007).
[66] VERFONDERN, K., "Potential for nuclear process heat application", Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications (Proc. Int. Conf. Oarai, 2007), IAEA, Vienna (2009) CD-ROM.
[67] KHAMIS, I., KOSHY, T., KAVVADIAS, K.C., "Opportunity for cogeneration in nuclear power plants", 2013 World Congress on Advances in Nano, Biomechanics, Robotics, and Energy Research, Seoul (2013), www.i-asem.org/publication_conf/anbre13/M5D.1.ER651_886F.pdf
[68] COLLINS, J.W., Next Generation Nuclear Plant Project Technology Development Roadmaps: The Technical Path Forward, Rep. INL/EXT-08-15148, Idaho National Laboratory, Idaho Falls (2009).
[69] BOUAICHAOUI, Y., BELKAID, A., AMZERT, S.A., Economic and safety aspects in nuclear seawater desalination, Procedia Eng. **33** (2012) 146–154.
[70] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).
[71] SASHIDHARAN, K., JAIN, U.C., RAINA, V.K., "Utilisation of nuclear research reactor waste heat for desalination of seawater", Desalination and Water Reuse (Proc. Trombay Symp. Mumbai, 1999) 138–144.
[72] COLLINS, J.W., "Assessing risk and driving risk mitigation for first-of-a-kind advanced reactors" (Proc. ASME 2011 Small Modular Reactors Symp. Washington, DC, 2011), paper 6585.
[73] IDAHO NATIONAL LABORATORY, Next Generation Nuclear Plant Probabilistic Risk Assessment White Paper, Rep. INL/EXT-11-21270, INL, Idaho Falls, ID (2011).
[74] HANSON, D., TURNER, R., SC-MHR Engineering Development Plan, Rep. NGNP-T00001, General Atomics, San Diego, CA (2010).
[75] IDAHO NATIONAL LABORATORY, Options for Kentucky's Energy Future, Rep. INL/EXT-12-26710, INL, Idaho Falls, ID (2013).
[76] INTERNATIONAL ATOMIC ENERGY AGENCY, DEEP 5 User Manual, 2013, www.iaea.org/NuclearPower/Downloadable/NEA_Desalination/DEEP/DEEP5_Manual.pdf
[77] KAVVADIAS, K.C., KHAMIS, I., The IAEA DEEP desalination economic model: A critical review, Desalination **257** (2010) 150–157.
[78] KHAMIS, I., MALSHE, U.D., HEEP: A new tool for the economic evaluation of hydrogen economy, Int. J. Hydrog. Energy **35** (2010) 8398–8406.
[79] BJÖRNSDÓTTIR, A.R., Financial Feasibility Assessments: Building and Using Assessment Models for Financial Feasibility, MSc Thesis, Univ. Iceland (2010).
[80] SAFA, H., "CO_2 emission from nuclear electricity" (Proc. ICAPP 2011, Nice, 2011).
[81] DONES, R., HECK, T., HIRSCHBERG, S., Greenhouse gas emissions from energy systems, comparison and overview, Encycl. Energy **3** (2004) 77–95.
[82] UNITED NATIONS, Development and International Co-operation: Environment, UN document A/42/427, UN, New York (1987).
[83] UNITED NATIONS, Rio Declaration on Environment and Development, UN document A/CONF.151/26 (Vol. I), UN, New York (1992).
[84] MIDILLI, A., DINCER, I., Development of some exergetic parameters for PEM fuel cells for measuring environmental impact and sustainability, Int. J. Hydrog. Energy **34** (2009) 3858–3872.

[85] RATLAMWALA, T.A.H., DINCER, I., GADALLA, M.A., “Comparative environmental impact and sustainability assessments of hydrogen and cooling production systems”, Causes, Impacts and Solutions to Global Warming (DINCER, I., COLPAN, C.O., KADIOGLU, F., Eds), Springer, New York (2013) 389–408.

[86] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental Impact Assessment of Nuclear Desalination, IAEA-TECDOC-1642, IAEA, Vienna (2010).

[87] JAPAN ATOMIC ENERGY AGENCY, Examination on Small-Sized Cogeneration HTGR for Developing Countries, JAEA, Ibaraki (2008).

[88] SAFA, H., BORGARD, J.M., “Non-electric applications of fast reactors”, Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13) (Proc. Int. Conf. Paris, 2013), Track 8: Deployment and Scenarios, IAEA, Vienna (2015) CD-ROM.

[89] WORRELL, E., GALITSKY, C., Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries, LBNL-56183, Univ. California, Berkeley, CA (2005).

[90] GUIDEZ, J., Phénix: Le retour d’expérience, EDP Sciences, Les Ulis (2013).

ABBREVIATIONS

BARC	Bhabha Atomic Research Centre
BWR	boiling water reactor
CANDU	Canada deuterium–uranium
CHP	combined heat and power
DEEP	Desalination Economic Evaluation Program
EPA	United States Environmental Protection Agency
GFR	gas cooled fast reactor
GHG	greenhouse gas
HEEP	Hydrogen Economic Evaluation Program
HTGR	high temperature gas reactor
HTTR	High Temperature Engineering Test Reactor
HWR	heavy water reactor
IHX	intermediate heat exchanger
JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
KANUPP	Karachi nuclear power plant
LCOE	levelized cost of electricity
LMFR	liquid metal fast reactor
LTE	low temperature evaporation
LWR	light water reactor
MAEC	Mangyshlak Atomic Energy Complex
MAPS	Madras Atomic Power Station
MED	multi-effect distillation
MHR	modular helium reactor
MHT	main heat transport
MSF	multistage flash
MSR	molten salt reactor
NGNP	next generation nuclear plant
NPV	net present value
NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
PWR	pressurized water reactor
RO	reverse osmosis
ROI	return on investment
SSCs	structures, systems and components
SCWR	supercritical water reactor
SFR	sodium cooled fast reactor
SMART	system integrated modular advanced reactor
SMR	small modular reactor
TDS	total dissolved solids
TVC	thermal vapour compressor

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