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No. NP-T-4.3

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INDUSTRIAL APPLICATIONS OF NUCLEAR ENERGY

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

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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.

Nuclear energy can be used for various industrial applications, including: seawater desalination; hydrogen production; district heating and cooling; process heat for industries; the extraction of tertiary oil resources; process heat applications such as cogeneration; coal to liquids conversion; and assistance in the synthesis of chemical feedstock. Owing to steadily increasing global energy consumption, the finite availability of fossil fuels and an increased sensitivity to the environmental impacts of fossil fuel combustion, the demand for nuclear energy for industrial applications is expected to grow rapidly.

This publication analyses industrial energy demand based on current practices and provides an overview of the use of nuclear energy for industrial systems and processes which have a strong demand for power generation and process heat and steam. It describes the technical concepts for combined nuclear-industrial complexes that are currently being pursued in various Member States, and it presents some of the concepts developed in the past. The publication explores the potential that nuclear energy could have in major industrial applications such as process steam for oil recovery and refineries, hydrogen generation, and steel and aluminium production applications, and presents a number of examples for nuclear concepts with such industrial applications.

The IAEA is grateful for the contributions of all those who participated in the drafting and review of this publication, in particular K. Verfondern (Germany). The IAEA officer responsible for this publication was I. Khamis of the Division of Nuclear Power.

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1. INTRODUCTION

1.1. BACKGROUND

Nuclear energy can be used for various industrial applications, such as seawater desalination, hydrogen production, district heating or cooling, the extraction of tertiary oil resources and process heat applications such as cogeneration, coal to liquids conversion and assistance in the synthesis of chemical feedstock. A large demand for nuclear energy for industrial applications is expected to grow rapidly on account of steadily increasing energy consumption, the finite availability of fossil fuels and the increased sensitivity to the environmental impacts of fossil fuel combustion. With increasing prices for conventional oil, unconventional oil resources are increasingly utilized to meet such growing demand, especially for transport.

Nuclear energy offers a low carbon alternative and has important potential advantages over other sources being considered for future energy. There are no technological impediments to extracting heat and steam from a nuclear power plant. This has been proven for low temperatures (<200°C) with nuclear assisted district heating and desalination with an experience of approximately 750 reactor operation years from around 70 nuclear power plants. Detailed site specific analyses are essential for determining the best energy option. The development of small and medium sized reactors would therefore be better suited for cogeneration and would facilitate non-electric applications of nuclear energy. The possibility of large scale distribution systems for heat, steam and electricity supplied from a central nuclear heat source (e.g. a multiproduct energy centre) could attract and serve different kinds of consumers concentrated in industrial parks.

1.2. OBJECTIVE

This publication analyses industrial energy demand based on current practices and provides an overview of the use of nuclear energy for industrial systems and processes with a strong demand for process heat and steam and power. It describes the technical concepts for combined nuclear–industrial complexes that are being pursued in various Member States today, and it presents some of the concepts developed in the past.

1.3. SCOPE

This publication analyses industrial energy demand based on current practices and describes requirements for nuclear process heat reactors to become suitable for industrial applications. This publication provides information on the use of nuclear power for industrial applications for stakeholders in academia, industry, government agencies and public institutions. 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

Section 2 reviews current and future energy demand and use in industry. Section 3 explores the industrial applications of nuclear reactors and the requirements they have to meet. It includes descriptions of past and present nuclear process heat reactor concepts. Sections 4–8 each focus on a specific major industry — petroleum, petrochemicals, hydrogen, steel and other industries, and industrial heat applications, respectively. Section 9 concludes.

2. ENERGY USE IN INDUSTRY

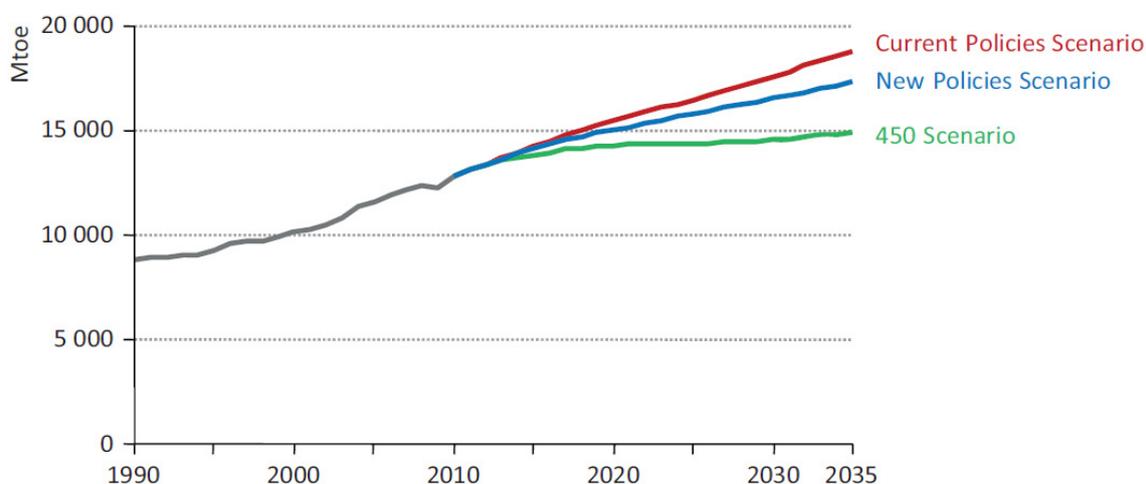
2.1. WORLD PRIMARY ENERGY DEMAND

The trend in world primary energy demand is steadily growing as the result of the increasing world population and the expansion of the global economy (see Fig. 1). With the introduction of new policies to encourage energy savings, the demand might grow at a slower pace (1.2% per year) but will nevertheless continue to rise. Assuming no change in policies, the average growth rate is estimated to be 1.5% per year for the next 20–30 years. However, even a fundamental transformation of the energy sector would lead to a modest growth rate of 0.6% per year [1]. The values for 2011 in Table 1 demonstrates the dominance of fossil fuels.

2.2. NUCLEAR ENERGY USE

With a total capacity of 382 GW(e) from 441 nuclear reactors in 30 countries (as of January 2016¹) and an accumulated experience from approximately 15 000 years of operation, nuclear energy has evolved to an industrially mature and reliable source of electricity and a key component in the global energy economy (see Fig. 2). Nuclear energy represents a low carbon technology with low amounts of greenhouse gas (GHG) emissions on a life cycle basis [2].

Currently, 64 nuclear power plants with a total capacity of over 63 GW(e) are under construction in 15 countries.² Just four countries — China, India, the Republic of Korea and the Russian Federation — account for 39 of them and 58% of the electrical capacity (37 GW(e)). China, with 21 nuclear power plants (21.1 GW(e)) is constructing the largest capacity.



Source: Figure 2.1 of Ref. [1].

Note: Current Policies Scenario — business as usual, no implementation of policies beyond those adopted by mid 2012; New Policies Scenario — existing policy commitments and assuming that those recently announced are implemented (targeted use of renewables, nuclear phaseout), global temperature increase by 3.6°C; 450 Scenario — assuming policy actions having a 50% chance of limiting the long term global temperature increase to 2°C (450 = long term concentration in atmosphere of 450 ppm CO₂ equivalent).

FIG. 1. World primary energy demand by scenario.

¹ See www.iaea.org/pris

² Ibid.

TABLE 1. WORLD PRIMARY ENERGY DEMAND BY SCENARIO (Mtoe)

Year	2000	2011	New Policies Scenario		Current Policies Scenario		450 Scenario	
			2020	2035	2020	2035	2020	2035
Coal	2 357	3 773	4 202	4 428	4 483	5 435	3 715	2 533
Oil	3 664	4 108	4 470	4 661	4 546	5 094	4 264	3 577
Gas	2 073	2 787	3 273	4 119	3 335	4 369	3 148	3 357
Nuclear	676	674	886	1 119	866	1 020	924	1 521
Hydro	225	300	392	501	379	471	401	550
Bioenergy ^a	1 016	1 300	1 493	1 847	1 472	1 729	1 522	2 205
Other renewables	60	127	309	711	278	528	342	1 164
Total	10 071	13 070	15 025	17 387	15 359	18 646	14 316	14 908
Fossil fuel share (%)	80	82	80	76	80	80	78	64
Non-OECD share ^b (%)	45	57	61	66	61	66	60	64

Source: Table 2.1 of Ref. [2].

^a Includes traditional and modern biomass uses.

^b Excludes international bunkers.

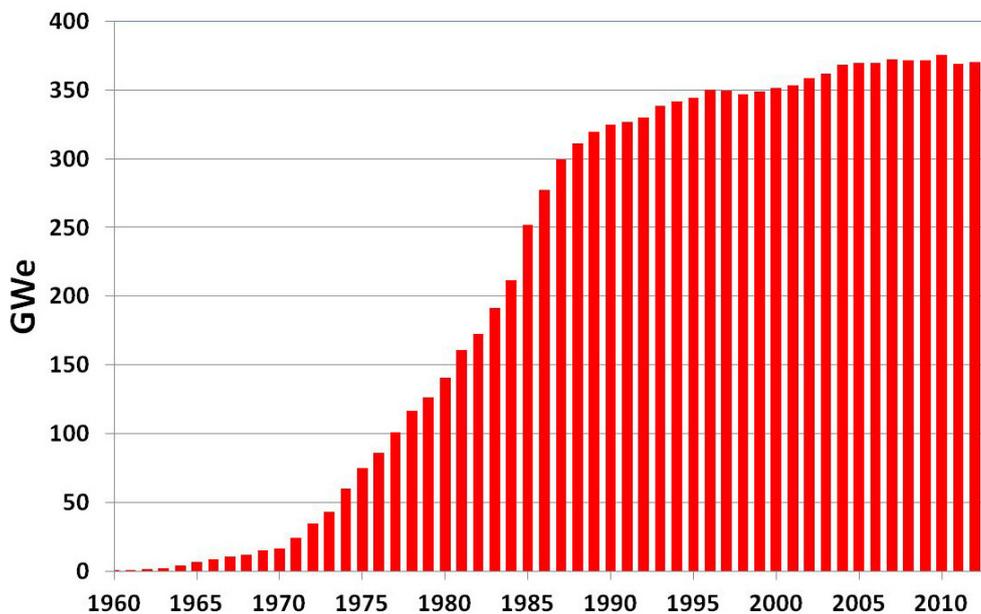


FIG. 2. Evolution of nuclear electricity capacity worldwide.

From the global electricity production in 2010 of approximately 21 400 TW·h, around 13% was generated by nuclear power. It dropped to 11% in 2011 following the substantial decline in nuclear power generation in Japan (-44%), Germany (-23%) and the United States of America (-2%).

2.2.1. Japan

With the loss of Fukushima Units 1–6, Japan went from 54 nuclear reactors down to 48. For five of the older light water reactors (LWRs), however, the decision to shut them down permanently from the end of April 2015 reduced the number of reactor units to 43, with a total installed nuclear capacity of 40 GW(e).³ Additional capacity came from natural gas fired power generation, low sulphur crude oil and fuel oil — albeit insufficient to avoid power cuts. In 2011, Japan imported 12.2% more liquefied natural gas compared to 2010. Discussion has begun on restarting idle LWRs under tougher safety standards. The first nuclear facility (Ohi) was brought back into operation in July 2012, followed by Sendai-1 and 2 in September 2015.

2.2.2. Germany

In June 2011, the German Parliament voted to shut down permanently seven of its older nuclear reactors built before 1980 and to close the remaining plants by 2022. The political move toward the transformation of the energy system ('Energiewende') is accompanied by a comprehensive legislative package to favour and promote green technologies. In addition to the expansion of subsidized wind and solar energy toward the 35% target share of electricity by 2020, the Energiewende calls for the enhanced use of decentralized cogeneration stations (mainly natural gas driven), an increase in energy efficiency and energy savings. An immediate consequence of the nuclear shutdown, however, has been the increased use of coal, which means Germany is rather unlikely to meet the self-imposed stringent target in the reduction of carbon dioxide emissions. Furthermore, the reduced load factor of gas fired power plants (due to the priority of variable renewables in the grid) has made them unprofitable to run, and so utilities have taken several new gas fired power plants off-line.

2.2.3. Projected development of nuclear power

Regarding the future development of nuclear power worldwide, the IAEA [3] reports that in the 2012 updated low projection (see below), global installed nuclear power capacity will grow from 370 GW(e) to 456 GW(e) by 2030. This would be accomplished by an additional 21 nuclear power plants (206 new builds minus 185 retirements). In the updated high projection, it will grow to 740 GW(e) by 2030, with 327 more nuclear power plants (386 new builds minus 59 retirements). The IAEA [3] makes the predictions under the following assumptions:

“The low projection assumes current trends continue with few changes in policies affecting nuclear power. It does not assume that all national targets for nuclear power will be achieved. It is a ‘conservative but plausible’ projection.

“The high projection assumes that the current financial and economic crises will be overcome relatively soon and past rates of economic growth and electricity demand will resume, notably in the Far East. It assumes stringent global policies to mitigate climate change.”

Compared with the projections made before the Fukushima Daiichi nuclear accident, the new figures represent a reduction of 16% for the low projection (corresponding to a ten year delay due to the accident) and 8% for the high projection [1, 3]. For comparison, the OECD Nuclear Energy Agency (NEA) forecasts a low of 441 GW(e) and a high of 554 GW(e) of installed nuclear gross capacity for 2025 [4]. Furthermore [3]:

“Most of the growth will occur in regions that already have operating nuclear power plants.

“Projected growth is strongest in the Far East, which includes China and the Republic of Korea. From 80 GW(e) at the end of 2011, capacity grows to 153 GW(e) in 2030 in the low projection and to 274 GW(e) in the high.

³ Ibid.

“Western Europe shows the biggest difference between the low and high projections. In the low projection, Western Europe’s nuclear power capacity drops from 115 GW(e) at the end of 2011 to 70 GW(e) in 2030. In the high projection, nuclear power grows to 126 GW(e).”

2.2.4. Nuclear fuel resources

Global annual consumption of uranium is greater than production, with the temporary difference being compensated by high enriched uranium retrieved from dismantled nuclear weapons [5]. World uranium production increased from 31 kt in 1994 to 54 kt in 2010 and to 60 kt in 2013, mainly owing to higher production volumes in Kazakhstan (see Table 2). Based on the ten States that provided data to the 2014 Red Book [7], the total identified uranium resource base is estimated to be around 1.4 Mt at cost of under US \$80/kgU and around 4.8 Mt at under US \$130/kgU.

TABLE 2. COUNTRIES WITH URANIUM PRODUCTION IN 2013 [6] AND THEIR IDENTIFIED RESOURCES RECOVERABLE AT A CERTAIN COST [7]

Country	Uranium production in 2013 (t)	Global share (%)	Identified resources recoverable at	
			<US \$130/kgU	<US \$80/kgU
Kazakhstan	22 451	38	515 749	679 316
Canada	9 331	16	418 311	493 854
Australia	6 350	11	— ^a	1 706 100
Niger	4 518	8	15 449	404 914
Namibia	4 323	7	0	382 870
Russian Federation	3 135	5	42 300	505 900
Uzbekistan	2 400	4	— ^a	— ^a
Rest of the world	6 823	11	— ^a	— ^a
Total	59 331	100		

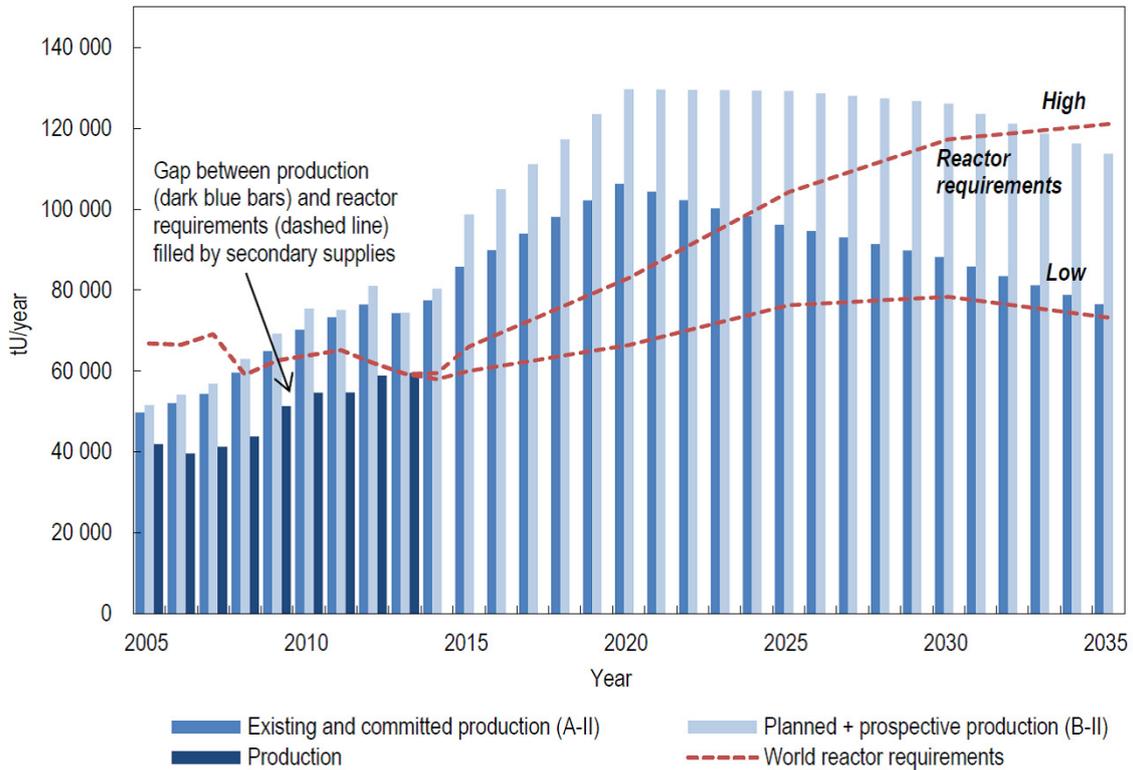
^a —: data not available.

The Red Book [7] concludes that (see Fig. 3):

“The uranium market is currently well-supplied and projected primary uranium *production capabilities* including existing, committed, planned and prospective production centres would satisfy projected high case requirements through 2032 and low case requirements through 2035 if developments proceed as planned.”

Of the 31 countries with nuclear power plants, there are three which are self-sufficient in their uranium needs: Canada, the Russian Federation and South Africa [5].

While about 20% of the uranium produced is from open pit mining and 26% from underground mining, the dominant production method today has become in situ leaching with 45% (data as of 2012 [7]). Economically recoverable uranium mines have uranium concentrations of at least 0.03%. Unconventional uranium resources include phosphate deposits and sea water. From sea water, it is thought that about 4 billion t of uranium is technically extractable [2]. The World Nuclear Association [8] reports that phosphate rock contains 18–40% P₂O₅, as well as some uranium and all its decay products, often 70–200 ppmU, and sometimes up to 800 ppm. This can



Source: Figure 2.11 of Ref. [7].

Note: Includes all existing, committed, planned and prospective production centres supported by reasonably assured resources and inferred resources recoverable at a cost of under US \$130/kgU.

FIG. 3. Projected annual world uranium production capability to 2035 compared with projected world reactor requirements.

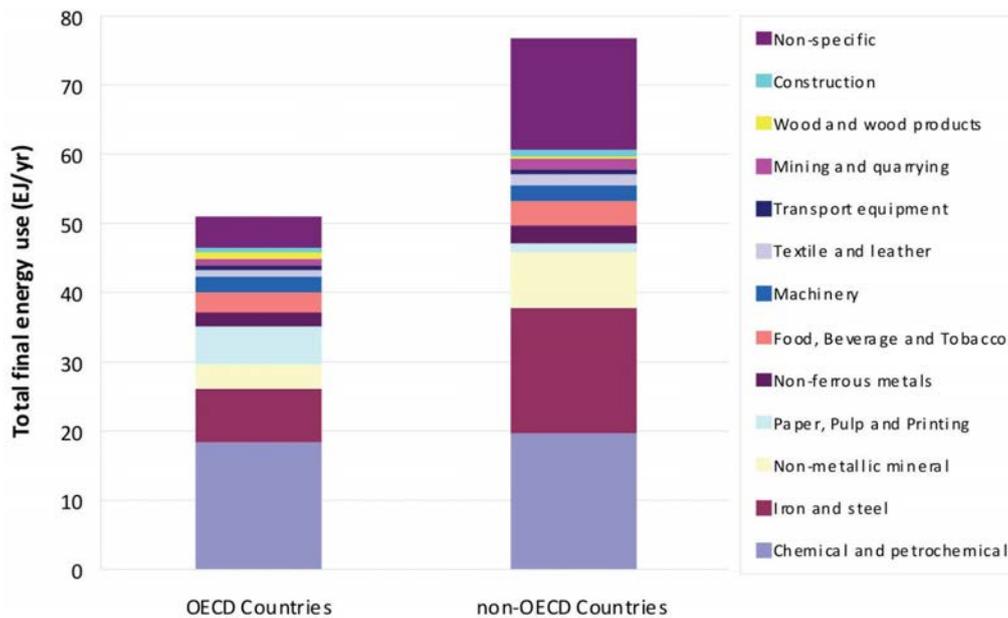
accumulate to uranium resources of an estimated 9 Mt/a, which can be extracted (as well as other heavy metals) as a by-product of phosphate fertilizer production [8]. About 50 Mt/a of P_2O_5 are taken to make phosphoric acid, with phosphogypsum as a waste product, from which appreciable quantities of uranium are recoverable by solvent extraction or, more promisingly, membrane separation [8]. Approximately 20 000 t of uranium have been recovered from such rock phosphate deposits. Total resources are estimated to be 9–22 Mt of uranium, and three quarters of the phosphate rock based uranium resources are estimated to be in Morocco [8].

A significant increase in extraction costs has been observed, which has caused a reduction in the lower cost range [2]. However, the uranium production supplied at under US \$130/kg might still perhaps meet the fuel demand in the IAEA low case scenario for the next 10 to 20 years [9]. A new category added in 2009 defines resources recoverable at costs in the range of US \$130–260/kgU. Including this category, the identified resources would then be 7.1 Mt of uranium [9].

2.3. ENERGY CONSUMPTION IN THE INDUSTRY SECTOR

Of the total final energy consumption of the global economy in 2010, around 28% was consumed in the industry sector. The United Nations Industrial Development Organization (UNIDO) [10] reports that (footnote omitted):

“In 2007, the industry sector worldwide used approximately 127 exajoules (EJ) of final energy, accounting for more than one-third of global final energy use.... OECD countries...accounted for approximately 51 EJ, i.e. around 40% of industrial final energy use worldwide...[see Fig. 4]. The remaining 76 EJ is consumed in non-OECD countries....



Source: Figure 1 of Ref. [10].

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

FIG. 4. Sectoral breakdown of total final industrial energy use in OECD members and non-members in 2007.

“Energy costs as a proportion of production costs vary significantly between different end-products, amounting to as much as 80% of ammonia production costs and between 1% and 10% in yarn making and the machinery sector.”

One of the key findings in the UNIDO report [10] is that:

“The bulk of industrial energy use is accounted for by the production of a relatively small number of energy intensive commodities. Chemicals and petrochemicals and the iron and steel sector account for approximately half of all industrial energy used worldwide. Other sectors that account for a significant share of industrial energy use are non-ferrous metals, non-metallic minerals and the pulp and paper sector.”

The total share of GHG emissions in 2010 from the industrial sector was an estimated 29% [11]. A breakdown by industrial branches shows that the industry sectors of non-metallic industries (e.g. cement), iron and steel, and chemicals and petrochemicals are the largest GHG emitters (see Table 3).

2.4. ENERGY USE IN TRANSPORT

Energy consumption in the transport sector is dominated by petroleum based liquids. Pielke [12] concludes that:

“...the share of world transportation energy use attributed to petroleum-based liquids does not change significantly over the projection period, but oil’s dominance may begin to be challenged by advancing technologies. Uncertainty about the security of oil supplies, the prospect of rising oil prices, and environmental concerns about emissions associated with the combustion of petroleum pose challenges to countries that are experiencing rapid motorization and have to import large portions of their transportation fuel supplies. As a result, future trends in transportation demand will be influenced by government policies directed at reducing emissions and congestion while promoting alternative fuels, advanced vehicle technologies, and mass public transportation.”

TABLE 3. INDUSTRIAL GHG EMISSIONS IN 2010

Industry sector	Share of GHG emissions in 2010 (%)
Non-metallic minerals	6.0
Iron and steel	4.8
Chemical and petrochemical	4.3
Non-ferrous metals	1.4
Food and tobacco	1.1
Paper, pulp and printing	1.0
Other industries	10.5
Total industry sector (rounded)	29

Source: See Ref. [11].

Richards et al. [13] reports that (see also Table 4):

“Energy consumption in the transportation sector results almost entirely from combustion of petroleum based liquids and accounts for about 25% of the world’s energy consumption and CO₂ emissions. With the development of advanced electric and fuel cell vehicles, nuclear energy could displace a significant portion of the petroleum based liquids consumed in the transportation sector, which would significantly reduce CO₂ emissions. During the transition to advanced vehicles, HTRs [high temperature reactors] can also be used to provide some of the energy needs to convert coal and/or natural gas to transportation fuels for conventional vehicles. The market for HTRs in the transportation sector is potentially very large, even if there is significant demand and market penetration for advanced vehicles. The steam-cycle HTR is a demonstrated technology and could be deployed in a relatively short time frame to supply electricity for AEVs [all electric vehicles]. Hydrogen production using thermochemical water splitting and HTSE [high temperature steam electrolysis] are longer-term, developmental technologies that can be coupled to VHTRs [very high temperature reactors] to provide hydrogen for FCEVs [fuel cell electric vehicles].”

TABLE 4. WORLD TRANSPORT ENERGY DEMAND

Year	Energy use (Mtoe)		
	2011	2020	2035
Oil	2264	2572	2878
Gas	93	122	186
Coal	3	2	0
Electricity	25	35	63
Biofuels	59	101	192
Total	2444	2832	3319

Source: Table 7.4 of Ref. [2].

A case study of the potential opportunities for early high temperature gas cooled reactor (HTGR) deployment in Japan is explored in Ref. [14] and deployment of FCEVs in Japan is described in Ref. [15].

2.5. FUTURE ENERGY DEMAND

In 2012, BP [16] reported the following findings:

“— The fuel mix changes slowly, due to long gestation periods and asset lifetimes. Gas and non-fossil fuels gain share at the expense of coal and oil. The fastest growing fuels are renewables (including biofuels)....

“— OECD total energy consumption is virtually flat, but there are significant shifts in the fuel mix. Renewables displace oil in transport and coal in power generation; gas gains at the expense of coal in power. These shifts are driven by a combination of relative fuel prices, technological innovation and policy interventions.

.....

“— Nuclear output is restored to pre-Fukushima levels by 2020, but thereafter shows only modest growth. Hydro continues to grow slowly, constrained by the availability of suitable sites.

“— In the non-OECD growth is more evenly split between renewables, nuclear and hydro, as rapidly growing economies call on all available sources of energy supply. Nuclear output grows rapidly, averaging 7.8% p.a. 2010–30, as China, India and Russia pursue ambitious expansion programmes.

.....

“— Industry leads the growth of final energy consumption, particularly in rapidly developing economies. The industrial sector accounts for 60% of the projected growth of final energy demand to 2030.”

The generation of electricity will rise significantly by 2030. The worldwide installed capacity is estimated to grow from 5549 GW(e) in 2012 to 9760 GW(e) by 2035, by which time a capacity of 1940 GW(e) will have been retired (mainly coal fired plants) [2]. As of 2010, the global industry sector accounted for a total final energy use of 2421 Mtoe, equivalent to almost one third of the total final energy consumption of the global economy.

The industry sectors of iron and steel and chemicals and petrochemicals do not follow a short term demand, but rather tend to operate at full capacity. Enhanced energy utilization could be achieved by improving performance in these sectors. Boilers and steam distribution systems can be major contributors to energy losses. Moreover, some industries are moving toward more sustainable energy technologies to reduce their carbon footprint. However, they are outpaced by the increase in energy consumption.

Most primary fuels consumed in the industrial sector are petroleum and natural gas, which have highly volatile prices. Replacing fossil fuels with nuclear energy might not only help to reduce carbon dioxide and toxic gas emissions, it may even become more economically competitive on account of the low and stable marginal fuel cost. For larger, centralized industries, the supply of safe, reliable process heat and cogenerating electricity from medium sized nuclear reactors of the next generation can represent an appropriate choice.

3. NUCLEAR REACTORS FOR INDUSTRIAL APPLICATIONS

3.1. ELECTRIC APPLICATIONS

Reporting on the three generations of nuclear power plants, Verfondern [17] finds that:

“Like any other established technology, nuclear power has passed through different levels of development.... The first generation of nuclear reactors from the 1950s and 1960s was characterized by a relatively simple and cheap technology for a rapid realization of electricity generation.

.....

“The second generation is formed by the plants constructed from the 1970s to the early 1990s. The deployment of nuclear reactors was advancing rapidly in that period. Like for the reactors of the first generation, operation was basically in an open fuel cycle with the uranium burnt once and then disposed. But activities were intensified on the reprocessing of nuclear fuel by extraction of the fissile material, the generated Pu and still unburnt U, using a mixture of Pu and U oxides to form MOX fuel for nuclear plants, a way towards closure of the fuel cycle....

.....

“Up to today, most of the nuclear power plants are of LWR-type, either pressurized water reactors or boiling water reactors. Light Water Reactors will most certainly continue to dominate for the next decades. New nuclear reactors which are ready for today’s market are counted to the third generation. They are characterized by a simpler design with a higher level of passive (inherent) safety systems based on the physical principles of gravitation, natural circulation, evaporation, condensation rather than active components.... Design improvements are given in the fuel technology allowing higher burnups to reduce the amounts of fuel and waste.”

These systems include both evolutionary and innovative approaches (see Ref. [17] for further information).

3.2. NON-ELECTRIC APPLICATIONS

Majumdar [18] finds that less than 1% of the heat generated in nuclear reactors is used for non-electric applications:

“Direct use of heat energy is more desirable from an energy efficiency point of view and nuclear energy is an enormous source of greenhouse-gas-free energy. However, nuclear power has remained primarily a source for electricity generation. Presently about 30% of the world’s primary energy is used for electricity production, and approximately 2/3 of this energy is thrown away as waste heat. Yet despite past and current use models, it is possible to optimise the use of nuclear heat for both electric and non-electric applications, thereby making more efficient use of nuclear energy. Experience in co-generation of nuclear electricity and heat has been gained in Bulgaria, Canada, China, Hungary, Kazakhstan, Russia, Slovakia and Ukraine”.

The utilization of nuclear non-electric process heat has potential in four areas: desalination of sea water and waste water; district heating of residence and commercial buildings; industrial process heat supply; and fuel synthesis (see Refs [18, 19] for a detailed review).

3.3. ROLE OF REACTOR SIZE

Industrial and commercial sectors consume large quantities of energy in boiler systems which are used for heating with hot water or steam in industrial process applications. The demand for industrial heat is highly variable, and combined heat and power (CHP) system sizes are typically in the range of 1–500 MW(e) [20]. In terms of thermal power, the needs of the vast majority of industrial users are less than 300 MW(th), which accounts for about 80% of the total energy consumed, and half of industrial users require less than 10 MW(th) [21].

Size requirements of a nuclear unit for industrial applications can lead to designs that are larger and smaller than the current norm. For example, nuclear hydrogen production for petroleum refining, which might be a near term opportunity, and other industrial processes may need smaller units in the range of 50–500 MW(th). As a customer can operate more than one boiler, its size is most pertinent when deciding on the application of a (single use) nuclear boiler [22].

For the most part, Generation IV reactors are not specifically designed for the smaller power levels. Centrally generated hydrogen, for example, would call for quite large nuclear plants as well. Hydrogen plants currently under design using non-nuclear sources would require a reactor (assuming 50% production efficiency) of 1600 MW(th). This is well within current parameters, but depending on how the hydrogen market evolves over the next few decades, reactors conceivably two or three times this output might be needed to meet market requirements. Small Generation IV concepts are aimed at 200 MW(th) and greater, although some concepts might be adaptable to the lower power range (see Section 3.7.2). Further evaluation is needed for the adaptability of current Generation IV designs for smaller applications.

3.4. AVAILABILITY AND RELIABILITY REQUIREMENTS

Most industries need to rely on a secure and economic supply of energy to guarantee continuous and reliable operation of their process units. Ensuring supply security by diversification of the primary energy carriers and, at the same time, limiting the effects of energy consumption on the environment will become more important goals in future. Hittner et al. [23] report that:

“...the conclusions of the IUAG [Industrial Users Advisory Group] and the first results of the EUROPAIRS [End user requirement for process heat applications with innovative reactors for sustainable energy supply] have shown that the use of the nuclear reactor as a heat source for industrial process heat/steam supply and not only for electricity generation imposes new constraints on the design of the reactor, as well as new R&D needs”.

Furthermore [22]:

“The supply has to be reliable... Such high levels can be ensured only by the combination of a high reliability of the heat sources and an availability of reserve capacity. The latter is easier to implement by using several production units that are relatively small in comparison with the required capacity or by supplying steam as a relatively small coproduct from a group of electricity producing reactors.”

The industrial requirement of full availability and reliability on energy supply needs additional backup systems, since any interruption of industrial processes can lead to disturbances, with potentially severe technical and financial consequences (see Ref. [24] for a review).

A final requirement is the need to ensure that under no circumstances can radioactive material find its way to industrial circuits and contaminate the end products delivered to the consumers. This will definitely have impacts on the nuclear design and the coupling system by defining a sufficient safety distance between the reactor and industrial applications. Potential contamination refers in particular to the highly mobile tritium and the possibility of permeation from its origin in the primary system through heat exchanging systems or the gas purification plant toward the outside environment [24]. In practice, however, the risk of tritium contamination is considered very low, since isolation devices and physical separations between primary fluid and heat transfer fluid will be employed.

Requirements and acceptance criteria to deal with the risk of contamination of end user products will be subject to discussions with safety authorities [25].

3.5. COGENERATION APPLICATIONS

An IAEA publication in 2017 on the opportunities of cogeneration finds that [19]:

“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 CO₂ emissions.

.....

“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 [see Table 5] (and also iron and steel) are the most energy intensive, accounting for approximately 50% of the total final industrial energy use [Ref. [10]]. Together with food, pulp and paper sectors, they represent more than 80% of the total electric capacities at existing CHP installations [Ref. [26]].”

TABLE 5. COGENERATION IN THE CHEMICAL AND PETROCHEMICAL INDUSTRIES IN SELECTED COUNTRIES

Country (year)	CHP capacity (GW(e))	Power production by CHP (PJ(e))	Ratio of CHP power over total power (%)
Brazil (2005)	0.7	20.4	26
Canada (2004)	1.7	49.0	73
China (2005)	3.0	86.4	8
Germany (2006)	2.6	76.1	43
Italy (2003)	0.7	20.2	30
Japan (2008)	5.7	164.2	83
Netherlands (2006)	1.7	45.4	99
Spain (2003)	0.6	17.3	35
Russian Federation (2004)	0.7	20.2	13
United Kingdom (2007)	1.9	35.6	48
USA (2008)	25.3	729.9	80

Source: Table 17 of Ref. [27].

The International Energy Agency (IAE) [26] reports that:

“Moreover, the share of industrial CHP within the total CHP capacity varies, due to differences in a country’s economic structure, e.g. energy intensive sectors, climate, role of district heating, and the history of barriers and policies to promote CHP.

.....

“Only a few countries have a CHP contribution to power generation larger than 20%. China, the EU countries, Japan, Korea, Russia and the United States show the highest estimated fuel savings from CHP.”

Industrial CHP systems include components such as steam turbines, gas turbines, combined cycle systems, reciprocating engines, or fuel cells to deal with all kinds of fuel (primary and waste) fuel (see Table 6). The IEA [26] reports that widely spread combustion turbines are most typically fuelled with natural gas; however, coal, wood and process by-products are also extensively consumed, especially in large CHP systems, in industrial processes such as heating, cooling, drying and torrefying, or in indirect applications such as the generation of steam, hot water or hot air [26].

TABLE 6. TOTAL EFFICIENCIES OF DIFFERENT CHP TECHNOLOGIES

CHP technology	Estimated total efficiency (%)
Gas turbine based systems	70–75
Microturbines	65–75
Natural gas spark engines	75–80
Steam engine	~80
Fuel cell	65–75

Source: See Ref. [26].

Cogeneration plants (both nuclear and fossil fuel) that operate under the low temperature conditions of existing LWRs derive their principal revenues from electricity. This poses challenges to the nuclear heat option [22]:

- (a) Two thirds of the nuclear energy produced in existing reactor types is heat, which is usually lost to the environment. To provide this heat at a high quality (higher temperatures and pressures), some of the electricity production needs to be sacrificed, further increasing the share of heat.
- (b) While the economy of scale principle is applicable to the generation of electricity, this does not hold for process heat, since heat cannot be as easily distributed as electricity.

For HTGRs, revenues are likely to depend more on the value of the process heat [22]. What is definitely different from LWRs is the much smaller size of process heat HTGRs. It is anticipated that a first of a kind HTGR is unlikely to be competitive with alternative fossil fuel options.

With regard to economical and thermal efficiency, the coupling of the nuclear plant to process heat applications as topping or bottoming cycles for power conversion promises a significant improvement in efficiency. Since all types of nuclear reactor can be principally operated in the CHP mode, with any heat to electricity ratio possible, CHP nuclear plants can be readily integrated into an electrical grid system supplying any surplus electricity or serving as backup system for electricity generation.

3.6. MAPPING REACTORS AND APPLICATIONS

3.6.1. Industrial heat requirements

In today’s concepts for nuclear process heat applications, intermediate circuits will be employed for the transfer of process heat from the nuclear plant to the chemical plant. At the same time, it represents a clear separation between the two islands preventing a direct access of fluids and products from one island to the other. It has the advantage that both plants can be treated independently, and particularly the chemical plant be operated and maintained as a conventional plant (i.e. under non-nuclear conditions).

Whether or not a nuclear system is appropriate for being coupled to a certain industrial application is determined by the level of the reactor coolant outlet temperature. All of the Generation IV nuclear reactor concepts promise an average coolant temperature at the exit of at least 550°C (see Fig. 5), which already meets the demand of quite a number of applications in various industries. Lead cooled fast reactors (LFRs), molten salt reactors (MSRs), gas cooled fast reactors (GFRs) and VHTRs would enable steam reforming and hydrogen production processes.

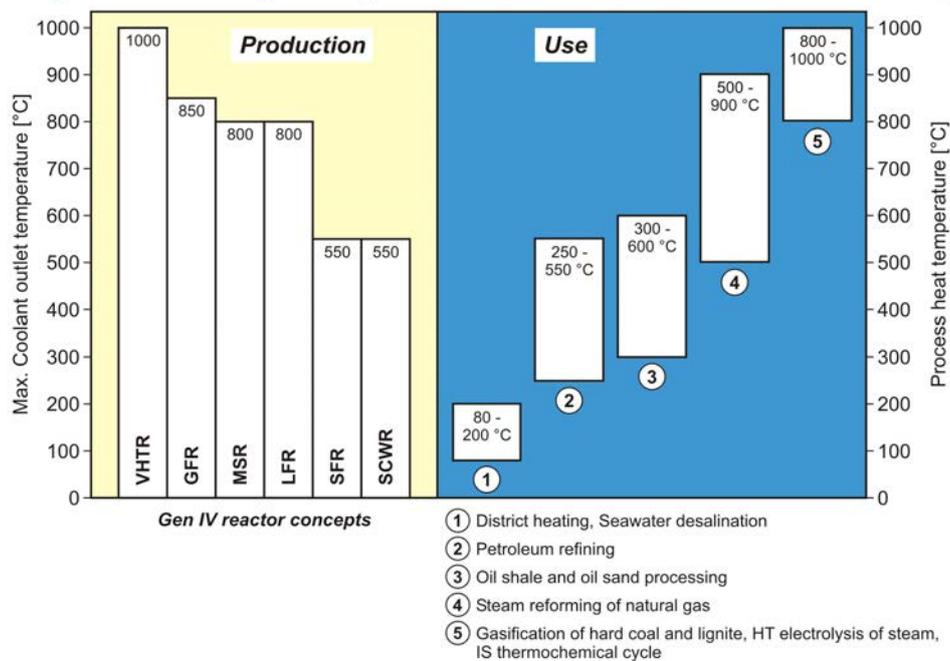
In an HTGR, the typical helium temperature drop expected when transferring heat via the intermediate heat exchanger (IHX) to the secondary circuit is around 50°C [28]. In the first high temperature experiment in 2004 at the High Temperature Engineering Test Reactor (HTTR), the coolant temperatures measured in the IHX were 941°C on the primary side and 859°C on the secondary side, the still somewhat larger difference being due to the requirement to stay below the actual licencing limit [29].

Industrial heat demands are characterized by a wide diversity with respect to countries, branches and energy supply. Heat demand can be classified in three different temperature ranges (see Table 7):

- (a) Low temperature level ($\leq 100^\circ\text{C}$): Industrial processes include on-site hot water preparation, washing and rinsing.
- (b) Medium temperature level (100–550/600°C): Heat is normally supplied through steam as a local heat carrier, mainly for the purpose of evaporating or drying.
- (c) High temperature level ($>550/600^\circ\text{C}$): High quality heat is typically needed for the manufacture of metals, ceramics and glass (e.g. provided by hot flue gases or electric induction).

In a European Commission study, Pardo et al. [30] explore the industrial demand of heat and cooling for 27 EU Member States (EU27) (see Fig. 6). The total heat consumption numbers (as listed in the last column of Table 8) show that 55% of the industrial heat demand is low temperature heat ($<100^\circ\text{C}$), while 19% is in the medium range and 26% in the high temperature range ($>400^\circ\text{C}$). Total industrial heat consumption in the EU27 in 2009 decreased by around 20% compared to 2005. The sectors iron and steel, non-metallic minerals and chemicals

Temperature ranges in production and use of nuclear energy



Note: GFR — gas cooled fast reactor; HT — high temperature; LFR — lead cooled fast reactor; MSR — molten salt reactor; SCWR — supercritical water cooled reactor; SFR — sodium cooled fast reactor; VHTR — very high temperature reactor.

FIG. 5. Long term target temperature ranges produced in Generation IV reactor systems in comparison to those needed in various industrial processes.

TABLE 7. HEATING REQUIREMENTS OF PRINCIPAL INDUSTRIAL PROCESSES

Industrial process	Approx. temp. range (°C)
Home and building heating	100–170
Desalination	100–130
Vinylchloride production	100–200
Urea synthesis	180–280
Process steam	200–400
Paper and pulp production	200–400
Oil refining	200–600
Oil shale and oil sand processing	300–600
Crude oil desulphurization	300–500
Petroleum refineries	450–550
Production of synthesis gas and H from natural gas or naphtha	400–800
Steel making via direct reduction	500–1000
Iron industry	600–1600
Production of ethylene from naphtha or ethane	700–900
Hydrogen production by thermochemical reaction	600–1000
Coal processing	400–1000
Coal gasification	800–1000

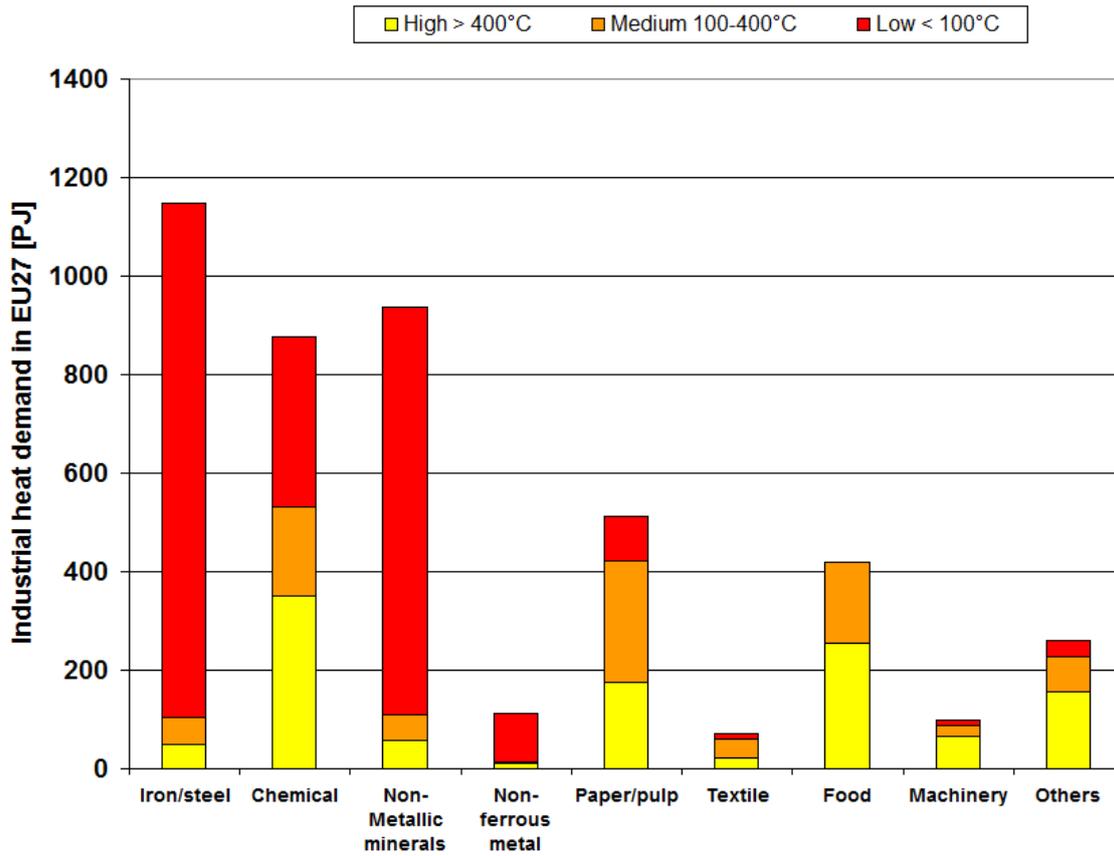
Source: Table I of Ref. [18].

have the largest heat demands and also the largest high temperature heat demands. High and medium temperature processes often generate waste heat at a temperature level high enough to be recoverable in bottoming systems (i.e. district heating). Medium and low temperature processes can be supplied with heat from industrial CHP plants, which may in part explain the reduction in heat consumption. The data in Table 8 also include respective industrial electricity demand with a comparison to the corresponding data of 2005 and shows that energy consumption has been decreasing in all sectors.

Angulo et al. [31] report that within the EU project EUROPAIRS, with the target to establish a roadmap for the design of an HTR for cogeneration of heat and electricity to be coupled with an industrial heat consuming plant, a categorization of chemical processes in three classes according to temperature and the technology used was made:

“The first family corresponds to the ‘*steam class*’ of processes, i.e. processes using steam as heat transport and heating media. The steam class extends from 150°C to approximately 600°C. Examples of processes belonging to this class are:

- the distillation unit in a refinery;
- district heating;



Source: See Ref. [30].

FIG. 6. Industrial heat demand in the EU27 by temperature range and sector (2009).

TABLE 8. INDUSTRIAL ENERGY CONSUMPTION IN THE EU27 (2005 AND 2009)

Sector	Electrical energy (PJ)		Useful heat demand (PJ)		Total final energy (PJ)	
	2005	2009	2005	2009	2005	2009
Iron and steel	488	393	1 695	1 147	2 622	1 853
Non-ferrous metals	291	223	149	113	486	373
Chemicals	736	629	955	877	2 480	2 109
Non-metal minerals	298	267	1209	937	1 820	1 529
Paper and pulp	510	443	549	512	1 476	1 383
Food, drink and tobacco	401	393	481	418	1 261	1 149
Textiles	119	85	120	72	331	216
Other industries	1 228	1 099	191	358	3 163	2 669
Total	4 072	3 532	5 349	4 434	13 640	11 282

Source: Table 3.3 of Ref. [30].

- drying processes;
- power generation in steam turbine;
- desalination by multi-stage flash evaporation.

“The second class of processes is called ‘*the chemical class*’ because heat is the driver of chemical reactions and is consumed as reaction enthalpy at constant temperature. The process temperature lies between 600°C and 900°C. Heat is mainly supplied by combustion and sometimes also by electrical heating. Major examples of this class are:

- oil derivatives;
- methane, biomass and coal derivatives.

“The third class is called ‘*the mineral class*’ because heat is used to melt solid or to drive reactions between solids. For this class of processes, the temperatures required are usually above 1000°C.”

Reporting on nuclear heat supply, Kupitz and Podest [32] find that:

“On the one hand, with a view to efficiency and economy, it is necessary to locate these nuclear units as close as possible to the population areas. At the same time it is, of course, necessary to take all achievable safety measures.

“...In this respect, several projects show that transmission distances of about 30 to 40 kilometres are quite satisfactory. An exception is seen in a Finnish study on possible heat supply from the future Loviisa WWER-1000 reactor, which would have an 80-kilometre transmission line. This was still found to be economically competitive with an alternative coal-fired plant.”

Table 9 shows that the costs grow significantly with distance and hence that an on-site installation or a location close to the demand site is preferable [22]:

“Some process heat applications do not necessarily need to be sited close to populated areas. For example, hydrogen production could either be concentrated in remote industrial centres, with the product transported as needed, or with electricity transmitted to low temperature electrolyzers close to the demand.”

TABLE 9. IMPACT OF DISTANCE ON HEAT TRANSPORTATION COSTS

Distance (km)	Cost of heat transport ^a
5	1.0
10	2.5–3.5
15	4.5–5.5
20	6.5–8.0

Source: Table 27 of Ref. [22] is based on data from Ref. [33].

^a Cost is relative to the cost for 5 km. The range reflects the effect of varying steam parameters.

3.6.2. Generation IV systems for non-electrical energy missions

In 2000, the Generation IV International Forum (GIF) was created to promote and provide “a framework for international cooperation in research for a future generation of nuclear energy systems” [34]. The GIF charter was

signed in 2001 by nine founding members (Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, United Kingdom and United States of America); Switzerland, the European Atomic Energy Community (Euratom), China and the Russian Federation joined later, between 2002 and 2006 [35]. Working groups and committees were formed by interested members to elaborate a technology roadmap for Generation IV nuclear systems, with a project management board to oversee the R&D works and compare with the goals defined [34, 35].

Kelly [35] reports that the goals to be achieved with the new generation of nuclear technologies were set at a high level:

“The four pillars of Generation IV development are sustainability, economics, safety and proliferation resistance:

1. *Sustainability*: Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel. They will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden in the future, thereby improving protection for the public health and the environment.
2. *Economics*: Generation IV nuclear energy systems will have a clear lifecycle cost advantage over other energy sources. They will have a level of financial risk comparable to other energy projects.
3. *Safety and Reliability*: Generation IV nuclear energy systems operations will excel in safety and reliability. Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage, and they will eliminate the need for offsite emergency response.
4. *Proliferation Resistance and Physical Protection*: Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.”

The new reactor generation will further enhance the role of nuclear energy in the reduction of GHG emissions by expanding its product spectrum beyond electricity. The generation of high quality process heat and steam will allow serving in numerous energy intensive industrial applications to substitute for conventional fossil fuels. Reduction of long term radiotoxicity will simplify the requirements for safe performance of repositories.

In the first two years of development of the Generation IV technology roadmap, Technical Working Groups identified and evaluated some 130 nuclear energy system concepts proposed, categorizing them in four system families — water cooled, gas cooled, liquid metal cooled and non-classical — comprising 19 homogeneous classes and screening for their potential to meet the Generation IV goals [36, 37]. The most important homogeneous classes are described in Sections 3.6.2.1–3.6.2.5.

3.6.2.1. *Water cooled reactor concepts*

The three concepts of a water cooled reactor under consideration are the supercritical water cooled reactor (SCWR), the integral primary system reactor (IPSR), and the next generation Canada deuterium–uranium (CANDU-NG) reactor covering a wide range of thermal and power outputs and operating temperatures (see Table 10). The CANDU-NG reactor is designed for the medium power range of 400–1200 MW(e) and the reference concept with 650 MW(e) [38]. CANDU-NG reactors are expected to combine the advantages of both CANDU reactors and pressurized water reactors.

Evolving from conventional LWRs, SCWRs operate at very high pressures, above the critical point, to allow for high coolant exit temperatures (up to 625°C) and high thermal efficiencies [39]. Such a temperature level is suitable for medium temperature process heat applications. Since water systems operate at elevated pressures, intermediate systems will be needed to convert thermal energy to lower pressure fluids used in industrial applications. All of the water cooled concepts can be used for bottoming cycles that include district heating and desalination. The SCWR concepts proposed in GIF have thermal ratings of 900–3800 MW(th). The reference concept has a thermal power of 3575 MW(th) to produce 1600 MW(e) with a coolant exit temperature of 500°C [40].

TABLE 10. POTENTIAL FOR ENERGY PRODUCTS FROM GENERATION IV WATER COOLED REACTOR SYSTEMS

Specification	Reactor class		
	W1 IPSR	W3 CANDU-NG	W4, W5 SCWR
Thermal power (MW(th))	100–1000	1786	900–3800
Electric power (MW(e))	30–300	650	200–1700
Neutron spectrum	Thermal	Thermal	Thermal, fast
Coolant	Light water	Light water	Light water
Outlet temp. (°C)	310–345	330	400–625
Primary pressure (MPa)	12.3–15.5	13	25

Note: Classes not listed here include W2 (SBWR) and W6 (HC-BWR).

The IPSR [41, 42] is a smaller pressurized water reactor system in which all major components are integrated in the pressure vessel. Thermal power envisioned is in the range of 30–300 MW(th). Examples for this class include the following:

- CAREM (Central Argentina de Elementos Modulares, Argentina);
- SMART (system-integrated modular advanced reactor, Republic of Korea);
- IRIS (International Reactor Innovative and Secure, international);
- IMR (integrated modular water reactor, Japan).

Of these IPSR concepts, SMART was the first to be granted a standard design approval.

3.6.2.2. Gas cooled reactor concepts

Gas cooled reactor (GCR) concepts include the pebble bed reactor (PBR), the prismatic modular reactor, the GFR and the VHTR (see Table 11). Helium pressures enhance the coolant capacity to transmit heat. The coated particle fuel used in the thermal spectrum concepts is capable of high burnups, and they are easily adjustable to a wide range of fuel cycles.

VHTRs comprise four concepts [43]:

- GCRs aiming at ultrahigh helium temperatures of 1200–1500°C;
- Modular helium reactor (MHR);
- Annular PBR for the power range of 300–600 MW(th);
- Advanced High Temperature Reactor (AHTR), which is the reference concept.

Initially, the fuel cycle will be a once through cycle achieving very high burnups. The VHTR system has been primarily developed for non-electric process heat applications because of its ability to provide temperatures above 700°C. Operating in the cogeneration mode, the VHTR is capable of providing both electricity and process heat delivered at various temperature levels needed in industrial processes (e.g. in chemical and metal industries).

The GFR is a helium cooled, fast reactor with a fully closed fuel cycle, also with high helium exit temperatures [44]. Apart from the smaller reference size given in Table 11, there is also the larger size reactor with 2400 MW(th)/1100 MW(e) composed of three primary cooling loops each connected to an 800 MW(th) IHX/blower unit and coupled to a power conversion system (PCS) for dedicated electricity generation. Innovative fuel designs such as composite ceramic fuel, advanced fuel particles and ceramic clad elements of actinide

TABLE 11. POTENTIAL FOR ENERGY PRODUCTS FROM GENERATION IV GCR SYSTEMS

Specification	Reactor class			
	G1 PBR	G2 PMR	G3 VHTR	G5 GFR
Thermal power (MW(th))	250	600	600	600
Electric power (MW(e))	110	286	300	288
Neutron spectrum	Thermal	Thermal	Thermal	Fast
Coolant	He	He	He	He
Outlet temp. (°C)	850	850	850–950	850
Primary pressure (MPa)	7.8	7.07	6.8	9.0

Source: See Ref. [36].

Note: Class not listed here include HTGR closed cycle.

compounds have been developed and could have the potential to operate at high temperatures and to retain fission products. Core configurations can be based on prismatic blocks and pin or plate based fuel assemblies. An experimental demonstration version, ALLEGRO, with 80 MW(th) is planned by Euratom.

3.6.2.3. Liquid metal cooled reactor concepts

All concepts in the liquid metal systems category are driven toward medium to large scale electrical power production (see Table 12). Closed fuel cycles are employed for the purpose of maximizing the uranium resource utilization and minimizing the amount of high level radioactive waste.

TABLE 12. POTENTIAL FOR ENERGY PRODUCTS FROM GENERATION IV LIQUID METAL COOLED REACTOR SYSTEMS

Specification	Reactor class			
	L1 SFR loop	L2 SFR pool	L4 LFR	L6 LFR battery
Thermal power (MW(th))	3570	1525	2400	125–1000
Electric power (MW(e))	1500	600	1000	50–150
Neutron spectrum	Fast	Fast	Fast	Fast
Coolant	Na	Na	Pb–Bi	Pb–Bi
Outlet temp. (°C)	550	545	540	550
Primary pressure (MPa)	0.1	0.1	0.1	0.1

Note: L1 — sodium cooled, oxide fuel; L2 — sodium cooled, metal fuel; L4 — medium lead/lead–bismuth cooled (USA); L6 — small lead/lead–bismuth cooled. Class not listed here is L5 — lead–bismuth large. There is no L3 class.

These concepts have been optimized for power production. Most of these concepts operate with core outlet temperatures in the range of 500–560°C. One such concept, lead cooled with a plutonium–uranium–minor-actinide fuel in a nitride matrix, has a core exit temperature of 780°C, already in compliance with the needs of higher temperature applications. Several of the liquid metal systems including sodium cooled fast reactors (SFRs) could play a role using hybrid approaches to meet industrial temperature requirements. The medium temperature liquid metal systems could contribute to hydrogen production nuclear assisted steam reforming of natural gas and membrane reformers. However, the fact that the liquid metal concepts are designed to operate at relatively high thermal powers optimal for electrical power production could make them less attractive for alternative energy product applications.

The operation experience of SFRs in several countries has already been gathered [45]. The GIF concepts are considered to cover a power range from smaller sized (150–500 MW(e)) modules to larger plants (up to 1500 MW(e)). They are designed for management of high level wastes, and the nominal outlet temperature is 550°C for all options. An intermediate sodium circuit is used between primary system and the tertiary steam cycle.

LFR systems use pure lead or lead–bismuth eutectic liquid as coolant [46]. Plant sizes are in the range of 1200 MW(e) for a large plant and 50–150 MW(e) for a battery type. High coolant temperatures allow for process heat applications, including the production of hydrogen by HTSE. The battery system LFRs with their long life without refuelling (up to 20 years) are designed to serve as power sources in isolated locations or on small grids, and also can be used for distributed generation of electricity and other energy products. An example is the Secure, Transportable, Autonomous Reactor (United States of America) concept, with a size of 300–400 MW(th) and uranium–transuranic nitride fuel, which needs to be replaced every 15 years. A congenial variant is the Small, Sealed, Transportable, Autonomous Reactor (Japan) concept, with a smaller size of 45 MW(th)/20 MW(e). After a 20 year life without refuelling, the whole reactor unit is returned to recycle the fuel.

3.6.2.4. Non-classical reactor concepts for other energy missions

The three Generation IV concepts characterized as non-classical reactors are the MSR, the vapour core reactor (VCR) and the AHTR (see Table 13) [34].

TABLE 13. POTENTIAL FOR ENERGY PRODUCTS FROM GENERATION IV NON-CLASSICAL REACTOR SYSTEMS

Specification	Reactor class		
	N1 MSR	N2 VCR	N3 AHTR
Thermal power (MW(th))	2250	1675	3400
Electric power (MW(e))	1000	1000	1530
Neutron spectrum	Fast, epithermal		Thermal
Coolant	Fluoride salt		2LiF–BeF ₂
Outlet temperature (°C)	704	1527	700
Primary pressure (MPa)	0.52	5.0	Atmospheric

The MSR transmutes actinides while producing significant amounts of electricity [47]. The power is nominally 2250 MW(th), although it is not limited by inherent reactor characteristics. With a nominal outlet temperature of 700°C, the efficiency is expected to be around 45%. The design pressure of the system is as low as 520 kPa to allow for pumping losses and hydrostatic head. MSR development is going in two directions: the first is a fuel that is a liquid mixture of sodium, zirconium and uranium fluorides flowing through graphite core channels;

the second is a fuel that is kept in graphite prisms separate from the molten salt coolant. A 5 MW(th) demonstration version is currently being developed at the Shanghai Institute of Applied Physics.

The VCR has the highest outlet temperature of the non-classical concepts [48]. It operates with a UF_4 fuel at sufficiently high temperatures to vaporize the fuel which is then uniformly mixed with the working fluid. The temperature is limited by reactor vessel and heat exchanger materials. The VCR has the primary mission to produce heat at very high temperatures for use either in efficient electricity generation (magnetohydrodynamic generation as topping cycle plus a conventional Brayton gas turbine bottoming cycle) or in the production of hydrogen and high grade process heat.

The AHTR is essentially a prismatic graphite moderated, molten salt cooled pool type reactor in the power range of 600–2400 MW(th) [49]. The data given in the Table 13 refer to an even larger size of 3400 MW(th) [50]. The molten salt coolant can be at temperatures of up to 1000°C in a non-pressurized reactor vessel. The thermal power is limited due to the need for passive heat removal in the event of a loss of coolant. The outlet temperature is similar to that of the VHTR and its upper limit mainly dictated by heat exchanger and reactor vessel liner materials rather than by temperatures of the coated particle fuel. Respective development and improvement of the materials could make the reactor attractive for industrial high temperature heat applications.

3.6.2.5. Generation IV reactors

With the overall goals established, GIF selected six concepts of advanced nuclear reactors for indepth study: GFRs, LFRs, MSRs, SFRs, SCWRs and VHTRs [34]. Many studies investigate nuclear reactor modifications and progress required to produce cheap electricity and high temperature heat with efficient coupling with industrial process plants. With respect to the process heat temperature level that they offer, GCRs, MSRs and heavy metal cooled reactors appear to be the most promising technologies for higher temperature industrial processes such as hydrogen production. The various nuclear reactor technologies combined with thermally driven hydrogen production processes adaptable to nuclear reactors will complement, and not compete, in shaping the future nuclear based process heat and steam generation capabilities. Majumdar [18] reports that:

“...liquid metal and gas-cooled reactors can generate very high temperatures, which could be used to create new synthetic fuels for energy. This will be an innovative application of nuclear energy and can considerably expand its use. This is because the transportation sector is responsible for about a quarter of the total energy use and almost 99% of this is currently supplied by organic fuel. Nuclear power can penetrate this large market through use of electric cars and production of synthetic fuels such as methanol, ethanol and their derivatives; nuclear power can also be used for coal gasification, oil extraction and hydrogen production. All of these are being seriously considered in the 21st century. However, the infrastructure for use of these fuels needs to be created first, particularly in the case of environmentally ideal hydrogen fuel.”

Majumdar [18] concludes that:

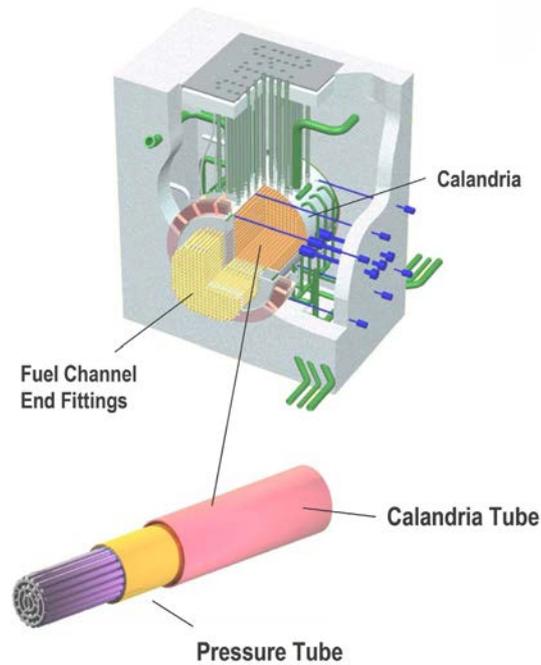
“Innovative applications are being explored with gas-cooled reactors because of their high temperatures....

“Cost-effectiveness is in general a crucial issue for non-electric applications of nuclear power.... For some applications, however, close proximity of the power plant to a population centre is needed (to reduce energy and/or product transmission losses) and this requires further public acceptance. Some large applications also require the development of infrastructure — heat-distribution networks for district heating and water distribution systems (water pipes and pumps) for fresh water.”

3.7. EXAMPLES OF NUCLEAR PROCESS HEAT REACTOR DESIGNS

3.7.1. ACR-700

The CANDU-NG reactor concept pursued in Canada is the Advanced CANDU Reactor (ACR) (see Fig. 7). The ACR-700 is a third generation, pressurized light water cooled, heavy water moderated reactor with a design of



Source: See Ref. [51].

FIG. 7. Schematic of a typical ACR plant.

2000 MW(th)/700 MW(e). The ACR-700 concept was later upscaled to the ACR-1000, a reactor in the 1200 MW(e) class. Similar to all CANDU reactors, the ACR design is based on the use of horizontal fuel channels surrounded by a deuterium hydroxide moderator and arranged in a square pitch. The fuel channels contain the slightly enriched uranium fuel and the high pressure light water coolant. They are mounted in a calandria vessel containing the heavy water moderator. Individual calandria tubes surround each individual fuel channel. The fission heat is carried by the reactor coolant to two steam generators provided in the heat transport system (see Table 14) [51].

The fundamental product of the nuclear reactor is steam from the coolant system steam generators. As an alternative to routing this steam to a turbine, it could also be used as process steam for oil sands application. Each oil sands project, however, will have its own specific features regarding steam amount, steam pressure, electricity demand and location and therefore needs its individual solution in order to optimize ACR economics as far as possible [51]. Utilization of the ACR-700 concept has been proposed for the oil sands-bitumen deposits in the Canadian province of Alberta.

3.7.2. AVR-II

The Joint Venture Experimental Reactor (Arbeitsgemeinschaft Versuchsreaktor, AVR) in Germany was the first PBR, starting operation in 1967 and terminating in 1988 after having successfully demonstrated the essential principles of a pebble bed HTGR. In the core, which produced 46 MW(th), the helium coolant at 1.1 MPa would flow upwards and be heated before entering the steam generator. The first time the AVR reached an average coolant outlet temperature of 950°C was in 1974. For about one third of its total operation time, the AVR operated at helium outlet temperatures of 900–950°C. The AVR was fully dedicated to electricity production and generated 1.67×10^9 kW·h during its lifetime [52].

In two large scale R&D projects pursued in Germany in the 1970s and 1980s, theoretical investigations and experimental demonstrations of nuclear assisted steam-coal gasification and steam-methane reforming were successfully demonstrated. Consequently, it was suggested that the steam reformer component could also be demonstrated under nuclear conditions (e.g. in combination with the AVR plant). A concept was developed to convert the AVR plant to a process heat source. This reconstruction to an AVR-II consisted mainly of the addition of a parallel helium loop for the system demonstration of process heat components. Helium coolant at approximately 1000°C in the hot gas region above the core was planned to be split in two halves, with one half to be routed

TABLE 14. MAJOR CORE DESIGN PARAMETERS FOR THE ACR

Specification	ACR-700	ACR-100
Thermal power (MW(th))	2 037	3 200
Primary coolant	Light water	Light water
Coolant inlet/outlet temp. (°C)	280/326	275/319
Coolant pressure (MPa)	13.3	11.6
Coolant mass flow rate (kg/s)	7 130	13 100
Electric power (MW(e))	753	1 165
Moderator	Heavy water	Heavy water
No. of fuel channels	292 with 12 fuel bundles each	520 with 12 fuel bundles each
Fuel	1.5–2% enriched UO ₂	2.4% enriched UO ₂
Av./max. fuel burnup (GWd/tHM)	20.5/28	20/
Calandria inside diameter (mm)	5 200	7 440
Steam temp. (°C)	281	275.5
Steam pressure (MPa)	6.5	6
Steam mass flow rate (kg/s)	550	1 728

— as in the original AVR — to the steam generator for electricity production and the other half to transfer heat at approximately 950°C to heat consuming components in the new process heat loop. The two halves would be joined again at the cold end of the steam generator. Lifetime of the heat consuming components was expected to be 40 000 operating hours (see Table 15).

Components of the process heat loop were the hot gas duct of 70 m in length, the steam reformer, with 54 splitting tubes, the process steam generator, the process loop circulator and the cold gas duct. All of these components were to be arranged in a separate building for greater flexibility and easier accessibility.

In a later phase of the project, other heat consuming components were thought worthy of study, such as an IHX and a gas generator for steam–coal gasification. The gasifier was designed for an upright position, feasible for thermal powers up to 250 MW(th), with the pyrolysis zone in the upper section, the gasification zone in the lower section, heat input through helically shaped heat transfer tubes forming the boundary between primary and secondary circuit [53].

3.7.3. CHTR

Under the high temperature reactor programme, the Bhabha Atomic Research Centre, in India, is currently developing a compact high temperature reactor (CHTR) as a demonstrator for associated innovative technologies (see Refs [24, 54] for a full review).

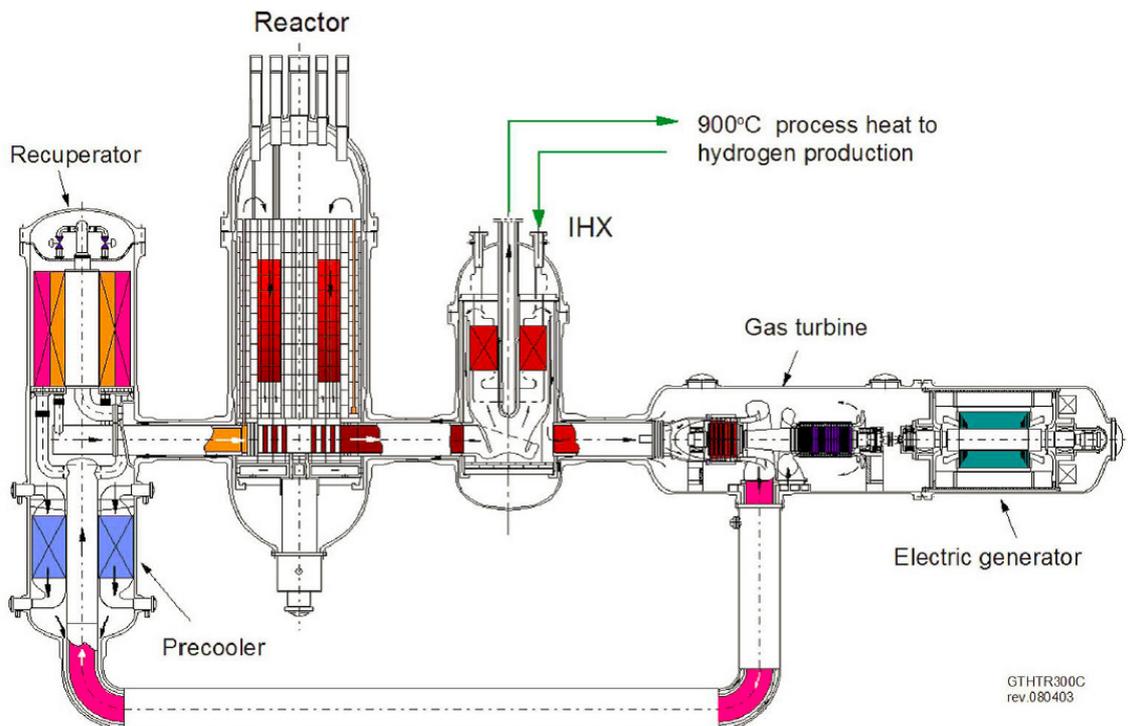
3.7.4. GTHTR300C

The Japan Atomic Energy Agency (JAEA) reference concept for commercial nuclear hydrogen production in Japan is based on the Gas Turbine High Temperature Reactor 300 Cogeneration (GTHTR300C) reactor to be connected to a sulphur–iodine thermochemical water splitting process [55, 56] (see Fig. 8).

TABLE 15. MAJOR CORE DESIGN PARAMETERS OF THE AVR-II FOR STEAM–METHANE REFORMING

Specification	Value
Thermal power (MW(th))	46, to be split in two parallel loops
Av. thermal power density (MW(th)/m ³)	2.6
Primary coolant	He
Coolant inlet/outlet temp. (°C)	200/1 000
Coolant pressure (MPa)	1.1
Coolant mass flow rate (kg/s)	13, to be split in two parallel loops
Electric power (MW(e))	9, in one loop
Reactor core equiv. diameter/height (mm)	3 000/2 470
No. of spherical fuel elements	98 000
Power of steam reformer (MW(th))	8.5
He temp. at steam reformer inlet/outlet (°C)	950/556
Methane feed mass flow rate (kg/s)	3.65
Steam temp. (°C)	500
Flow rate of superheated steam (kg/s)	96

Source: Forschungszentrum Jülich.



Note: IHX — intermediate heat exchanger.

FIG. 8. Schematic of the GTHTR300C.

Verfondern [57] reports that the block type HTGR with a thermal power of 600 MW(th) provides a primary coolant outlet temperature of 950°C. The direct cycle gas turbine efficiently circulates the reactor coolant and generates electricity. Hydrogen cogeneration is enabled by adding an IHX arranged in series between reactor and gas turbine [57]:

“In the IHX, a part of the thermal power, 168 MW, is transferred to the H₂ generation process with the remaining power to be used for electricity generation of 202 MWe. Assuming an efficiency of 50% and an availability of 90%, the average amount of hydrogen is 24,000 Nm³/h corresponding to the supply of some 100 refueling stations (assuming ~6000 Nm³/d) to keep a total of about 160,000 FCV [fuel cell vehicles] (~3.6 Nm³/d) being operated”.

The by-product is oxygen at a rate of approximately 13 500 Nm³/h (see Table 16).

TABLE 16. MAJOR CORE DESIGN PARAMETERS OF THE GTHTR300C FOR HYDROGEN PRODUCTION

Specification	Value
Thermal power (MW(th))	600
Av. thermal power density (MW(th)/m ³)	5.8
Primary coolant	He
Coolant inlet/outlet temp. (°C)	594/950
Coolant pressure (MPa)	5.1
Coolant mass flow rate (kg/s)	322
Electric power production (MW(e))	202
Reactor core equiv. inner–outer radius/height (mm)	3600–5500/8000
No. of fuel blocks	720 (in 90 columns)
Av. fuel burnup (GWd/tHM)	120
He temp. at IHX inlet/outlet (°C)	950/556
Secondary He temp. at IHX inlet/outlet (°C)	900/850
H conversion process	sulphur–iodine thermochemical cycle
Efficient thermal power input to H ₂ production (MW(th))	219
H production rate (t/h)	1.9–2.4

Source: See Refs [55, 56].

The system arrangement with the topping hydrogen process offers variable cogeneration. Operation methods to achieve transition among a number of cogeneration modes have been simulated (see Ref. [58] for a full review).

3.7.5. HTR-Modul

Reference [24] reports that the baseline concept for a German small modular HTGR is the electricity producing 200 MW(th) HTR-Modul PBR designed by Siemens Interatom [59]. It is characterized by a tall and slim core, which ensures — in combination with a low power density — that even in hypothetical accidents, the release of fission products from the core will remain sufficiently low to cause no harm to people or the environment (see Table 17).

TABLE 17. MAJOR CORE DESIGN PARAMETERS OF THE HTR-MODUL

Specification	HTR-Modul for electricity generation	HTR-Modul for process heat application
Thermal power (MW(th))	200	170
Thermal power density (MW(th)/m ³)	3	2.55
Primary coolant	He	He
Coolant inlet/outlet temp. (°C)	250/700	300/950
Coolant pressure (MPa)	6.0	5.0 (with IHX: 4)
Coolant mass flow rate (kg/s)	85.5	50.3
Active core diameter/height (mm)	3 000/9 430	3 000/9 430
Electric power (MW(e))	80	n.a. ^a
No. of spherical fuel elements	360 000	360 000
Av. fuel burnup (GWd/tHM)	80	80
Coolant temp. at steam reformer outlet (°C)	n.a. ^a	680
Coolant temp. at steam generator outlet (°C)	n.a. ^a	293
Process gas temp. (°C)	n.a. ^a	810
Process gas pressure (MPa)	n.a. ^a	5.2
Steam temp. (°C)	525	540
Steam pressure (MPa)	19.0	11.5
Steam mass flow rate (kg/s)	81.7	37.6
H ₂ + CO production rate (m ³ /s)	n.a. ^a	25.6

^a n.a.: not applicable.

The principal cornerstones of the process heat version are a thermal power of 170 MW and a helium outlet temperature of 950°C to deliver process heat for the steam–methane reforming process. The thermal power was reduced compared to the baseline due to the requirement of self-acting decay heat removal from the core (i.e. for the maximum fuel temperature to stay below an upper limit of 1600°C). A reduced system pressure of 5 MPa

(IHX: 4 MPa) was chosen as compromise between a high pressure desired for its favourable effect on operating and accident conditions of the nuclear reactor and a low pressure desired for chemical process reasons in the secondary and tertiary circuit. Another difference was the choice of two fuel zones which are expected to minimize the occurrence of hot/cold gas strains in the core to achieve a radial temperature profile as uniform as possible, in order to avoid additional loads on the high temperature heat exchanging components operating under extreme conditions. Finally, a ceramic (graphite) liner was planned to replace the metallic liner because of the higher temperatures.

Without employing an IHX (which was deemed feasible and licenceable at that time), the hot helium coolant is directly fed to the steam reformer which consumes 71 MW(th), and to the steam generator operated with 99 MW(th) [24]. From the total heat transferred into the steam reformer, 85% are used for the reforming process, while 15% are taken to heat up the feed gas (see Ref. [24] for further information).

3.7.6. HTR-10

Based on a long term cooperation with Siemens Interatom, the Institute of Nuclear and New Energy Technology (INET), of the Tsinghua University, China, has developed and constructed the pebble bed HTR-10 for multipurpose use. The test reactor is designed for a nominal power of 10 MW(th). Reactor core and steam generator are separately arranged in two pressure vessels which are connected by the hot gas duct pressure vessel (see Ref. [60] for further information). Helium inlet/outlet temperatures are 250/700°C at an operating pressure of 3.0 MPa (see Table 18).

TABLE 18. MAJOR CORE DESIGN PARAMETERS OF THE HTR-10

Specification	Value
Thermal power (MW(th))	10
Av. thermal power density (MW(th)/m ³)	2
Primary coolant	He
Coolant inlet/outlet temp. (°C)	250/700°C
Coolant pressure (MPa)	3.0
Coolant mass flow rate (kg/s)	4.3
Reactor core equiv. diameter/height (mm)	1 800/1 970
Electric power (MW(e))	2.5
No. of spherical fuel elements	27 000
Av./max. heavy metal burnup (GWd/tHM)	80/87
Steam temp. (°C)	435
Steam pressure (MPa)	3.5
Steam mass flow rate (kg/s)	3.5

Source: Table 1 of Ref. [60].

The test reactor reached first criticality in 2000 and full operation conditions in 2003. Many tests have since been conducted to demonstrate different safety aspects of HTGRs. The reactor was operated at different power

levels for different periods of time including many shutdown phases. From 2003 to 2007, the reactor was operated over 569 days, accumulating a total of 250.3 equivalent full power days.

In a later stage, the HTR-10 is planned to be connected to one of the two hydrogen production methods currently under investigation at INET, which are high temperature electrolysis and the sulphur–iodine thermochemical cycle. A laboratory of nuclear hydrogen for comprehensive studies on both methods has been established. R&D efforts on nuclear hydrogen are planned to proceed in five phases. Phase I (2005–2007) is the initiation of both production methods, Phase II (2008–2009) deals with process verification with hydrogen production rates of around 1 L/h. Phase III (2010–2014) expands experimental work to laboratory scale increasing rates to around 60 L/h of hydrogen and begins to develop the concept for a pilot plant. Phase IV (2015–2020) deals with R&D on key technologies for the pilot scale demonstration. Beyond 2020, the pilot plant is expected to be coupled to the HTR-10 reactor to develop the engineering scale of nuclear hydrogen production.

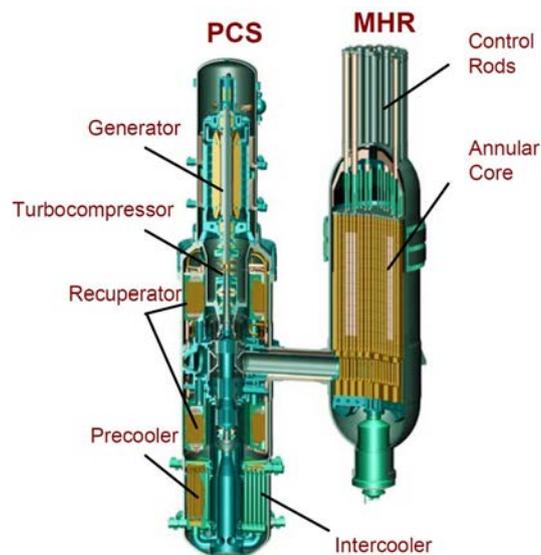
3.7.7. HTTR

The 30 MW(th) HTTR located at JAEA, is designed as a research tool to demonstrate the use of nuclear heat for industrial applications (see Refs [61, 62] for a full review).

3.7.8. H2-MHR

As reported in Ref. [24], the gas turbine modular helium reactor (GT-MHR) design, developed by General Atomics, is characterized by a helium cooled, graphite moderated, thermal neutron spectrum reactor, with a prismatic and annular core directly coupled to a Brayton cycle PCS and with a filtered confinement (see Fig. 9). The reactor core produces a thermal power of 600 MW(th) and is designed for averaged coolant outlet temperatures of 850°C working with an efficiency in the range of 48–52% for electricity production. The option for cogeneration of electricity and process heat has also been studied. The GT-MHR for hydrogen production is referred to as H2-MHR (see Table 19).

The coolant inlet/outlet temperatures are increased to 590/950°C for the H2-MHR core. The increased outlet temperature improves the efficiency and economics of hydrogen production, but is limited to 950°C to avoid any potential adverse impacts on fuel performance and materials during normal operation. A higher coolant outlet temperature could also require significant advances in technology to develop a viable IHX design. The increased



Source: General Atomics.

Note: MHR — modular helium reactor; PCS — power conversion system.

FIG. 9. Gas turbine modular helium reactor.

TABLE 19. MAJOR CORE DESIGN PARAMETERS OF THE GT-MHR AND THE H2-MHR

Specification	GT-MHR for electricity generation	H2-MHR for hydrogen generation	
		S-I	HTSE
Thermal power (MW(th))	600	600	
Av. thermal power density (MW(th)/m ³)	6.6	6.6	
Primary coolant	He	He	
Coolant core inlet/outlet temp. (°C)	491/850	590/950	
Coolant pressure (MPa)	7.07	7.0	7.0
Coolant mass flow rate (kg/s)	320	320	280 (PCS) + 42 (IHX)
Active core inner–outer diameter/height (mm)	2960–4830/7930	2960–4830/7930	
Net electric power output (MW(e))	286		292
No. of hexagonal fuel blocks	720	720	720
Av. fuel burnup (GWd/tHM)	640	640	640
IHX heat load (MW(th))		600	59
Secondary He IHX inlet/outlet temp. (°C)		565/925	292/917
Secondary He pressure (MPa)		7.1	
Secondary He mass flow rate (kg/s)		320	
Steam temp. (°C)			827
Steam mass flow rate (kg/s)			23.6
H production rate (kg/s)		11.7 (4.0 MPa)	8.5 (4.95 MPa)

Source: See Refs [63, 64].

coolant inlet temperature maintains the same coolant flow and convective heat transfer rates within the core as that for the GT-MHR.

For the HTSE based H2-MHR, approximately 68 MW(th) of heat is transferred through the IHX to generate superheated steam and the remaining heat is used to generate electricity. Helium at 924°C and 7.1 MPa enters the thermochemical plant. For the sulphur–iodine cycle based H2-MHR, nearly all of the heat is transferred through the IHX to a secondary helium loop that supplies heat to the sulphur–iodine process.

3.7.9. MHR-100 SMR

The reference design for a nuclear process heat complex is the MHR-T energy technological complex, which comprises four 600 MW(th) reactor modules and is designed for the production of electricity and of hydrogen through steam reforming of methane or HTSE (see Ref. [24] for further information).

In the heat and power cogeneration plant, additionally steam is delivered at a temperature of 145°C. In the steam–methane reforming version, the MHR-100SMR reactor is operated at a coolant outlet temperature of 950°C (see Table 20). The hot helium enters then the steam reformer, which comprises three individual heat exchangers (HX1, HX2 and HX3). The heat exchanger sections are arranged in parallel to the primary coolant flow, and arranged in sequential order to the process gas mixture flow. The downstream gas mixture with high hydrogen concentration passes then through carbon dioxide and water purification stages before the hydrogen gas is separated.

TABLE 20. MAJOR CORE DESIGN PARAMETERS OF THE MHR-100SMR

Specification	Value
Thermal power (MW(th))	215
Primary coolant	He
Coolant inlet/outlet temp. (°C)	450/950
Coolant pressure (MPa)	5.0
Coolant mass flow rate (kg/s)	81.7
No. of hexagonal fuel assemblies	1584
Av. fuel burnup (GWd/tHM)	120
Reactor core equiv. height (mm)	7800
Electric power (MW(e))	0
HX1 thermal power (MW(th))	31.8
Primary helium mass flow rate (kg/s)	12.1
Secondary steam–methane mixture mass flow rate (kg/s)	43.5
Secondary steam– methane mixture inlet/outlet temp. (°C)	350/650
HX2 thermal power	58.5
Primary helium mass flow rate (kg/s)	22.2
Secondary steam–methane mixture mass flow rate (kg/s)	60.9
Secondary steam– methane mixture inlet/outlet temp. (°C)	350/750
HX3 thermal power	125
Primary helium mass flow rate (kg/s)	47.4
Secondary steam–methane mixture mass flow rate (kg/s)	101
Secondary steam– methane mixture inlet/outlet temp. (°C)	350/870

Source: See Ref. [24].

3.7.10. NGNP

In the United States of America, the next generation nuclear plant (NGNP) was originally a United States Department of Energy (DOE) based project with the objective to develop and demonstrate a first of a kind nuclear system based on a 400–600 MW(th) GCR using an indirect cycle with intermediate circuit [24]. It has shifted since 2009 to an industry based project led by the NGNP Industry Alliance, while DOE support is still given for the critical technology development programmes (e.g. fuel and graphite qualification). The initial reactor concept has foreseen the cogeneration of electricity and process heat at 950°C to make the system capable of generating electrical power and process heat for hydrogen production with the sulphur–iodine process and other high temperature applications. However, following a market analysis and discussions with potential end users, in order to speed up deployment and to reduce the technology development risks, it was deemed wise to focus — in an interim step — on a modified reference design by a reduced coolant outlet temperature of 750–800°C and a secondary Rankine steam cycle for initial demonstration of general technical performance and reliability of the primary and support structures [65].

The modular HTGR concept designed by General Atomics for electricity generation in the 1980s was taken as baseline for the development of the steam cycle modular helium reactor (SC-MHR) concept as the NGNP for cogeneration of process steam and electricity for near term deployment (see Fig. 10). The annular prismatic reactor core consists of hexagonal graphite fuel elements and produces a thermal power of 350 MW(th) in a single primary helium loop at 7 MPa with an average helium outlet temperature of 725°C and a secondary water/steam cycle for high quality steam production. Electricity generation will be done in a Rankine cycle, while process steam will be generated in a tertiary system via a steam converter.

AREVA [66] suggested a prismatic core modular HTGR with a nuclear steam supply system based on a 625 MW(th) annular reactor core with a coolant outlet temperature of 750°C. The reactor operated at a system pressure of 6 MPa is connected to a two loop system (i.e. two parallel steam generators and helium circulators to produce high temperature superheated process steam and/or electricity). Life steam parameters are a temperature of 566°C and a pressure of 16.7 MPa (see Table 21). Estimating an overall nuclear heat and power market of about 200 GW(th) (corresponding to ~335 HTGR modules) in the United States of America alone, the targeted energy products to be delivered are electricity, process heat and high temperature process steam (see Ref. [66] for a detailed review).

3.7.11. PBMR

Reference [24] reports that in cooperation with Westinghouse, the PBMR company has developed the preconceptual design of a nuclear plant for the production of hydrogen [67]. The latest reference concept is the Pebble Bed Modular Reactor Demonstration Power Plant (PBMR-DPP), a 400 MW(th) PBMR with annular core geometry utilizing a direct Brayton cycle to produce a net electric power of 165 MW(e). Hot helium gas at 900°C exits the reactor core and flows directly to the gas turbine.⁴

3.7.12. PNP

Verfondern [68] reports that the concept for a nuclear process heat plant with a pebble bed HTR was originally based on thermal power sizes of 500 MW (PR-500) and 3000 MW (PNP-3000) (see Refs [24, 68] for a full review).

3.8. SAFETY ASPECTS OF INTEGRATED NUCLEAR–CHEMICAL PLANTS

The principal requirement of an NGNP is that radioactivity is completely retained inside the plant even in extreme accidents, with no severe consequences outside the fence (see Ref. [24] for a full review). Potential hazardous events in connection with the combined nuclear–industrial systems include the following [24]:

- Tritium transport from the core to the product hydrogen and methanol;
- Thermal turbulence induced by problems in the chemical system;

⁴ For a full review, see Ref. [24] and <https://aris.iaea.org/PDF/PBMR.pdf>

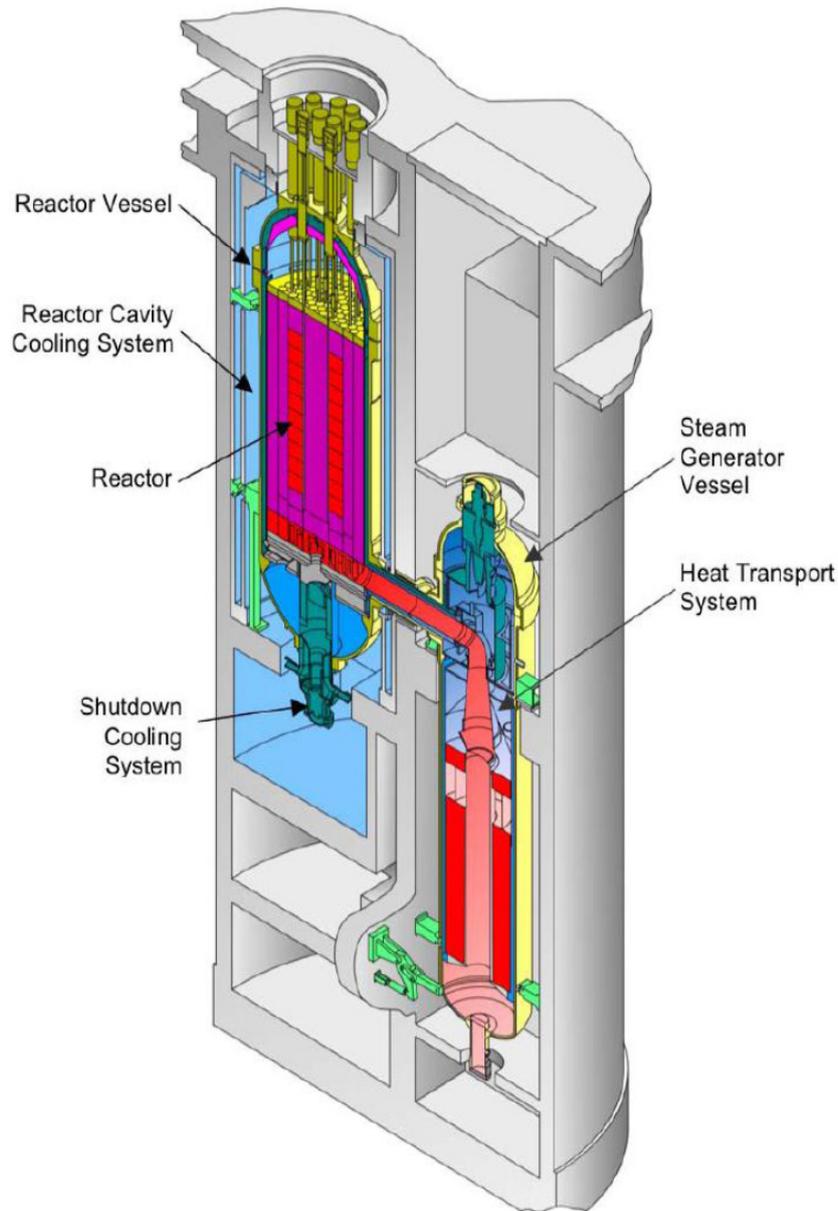


FIG. 10. General Atomic proposed SC-MHR reactor system as NGNP standard module.

- Fire and explosion of flammable mixtures with process gases present in the system;
- Release of toxic material.

Operational and safety independence of the two systems are required to make the nuclear energy supply approach practical. Since the industrial application needs to remain a conventional plant for practical cost reasons, its performance should not undermine the operation stability and safety of the nuclear plant. Most importantly, reports Verfondern [57], “the production process system is not designed to take over safety functions for the nuclear system; these are exclusively left to the reactor cooling system.” An abnormal loss of the heat sink on the industrial side, for example, should not force the nuclear reactor to scram, but rather lead to an orderly transit to idle running conditions. Extensive simulation and practical experience with the thorium HTR have confirmed that the nuclear plant can quickly resume full power upon load recovery of the industrial plant [58].

The overall safety concept for a nuclear plant coupled to an industrial facility consuming nuclear energy has to consider all conceivable mutual interactions given the proximity of the two plants. A first boundary, still part of the nuclear system, is the IHX, representing a barrier against primary coolant to transport radioactivity toward

TABLE 21. MAJOR CORE DESIGN PARAMETERS OF THE TWO NGNP CONCEPTS

Specification	SC-MHR (GA)	SC-HTGR (AREVA)
Thermal power (MW(th))	350	625
Average thermal power density (MW(th)/m ³)	5.9	5.8–6.6
Primary coolant	He	He
Coolant inlet/outlet temp. (°C)	322/750	325/750
Coolant pressure (MPa)	6.39	6.0
Coolant mass flow rate (kg/s)	157.1	281.9
Reactor core inner–outer diameter/height (mm)	1 650–3 500/7 900	/24 000
Electric power (MW(e))	139	296
No. of prismatic fuel assemblies	660	1 020
Steam temperature (°C)	541	566
Steam pressure (MPa)	17.3	16.7
Steam mass flow rate (kg/s)		140.7

the industrial site. Impact on this component is principally given by temperature, pressure and corrosive attack. Rapid changes in these parameters including respective differences between primary and secondary side may be encountered under abnormal operating conditions on either side — resulting from loss of the heat source (nuclear reactor scram) or loss of the heat sink on the industrial side.

A safety distance is the required distance between the location of leakage of a hazardous material (e.g. hydrogen) and the object to be protected which takes account of the evolving flammable atmosphere and, if ignited, the subsequent pressure and heat wave or the throw of debris and projectiles. The definition of the safety distance is based on physical criteria, for example the dose of thermal radiation or the peak overpressure and usually determined as a function of the released amount of hydrogen or any other hazardous material. A particular risk can be seen in low rate leakages, such as from small cracks that can remain undetected for long times. Distance requirements may be reduced by the use of barricades. A minimum safety distance is desirable for economic purposes.

There are other measures possible to minimize risk both on the nuclear and the industrial side, such as shutdown and disconnection systems or underground placement of the reactor building, positioning of the nuclear control room out of reach for any serious consequence of an industrial accident (e.g. blast wave and toxic vapor cloud dispersion), or minimization of the amounts of hazardous materials present on the industrial site [69].

The major safety concerns in oil refineries are fire and explosion. For this reason, nuclear plants should be located in separate zones, away from hazardous areas, and should be operated independent of the conventional refinery side. Other constraints to the choice of location of the nuclear plant are given by the need for proximity to the industrial site, such as feedstocks, fuel, transport and other resources [70]. Due to the limitation of the consequences to the plant site as is expected from a Generation IV nuclear reactor, the typically defined evacuation area is not to overlap with the industrial site.

Another environmental concern of nuclear hydrogen production via thermochemical cycles is the potential release of toxic gases from the process that may, by atmospheric dispersion reach the control room of the nuclear plant and jeopardize personnel. The JAEA has studied where the dispersion behaviour of a 1000 kg toxic gas cloud release from the sulphuric acid decomposition process in the sulphur–iodine process. Gas concentrations in the field strongly depend on the meteorological conditions. Gas concentrations in the control room were evaluated under the condition of an air exchange rate of 0.06 per hour, which has low leakage construction features and

automatic isolation system. Levels of high gas concentrations were found to persist over for 20 minutes after release. A separation distance of 227 m against toxic gas release was determined from the analytical results representing the minimum distance to meet design limits.

3.9. CONCLUDING REMARKS

Globally, there are numerous industrial sites with a large market potential for nuclear process heat utilization encompassing a wide range from low to high process temperatures: desalination, district heating, industrial process heat and steam delivery and synthetic fuel production. High temperature applications of nuclear energy, particularly for production of new fuels like hydrogen on a carbon dioxide emission free basis can have great potential for the future.

The simplest and most near term application with very large market potential for small sized modular nuclear reactors is the generation of high quality steam for consumers in the chemical and petroleum industries. Small units with the size of existing fossil fired cogeneration plants can take advantage of matching with the needs of the industries. In contrast, the large size of typical LWR units makes their thermal power levels too big to be consumed by any CHP application. While it certainly is feasible to employ LWRs for the cogeneration of electricity and heat, the diversion of high quality steam or heat for non-electric purposes will definitely be at the expense of the efficiency for electricity production due to the low operational temperatures.

The realization of nuclear cogeneration systems connected to conventional industrial processes requires intensive partnership of nuclear organizations and end user industries, but also the early and close involvement of national regulators and the IAEA to deal with safety evaluation and emergency planning and to determine safety requirements and related R&D needs.

4. NUCLEAR ENERGY FOR PETROLEUM INDUSTRIES

4.1. POTENTIAL MARKET FOR NUCLEAR ENERGY

4.1.1. Nuclear application in oil and gas extraction

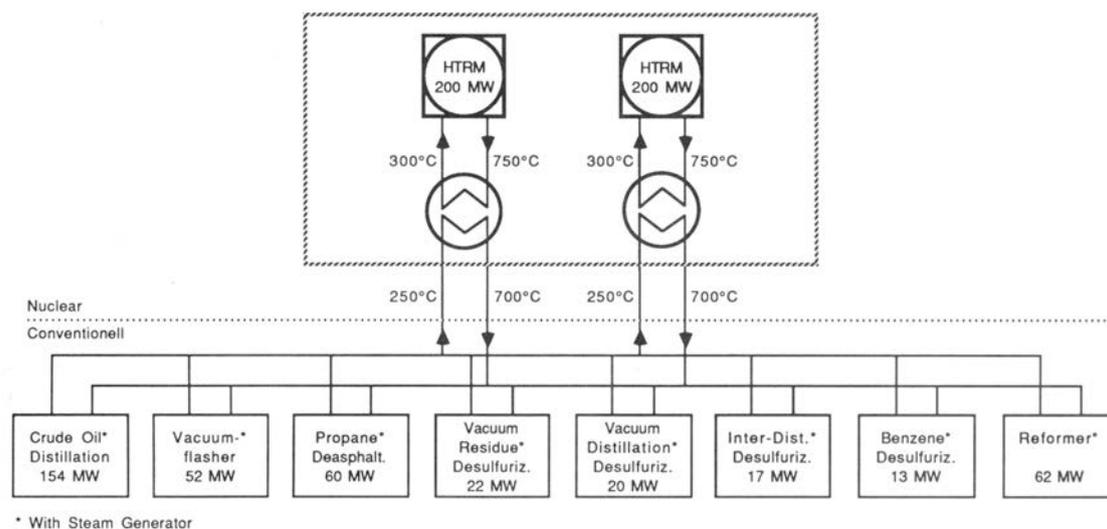
Advanced nuclear systems that are able to provide high pressure steam of the required quality and quantity and in the temperature range of 200–300°C are suitable for steam injection processes for enhanced oil recovery, which includes the extraction of heavy oil (and oil from tar and oil sands) and the extraction of the oil remaining in depleted deposits. Steam and electricity might also be needed in the course of oil processing following extraction [71].

HTGR technology fulfils the requirements for using nuclear energy in oil extraction, but also other reactor concepts are applicable because the required steam parameters are sufficiently low. Canada with its huge tar sands deposits, for example, is pursuing the idea of applying steam assisted gravity drainage using CANDU reactors as a promising concept with long term benefits (see Ref. [24] on heating the oil shale with nuclear heat).

4.1.2. Nuclear application in oil upgrading and refining

In a feasibility study conducted by the German company Lurgi for the introduction of nuclear process heat into industrial processes, various concepts were elaborated for different industries [72, 73]. For the case of heavy crude oil production in a 6 Mt/a capacity model refinery, a concept with two integrated modular HTGRs has been developed. As can be seen from Fig. 11, a refinery comprises a large number of individual plants interlinked with each another and demanding 540°C as the highest process temperature. About 70% of the total demand is needed for separation processes: distillation and stabilization (reboilers).

For a 6–7 Mt/a capacity plant, the required thermal rating is about 400 MW(th), which could be served by two 200 MW(th) modular HTGR units [73, 74]. Primary helium heated up to around 750°C in the nuclear reactor



Source: See Ref. [74].

Note: HTRM — module high temperature reactor.

FIG. 11. Heat supply of investigated model refinery.

will transport its heat to an IHX where secondary helium gas is heated up to around 700°C delivered via process heat exchangers to the various refinery components.

Essential components, for which detailed designs would need further development, are the process heat exchangers to transfer heat from the secondary helium to the process medium. They will certainly be of conventional rather than of nuclear design, since the process gases will not come into contact with the primary helium, so tritium contamination in this tertiary, conventional circuit will be sufficiently low. Some examples for process heat exchangers are listed in Table 22 with their respective temperature ranges on the primary and secondary side. The secondary helium is considered to enter and exit the process heat exchangers at the bottom, and to flow upwards through the process medium tube bundles and downwards through the centrally located steam generator tube bundles. It returns with 300°C to the intermediate He/He heat exchanger within the nuclear containment. The helium flow in each branch of the secondary helium loop can be individually controlled and stopped for cleaning and repair purposes of the refinery components [72].

TABLE 22. HELIUM HEATED PROCESS HEAT EXCHANGERS IN A REFINERY

Process heat exchanger	Temp. range (°C)	
	Primary side	Secondary side
Secondary helium: steam cracker	900–800	840–600
Secondary helium: super heater	800–290	600–250
Secondary helium: naphtha evaporator	290–200	250–120

The main challenge for the heat exchangers is not to exceed the cracking temperature of the feed to be heated while maintaining reasonable heat transfer rates. Important design features of the heat exchangers are limited heat transfer rates and temperature tolerances within very close limits to avoid any local overheating that may cause plugging of the pipes through coking of hydrocarbon media. This requires the helium flow over the whole heat

exchanger cross-section as uniform as possible (see Ref. [73] for an example of a helium heated process heat exchanger).

4.1.3. Nuclear assisted steam reforming of natural gas

In conventional steam reforming of methane, the high temperature process heat required in the endothermic reaction is provided by combustion of additional methane feedstock. Alternatively, provision of the necessary process heat by an external source such as nuclear or solar is also feasible [75]. In the concept of nuclear assisted steam reforming, the heat generated in the reactor core is exchanged from the primary to a secondary coolant in the IHX, and then transported to the steam reforming system. The option of having the nuclear steam reformer component included directly within the HTGR primary circuit is also possible (see Refs [24, 76] for further information).

4.1.4. SYNKOPE project

The goal of the R&D project SYNKOPE is the design of a nuclear cogeneration system for the refinement of coal mined where the Czech Republic, Germany (Saxony) and Poland border. The project has been approved and sponsored by the Saxon regional government (Staatsministerium für Wirtschaft, Arbeit und Verkehr) in the framework of the European Regional Development Fund. The goal is to identify future options for exploiting regional coal resources while meeting ambitious carbon dioxide reduction targets. Essentially, a solution for the efficient transformation of coal into a valuable liquid or gaseous energy carrier is sought, which yields a higher value creation per tonne of carbon dioxide emitted compared to the steam electric generation currently pursued. The system to be designed needs to comply with two boundary conditions:

- Nuclear heat source with the highest possible degree of passive safety;
- Compatibility with the quality of the coal mined in the region.

Within the project, a steam gasification process was identified to be most promising with regard to carbon dioxide reduction potential (see Fig. 12). High temperature steam is provided by an HTGR rated at 350 MW(th) and a maximum coolant outlet temperature of 850°C. The products of the gasification process, hydrogen and carbon monoxide and methane, can be used as input either for downstream refinement processes such as carbon dioxide hydrogenation or for alternative industrial and residential heat applications.

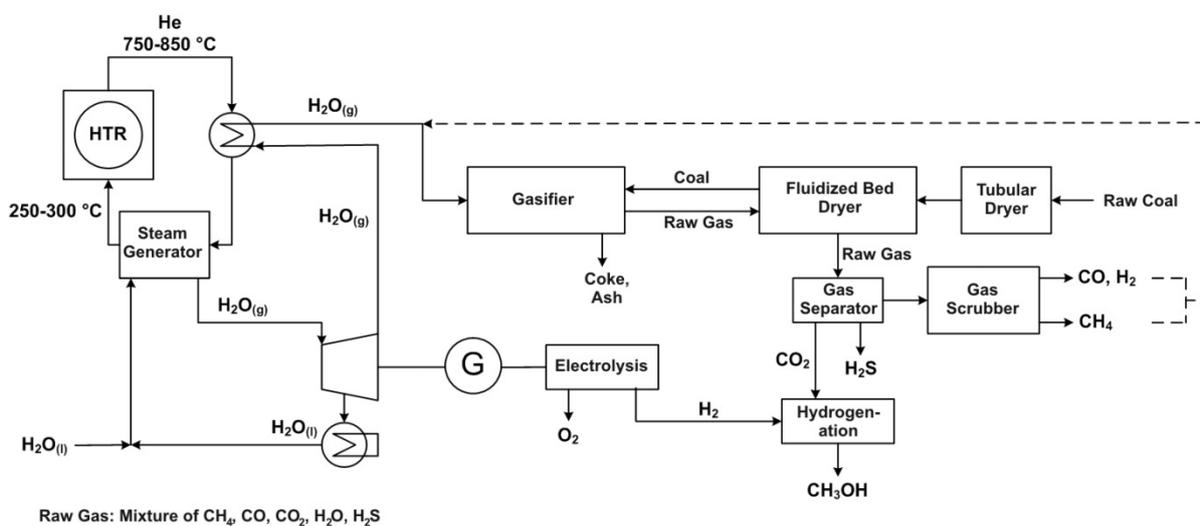


FIG. 12. Nuclear cogeneration process for steam gasification of coal with supplementary electrolysis and hydrogenation processes for methanol production.

The research work is carried out by four German research institutions, led by the university TU Dresden, and supported by the Research Centre Řež, in the Czech Republic. It focuses on key issues of a nuclear cogeneration system with regard to both technological feasibility and economic viability:

- (a) Thermalhydraulics and heat transfer simulations to confirm the passively safe decay heat removal during normal operation and under accident conditions. The worst case scenario considered is a station blackout with subsequent outage of the helium blowers.
- (b) Optimization of SiC coatings for enhanced retention of metallic fission products in the tristructural isotropic fuel particles.
- (c) Qualification of SiC bulk materials and joints for use in chemically aggressive high temperature process atmospheres.
- (d) Optimization of the refinement process as a function of the quality of the available coal.
- (e) Integration of supplementary refinement technologies for hydrogen generation (ultrasound assisted electrolysis) and carbon dioxide hydrogenation.
- (f) Carbon dioxide life cycle analysis of the overall cogeneration system and economic viability study.

The SYNKOPE project is conducted in close collaboration with the EU sponsored projects NC2I-R and ARCHER. After its completion in 2014, a follow-on project is to be pursued, which will also take into account socioeconomic aspects, such as the public acceptance of a cogeneration project in the region and its political feasibility. Furthermore, the process will be compared to competing low carbon energy technologies currently evolving, such as concentrated solar power, biomass gasification and shale gas production.

4.2. CONCLUDING REMARKS

Great significance is to be attached to the production of synthesis gas ($\text{CO} + \text{H}_2$) using nuclear process heat in steam reforming systems. The introduction of refining processes to improve the hydrogen:carbon ratio of fossil primary energy carriers requires the provision of large quantities of low cost hydrogen. The nuclear assisted production of synthetic fuels such as gasoline, diesel and kerosene is also feasible in a carbon dioxide neutral way. The generation of nuclear hydrogen from water splitting and the extraction of carbon dioxide from the atmosphere or use of carbon dioxide captured from integrated gasification combined cycles and its conversion to carbon monoxide will result in synthesis gas as the starting material for gas to liquid processes (e.g. the Fischer–Tropsch synthesis). The use of nuclear primary energy would provide the option of unlimited liquid fuels production without any greenhouse impact.

5. NUCLEAR ENERGY FOR PETROCHEMICAL INDUSTRIES

5.1. NUCLEAR ASSISTED AMMONIA PRODUCTION

The energy required for the ammonia synthesis is mainly consumed in hydrogen generation, air liquefaction, compression and the supply of elevated process temperatures. In the future, nuclear energy could assist in the large scale GHG emission free production of hydrogen from water splitting processes and the provision of high temperature process heat (see Section 6.3 for further information on nuclear based water splitting processes).

5.2. NUCLEAR ASSISTED METHANOL PRODUCTION

Starting material for the synthesis of methanol (and numerous other chemical products) is synthesis gas, which itself is the result of various reforming processes, today mostly based on natural gas and coal, but also heavy

oil or biomass can be used. With regard to the potential nuclear process heat applications of HTGRs, several studies have been conducted to develop concepts of nuclear assisted methanol production.

5.2.1. Germany

With large domestic coal resources, Germany investigated methanol production based on the gasification of lignite and hard coal using HTGR process heat (see Section 3.7.12 and Refs [24, 68]). The process for producing methanol from coal comprises two steps: (i) production of synthesis gas from coal gasification plus reforming of the methane fraction; and (ii) reaction of carbon monoxide and carbon dioxide with hydrogen to form methanol.

In the German version of nuclear methanol production [77], the nuclear heat source was a four module plant using the process heat variant of the HTR-Modul with an output of 170 MW(th) per unit (see Section 3.7.5 and Ref. [24]). Coal is gasified with the hydrogen at 920°C and 8 MPa to provide synthesis gas for the methanol synthesis. After separation from the residual gases and following the methanol synthesis, methane is recycled to the nuclear steam–methane reformer in the primary circuit for hydrogen (and more synthesis gas) production, hydrogen to the hydrogasification process, and carbon monoxide added to the feed gases for the methanol synthesis, respectively. The steam generator supplies steam to the reforming process and also runs a turbine for electricity generation. With regard to electricity and steam, the total system is self-sufficient. The four module plant with 680 MW(th) is laid out to produce 2530 t/d of methanol at a coal throughput of 2690 t/d. In addition, 1050 t/d of charcoal are produced.

Methanol synthesis can also be performed based directly on steam–methane reforming to deliver synthesis gas to the methanol production step. Surplus hydrogen extracted from the residual gases represents an additional product. For the same nuclear power input from a four module plant, the products are 3182 t/d of methanol and 2.3×10^6 Nm³/d of hydrogen at a natural gas throughput of 2.76×10^6 Nm³/d. There is also a generation of surplus electrical power of 5.9 MW(e) [77] (see Ref. [24] for further information on nuclear assisted biomass conversion to methanol using an HTGR).

5.2.2. United States of America

Large coal resources are to be found in the United States of America that could be converted to transport fuels. In a 1992 publication, Schleicher and Lewis [78] report that:

“A privately funded study was recently carried out at General Atomics to investigate the use of a Modular High Temperature Gas-Cooled Reactor (MHTGR) for...the production of methanol from coal without producing CO₂. This study compared two alternative conversion processes, steam-coal gasification and hydro-gasification ([Ref. [71]]), both of which require nuclear generated heat in the range of 850°C core outlet temperature.

.....

“Two possible configuration arrangements have been recognized for nuclear coal conversion schemes: steam-coal gasification and hydro-gasification ([Ref. [71]]). In the steam-coal gasification process, excess H₂ from the steam-methane reforming reaction compensates for the lack of H₂ in the steam-coal gasifier. The combined reformer and gasifier outputs constitute the necessary feed for stoichiometric methanol synthesis.”

On the other hand, this configuration requires another heat exchanger in the form of an IHX in the primary circuit. The second option based on hydrogasification requires only the nuclear steam reformer component to provide carbon monoxide and hydrogen to the methanol synthesizer, which is the same arrangement as shown for the German concept (see Ref. [78] for further information).

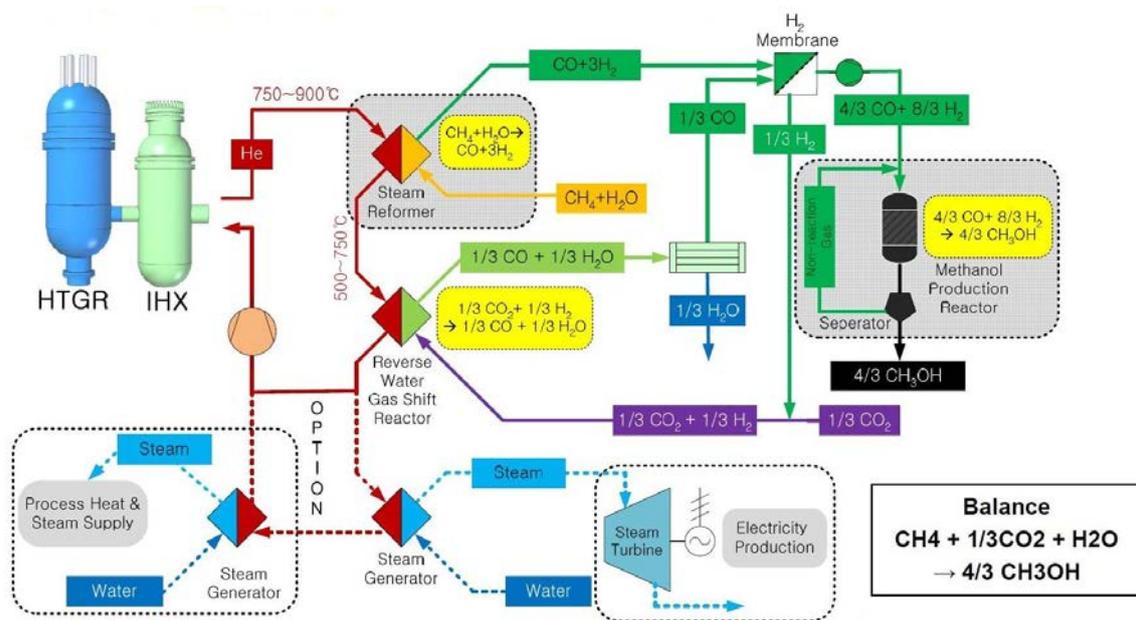
5.2.3. Japan

In Japan, methanol was considered chemically easy to produce with nuclear process heat by connecting the HTTR with a steam–methane reforming system. The design of a steam reformer for the nuclear system is

described in more detail in Ref. [24]. For the purpose of achieving economic competitiveness, the concept includes an effective waste heat utilization, for example for preheating the liquid natural gas feedstock and feed water in the HTTR steam reforming hydrogen and methanol coproduction system.

5.2.4. Republic of Korea

Future nuclear process heat applications will include not only existing markets, such as oil refineries and industrial steam supply, but also emerging markets, such as the production of synthetic methanol needed in various upgrading processes. Lee et al. [79] report on methanol production in the chemical industries, where an advanced HTGR supplies process heat in the range of 750–850°C via an IHX to steam reforming for syngas production used for downstream methanol synthesis (see Fig. 13). Recycling captured carbon dioxide can also be employed as feed to the reforming process.



Source: Figure 6 of Ref. [79].

FIG. 13. Concept of nuclear methanol production in the Republic of Korea.

5.3. NUCLEAR ASSISTED ETHANOL PRODUCTION FROM BIOMASS

The production of fuel ethanol from biomass requires large quantities of low temperature steam, which is around 100 MW(th) for a large plant. The size of a plant is limited by biomass transport costs. Forsberg et al. [80] report that, on account of rapid growth in biomass to ethanol plants, the total market is estimated to be hundreds of gigawatts of thermal energy. A major near term market for steam from nuclear power plants might develop. In the longer term, there could be a significant market for steam-to-cellulose-to-ethanol plants. On account of the market limitation to a few hundred megawatts, nuclear energy would most likely be in the form of cogeneration of electricity and steam from small modular reactors.

5.4. NUCLEAR ASSISTED ETHYLENE PRODUCTION

In a 1970 study, Kugeler et al. [81] explore a conceivable combination of nuclear heat and steam production, in which a HTGR delivers steam/heat to various stages in the chemical process (see Fig. 14). The primary helium

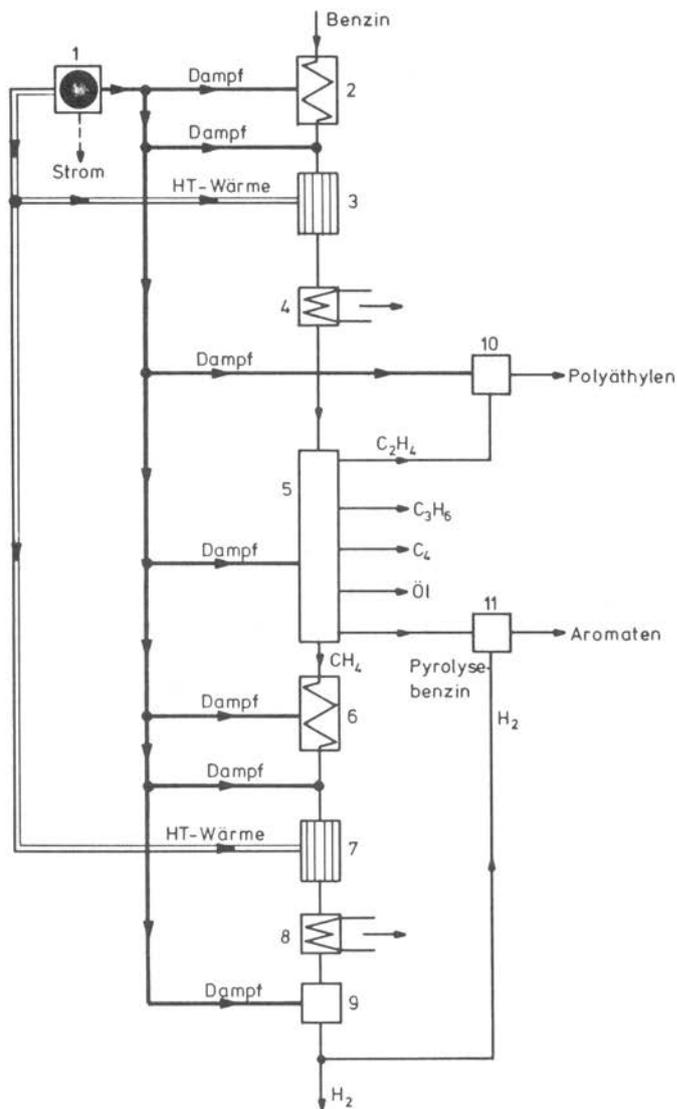


ABB. 4

Kernreaktor als Energiezentrum

- | | |
|----|--|
| 1 | Hochtemperaturkernreaktor |
| 2 | Benzinvorwärmung |
| 3 | Steam-Cracker |
| 4 | Quenchkühler |
| 5 | Produktzerlegung
(Ölwäsche + TT-Zerlegung) |
| 6 | Methanvorwärmung |
| 7 | Röhrenspaltöfen |
| 8 | Kühlen |
| 9 | Gasaufbereitung
(CO-Konvertierung + CO ₂ -Wäsche
+ CH ₄ -Abtrennung) |
| 10 | Polymerisationsstufe
(einschließlich Kompressoren) |
| 11 | Pyrolysebenzinaufarbeitung |

Source: Figure 4 of Ref. [81].

Note: 1 — high temperature reactor; 2 — naphtha preheating; 3 — steam cracker; 4 — quenching cooler; 5 — product decomposition; 6 — methane preheating; 7 — splitting furnace; 8 — cooling; 9 — gas conditioning; 10 — polymerization stage and compression; 11 — pyrolysis naphtha processing.

FIG. 14. Flow diagram of ethylene production using the PR-3000 nuclear process heat plant.

(750–950°C) is fed to the steam cracker to transfer the heat via a countercurrent heat exchanger to the splitting process. The lower temperature heat is given to the gas processing and separation stages. The methane fraction of the product gas mixture (~430 kg of methane per tonne of ethylene), but also other hydrocarbon fractions, could be routed to a nuclear steam reformer for hydrogen production. Based on a nuclear input of 3000 MW(th), the estimated annual output is estimated to be 1.5 Mt/a of polyethylene, together with higher olefins, and $4.5 \times 10^5 \text{ Nm}^3/\text{h}$ of hydrogen.

The critical component is the helium heated splitting furnace with its large pressure difference between primary and secondary side. While the reactor side favours high pressures to provide a large heat transfer, the olefin production process favours low pressures to maximize the ethylene yield. Consequently, smaller diameter tubes and large wall thicknesses hamper maintenance, in particular, removal of deposited soot. Relief to the pressure problem could take the form of an additional intermediate circuit with a different coolant, such as a liquid metal or liquid salt.

6. NUCLEAR HYDROGEN PRODUCTION FOR INDUSTRY

6.1. WORLD PRODUCTION AND CONSUMPTION OF HYDROGEN

The key features of energy systems based on the use of hydrogen as a key energy carrier are:

- The use of GHG emission free primary energy sources;
- The use of hydrogen and electricity as interchangeable main secondary energy carriers;
- The marginal use of fossil fuels (for end use niches only).

The negligible share of hydrogen of the global energy supply is explained by the practical difficulties in its introduction in the energy system. Hydrogen is not available in a form ready for use, and has to be produced by applying suitable technologies and a primary source of energy. The overall energy efficiency of the use of hydrogen therefore needs to include its production process, which has implications for the economics of hydrogen production and use.

6.2. CURRENT CONVENTIONAL PRACTICES FOR HYDROGEN PRODUCTION

Reference [24] reports that contemporary industrial hydrogen production is primarily based on the extraction from fossil resources [82]. Electrolysis contributes with only about 4%, half of it being generated as a side product in the chlorine–alkaline electrolysis. The high cost of electricity, however, allows commercial electrolysis only at locations with low electricity prices. Raw materials for hydrogen production in future, however, will definitely be water and biomass; and carbon dioxide emission free primary energies should provide the process heat for the hydrogen extraction by water splitting processes or — at least in a carbon dioxide neutral way — by biomass gasification. The production methods for hydrogen and the current status of technologies will be concisely summarized in the following sections (see Refs [24, 83] for further details).

6.2.1. Hydrogen from fossil resources

Of the current global production of industrial hydrogen, 96% is based on the extraction from fossil fuels.

- (a) The commercially most widely applied production method is steam reforming of natural gas (methane), which accounts for 48% of all hydrogen produced. It is a mature technology and, despite fluctuating feedstock prices, is the most economic method to generate hydrogen on a large scale with low specific carbon dioxide emissions when compared to coal and oil.
- (b) About 30% of hydrogen is produced from partial oxidation of oil. This process can be applied to all kinds of heavy hydrocarbon feedstock, and it includes a gasification step that generates synthesis gas with the desired carbon monoxide to hydrogen ratio determined by the steam added to the process.
- (c) Coal gasification accounts for 18% of global hydrogen production. Although coal has a comparatively low hydrogen content, it represents a cheap resource in States with coal sources.

6.2.2. Hydrogen from water splitting by electrolysis

There are principally three classes of water electrolysis, characterized by the electrolyte used:

- Electrolysis with a liquid, alkaline electrolyte;
- Polymer electrolyte membrane electrolysis with a proton conducting, solid polymer electrolyte;
- High temperature steam electrolysis with a solid oxide electrolyte.

In all cases, the water molecule is dissociated by applying an electrical current (see Refs [24, 57, 84] for further information).

6.2.2.1. *Low temperature alkaline electrolysis*

Verhondern [57] reports that:

“In an alkaline electrolysis cell containing an aqueous caustic solution with usually 20–40% KOH or NaOH, electrical energy is applied to two electrodes, which are plates made of nickel or chromium-nickel steels. Water decomposes at the cathode to H_2 and OH^- where the latter migrates through the electrolyte and a separating diaphragm, respectively, and discharging at the anode liberating the O_2 . The hydrogen gas is dissolved in the water and extracted in a separating chamber.

.....

“Operation temperatures are $< 150^\circ C$. The ideal reversible cell potential needed to split water is 1.229 V @ $25^\circ C$ which corresponds to a theoretical dissociation energy of 237 kJ/mol or an electricity demand of 3.56 kWh/Nm³ H_2 . Caused by irreversible processes in the reaction mechanism to account for gas expansion at the electrodes and to maintain the operation temperature, however, typical cell voltages are 1.85 to 2.05 V. The electrical energy requirement is in the order of 4 to 4.5 kWh/Nm³ of H_2 corresponding to an efficiency of 80% and higher. The water demand is theoretically 0.8 l/Nm³ of H_2 , in practice 1.0 l/Nm³.”

6.2.2.2. *Low temperature polymer electrolyte membrane electrolysis*

Verhondern [57] reports that:

“The more advanced method is the solid polymer electrolyte water electrolysis (SPEWE) using an acidic, proton conducting (exchange) polymer membrane (PEM) as the diaphragm, thus making an additional electrolyte obsolete. Here the hydrogen ions are migrating through the membrane and recombine with electrons to hydrogen molecules. The oxygen remains in the water. The SPEWE can be operated at higher pressures and at higher current densities due to the compact design compared to cells with a KOH electrolyte. Typical operation temperatures are $200\text{--}400^\circ C$; pressures may go up to several tens of MPa. Membrane electrolysis is simpler in its design, safer, and promises a longer lifetime and a higher efficiency. The requirement of electricity will be reduced to values below 4 kWh/Nm³ of H_2 .”

6.2.2.3. *High temperature steam electrolysis*

Verhondern [57] reports that (see Ref. [24] for further details):

“Another principal variant of electrolysis considered promising for the future is the high temperature electrolysis (HTE). Unlike water electrolysis, the total energy demand of electrolysis in the vapor phase is reduced by the heat of vaporization which can be provided — much cheaper — by thermal rather than of electric energy. The electricity input is decreasing with temperature..., and is about 35% lower compared to conventional electrolysis in the high temperature range of $800\text{--}1000^\circ C$.”

6.2.3. **Hydrogen from water splitting by thermochemical cycles**

Ozbilen et al. [85] report that a major potential method to produce large amounts of hydrogen by high temperature water splitting is the thermochemical process. Studies have shown that thermochemical cycle systems

can be expected in future to compete with the conventional hydrogen production methods by promising to be cleaner and more cost effective [86, 87] (see Ref. [24] for further information).

6.3. REVIEW OF NUCLEAR HYDROGEN PRODUCTION METHODS

Dincer and Zamfirescu [88] find that:

“Using nuclear energy as the primary energy source for hydrogen production is attractive because (1) the greenhouse gas emissions associated with nuclear energy production are much lower than those with conventional fossil fuel combustion, and (2) nuclear energy is adaptable to large-scale hydrogen production.”

Nuclear assisted hydrogen production methods of the future will be based on water splitting processes, such as conventional (low temperature) water electrolysis, high temperature electrolysis, thermochemical water splitting and hybrid thermochemical cycles [84]. In contrast, nuclear assisted, fossil based methods, such as steam reforming or coal gasification, may be rather considered transition technologies (see Ref. [88] for a review).

Morozov [89] reports that:

“The production of hydrogen by nuclear reactors can be realized by the use of various technological processes, which provides considerable flexibility:

- Using electricity from NPPs [nuclear power plants];
- Using high temperature heat from high-temperature nuclear reactors;
- Using hybrid processes (heat plus electricity).

“The first option is to be noted in particular, because it implies that all available nuclear designs for electricity generation would fit into a hydrogen based energy system. For the second and third options the HTGR is a suitable and promising technology for hydrogen production.”

6.3.1. Nuclear assisted water splitting by electrolysis

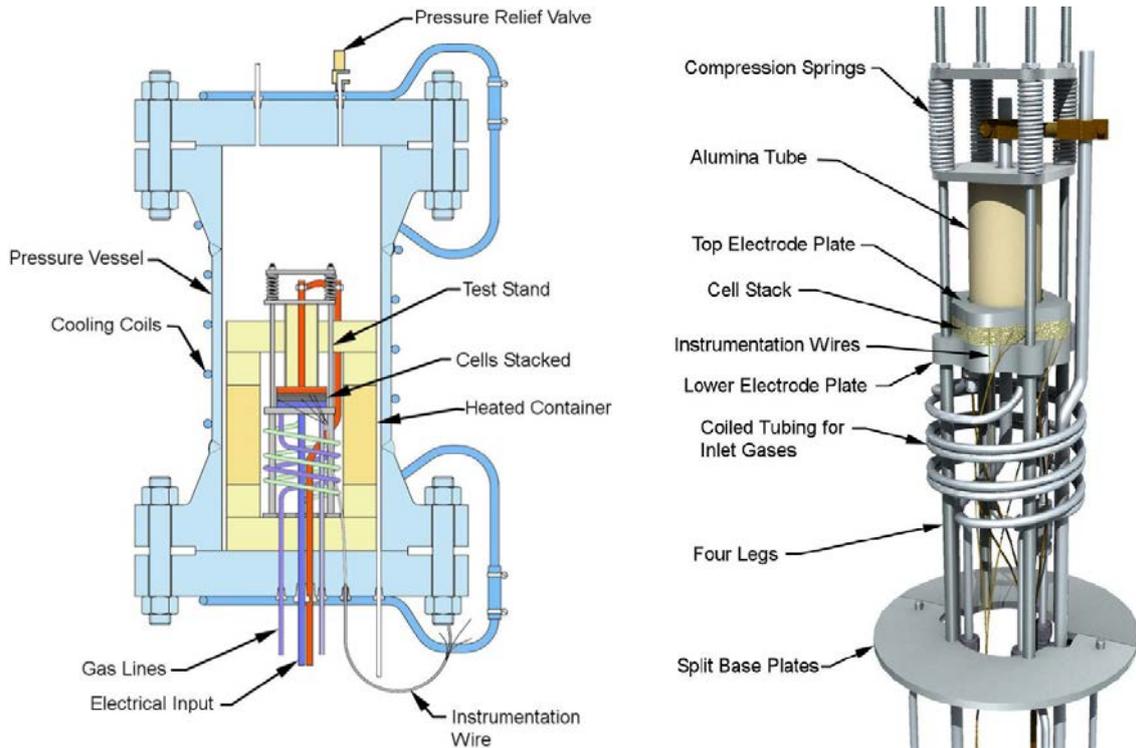
The simplest method to obtain hydrogen from nuclear power is by coupling an electrolyzer to a nuclear power plant. A full review of both low and high temperature electrolysis is given in Refs [24, 83].

The most advanced research is the experimental activities in the United States of America. Sponsored by the DOE between 2003 and 2009, the Idaho National Laboratory (INL) investigated HTSE for large scale hydrogen production coupled to advanced nuclear reactors. In conjunction with several industrial partners for solid oxide electrolysis cell (SOEC) stack development and with university partners, a comprehensive experimental programme has been established aimed at testing SOEC stacks combined with materials research and detailed modelling with computer fluid dynamics codes and process flow sheet analyses (see Refs [24, 90] for further information).

A new HTSE multi-kW test facility was constructed in 2012 at INL to demonstrate operation at the 4 kW scale with advanced cell and stack technology (see Ref. [91] for a review). Discussing activities at INL, O’Brien et al. [92] report:

“A new facility has been developed at the Idaho National Laboratory for pressurized testing of solid oxide electrolysis stacks. Pressurized operation is envisioned for large-scale hydrogen production plants, yielding higher overall efficiencies when the hydrogen product is to be delivered at elevated pressure for tank storage or pipelines. Pressurized operation also supports higher mass flow rates of the process gases with smaller components.”

Two views of the test fixture are shown in Fig. 15 (see Ref. [92] for further information).



Source: Figure 5 of Ref. [92].

FIG. 15. Instrumented apparatus for pressurized testing of HTSE stacks.

O'Brien et al. [93] report that:

“The INL HTE programme also includes an investigation of the feasibility of producing syngas by simultaneous electrolytic reduction of steam and carbon dioxide (co-electrolysis) at high temperature using solid-oxide cells.... This concept, coupled with nuclear energy, provides a possible path toward reduced greenhouse gas emissions and increased energy independence, without the major infrastructure shift that would be required for a purely hydrogen-based transportation system.... Furthermore, if the carbon dioxide feedstock is obtained from biomass, the entire concept would be carbon-neutral.”

Further information on coelectrolysis can be found in Refs [24, 93].

In addition to the work done in the United States of America, R&D on hydrogen production through water splitting using HTGR as a process heat source was initiated in 2005 as one component of China's High Temperature Reactor-Pebble Bed Module (HTR-PM) demonstration project [24]:

“Both the S-I thermochemical cycle and high temperature steam electrolysis have been selected as potential processes for nuclear hydrogen production. Beginning with preliminary studies, the R&D programme, now part of the HTR-PM project, will be conducted in phases:

- Phase one (2005–2009): verification of nuclear hydrogen production;
- Phase two (2010–2012): bench-scale testing;
- Phase three (2013–2020): pilot-scale testing, R&D on coupling technology with reactor, nuclear hydrogen safety;
- Phase four (after 2020): commercialization of nuclear hydrogen production.”

In 2013, the HTE-60 assembly, consisting of an eight cell stack, successfully verified hydrogen production at the targeted rate above 60 L/h (see Figs 16 and 17 and Table 23).



FIG. 16. INET eight cell stack.

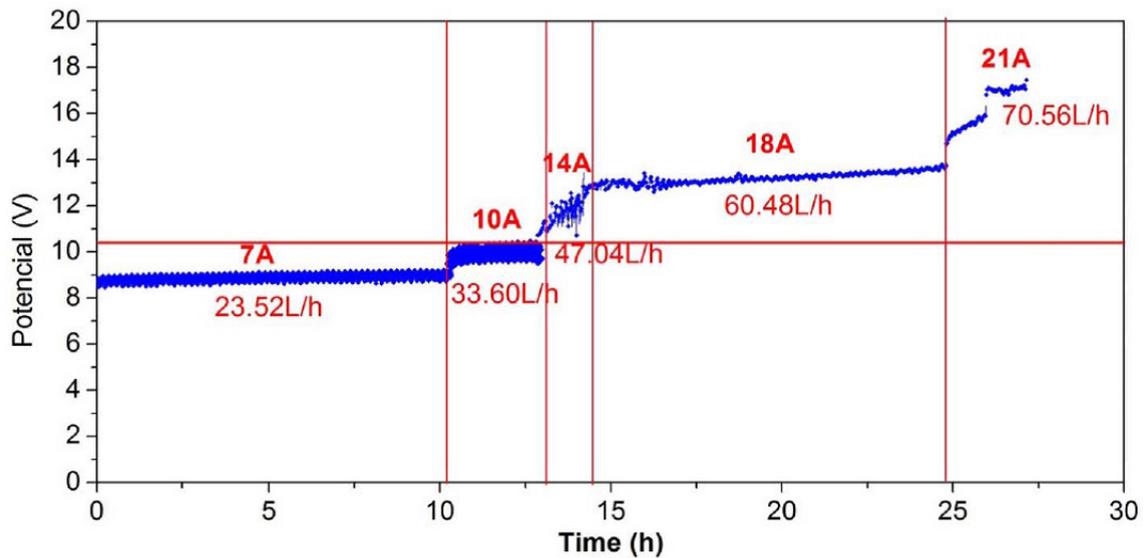


FIG. 17. Stack performance of an INET eight cell stack achieving 60 L/h of hydrogen production.

The future phases of the HTSE R&D programme include design and construction of pilot plant scale equipment to demonstrate hydrogen production at a rate of up to 5 Nm³/h, and also R&D studies on the coupling technology with a nuclear reactor [94]. The final phase, after 2020, will be the connection of the process with the HTR-10 and the commercialization of nuclear hydrogen production [94].

TABLE 23. INCREASE IN HYDROGEN PRODUCTION RATE IN THE INET HTSE TESTING PROGRAMME

Technical specifications	2010	2011	2012	2013
Current density (mA/cm ²)	30.5	44.3	83.2	>300
Hydrogen production rate (L/h)	5.2	7.6	14.3	60.5

Beginning in 2010, INET has also launched a programme to investigate the coelectrolysis of steam and carbon dioxide for the production of synthesis gas. The main objectives are to extend the use of nuclear energy to liquid fuels production, improve the economics of nuclear energy by peak electricity production, and facilitate the integration of nuclear, wind and solar energy into the electric grid.

6.3.2. Nuclear assisted water splitting by thermochemical cycles

Several Member States are investigating thermochemical cycles for large scale hydrogen production to be connected with a nuclear (or solar) heat source. Among the most promising cycles considered are the sulphur–iodine cycle and the copper–chlorine hybrid cycle. A detailed description of this method of hydrogen production is given in Refs [24, 83, 95].

6.3.2.1. R&D on the sulphur–iodine process in China

HTGR technology has undergone extensive development in China since the 1970s. A 10 MW(th) test reactor (HTR-10) with spherical fuel elements was constructed in 2000 and is currently in operation. One of the more recent major national science and technology special projects and currently ongoing is the construction of the commercial demonstration plant HTR–PM.

Since the HTGR is considered in China to be a highly suitable nuclear heat supplier for hydrogen production, R&D on nuclear hydrogen has been initiated at INET as a part of the R&D objectives of the HTR–PM project [96–101]. The sulphur–iodine thermochemical cycle for splitting water and the HTSE process were selected as the probable processes for nuclear hydrogen production. Since 2005, INET has conducted preliminary studies on these processes. A laboratory with all the necessary facilities has been established for process studies of nuclear hydrogen. The HTR-10 will provide a suitable nuclear reactor facility for future R&D of nuclear hydrogen production technology.

The sulphur–iodine process is regarded as the most suitable thermochemical cycle for nuclear hydrogen production and widely studied in many institutions across the world, including INET. Since 2005, fundamental studies on the sulphur–iodine process have been conducted intensively. Reference [102] lists some of these studies as the following:

- Process study on the Bunsen reaction and phase separation characteristics of HI–I₂–H₂SO₄–H₂O mixtures (i.e. the products of the Bunsen reaction);
- Purification of the HIx and sulphuric acid phases produced by the Bunsen reaction through the reverse Bunsen reaction;
- Preconcentration of hydroiodic acid over azeotropic compositions by electro–electrodialysis (EED) and concentration of hydroiodic acid by conventional distillation;
- Catalytic decomposition of hydroiodic acid, and the development of efficient catalyst/supporters and novel preparation methods, such as electroplating of platinum on various supporters;
- Catalytic decomposition of H₂SO₄ on platinum and non-noble metal catalysts, including iron/copper oxides and chromium/copper oxides;
- Correlations between the density and composition of the HI–I₂–H₂O and HI–H₂O–I₂–H₂SO₄ systems.

A proof of concept closed cycle sulphur–iodine facility shown in Fig. 18 with a hydrogen production rate of 10 NL/h (IS-10) has been designed and established at INET based on these basic studies. A closed cycle experiment



FIG. 18. Proof of concept experimental facility of the sulphur–iodine process at INET.

was carried out successfully with the hydrogen production process lasting for over six hours (see Ref. [102] for a review). It was found, however, that under certain operating conditions such problems as clogging caused by iodine and formation of sulphur arose [102]. These issues may lead to mass imbalance or failure of long term operation. To achieve process scaleup and longer and more stable operation, the INET initiated bench scale R&D on the sulphur–iodine process [83].

In 2010, the INET initiated R&D on the sulphur–iodine cycle with financial support of the Government of China. The objectives are the construction of an integrated, bench scaled sulphur–iodine facility with hydrogen production capacity of 100 NL/h (IS-100) and the achievement of a long term, continuous closed cycle operation. The R&D goals of the sulphur–iodine process study in this phase are:

- (1) To verify and acquire the knowhow of long term, stable and continuous sulphur–iodine thermochemical water splitting hydrogen production;
- (2) To test the corrosion resistance of the screened engineering materials;
- (3) To supply the technical basis for further scaleup and pilot scale process.

To achieve these goals, the following R&D items are scheduled:

- (a) Process simulation and optimization: Considering the complexity of the process, it is necessary to conduct simulations in addition to experiments. The computer model Aspen Plus was used to simulate the process. However, because some important unit operations, such as Bunsen reaction product separation and EED, were developed and implemented in Aspen Plus. The simulation for the global process was successfully conducted. The models built included the phase separation and composition calculation models for Bunsen reaction products, the EED model and the H₁x distillation column model. In addition, some models embedded in Aspen Plus proved effective for simulating some unit operations. Finally, simulation software was developed, and the simulation for the global sulphur–iodine process was successfully conducted. The models and software were validated and verified using the experimental data acquired through the IS-10 closed cycle experiment.
- (b) Optimization of the process: The process, including optimization of the parameters for the process units and inner cycling of the streams inside the HI section, was optimized through development of the simulation software.

- (c) EED stack development: The EED stack, with an effective area of 2800 cm², was built to meet the requirements of HI solution concentration in the bench scale sulphur–iodine facility. The performance of EED stacks was also evaluated.
- (d) Corrosion resistance test of the engineering materials: Much effort was focused on screening the materials that could resist the harsh corrosion conditions of the process, and some candidates for various reactors were selected. However, considering the cost and challenges of constructing the components, most of the reactors and apparatus in the bench scale facility are still built with quartz and B–Si glass. Few components are built using Teflon lining or stainless steel coating.
- (e) Purification technology of Bunsen products: Purification of the HI_x phase in the Bunsen section is a crucial and difficult issue affecting the process. Much effort to this end is still in progress.
- (f) Measurement and control technology: Some simple analytical methods and codes were developed in INET to quickly analyse the species involved in the sulphur–iodine process. Efforts were made to develop the online measurement technology and the control technology for the interface of the HI_x and sulphuric acid phases.
- (g) Construction and operation of the bench sulphur–iodine loop: The design of IS-100 has been completed, and current efforts are focused on the development of key reactors and construction of the loop.

Construction of the IS-100 facility was completed in 2013, and its long term operation testing has started. The features of IS-100 are shown in Table 24. The finished sulphuric acid skid is shown in Fig. 19; the two other skids are still under construction.

TABLE 24. SPECIFICATIONS OF THE BENCH SCALE IS-100 FACILITY AT INET

Specifications	Contents
Capacity	Hydrogen production rate 100 NL/h
Main parts	Bunsen reactor and separator, H ₂ SO ₄ decomposition reactor, HI decomposition reactor, purification columns of HI _x and H ₂ SO ₄ phases, EED stack, control system and pumps
Heating	Electricity
Materials	Teflon coating, Ta/W alloy, quartz glass and B–Si glass
Features	Skid types: H ₂ SO ₄ skid, HI skid, Bunsen skid EED for HI concentration over azeotropic composition Automated temperature control and record, liquid flowrate control (diaphragmatic metric pump and mass flow controller) Multi-running mode (section continuous, open cycle and closed cycle)

Source: Table 27.1 of Ref. [102].

The final goal of the R&D plan on nuclear hydrogen production is to achieve coupling of the INET HTR-10 and hydrogen production technology. After completing the bench scale experiment of the sulphur–iodine process, INET will begin key technology research for pilot scale hydrogen production. Expected studies on the sulphur–iodine process include development of the key prototype components, engineering skids of the three sections, thermalhydraulics test, heat recovery and efficiency improvement. Issues on the safety of nuclear hydrogen production and IHX, among others, will also be addressed.

6.3.2.2. R&D on the copper–chlorine process in Canada

The copper–chlorine thermochemical cycle has gained particular interest because of the lower temperature requirement compared to other cycles, which allows more of the next generation reactor concepts to be considered as the nuclear heat source. This is true, for example, for the SCWR, regarded as Canada’s future nuclear reactor type of choice, which can meet the maximum temperature of 550°C necessary for the copper–chlorine cycle.



FIG. 19. Sulphuric acid section of IS-100.

Naterer et al. [103] report that Atomic Energy of Canada Limited (AECL) has verified a CuCl electrolyzer where hydrogen is produced at the cathode and Cu(I) is oxidized to Cu(II) at the anode. A large scale lab facility successfully demonstrated the cycle and will eventually be scaled up to a pilot plant. The Argonne National Laboratory (ANL) has shown the thermodynamic viability of all reactions of the copper–chlorine cycles. In particular, the principle of CuCl decomposition and hydrogen production with a CuCl/HCl electrolyzer was proven in a long term, 341 h experiment with a steady state period of the cell voltage between 74 h and 238 h exhibiting very good overall performance [103].

An assessment with Aspen Plus yielded a heat to hydrogen efficiency of 54% which was based on ideal heat transfers. More realistic estimations have reduced the ideal efficiency of the cycle to a maximum value around 30%. Exergy analyses of the Cu–Cl cycle might help to understand and reduce losses and thereby to improve efficiencies based on energy or exergy expected to be approximately 40% [104]. Naterer et al. [103] estimate 43% net efficiency.

The challenges associated with the Cu–Cl cycle include the development of a cation exchange membrane with high conductivity for hydrogen ions but low conductivity for copper and good corrosion resistance, a better understanding of the mixing performance of liquid and solid particles in the hydrogen production section or the development of heat exchangers with improved heat transfer and sufficient corrosion resistance at high temperatures. Naterer et al. [105] find that a particular challenge for material development is the high temperature oxidizing atmosphere in the reactor for copper oxychloride decomposition, where pure oxygen is produced at 450–550°C.

Experiments have also been conducted on heat recovery from molten CuCl in the thermolysis reactor. The investigations included the heat transfer from molten CuCl flowing inside a tube to a coolant surrounding the tube and direct contact heat recovery through droplet atomization, where the temperature of falling molten CuCl droplets through air into a water bath was measured (see Ref. [103]).

7. NUCLEAR ENERGY FOR OTHER INDUSTRIES

7.1. CURRENT PRACTICES FOR STEEL PRODUCTION

The primary output of the iron and steel industry is crude iron or crude steel of different qualities. Steel is currently produced in furnaces by reducing iron ore from fossil fuel as hydrocarbon source. While exact implementation varies in practice, the chemical reaction is effectively a combination of ore with either coal or natural gas as the reducing agent. Besides the reactant role, additional fossil energy is used to heat the furnaces and, in the case of most widely used blast furnaces, to melt the ore. In both processes, carbon dioxide is produced. The principal and most commonly applied routes applied for the production of crude steel include: coke ovens, blast furnaces and basic oxygen furnaces using mainly iron ore but also scrap; and electric arc furnace using directly reduced iron (sponge iron), scrap and cast iron or pig iron.

7.1.1. Blast furnace

In a blast furnace, iron ore is chemically reduced and melted into hot, liquid iron. Iron ore and coke agglomerate are added from the top and gradually move down the vessel as the coke oxidizes and the ore melts. The coke used in the blast furnace process is gasified in the lower part of the furnace and serves the process requirements to provide energy for heating and smelting. Larger blast furnaces have less heat loss than smaller ones. A large blast furnace plant at a power level of 1600 MW(th) produces a tonne of iron every 10 seconds. At around 99.5%, the overall iron yield is very high.

7.1.2. Electric arc furnace

Electric arc furnaces use electricity to melt scrap, direct reduced iron and pig iron. Purified iron is required for the production of high quality steels. Electric arc furnaces are less harmful to the environment than traditional blast furnaces. The heat needed to melt the metal is produced by electricity. This process would require cheap sources of hydrogen if the old production methods were to be replaced with electric arc furnaces.

7.1.3. Direct reduction of iron ore

Unlike blast furnaces, which produce liquid iron, iron ore can also be reduced in the solid state. Reducing gases can be carbon monoxide or hydrogen (or its combination). A mixture of carbon monoxide and hydrogen is preferable from the heat balance point of view, whereas pure hydrogen has the advantages of shorter reaction times (reducing the furnace volume) and leaving water vapor in the exhaust gas (which is easier to partition off compared to carbon dioxide). The reaction temperature should be around 900°C to maximize reaction rates without sintering or softening of the ore. The hydrogen requirement is 610 Nm³ per tonne of iron product (see Ref. [83] for further information).

7.2. POTENTIAL MARKET FOR NUCLEAR ENERGY

7.2.1. Iron and steel

Since the iron and steel sector is the largest industrial emitter of carbon dioxide, efforts are being made to improve the industry sustainability by reducing GHG emissions while diversifying energy sources. Near term approaches focus on making the existing processes more efficient and carbon leaner, whereas longer term strategies are directed to developing breakthrough processes utilizing carbon neutral energy, non-fossil electricity and feedstock such as hydrogen or biomass. The potential application of nuclear hydrogen and electricity is included in these strategies.

7.2.1.1. Lurgi analysis of nuclear assisted steel production

In addition to nuclear industrial process heat applications, Lurgi, a German company, has also analysed the steel manufacturing process. It was not, however, deemed advisable on account of estimated low share of nuclear process heat that could be introduced into the industrial process. The analysis was on an integrated steel plant combined with a cokery that produced 1.6 Mt/a pig iron, and a high temperature reactor to deliver heat, steam and electricity (a full analysis can be found in Ref. [73]).

7.2.1.2. JAEA concept of nuclear assisted steel production

Yan et al. [106] propose and evaluate a steel making system based on the nuclear plant concept GTHTR300C (see Section 3.7.4):

“The objective is use of the GTHTR300C to supply all consumption of steelmaking with the exception of iron ore. Use of a hydrocarbon source as reactant or fuel is ruled out, the obvious benefit of which besides not requiring fossil fuel is absence of carbon dioxide by-production and emission in any steel furnace. The actual design method uses a multidisciplinary approach involving nuclear fission energy production, process heat and power conversion, thermochemical feedstock manufacturing, endothermic reduction of iron ore by hydrogen and oxygen, and oxygen steel refinement.”

Although there is a balanced set of process parameters supplied by the nuclear plant heat and power cogeneration for continuous steel making, the nuclear plant is designed to offer the flexibility of independent supply to gas generating facility, shaft furnace and electric arc furnace. For example, in case of planned or forced downtime of an electric arc furnace, nuclear heat is continuously produced and supplied to the gas generating facility production to support uninterrupted operation of the shaft furnace. On the other hand, in case of shaft furnace downtime, electricity production from a nuclear plant can be raised to support increased electric arc furnaces production or grid export. Such flexibility eases operation management of the steel plant while maximizing economic return from various operation modes (see Ref. [106] for further information).

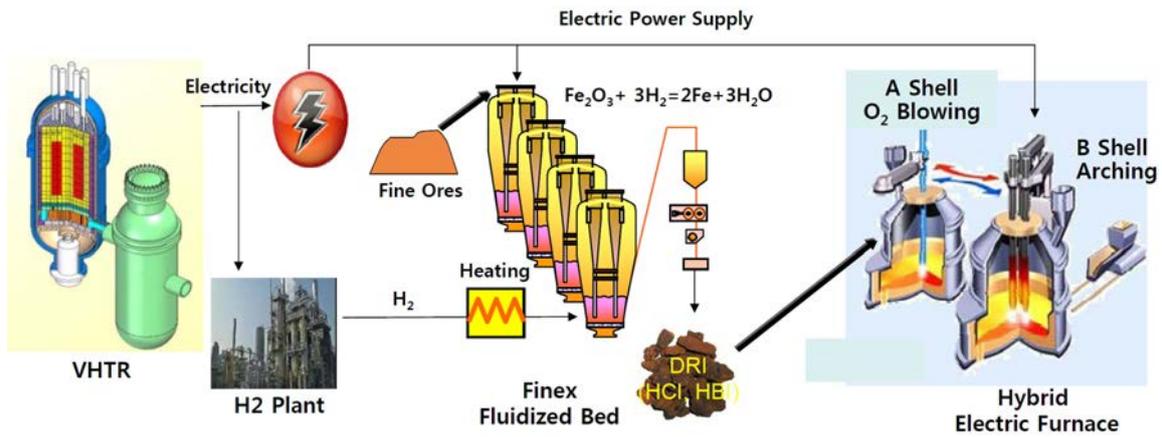
7.2.1.3. POSCO concept of nuclear hydrogen steel making

The SMART is a 100 MW(e) class system-integrated modular advanced pressurized water reactor proposed by the Korea Atomic Energy Research Institute (KAERI). Developed by an industry led consortium, the design is characterized by in-reactor vessel steam generators and advanced safety features that eliminate loss of coolant events resulting from a large pipe rupture. Design lifetime is sixty years, with a three years refuelling cycle. SMART obtained the standard design approval by the national regulatory authority, the Nuclear Safety and Security Commission, in 2012. The reactor is available for hydrogen production through electrolysis.

Since 2011, the steel company POSCO has been involved in a project with KAERI. The Nuclear Hydrogen Development and Demonstration project develops VHTR reactor technologies and thermochemical hydrogen production applying the sulphur–iodine process. The sulphur–iodine process development, planned for a period of six years with equal share of government and private funding, has completed a laboratory scale experiment and is currently demonstrating operation of an integrated system at a production rate of 50 L/h of hydrogen, with a 1000 L/h pilot plant planned. Figure 20 is a schematic of the steel making process combining VHTR, hydrogen plant based on the sulphur–iodine process and FINEX. VHTR produced hydrogen is used as ore reducing gas and fuel for preheating the gas. About 50% of the hydrogen is recycled from FINEX offgas. POSCO estimates that 1300 MW(th) thermal power from about twin units of VHTR is required to produce 2 Mt/a of hot compacted iron.

7.2.1.4. Tokyo Institute of Technology concept of nuclear supplied carbon recycle steel making system

A general energy transformation concept based on carbon recycling, called the active carbon recycling energy system (ACRES) is reported for steel making by the Tokyo Institute of Technology by Kato [107]:

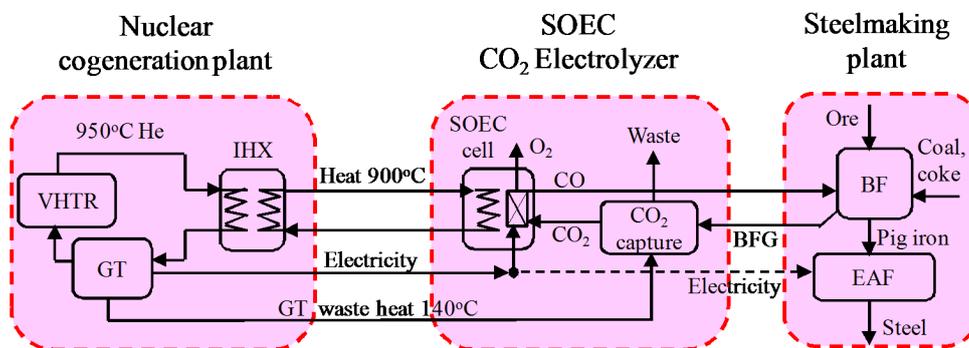


※ DRI: Direct Reduction Iron, HBI: Hot Briquetted Iron, HCI: Hot Compacted Iron

FIG. 20. Future nuclear assisted, carbon dioxide free steel making process.

“In this system, hydrocarbons are regenerated from carbon dioxide by using a heat source that does not emit carbon dioxide, allowing the hydrocarbons to be re-used cyclically as energy carrier media.... Carbon monoxide has a higher energy density than hydrogen and is highly compatible with conventional chemical, steel, and high-temperature manufacturing processes. Thus, it is a suitable carbon medium for ACRES.”

The flowsheet of a specific configuration of ACRES steel making process shown in Fig. 21 has been calculated using the commercial process simulator Aspen Plus. The nuclear plant is modelled according to the GTHTR300C design. The SOEC electrolyzer mainly consists of a carbon dioxide capture column, a carbon dioxide preheater (not shown) and an SOEC type electrolysis cell. The steel making plant consists of a blast furnace and an electric arc furnace. Pure carbon dioxide is separated by chemical absorption from the blast furnace gas. Nuclear heat at 900°C is transferred through the IHX and a closed secondary circulation loop to raise the temperature of the separated carbon dioxide stream in the preheater before entering the SOEC electrolysis cell. The substantial heat requirement for the carbon dioxide capture column at 140°C is met in part by the recovery of waste heat from the gas turbine power generation cycle and in part by waste heat recovered in the steel making plant. The hot, pure carbon dioxide is decomposed at 800°C into carbon monoxide and oxygen in the electrolytic cell using electricity efficiently produced by the nuclear reactor gas turbine.



Note: BF — blast furnace; BFG — blast furnace gas; EAF — electric arc furnace; GT — gas turbine; IHX — intermediate heat exchanger; SOEC — solid oxide electrolysis cell; VHTR — very high temperature reactor.

FIG. 21. Schematic of the ACRES steel making process with VHTR.

Although not explicitly modelled in the present flowsheet calculation, it is straightforward for the nuclear plant to meet the electricity demand by the electric arc furnace. Table 25 details the calculation condition for the flowsheet. Table 26 is the calculation result of heat and electricity balance for the flowsheet.

TABLE 25. CALCULATION CONDITIONS FOR ACRES PROCESS BASED ON 600 MW(th) VHTR

Plant	Parameter	Value
VHTR		
Primary He loop	Reactor heat (MW)	600
	Reactor outlet temp. (°C)	950
	IHX temp. drop (°C)	50
Secondary He loop	He temp. at inlet/outlet of SOEC (°C)	900/850
SOEC		
CO ₂ capture column	Inlet blast furnace gas flow rate (kmol/s)	6.486
	CO ₂ fraction from BFG stream (mol%)	27.6
	CO ₂ capture ratio (mol%)	90
	Heat for CO ₂ capture at 140°C (GJ/tCO ₂)	4.0
CO ₂ electrolysis	CO ₂ conversion ratio (mol%)	60
	Current (A)	1.87 × 10 ⁸
	Current density (A/cm ²)	0.30
	Theoretical voltage (V)	0.980
	Over potential (V)	0.371
	Total voltage (V)	1.351
	Cell temp. (°C)	800
Steel plant	Steel output (Mt/a)	1.16

TABLE 26. ENERGY BALANCE IN THE ACRES PROCESS FOR 1.16 Mt/a STEEL PRODUCTION

	HTGR supply	SOEC consumption
Heat		
CO ₂ capture column (MW(th))	183 at 140°C	183
SOEC cell (MW(th))		21
SOEC preheating (MW(th))		18
Total (MW(th))	39 at 900°C	39
Electricity		
SOEC (MW(e))		252
CO compressor (MW(e))		14
Total (MW(e))		266

7.2.2. Nuclear assisted alumina production

As part of the primary aluminium manufacturing process, alumina (aluminium oxide) production from bauxite requires the following main process stages:

- Leaching of the aluminium hydroxide from the bauxite by caustic soda (sodium hydroxide) where hot liquid salt heats the caustic soda solution to 250°C at 10 MPa;
- Separation of the aluminium hydroxide from the caustic soda solution, for which process steam is required;
- Calcination of the aluminium hydroxide to alumina at 200–850°C and 0.4 MPa.

For connection of these processes to an HTGR, the conventional heat exchangers should be converted to components heated by secondary helium. Apart from the He-He IHX in the primary circuit, the potential nuclear process heat exchanging components are utilizing the heat of the secondary helium for transfer to the purposes as indicated in Table 27.

TABLE 27. NUCLEAR PROCESS HEAT EXCHANGERS IN ALUMINA PRODUCTION

Process heat exchanger	Secondary helium inlet/outlet temp. (°C)	Tertiary fluid inlet/outlet temp. (°C)
Fluidized powder heat exchanger	900/680	850/190
Steam generator	680/419	500/170
Liquid salt heat exchanger	419/250	400/240

Source: See Ref. [74].

Since with present design HTGRs, the necessary process temperature of 950°C cannot be delivered to the secondary circuit (not to mention the tertiary circuit), additional R&D work on the nuclear heat source or on the calcination process would be required [73]. A potential for the integration of nuclear high temperature heat into the above described first process step was seen. The respective study conducted by Lurgi resulted in the development of concepts for heat exchangers transferring nuclear heat from a 170 MW(th) modular HTGR to industrial alumina production at higher and lower temperatures (see Fig. 22) [73, 74].

The low temperature process proposed is the processing of the bauxite by applying sodium hydroxide (210–250°C and 10 MPa) for the conversion to sodium aluminate. For this purpose, heat from the hot secondary helium is transferred to a molten salt in a tertiary circuit, before the 250°C hot salt transfers its heat to the caustic soda solution. For the high temperature section of the process, which is the calcination step to obtain alumina, the

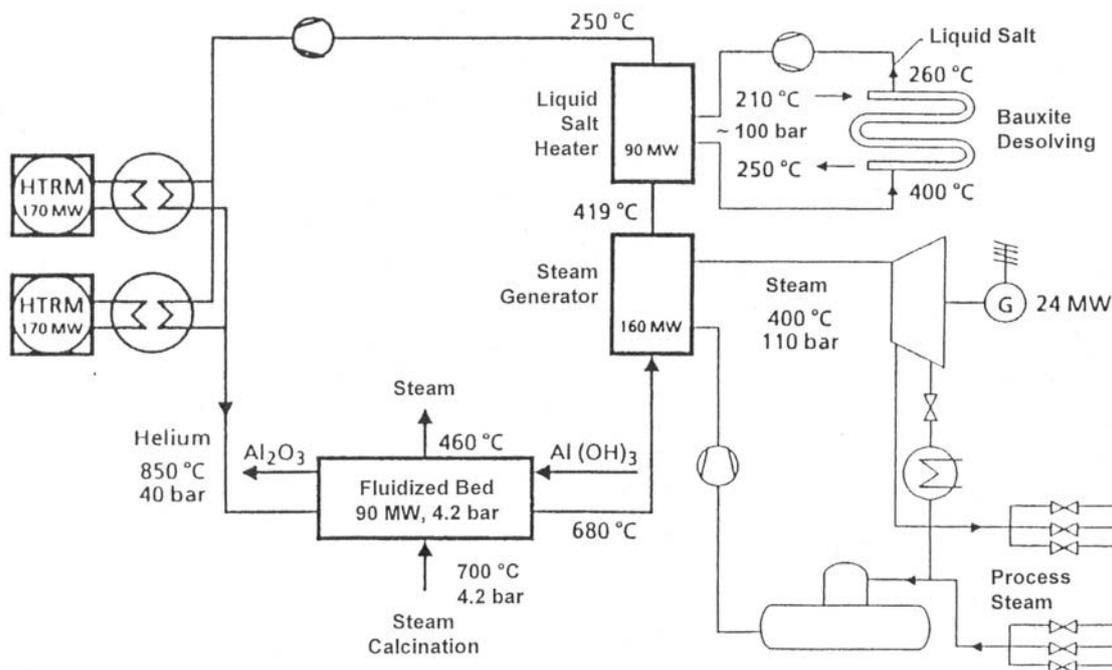


FIG. 22. Process heat exchangers in nuclear assisted alumina production [74].

temperatures required actually exceed the capability of an HTGR. The concept of a fluidized bed heater suggests here to take hot helium at 850°C plus additional electric heating to introduce sufficient heat into the process where aluminium hydroxide enters at 200°C and leaves as alumina at 950–1000°C. The final temperature of the alumina using the electric heating is obtained in the last chamber of the fluidized bed heater. The secondary helium leaves the heat exchanger at 680°C. A schematic of the fluidized bed heater is shown in Fig. 23.

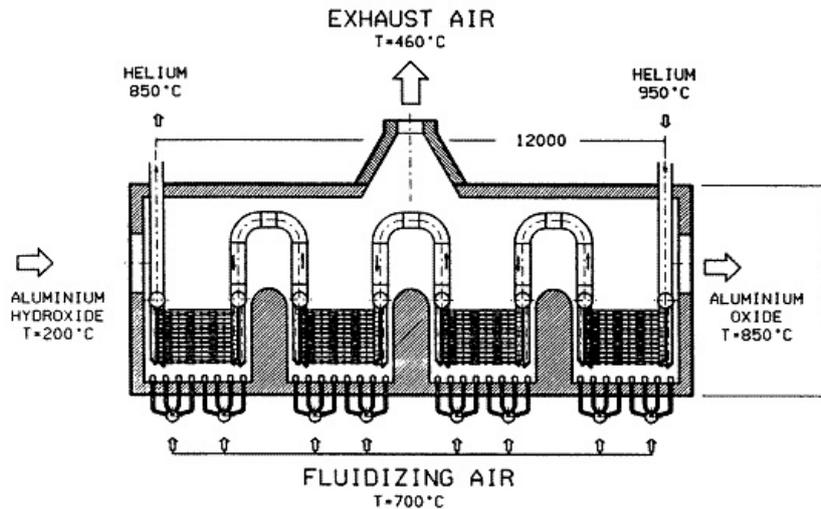


FIG. 23. Fluidized bed heater [74].

7.3. CONCLUDING REMARKS

Nuclear energy could be used in the existing furnaces of the steel industry by generation of synthesis gas either from nuclear assisted steam reforming or from high temperature coelectrolysis of water and carbon dioxide. The application of nuclear heat just for air preheating is considered a comparatively small market but could be extended also to the production of argon, nitrogen and oxygen from air liquefaction. Oxygen could also come from water splitting processes, with the hydrogen being consumed in large quantities in the upgrading process of raw iron to steel. In electric arc furnaces, nuclear plants could also provide the electricity. In the recycling of scrap steel, nuclear energy could again take over the preheating step to reduce electricity consumption.

8. EXAMPLES FOR NUCLEAR CONCEPTS WITH INDUSTRIAL PROCESS HEAT APPLICATIONS

A whole variety of conceptual designs for nuclear non-electric industrial process heat and steam applications has been developed, and many are based on HTGRs. The first part in this section describes experience with nuclear industrial cogeneration other than district heating and seawater desalination; the second part describes examples of future nuclear reactor concepts dedicated to the (co)production of hydrogen, electricity and other industrial applications.

8.1. EXPERIENCE WITH NUCLEAR INDUSTRIAL COGENERATION APPLICATIONS⁵

8.1.1. 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.

8.1.2. 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 boiling water reactor with a maximum power of 25 MW(th) (20 MW(th) nominal). The coolant is deuterium hydroxide, and it flows 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 character, the process steam supply is regulated by an international research programme.

8.1.3. 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 extended 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.

The diversion of (higher quality) process steam to industrial end users is at the expense of a reduction in electric power output from the nuclear plant. With regard to the Gösgen plant and its delivery of high quality steam to the paper factories, the loss of nuclear electric power is 1 kW(e) for each 3 kW(th) delivered. This is to be compared with the Beznau nuclear power plant, also in Switzerland, which supplies a district heating network at an electric power reduction of 1 kW(e) for each 8 kW(th) delivered [108].

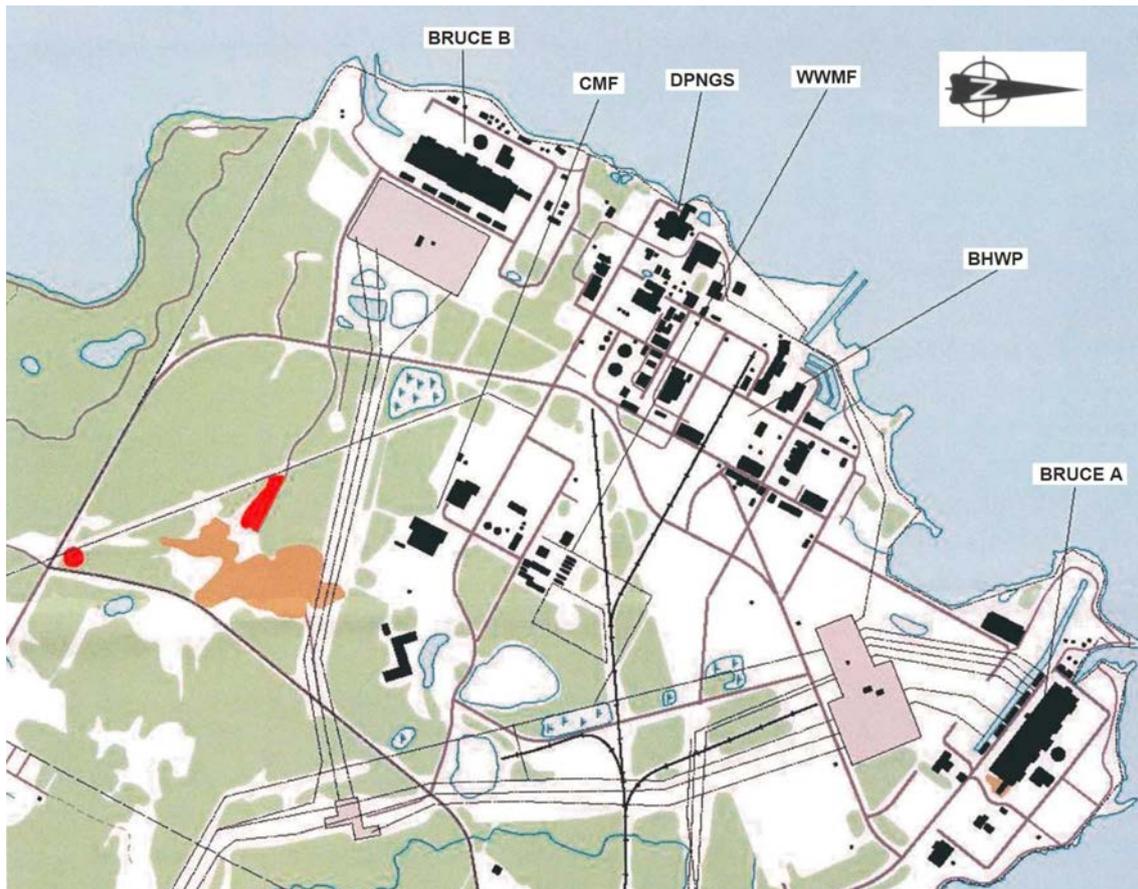
8.1.4. Bruce Nuclear Power Development park, Canada

8.1.4.1. Bruce nuclear power plant

With eight CANDU reactors (plants A and B with four units each) and a total net electricity production of 6232 MW, the Bruce nuclear power plant in Ontario, Canada, is one of the largest nuclear facilities in the world (see Fig. 24). While the four units of plant A, which started operation in the 1970s, were taken out of service in the 1990s, all four have resumed operation in the meantime. The units of plant B went into service between 1984 and 1987 and are still in operation. The nuclear site's purpose was to ensure a reliable supply of reactor grade heavy water to meet the needs of future CANDU plants, where it is used as a moderator and coolant [109].

The secondary heat transport system of Bruce A diverted high pressure steam via a steam transformer plant to the Bruce bulk steam system (BBSS), which became one of the largest process steam supply systems in the world, with a capacity of 5350 MW(th) delivered through piping of more than 6 km length. It produced medium pressure process steam for the heavy water plants (~750 MW(th)), which were as well supplied with steam from the adjacent Douglas Point nuclear generating station — used as heat source until the late 1970s and shutdown in 1984 — and from the backup oil fired boilers at the Bruce steam plant. A portion of around 15 MW(th) was supplied for

⁵ Section 8.1 is based on Ref. [19].



Source: Figure 1.2 of Ref. [109].

Note: BHWP — Bruce Heavy Water Plant; CMF — Central Maintenance Facility; DPNGS — Douglas Point Nuclear Generating Station; WWMF — Western Waste Management Facility.

FIG. 24. Map of the Bruce Nuclear Development park.

heating buildings on-site. An additional 72 MW(th) of steam from BBSS was also delivered to the Bruce energy centre industrial park, supplying a plastic film manufacturer, a greenhouse, an ethanol plant, an alfalfa plant, an apple juice concentration plant and an agricultural research facility. At times, the Bruce A CANDU reactors were unavailable, the steam supply was maintained with oil fired power plants. The BBSS was eventually demolished in 2006.

The Canadian Nuclear Safety Commission [109] reports that steam from the Bruce A secondary heat transport system or the Douglas Point generating station sometimes contained low levels of tritium owing to occasionally failing heat exchanger tubes, before steam transformer components were implemented. Routine sampling, however, did not detect any significant tritium cross contamination and never exceeded the limit of 7000 Bq/L (as fixed in Ontario's water quality guidelines). The design of the steam transformer plant, however, prevented any steam from Bruce A from mixing with the medium pressure process steam generated for the Bruce Heavy Water Plant.

8.1.4.2. The Bruce Heavy Water Plant

Plant A, with a design capacity of 96.6 kg/h of 99.75% purity heavy water, started operation in 1973 (ending in 1984). Improvements made raised the official capacity to 100.6 kg/h [110]. Owing to successful operation, the construction of three more plants with the identical design was planned. While plant B was operated between 1979 and 1997, plant D was completed by 70% before being cancelled, and the plan for plant C was abandoned following a cutback in the Canadian nuclear programme and an improved efficiency in the use and recycling of heavy water [109].

Each plant was composed of two identical enriching units, one finishing unit, and associated auxiliary systems and buildings. An enrichment unit (see Fig. 25) was divided into three sections, an absorption/desorption section for water/gas treatment, an extraction section representing the first stage where the deuterium is actually extracted from the water and hydrogen sulphide, respectively, while the enriching section is simply further concentrating the product.

The plant was in continuous operation since April 1973. It became the world's largest heavy water production plant with a capacity of 700 t/a and an overall production of 16 000 t. Enrichment unit E4 of plant B was shut down in May 1997 owing to a problem with the steam supply from Bruce A. Eventually, the Bruce Heavy Water Plant was permanently shut down in 1998 and gradually dismantled since.

8.1.5. Stade nuclear power plant, Germany

Between 1983 and 2003, the Stade plant supplied a 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 returned in the form of condensate. After plant shutdown, the operation of the salt refinery was also shut down.

The salt production was based on solution mining where water is brought into an underground salt bed, with the brine pumped to the surface, heated and evaporated in pressure vessels (vacuum evaporation). Remaining moisture in the crystallized salt was removed in a final drying step. The external steam decoupling resulted in a reduction of the net electricity production by around 10 MW. Backup systems during power outage periods was provided by a nearby heavy oil fired power plant, later by an on-site oil fired boiler.

Figure 26 contains the record for the twenty years operation of the external steam system of the monthly gross electric power production (in blue), a part of which was provided as steam (in green), was typically in the range of 1–1.5% of the gross electricity produced (or the above mentioned 10 MW). The light blue line represents



FIG. 25. Enrichment unit E4 of plant B (87 m high and 8.5 m in diameter) [109].

the accumulated steam energy, which reached a total of 1032 GW·h of thermal energy delivered to the salt refinery over the twenty years. Its steady increase demonstrates the virtually problem free operation of the external steam system.

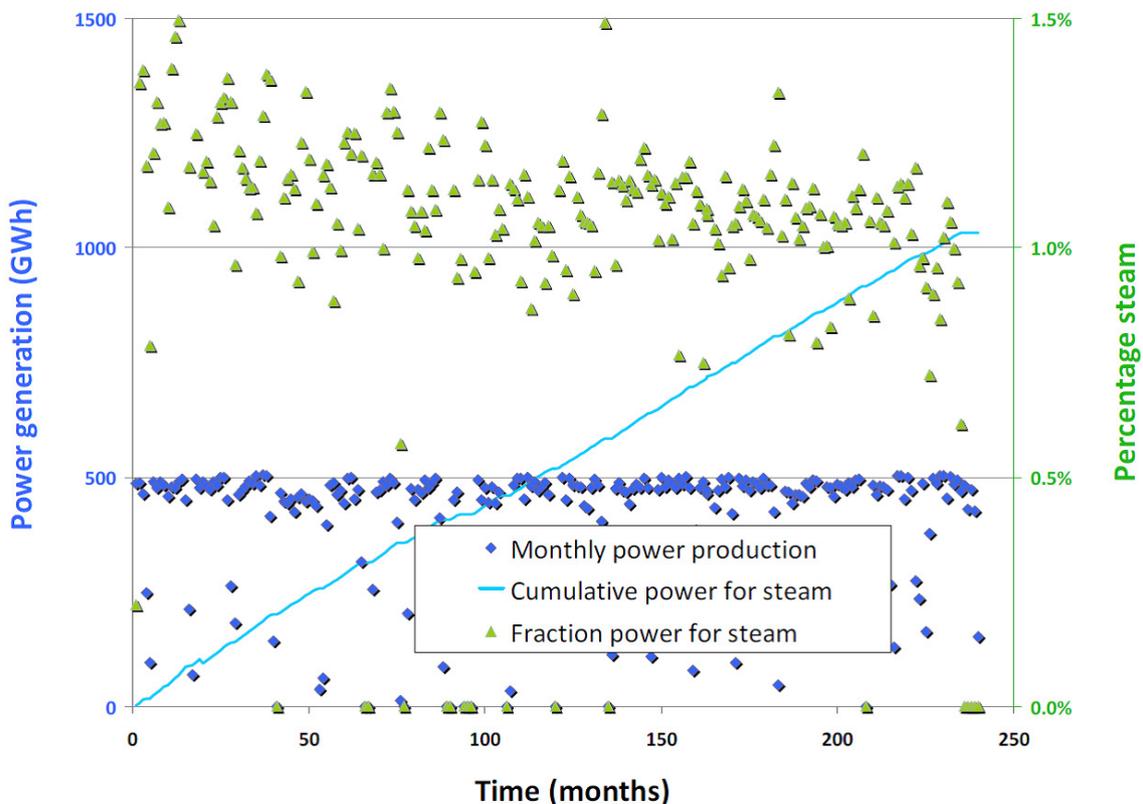
8.2. SPECIFIC CONCEPTS FOR NUCLEAR LOW TEMPERATURE INDUSTRIAL APPLICATIONS

8.2.1. Canada: ACR-700 with tertiary oil recovery

Canada has large petroleum deposits. Gibbs and Asgarpour [111] estimate that the Athabasca region, Alberta, contains approximately 1.7 trillion barrels of bitumen, with a recoverable volume quoted as 170 billion barrels. Reference [24] reports that:

“Canada has the second-largest petroleum deposits in the world (after Saudi Arabia). Its oil sands produce 1.3 million bbl/d of oil today, up from 600 000 bbl/d in 2000. But the development of oil sands projects has been sharply criticized for its impact on the environment and its intensive use of both water and natural gas. The growth in oil sands exploitation is one of the reasons that Canada has failed to contain its GHG emissions in recent years despite its commitment to do so.”

In the tertiary oil recovery, the largest cost factor is energy for steam, electricity and hydrogen production, which is currently extracted from natural gas. For the conversion of oil sands into a synthetic crude oil, several large scale hydrogen production plants based on steam reforming of natural gas are employed. Each of those have a production capacity of 2.8 million Nm³/d (~255 t/d of hydrogen), while consuming about 0.94 million Nm³/d



Source: Data from monthly statistics published in *atw* – International Journal for Nuclear Power.

FIG. 26. Monthly electric energy generation and steam delivery to the salt refinery.

of natural gas, a rate that will grow by more than 30% according to the projected demand by 2015 of 60 million Nm³ [112]. The World Nuclear Association [113] reports that:

“About 1.05 GJ of natural gas is typically required to produce a barrel of bitumen by in situ methods, and this must then be upgraded to oil. The extraction represents almost 30 cubic metres per barrel of oil (embodying 6 GJ), and in 2006 it accounted for more than 40% of Alberta’s natural gas demand.

“From about 2003, various proposals have been made to use nuclear power to produce steam for extraction of the bitumen from these deposits and also to produce electricity for the major infrastructure involved.

.....

“One proposal from Energy Alberta suggested that a single Candu 6 [700 MW class] reactor configured to produce 75% steam and 25% electricity would replace 6 million cubic metres (220 TJ) per day of natural gas and support production of 175–200,000 barrels per day of oil. It would also save the emission of 3.3 million tonnes of carbon dioxide per year.”

The World Nuclear Association [113] also reports that another suggestion was the project known as the Peace Region Nuclear Power Plant Project, which would involve the construction of up to four reactors to provide between 3200 and 4400 MW(e) of capacity. None of the proposals, however, materialized, mainly due to changing market conditions (see Ref. [24] for details on the ACR-700, an earlier candidate nuclear system).

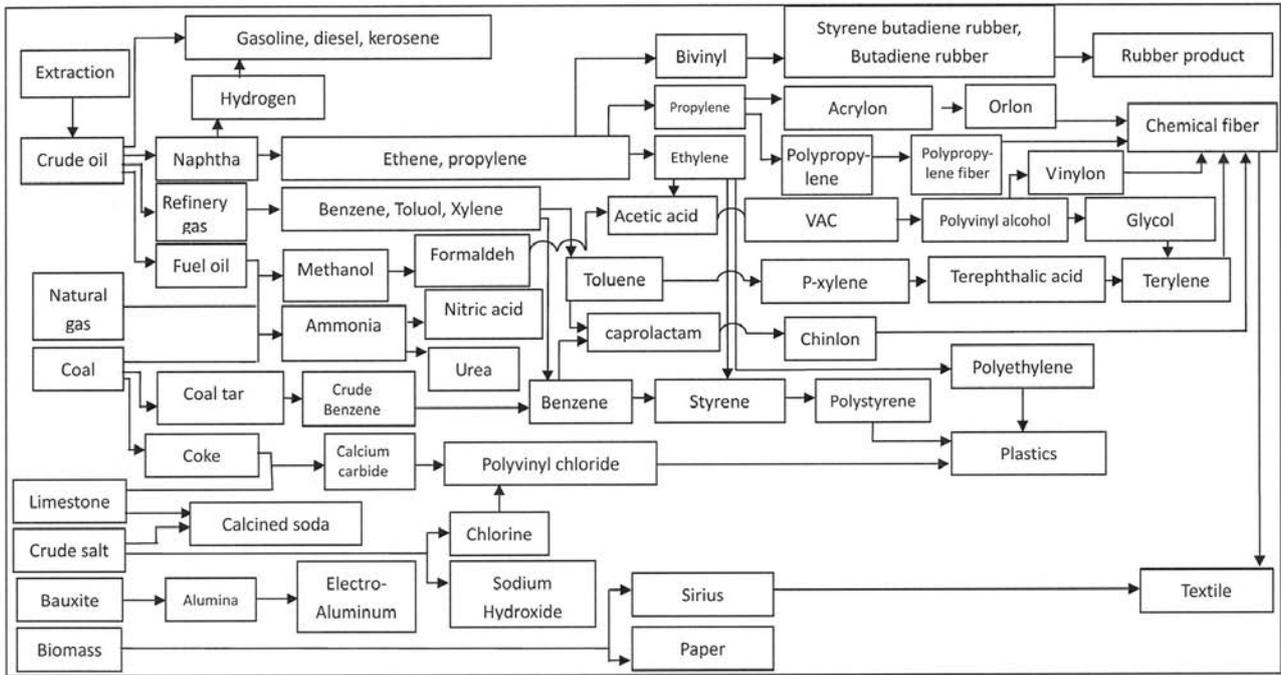
8.2.2. China: Heavy oil recovery

In 1985, Gao [114] proposed a concept to utilize the very heavy oil fields in the north-east of China by the use of process steam from an HTGR. These very heavy oil resources with an estimated total amount of 90 Mt buried at a depth of 1500–1700 m could be easily recovered if heated up by means of injection of steam at 370–390°C. Steam consumption is approximately 3–5 t per tonne of oil delivered. The energy input was assumed to be 30–50% of that contained in the produced oil. The oil production rate was expected to be up to 2 Mt/a. Pebble bed HTGRs to provide a total of 1000 MW(th) were shown to be able to deliver steam with the required quality. The objective of a cooperation project (1986–1988) following this study was to evaluate the use of high temperature reactors for application in enhanced oil recovery and to examine the oil field technology with respect to the supply of steam and electricity from an HTGR in the chemical industry for upgrading crude oil (see Ref. [115] for a review).

8.2.3. HTR–PM project

After several decades of HTGR technology development in China, the start of construction of the HTR–PM in 2012 signalled the beginning of a commercialization phase for this type of reactor. The HTR–PM is a modular HTGR reactor designed for 200 MW(e) output with a steam turbine driven by two reactor modules. The live steam produced is of high quality (556°C and 13.6 MPa). The thermal efficiency of the HTR–PM is higher compared to conventional LWR nuclear plants. Although the HTR–PM demonstration reactor is designed for power generation only, HTGRs are regarded as important nuclear heat and supplementary electricity sources, considering also their versatility to supply both electricity and heat in the CHP mode. The modular HTGR design is characterized by safety features that could allow its close vicinity to other industrial facilities or its location at the periphery of cities. The high coolant outlet temperatures provide a temperature level for heat output that can be utilized in many industrial processes and replace conventional fossil energy resources. With some retrofitting, the temperature of the primary coolant can reach 950°C, meeting industrial thermal demand up to 850°C. Numerous potential industrial processes applicable to future modular HTGRs are shown in Fig. 27. The total primary energy consumption for all of these processes in China has reached 290 Mtoe/a, accounting for 15.6% of the national total energy consumption, of which about 60% is heat demand and about 40% is electricity.

The national total heat demand spectrum within different temperature ranges is shown in Fig. 28 (space heating is also included as an average). The results show a enormous heat market in China. It reached 192 Mtoe for temperatures up to 1050°C and accounted for 10.3% of the total national primary energy consumption in 2007. Even



VAC = vinyl acetateacrylate copolymer

FIG. 27. Potential industrial processes, to which HTGR process heat and electricity is applicable.

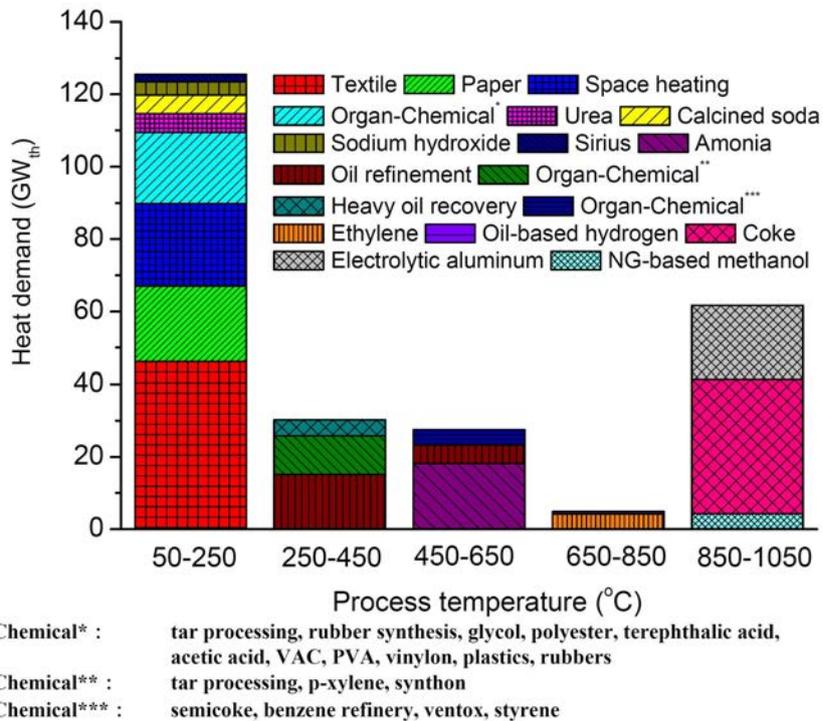


FIG. 28. Process heat demand spectrum in China.

the potential for the present state of the art HTGR technology to provide primary helium at an outlet temperature of 750°C, capable of meeting the process heat demand of up to 650°C, comprises a total primary energy of 138 Mtoe, which corresponds to about 7.4% of the total national energy consumption. The number of modular HTGR units to

meet this potential heat market could further grow if part of the nuclear fleet is operated in the CHP mode to deliver electricity as well.

Under the assumption that conventional heating with non-coal liquid heating fuels (fuel oil, refinery gas, blast furnace gas, coke oven gas and natural gas) were replaced with HTGR heating, a significant reduction in overall Chinese oil imports (or their use for other purposes) could be achieved (see Fig. 29). It can be concluded that the effect of liquid fuel conservation in the temperature range of 50–250°C is not as significant as that of fossil fuel replacement or GHG reduction, which is due to the dominant utilization of coal for steam generation and hot water supply in pertinent processes. For example, the fuel for the 850–1050°C range is dominated by natural gas for ammonia synthesis and the by-product coke oven gas, leading to a large potential of liquid fuel replacement, independent of its smaller heat demand compared to the 50–250°C temperature range. The results also show that massive deployment of available HTGR technology for heating below 650°C could lead to liquid fuel savings of 32.6 Mtoe.

The establishment of an HTGR deployment strategy requires considerations of different aspects. First, the heat supplied by HTGR should be consumed locally, since transport losses of heat are greater with distance compared to electricity transport. The heat transport distance limit requires major heat consumers to be located nearby the nuclear heat sources. The situation in China is changing with the emerging and booming of ecological industrial parks where factories from different sectors geographically aggregate in one district, aiming at sustainable development by means of an optimized energy flow. These parks represent another potential market for HTGRs, which is versatile to meet various demands in terms of energy type and grade with zero carbon emission.

With regard to the economical competitiveness of HTGRs, premium liquid fuels should be given priority for replacement, especially during the initial market penetration phase. This leads to the conclusion that the initial HTGR market should be focused on urban district heating and oil refining industries. One of the important sectors for deployment of HTGRs is the oil refining industry, which generally has a large heat demand within a limited plant area and, therefore, consumes large quantities of heating fuel. An enlargement of the HTGR market potential is possible by increasing the reactor outlet temperature up to a range that allows the production of chemicals, including hydrogen, synthesis gas and synthetic liquid fuels. Nuclear based production of hydrogen, one of the most important industrial chemicals, is the long term goal of HTGR process heat utilization. While fossil based hydrogen production leads to severe GHG emissions and threatens the energy supply security, and renewable energy based hydrogen is not cost effective, the HTGR is a prospective carbon neutral, efficient and cost effective hydrogen source on the basis of water splitting generation methods.

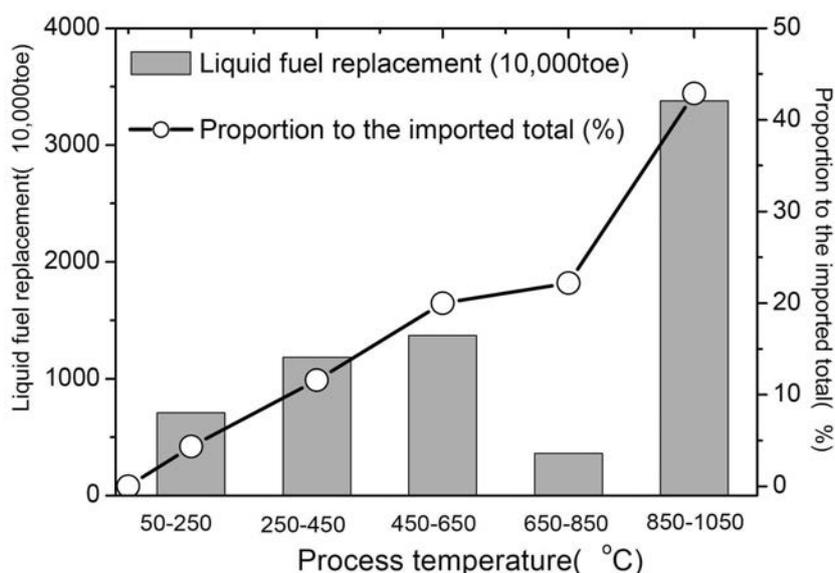


FIG. 29. The effect of HTGR in liquid fuel conservation.

8.2.5. South Africa: PBMR for ethylene production

The process of ethylene production (see Section 5.4) is analysed by Scarlat et al. [121] for a potential connection with a PBMR. In this process, most of the energy is consumed in the cracking of naphtha (or other feedstock) which is conventionally done in a natural gas fuelled furnace. Since the input is basically concentrated in one process step, ethylene production is a promising system to be coupled to a nuclear heat source. In addition, the 400 MW(th) output of the PBMR is close to the power consumption of the pyrolysis section of a large ethylene production train (see Ref. [121]) for a full review).

8.2.6. United States of America: SC-MHR as NNGP for process steam production

8.2.6.1. Next Generation Nuclear Plant project

Reference [24] reports that:

“As a part of the Energy Policy Act of 2005, the USA has been designing a Next Generation Nuclear Plant (NNGP). This government sponsored demonstration programme of a VHTR Generation IV system is to be conducted by an alliance of suppliers of the technology, nuclear plant owner/operators, other support technology companies, and potential industrial end users of the technology. This alliance in partnership with the USDOE would provide the private sector perspective and support the selection of the specific operating conditions and configuration for the NNGP [Ref. [122]].”

8.2.6.2. Industrial process steam study with SC-MHR

Two cases have been studied in further detail with an NNGP HTGR as the basis: (i) cogeneration of electricity and process steam in the refinery industry (see Ref. [123] for further information); and (ii) cogeneration of electricity, process steam and hydrogen in the oil sands industry (see Ref. [111] for further information).

8.2.6.3. Studies for the States of Wyoming and Kentucky

In a cooperation between the NNGP Industry Alliance and the INL, studies have been conducted in which strategic action plans were elaborated for a modification of the future energy policy toward the development of a carbon conversion industry in the United States of America (see Ref. [124] for Wyoming and Ref. [125] for Kentucky).

8.3. SPECIFIC CONCEPTS FOR NUCLEAR HYDROGEN AND SYNTHETIC FUEL PRODUCTION

8.3.1. Canada: ACR-700 with Cu–Cl thermochemical hybrid cycle

In Canada, Alberta’s current needs for oil sands upgrading (see also Section 8.2.1) are 770 000 t/a of hydrogen, which is expected to increase to more than 2.8 Mt/a by 2020. Considering the growing need for hydrogen, the key issue is its production independent of fossil fuels, in large capacities, and at lower costs than existing technologies. GHG emission free production methods are based on water splitting processes utilizing primary energy from nuclear and renewable sources. Such combined systems might become in the future more competitive against the predominantly existing hydrocarbon based technologies [126]. A review of the cycle and the close cooperation of AECL with the ANL in the United States of America and the University of Ontario Institute of Technology and other universities can be found in Refs [24, 103–105, 127].

8.3.2. Germany: PNP reactor with coal gasification for synthetic gas production

Within the frame of the German prototype nuclear process heat (PNP) project in the 1970s and 1980s, comprehensive R&D activities on nuclear coal gasification were conducted in Germany in a joint cooperation

between the Research Center Jülich and partners from the coal and nuclear industries. A significant part of the efforts was dedicated to the design and demonstration of the ability of HTGRs to be used for process heat applications [128]. The concept for a nuclear process heat plant with a high temperature PBR was originally based on power sizes of 500 MW(th) (PR-500) and 3000 MW(th) (PR-3000) (see Ref. [68]).

8.3.3. Japan: GTHTR300C for hydrogen production

For commercial scale hydrogen production, the JAEA is offering the GTHTR300C, a gas turbine high temperature reactor of 600 MW(th) and 300 MW(e), respectively, for cogeneration of variable rates of electricity and hydrogen (see Section 3.7.4). The R&D activities at the JAEA on the sulphur–iodine thermochemical cycle are described in Refs [24, 83, 95].

8.3.4. South Africa: PBMR with steam reforming and thermochemical sulphur hybrid cycle

The PBMR company proposed a concept to generate nuclear electricity and process heat and steam to be used in a variety of process heat applications for the transport and industrial sectors including hydrogen production. Steam reforming of natural gas and conventional electrolysis as well as oil sands recovery, cogeneration for petrochemical industries and desalination were seen as near term strategies, while the carbon dioxide emission free hydrogen production through thermochemical cycles and high temperature electrolysis were considered feasible longer term options. The hydrogen can be utilized for downstream synthetic liquid fuels production (see Ref. [24] for details).

8.3.5. United States of America: H2-MHR with high temperature steam electrolysis

Reference [24] reports that, in 2005, the DOE initiated the international nuclear energy research initiative with the objective of the development and demonstration of technologies which enable the nuclear powered production of hydrogen by non-fossil based water splitting processes at target cost of (as of 2005) US \$2–3 per gallon of gasoline equivalent (which corresponds to 1 kg of H₂), independent of the pathway of hydrogen production and delivery. In a 2010 study, Park and Patterson [129] find that “HTSE is the hydrogen production technology that presents the greatest potential for successful deployment and demonstration at NGNP” (see Ref. [24] for further details).

8.3.6. Japan: Concept for nuclear steel production

Steel is a major manufacturing material and thus its production typically varies with the demand of national or global economic activities. Figure 31, which is based on data from the World Steel Association, displays the

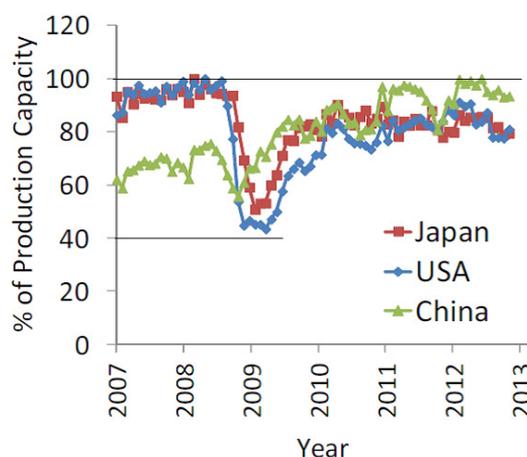


FIG. 31. Steel output normalized by maximum national capacity of top steel producing countries.

large variation of steel output from the top three producing countries of China, Japan and the United States of America. The three countries collectively accounted for 60% of the world output in 2013.

To enable the GTHTR300C to follow such variation in steel output, an integrated control technique allows a wide range of heat and power cogeneration while operating the reactor constantly at 100% base load. The control technique can be based on the selected use of the following control methods depending on the desired level of steel output:

- Reactor coolant inventory control;
- Gas turbine speed control;
- Reactor coolant flow bypass control.

When steel production is varied between 50% and 100% of the rated output, the coolant inventory and turbine speed control methods are used to change the heat rate delivered to the hydrogen plant while using the balance of the reactor thermal power for gas turbine power generation. The combination of these two methods are found to be capable of varying the gas turbine operating parameters without eroding the 20% surge margin required to secure stable operation of the gas turbine. On the other hand, when the steel out is reduced to less than 50%, the coolant inventory and bypass control methods are used while the turbine is kept unchanged at 100% operating speed. This control technique proves successful in simulation of the GTHTR300C system to follow the US case of 45–100% steel output, the largest load swing of the three countries included in Fig. 31. To cut down simulation run time, the load profile over the seven year period is imposed on the GTHTR300C in a period of 50 hours. The simulation results are given in Fig. 32, including the key operating parameters of the reactor, IHX and gas turbine. Note that the reactor is kept at constant thermal power and temperature, whereas the heat rate is varied in the IHX to supply the hydrogen production plant to follow the steel output and the balance of the reactor thermal power is used to increase or reduce the electricity generation rate of the gas turbine.

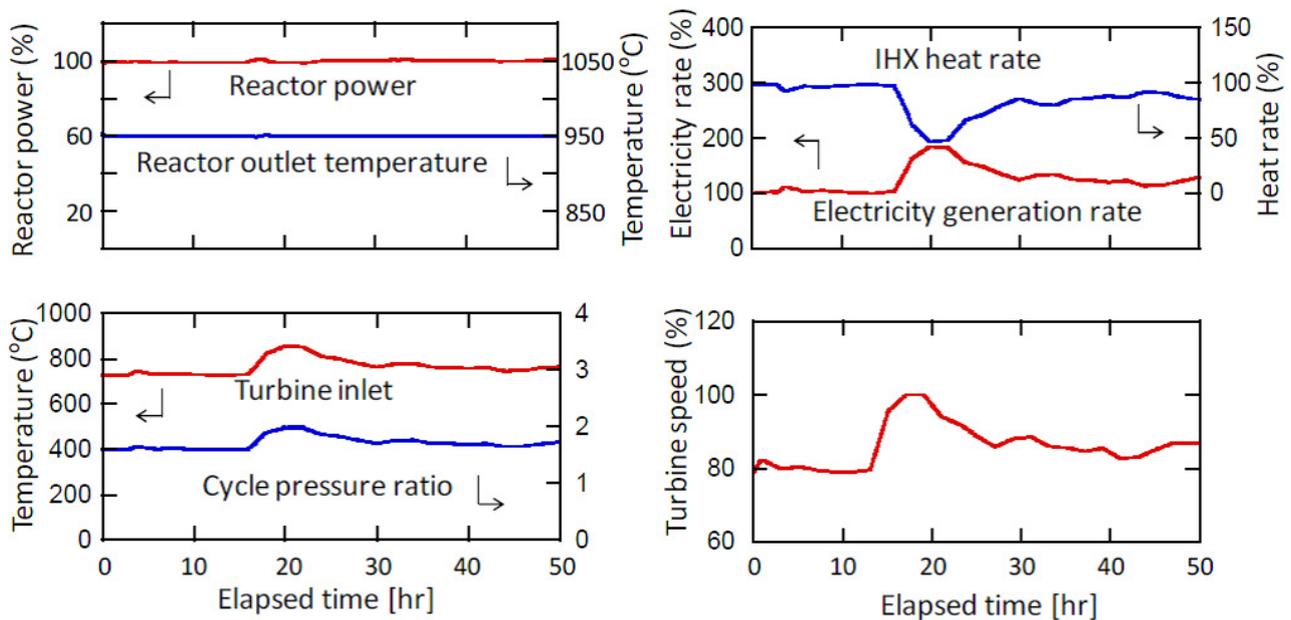


FIG. 32. Simulation results of nuclear steel making load follow.

9. CONCLUSION

With a continuously growing global energy demand and the need for both energy supply and supply security, nuclear power plays an important role in the national energy mix of many States expanding their options by providing reliable baseload electricity at stable and predictable generation costs and connected with low life cycle GHG emissions. The nuclear share in current final energy consumption worldwide is about 16%, almost exclusively dedicated to electricity generation. The role of nuclear power in serving the vast energy demand in a clean, effective and safe manner might ultimately be regarded as a better competitor for new energy products whether in terms of cost or other attributes.

There are no technological impediments to extracting heat and steam from a nuclear plant. Thus, all existing and prospective reactor types can be used, supported if necessary by conventional heating. Advanced nuclear systems of the next generation are well suited for cogeneration, since the nuclear steam systems of both can deliver primary steam at superheated conditions. They could be optimized by using various coupling schemes aimed at improving overall efficiency. Electric power production can be through a high pressure steam generator in a Rankine cycle or a direct cycle gas turbine in a Brayton cycle. The applicability to a specific purpose (i.e. industrial process) will be determined by the required temperature level. Detailed site specific analyses are essential for determining the best energy option. Process heat applications include cogeneration, coal to liquids conversion, and assistance in the synthesis of chemical feedstock. The complexity of the combined system requires the development of advanced safety concepts and techniques to ensure proper control. This certainly includes an efficient IHX, which is a key component transferring heat from the primary coolant to a secondary coolant, which will then transfer heat to a chemical process or a PCS.

The industrial heat market is highly fragmented. The possibility of large scale distribution systems for heat, steam and electricity supplied from a central nuclear heat source (e.g. a multiproduct energy centre) could attract and serve different kinds of consumers concentrated in industrial parks. The idea seems rather remote at present but could be the trend in the long run. Industries that consume large amounts of thermal and electric energy would therefore be the target clients for possible applications of nuclear energy and include petroleum and coal processing, chemicals, primary metals, paper and food.

Nuclear energy can be used for the extraction of tertiary oil resources such as heavy oil, the oil from tar and oil sands, and the oil remaining in depleted deposits. With increasing prices for conventional oil, these unconventional oil resources are increasingly utilized to meet the growing demand. The case of Canada is especially notable because although the resources of unconventional oil are very large, nuclear technologies suitable for such applications are available. Currently, the major energy source for oil extraction from tar sands is natural gas, which is expected to provide the required process heat, thus contributing to more GHG emissions. Nuclear energy offers here a low carbon alternative.

Processes requiring higher operating temperatures (850–900°C) include the production of methanol, ammonia, fertilizers, hydrogen and olefins. Many industrial processes are based on the steam reforming of natural gas, with synthesis gas as the main product. Coal gasification has the advantages of mitigation of air emissions from coal combustion, an increased thermal efficiency of combustion and the use of a large resource base. If coal gasification is applied more widely, technologies for the supply of gasification energy will be required which are both economically feasible and are not harmful to the environment.

Many industries require preheating processes, for example raw materials melting in the glass manufacture, heating of air or oxygen or steel scrap in the iron and steel production, or calcinations and drying processes, such as in the aluminium and ceramics industries. Nuclear energy could principally be used, but significant re-engineering might be necessary.

Many non-electric applications require energy sources that are relatively small (100–1000 MW(th)) in comparison with the size of existing power reactors. The development of nuclear reactors of small and medium sized reactors would therefore be better suited for cogeneration (i.e. electricity and heat) and would facilitate the non-electric applications of nuclear energy. Smaller scale nuclear process heat plants can penetrate the heat market on account of the simpler application designs, short construction periods and lower capital requirements. HTGR power applications might have to compete with plants that utilize low cost fuels in power generating grids. Early projects will have to confirm projected economics, performance, reliability and safety to support further investment.

The success of coupling a reactor to a chemical process depends on the ability to transport the heat economically, safely and reliably. The nuclear plant would displace the gas fired furnace, providing the advantages of higher reliability, reduced toxic gas emissions and increased safety. Some non-electric applications require a close siting of the nuclear plant to the customer. This will require specific safety features appropriate to the location. Maintaining a minimum distance between nuclear plant and hazardous materials containing sites, the construction of protective barriers or filtering of the reactor control room are subject to analysis in the safety assessment.

The main factors that would improve the competitiveness of nuclear options include lower specific overnight costs, shorter construction times, lower discount rates, the incorporation of environmental externalities in the price of energy and the expectation of rising fossil fuel prices. There is also a need for successful pilot projects to demonstrate, for example, the use of surplus nuclear capacity for hydrogen production using cheap offpeak electricity and the creation of local hydrogen markets near existing nuclear power plants. Hydrogen production using conventional low temperature electrolysis could open up the market for hydrogen fuelled vehicles in the near term.

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ABBREVIATIONS

ACR	Advanced CANDU Reactor
ACRES	active carbon recycling energy system
AECL	Atomic Energy of Canada Limited
AHTR	Advanced High Temperature Reactor
ANL	Argonne National Laboratory
AVR	Arbeitsgemeinschaft Versuchsreaktor (Joint Venture Experimental Reactor)
CANDU	Canada deuterium–uranium
CHP	combined heat and power
DOE	United States Department of Energy
EED	electro–electrodialysis
Euratom	European Atomic Energy Community
GCR	gas cooled reactor
GFR	gas cooled fast reactor
GHG	greenhouse gas
GIF	Generation IV International Forum
GTHTR300C	Gas Turbine High Temperature Reactor 300 Cogeneration
GT-MHR	gas turbine modular helium reactor
HTGR	high temperature gas cooled reactor
HTR	high temperature reactor
HTR–PM	High Temperature Reactor—Pebble Bed Module
HTSE	high temperature steam electrolysis
HTTR	High Temperature Engineering Test Reactor
IHX	intermediate heat exchanger
INET	Institute of Nuclear and New Energy Technology
INL	Idaho National Laboratory

IPSR	integral primary system reactor
JAEA	Japan Atomic Energy Agency
LFR	lead cooled fast reactor
LWR	light water reactor
MHR	modular helium reactor
MSR	molten salt reactor
NEA	OECD Nuclear Energy Agency
NGNP	next generation nuclear plant
OECD	Organisation for Economic Cooperation and Development
PBMR	Pebble Bed Modular Reactor
PBR	pebble bed reactor
PCS	power conversion system
SC-MHR	steam cycle modular helium reactor
SCWR	supercritical water cooled reactor
SFR	sodium cooled fast reactor
S-I	sulphur-iodine
SMART	system-integrated modular advanced reactor
SOEC	solid oxide electrolysis cell
VCR	vapour core reactor
VHTR	very high temperature reactor

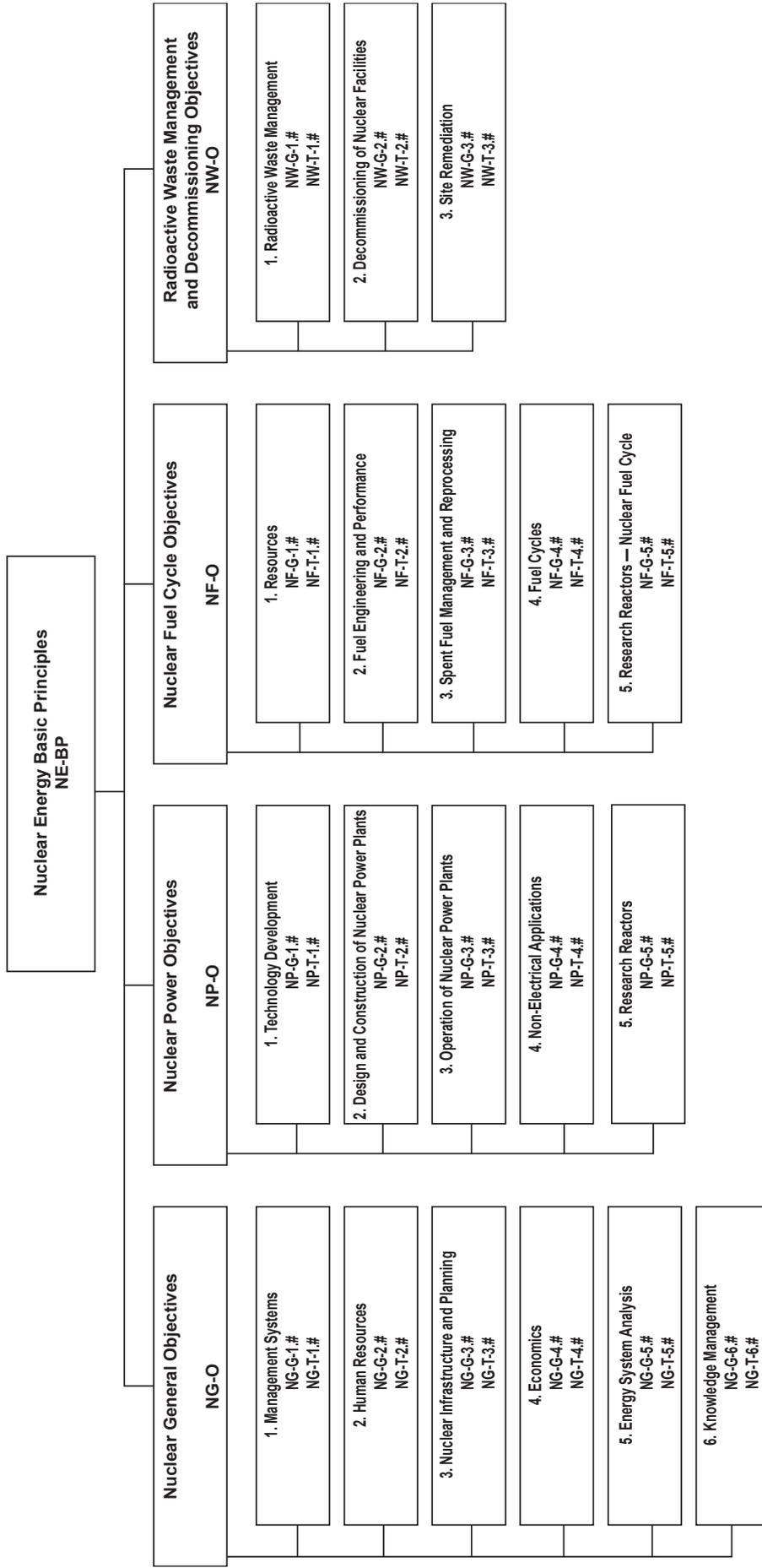
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