

R & D Trend in Innovative High-Temperature Gas-Cooled Reactors (HTGRs)

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6.1 Introduction

Today, the environment surrounding the atomic energy sector has become more and more complicated with movements such as the promoted liberalization of energy markets, the diffusion of decentralized power sources, the withdrawal from nuclear power generation especially in Europe, and the re-appreciation of nuclear energy in the U.S.

According to the OECD-International Energy Agency (IEA), it is estimated that nuclear energy's share in the world supply of primary energy will decrease from 7% at present to 5% in 2030, with a high uncertainty, because many of the existing nuclear power plants are being closed in turn especially in Europe, while the construction of new power plants are expected mainly in Asian countries^[1]. On the other hand, the important role of nuclear power generation is now recognized from the viewpoints of solving the environmental problems of the Earth and ensuring the stable supply of energy.

Under these circumstances, R&D efforts have been activated worldwide to develop innovative nuclear energy systems with excellent features such as safety, resistance to nuclear proliferation, economical efficiency, and social acceptance. Various options on reactors and fuel cycles are being proposed in terms of innovative nuclear energy systems, and the target time for commercialization varies from the year before 2010 to 2030. However, it is noticeable that HTGRs are attracting higher interest in the world, as described in the next chapter.

At present, HTGRs use helium gas for the coolant and graphite for the moderator, while

light water reactors (LWRs) as the current main commercial reactors use water (light water) both for the coolant and moderator. R&D efforts on HTGRs started in the 1950s, and several commercial units were introduced into the nuclear power sector by the 1980s. Today, however, there is no commercial HTGR under operation. Notwithstanding, in recent years, HTGR has been re-appreciated as one of the promising options for next-generation reactors. The reasons are; (i) that it has high inherent safety, (ii) that the high exit temperature of the coolant allows the nuclear heat to be used in various applications including the production of hydrogen, and (iii) that several promising designs have been proposed for small- and medium-sized modular reactors that are flexibly adaptable to the changing environment of the energy markets.

In Japan, the Japan Atomic Energy Research Institute (JAERI) has conducted researches on the utilization of nuclear heat by using a High-Temperature Engineering Test Reactor (HTTR) since the 1990s, and these researches have been ranked world-class, though many problems remain to be solved before a commercial plant using nuclear heat is realized.

In recent years, however, Japan and other countries have had a rapidly increasing interest in the safety of engineering systems, or in hydrogen energy systems. Under these circumstances, the U.S. and France are involved in full-scale R&D projects on HTGR, recognizing it as one of the promising options for future reactors. Given these conditions, we suppose that it is necessary for Japan to prepare its R&D strategy focusing on the various potentialities of HTGR, taking into account the social needs for future nuclear energy plants.

In this report, the next chapter covers the worldwide trends in research and development projects for innovative nuclear energy systems as well as the higher expectations aroused in the world for HTGRs. Chapter 6.3 describes the R&D history and features of HTGRs, and Chapter 6.4 focuses on the production of hydrogen to which special attention is given as a new application of the HTGR. Chapter 6.5 presents the main R&D and introduction projects for HTGRs being implemented worldwide, and Chapter 6.6 examines the problems to be solved under the Japanese R&D projects for HTGRs.

6.2 Development of innovative nuclear energy systems and expectations for high-temperature gas-cooled reactors

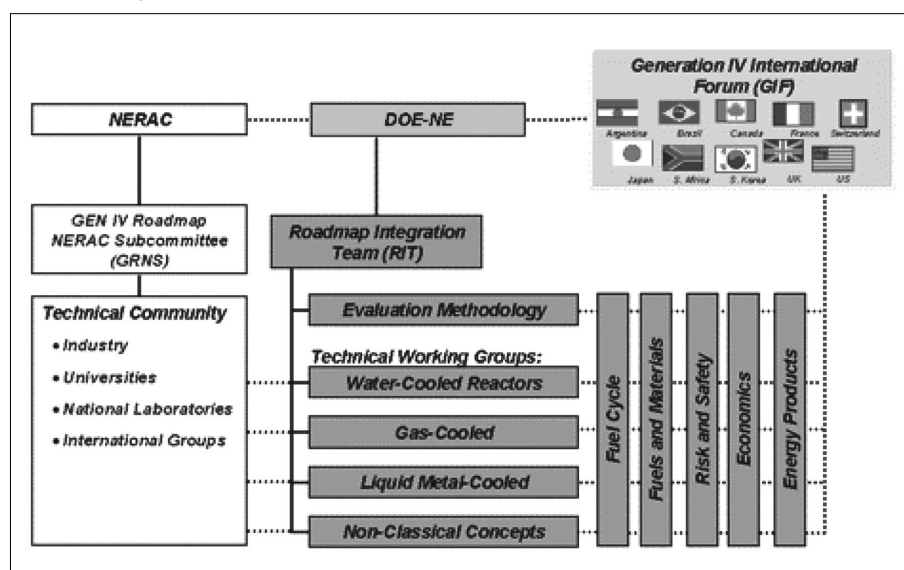
Today, international efforts are being more actively made in the field of research and development for innovative nuclear energy systems. And, it is the U.S. that leads these R&D efforts. The US Department of Energy (DOE) has implemented its technological development project for an innovative nuclear energy system as part of its Nuclear Energy Research Initiative (NERI). Ten countries (Argentina, Brazil, Canada, Japan, Korea, France, South Africa, Switzerland, the U.K. and the U.S.) are participating in the Generation IV International Forum (GIF)^{*1} for

the 4th-generation nuclear energy systems, which was organized by the DOE (see Figure 1). This Forum is engaged in selecting promising nuclear energy system options and examining internationally cooperative research projects to develop the generation IV nuclear energy system that is to be commercialized by 2030.

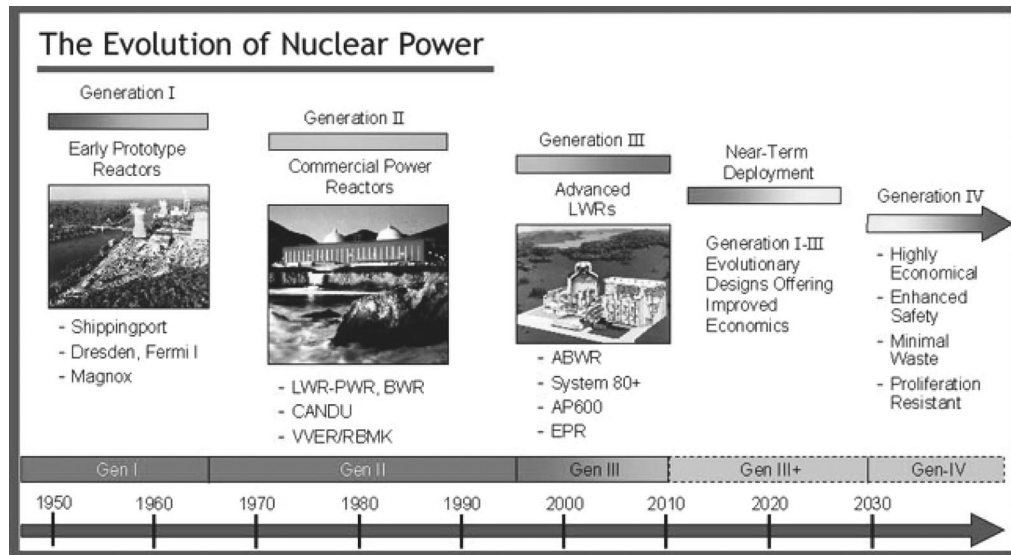
The concept of the generation IV nuclear energy system will be described hereinafter. Figure 2 shows the evolution of the generation I to IV nuclear reactors^[2]. The generation I includes the initial light water reactors (LWRs) developed in the 1950s and 1960s. The generation II includes the light water reactors, PWRs and BWRs that were introduced after the 1960s and that now constitute the main reactors under operation. The advanced light water reactors such as advanced boiled water reactors (ABWRs) are classified into generation III. The generation IV includes the reactors that are to be commercialized by 2030. The group of reactors that is to be put into practical use earlier (by 2015) than the generation IV is called the International Near-Term Development (INTD).

In September 2002, the GIF Policy Group held a meeting in Tokyo and selected 6 types of generation IV nuclear energy systems, as listed below, as the subjects for internationally cooperative research and development projects. It should be specially mentioned that 2 types of gas-cooled reactor systems were selected, and that 3 types are fast reactor systems.

Figure 1: Structure of the Generation IV International Forum (GIF)



Source: DOE homepage^[2]

Figure 2: Evolution of nuclear power systemSource: DOE homepage^[2]

- Gas-cooled fast reactor system
- Sodium-cooled fast reactor system
- Lead-cooled fast reactor system
- Supercritical pressure water-cooled reactor system
- Molten-salt reactor system
- Ultrahigh-temperature gas-cooled reactor system

Short- and medium-term introduction projects for commercial high-temperature gas-cooled reactors (HTGRs) are being implemented in foreign countries. For high-temperature gas-cooled modular reactors, introduction projects are being implemented to start operation by 2010, including the PBMR being developed by ESCOM in South Africa as well as the GTMHR developed mainly by the U.S. and Russia to be introduced into the U.S. and used in Russia for the disposal of plutonium from dismantled nuclear weapons. These may probably become the first next-generation reactors to be commercialized and introduced into the world, and they are classified into the INTDs as mentioned above.

These HTGR systems that are classified into the Generation IV and INTDs will be individually described in Chapter 6.5.

On the other hand, the Long-Term Program on the Researches, Development and Utilization of Nuclear Energy (hereinafter referred to as the “Long-Term Nuclear Energy Program”) in Japan^[3]

prepared in 2000, describes that the industrial, academic and governmental circles should work together to examine the R&D projects for innovative reactors, regardless of reactor sizes and systems, and take into consideration the effective utilization of various ideas. In November 2002, the Atomic Energy Commission of Japan (JAEC) published the document titled “How to Implement Future Research and Development Projects for Innovative Nuclear Energy Systems^[4],” which overviews the actual situation of R&D efforts made in Japan, points out the necessity of R&D efforts and describes JAEC’s policy for its R&D strategy. This document lists 9 concepts for innovative nuclear energy systems (17 types of reactors), including 3 types of HTGR, namely the pebble bed type HTGR, the prismatic type HTGR and a large type helium gas-cooled fast reactor.

In the 2002 fiscal year, the Ministry of Education, Culture, Sports, Science and Technology started to implement its proposal invitation type project “Technological Development of Innovative Nuclear Energy Systems” (with a budget of 4.3 billion yen for the 2002 fiscal year). In the 2000 fiscal year, the Ministry of Economy, Trade and Industry also started to implement its proposal invitation type project “Development of Innovative and Practical Nuclear Energy Technologies” (with a budget of 2.3 billion yen for the 2002 fiscal year).

France, which is the leader, like Japan, in the field of researches on sodium-cooled fast

Table 1: Main commercial reactors under operation

Type of reactor	Country	Number of units	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	U.S., France, Japan, Russia	252	Enriched uranium	Light water	Light water
Boiled water reactor (BWR)	U.S., Japan	93	Enriched uranium	Light water	Light water
Carbon acid gas-cooled reactors (Magnox & AGR)	U.K.	34	Natural uranium, enriched uranium	CO ₂	Graphite
Pressurized heavy water reactor (CANDU)	Canada	33	Natural uranium	Light water and heavy water	Heavy water
Graphite-moderated light water reactor (RBMK)	Russia	14	Enriched uranium	Light water	Graphite

Source: Author's compilation based on the materials published on the homepage of the World Nuclear Energy Association^[6]

reactors, not only decided to decommission its demonstration reactor “Super-Phoenix” and postpone the commercialization of this type of reactor to 2050 or a subsequent year, but also worked out its policy that the development of innovative reactors would be focused on gas-cooled reactors, paying attention to the high safety and economical efficiency of these reactors^[4]. In its long-term program, France aims to commercialize very high-temperature gas-cooled reactors and high-temperature gas-cooled breeders. In September 2002, the Japan Atomic Energy Research Institute (JAERI) and Le Commissariat à l'Énergie Atomique (CEA) updated the “Comprehensive Agreement for Cooperation in the Field of Atomic Energy Development,” to which cooperation for the development of high-temperature gas-cooled reactor systems was newly added^[5].

6.3 Development history and features of high-temperature gas-cooled reactors

6.3.1 Development history of gas-cooled reactors

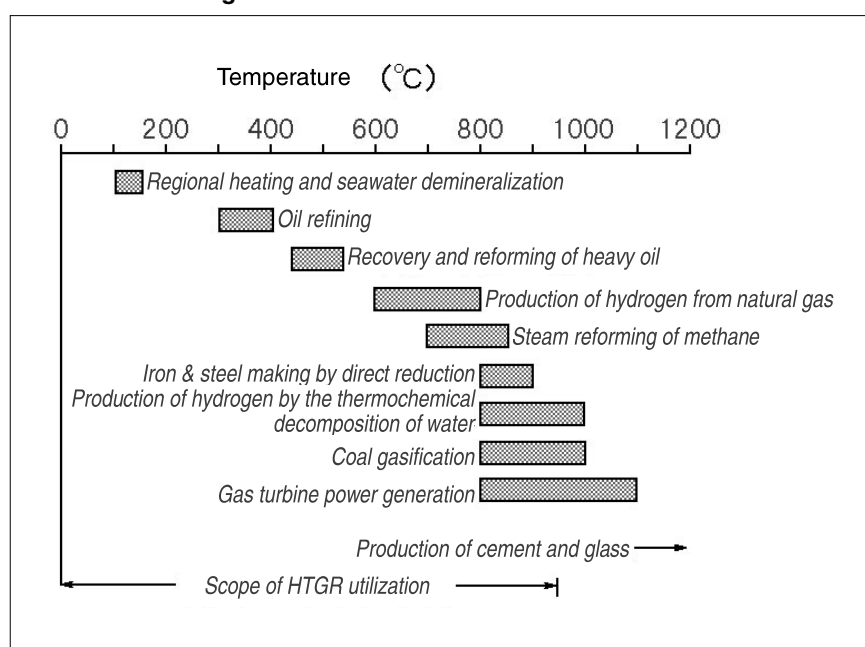
Light water reactors - pressurized water reactors (PWRs) and boiled water reactors (BWRs) - account for about 80% of existing commercial reactors under operation, and use water for both the coolant and moderator, as indicated in Table 1. In addition, Canadian type heavy water reactors (CANDUs), carbonic acid gas-cooled reactors (Magnox and AGRs), and

graphite-moderated light water reactors (RBMKs) are operating in Canada, the U.K. and Russia, respectively.

As gas-cooled reactors, Magnox reactors and advanced gas-cooled reactors (AGRs) were mainly introduced into the U.K. during the period from the second half of the 1950s through the 1970s. The two types of reactors use CO₂ gas for the moderator. The Magnox reactor uses fuel rods of natural uranium covered with magnesium alloy and a coolant temperature of about 400°C. The advanced gas-cooled reactor (AGR) is an original type of reactor developed in the U.K. to improve the economical efficiency of Magnox reactors. It uses fuel rods of uranium oxide covered with stainless steel plates and a coolant temperature of about 650°C. A reactor of this type has not been constructed since the 1980s, and there are more than a few AGRs that have stopped operating. Today, however, most of the existing reactors under operation are still AGRs in the U.K.

On the other hand, the HTGRs as described in this article use helium for the coolant and a high coolant temperature of about 800°C or more.

R&D projects for such HTGRs^[7] were drawn up and implemented in the 1950s, and several experimental and prototype reactors of this type were constructed in Germany and the U.S. in the 1960s, though they have already stopped operating. In the 1970s, the introduction of commercial HTGRs was planned, but not realized in the U.S. In 1980s and 1990s, the design concepts of plants having a high inherent safety were proposed in the U.S. and Germany, and R&D

Figure 3: Diversified utilization of nuclear heatSource: The atomic energy encyclopedia ATOMICA^[8]

projects were implemented mainly in Germany, Japan and Russia to use HTGRs in various applications other than power generation; for example, the gasification of coal, the production of ammonium, and cogeneration systems. In Japan, the High-Temperature Engineering Test Reactor (HTTR) reached its criticality in 1998, and experiments and researches have since been conducted on subjects such as the production of hydrogen. Today, however, there is no commercial HTGR plant under operation in the world.

6.3.2 Features of HTGR

The past R&D and introduction projects for HTGRs in the world were not always smoothly implemented, as described in the previous section. Some of the reasons were that the cost for producing fuels was high, that the construction costs were high due to the low exothermic density of cores, and that the spread of light water reactors had a lock-in effect on technologies. However, several new designs of HTGR have been proposed on the basis of the accumulated R&D results. These designs present advantages such as high inherent safety, high economical efficiency and diversified utilization of nuclear heat including the production of hydrogen. With this as the background, HTGRs have been re-appreciated in recent years. The features of HTGRs will be described hereinafter.

(1) Applicability of nuclear heat to uses such as the production of hydrogen

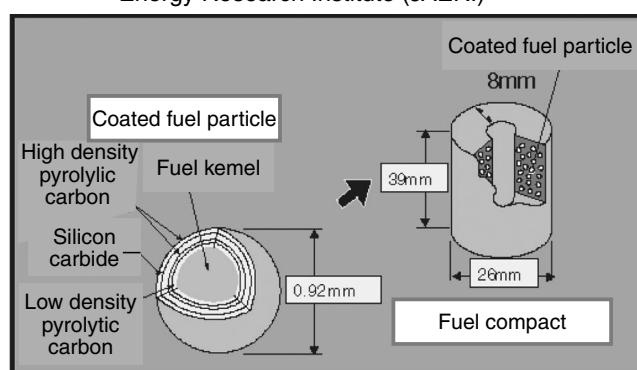
The temperature of a coolant at the exit of a reactor is about 800 to 950°C for a HTGR, while it is about 330°C for a LWR. Therefore, the power generation efficiency may reach 45 to 50% for a HTGR if a gas turbine is used for power generation.

Recently, much attention has been devoted to the utilization of the coolant, having a high temperature as heat source, especially in the application for mass production of hydrogen. The processes of producing hydrogen by using nuclear energy include the electrolysis of water, the steam reforming of fossil resources, and the thermochemical decomposition of water. The thermochemical water decomposition process using a HTGR as the heat source has a high efficiency, and has attracted much attention because it ensures the mass production of hydrogen with substantially no emission of CO₂. The other applications of nuclear heat include iron & steel making, coal gasification, oil refining, seawater demineralization and regional heating, as shown in Figure 3. The production of hydrogen by using a HTGR will be detailed in the next chapter.

(2) High inherent safety

The HTGR uses pebble beds (balls) or blocks of compacted fuel particles having a diameter of

Figure 4: Fuel in the High-Temperature Engineering Test Reactor (HTTR) of the Japan Atomic Energy Research Institute (JAERI)



Source: JAERI homepage^[9]

about 1mm and made of low enrichment uranium dioxide coated with multiple layers of ceramics such as silicon carbide. Figure 4 shows a schematic view of the fuel (of block type) used in the High-Temperature Engineering Test Reactor (HTTR) of the Japan Atomic Energy Research Institute (JAERI)^[9]. The fuel compact as shown in the Figure will be inserted into a fuel rod.

The ceramics with which the fuel particles are coated have such high heat resistance that they remain intact at a temperature of 1600°C or more. If the helium coolant is lost through an accident (depressurization accident) in the HTGR, it is anticipated that the removal of decay heat only by the natural radiation of heat may prevent the temperature of the coating material from reaching 1600°C or more, so that any radioactive substance inside the coating material will not be released^[10]. In addition, graphite as the moderator has such large heat capacity that the temperature of the system changes more slowly in the event of an accident. Therefore, the operator may have sufficient time to take an appropriate action against the accident. Furthermore, the HTGR has other safety factors such as a high negative temperature coefficient throughout the operation and the helium coolant is inactive.

(3) Economical efficiency improved by smaller module and flexible adaptability to the environment of the energy markets

Many LWR plants have a maximum output of 1 million kWe or more. As for HTGRs, however, much attention is concentrated on the modular reactors with outputs of 0.1 to 0.3 million kWe,

as described in Chapter 6.5. In general, a larger sized plant has higher economical efficiency (scale merit). For small HTGRs, however, economical efficiency is improved through the simplification of the safety system based on high inherent safety and improvement of power generation efficiency due to the use of a gas turbine.

Today, liberalization of the energy markets is being promoted in many countries. As a result, smaller power producers, especially independent power producers (IPPs), are more often than ever exposed to risks such as changes in electricity fees and the changing environment of the energy markets, making it more difficult for them to launch into the construction of large plants that require a longer period of time to recover the invested capitals (especially nuclear power plants for which the percentage of fixed costs is higher). Thus, much attention is concentrated on the smaller modular reactors for the reasons that they have a lower initial cost and consequently a smaller risk in recovering invested capitals, that the output of the whole site can be adjusted by changing the number of modules constructed in the site, and that they may be flexibly adaptable to future changes in the environment (such as electric power prices and the supply and demand of energy).

6.4 Production of hydrogen by HTGR

At present, there are growing expectations for hydrogen energy systems including fuel cells. To spread these systems substantially, however, one of the challenges is in how to produce hydrogen

Figure 5: Pyrolytic process of water by using the IS process

Bunsen reaction	$2\text{H}_2\text{O} + \text{I}_2 + \text{SO}_2 = 2\text{HI} + \text{H}_2\text{SO}_4$	At room temp. to 100°C
Decomposition of hydrogen iodide	$2\text{HI} = \text{H}_2 + \text{I}_2$	At 400°C
+ Decomposition of sulfuric acid	$\text{H}_2\text{SO}_4 = \text{H}_2\text{O} + \text{SO}_2 + 1/2\text{O}_2$	At 800°C
$\text{H}_2\text{O} = \text{H}_2 + 1/2\text{O}_2$		

Source: Developed by General Atomics (U.S.)

as fuel. One of the reasons for the increasing interest in HTGRs is that these reactors are applicable to the clean and economical mass production of hydrogen.

The industrially established process of producing hydrogen uses the reforming of fossil resources such as natural gas. In this case, a great amount of carbon dioxide is emitted during the production of hydrogen. From the viewpoint of the 3E problem, therefore, it is desirable to commercialize and spread the process of producing hydrogen from water or biomass^[11]. Especially, the thermochemical decomposition of water by using a HTGR is expectable as a mass production process for clean hydrogen.

A high temperature of 2500°C or more is required to pyrolyze water directly. However, several thermochemical cycles comprising the different combinations of several thermochemical reactions respectively have been proposed to pyrolyze water at around 800°C. A HTGR may be used as the heat source in this range of temperatures.

The Japan Atomic Energy Research Institute (JAERI) has conducted tests and researches on the pyrolytic process of water by using the IS process^[12]. The IS process is a technique developed by GENERAL ATOMCS (U.S.), which comprises of 3 chemical reactions as shown in Figure 5. In this process, the compounds produced by the reactions of water with iodine and sulfur are circulated inside the process so that any detrimental substance is not emitted to the exterior.

In 2001, the JAERI completed a continuous hydrogen production system (with the output of 50 liters/hour) by using the IS process, and started to conduct tests and researches on the pyrolytic process of water. It plans to connect this system with its High-Temperature Engineering Test Reactor (HTTR) by 2008.

In the U.S., the Freedom CAR Initiative (with a budget request of \$150.3M for the 2003 fiscal year) was started last year in a technological development partnership between the Federal Government and automobile makers under the direction of the Department of Energy (DOE). In addition, the DOE bill of budget for the 2004 fiscal year published in February 2003^[13] proposed a new Hydrogen Fuel Initiative^{*2} under which R&D efforts are made on the production and storage of hydrogen and the infrastructure, and requested a budget of \$273M both for the Freedom Car and Hydrogen Fuel Initiatives.

A Nuclear Hydrogen Initiative (with a budget request of \$4.0M for the 2003 fiscal year) was also proposed in the framework of the Hydrogen Fuel Initiative. In this new initiative, the HTGR or liquid-metal cooled reactor was selected as a candidate heat source, and will be demonstrated in commercial sizes by the 2015 fiscal year^[14].

The hydrogen production processes using nuclear energy as listed in Table 2 have been proposed in addition to the above-described thermochemical decomposition of water by using a HTGR. All the processes have the feature that they can be used for the mass production of hydrogen, because they provide high plant outputs, compared with the processes using renewable or other energy^{*3}.

For example, the Research Meeting on the Fuel Cell Commercialization Strategy set an expected target of 5 million automobiles with fuel cells (in total) to be introduced by 2020^[16]. If all the automobiles with hydrogen run, the required supply of hydrogen will exceed 6 billion Nm³^[17]. On the other hand, the thermochemical decomposition of water by using a HTGR and the electrolysis of water by using a LWR may annually produce 3.4 billion Nm³ and 1.7 billion Nm³ of hydrogen respectively per output of 1 million kW^[18]. Therefore, several nuclear energy plants may satisfy the demand for

hydrogen as mentioned above.

From the viewpoints of economical efficiency and technical feasibility, it is considered that the steam reforming of fossil resources such as natural gas by using the nuclear heat from a HTGR or fast breeder as the heat source may be introduced earlier than the thermochemical decomposition of water. To develop this process, therefore, the Japan Atomic Energy Research Institute (JAERI) and the Japan Nuclear Cycle Development Institute (JNC) are individually taking leading roles in extending R&D efforts.

6.5

R&D projects in Japan and foreign countries

Table 3 lists the typical R&D projects and commercial reactor introduction projects being implemented in Japan and in foreign countries. The test reactors under operation include HTTR (JAERI) and HTR-10 (China), the commercial reactors to be introduced by 2010 include PBMR (South Africa) and GTMHR (U.S. and Russia), and the reactors to be introduced in the

Table 2: Actual situation of the main hydrogen production processes using nuclear energy

Material	Supplied nuclear energy		Hydrogen production process	Price ratio of each system to the combustion and steam reforming of fossil fuel*
	Energy form	Plant (Temperature level)		
Water	Electricity	Power reactor	Electrolysis	2.5
	Heat	HTGR and high-temperature liquid-metal reactor (800 to 1000°C)	Thermochemical process	1.5
Fossil fuel and water		Na fast breeder (450 to 600°C)	Steam reforming process	0.9

* Estimated by the JAERI (without taking into account any carbon dioxide disposal cost).

Source: Reference^[15] (partly omitted)

Table 3: Key HTGR development and introduction projects

	Reactor name	Development organization	Output (MWt/MWe)	Fuel	Start of operation	Remarks
Test reactors under operation	HTTR	JAERI (Japan)	30/-	UO ₂ (Block)	Critical in 1998	H production & material development
	HTR-10	Tsinghua University (China)	10/-	UO ₂	Critical in 2000	Power generation + reforming of heavy oil, etc.
Commercial reactors for near-term introduction	PBMR	ESCOM (South Africa)	302/120 (1 Module)	UO ₂ (Pebble bed)	Expected in 2007	Gas turbine power generation
	GTMHR	GA-Minatom (U.S. & Russia)	600/285 (1 Module)	PuO ₂ (Block)	Expected in 2009	Combustion & disposal of Pu from weapons, and gas turbine power generation
		GA (U.S.)	600/285 (1 Module)	U-based (Block)	By 2010	H production
Reactors under future initiatives	VHTR	JAERI (Japan), GA (U.S.), etc.	Not published	Not published	By 2020	Exit gas at 1000 to 1500°C, and ZrC-coated fuel
	GCFR	CEA (France), TIT (Japan), MIT (U.S.), etc.	Ex. 600/288, 1400/not published	Pu- or U-based	By 2025	Exit gas at 850°C, and re-treatment and recycling of spent fuels

Source: Reference^[19]

far future under the initiatives include a very high-temperature gas-cooled reactor VHTR and a gas-cooled fast reactor GFR. This chapter will describe each of the projects.

6.5.1 HTTR (High-Temperature Engineering Test Reactor) (Japan)

The High-Temperature Engineering Test Reactor (HTTR), for which R&D efforts are being made mainly by the Japan Atomic Energy Research Institute (JAERI), received approval for installation as a test reactor for developing applications in the field of nuclear energy except electric power in 1990, started constructing in 1991, and reached the first criticality in November 1998. It uses block type fuel elements and a coolant temperature of 850 to 950°C at its exit. It will be connected with a hydrogen production system by 2008.

In the future, it is planned to conduct high-performance fuel irradiation tests, safety demonstration tests, nuclear-heat utilization tests (by using the hydrogen production - thermochemical process, the high-temperature steam electrolysis process, etc.), advanced basic researches (including ceramics irradiation tests, tritium recovery tests, and the development of high-temperature resisting materials and instrumentation systems), and researches on hydrogen/methanol production systems using a steam reforming process.

The JAERI is performing the system design of the modular gas turbine high-temperature gas-cooled reactor GTHTR300 developed by the Japanese. This reactor has an output of 100 to 300MWe, and its demonstration machine will be introduced in the 2010s.

6.5.2 HTR-10 (High-Temperature Gas-Cooled Test Reactor) (China)

HTR-10 is a high-temperature gas-cooled reactor (with an output of 10MW) developed by Tsinghua University in China with technical assistance provided by Germany. It was constructed for the purposes of; (i) obtaining the know-how on the designing, construction and operation of HTR, (ii) constructing the experimental equipment, (iii) demonstrating the inherent safety, (iv) testing cogeneration and gas

turbine technologies, and (v) implementing the R&D project for a high-temperature utilization process, and reached the criticality in December 2000. At present, tests are being made on this reactor to raise the output up to 100%.

The reactor HTR-10 uses pebble bed type fuel elements of 17% enriched uranium. Although a steam turbine is now used, a gas turbine will be installed to demonstrate the direct cycle gas turbine power generation system.

6.5.3 PBMR (Pebble Bed Type Modular High-Temperature Gas-Cooled Reactor) (South Africa)

PBMR is a small type modular reactor being developed mainly by ESCOM, the national power company in South Africa. This reactor is expected to be introduced ahead of the other small type modular HTGRs being researched and developed in the other countries.

In South Africa, projects to introduce the commercial prototype demonstration reactor No. 1 and to construct 10 additional commercial reactor modules are currently being developed with the capital participation by power companies and manufacturers in South Africa, Europe and the U.S. These projects are also receiving technical cooperation from Mitsubishi Heavy Industries (He gas turbine) and the Atomic Fuel Industry (fuel manufacturing equipment) in Japan. If the reactor project is smoothly implemented, it is expected that the reactor No. 1 will start to be constructed by 2004 and operated by 2007, after having received the final decision on whether or not it should be constructed as well as the license issued by the regulatory agency in South Africa. At the same time, the project of constructing 10 additional modules will be implemented.

In the U.S., however, uncertainty about the construction of new reactors is attracting much attention, because no reactor has been constructed in about 30 years. The U.S. power company Exelon, which planned to construct these reactors, started to explain its license application plan to the Nuclear Regulation Commission (NRC) in January 2001, and, in response to this, the NRC began to make its preliminary review of the license application

submitted by the company. It was expected that several reactors would be introduced by 2010 if the project went as planned. In April 2002, however, Exelon expressed its desire to withdrawal from the capital participation in the above-mentioned project in South Africa. As a result, the NRC stopped the review.

6.5.4 GTMHR (Block Type Modular High-Temperature Gas-Cooled Reactor) (U.S. and Russia)

Russia and the U.S. formed an internationally cooperative research consortium with the other countries to introduce GTMHRs (Gas Turbine-Modular Helium Reactors) into the two countries. The participants in this consortium include not only manufacturers and research institutions in Europe and the U.S., but also Fuji Electric in our country. The Russians consider GTMHR as a candidate reactor applicable to the disposal of plutonium taken out from dismantled excess nuclear weapons, while the Americans regard it as a reactor that is excellent in safety, economical efficiency and applicable to the production of hydrogen. The safety review is being prepared so as to start construction of GTMHRs by 2006 in Russia and by 2007 in the U.S.

The standard GTMHR plant comprises of 4 modules with an output of 286MWe each. Power generation efficiency as high as 45 to 50% may be attained by the direct cycle gas turbine power generation system. This reactor may consume a greater part of the quantity of Pu239 taken out from dismantled nuclear weapons, once it is loaded with fuel and operated. The plant with 4 modules may dispose of about 1 ton of plutonium from nuclear weapons annually.

6.5.5 Generation IV reactors

Last year, the Generation IV International Forum (GIF) selected 6 types of generation IV nuclear energy systems as the subjects of internationally cooperative researches and development projects. Of the six systems, two were gas-cooled reactors - VHTR (Very High-Temperature Gas-Cooled Reactor) and GFR (Gas-Cooled Fast Reactor). The system concepts of the reactor types will be described hereinafter, mainly based on the Technology Roadmap for

Generation IV Nuclear Energy Systems^[20].

(a) VHTR (Very High-Temperature Gas-Cooled Reactor)

The VHTR is a reactor having a coolant exit temperature of 1000°C or more, and its final target is set at about 1500°C. The most important application for this reactor is considered the production of hydrogen using the IS process. The reference design of VHTR shows an output of about 600MWth and uses the ZrC-coated particle fuel of low enriched uranium oxide (block or pebble bed type).

If a VHTR is used for a hydrogen production plant, the heat taken out of an intermediate heat exchanger will be introduced into an IS process plant. If a VHTR is used as a power reactor, the use of the direct cycle is supposed, and the power generation efficiency is estimated at 50% or more. In either case, it is assumed to use the one-through cycle that does not recycle any spent fuel. The future challenges include R&D efforts related to fuels coated with ZrC having a high heat resistance, heat resisting ceramics materials, a passive decay heat removing system, an intermediate heat exchanger, etc. JAERI (Japan), GA (U.S.) and others are currently extending R&D efforts, aiming to start operation of VHTR by 2020.

(b) GFR (Gas-Cooled Fast Reactor)

GFR is a helium-cooled fast reactor for which the use of a closed cycle is assumed to improve the efficiency of resource utilization and control actinides. Especially, the CEA in France has taken an attitude of attaching importance to the R&D efforts for this type of reactor. The Commission has set the target time for commercialization of GFR at around 2025.

The reactor GFR will be mainly used to recycle uranium, plutonium and actinides, and minimize the contents of long-lived nuclides in radioactive wastes. The reference design of GFR shows an output of 600MWth/288MWe and a coolant exit temperature of 850°C. The nuclear heat may be used for the production of hydrogen. However, the most important application for the nuclear heat is assumed to be the power generation by a direct cycle helium gas turbine, of which the efficiency is estimated at 48%. The most

promising fuel option is a ceramic compound fuel called “cercer” (UPuC/SiC (70%/30%) containing about 20% of Pu). Examinations will be made on spent fuel reprocessing systems including wet and dry options.

6.6 Conclusion

Focusing on high-temperature gas-cooled reactors (HTGRs), in which there is a rapidly increasing interest as the most promising options for short- and medium-term introduction reactors and generation IV reactors, this article described the current enhancement of expectations for HTGRs, the international R&D efforts related to these reactors, the features of the reactors, and the utilization of the reactors for the production of hydrogen, and provided an overview of the key R&D and introduction projects for HTGRs in Japan and foreign countries.

The HTGRs, which have a high inherent safety, may be used in various applications including the production of hydrogen and the high-efficient power generation by small- and medium-sized reactors. It can be considered that these features of HTGRs may be in harmony with the social needs for nuclear energy systems.

Today, many countries are involved in full-scale R&D projects for HTGRs, considering them clearly as the next generation reactor candidates. Under these circumstances, it is important for Japan to extend R&D efforts focusing on the various potentialities of HTGRs, taking into consideration the social needs for nuclear energy plants in the future. In addition, it is necessary for the public and private sectors to undertake examinations on the construction of reactors such as an alternative prototype reactors to HTTR as well as a small high-efficiency power generation test reactor.

Currently, we are facing an important problem of how to satisfy the enormous demand for hydrogen brought forth by the future diffusion of hydrogen energy systems. The mass production of clean hydrogen by using a HTGR as the heat source is attracting much attention, and may probably provide more applications to nuclear energy, used only for power generation, and make a great change in the role of HTGRs in overall

energy systems. The DOE budget requests for the 2004 fiscal year proposed a new Nuclear Hydrogen project as part of its Hydrogen Fuel Initiative. In Japan as well, it is desirable to launch into an R&D project for the production of hydrogen by using a reactor such as a HTGR.

Notes

- *1: Japan signed into the GIF Chapter in July 2001.
- *2: This was initially announced as the Freedom Fuel Initiative, and has recently been called the Hydrogen FUEL Initiative, or Freedom CAR and Fuel Initiative, combined with the Freedom CAR Initiative.
- *3: Large plants distant from consumption districts may face the problem of hydrogen transportation cost.

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