Modular High-temperature Gas-cooled Reactor for Expanding Nuclear Heat Utilization

Futoshi Okamoto † Kazutaka Ohashi ‡

ABSTRACT

The modular High Temperature Gas-cooled Reactor (HTGR) is a new generation type of the reactor with the inherent safety. The HTGR can supply heat of very high temperature of approximately 950 degrees C compared to that of the Light Water Reactor. Its development has started in many countries as it has a potential to expand the nuclear heat utilization to reduce CO_2 emission. Fuji Electric is focusing on the R&D towards the practical use of the modular HTGR based on the technologies gained during the development of Japan's first HTGR, HTTR. Major activities of our R&D work are development of the heat resistant core restraint mechanism to maximize the effective core coolant flow rate, development of the core design method to improve its safety characteristics during an accident, and improvement of the evaluation method of the decay heat removal from the core only by the natural phenomena, such as natural convection, core conduction and radiation.

1. Introduction

The modular high temperature gas-cooled reactor (HTGR) has excellent inherent safety characteristics. The modular HTGR is also a next-generation reactor capable of utilizing high temperature heat (up to 950 °C), which is significantly higher than the 300 °C temperature that can be used with light water reactors (LWRs). This reactor can be used for high efficiency power production with a direct gas-turbine using high temperature heat, hydrogen production from water using a thermo-chemical process, or as a process heat supply using high temperature steam for chemical plants. Modular HTGRs are being developed in Japan and overseas and have the potential to expand the range of nuclear heat utilization, which previously had been limited to power generation, and as a primary energy source that also is an alternative to fossil fuels, to bring about a large reduction in the amount of CO_2 emissions.

This paper discusses the design concepts and features of HTGRs, domestic and international development trends, and Fuji Electric's involvement in HTGR development.

2. HTGR Characteristics

2.1 Comparison of HTGR and LWR structures

Figure 1 shows a nuclear reactor concept of a HTGR.

An LWR uses metal-clad fuel. An HTGR, however, uses ceramic-coated fuel particles that have a diameter of approximately 1 mm. This coating serves to contain the radioactive material generated by nuclear fission. The coated fuel particles have excellent heat resistance characteristics. Even after long-term operation at high temperatures exceeding 1,000 °C, or at the super-high temperature limit of 1,600 °C under accident conditions, the radioactive material will be contained reliably inside the fuel, without damage to the integrity of the fuel coatings.

Heat generated within the fuel is extracted from the nuclear reactor using chemically inert helium gas as a coolant. Even at high temperatures, helium does not react chemically with fuel or structural materials.

To maintain nuclear fission reactions inside a nuclear reactor effectively, the fast neutrons generated by nuclear fission must be moderated. In a LWR, the light water, which is also a coolant, is used as a moderator. In a HTGR, graphite, having the characteristics of low neutron absorption, strong resistance to radiation, excellent heat resistance and good thermal conductivity, is used as a moderator. The graphite also functions as structural material of the core. Furthermore owing to its high thermal capacity, graphite also serves to mitigate rapid temperature increases during an accident.

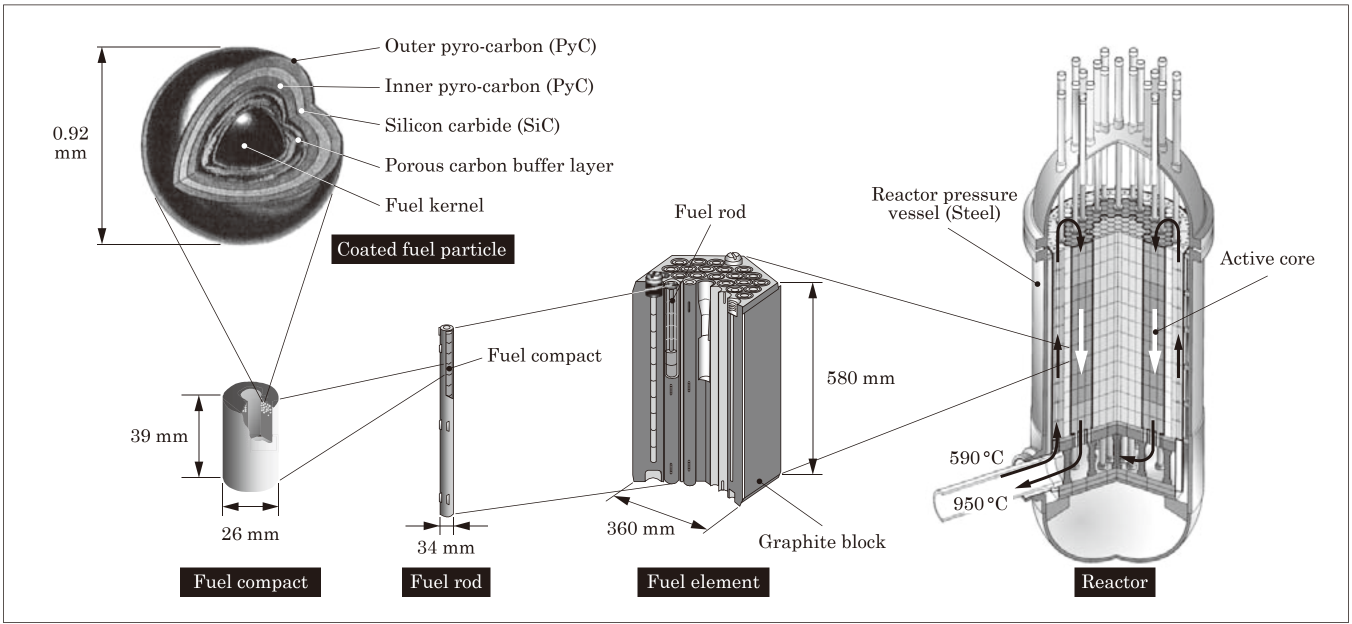
2.2 Modular HTGR

HTGRs use coated fuel particles that are highly resistant to heat. Graphite, used as a moderator, has a large thermal capacity and becomes a large heat sink during accidents. This feature, coupled with the negative temperature feedback characteristics of the core, mitigate abnormal power increase and slows temperature rises during accidents, resulting in excellent safety characteristics.

By limiting the thermal output of a reactor to below a certain level, these safety characteristics can be utilized to their full extent. A reactor can be con-

† Energy Solution Group, Fuji Electric Systems Co., Ltd.
‡ Technology Development Group, Fuji Electric Holdings Co., Ltd.

Fig.1 Reactor concept of HTGR



structed so that in the event of an accident, the reactor shuts down naturally, decay heat is removed naturally, and there is no risk of releasing large amounts of radioactive material that would necessitate the evacuation of the surrounding public of the site. The reactor with these features is the modular HTGR, which has a maximum thermal output on the order of 600 MWt (approximately 300 MWe of electric power). This safety characteristics makes a clear distinction with LWRs, which is aiming for improved economic efficiency through economies of scale, and have recently reached the 1,700 MWe level and scaling-up to larger sizes is planned. By increasing the safety of nuclear reactors and simplifying the safety systems needed in case of accidents, economic viability of the modular HTGR can be ensured even if the reactor power is reduced.

Modular HTGRs have the following safety features.

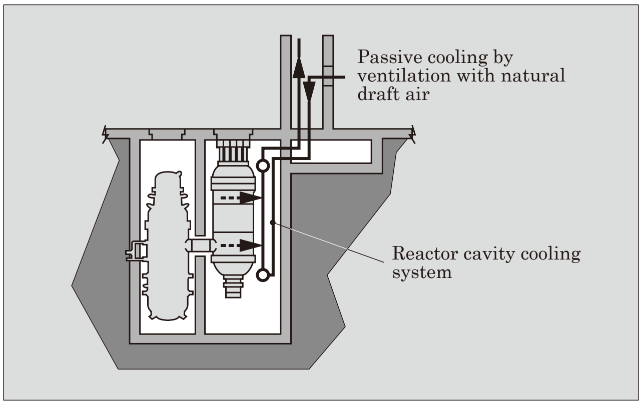
(1) Natural cooling during an accident

As mentioned above, a modular HTGR has a smaller sized reactor so that the decay heat of the reactor can be removed adequately by natural cooling, even during an accident. For example, even in the case of the loss of helium coolant due to rupture of the main cooling pipe (a Loss of Coolant Accident), heat will be removed from the reactor building naturally through the soil and atmosphere, so that the reactor can be cooled adequately, and the fuel temperature kept below the limiting temperature at which fuel integrity can be maintained (see Fig. 2).

(2) Passive shutdown of reactor at the time of an accident

In general, a reactor using low enriched uranium fuel has a characteristic whereby, as the temperature of the core rises, negative reactivity feedback acts so as to mitigate nuclear reactions naturally. The fuel

Fig.2 Natural cooling of the reactor by the reactor cavity cooling system



temperature of a HTGR during normal operation has sufficient margin to the limiting temperature under accident conditions, and therefore, at the time of an accident, even without an emergency shutdown action of the control rod, the reactor will be shut down passively due to the negative reactivity feedback.

(3) Radioactive materials are retained in fuel particles after an accident

As mentioned above, if an accident occurs, even if the operator takes no actions or if the safety system does not work, the integrity of the fuel will be maintained solely by natural physical phenomena. Accordingly, radioactive materials accumulated in the core will be reliably contained in the fuel, and there is no need for a pressure and leak-proof containment vessel as in the LWR.

2.3 Use of high-temperature heat

LWRs have become the mainstream type of nuclear power generation at present, but because of their useable upper limit temperature of about 300 °C, applications other than power generation by steam turbines are extremely limited. In contrast, an HTGR can utilize heat in the range of 700 to 950 °C, and thus can be utilized for direct gas turbine power generation with an efficiency of nearly 50% as a power plant. Additionally, without any power conversion stage, the heat obtained from the reactor can be utilized directly for the production of hydrogen from water by a thermochemical process, or as high temperature steam as the process heat source at a chemical plant. Moreover, when connected to a steam turbine cycle, an HTGR can be used as a cogeneration plant that supplies electric power and process steam for use in a chemical complex. Thus, HTGRs can significantly expand the range of utilization of nuclear power, which had previously been limited to power generation, and can substitute for fossil fuels as a primary energy source and contribute to reduce CO_2 emissions dramatically.

3. Current Status and Fuji Electric's Efforts in HTGR Development

3.1 History of HTGR development and Fuji Electric's achievements

(1) History of HTGR development

The development of the HTGR started with the construction of an experimental reactor in the UK with the Dragon Project launched by the OECD (Organization for Economic Cooperation and Development) in 1959. Later, during the 1960s and 1970s, experimental and prototype reactors were constructed and operated in the United States and Germany (then West Germany). The prototype reactor had an electric output of approximately 300 MWe, and performance demonstrations as power plants using a steam turbine were carried out for both reactors.

Through the 1970s, the development of HTGRs, as well as LWRs and other reactors, was advanced in the United States and Germany with a fundamental orientation toward large-size reactors. However, the Three-Mile Island and Chernobyl accidents led to worldwide interest in the concept of inherently safe reactors that ensure safety without relying on active components, and the direction of development shifted dramatically from large-size reactors to modular HTGRs. Thereafter, the focus of HTGR development in both the United States and Germany shifted to small-size modular HTGRs that use steam turbines for power generation.

In the 2000s, from the perspective of protecting the environment and preventing global warming, in the United States, the development of a modular HTGR aiming for a reactor outlet temperature of at least 950 °C, and a hydrogen production system that connects to the modular HTGR, was initiated as a NGNP (Next Generation Nuclear Plant) project with funding from the US Department of Energy.

In Germany, development of modular HTGRs started in the 1980s, and research was carried out vigorously. With the subsequent change in Federal government policy to suspend all nuclear power development, this development work was halted in the early 1990s. However, German HTGR technology has been come into China and South Africa, and both countries are moving ahead with plans to build HTGR demonstration reactors.

Recently, throughout the world, there has been heightened interest in HTGRs for hydrogen production and for use as a process heat source, and even in the Generation IV International Forum (GIF), which is a framework for cooperative international research and development that began as a proposal from the United States, HTGRs have been selected as one of the candidate plants, and international cooperation is also underway.

In Japan, the research and development of HTGRs for multi-purpose utilization other than power generation started in the late 1960s at the former Japan Atomic Energy Research Institute (currently the Japan Atomic Energy Agency (JAEA)). Thereafter, the construction of Japan's first HTGR, the High Temperature Engineering Test Reactor (HTTR), began in 1990. In 2001, this reactor achieved its rated power operation, and in 2004, 950 °C high-temperature helium gas was successfully produced by the HTTR[1].

(2) Fuji Electric's achievements

Fuji Electric has participated in cooperative HTTR design, research and development since the beginning of JAEA's research and development initiative. In tests of high temperature components, i.e., strength tests of the reactor internal structures, seismic tests of the core, performance tests of seals between blocks, thermal property tests of materials and so on, elemental technologies necessary for design and manufacturing have been developed. Fuji Electric installed an in-house high-temperature high-pressure helium loop, and performed demonstration testing on structures, reliability of components. With the Helium Engineering Demonstration Loop (HENDEL) for carrying out demonstration testing of the various HTTR high-temperature components, Fuji Electric has played a leading role in the construction. At the same time, Fuji designed, fabricated and installed a "Single Channel Fuel Stack Test Section" (HENDEL-T1) for evaluating the heat transfer and flow characteristics of coolant in the core and an "In Core Structure Test Section" (HENDEL-T2) (Fig. 3) for evaluating the integrity of core support structures, and supported research and development for demonstrating the performance and integrity of large-size components[2],[3]. For the core bottom structures, Fuji Electric has manufactured, installed and tested 1/5th scale and 1/3rd scale seismic testing equipment for the purpose of acquiring basic response data and for demonstrating integrity at the time of an earthquake[4].

In the construction of the HTTR plant, Fuji Electric, as a deputy administrative role, coordinated reactor construction, cooperated with JAEA regarding the design of the reactor core and in conducting safety analyses for the reactor system design, and was responsible for the design, manufacture and construction of major components such as the reactor internals, a fuel handling and storage system, and a radiation monitoring system. Figure 4 shows the appearance of the reactor internals as seen from the top layer of the reactor core. Figure 5 shows a fuel handling machine, a major component of the fuel handling system.

After construction of the HTTR was completed, Fuji Electric was responsible for constructing a spent fuel storage facility, which is a dry storage system for the long-term onsite storage of spent fuel, after having been stored in the reactor building and cooled, and for designing and manufacturing an irradiation creep test device for conducting creep testing inside the HTTR core[(5)].

Fig.3 Reactor internal structure demonstration test section (HENDEL-T2)

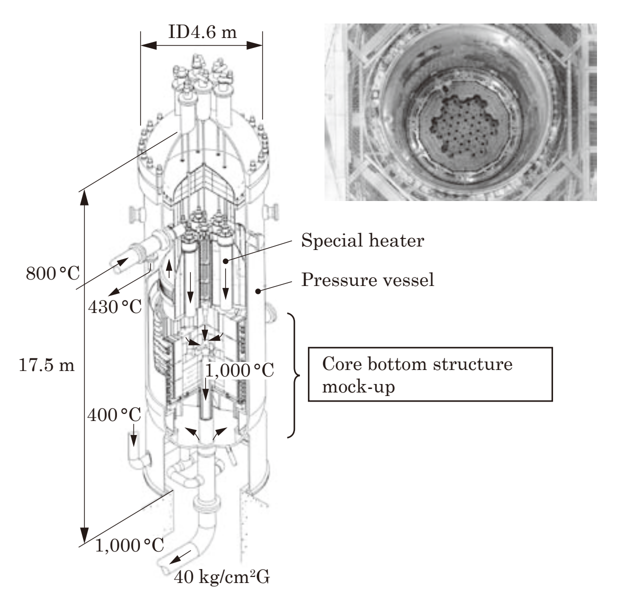
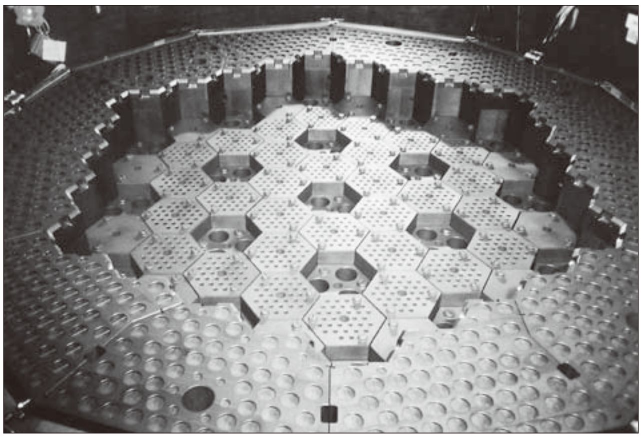


Fig.4 Top layer of High Temperature Engineering Test Reactor (HTTR) core



3.2 HTGR development efforts

In order to realize hydrogen production with an HTGR, a higher reactor outlet temperature of at least 950 °C is needed. Previously, HTTRs and other small test reactors have achieved this level of performance, but many challenges remain before they can be used in practical applications. In the case of practical application of a modular HTGR of 600 MWt power, its power level must be increased to 20 times of the 30 MWt HTTR. To ensure the inherent safety of this output power, the fuel temperature limits must be satisfied during normal operation and during accidents. During normal operation technical, measures are needed to ensure the effective core coolant flow rate. On the other hand, the power distribution shape must be optimized to meet the limiting fuel temperature under accident conditions and also to maintain higher plant availability due to a longer fuel burn-up period. Additionally, to reach the highest power level while maintaining the inherent safety, design margin in the evaluation of the decay heat removal capacity by natural cooling from the reactor vessel, it is also important to utilize this cooling capability as much as possible.

Based on the aforementioned technical issues, Fuji Electric is advancing research and development with

Fig.5 High Temperature Engineering Test Reactor (HTTR) fuel handling machine

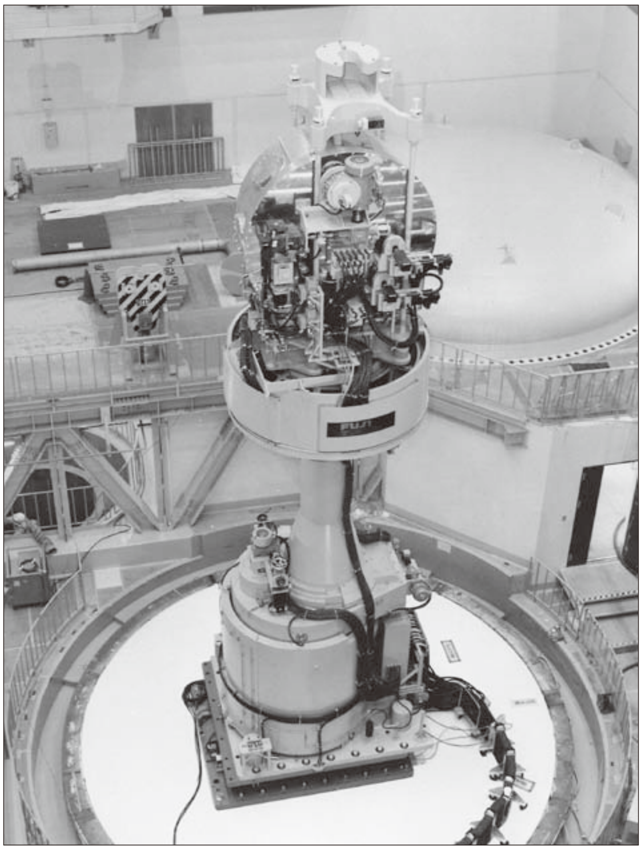


Fig.6 Heat-resistant restraint mechanism of the core for very high temperature gas reactor (VHTR)

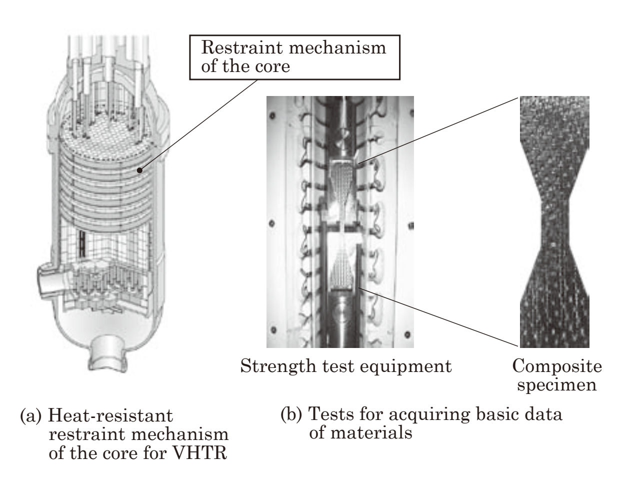


Fig.7 Concept of flattened power distribution shape core

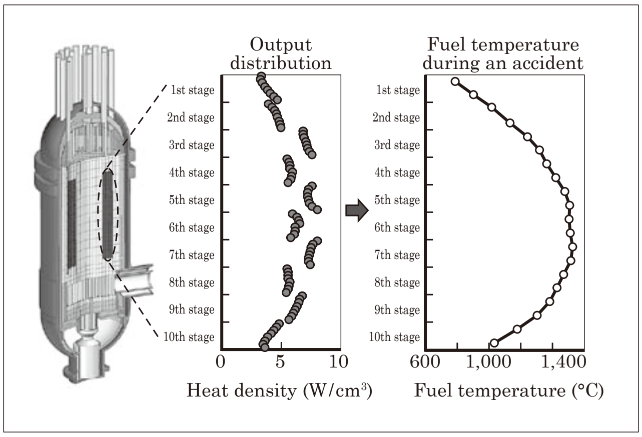
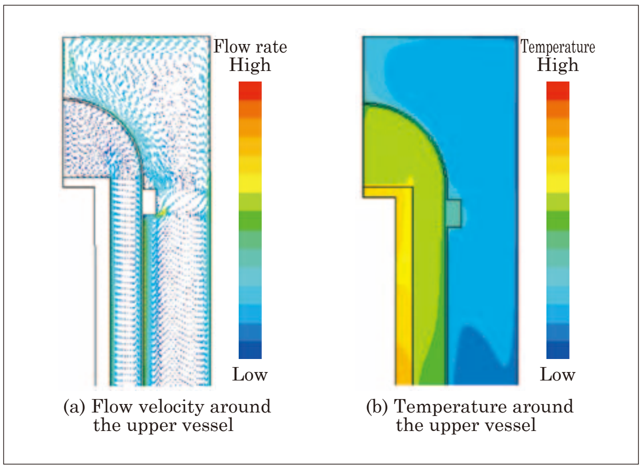


Fig.8 Example of analysis result of heat removal from reactor by natural cooling



the goal of achieving the practical application of a modular HTGR on a commercial scale aimed at realizing thermal power of 600 MWt and an outlet temperature of 950 °C. The major research and development items are introduced below.

(1) Heat-resistant restraint mechanism of the core

So that the fuel temperature does not rise excessively even if the reactor output temperature is increased to 950 °C, reactor internals of stacked graphite blocks must be tightened from the outside and the bypass flow through gaps between the blocks must be minimized so as to ensure the effective coolant flow rate of the fuel coolant channel. In the case of the HTTR, since the reactor inlet temperature is around 400 °C, a restraint mechanism was established using metal materials. In the case of a HTGR for hydrogen production, however, in order to ensure the plant thermal efficiency, a reactor inlet temperature of approximately 500 to 600 °C is required. For this purpose, composite ceramic materials having excellent heat-resistant properties are used instead of metal materials, and structural concepts, tests for acquiring basic data of the materials, development of a strength evaluation method are being performed (Fig. 6).

(2) Core design study with axially flattened power distribution shape

To ensure the inherent safety of a modular HTGR, the fuel temperature during an accident must not exceed the limit value. Since the decay heat during an accident is removed radially from the reactor vessel by natural cooling, the maximum fuel temperature will be in the vicinity of the maximum power point in the axial direction. Therefore, to reduce the fuel temperature during an accident, the axial power distribution of the core must be flattened. Fuji Electric is developing the methodology for designing the flattened power distribution shape core concept to meet the limit temperature of 1,600 °C during a depressurization accident, as shown in Fig. 7, with a reactor thermal output of 600 MWt, a reactor inlet temperature of 590 °C and output temperature of 950 °C as basic conditions, and a design target of 550 days × 2 batches as the refueling cycle and number of batches.

(3) Evaluation of decay heat removal characteristics from the reactor by natural cooling

Cooling of the reactor pressure vessel during normal operation and during an accident is carried out by two heat transfer phenomena, radiation and natural convection. Accordingly, if the decay heat removal capability of these phenomena can be precisely evaluated, the design margin could be reduced reasonably and cheaper materials for the reactor pressure vessel could be used. Thus, in order to enhance the accuracy of the evaluation of heat removal by natural cooling, experimental data[6] of scale model tests previously implemented by the JAEA is utilized effectively, and the validation of the evaluation method is being performed. An example of thermal hydraulic analysis results for a reactor vessel mock-up test facility is shown in Fig. 8.

4. Postscript

Modular HTGRs are the next-generation of nuclear reactors, and in addition to having excellent inherent safety characteristics, also have the potential to bring about a significant reduction in CO_2 emissions through expanding their application other than power generation, such as hydrogen production or the process heat supply for chemical plants. Fuji Electric will continue to cooperate with related organizations in Japan and overseas, and intends to apply its full resources to advance the commercialization of HTGRs.

References

(1) Fujikawa, S. et al. Achievement of Reactor-Outlet Coolant Temperature of 950°C in HTTR. Journal of Nuclear Science and Technology. 2004, vol.41, no.12, p.1245-1254.

(2) Shimomura, H. et al. Construction of Helium Engineering Demonstration Loop (HENDEL) Test Section T1. FAPIG. 1984, no.107.

(3) Akisada, T. et al. Construction of Helium Engineering Demonstration Loop (HENDEL) Test Section T2. FAPIG. 1986, no.114.

(4) Shiozawa, S. et al. Seismic Testing of Core Bottom in High Temperature Engineering Test Reactor. FAPIG. 1990, no.125.

(5) Shibata, T. et al. Development of HTTR I-I Type Material Irradiation Test Facility. FAPIG, 2002, no.161.

(6) IAEA-TECDOC-1163, Heat Transport and Afterheat Removal for Gas Cooled Reactors under Accident Conditions, IAEA, 2000.