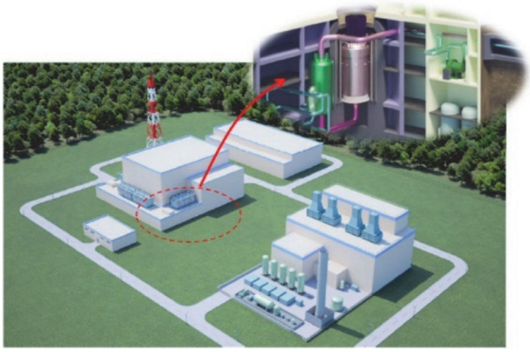
Development of High Temperature Gas-cooled Reactor for Hydrogen Production System



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As a measure for decarbonization in the industrial field in order to achieve carbon neutrality, the use of hydrogen is under consideration. One challenge is to provide a large and stable supply of hydrogen, and expectations for highly efficient hydrogen production using CO_2-free high-temperature heat from High-Temperature Gas-cooled Reactors (hereafter referred to as HTGR) are growing. Mitsubishi Heavy Industries, Ltd. is promoting the development of a demonstration HTGR for hydrogen production as a core company, and at the same time, is working on verification of connection technology with hydrogen production facilities, development of CO_2-free hydrogen production technology, and development of evaluation technology for design of HTGR. Through these efforts, we aim to realize a HTGR for hydrogen production and contribute to the realization of a carbon-neutral society.

1. Introduction

In order to achieve carbon neutrality, decarbonization in the industrial (steel, chemical, and other manufacturing industries) and transportation fields, which emit large amounts of CO_2, is inevitable (**Figure 1**). For this reason, various efforts are being carried out in various industries. The steel industry, which accounts for about 14% of domestic CO_2 emissions, is developing technologies for decarbonization by hydrogen reduction steelmaking, but this requires a large and stable supply of hydrogen. In addition, hydrogen has low combustion energy per volume (about 1/3 that of methane), easily leaks, and requires cryogenic temperatures for liquefaction, resulting in high transportation and storage costs. Therefore, local production for local consumption of hydrogen, where production is close to the place of consumption, is desirable.

Many methods for hydrogen production have been proposed from verification to practical application phase. Among these, methods to increase efficiency using high temperatures including steam methane reforming (hereafter referred to as SMR), high-temperature steam electrolysis method (hereafter referred to as SOEC (solid oxide electrolysis cell)), the methane pyrolysis method, and the thermochemical IS process(1) under development at Japan Atomic Energy Agency (hereafter referred to as JAEA). Using fossil fuels as heat sources generates CO_2, whereas nuclear energy does not. However, conventional light-water reactors operate at approximately 300°C, which is too low to serve as heat sources for the hydrogen production. In contrast, HTGR can provide heat at approximately 900°C, which is sufficiently high. Therefore, the high-efficiency hydrogen production by combining the HTGR with the hydrogen production methods is expected.

For HTGRs to produce a large amount of stable high-temperature heat (>900°C), highly heat-resistant materials (graphite and ceramic materials) for the core and fuel components and chemically stable helium gas (helium) as the coolant to extract heat generated by nuclear reactions, are used(2). In addition, the reactor is composed of highly heat-resistant materials and core power density is low, providing inherent safety features that prevent core meltdown even in the event of an emergency(2).

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In June 2021, the Japanese Cabinet approved the Green Growth Strategy Through Achieving Carbon Neutrality in 2050, which clearly states the government's commitment to promote R&D and demonstrate innovative hydrogen production technology using high-temperature heat sources such as HTGRs. In response, the Ministry of Economy, Trade and Industry launched a demonstration project for hydrogen mass production technology using ultra-high temperatures in 2022, followed by a project to develop a demonstration HTGR in 2023.

The overall plan for development of a HTGR for hydrogen production is shown in **Figure 2**. In 2023, Mitsubishi Heavy Industries, Ltd. (hereafter referred to as MHI) was selected as a core company to carry out the basic design of the demonstration HTGR and to be responsible for future manufacture and construction(3). MHI started design and development of the demonstration reactor, aiming to start operations in the late 2030s. To contribute to the development of this demonstration reactor, MHI has been cooperating in High Temperature Engineering Test Reactor (hereafter referred to as HTTR) heat application test conducted by the JAEA, and is working to demonstrate the connection technology between HTGR and hydrogen production facilities by connection HTTR and SMR method, which is already in practical use in the general industry. MHI is also investigating and developing CO_2-free hydrogen production technology for HTGRs that does not emit CO_2 during hydrogen production, and has also been developing evaluation technology for in-house HTGR design, such as a core nuclear thermal calculation code to evaluate reactor characteristics. This paper presents these efforts.

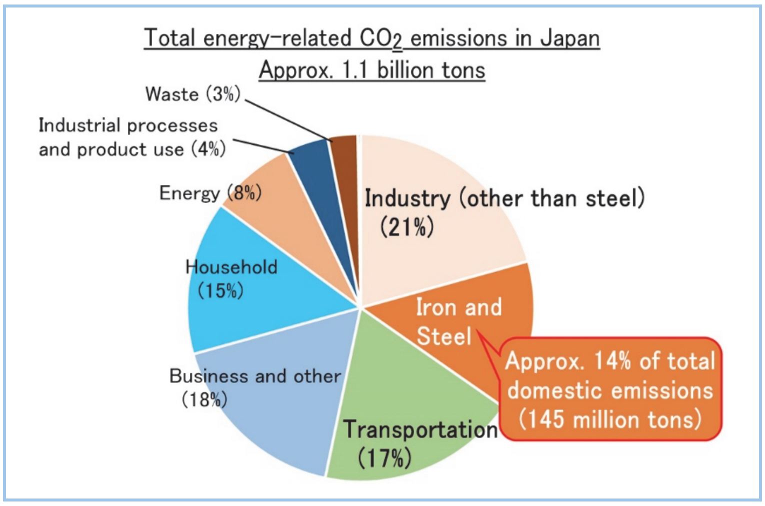

Figure 1　CO₂ Emissions in Japan by Sector (FY2021)

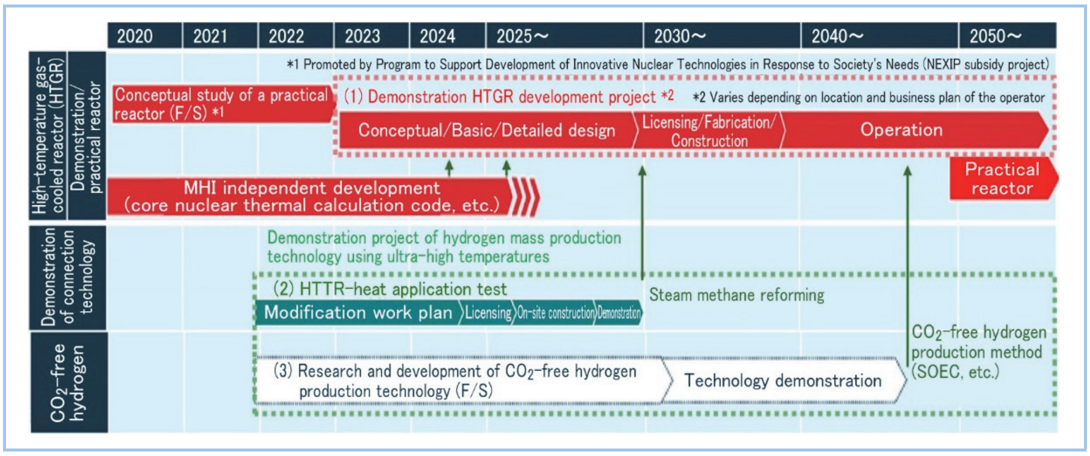

Figure 2　Overall plan for the development of HTGR for hydrogen production

2. Development of demonstration HTGR

Development of a demonstration HTGR should take into consideration that an HTGR in Japan would be only an HTTR with a thermal power of 30 MWt as an experimental research reactor. In addition, it is important to recognize that the next step after the demonstration reactor is a practical reactor.

From an economic standpoint, the future practical reactor is expected to be a high-power plant for large-volume hydrogen production. Therefore, the main objective of the demonstration reactor is to demonstrate upscaling from the HTTR, stable and large-volume hydrogen production, and to obtain the economic prospect through the realization of these activities as soon as possible.

To achieve this objective, the following four requirements which must be fulfilled in development were established.

- Maximization of the inherent safety features that prevent core meltdown even in the event of an accident.
- Improvement in hydrogen production efficiency by a high-temperature heat source (up to approximately 900°C).
- Improvement of economic efficiency by increasing power output and simplifying equipment configuration.
- Realization of the demonstration reactor as soon as possible by maximizing the use of existing technologies/knowledge centered on the HTTR.

Specifications of the demonstration reactor that considers these requirements is shown in **Table 1**. The core type of the demonstration reactor was set as pin-in-block type (the core is comprised of stacking fuel blocks made by inserting rod-shaped pins containing nuclear fuel into hexagonal-column-shaped graphite blocks with holes in them), which had been proven in HTTR, in order to maximize use of existing HTTR technology(2). Power output of the reactor is assumed to be 150 MWt to 250 MWt, which is approximately one order higher magnitude than that of HTTR.

Results obtained from the HTTR connection technology demonstration described in Chapter 3 are planned to be used as connection technology between HTGR and the hydrogen production system. In order for early realization, consideration is planned to proceed by applying the SMR method, which has already been put into practical use, although CO_2 is produced during hydrogen production. However, with a view to the future, consideration which connects to CO_2-free hydrogen production technology currently under development is also carried out, as described in Chapter 4.

In addition, a core nuclear thermal calculation code is being developed in-house as evaluation technology to design the demonstration HTGR. Details are described in Chapter 5.

Table 1 Specifications of HTGR demonstration reactor

Item	Specifications	(Reference) HTTR specifications
Power	150 to 250 MWt	30 MWt
Core type	Pin-in-block type	Pin-in-block type
Reactor outlet temperature	Up to approximately 900°C	Normal operation: 850°C High-temperature operation: 950°C
Hydrogen production method	SMR or applicable CO_2-free hydrogen production technology	— (Connection with SMR is planned.)

3. Demonstration of technology to connect hydrogen production system (HTTR heat application test)

Hydrogen production using heat from a HTGR is unique in the world. For this reason, JAEA is promoting an HTTR heat application test in connection with the HTTR, which has achieved a reactor coolant outlet temperature of 950°C, with a hydrogen production system that uses current practical application of SMR(4). MHI has been cooperating with JAEA and started system design and technical development of connecting equipment in 2022.

An overall outline of the HTTR heat utilization test facility is shown in **Figure 3**(5). Primary helium heated to a high temperature in the HTTR reactor transfers its heat to secondary helium through an intermediate heat exchanger, and part of the secondary helium leaves the reactor containment vessel, exiting the reactor building through the high-temperature isolation valve, to supply reaction heat to the steam reformer through the newly constructed high-temperature helium piping (high-temperature insulated piping). After hydrogen is produced with the supplied heat, the low-temperature secondary helium is returned to the intermediate heat exchanger by a helium circulator. In the system design, review of new equipment configuration, heat/mass balance, and operation method is planned.

Connection technology to be developed includes “high-temperature insulation piping”, “a high-temperature isolation valve”, and “a helium circulator”. The high-temperature insulation piping is used to efficiently transfer heat generated in the reactor to the hydrogen production system. The internal insulation method, which can reduce heat loss and temperature decrease in the pressure-resistant boundary, has been adopted, and selection of better materials to replace the internal insulation used in the HTTR construction is planned. The high-temperature isolation valve is installed in the piping that passes through the reactor containment vessel and the reactor building. In cases of abnormalities in the hydrogen production system, etc., the valve can be closed as needed in order to isolate the reactor facility from the hydrogen production system, preventing the hydrogen production system from affecting the reactor facility. This valve needs to be newly installed in the HTTR and must provide sealing and heat resistance in a high-temperature helium environment, while preventing fusion between the valve element and valve seat when the valve is closed. Development of a drive system to ensure appropriate shut-off surface pressure for this valve is planned. A helium circulator is indispensable for transferring the coolant helium, but increasing the size of the gas bearing type helium circulator employed since construction of the HTTR is difficult due to the weight limitation of the rotor. Therefore, we are developing a magnetic bearing type helium circulator that can be further increased in size, with a view to greater capacity in the future.

MHI will continue its efforts to demonstrate the connection technology between a HTGR and a hydrogen production system through the HTTR heat application test. In addition, utilization of the obtained results on a larger scale in the development of the demonstration reactor and to apply them to the demonstration reactor.

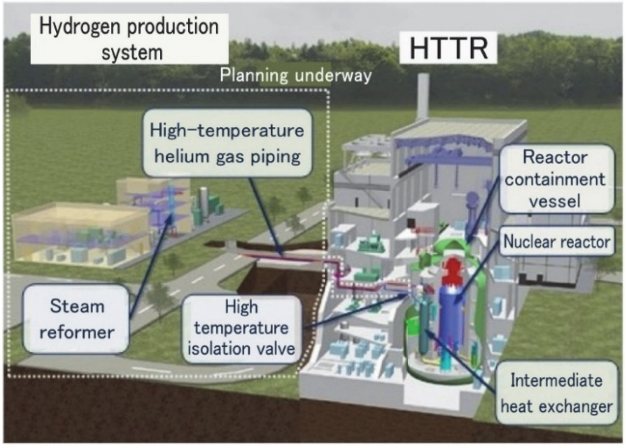

Figure 3 HTTR heat utilization test facility

4. Development of CO_2-free hydrogen production technology to connect to HTGR

The hydrogen production method currently used for industrial-scale is the SMR method, which inevitably emits CO_2 when producing hydrogen from methane and steam. Achieving carbon neutrality requires a large-scale and stable supply of CO_2-free hydrogen, produced without generating CO_2 emissions. The combination of a HTGR and CO_2-free hydrogen production technology can meet this need. HTGRs offer the advantage of supplying high-temperature heat, exceeding approximately 900°C or higher. Technologies that utilize this high temperature heat to efficiently extract hydrogen include the SOEC and the methane pyrolysis methods, both under development by MHI. The following sections outline MHI’s plans for a hydrogen production study combining the SOEC and methane pyrolysis methods with a HTGR.

4.1 Hydrogen production using a combination of HTGR and SOEC method

The SOEC method electrolyzes high-temperature steam to produce hydrogen, which is suitable for high-efficiency, large-capacity hydrogen production. The typical SOEC method requires significant amounts of electricity to perform electrolysis - splitting steam into hydrogen and oxygen – as well as to compensate for heat absorption associated with electrolysis, and to generate steam. On the other hand, when integrated with a HTGR, the high-temperature heat supplied by the HTGR can be utilized for steam generation and heat compensation. As a result, a large amount of hydrogen can be produced with a small amount of electricity.

MHI is currently developing its proprietary cylindrical SOEC technology. A demonstration unit, consisting of several cartridges each containing approximately 500 SOEC cells, was installed at Takasago Hydrogen Park (**Figure 4**) and began operations in March 2024. The unit has successfully achieved hydrogen production at a rate of 125 Nm^3/h, and plans are underway to accelerate the scale-up study while conducting various component tests. Based on the technology of the cylindrical SOEC, a heating mechanism will be incorporated to supply heat for steam generation and to compensate heat absorption during electrolysis. A demonstration test simulating the utilization of heat from a HTGR is planned for around 2027.

Figure 4 SOEC demonstration unit installed at Takasago Hydrogen Park

4.2 Hydrogen production using a combination of HTGR and methane pyrolysis method

In methane pyrolysis, natural gas is thermally decomposed into hydrogen and solid carbon using a catalyst at high temperatures approximately 800°C. This technology is commonly employed in the production of carbon materials such as carbon black, an industrial material. Typically, the thermal decomposition process uses electric heating or combustion heat from fossil fuels. However, utilizing heat from a HTGR enables the large-scale and stable production of CO_2-free hydrogen.

MHI has been developing methane pyrolysis technology, and has already achieved over 40-hour continuous operation, at a hydrogen production rate of 2 Nm^3/h using test equipment that includes a fluidized bed reactor, heater, catalyst supply and by-product carbon removal mechanisms inside a pressure vessel (**Figure 5**). Based on this technology, a heat input mechanism to the reactor using high-temperature helium will be integrated, with plans to conduct demonstration test simulating heat utilization from a HTGR around 2028.

The integration of a HTGR with technologies such as SOEC or methane pyrolysis holds significant potential for the stable, large-scale CO_2-free hydrogen. To realize this potential, development efforts will continue, with plans to connect a technically validated hydrogen production method to a HTGR in the long term.

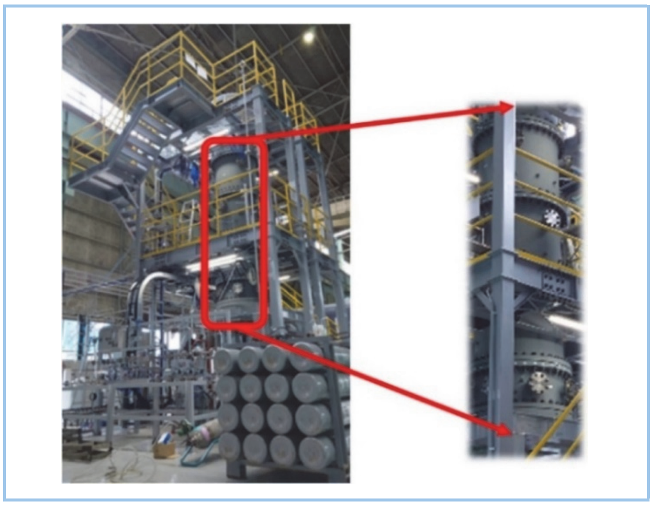

Figure 5 Continuous fluidized-bed testing equipment

5. Development of a core nuclear and thermal calculation code, a fundamental technology

In the development of a demonstration HTGR, various performances such as reactor characteristics, safety performance, and structural integrity are important, and are evaluated by simulation analysis where analytical models that simulate the reactor, intermediate heat exchanger, and other components of the HTGR are constructed. Status of the development of the core nuclear and thermal calculation code, which is a tool to evaluate reactor characteristics within simulation analyses carried out in the development of the demonstration HTGR, is presented in this chapter.

The core nuclear and thermal calculation code evaluates the nuclear and thermal characteristics of a HTGR and consists of the core nuclear calculation code and the core thermal- hydraulic calculation code. The core nuclear calculation code evaluates power and irradiation distributions, and the results are input into the core thermal-hydraulic calculation code to evaluate fuel and graphite temperatures. The results are then fed into the core nuclear calculation code again, and the obtained results are then fed into the core thermal-hydraulics calculation code to perform coupled nuclear-thermal calculations.

MHI has been developing its own core nuclear thermal calculation code in the design of a demonstration HTGR, by taking advantage of its development capabilities cultivated through the development of its core nuclear thermal calculation codes for light water reactors and fast reactors.

5.1 Core nuclear calculation code

When designing light water reactors and fast reactors, analyses are performed for each fuel assembly, which corresponds to the fuel block for HTGRs. However, for HTGRs, neutronic behavior is evaluated for each fuel pin, since calculation accuracy easily degrades where the fuel block are adjacent to graphite blocks. A deterministic core nuclear calculation code GALAXY-Z, which can handle detailed behavior including thermal feedback effects of each fuel pin in a three-dimensional whole core system, has been developed. To apply GALAXY-Z to HTGRs, features for neutron moderation by graphite and for handling coated fuel particles in fuel compacts, which will be described later, were implemented.

Since fuel used for HTGRs consists of fuel compacts, which are sintered coated fuel particles approximately 1 mm in diameter(6), the fuel compacts contain randomly dispersed coated fuel particles. In order to make a deterministic and efficient evaluation, GALAXY-Z uses homogenized cross-sections in the fuel compacts and spatial distribution effect of the neutron flux due to coated fuel particles in the fuel compacts is considered as a correction factor. Geometry of the reactor, including fuel compacts, were modeled with a heterogeneous spatial mesh as shown in **Figure 6**. A neutron transport calculation method that handles neutron flight directions in detail was adopted, and an acceleration method that improves the convergence of iterative calculations and parallel processing based on the latest computer technology were utilized. As a result, nuclear calculations considering coated fuel particles in HTGRs can be carried out without compromising either analytical accuracy or acceptable computation time.

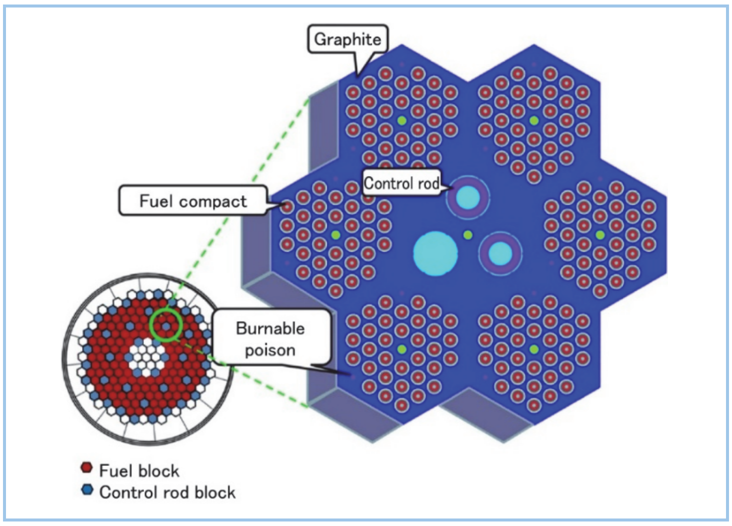

Figure 6 Spatial mesh of core nuclear calculation code

5.2 Core thermal-hydraulic calculation code

In the core thermal-hydraulic design, various calculation codes are usually required for different types of reactor core, that involve the particular physical phenomena relevant to the coolant flow and fuel design. In contrast, the code under development in MHI is aimed to be the universal platform applicable to the arbitrary core thermal-hydraulic evaluation by individually implementing the specific physical models and numerical solution method appropriate to the intended reactor type and physical phenomena. The flexible structure of the code designed by an object-oriented scheme enables easy extensions of the physical models related to flow and heat transfer. The code solves three conservation laws of a fluid (continuity, momentum, and energy equations) in a subchannel system, in which the coolant flow area of the core is modeled as a bunch of subchannels, using a versatile numerical solver based on the Jacobian Free Newton Krylov method, that provides the highly efficient Newton iterative solution method for nonlinear equation system by merging with the Krylov subspace method as a linear system solver(7). Also, the convergence acceleration technics like as physical-based preconditioning are available to enhances the performance for large scale system. For the core thermal-hydraulic calculation of HTGR core, physical models relevant to its core coolant flow and heat transfer were implemented.

The cooling system of HTGR adopting a pin-in-block type fuel consists of the downflow of helium gas introduced from the top of the core and distributed into the fuel block, control rod block, and inter-block gap. Since the helium gas flow through the control rod block and the inter-block gap does not directly contribute to fuel cooling, it is required to evaluate the net flow rate through the fuel block. An example of calculation model for HTGR is shown in **Figure 7**. MHI code evaluates flow distribution and fuel temperature in the HTGR core using pressure drop and heat transfer model based on the HTGR core geometry. Verification and validation is planned in future using the experimental data for the HTTR design.

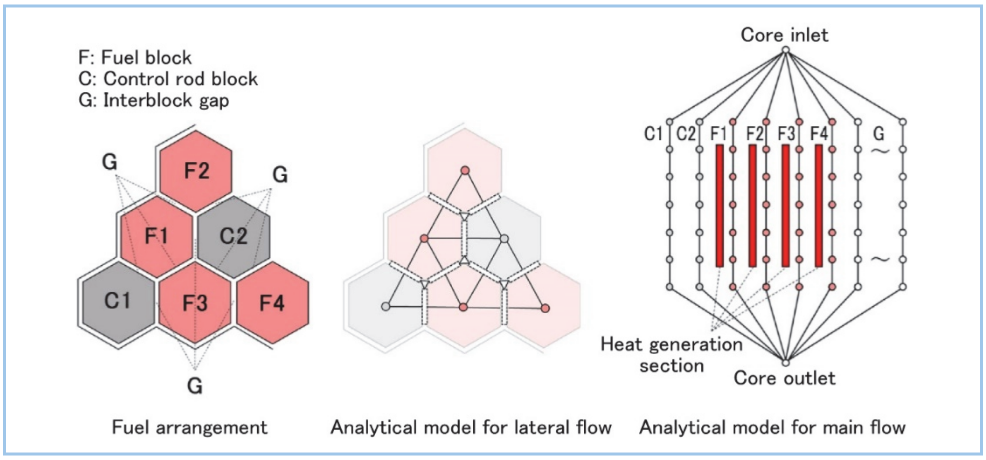

Figure 7 Examples of analytical models for core thermal-hydraulic calculation code

6. Conclusion

In order to achieve carbon neutrality, CO_2 emissions from the industrial field must also be reduced, and a large and stable supply of hydrogen by HTGRs could be an effective means of achieving this.

MHI was selected as a core company in the development of a demonstration HTGR in fiscal 2023, and has been developing a demonstration HTGR for hydrogen production. In order to contribute to this, verification of connection technology with hydrogen production facilities, development of CO_2-free hydrogen production technology connected to HTGR, development of core nuclear heat calculation code as evaluation technology related to HTGR design, etc. are tackled.

MHI will continue to contribute to the realization of carbon neutrality, stable energy supply, economic security, and a recycling-oriented economy (local production for local consumption) through nuclear technology, including the realization of a HTGR for hydrogen production.

In this report, some results from the fiscal 2022 large-scale hydrogen production demonstration project utilizing very high temperature by the Ministry of Economy, Trade and Industry (hereafter referred to as METI) and METI Development Project for Demonstration HTGR Program Grant Number JPMT007141 are included.

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