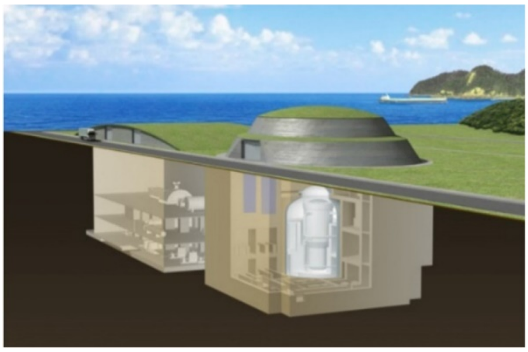
Development of Mitsubishi Innovative Nuclear Reactor toward the future; Small-PWR, High Temperature Gas-cooled Reactor and Micro-Reactor



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Nuclear energy is an effective option for decarbonization, which has significant potential to be utilized in a wide range of industrial fields—not only for the purpose of power generation, but also for heat utilization and other applications. Meanwhile, with respect to the utilization of nuclear energy, operations with both an extremely high level of safety after the Fukushima Daiichi Accident and economic efficiency sufficiently competitive with other energy sources are required. Mitsubishi Heavy Industries, Ltd. (MHI) has been working on the development of the Small Pressurized Water Reactor (Small-PWR), High Temperature Gas-cooled Reactor (HTGR) and Micro-Reactor, positioning them as "future reactors," in addition to conventional large- and medium-scale light-water reactors and fast reactors developed in accordance with the national fuel cycle policy, in order to meet various different needs in the future. This report will introduce three future reactors and their characteristics, advantages, application technologies and other relevant information.

1. Introduction

Utilization of nuclear energy is one effective option for achieving decarbonization, one of the biggest societal needs in recent years. In addition to power generation, nuclear energy has significant potential to be utilized in many other different situations as an alternative to fossil fuels for various purposes such as heat supply (hydrogen production, use in cold districts, etc.) and energy supply to disaster-hit areas, remote areas and islands where fuel supply is problematic. So far, the general trend has preferred large-scale power generation plants, taking advantage of their scale. Recently, however, in addition to large-scale plants, innovative reactors featuring a simple and compact structure have attracted attention due to diverse societal needs such as distributed power supply and heat utilization for the future. These are called Small Modular Reactors (SMRs) and there are several types. MHI positions these innovative types as future reactors and mainly focuses on the development of the Small-PWR, HTGR and Micro-Reactor in accordance with the national policy.

2. Development of MHI Future Reactors

The requirements for future reactors include securing the values (purposes) achieved by their public implementation, economic efficiency to sustain them and above all, safety that provides a sense of security accepted by the general public. In terms of the Small-PWR, HTGR and Micro-Reactor, which MHI positions as our future reactors, we have been working on their concepts and specifications keeping these requirements in mind at all times, while making sure that we secure a certain level of economic competitiveness in comparison with other energy sources.

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After the Fukushima Daiichi Accident, Japan in particular, being an earthquake country, imposed the highest level of seismic resistance requirements and the strictest safety regulations in the world. Achieving both safety and economic efficiency has become even more important. MHI has been working on the development of concepts and specifications acceptable to the society, being constantly aware of these challenges from a very early stage.

3. Small-PWR

In addition to large- and medium-scale nuclear power plants, the current mainstream, the practical application of the Small-PWR is expected to serve as a carbon-free power source available in small-scale grid areas such as emerging countries and areas where transmission grids are not in place. It is also expected to meet the needs for a compact mobile power source available in remote islands and disaster-hit areas, for which we aim to provide a low electrical output of around 300,000 kWe or less. The characteristics of the Small-PWR include (1) achieving the level of safety intrinsic to a small-scale and simplified reactor cooling safety system at the time of an accident and (2) enabling factory production through the adoption of a modular design and thereby shortening the time period required for the on-site construction work.

MHI has been involved in the design, construction and maintenance of our 24 Pressurized Water Reactors (PWRs) in Japan and has been working on the development of various innovative nuclear technologies including small reactors alongside the enhancement of the safety and reliability of our PWRs, as well as the technical development for their long-term use. Small reactor development began with the power reactor for nuclear-powered ship “MUTSU” (1967-1972; The Japan Nuclear Ship Development Agency) before the introduction of light-water reactors. Since then, we started working on the development of a small Integrated Modular Water Reactor (IMR) where we carried out verification tests on the characteristic element technology for small integrated reactors as well as the concept design and accumulated various developmental knowledges. Based on such knowledges, we have been trying to make the most of the proven PWR characteristics through various applications of the unique safety design and modular design of small reactors for different purposes, while having the possible future application as a mobile Small-PWR (reactors onboard ships) in mind, which would meet the needs for a power supply for micro grids such as on remote islands, temporary power supply for disaster-hit areas and marine power, in addition to generating power as a small-grid power source. **Figure 1** illustrates the applications of the Small-PWR development.

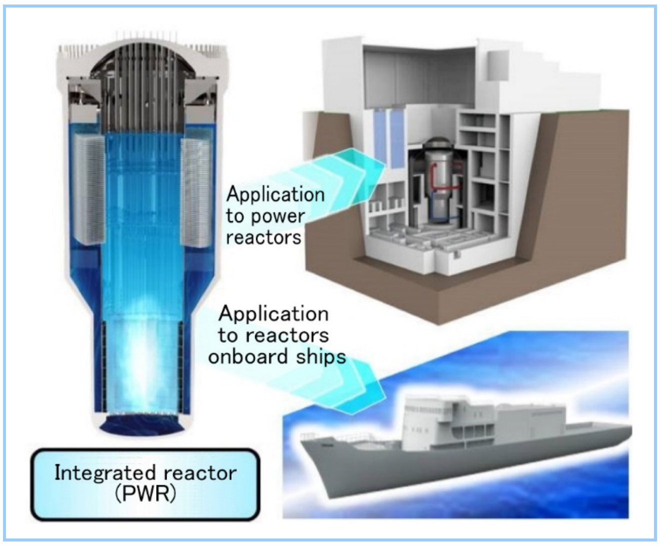

Figure 1 Applications of Small-PWR development

The concept for the Power-Generating Small-PWR and the mobile version is to use an integrated reactor that incorporates main components of the primary system (steam generator, primary coolant pump, pressurizes, etc.) into the reactor vessel and removal of primary coolant piping, thereby in principle eliminating the risk of accidents caused by the loss of coolant due to ruptures in the primary coolant piping. Furthermore, the level of safety and security is improved by taking safety measures that would enable swift accident containment and reactor cooling, taking advantage of the characteristics of low-output reactors. With respect to compliance with the new Japanese regulations introduced in the light of lessons learned from the Fukushima Daiichi

Accident, taking into account our experience in supporting the restart of existing Japan' power plants, we have incorporated the stricter requirements for seismic resistance, measures against natural disasters (external hazards) such as Tsunami and tornadoes—as well as anti-terrorism and intentional aircraft crash measures—in our design. While securing the required level of safety by addressing these issues, the containment vessel has been downsized by making the system configuration and facility design as simple as possible. Moreover, the construction work has been streamlined and the work period has been shortened by utilizing a modular design with latest technologies and advanced construction methods, thereby achieving a significant reduction in the construction cost.

The Mobile Small-PWR is designed to have a one-rank smaller output capacity than power-generating Small-PWRs and can be installed onboard a ship due to the further downsizing of its reactor vessel. Even under the circumstances where a certain level of pitching and rolling inherent to marine operations is expected, the design ensures stable operation, making the most of the PWR advantages. Furthermore, in order to maximize the operability as a mobile power source, we aim to minimize the large-scale replacement of equipment and repair/maintenance on remote islands and to eliminate the need for refueling except for after long intervals.

As explained above, the application of the Small-PWR MHI develops is expected to include utilization as a mobile-orientated power source, which could serve as a shipboard reactor, or marine power, in addition to power-generating purposes in small-scale power grids and off-grid areas. MHI will endeavor to provide carbon-free nuclear energy that can satisfy various needs and purposes in the future.

4. High Temperature Gas-cooled Reactor

The High Temperature Gas-cooled Reactor (HTGR) offers inherent safety features that prevent core meltdowns while supplying heat of over 900°C. It is possible to serve as a high-temperature carbon-free heat source with stable supply that can be used not only for conventional power generation, but also for other purposes including hydrogen production.

Toward decarbonization, Japan has set a long-term goal of reducing greenhouse gas emissions by 80% by 2050, for which CO_2 reduction has been required not only in the power generation fields, but also in other industrial fields. For example, the Japanese steel industry has established a goal called "CO_2, Ultimate Reduction in Steelmaking Processes by Innovative Technology for Cool Earth 50 (COURSE50)" that will be pursued toward its planned practical use in the 2030s. Beyond that in the future, the industry is targeting a shift to hydrogen reduction steel-making as an ultra-innovative technology for achieving zero carbon. In terms of the future practical use of hydrogen reduction steel making, there are significant expectations for hydrogen supply powered by nuclear energy from the aspects of large volume, low cost and stable supply.

Japan's HTGR development has been led by the Japan Atomic Energy Agency (JAEA) (the former Japan Atomic Energy Research Institute), which began research and studies on HTGR. In 1991, the construction of the High Temperature Engineering Test Reactor (HTTR) started for the first time in Japan. In 1998, the first criticality was achieved and in 2004, full-power operation at a helium exit temperature of 950°C was achieved. Further safety validation tests have been carried out where the supply of high temperature nuclear heat by the HTGR and its inherent safety have been demonstrated.

MHI joined this research and development for HTTR construction at an early stage, where, as an organizer leading four design companies, MHI has been engaged in HTTR plant engineering and the design/production of nuclear reactor containment vessel, primary coolant systems and high temperature piping. Since then, as part of the development of element technologies toward the practical use of HTGR, MHI has been involved in the development of an ultra-dense plate-fin heat exchanger and high temperature isolation valve, as well as design studies for a gas turbine high temperature reactor (GTHTR300 : Gas Turbine High Temperature Reactor of 300 MWe) in collaboration with JAEA. In terms of hydrogen production systems, MHI also has a proven track record in the design studies for an HTTR linked hydrogen production system that were conducted in collaboration with JAEA.

Based on these accumulated technologies and experience, MHI is currently working on the development of an HTGR cogeneration plant offering high economic efficiency and operational flexibility that is expected to meet various future societal needs such as decarbonization and a hydrogen society. **Figure 2** demonstrates an HTGR cogeneration plant.

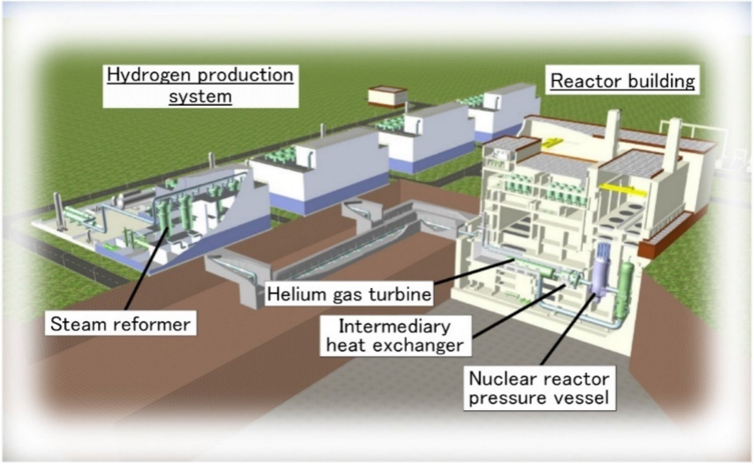

Figure 2 HTGR Cogeneration Plant

This plant carries out the cogeneration of hydrogen production and power generation with the reactor exit temperature at 950°C, utilizing our technologies acquired through the construction of the HTTR. Nuclear power plants generally have rather high initial costs due to the construction, even if the fuel cost is quite low. Therefore, it is desirable to operate reactors at the rated electrical output since the plant utilization rate needs to increase in order to recover the capital investment. This cogeneration plant maintains the balance between electrical output and hydrogen production in accordance with fluctuations in demand for hydrogen and power supply. It is designed to boost the utilization rate by keeping the reactor power at a certain level, while taking coexistence with renewable energy into account.

The high reactor exit temperature of 950°C is expected to boost efficiency in both hydrogen production and power generation. In particular, it is also designed to achieve higher efficiency than the Rankine cycle using a steam turbine by utilizing a helium gas turbine directly for the primary system for power generation.

In terms of safety, based on the inherent level of safety that has been demonstrated in the HTTR, the safety level will be validated through a series of analyses after examining MHI's original fuel/reactor core design and structure, in order to maintain the same level of safety even with a scaled-up reactor power.

With respect to the hydrogen production technology, the steam reforming process is applied first for the purpose of demonstrating hydrogen production powered by nuclear energy. Based on this demonstration of the HTTR, we aim to a power plant that is capable of the stable mass production of low carbon hydrogen. This plant aims to achieve a hydrogen production volume of 120,000 Nm^3/hr (more than 900 million Nm^3/hr annually) with approximately 220MWt of thermal. We also assume the practical use of various carbon free hydrogen production methods after 2050, such as the high temperature steam electrolysis process and iodine sulfur process, and aim to achieve the stable mass production of carbon free hydrogen at the HTGR cogeneration plant to which these hydrogen production facilities are linked. In terms of economic efficiency, we aspire to accomplish low cost hydrogen production enabled by nuclear heat utilization while securing high power generation efficiency achieved through the simplification/optimization of safety systems supported by the inherent level of safety, simple system configurations where a helium gas turbine is applied directly to the primary system, high-efficiency power generation with high temperature helium gas and reduced construction costs by utilizing a modular design. As described so far, MHI intends to work on research and development toward the practical use of the HTGR cogeneration plant in collaboration with users in the steel industry who intend to switch to hydrogen reduction steel making, while coordinating with decarbonization promoted under the national policy and efforts in the industry such as the innovation for realizing a hydrogen society.

5. Micro-Reactor

The Micro-Reactor has an even smaller output level and size than regular small reactors. It is one of the viable options that is capable of providing new value different from what existing onshore power reactors can offer, with the portability based on its inherent safety. MHI is developing a multi-purpose modular Micro-Reactor intended for use as a power/heat source in off-grid areas, energy stockpiling, etc., as shown in **Figure 3**.

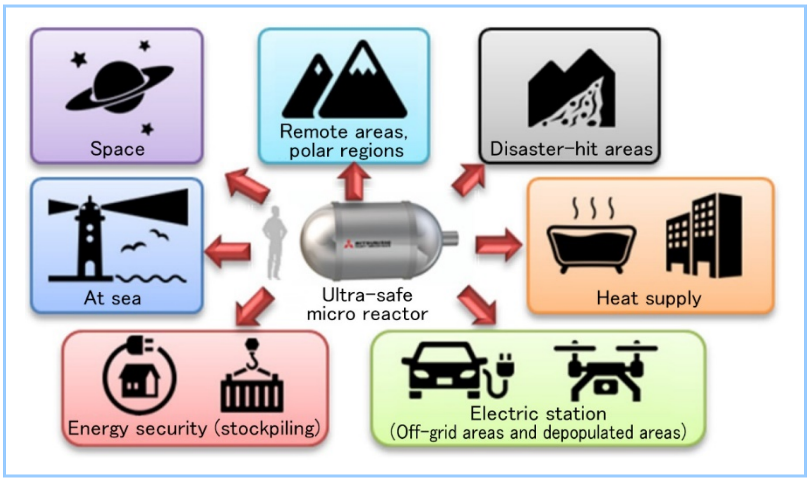

Figure 3 Applications of Micro-Reactor

In order to respond to the purpose of a multi-purpose use and its installation environment, the Micro-Reactor is placed in a location close to the general public compared with existing large-scale reactors. Therefore, for the practical use of the Micro-Reactor, the most important thing is to pursue the ultimate level of safety as the basic development principle, from the perspective of protecting the general public and the environment from the impact of radiation due to its use. In terms of existing reactors, the risk of radioactive substance leak increases the most when the reactor coolant is lost due to an accident. In order to fundamentally eliminate such an accident factor, the Micro-Reactor utilizes the concept of "an all-solid-state reactor" where a liquid coolant is not used. The all-solid-state reactor uses a highly thermal conductive graphite-based material for the core structure that transfers the core thermal energy to the power generation system. This concept can fundamentally eliminate accidents attributable to liquid coolants, significantly improve reactor safety and reduce the impact of radiation on the general public and the environment. Even if an accident occurs, because of the small output and highly thermal conductive graphite-based material, natural air cooling is sufficient to remove the decay heat in a stable manner. In other words, it is designed to prevent the kind of fuel-melting accident like the one that occurred at the Fukushima Daiichi Accident. In addition, the design enables unmanned automatic operation by this inherent safety and simple control system. Furthermore, in order to achieve a long-life core that requires no fuel exchange, HALEU (High-Assy, Low-Enriched Uranium) fuel with uranium enrichment of up to 20% is used.

The Micro-Reactor is expected to have a maximum output of 1MWt per module, for which multiple units are available depending on the scale of demand. A factory production line is intended for manufacturing where cost reduction is possible due to mass production. Furthermore, the reactor is made lighter in weight by making the maximum use of the graphite-based material that can reduce the weight by as much as 70% of metallic materials, making the reactor transportable by truck. Plans call for the reactor core to be downsized as much as possible by utilizing HALEU fuel. All the reactor core and power generation systems are intended to fit into a 40ft international marine cargo container. **Table 1** shows the specifications of the development plan for the Micro-Reactor.

As described above, MHI will continue working toward the implementation of the portable modular Micro-Reactor in order to create new value for reactors that will meet various different future needs.

Table 1 Proposed primary specifications for Micro-Reactor

Item	Specifications
Reactor type	High-thermal-conductor-cooled reactor (All-solid-state reactor)
Core structure	Graphite material
Thermal output	Up to 1MWt
Electrical output	Up to 0.5MWe
Operation control	Unmanned automatic operation
Safety/Final heatsink	Static decay heat removing system (Natural air cooling)
Portability/Size	International marine cargo container

6. Further prospects

MHI will continue discussions with the government and various business operators regarding the development of our future reactors and proceed with design studies so that our plants will match the needs of our customers.

7. Conclusion

As part of nuclear energy technologies to enable the decarbonization demanded by society, MHI considers the development of the Small-PWR, HTGR and Micro-Reactor to be an important step in preparing to meet the future needs of society. All of these technologies have significant potential for implementation in society, taking advantage of their individual unique features in addition to conventional power generation applications. We will continue discussions with our service providers and move forward with development. We also believe that the individual innovative technologies need to be verified and that it is necessary to continue seeking to ensure safety and security while realizing economic competitiveness. With regard to safety regulations, we hope that discussions over regulations suitable for their low-output and innovative safety concepts that differ from conventional large- and medium-scale reactors will be held soon.

References

(1) Kazumasa Suyamaet al., Development of Small Modular LWRs for Multi-Purpose Use Development goals and plant concept, The Atomic Energy Society of Japan 2020 Fall Meeting, 1I05.

(2) Kazumasa Suyama et al., Development of High Temperature Gas cooled Reactor cogeneration plant (hydrogen production and power generation) without core melting, The Atomic Energy Society of Japan 2020 Fall Meeting, 1K08.

(3) Tadakatsu Yodo et al., Development of Mitsubishi multi-purpose modular ultra-safety micro reactor, The Atomic Energy Society of Japan 2020 Fall Meeting, 2I07.