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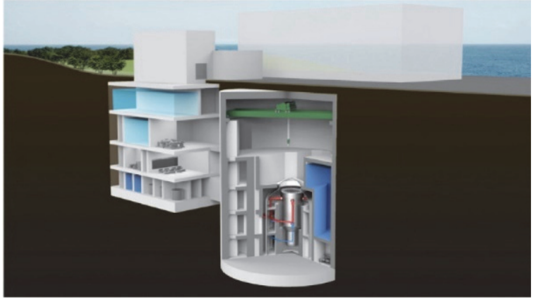
Development of Small PWR to Meet Diverse Needs for a Carbon Neutral Society



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Nuclear energy is a promising option for decarbonization and has the potential to be used not only for power generation but also for a wide range of other applications, including heat utilization and hydrogen production. On the other hand, the use of nuclear energy requires an extremely high level of safety in the wake of the Fukushima Daiichi Accident. Mitsubishi Heavy Industries, Ltd. has been developing small-PWR, which are advanced and capable of meeting various needs of the future. This report presents the concept, technical characteristics, and related technologies of small-PWR for power generation with high safety features.

1. Introduction

In order to realize a carbon-neutral society, the use of nuclear power generation, which can provide a stable energy supply, is desired. In Japan, large-scale power plants have been favored due to their advantages, such as unit cost of power generation and the so-called economies of scale. However, the needs of society are expected to diversify in the future, including use as off-grid power sources, and small reactors, which have the advantage of a relatively short construction time due to their simple and compact structures, are attracting attention. With small reactors, the area affected in the event of an accident is considered to be smaller due to their smaller power output. In addition, since innovative concepts that take advantage of their small size can be incorporated, further improvement in safety compared to that of conventional nuclear power plants, can be sought. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) is developing small Pressurized Water Reactor (PWR), which are innovative PWRs that can meet the diverse needs of the future.

2. Background of development

In the 6th Basic Energy Plan, nuclear power generation is positioned as a baseload power source for the future and is expected to be a practical decarbonization option. In addition, nuclear power is positioned as a quasi-domestic energy source, and generation of nuclear power utilizing Japanese technology is also important from the standpoint of energy security. Under these circumstances, having a plant with a high level of safety developed from an innovative concept that takes advantage of its small size is considered desirable as an option to meet the various demands of society in the future. Therefore, MHI started to develop an innovative small-PWR in FY2019, utilizing the design, fabrication, installation, inspection, and maintenance technologies of PWRs cultivated by MHI over many years. In this development, MHI is collaborating with research institutes, universities, and electric power companies to study the practical use of small-PWRs with the assistance of the Japanese government.

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3. Small-PWR concept

Seeking practical application of small-PWR in the 2040s, future social and energy situations were analyzed and the concepts required for a plant with an electrical output of 300MW class were considered as follows.

(1) Social acceptability

While ensuring a high level of safety in nuclear power generation has always been required, since the Fukushima Daiichi Accident, an even higher level of safety and reliability is demanded. Safety of small-PWR can be increased by adopting a structure (integrated reactor) that eliminates accident factors such as loss of coolant, employing airplane crash protection by locating important facilities such as the reactor building underground, and strengthening the radioactive confinement function of the reactor building, etc., thus achieving a more socially acceptable plant.

(2) Location flexibility

Since the output power of a small reactor is small, a passive safety system that uses natural forces such as gravity injection instead of dynamic devices (pumps, etc.) can also be employed for containment in the event of an accident. The atmospheric air can be used as the final heatsink instead of seawater, eliminating the need for a seawater system as the safety system, resulting in a higher degree of plant location flexibility, including the possibility of construction on high ground within the power station site.

(3) Economic efficiency

While economies of scale tend to become less favorable as the output scale becomes smaller, MHI aims for a competitive economic efficiency with the small-PWR by reducing the number of dynamic components, a smaller footprint, and application of advanced construction methods.

4. Major technical characteristics of small-PWR

4.1 Integrated reactor

Current PWR plants generally have a loop-type configuration where the primary components including the reactor vessel (hereinafter referred to as RV), steam generator (hereinafter referred to as SG), and reactor coolant pump (hereinafter referred to as RCP) are connected by piping with a large diameter. However, a small reactor has a smaller power output, and each component can be designed to be compact. Furthermore, in the small-SWR, an integrated reactor, these components are built into and integrated within the RV, is adopted. This integration of the main components eliminates the need for a large-diameter loop piping (main coolant pipe, hereinafter referred to as MCP) and essentially removes the risk of loss-of-coolant accidents due to MCP rupture. As a result, consideration of accident response equipment is not needed. The structural concept of the integration of the main components is shown in **Figure 1**.

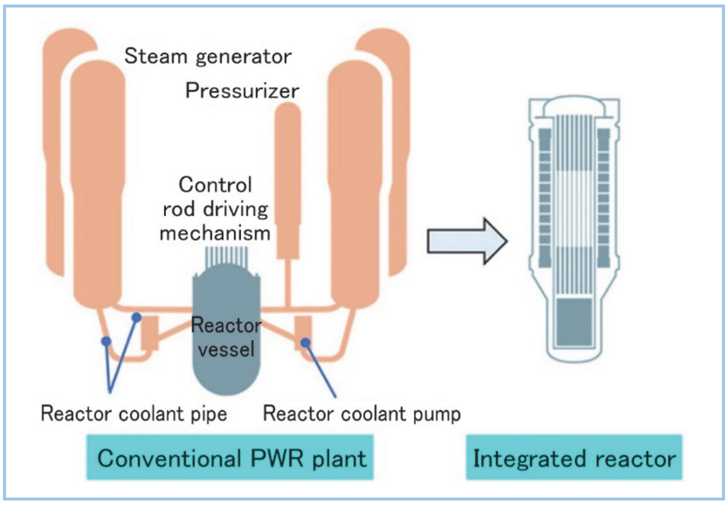

Figure 1 Structural concept of the integration of main components

Structure of the integrated reactor is shown in **Figure 2**: the fuel assembly is housed in the lower part of the RV, while the control rod driving mechanism (hereinafter referred to as CRDM), and the once-through SG, which generates steam to the secondary side, are installed in the upper part of the RV.

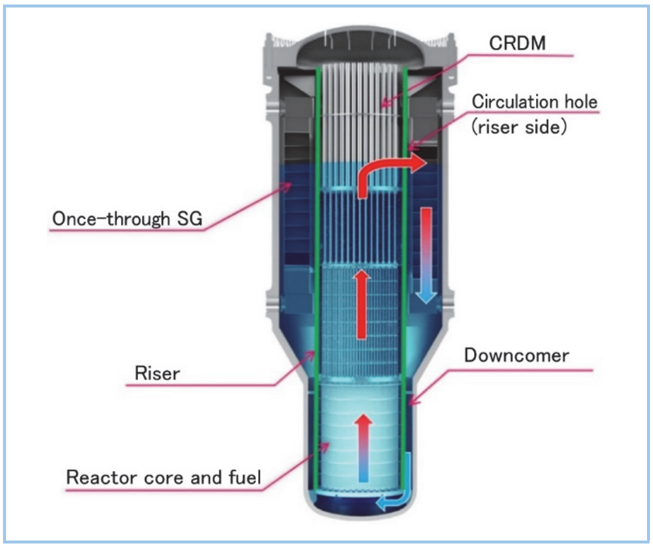

Figure 2 Reactor integrated with the main components

4.2 Two-phase natural circulation cooling

The reactor coolant flow is generated by the driving force from natural circulation. The reactor coolant is heated in the core loaded in the lower part of the RV and rises inside the riser, a cylinder above the core, heat is transferred to the secondary coolant via SGs outside the riser, the coolant descends as it is cooled, passing through the downcomer, an annular section in the lower part of the RV, and then flow back to the core. When the driving force of natural circulation is used for the primary system, the RCP, which required for forced circulation, is no longer needed, resulting in the essential elimination of several accident scenarios, such as RCP locked rotor and reactor coolant leakage from the RCP seal.

Flow rate in a natural circulation system is determined by the balance between the driving force due to water head difference and resistance due to pressure drop. Water head difference is caused by the difference in density of the reactor coolant between core side (hot side of the primary system) and downcomer side (cold side of the primary system). Furthermore, when two-phase flow is used for reactor coolant circulation, density difference increases significantly and a higher flow rate can be achieved compared to single-phase flow, and as a result, the specified heat output can be achieved.

4.3 Passive safety system

Small-PWR actively utilize passive safety systems in their accident response equipment to respond to anticipated accident events, resulting in improved safety.

(1) Passive SG cooling system

In the event of an accident in a small-PWR, decay heat is removed by a stand-alone direct heat removal system (hereinafter referred to as SDHS), which is a passive SG cooling system. The basic concept of the SDHS, consisting of a closed circuit connecting the SG built into the RV and the static SG cooler, which releases heat directly into the atmosphere via piping, is shown in **Figure 3**. The static SG cooler is installed submerged in the cooling tank and is in standby mode, disconnected from the operation line during normal operation. However, when an abnormality occurs, steam generated in the SG is sent to the heat transfer tube of the static SG cooler. The steam is cooled and condensed, and condensate returns to the SG by gravity. In other words, the drive of this SDHS is achieved by natural circulation (using gravity) caused by density difference of the cooling water itself. In addition, the static SG cooler is used in the early phase after an accident occurs while the decay heat level is still high, and cools by boiling evaporation of the cooling tank water. When the cooling tank water runs out due to evaporation, an air channel is formed for air cooling, and air is supplied from the air intake by natural convection, providing long-term air cooling and thereby enhancing safety. As described above, the SDHS is a completely stand-alone safety system and does not require external energy or physical support from the outside.

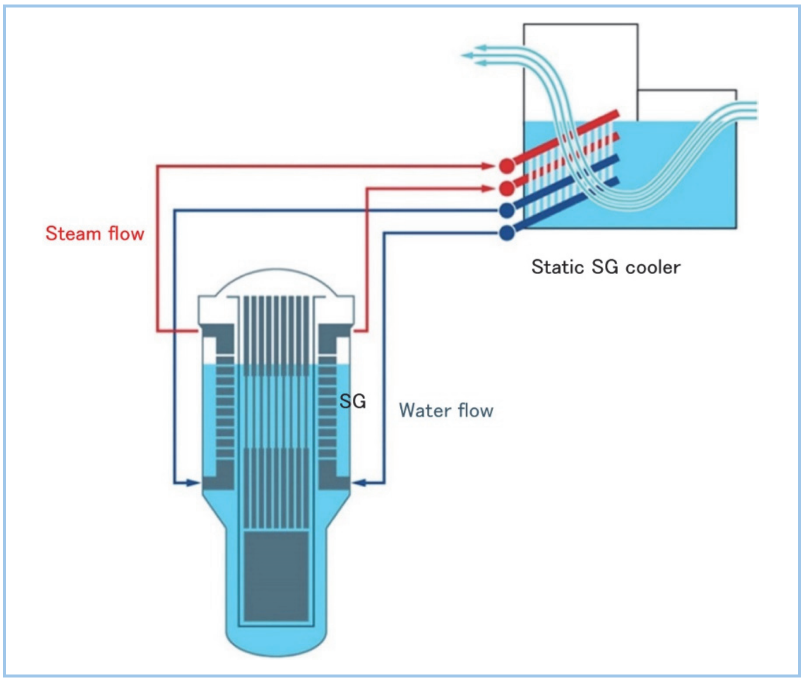

Figure 3 Basic conceptual diagram of SDHS

(2) Passive core injection cooling system

The basic concept of the passive core injection cooling system of the small-PWR is shown in **Figure 4**. This system is a static core/Containment Vessel (hereinafter referred to as CV) cooling system for multiple failures in the event of an accident (loss of SG functions and, at the same time, the passive SG cooling system is not functioning is assumed). Cooling water is stored in the plant in advance and the RV and inside the CV are cooled without human intervention using gravity or a driving force independent of dynamic equipment such as nitrogen pressurization to prevent core damage and CV failure(1).

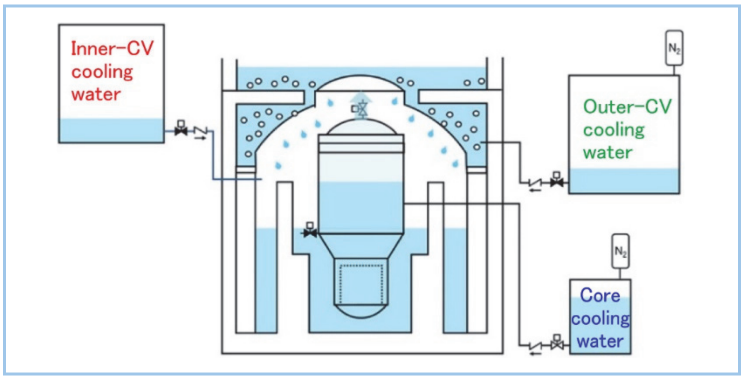

Figure 4 Basic concept of passive core injection cooling system

4.4 Underground location of the reactor building

The small-PWR has a reactor building to house the RV and CV, and an auxiliary reactor building to house the central control room and other equipment critical for safety.

The primary cooling system of the small-PWR is greatly simplified compared to conventional PWRs due to the adoption of a structure where the main components are integrated. Consequently, the size of the reactor building to house the RV and CV can also be much smaller than that of a conventional PWR, allowing the entire reactor building to be constructed underground. The surrounding ground is used as a barrier, and a very high level of resistance to external hazards, such as large aircraft collisions and tornadoes, can be expected. In addition, by installing equipment critical to safety in the auxiliary reactor building at basement level, a high level of resistance to external hazards can be expected, similar to the reactor building. Exterior walls of the underground buildings are strong enough to withstand ground pressure at all times, including earthquakes, etc. In addition, by constructing the reactor building and other equipment underground, the effect of seismic movement on the building and equipment is expected to decrease, and seismic resistance can be ensured even in locations where high seismic movement is predicted.

Countermeasures for a tsunami can be either dry-site installation (setting the site at a level higher than the reference tsunami height) or permanent external barriers such as levees, seawalls, and bulkheads, depending on the corresponding site conditions.

4.5 Enhancement of radioactive material confinement function

The reactor of the small-PWR is integrated with the main components installed in the CV and functions to contain radioactive materials in the CV in the event of an assumed accident. This CV is a hybrid type that uses high-strength steel plates. As a characteristic of a hybrid-type CV, the CV cylinder and dome are made of high-strength steel plates to secure pressure and leakage resistance. The CV bottom ensures pressure resistance with the foundation plate and leakage resistance with the bottom liner. As a result, the CV itself can be downsized while maintaining high pressure resistance and leakage resistance.

To further enhance the radioactive confinement function, even in cases where safety functions are lost and CV pressure limit is exceeded due to an event exceeding design standards or a severe accident, atmosphere in the CV is discharged into a compartment with a confinement function located outside the CV, as shown in **Figure 5**. This compartment, located outside the CV, can cool the atmosphere for long term dethermalization and depressurization of the compartment by vapor condensation of gases and contraction of non-condensable gases released from inside the CV, thereby preventing damage to the CV and the release of large amounts of radioactive materials into the surrounding environment.

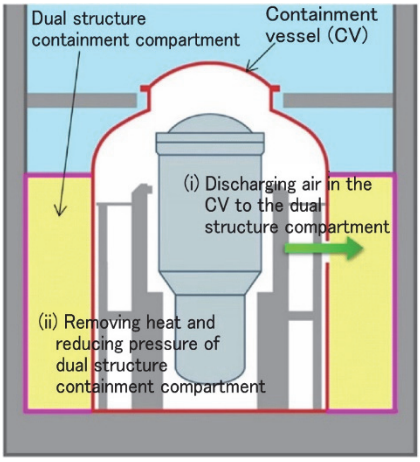

Figure 5 Radioactive material confinement function

4.6 Compliance with domestic regulatory standards

The small-PWR is developed in consideration of new regulatory standards established after the Fukushima Daiichi Accident. Ensuring safety through a static safety system that does not rely on dynamic components is planned. In addition, as a countermeasure against external hazards, earthquake resistance of the building meets the harsh seismic conditions of Japan. For practical application of the small-PWR, further discussions with related organizations, including academic societies, on regulatory standards for small reactors, especially with regard to characteristic safety features of small reactors that essentially eliminate accidents compared to existing plants will be conducted.

4.7 Advancement of construction methods

Regarding construction of the small-PWR, pre-fabrication or pre-cast construction methods, which have been achieved in fields other than nuclear power plant construction, will be utilized to shorten the construction period and reduce the on-site construction costs. In addition, advanced construction methods such as the continuous underground wall method(2) will be used to offset the increase in construction costs incurred by underground installation of critical facilities as a measure against external hazards.

In addition, since the main-components are integrated in the small-PWR, the primary system components can be manufactured as a unit at a factory. This unitization of the integrated reactor leads to a reduction in the degree of on-site work and a shorter construction period.

5. Related technologies

5.1 Mobile small-PWR

Based on the expertise regarding power plants described in the previous chapters, the mobile small-PWR is an integrated reactor with an electrical output in the 30,000 kW class. As one of the multi-purpose needs of the future, it is designed for installation on a ship. The concept of installation on a ship, such as a nuclear power generation ship, is shown in **Figure 6**. It is used to supply power to off-grid areas such as remote islands and isolated areas, provide emergency power supply, used in seawater desalination, a heat source in disaster areas, or a number of other purposes.

This mobile small-PWR is designed to operate stably even under environmental conditions assume offshore operations, such as swaying and tilting on the water. In addition, in order to maximize the operability as a mobile power source, minimizing maintenance and eliminating the need for fuel replacement by using long-life fuels such as uranium nitride are planned.

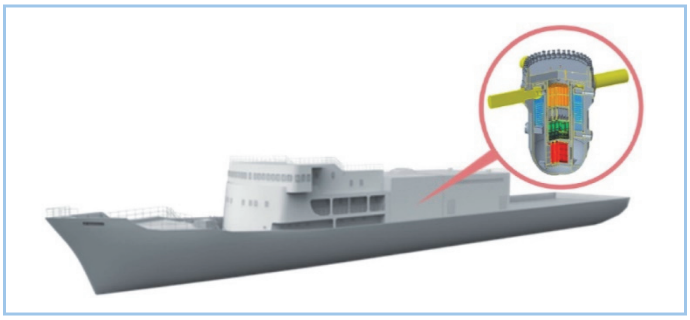

Figure 6 Mobile small-PWR (shipboard installation)

5.2 Uranium nitride fuel

Uranium nitride fuel is suitable as a long-life fuel due to its higher uranium filling density than that of uranium dioxide fuel, and has the safety advantage to suppress fuel temperature especially in the event of an accident due to its high thermal conductivity. On the other hand, uranium nitride fuel is known to be highly reactive with water at high temperatures, leading to oxidation and grain fragmentation. Consequently, knowledge related to its application and to water reactors in general is scarce.

Due to its excellent features as a nuclear fuel, MHI has been considering methods to control uranium nitride fuel’s high reactivity with water, which has been an issue, with a view to application in mobile small-PWRs in the future and has been working on an additive uranium nitride fuel. Also in this effort, various samples of uranium nitride fuel were reacted with steam, and the effect of additives to control uranium nitride fuel’s reactivity with water was evaluated by measuring the degree of reaction. As a result, the possibility that the addition of carbon may control uranium nitride fuel’s reactivity with water was indicated(3).

With a method to control uranium nitride fuel’s high reactivity with water by adding additives in mind, MHI plans to continue research and development, including steam reaction tests, post-test analysis, and computational science studies, in order to further investigate the detailed mechanism and fuel specifications needed to control uranium nitride fuel’s reactivity with water by the addition of carbon.

6. Conclusion

MHI has been developing a small-PWR with excellent safety features and competitive economic efficiency as an innovative PWR to meet various needs of the future. Aiming for practical application in the 2040s, MHI is currently working on forming plant specifications, and establishing a plan to test underlying technology. MHI will continue toward practical application in collaboration with electric power companies, research institutes and suppliers, and promote development and demonstration tests of innovative technologies with the support of the Japanese government.

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