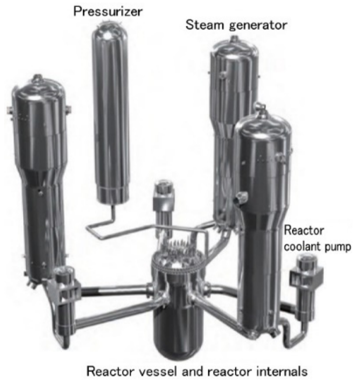
Advanced Light Water Reactor "SRZ®-1200" Development of Primary System Major Components for Improvement of Safety, Reliability and Economic Efficiency



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The advanced light water reactor SRZ-1200 is a 1,200-MW-class power reactor that is designed to provide a stable energy supply for Japan in the future, has greater safety than conventional pressurized light water reactors and is being developed based on new regulatory standards reflecting what has been learned from the Fukushima Daiichi Accident, to improve safety, reliability and economic efficiency. To achieve this, the reactor vessel and reactor internals, which are some of the primary components, adopt a top mounted in-core instrumentation system, and reduce the volume of the reactor vessel's lower part to improve plant safety. The steam generator adopts 3/4-inch heat transfer tubes and high-performance small-size primary separators and a secondary separator, and has improved reliability and economic efficiency by developing enhanced evaluation methods for flow-induced vibration and seismic resistance of the heat transfer tubes. The pressurizer adopts a large-capacity heater to reduce the total number of heaters by half to reduce the number of penetrations, and has a lower overall height to achieve a lower center of gravity and higher rigidity, thereby improving reliability.

1. Introduction

A reactor vessel and reactor internals house the core and control rod clusters necessary for power control, and form a flow path of reactor coolant. A steam generator is a component that generates high-temperature and high-pressure steam to drive the steam turbine for power generation by transferring heat generated in the reactor core from the reactor coolant to the secondary coolant. The pressurizer maintains equilibrium between the liquid and gas phases under saturated conditions in the pressurizer and controls the pressure in the primary system. As such, these components are required to have particularly high safety and reliability among the primary components. This paper presents the component specifications and design features of the reactor vessel and reactor internals as well as the steam generator and the pressurizer, which were newly designed from the viewpoints of improving safety, reliability, and economic efficiency for the realization of SRZ-1200, and the efforts made to verify the design.

2. Features of primary components of SRZ-1200

As a reactor type that combines the world's highest level of safety with economic and operational efficiency, the SRZ-1200 is being designed and developed to improve reliability, taking into account the balance between reliability and economic efficiency, by retaining the highly reliable design of the primary components that have been proven in existing nuclear power plants and adding improvements based on operating experience and the latest expertise. The features of the primary components are as follows, and are summarized in the following chapters.

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(1) Reactor vessel and reactor internals (see Chapter 3)

Based on the design of the existing 1.2-MW-class standard four-loop plant with extensive operation experience, a top mounted in-core instrumentation system (hereinafter referred to as ICIS) is adopted and the volume of the reactor vessel's lower plenum is reduced, thereby improving plant safety. In addition, by adopting a three-loop configuration while loading the same 193 fuel assemblies as the standard four-loop plant, the construction cost is rationalized.

(2) Steam generator (see Chapter 4)

To achieve the output of the existing standard four-loop plant with three loops, the SRZ-1200 requires a larger heat exchange capacity per steam generator. To realize a high-performance and small-size steam generator with such a larger capacity, 3/4-inch heat transfer tubes, high-performance and small-size primary separators and a secondary separator are adopted, and the evaluation methods for flow vibration and seismic resistance of the heat transfer tube are enhanced to improve reliability and economic efficiency.

(3) Pressurizer (see Chapter 5)

The SRZ-1200 uses large-capacity heaters to reduce the total number of heaters installed in the pressurizer, thereby reducing the number of penetration points and the risk of leakage. In addition, the overall height is reduced by enlarging the inner diameter, resulting in a lower center of gravity and higher rigidity thereby improving seismic resistance.

3. Development of reactor vessel and reactor internals

The reactor vessel is made of low alloy steel and a vertical cylindrical structure with a hemispherical-shaped top and bottom head (**Figure 1**). The closure head of the reactor vessel is bolted to the vessel shell with a flange. The reactor vessel houses fuel assemblies, reactor internals, control rod clusters, and other core auxiliary components. The reactor internals in the reactor vessel consist of the lower reactor internals, which houses the fuel assemblies, and the upper reactor internals, which supports them from above (Figure 1). The reactor internals have functions such as supporting the fuel assemblies in the core region and forming flow paths for reactor coolant. Each of the elemental technologies is outlined below.

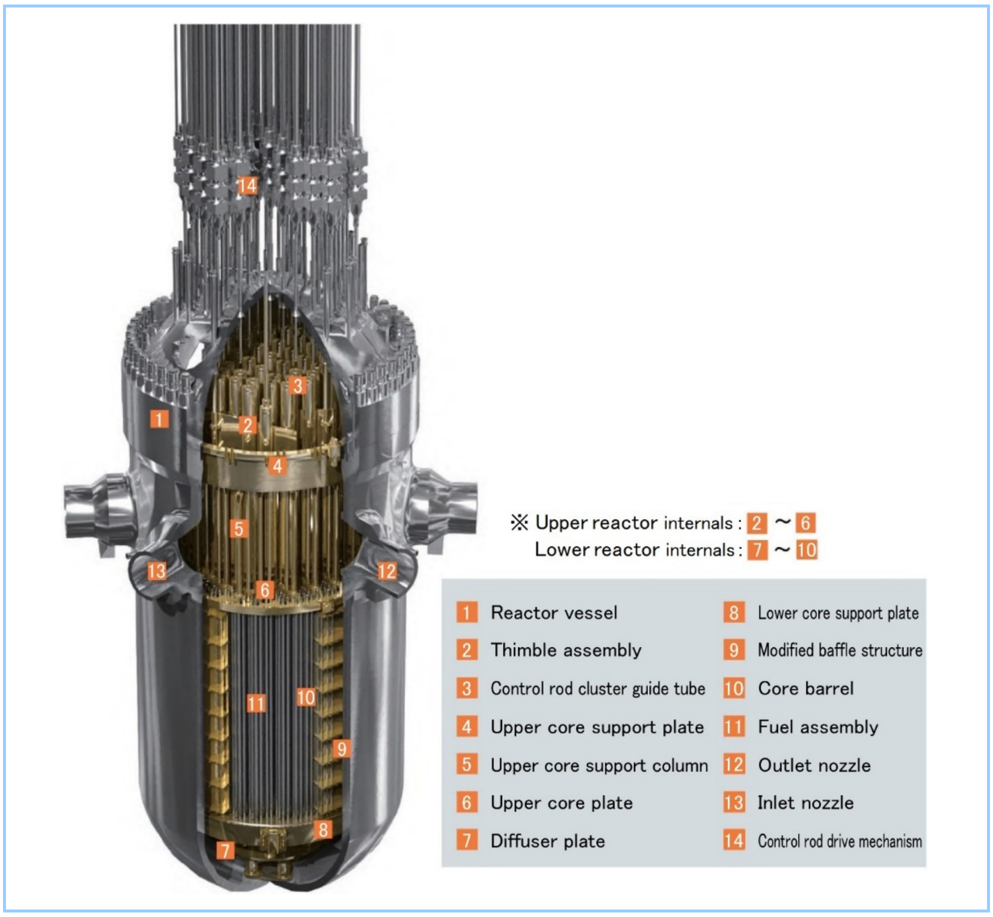

Figure 1 Reactor vessel and reactor internals

(1) Adoption of top mounted ICIS

The SRZ-1200 has a new design in which the in-core neutron detector is inserted from the reactor vessel's upper part, instead of the conventional design in which the detector is inserted from the reactor vessel's lower part, thereby eliminating the penetration at the bottom of the reactor vessel to reduce the potential risk of reactor coolant leakage. To achieve this, a thimble assembly (**Figure 2**), one of the reactor internals, is being developed.

The thimble assembly (hereinafter referred to as TA) is installed on the upper core support plate and mainly consists of the TA support column and the TA support plate. The in-core neutron detector is inserted from the instrumentation guide nozzle on the reactor vessel's closure head, through the TA support column and TA support plate, and into the guide thimble fixed to the lower end of the TA support plate. TA can protect the in-core neutron detector from reactor coolant flow, which circulates in the top plenum surrounded by the reactor vessel's closure head and the upper core support plate, while guiding the detector from the reactor vessel's closure head penetration to the reactor core. In addition, TA can be easily pulled up from above the upper core support plate together with the in-core neutron detector during outage, thus ensuring ease of maintenance.

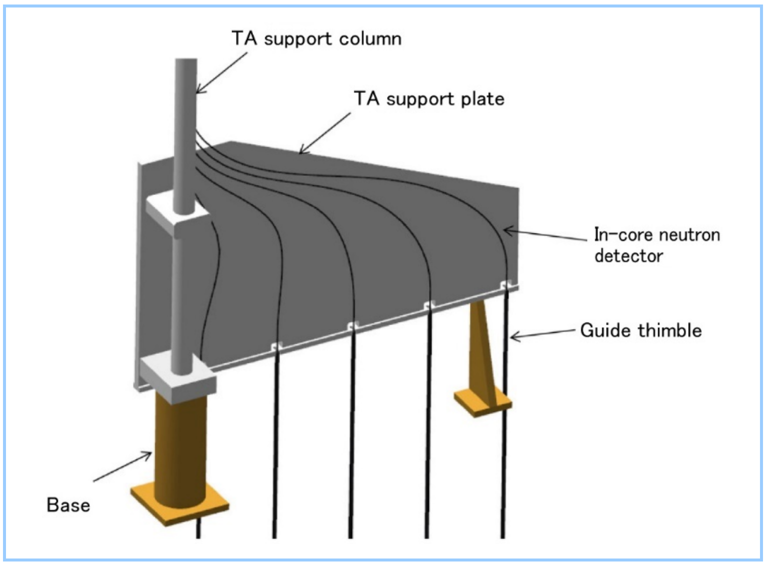

Figure 2 Thimble assembly

(2) Reduction in volume of reactor vessel's lower plenum

The coolant volume in the reactor vessel's lower plenum of the SRZ-1200 is reduced to shorten the water storage period in the lower plenum in the event of a loss of coolant accident, and to reduce the fuel temperature at the start of re-flooding to mitigate progression of the accident. To achieve this, design of the lower reactor internals is optimized and the shape of the reactor vessel bottom head is changed (**Figure 3**)

The existing plant has two plates installed below the core region: the lower core plate and the lower core support plate, which support and position the core and function as a rectifier to properly distribute reactor coolant to the core region. The SRZ-1200 has a lower core support plate that has an orifice in the flow path hole to provide a flow distribution effect due to the flow resistance, thereby enabling the lower core support plate alone to both support the core region and distribute reactor coolant flow appropriately. As a result, the lower core plate (and lower core support column) can be eliminated, and the volume corresponding to the space between the lower core plate and the lower core support plate is reduced. Furthermore, the shape of the reactor vessel bottom head is made flatter than that of the conventional plant by increasing the radius, which was achieved by moving the position of the center of the radius of curvature of the reactor vessel bottom head upward, thereby reducing the volume of the reactor vessel's lower plenum.

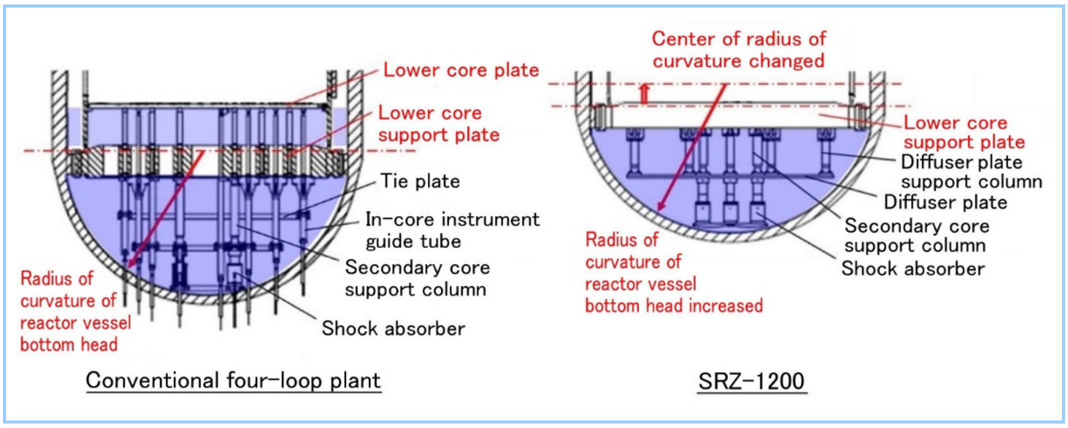

Figure 3　Change of reactor vessel bottom head shape

(3)　Three-loop configuration based on standard four-loop plant

The SRZ-1200 adopts a three-loop configuration while loading the same 193 fuel assemblies as the standard four-loop plant, thus achieving a high-power output for the 1,200-MW-class with a smaller number of loops and improved economic efficiency. To achieve this, the reactor vessel outlet nozzle shape is changed and the lower reactor internals are designed while evaluating the flow inside the reactor vessel using flow analysis (**Figure 4**).

To achieve a reactor coolant flow rate equivalent to four loops with a three-loop configuration, it is necessary to properly rectify the flow distribution before reaching the core region. A diffuser plate is placed in the lower plenum, where the in-core instrument guide structure has been eliminated, to provide flow resistance and disperse and rectify the high-velocity region of reactor coolant flow into the lower plenum, thereby enabling proper distribution of reactor coolant flow to the core region.

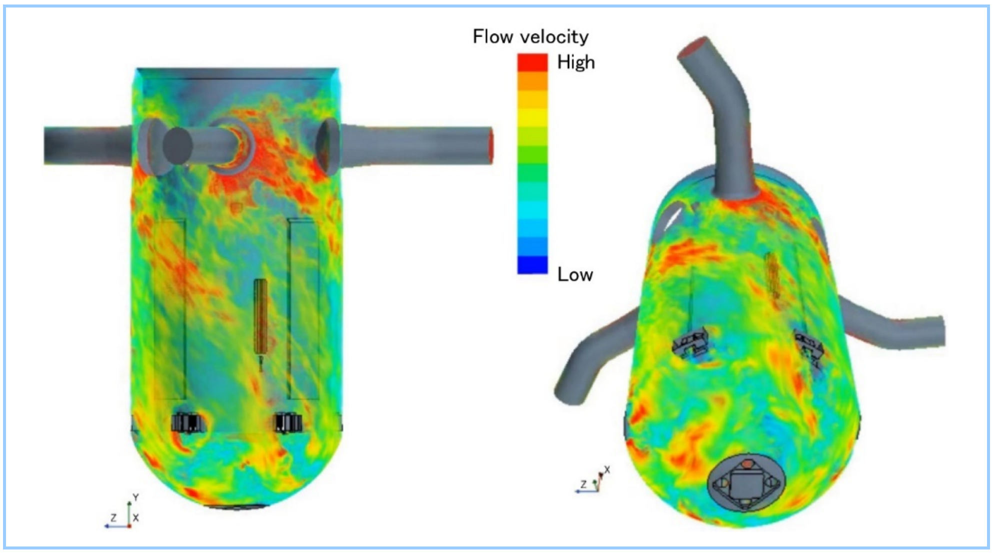

Figure 4　Evaluation of flow inside the reactor vessel using flow analysis

4. Development of steam generator

The steam generator is one of the components of the reactor coolant circulation circuit of a pressurized light water reactor, and is a large heat exchanger that generates high-temperature and high-pressure steam to drive a power generation steam turbine by transferring heat generated in the reactor core from the reactor coolant to the secondary coolant. As shown in **Figure 5**, the lower part of the steam generator contains U-shaped heat transfer tubes for heat exchange, and the upper part of the steam generator contains primary separators and a secondary separator for separating water and steam. Each of the elemental technologies is outlined below.

Figure 5 Steam generator

(1) Adoption of 3/4-inch heat transfer tubes

To suppress the increase in the size of the steam generator accompanying the increase in capacity, it is effective to reduce the diameter of the heat transfer tubes, which improves the heat transfer performance and enables a more compact arrangement of heat transfer tubes, thereby reducing the required heat transfer area and tube bundle size. When using 7/8-inch heat transfer tubes, which are used in existing plants, for larger capacity, the required heat transfer area is approximately 7,500 m^2 per unit. When using 3/4-inch heat transfer tubes, however, the required heat transfer area can be reduced by approximately 1,000 m^2 per unit (more than 10%) to approximately 6,500 m^2.

In addition, to further improve economic efficiency, the required heat transfer area of the SRZ-1200 is rationalized by taking advantage of the experience and scale management knowhow for the secondary system that has been accumulated with existing plants. Throughout operation, scale adheres to the heat transfer tubes on their outer surfaces and decrease their heat transfer performance over a long period during the service life of the plant. Experience and scale management knowhow have been accumulated with existing plants, which enables change in heat transfer performance over time to be delayed through measures such as the improvement of secondary water treatment. The SRZ-1200 utilizes this experience and knowhow to rationalize the required heat transfer area assuming the implementation of measures to prevent change over time. As a result, the required heat transfer area is approximately 6,100 m^2 per unit when combined with the use of 3/4-inch heat transfer tubes, achieving a size reduction of approximately 1,400 m^2 per unit (approximately 20%) in total (**Figure 6**).

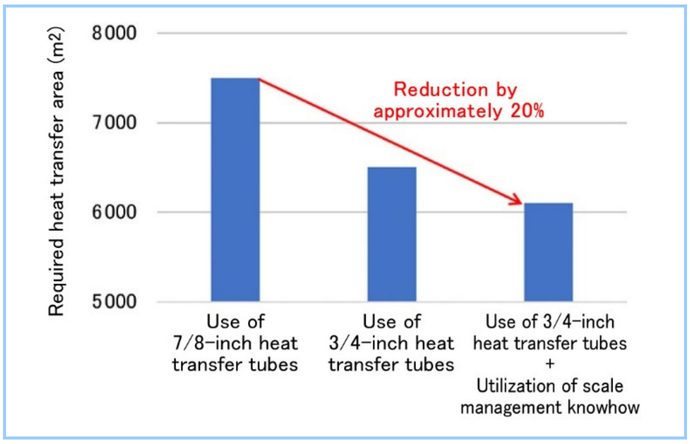

Figure 6 Reduction in required heat transfer area by using 3/4-inch heat transfer tubes

(2) Adoption of high-performance small-size primary separators and secondary separator

As the steam flow rate increases, the load on the primary separators and secondary separator increases, causing the steam moisture content to increase. A small increase in moisture content will not have a significant impact. However since the tendency of moisture increase becomes remarkable when steam flow rate exceeds certain threshold, which may affect plant performance and turbine integrity, it is necessary to enhance the moisture separation performance to deal with the increase in steam flow rate. As shown in **Figure 7**, the SRZ-1200 uses a larger number of small-size and high-performance primary separators (20 units) and a single-stage secondary separator instead of the large-size primary separators (3 units) and two-stage secondary separator used in the existing plant to improve moisture separation performance. By feeding steam with less moisture to the turbine, the reliability is improved in terms of the plant performance and the turbine integrity.

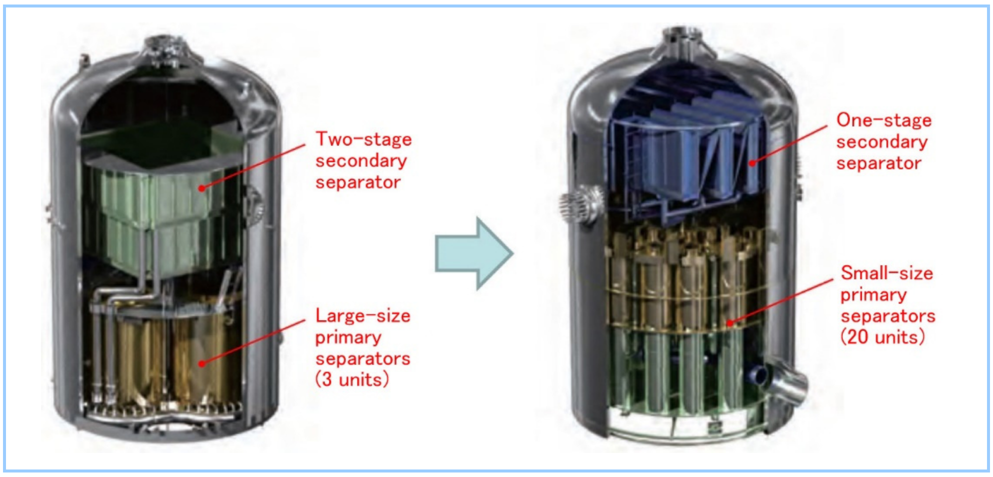

Figure 7 Adoption of high-performance small-size primary separator and secondary separator

(3) Enhancement of evaluation methods for flow-induced vibration and seismic resistance of heat transfer tubes

Maintaining the integrity of heat transfer tubes and their evaluation for this purpose are important from the viewpoint of ensuring plant safety. Such evaluation is conducted also in existing plants to confirm safety. The performance of computers used for the evaluation is continuously improving, and advanced analysis became possible in response to these improvements. This section presents examples of the enhancement of evaluation methods for flow-induced vibration and seismic resistance of heat transfer tubes we are working on for the SRZ-1200.

First, this paragraph describes the evaluation of flow-induced vibration in heat transfer tubes. Analysis has conventionally been conducted to confirm that fluid-elastic instability do not occur; for this purpose, a three-dimensional thermal-hydraulic analysis in the secondary vessel of a steam generator has been conducted. However, the analysis code used in the past has a lower degree of freedom in terms of the geometry (mesh) of the analysis system compared to the latest general-purpose codes. In addition, when various plant operation modes (for example, load-following operation (partial output operation that is much lower than the rated output)) are adopted in the future, the flow field will have a large proportion of liquid phase, and the gas-liquid separation phenomenon may cause the flow field in which the gas and liquid phases flow in different directions. Although there was no need for such evaluation in existing plants, in order to enable various plant operations in the future, a three-dimensional thermal-hydraulic analysis method capable of evaluating gas-liquid velocity difference has been developed based on a general-purpose code platform, while ensuring the shape freedom of the analysis system (**Figure 8**).

Next, this paragraph describes the evaluation of the seismic resistance of heat transfer tubes. Conventionally, an analytical model in which heat transfer tubes (U-bend tube bundle) are simulated with beam elements into which the tubes are aggregated has been used in the response analysis of heat transfer tubes. This analytical model has been verified by excitation tests, but it is not possible to evaluate the stress generated in each heat transfer tube on a single-tube basis. Therefore, we developed an analytical model in which all parts of the heat transfer tubes in the U-bend tube bundle are simulated in detail individually with beam elements to precisely evaluate the stresses in all the heat transfer tubes. This established an analytical method that can more precisely reproduce the results of existing excitation tests. Due to individual modeling, complex shapes can be simulated, and the seismic resistance of various shapes can be determined, enabling design studies aiming for high seismic resistance (**Figure 9**).

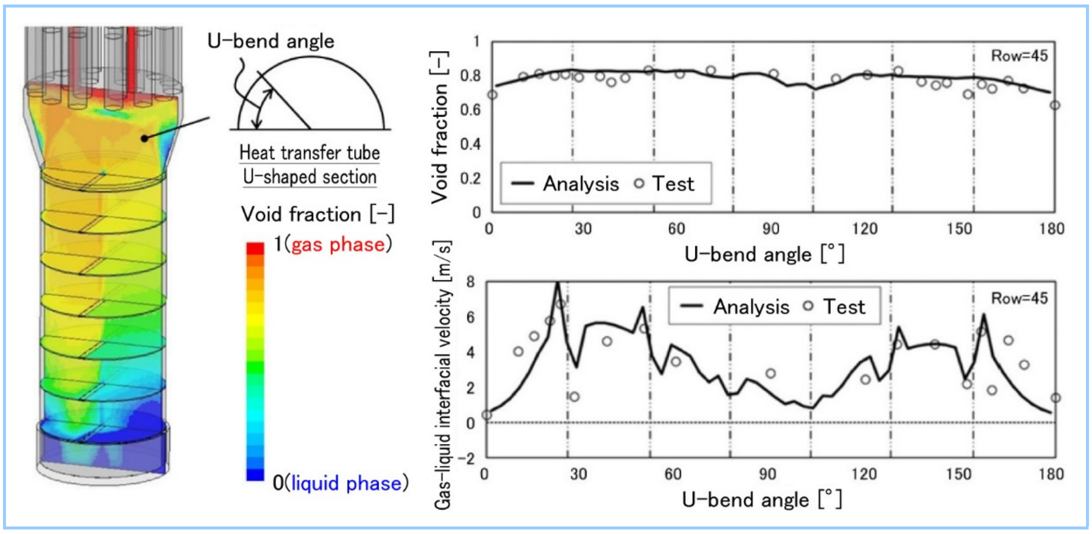

Figure 8 Example of verification in development of three-dimensional thermal-hydraulics analysis method

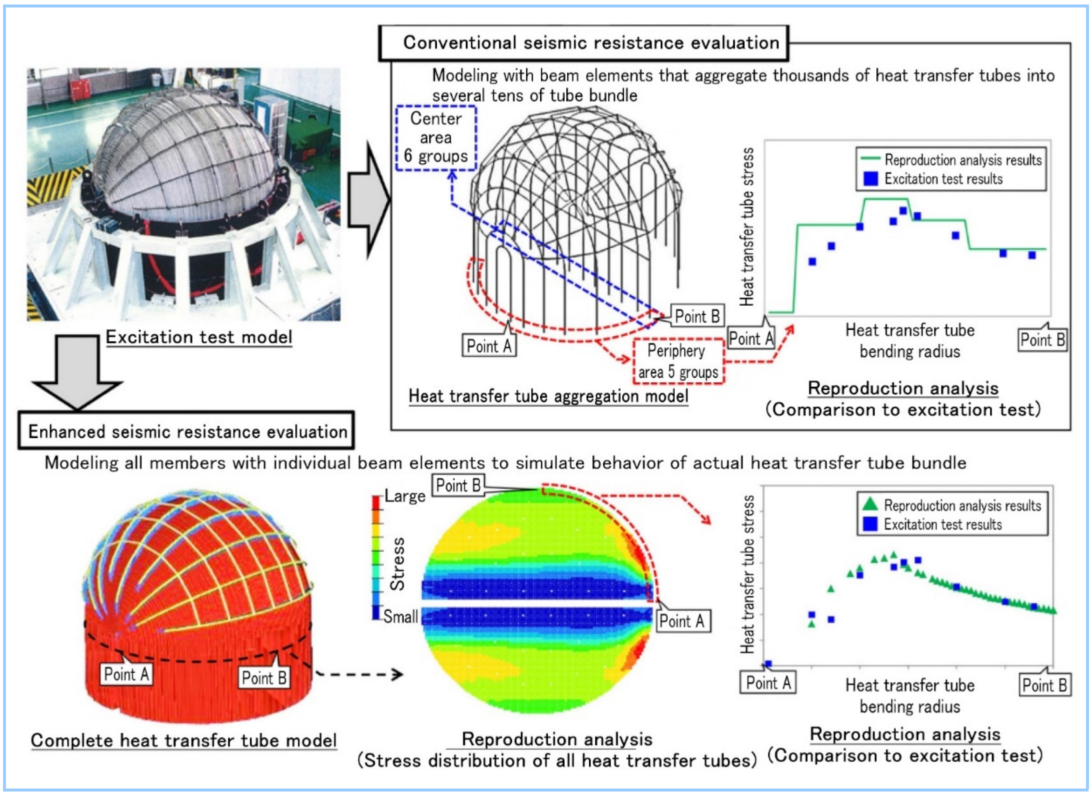

Figure 9 Reproduction results of excitation test using enhanced seismic resistance evaluation model (square array)

5. Development of pressurizer

The pressurizer has a vertical cylindrical low alloy steel structure with a hemispherical-shaped top and bottom (**Figure 10**) with electric heaters inserted from the bottom for pressurization. At the top of the pressurizer is a spray nozzle for depressurization, which sprays water from the reactor coolant tube cold leg into the pressurizer. Also at the top of the pressurizer, a relief valve and a safety valve for depressurization are installed via piping. Each of the elemental technologies is outlined below.

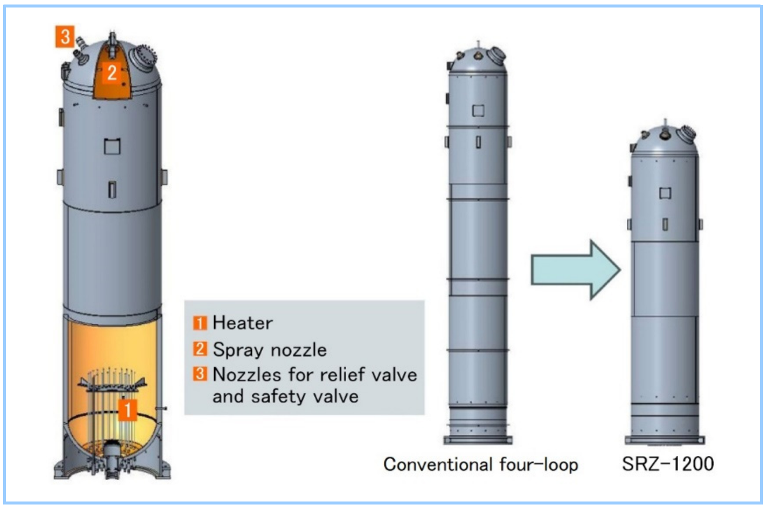

Figure 10 Pressurizer

(1) Adoption of large-capacity heaters

The SRZ-1200 adopts heaters with twice the capacity of conventional heaters, thereby reducing the total number of heaters installed by half. This reduces the number of penetrations in the bottom of the pressurizer where heaters are inserted, which contributes to the improvement of plant safety by reducing the risk of reactor coolant leakage in case of emergency.

(2) Reduction of overall height

The adoption of large-capacity heaters in the SRZ-1200 shortens the overall length of the heaters themselves. Accordingly, the pressurizer inner diameter is enlarged (from approximately 2.1m to 2.4m) and the overall height is reduced (from approximately 16m to 13m) while satisfying the required volume, thereby lowering the center of gravity to improve seismic resistance and increasing rigidity.

6. Future development and prospects

The reactor vessel/reactor internals and steam generator of SRZ-1200 have adopted new technologies for further improvement of safety, reliability and economical efficiency. To verify the design of primary components for the adoption of these new technologies, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has been conducting verification tests (flow inside the reactor vessel test) of the reactor vessel and reactor internals using a scale mock-up since fiscal 2022 as a government-subsidized project (**Figure 11**). MHI plans to continue to obtain experimental data through the verification tests to support the application for the installation permit, design and construction plan approval required for plant construction, and will standardize the evaluation methods. MHI will continue to promote the development of the SRZ-1200 in cooperation with four domestic electric power companies (Kansai Electric Power Co., Inc., Hokkaido Electric Power Co., Inc., Shikoku Electric Power Co., Inc., Kyushu Electric Power Co., Inc.).

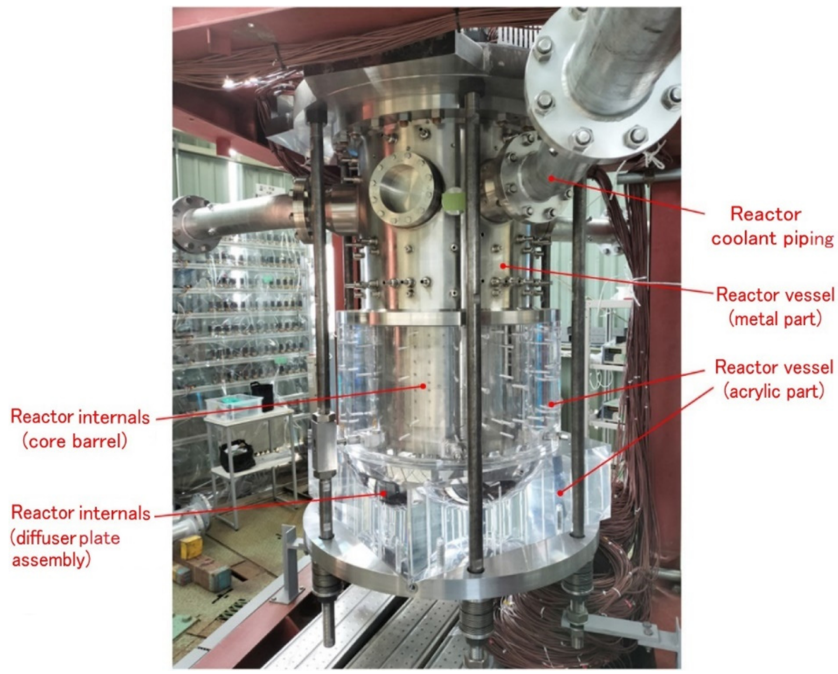

Figure 11 Verification test equipment (flow inside the reactor vessel test)

7. Conclusion

For the stable supply of energy in Japan, MHI is developing the SRZ-1200 with improved safety, reliability, and economic efficiency, while taking into account the new regulatory standards that reflect what has been learned from the Fukushima Daiichi Accident.

For the reactor vessel and reactor internals, which are some of the primary components, a thimble assembly to enable a top mounted in-core instrumentation system, a reactor vessel bottom head and lower core support plate to reduce the volume of the reactor vessel's lower plenum, and a diffuser plate to rectify reactor coolant flow have been developed. For the steam generator, 3/4-inch heat transfer tubes as well as high-performance and small-size primary separators and secondary separator have been adopted, and enhanced evaluation methods for flow-induced vibration and seismic resistance of the heat transfer tubes have been developed. For the pressurizer, large-capacity heaters have been employed to reduce the total number of heaters by half and the overall height of the pressurizer has been reduced.

At present, MHI plans to conduct verification tests using a scale mock-up to verify the design of the primary components of the SRZ-1200, and will continue to work on the development of the SRZ-1200 in cooperation with the government and electric power companies.

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References

(1) M. Matsubara et al., Design Improvement and Evaluation Technology Enhancement of PWR Main Components for Higher Reliability, Mitsubishi Heavy Industries Technical Review Vol.57 No.4 (2020)