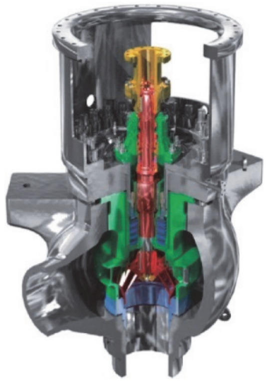
Development of Reactor Coolant Pump (RCP) with Large Capacity and Highly Reliability for Advanced Light Water Reactor



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PWRs have Reactor Coolant Pumps, which are dedicated to circulating reactor coolant to extract the thermal energy generated by the reactor. Mitsubishi Heavy Industries, Ltd. has delivered Reactor Coolant Pumps to PWR plants in Japan and overseas, and accumulated a great deal of technical knowledge and experience. By feeding back the accumulated knowledge and experience, we have solved the problems of conventional Reactor Coolant Pumps and developed a new type of Reactor Coolant Pump with a large capacity and high reliability that is suitable for the specifications of the SRZ-1200 advanced light water reactor.

1. Introduction

Reactor Coolant Pumps (hereinafter referred to as RCPs) installed in Pressurized Water Reactor (PWR) is a pump to circulate high-temperature and high-pressure light water which is the primary coolant in order to extract thermal energy generated in the reactor. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has delivered RCPs to PWRs in Japan and overseas since the initial stages of plant construction. For our SRZ-1200 advanced light water reactor, the RCP to be applied is required to satisfy various plant conditions, such as large-capacity specifications, against the background of the balance between power output and the number of major components, which is set in consideration of economy, plant operation, and coexistence with other power sources including renewable energy. In addition, its structure should have the world's highest level of reliability based on the knowledge of RCP development, design, and manufacturing acquired so far, as well as benchmarking of RCP operation records and failure information in each country.

This report presents the concept, structure, and improvements and latest technologies in the design of a new-type RCP that has been developed and verified for application to the SRZ-1200, and explains the contents and results of its verification tests.

2. Development of MA25S large-capacity and high-reliability RCP

2.1 Structure of RCP

RCPs are single stage/single suction, vertical type mixed-flow pumps for circulating high-temperature and high-pressure reactor coolant. There are two types of RCPs: canned motor pumps and mechanical seal-type pumps. RCPs used in power generation PWRs in Japan are mainly the mechanical seal-type pumps, which limit the amount of leakage from the penetration area.

In PWRs, thermal energy generated in the reactor is transported to the steam generator (hereinafter referred to as SG) by circulating reactor coolant. SG is an equipment which generates steam by heat taken out from a nuclear reactor, and PWR is a system which generates steam of the secondary system using SG and generates power by steam turbine. **Figure 1** shows a configuration diagram of a PWR. The RCP is used to circulate the reactor coolant.

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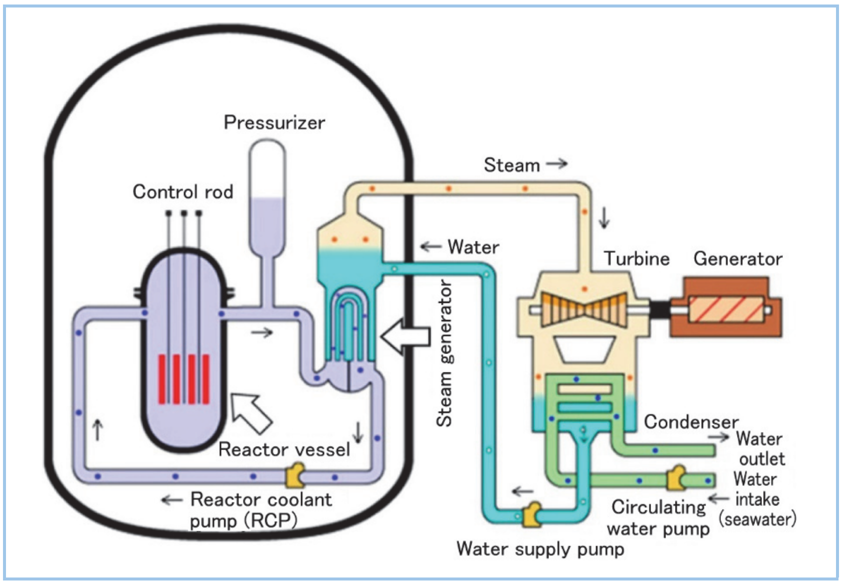


Figure 1 Configuration of PWR power plant

Figure 2 shows the overall structure of the RCP. The motor (electric motor) is connected by a coupling, and the weight of the rotor and hydraulic axial (vertical) loads are supported by the thrust bearing of the motor, while the radial (horizontal) loads are supported by the bearings of the pump and motor.

The overall structure of the RCP consists of three elements: “the hydraulic section”, which mainly consists of impeller, diffuser and casing; “the shaft seal section” has three stages. First-stage is non-contact controlled- leakage seal and second and third-stages are contact seals in order to seal the high-pressure reactor coolant; and “the motor section”, which supplies the pump driving force and supports the axial thrust loads.

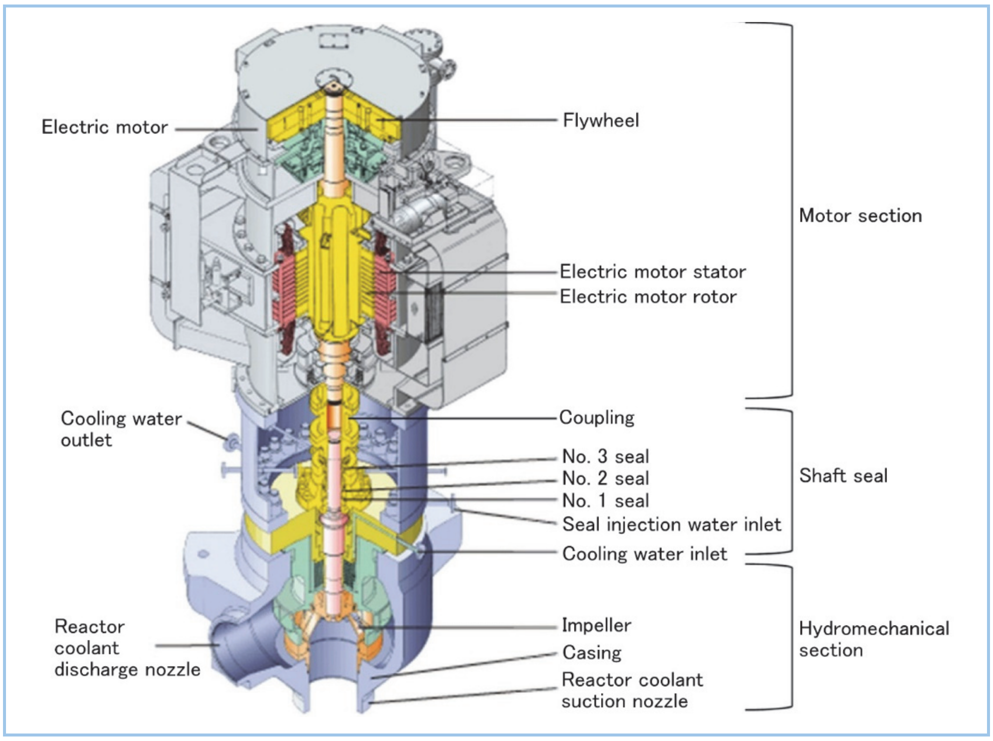


Figure 2 Overall structure of RCP (MA25S)

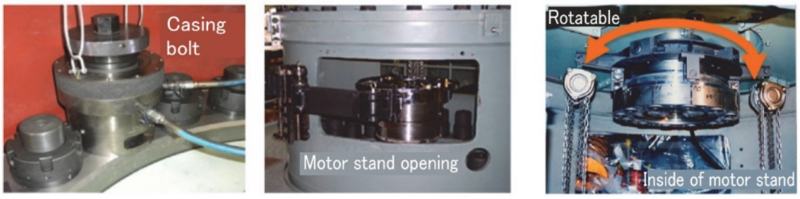
2.2 Development and design of RCP at MHI

Up to now, plant output has been increased by increasing the number of SGs installed in the PWR, and the number of RCPs installed has increased accordingly. On the other hand, to increase the power output without increasing the number of major components, it has been required to increase the RCP capacity. In addition, as the number of years of RCP operations has increased both in Japan and overseas, various problems and defects have been found.

MHI is the only company in Japan with the technology and facilities to develop and manufacture RCPs, and has delivered many RCPs, mainly to PWRs in Japan. MHI also has delivered RCPs to overseas PWRs.

We have continuously benchmarked our RCPs both in Japan and overseas and have collected information on RCP failure cases to develop a number of unique technologies and thereby solve technical problems related to RCPs. **Figure 3** summarizes some of the major improvement designs we have developed so far.

	Item	Details	Advantage
(1)	Improved RCP seal	– Enlargement of rubbing parts and material changes of No. 1 seal	– Stable sealing characteristics against external disturbances
(2)	Higher reliability of major components	– Shift to forged large metal parts – Anti-whirl bearing	– Elimination of risk of cast voids in cast parts – Prevention of shaft vibration cases
(3)	RCP shutdown seal	– Mechanism that automatically operates in event of emergency to prevent leakage from shaft seal	– Reinforcement of countermeasures against LOCAs caused by RCP seal in event of SBO or similar event
(4)	Maintenance jigs and tools * See the figures below.	– Hydraulic bolt tensioner – Seal handling equipment, etc.	– Improved operability, time savings, and reduced exposure during on-site maintenance



Hydraulic bolt tensioner   Seal handling equipment   Hoist crane for seals

Figure 3 Design improvements related to RCP

(1) Improved RCP seal

RCP seals, which prevent leakage of reactor coolant from the shaft penetration area of the RCP, are directly related to whether the PWR can continue to operate, and therefore are required to have stable performance. Among the three stages of seals that make up the RCP seal, the non-contact controlled- leakage No. 1 seal, which has the most complicated mechanism, has been required to have particularly high accuracy and stable performance. The cause of instability cases, which have been an issue both in Japan and overseas, include external disturbances, such as changes in pressure, temperature, and water quality. MHI has developed an improved RCP seal with stable seal characteristics against disturbance by incorporating various improvement, including structural changes, such as enlargement of rubbing parts, and material changes. This improved RCP seal has been applied to actual RCPs in PWRs in Japan, contributing to stable plant operation.

(2) Higher reliability of major components

Large metal components such as impellers and diffusers that make up the hydraulic section of RCPs initially used cast parts, which are relatively easy to manufacture in complex shapes. However, the risk of developing internal defect in cast parts cannot be eliminated and may become apparent when RCPs are operated for a long period of time. The maintenance of RCPs requires work under high radiation doses, so we are proceeding with the shift of RCP metal parts, such as the impeller, from cast parts to forged parts fabricated using our plant facilities to minimize repair opportunities and associated worker exposure.

Bearings of RCPs, which constantly support the stable shaft rotation of the RCP, have a risk of whirl vibration, a phenomenon in which self-excited vibration occurs at a period of half the RCP rotation speed under certain temperature conditions around the bearing, resulting in large shaft vibration. To eliminate this risk, we developed an anti-whirl bearing with a special structure.

(3) RCP shutdown seal

During normal operation, the shaft seal section of RCPs is cooled constantly by injection water from a injection pump and kept under low-temperature conditions to maintain its integrity. However, in the event of a station blackout (hereinafter referred to as SBO) or similar event, the seal cooling function is lost and the shaft seal section is exposed to high-temperature and high-pressure conditions. If this continues for an extended period of time, the seal performance cannot be maintained, and a loss-of-coolant accident (hereinafter referred to as LOCA), in which the reactor coolant is lost due to the loss of RCP seal function, may be caused. Since the Fukushima Daiichi Accident, there has been a strong demand for ensuring integrity in the case of severe accidents both in Japan and overseas. As a mechanism to prevent an LOCA caused by the RCP seal, MHI has developed the RCP shutdown seal (hereinafter referred to as SDS). The SDS consists of a seal section and a drive source that operates without a power supply, as shown in **Figure 4**. If the shaft seal section is exposed to high-temperature/pressure conditions, the drive source operates passively and the seal section contacts the RCP main shaft, thereby limiting reactor coolant leakage.

By using this equipment, the integrity of the RCP seal section can be maintained and the reactor coolant can be secured even in the event of an SBO or similar event, thus strengthening the cooling and confining functions, which are important for ensuring the safety of reactor facilities and leading to further safety improvements.

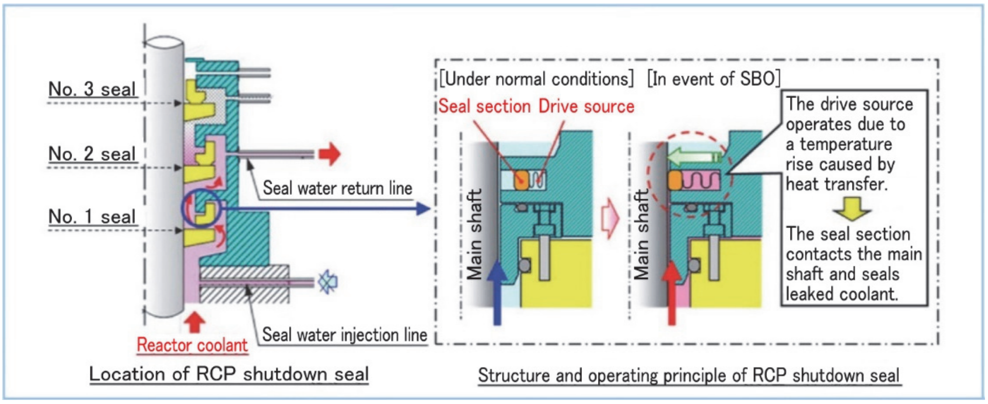


Figure 4 Overview of RCP shutdown seal (SDS)

(4) Maintenance jigs and tools

During the periodic inspection of PWRs, maintenance such as overhaul and bolt tightening of the hydraulic section and the shaft seal section of the RCP is performed. Improving the maintainability of RCPs is an extremely important issue because it leads to fewer operator errors and reduced radiation exposure. Based on requests from end-users who have been operating RCPs for a long time, MHI has developed and delivered various jigs and tools such as hydraulic bolt tensioners, seal handling devices, etc. for simplifying maintenance work and reducing work time.

2.3 Features of MA25S RCP

The RCP to be used for the SRZ-1200 needs to be based on a pump hydraulic design that achieves a larger capacity and higher efficiency than existing RCPs in consideration of the plant requirements and have a structural design that takes into account more severe accident environment conditions (such as enhanced measures against LOCAs caused by the RCP seal) to meet new regulatory requirements, and also needs to reflect a number of improvements that will enhance reliability and improve maintainability by utilizing the knowledge accumulated over many years as an RCP manufacturer.

MHI has developed the MA25S RCP, which satisfies all of these requirements, conducted its verification tests under the high-pressure and high-temperature coolant conditions of an actual PWR using MHI's RCP loop test facility, and confirmed that there were no problems with its overall appropriateness, including design, manufacturability, performance and structural reliability

The MA25S RCP has three main features: (1) hydraulic design for large capacity and high efficiency, (2) enhanced safety and reliability, and (3) improved maintainability.

(1) Hydraulic design for large capacity and high efficiency

To achieve a high flow rate and high head that the existing RCP models cannot achieve, and at the same time to achieve high efficiency that contributes to plant economy, we have implemented improved designs based on the hydraulic design of RCPs that have been applied to

PWRs in Japan, including a fundamental review of the connection between the main shaft and impeller and of the main shaft, impeller, and diffuser structure. Then we conducted Computational Fluid Dynamics and water flow tests using a scale model for the improved hydraulic model and confirmed a higher hydraulic performance. In addition, we also obtained data on the hydraulic characteristics in the case where the reactor coolant flows in the direction of reverse-rotating the RCP, which is a requirement specific to PWR plant design (together with the performance in normal forward flow, referred to as the complete characteristic), and used this as an input condition in the analysis of the plant in the event of an accident.

Table 1 compares the specifications of the existing RCP and the newly developed MA25S RCP.

Table 1 Comparison of specifications of existing RCP and MA25S RCP for SRZ-1200*

Item	Existing model	Model for SRZ-1200 (MA25S)
Flow rate (m^3/h)	Approximately 20000	Approximately 25000
Head (m)	Approximately 85	Approximately 90
Efficiency (%)	Approximately 80 or higher	Approximately 85 or higher

* 60 Hz spec.

(2) Enhanced safety and reliability

The MA25S RCP incorporates as standard design the improvements shown in Figure 3, including the installation of an SDS. In addition to these, the major structural design change includes a simplified flange structure (**Figure 5**) to minimize thermal effects, considering that the temperature of reactor coolant flowing into the RCP is very high.

In addition, to prevent shaft vibration fluctuation (thermosiphon phenomenon) caused by a convection phenomenon generated at the thermal sleeve, which is a cylindrical part installed for thermal protection of the main shaft, an improved thermal sleeve, which incorporates a reduced gap to the main shaft, an extended structure of the connection, etc., is adopted.

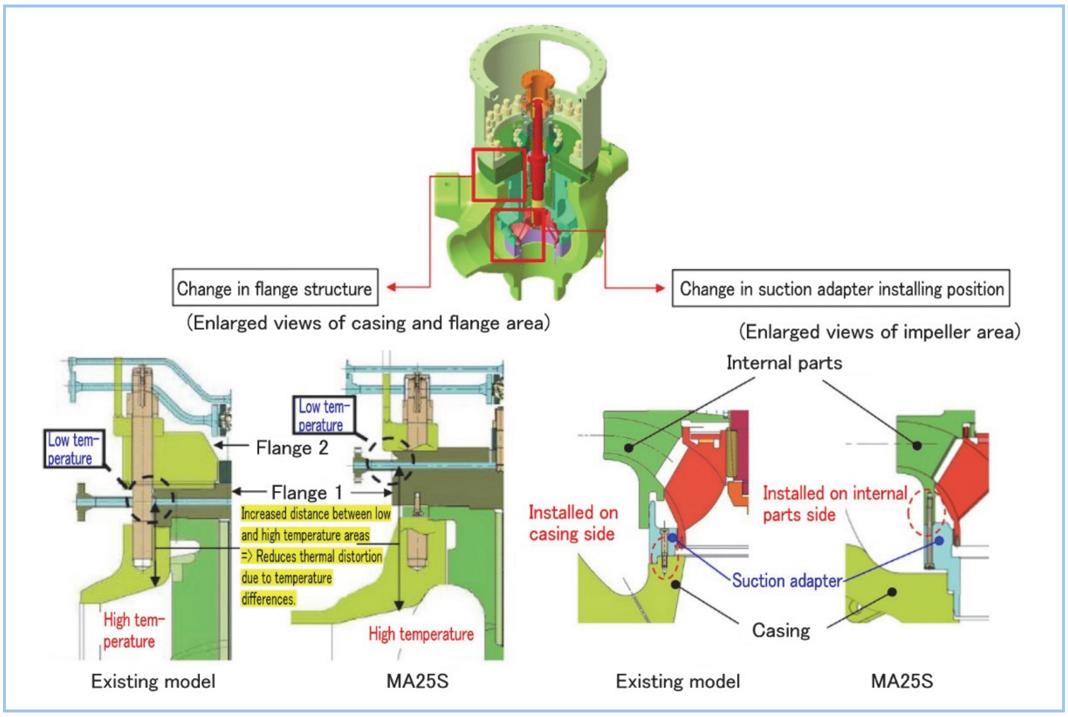


Figure 5 Examples of new designs applied to MA25S RCP

(3) Improved maintainability

During the periodic inspection of PWRs, maintenance such as overhaul and bolt tightening of the seal section of the RCP is performed. Improving the maintainability of RCPs is an extremely important issue because it leads to fewer operator errors and reduced radiation exposure. The MA25S RCP employs a motor stand with a larger opening and interior space than existing RCP models, making it easier for operators to perform maintenance inside.

Furthermore, as shown in Figure 5, the MA25S RCP has been design-changed so that the suction adapter, which was bolted to the bottom of the casing in the existing RCPs, is now bolted to the internal parts side (diffuser). This allows the internal parts (parts set of spindle, impeller, diffuser, etc.) to be pulled out together with the suction adapter during maintenance, reducing the maintenance procedure.

3. Verification test of MA25S RCP

3.1 Shop test facility and prototype RCP

MHI has a shop test facility that can simulate the operating conditions (high pressure, high temperature, and high flow rate) of RCPs in PWRs. We manufactured a full-scale prototype MA25S RCP and conducted operational tests under various severe conditions. As a result, we have verified that there were no problems or concerns regarding the overall feasibility of the MA25S RCP, including various new design elements. **Table 2** provides an overview of the test conditions.

Table 2 MA25S RCP verification test conditions

Heat-up and cool-down repetition test		
Rotation speed	0 min^{-1} <=> Approx. 1,200 min^{-1}	Measure the coasting (coast down) time
Voltage	0 V <=> Approx. 6,000 V	Check characteristics during startup/stop
Performance test		
Flow rate	Approx. 25,000 m^3/h rated	Measure multiple points of approx. 80% to approx. 120% flow rate
Head	Approx. 90 m rated	
Suction pressure	Approx. 15 MPa	Simulate reactor coolant pressure similar to that of actual equipment
Fluid temperature	Approx. 290°C	Simulates reactor coolant temperature similar to that of actual equipment

* Other special function tests were conducted under conditions set

Figure 6 shows an overview of our shop test facility and the prototype of the MA25S RCP (pump for verification testing). Using this test prototype RCP, which has the same dimensions and shape as the actual RCP, we conducted tests in a high-temperature and high-pressure loop, which is equivalent to the conditions of actual PWRs, to precisely verify the pump performance and to validate the new designs without omissions. From these verification results, it was confirmed that the MA25S RCP has high performance and high efficiency in accordance with the required specifications of the SRZ-1200, as well as soundness under anticipated accident events and high reliability for long-term operation.

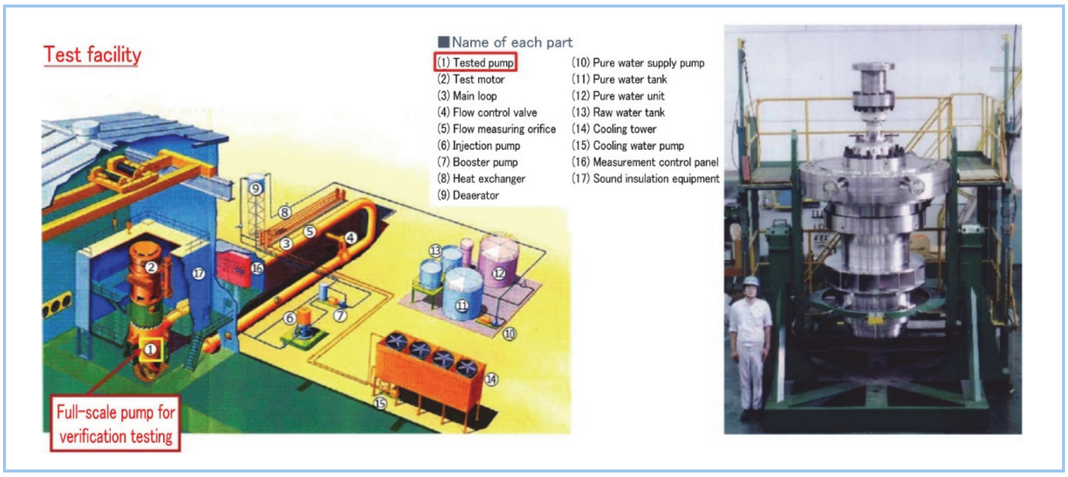


Figure 6 Overview of plant test facility and full-scale test piece of MA25S RCP (internal parts assembled)

3.2 Verification test items and results

We set up the verification test items for the MA25S RCP to conduct, in addition to general pump performance tests, tests under special conditions such as repeated startup and shutdown and tests based on PWR behavior, considering the position of this test as a comprehensive verification test for the first unit of a new RCP model. Data measurements during operation and post-test overhaul inspections confirmed that there were no problems with the application of the various new designs.

The three main verification tests, (1) repeated heat-up and cool-down test, (2) performance test, and (3) special function test, were conducted.

(1) Heat-up and cool-down repetition test

A test to confirm the integrity of the pump structure and functions by simulating the repeated heat-up (temperature/pressure increase) and cool-down (temperature/pressure decrease) cycles that occur during the PWR operation cycle. From this testing, it was confirmed that no problems such as abnormalities in operating parameters or defects in various component structures were observed after repeated loading.

(2) Performance test

A test to check the characteristics of total head, shaft power, and pump efficiency at each flow rate point at the specified pump speed and to confirm that they meet the required specifications. From this test, it was confirmed that the prototype sufficiently met the performance specifications of the MA25S RCP shown in Table 1 in Section 2.3. The performance characteristics including the case where the water flow in the pump is in the opposite direction of the normal flow, which is unique to RCPs, were also measured under different additional tests, and it was confirmed that there were no problems with the hydraulic characteristics based on the plant requirements.

(3) Special function test

A test to confirm that the RCP does not lose its function under severe conditions, assuming not only normal PWR operation but also suspension of water supply by auxiliary pumps due to loss of power. Specifically, the test was to confirm that normal operation can be continued for a certain period of time even in the event of loss of cooling water or loss of sealing water injection to the seal section. The test was also to verify that the pump will stop normally even if both of these loss events occur simultaneously, which is a more severe condition. As a result of this test, it was confirmed that no fatal problems, such as the inability to restart the RCP, occurred under either condition.

4. Conclusion

This report presented the latest design applied to the MA25S RCP, which has been developed for the SRZ-1200, and the results of its verification tests. The MA25S RCP not only improves hydraulic performance, but also incorporates various design improvements that contribute to improved reliability and maintainability, such as the adoption of an SDS, simplification of the flange structure, and improved maintenance. MHI has provided RCPs, which are used in many PWR plants, and will continue to manufacture and deliver RCPs that contribute to improved reliability and operational sophistication of nuclear power plants in Japan and overseas.