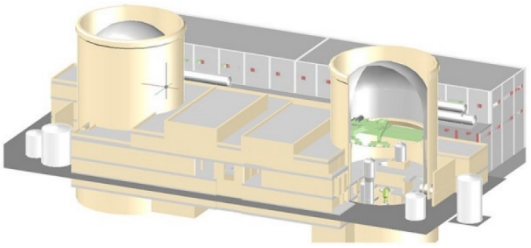
Activities toward Rational Decommissioning of Nuclear Facilities



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For many years, Mitsubishi Heavy Industries, Ltd. (MHI) has been working on technological development related to the decommissioning of nuclear reactors, etc., centered on commercial nuclear power generation facilities. This effort has been based on the experience gained through the construction and maintenance of various nuclear facilities such as pressurized water nuclear power plants. The technologies required for decommissioning include the system engineering and residual radioactivity evaluation technology at the planning stage, the decontamination and dismantling technology at the full-blown work operation stage and the waste packaging, which is processing such as solidification to a container for buried processing of radioactive waste disposal and radioactivity measurement technology required for generated waste. This report introduces the latest state of the activities for each of these technologies.

1. Introduction

Beginning with the decommissioning study for a PWR (Pressurized Water Reactor) model plant in 1979, MHI has been developing both hardware and software technologies for decommissioning through joint research with electric power companies, commissioned research from institutions such as the former NUPEC (Nuclear Power Engineering Corporation), The Institute of Applied Energy and Japan Atomic Energy Agency, in addition to our in-house research [(1)(2)]. This paper describes the state of our activities for rational decommissioning of light water reactors using various technologies.

2. Our activities for decommissioning

The decommissioning plans in Japan are roughly classified into four stages: “dismantling preparation,” “reactor auxiliary component dismantling,” “reactor area dismantling” and “building dismantling,” with periods of about 30 to 40 years (**Figure 1**).

We support rational and reliable decommissioning at each stage from dismantling preparation to building dismantling using required technologies (**Figure 2**). An overview is presented below.

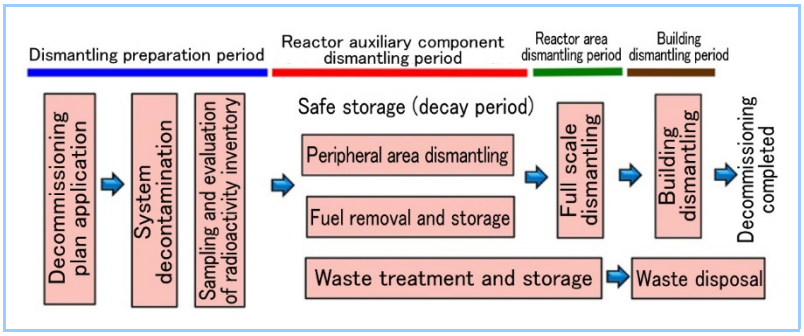

Figure 1 Example of decommissioning plan

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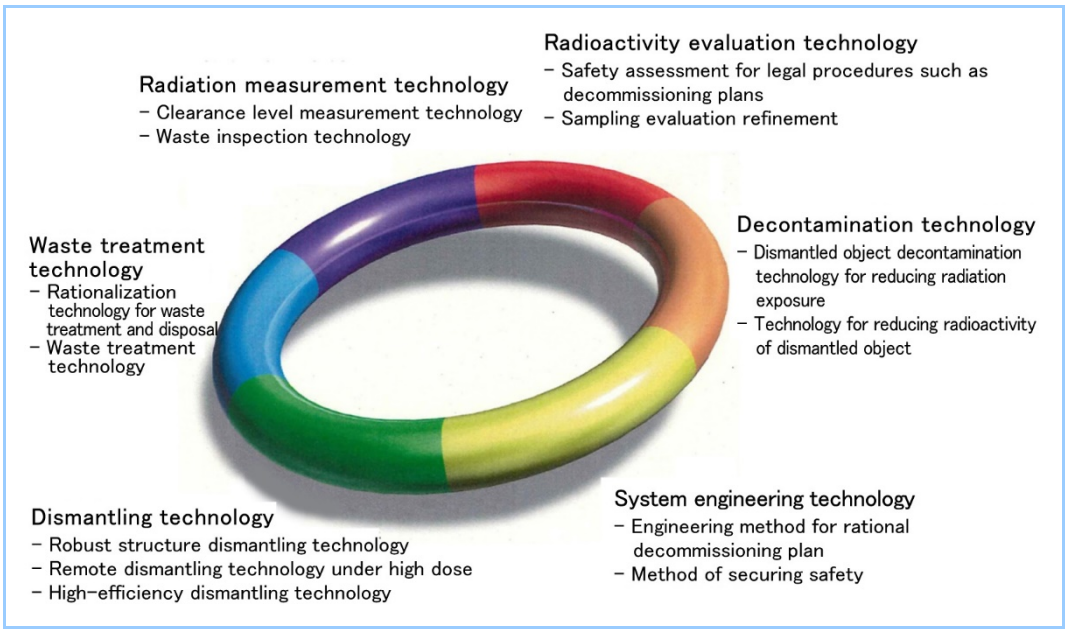


Figure 2 Technology required for decommissioning of nuclear facilities

2.1 Radioactivity evaluation technology

2.1.1 Evaluation of radioactivity inventory

To formulate a decommissioning plan, it is necessary to appropriately evaluate the radioactivity concentration (radioactivity inventory) remaining in the equipment. Radioactivity inventories can be derived from activation or secondary contact contamination. This section presents an activation evaluation method using a three-dimensional neutron transport calculation code (MCNP code), which is one of the recent activities [(3)].

By evaluating the radioactivity concentration in detail and accurately determining the disposal category based on the obtained radioactivity concentration, it is possible to reduce the disposal cost in decommissioning. The current license evaluation is carried out based on a two-dimensional neutron transport calculation code, but when using the two-dimensional code, it is necessary to simplify the evaluation model for complex-shape parts to ensure a conservative evaluation. On the other hand, the use of a three-dimensional neutron transport calculation code makes it possible to perform evaluation with the actual plant structure modeled in detail, but in the case of the calculation of a huge system with large changes in the neutron flux, there is the problem that the calculation takes time.

To solve this problem, by efficient calculation for the area to be evaluated using a model, the calculation, which used to take more than a week conventionally, can be completed in a few hours.

By comparing the three-dimensional calculation results of the evaluation of neutron flux in the upper core internal structure in the reactor vessel (RV) and the radioactivity concentration of Co-60, which is a major activated nuclide, with the calculation results using a two-dimensional code, it has been verified that the three-dimensional evaluation can evaluate the activation range more rationally as shown in **Figure 3**.

Currently, the evaluation target area has been expanded in the reactor containment vessel, and verification is being carried out by comparing the calculation results with the analytical values obtained by sampling inside and outside the reactor. The next section introduces sampling.

2.1.2 Sampling for refinement of evaluation [(4)]

It is necessary to appropriately evaluate the radioactivity concentration distribution using the calculation results, measurement results, etc., based on the “Examination Criteria for Decommissioning Plans for Nuclear Power Reactor Facilities and Nuclear Research Reactor Facilities” established by the Nuclear Regulation Authority. Therefore, in order to evaluate the radioactivity concentration distribution in the core using the analysis results of the samples collected from actual equipment, in-core sampling is performed for the L1 and L2 [(Note 1)]

regions where the radioactivity concentration is high. **Figure 4** illustrates the flow of the series of examinations related to the evaluation of the radioactivity concentration.

(Note 1) L1 means low-level waste with a relatively high radioactivity level. L2 means low-level waste with a low radioactivity level. There are further lower-level categories: L3 and the clearance level.

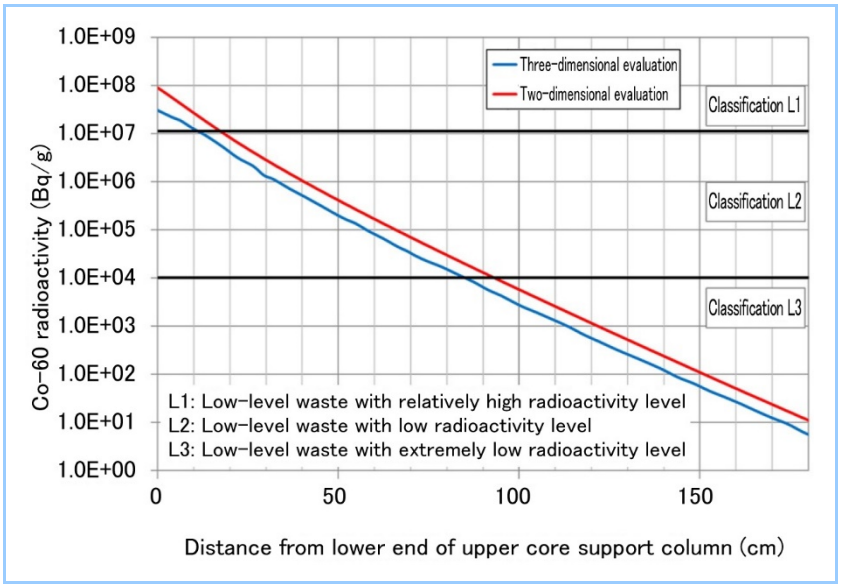


Figure 3 Evaluation result of radioactivity inventory

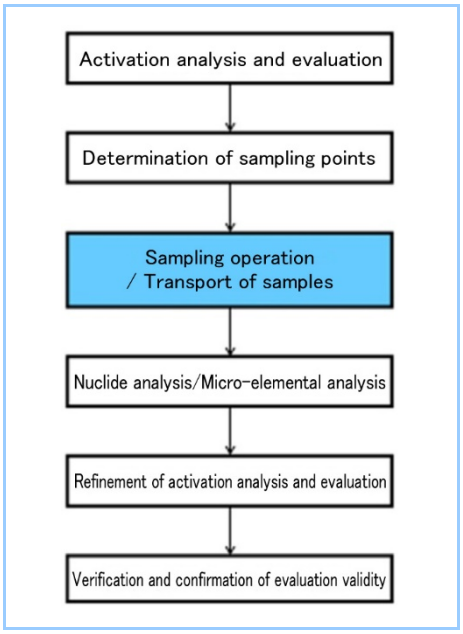


Figure 4 Evaluation flow of residual radioactivity concentration

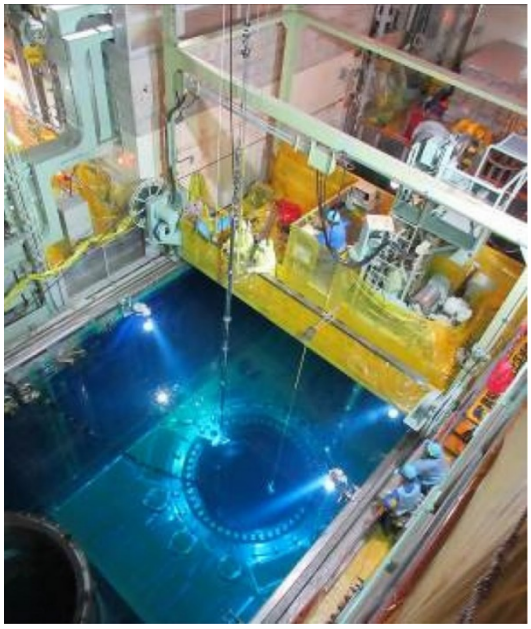


Figure 5 Sampling situation at Mihama Nuclear Power Station Unit 1

We carried out in-core sampling work at Mihama Nuclear Power Station Units 1 and 2 of Kansai Electric Power Co., Inc. (Unit 2 in September 2018, Unit 1 in November 2018), Genkai Nuclear Power Station Unit 1 of Kyushu Electric Power Co., Inc. (March to April 2019) and Ikata Nuclear Power Station Unit 1 of Shikoku Electric Power Co., Inc. (October to November 2019). This section presents an overview of the in-RV sampling work in a PWR at Mihama Nuclear Power Station Units 1 and 2, which was performed for the first time in Japan (**Figure 5**).

The points and number of samplings from the inside of an RV are determined in consideration of the neutron flux, element composition, activation cross section and irradiation history, which is a parameter that affects the radioactivity concentration in activation evaluation. In the case of Mihama Nuclear Power Station Unit 2, twelve samples were collected from the L1 and L2 areas.

Based on the sample analysis results of Mihama Nuclear Power Station Unit 2, a

radioactivity concentration evaluation method was established. For the subsequent plants, by using this evaluation method, the number of samplings was rationalized and reduced to 6 (**Figure 6**).

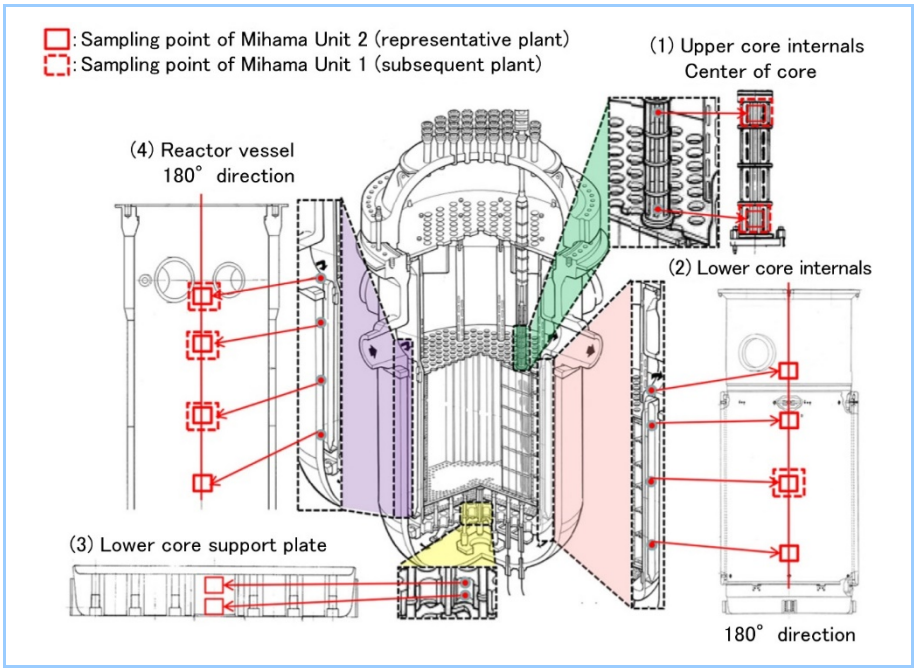


Figure 6 Sampling points of Mihama Nuclear Power Station Unit 1 and Unit 2

(1) Overview of sampling device

As the sampling method, electric discharge machining was selected based on its characteristics that [1] machining is possible regardless of the material (SUS or low alloy steel), [2] there is less cutting reaction force and size reduction is possible in contrast to mechanical machining and [3] it is highly-reliable technology with proven results in past maintenance work. For positioning and handling the device, a method of assembling connection poles was adopted in consideration of on-site workability and remote positioning.

In addition to the aforementioned reduction in the number of samples, by sharing sampling device across multiple nuclear power plants, the equipment cost for each nuclear power plant is being reduced.

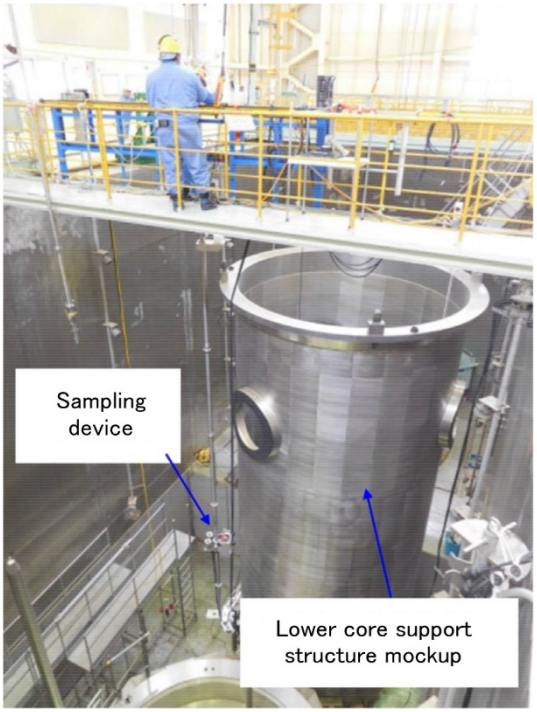


Figure 7 Mockup training situation of in-core sampling operation

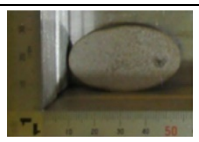
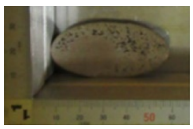
(2) Preparation for sampling work

As preliminary preparations for sampling work, verification using a mockup of the sampling device and training with equipment that simulates the actual equipment are conducted at our Comprehensive Maintenance Training Center. In particular, since the device needs to be installed by handling long poles over 10 m in length while being checked with an underwater camera, the training used a full-scale mockup. **Figure 7** depicts the training.

(3) Result of sampling work

Table 1 lists the samples collected during the in-RV sampling work. The samples necessary for evaluating the radioactivity concentration distribution could be collected as planned. These samples were stored in a highly-radioactive material transport container (type A transport container) and transported to Nuclear Development Corporation, our affiliate, for measurement of the radionuclides.

Table 1 Dimensions and weight of collected samples (example)

Sampling point	Sample size (mm) Width × Length × Thickness	Sample weight (g)	Shape (photo)
Reactor vessel	Approx. 30 × Approx. 90 × Approx. 20	Approx. 300	
Lower core internals	Approx. 25 × Approx. 50 × Approx. 5	Approx. 30	
Upper core internals	ϕ 17.5 × Approx. 120	Approx. 90	
Lower core support plate	Approx. 30 × Approx. 60 × Approx. 5	Approx. 30	

2.2 Decontamination technology [5]

We carried out system decontamination work at Mihama Nuclear Power Station Units 1 and 2 of Kansai Electric Power Co., Inc. (Unit 1 in August 2017, Unit 2 in late November to early December 2017) and Genkai Nuclear Power Station Unit 1 of Kyushu Electric Power Co., Inc. (June to July 2018). This section presents an overview of the system decontamination work at Mihama Nuclear Power Station Units 1 and 2.

The system decontamination work uses the chemical action of a chemical circulated in the system to remove radioactive substances adhering to the inner surface of the equipment. In order to improve the working environment (reduce the exposure of workers) and reduce the radioactivity level of radioactive waste at the time when the equipment is dismantled in the future, it was implemented in the first stage of decommissioning (dismantling preparation stage).

2.2.1 System decontamination work plan

(1) System decontamination area

Since a large amount of radioactive material remains on the inner surface of the equipment that comes into contact with the primary coolant, the target area of the system decontamination work was set to the reactor cooling system, the chemical volume control system and the residual heat removal system, in which the primary coolant mainly circulates during operation (**Figure 8**).

Table 2 lists the volume and surface area of the system decontamination area. As shown in Table 2, the surface area of the system decontamination area is about 80% occupied by nickel-based alloys, and most of these nickel-based alloys consist of the steam generator (SG) heat transfer tubes. Therefore, for system decontamination work in a PWR, it is necessary to select a method in consideration of the decontamination effect in the SG heat transfer tubes. However, nickel-based alloy materials contain a large amount of chromium

and nickel, and it is difficult to obtain a decontamination effect compared with other metal materials (stainless steel, etc.). The system decontamination work for the 690 nickel-based alloy used in the SG heat transfer tubes of Mihama Nuclear Power Station Units 1 and 2 was the first chemical decontamination work anywhere in the world.

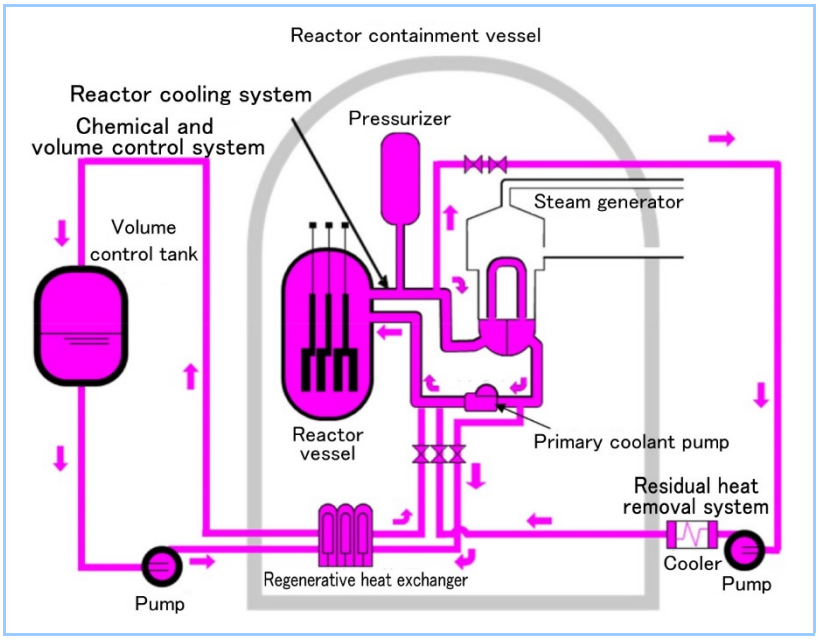


Figure 8 Full system decontamination area

Table 2 Volume of system decontamination area and surface area of stainless steel and Ni-based alloy at Mihama Power Station Unit 1 and Unit 2

Plant	Volume [m^3]	Surface area [m^2]	
		Stainless steel	Ni-based alloy
Mihama Unit 1	Approx. 180	Approx. 1470	Approx. 6250
Mihama Unit 2	Approx. 220	Approx. 1930	Approx. 8080

(2) System decontamination method

For the system decontamination work at Mihama Nuclear Power Station Units 1 and 2, the CORD (Chemical Oxidation Reduction Decontamination) method of Framatome, which has a wealth of experience in system decontamination work at PWR plants overseas, was adopted, considering its advantages that a decontamination effect on the SG heat transfer tubes, which make up about 80% of the area of the system decontamination area, can be expected, the amount of secondary waste generated by decontamination is small, chemicals used for decontamination can be disposed of using the equipment inside the nuclear power plant, etc.

The CORD method attains the target decontamination effect by repeating the cycle consisting of ① oxidation, ② decontamination, ③ decomposition and ④ purification multiple times. The period of one cycle is about one week.

(3) System decontamination equipment

For system decontamination work, the plant equipment is effectively used. Circulation of decontamination liquid, temperature maintenance, pressure adjustment, etc., are performed by the plant equipment, while chemical injection, etc., is handled by the temporary equipment (**Figure 9**).

Similar to sampling work, system decontamination work is rationalized by sharing the equipment across multiple nuclear power plants.

Among plant equipment, the primary coolant pump is used for circulating the heat source that maintains the temperature and for circulating the decontamination liquid and the equipment around the filling pump is used for injecting sealing water into the primary coolant pump and circulating the decontamination liquid. The residual heat removal system equipment is used for cooling to maintain the temperature and for circulating the

decontamination liquid, while the accumulator is used for controlling the pressure. However, since this is the first system decontamination using the CORD method in a domestic PWR plant, we examined in detail and optimized the equipment operation procedure and the system operation procedure in each decontamination process based on our knowledge as a plant manufacturer.

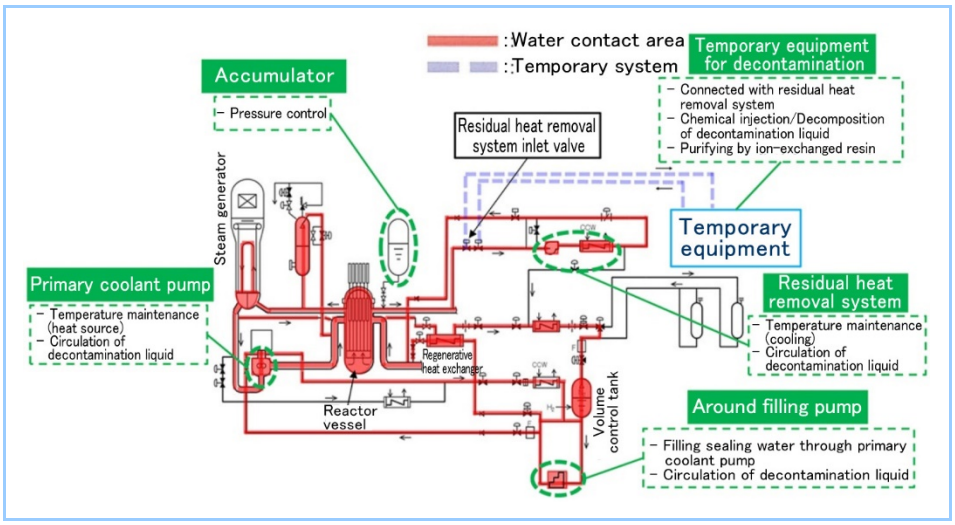


Figure 9 Schematic illustration of system decontamination work at Mihama Nuclear Power Station Unit 1 and Unit 2

2.2.2 Result of system decontamination work

Table 3 lists the decontamination effect of system decontamination work, The decontamination effect achieved the initial removal rate target of 90% or more (decontamination factor of 10 or more), which was set in consideration of worker exposure during future dismantling of equipment and pipes, and the dose equivalent rate of primary coolant system pipes, etc., that was relatively low before system decontamination was decreased to less than 0.05 mSv/h. For the SG heat transfer tubes made of 690 nickel-based alloy, the target removal rate of the chemical decontamination work—carried out for the first time anywhere in the world—was achieved, and the dose equivalent rate saw an approximately double-digit decrease with this system decontamination.

As a result, the exposure of workers during future dismantling of plants can be significantly reduced and the risk of internal exposure of workers can be sufficiently suppressed due to the reduction of radioactive dust generated during dismantling.

Table 3 Decontamination effect of system decontamination work at Mihama Power Station Unit 1 and Unit 2

Part	Mihama Unit 1			Mihama Unit 2		
	Average decontamination factor *1	(For reference) Dose equivalent rate of representative part [mSv/h]		Average decontamination factor *1	(For reference) Dose equivalent rate of representative part [mSv/h]	
		Before decontamination	After decontamination		Before decontamination	After decontamination
Heat exchanger tubes of steam generator	89	36	0.43	174	20	0.36
Shell of steam generator *2	140	0.21	0.001	67	0.11	<0.001
Primary coolant system piping, etc.	32	1.7	0.025	30	0.7	0.0015

*1: Decontamination factor = (Surface dose equivalent rate of equipment before decontamination) / (Surface dose equivalent rate of equipment after decontamination)

*2: The steam generator shell itself was not decontaminated, but the dose rate of the shell was reduced due to the decontamination of heat exchanger tubes of the steam generator.

2.3 System engineering technology

The decommissioning is not only to carry out work safely, but also to drastically reduce the cost burden of the electric power company compared with the in-service period. Therefore, we are working on the reduction of the decommissioning work costs and the maintenance equipment

management costs during the decommissioning period (rationalization of dismantling, installation of alternative equipment, etc.)

2.3.1 Creation of waste storage area by rationalizing dismantling of steam generator

The SG used and replaced at the nuclear power plant is stored on the premises of the nuclear power plant. If the SG can be dismantled and disposed of, the SG storage area can be used to temporarily store waste. The SG is a large component which contains low-level waste and clearance substances in a mixed manner, so it is desirable for rationalization to separate them and reduce the volume. We are considering the dismantling of SGs at overseas facilities that have many achievements as one of the options.

2.3.2 Elimination of need to maintain seawater system by stopping spent fuel cooling

Most of the plant equipment that requires cooling is maintained with the auxiliary cooling seawater system (the seawater system) as the final cooling source. However, during decommissioning, the heat load of the auxiliary equipment to be cooled decreases compared with the in-service period, so the auxiliary equipment cooling capacity of the seawater system is excessive. The maintenance of the seawater system is large in terms of scale and extensive. In order to rationally proceed with decommissioning from the perspective of the cost burden of the electric power company, it is desirable to eliminate the need to maintain the seawater system by replacing the existing equipment that the seawater system is responsible for cooling with equipment that does not use seawater cooling.

In particular, we are considering, as one of the options, the adoption of cooling with natural heat dissipation and air fin coolers as an alternative cooling means for the seawater system according to the heat amount of the spent fuel, which is the main cooling target of the seawater system during decommissioning.

2.3.3 Reduction of maintenance cost by introducing integrated decommissioning panel

Characteristically, during the long decommissioning period, the scale of functions that need to be maintained gradually shrinks from that during the in-service period.

With the situation that maintenance functions are scattered across multiple, aging control panels, we are considering the application of an integrated instrumentation control panel into which the scattered maintenance functions are combined according to the progress of decommissioning, such as demolition of the buildings.

2.4 Dismantling technologies

The dismantling work of core internal structures, reactor vessels, biological shields, etc., which have high radiation doses, is basically performed by remote control from the perspective of preventing exposure of workers. In order to efficiently carry out remote operation, a remote device (robot) equipped with advanced work functions is required.

We have a large number of remote work achievements using manipulators (**Figure 10**) in the maintenance work (nozzle inner surface buildup welding, improvement of residual stress at welds on nozzle inner surface, other inspection work, etc.) of PWR power plants. We plan to work on the dismantling of highly-radioactive equipment in decommissioning based on these experiences.

We are evaluating the applicability of cutting technologies, which are important for dismantling equipment, to decommissioning, and are planning to carry out rational dismantling in actual work by appropriately combining these mainly thermal and mechanical cutting technologies.

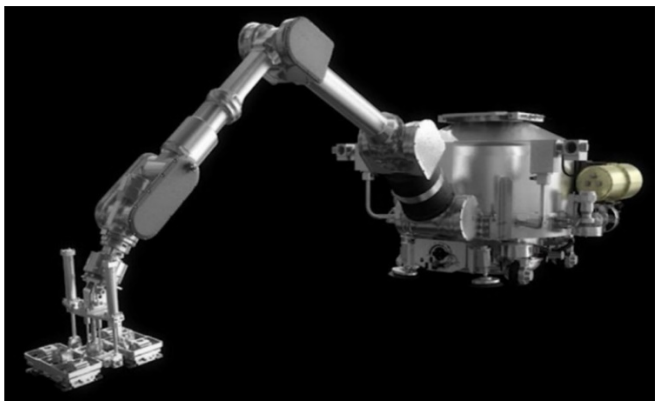


Figure 10 Example of remote device manipulator

2.5 Waste treatment technology

Radioactive waste generated in decommissioning is classified into L1, L2 and L3 based on the radioactivity concentration and then disposed of. L1 and L2 waste is, for example, stored in a square disposal container of about 1.6 m x 1.6 m x 1.6 m, fixed with sand or mortar, covered with a lid, inspected and then transported to the disposal site. At present, none of the nuclear power plants have equipment to perform these series of operations, and it is necessary to take this into consideration when dismantling equipment.

We are considering the flow of waste treatment and waste packaging and the concept of this equipment, as well as establishing technologies such as remote tightening of lids with bolts to proceed with preparations for the installation of rational waste treatment and waste packaging equipment (**Figure 11** and **Figure 12**).

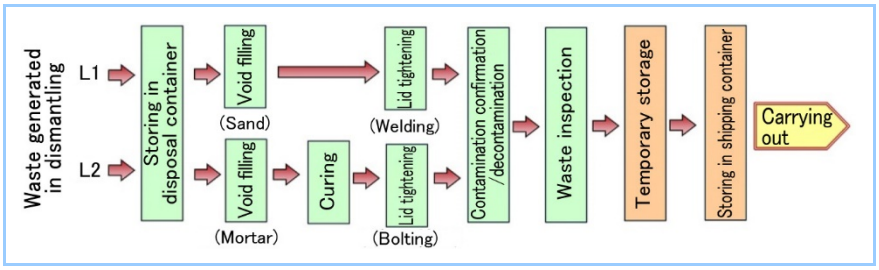


Figure 11 Waste treatment procedure for low-level radioactive waste

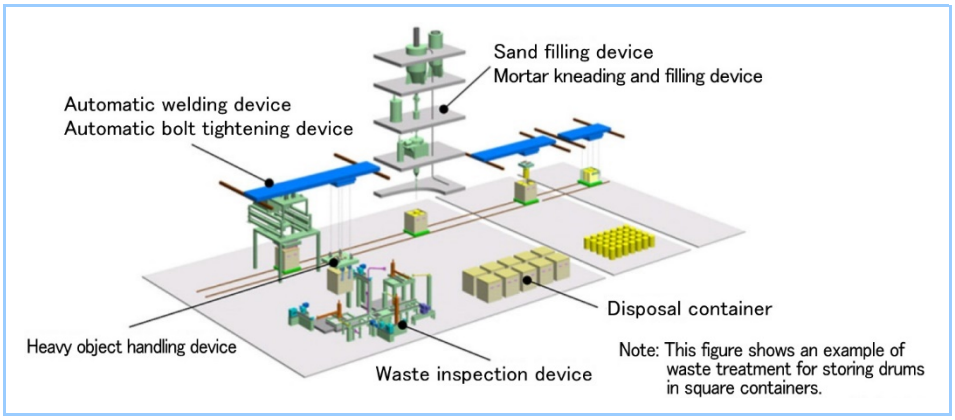


Figure 12 Image of waste treatment equipment for low-level radioactive waste

2.6 Radiation measurement technology

To finally dispose of radioactive waste, it is necessary to measure the concentration of radionuclides contained in the waste and confirm that the concentration is below the standard. The nuclides that need to be or are expected to need to be confirmed as described above depend on the type of waste (nuclear power plant waste or clearance waste). However, both types of waste have nuclides that can be measured directly and those that are difficult to measure directly. The goal of the measuring device should be to obtain the concentration of nuclides that can be directly measured with good accuracy in an appropriate amount of time.

The clearance system, which enables the handling of waste that has extremely low radioactivity and does not need to be treated as radioactive material in the same manner as general industrial waste, was institutionalized in 2005. However, since 1999, we have developed a device that measures radiation at a level lower than that in nature, and commercialized dedicated tray-type and box-type clearance measuring devices based on the development results. **Figure 13** shows the appearance of a box-type device, which is more suitable for measuring a large amount of waste and can efficiently determine clearance compared with a tray-type device.

We will propose the application of radioactivity measuring devices such as clearance level measuring devices to plant decommissioning sites from the perspective of reducing the amount of radioactive waste.

Figure 13 Appearance of box-type clearance level measuring device

3. Conclusion

As described above, MHI has been comprehensively working on the decommissioning of light water reactors with the guidance and cooperation of all concerned parties. We will continue to utilize our experience as a PWR manufacturer to cooperate with electric power companies and their affiliated companies to promote safe and rational decommissioning.

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