Estimation of the reasons for high dose rate not being observed in Unit 2 reactor building cooling water system

■ 1. Introduction

In the air dose rate survey of Unit 1, high dose rate was observed near the piping of the reactor building cooling water (RCW) system in the reactor building (R/B) and in the radioactive waste treatment building (Rw/B) (Unit 1 Issue-9). These observations are believed to be a result of molten fuel falling into the containment vessel (PCV) and damaging the RCW piping that cools the equipment drain sump in the pedestal, causing radioactive materials to migrate into the RCW piping. This estimation is detailed in Attachment 1-9.

On the other hand, in the air dose rate survey for Unit 2, high dose rate was not observed around the RCW system in R/B and Rw/B as in Unit 1. The cause of this difference is discussed.

■ 2. Outline of the Unit 2 RCW system

The RCW system supplies cooling water to the drywell (D/W), R/B, Rw/B, and auxiliary units of the reactor installed in the turbine building so that each auxiliary unit can maintain its function. The RCW system consists of surge tanks, pumps, heat exchangers, etc., necessary piping and instrumentation. The cooling water that has exchanged heat with seawater in the RCW heat exchanger reaches each auxiliary machine through many branches, and the cooling water, heated by cooling each auxiliary machine, returns to the RCW heat exchanger to be cooled again by heat exchange before being supplied once more to each auxiliary machine in a closed cycle.

Since the RCW system has no openings to the reactor pressure vessel (RPV) or PCV, radioactive materials do not directly enter the system when the RCW system is not damaged, and high dose rate are not observed in the RCW piping or auxiliary equipment.

■ 3. Measurement results of air dose rate for Unit 2 R/B and Rw/B

Figures 1 to 4 show the air dose rate measurement results for Unit 2 R/B 2nd to 4th floors and Rw/B 1st floor announced by TEPCO. Although dose rate was not necessarily measured at the same time in Units 1 and 2, the figures indicate that high dose rate tended to be observed around the equipment loaded in the RCW system of the Unit 1 R/B, as described in Attachment 1-9, while this high dose rate tendency was not observed around the same equipment in Unit 2.

In addition, for the purpose of contrasting the contamination situation in the Unit 1 RCW system equipment listed in Attachment 1-9, Table 1 summarizes the air dose rate around the RCW heat exchangers, the drywell dehumidification system (DHC) equipment, recirculation system (PLR), the MG set oil coolers, the RCW surge tank, and the recirculation coolers for waste collection filters. Although it is not appropriate to simply compare the same equipment between Units 1 and 2 because the locations of each piece of equipment in the buildings differ between Units 1 and 2 and the piping routings are also different, it can be seen, for example, that the dose rate for the RCW heat exchanger installed on the same 2nd floor was lower in Unit 2 than in Unit 1.

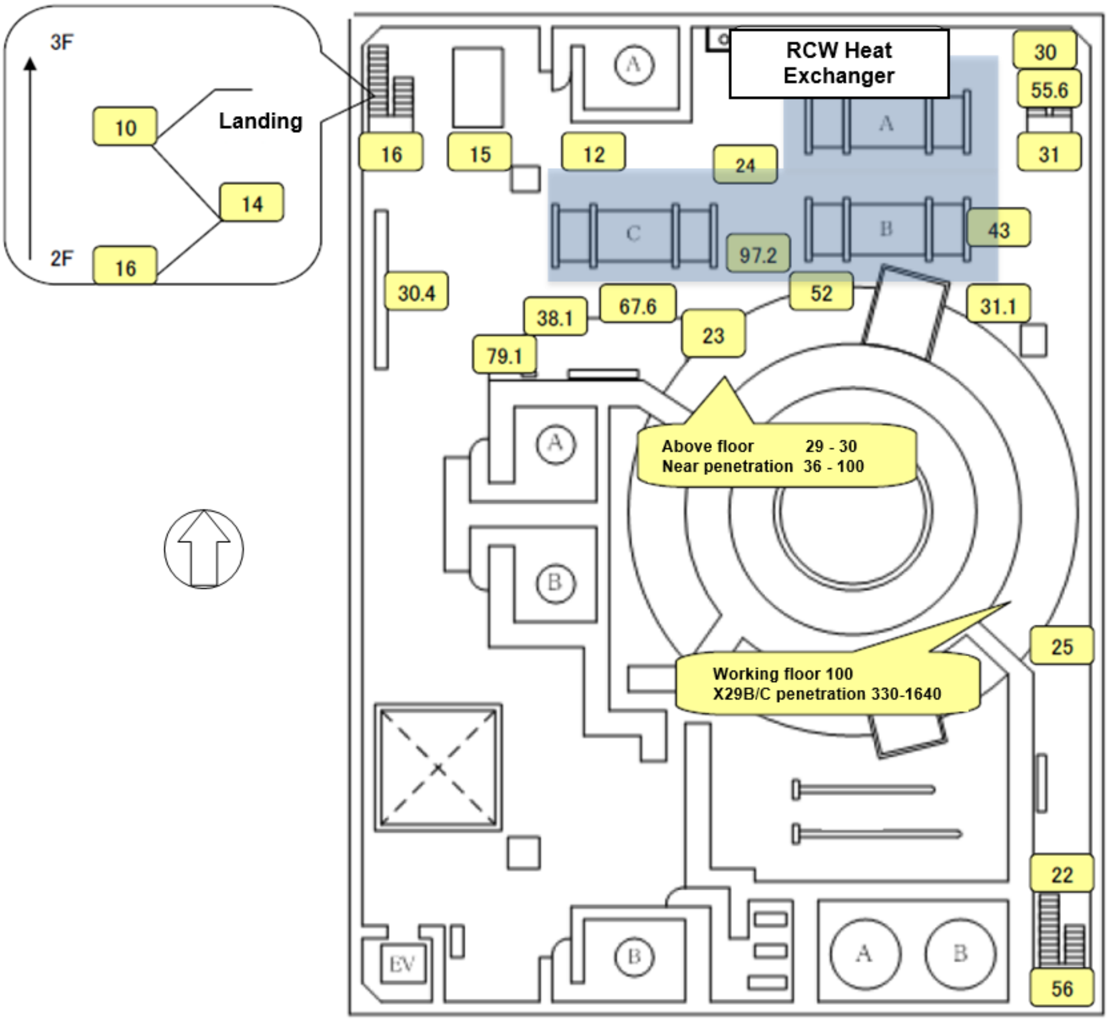


Figure 1 Air dose rate at the 2nd floor of Unit 2 R/B (unit: mSv/h) [1]

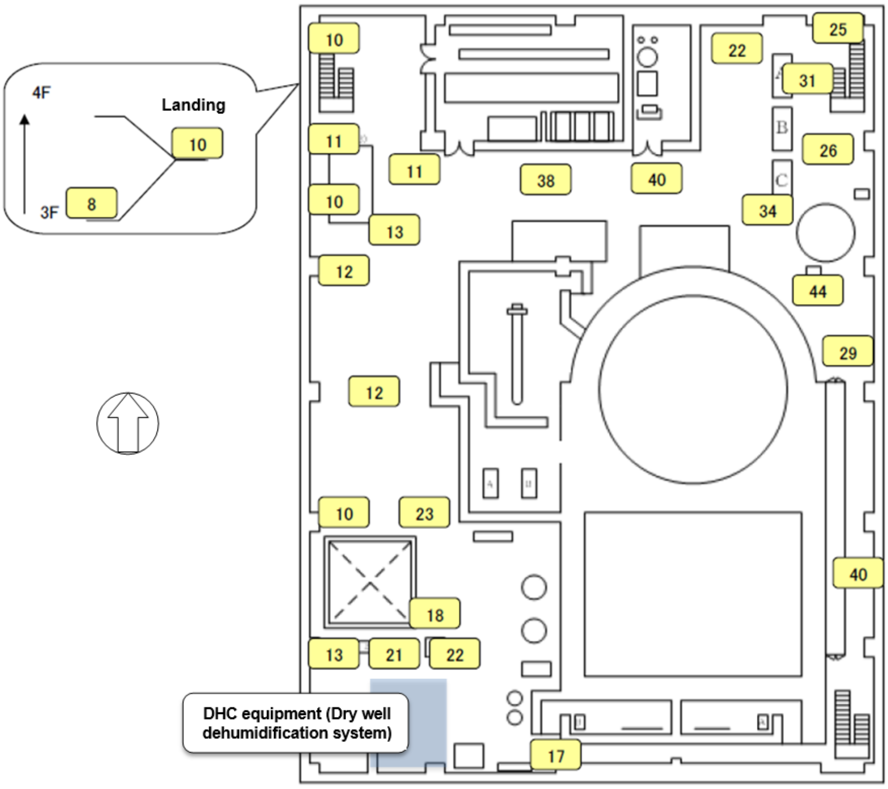


Figure 2 Air dose rate at the 3rd floor of Unit 2 R/B (unit: mSv/h) [1]

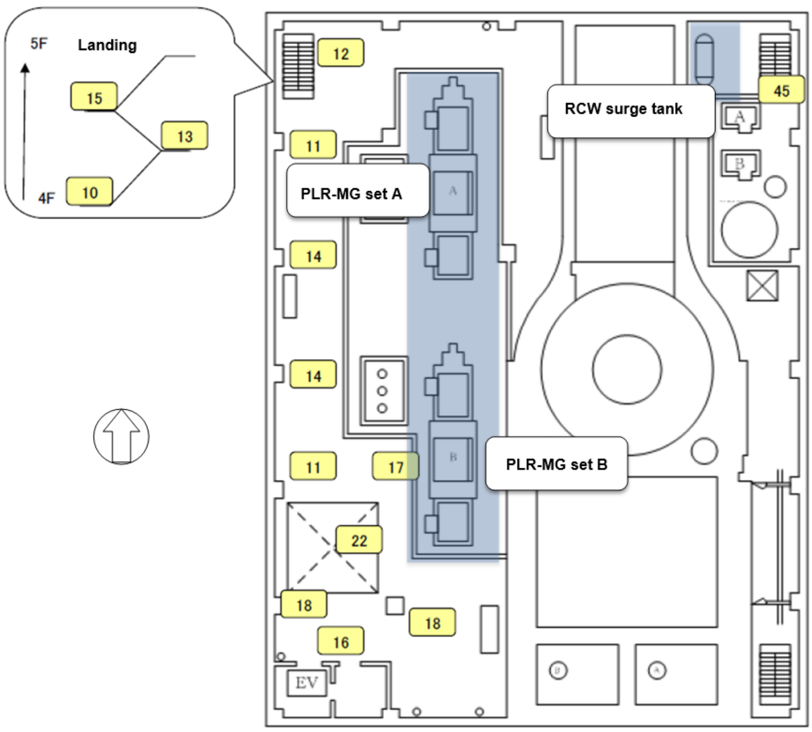


Figure 3 Air dose rate at the 4th floor of Unit 2 R/B (unit: mSv/h) [1]

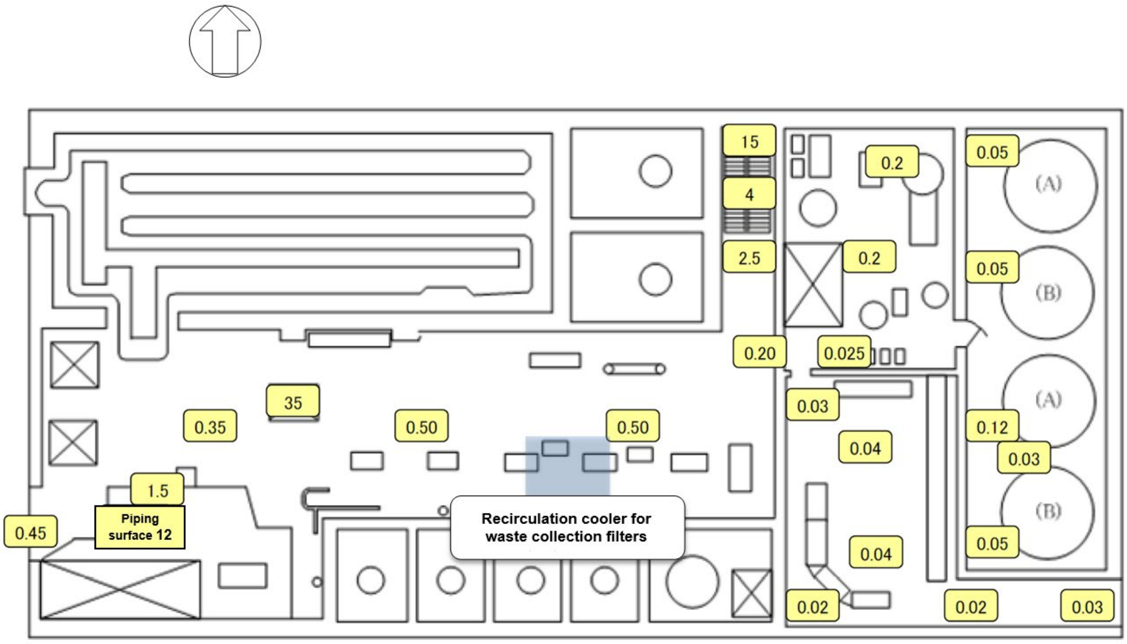


Fig. 4 Air dose rate at the 1st floor of Rw/B, Unit 2 (unit: mSv/h) [1]

Table 1 Comparison of RCW system contamination status

Equipment	Unit 1	Unit 2
RCW heat exchangers	Above 1000mSv/h (R/B 2nd floor)	About 100mSv/h (R/B 2nd floor)
Drywell dehumidifying system (DHC) equipment	About 100mSv/h (R/B 1st floor)	About 20mSv/h (R/B 3rd floor)
MG-set oil cooler for recirculation system (PLR)	About 150mSv/h (R/B 3rd floor)	About 20mSv/h (R/B 4th floor)
RCW surge tank	About 90mSv/h (R/B 4th floor)	About 45mSv/h (R/B 4th floor)
Recirculation coolers for waste collection filter	About 350mSv/h (Rw/B 1st floor)	About 0.5mSv/h (Rw/B 1st floor)

Note: If dose rate measurement near the target equipment was not available, the dose rate for the nearest location was listed.

The highest dose measured near MG Set B (R/B 3rd floor) is listed because MG Set B has the strong influence of the dose from the RCW heat exchanger near MG Set A (R/B 2nd floor) in Unit 1 (see Attachment 1-9). MG sets A and B of Unit 2 were located adjacent to the 4th floor of R/B.

■ 4. Discussion on the reasons for the lack of contamination in the Unit 2 RCW system

The PCV isolation valve in the Unit 2 RCW system is a motorized valve. The valve is considered to be open for the following reasons.

・The system did not have an interlock, so it did not close automatically before the tsunami arrived.
・After the tsunami arrived, both AC and DC power sources were lost, so operation was no longer possible.
・There was no record of manual closing.

Based on the analysis of the accident progression in Unit 2 and the results of the on-site investigation, it is estimated that some fuel debris has fallen to the bottom of the PCV in Unit 2. The RCW system in Unit 2 is used to cool the equipment drain sump at the bottom of the RPV pedestal, as in Unit 1.Therefore, as in Unit 1, there was a possibility that the RCW piping would be damaged by fuel debris that fell to the bottom of the PCV, causing radioactive materials to enter the RCW system and contaminate the RCW system in the R/B. However, unlike Unit 1, no contamination was observed around the RCW system in R/B in Unit 2, and the reasons for this lack of contamination have not been identified. In this regard, based on the results of an internal PCV investigation of Unit 2 conducted in January 2018, the following reasons were estimated.

In Unit 2, a telescopic survey device was inserted in January 2018 from the X-6 penetration along the CRD replacement rail and a camera was suspended down from the missing grating on the platform in the pedestal to observe the pedestal floor [2].

The images obtained from the survey showed that sediments were spread over the entire bottom of the pedestal (Figure 5). In addition, as shown in Figure 6, the upper tie plate of the fuel assembly can be seen as having fallen to the pedestal floor. Assuming that the fuel debris also fell through the hole in the RPV through which the upper tie plate fell, the deposits near the upper tie plate that fell to the pedestal floor are considered to contain fuel debris. Although the height of the deposits varies depending on the location, the deposits including fuel debris are spread over the entire pedestal floor, and thus the deposits are considered to have fallen and accumulated in a somewhat fluid state.

In relation to fluidity, the temperature of material deposited on the pedestal floor as it fell is qualitatively estimated from the state of damage to structures at the bottom of the PCV. No noticeable damage, including thermal effects, has been observed on structures such as cable trays located all around the walls in the pedestal and the CRD exchanger lifting trolley in the center of the pedestal. Therefore, it is considered that the temperature of the sediments containing fuel debris did not reach the melting point of those structures or the temperature that would cause significant deformation of the structures from the time of the accident to the present.

The RCW piping in the D/W of Unit 2 is routed from outside the pedestal into the pedestal through the worker access opening of the pedestal. The RCW piping is routed along the inner wall side of the pedestal at a height of about 40 to 50cm above the floor, and then led into the equipment drain sump. Figure 7 shows the area around the equipment drain sump in Unit 5. Unit 2 has a similar structure. It can be seen that the RCW piping is leading into the equipment drain sump.

As shown in Figure 8, the area near the worker access opening is an area where sediments may have accumulated higher than the surrounding area (there is a damaged opening of the RPV directly above and sediments including fuel debris may have fallen from above). The top of the cable tray is approximately 70cm high, and sediments appear to be deposited above it as well, which suggests that it is higher than the approximately 40-50cm height of the CRD changer lifting cart buried near the center of the pedestal. Therefore, it is quite possible that the RCW piping is in contact with sediments including fuel debris deposited at the bottom of the pedestal.

The potential for damage to RCW piping is shown below in comparison to cable trays. The cable tray is made of stainless steel (melting point: about 1450°C) that is about 4mm thick. Since no deformation was observed within the surveyed area, the temperature of the sediment including fuel debris when it started to accumulate on the cable tray may not have been high enough to cause thermal deformation of the cable tray.

The RCW piping in the pedestal is made of carbon steel (melting point: about 1500°C) that is about 3.7mm thick. It has about the same thickness and melting point as the cable tray. Similarly, the RCW piping was not damaged by contact with deposits containing fuel debris, and as a result, it is considered that radioactive materials did not enter the RCW system.

The lid (checker plate) of the equipment drain sump is made of carbon steel (melting point: about 1500°C) that is about 3mm thick. Although the thickness is slightly thinner than that of the cable trays and RCW piping, it has not been confirmed that the height of deposits is particularly low at the equipment drain sump position. Based on these facts, it is not possible that the lid of the equipment drain sump was severely damaged by the thermal effects of the sediments containing fuel debris, and that a large amount of sediments entered the sump. The equipment drain sump lid has a notch to guide the RCW piping, and it is possible that sediments including fuel debris entered the equipment drain sump through the notch (see Figure 7). However, even if the sediments came in contact with the RCW piping in the sump, the temperature of the sediments was not high enough to damage the RCW piping, as described above.

The air dose rate and temperature in the lower part of the pedestal were also measured during the containment interior survey in January 2018, and there was almost no change in the dose and temperature conditions when approaching the pedestal floor from the platform (air dose rate, 7-8 Gy/h; temperature, 21.0 °C, which were almost constant regardless of the location in the height direction (Figure 9). In other words, the contribution of the radiation dose from the sediments including the fuel debris that fell on the pedestal floor and the contribution as a heat source are not considered to be large at present.

Similarly, dose rate and temperatures in the height direction in the lower part of the pedestal were measured during the February 2019 PCV interior survey, and while there were a slight increase in air dose rate as the floor surface was approached and a slight decrease in temperature, the changes were generally not significant (Figure 10). Together with the fact that there was no noticeable damage to the structure below the pedestal, it is possible that the fuel debris on the pedestal floor is metal-rich with a relatively small dose and decay heat.

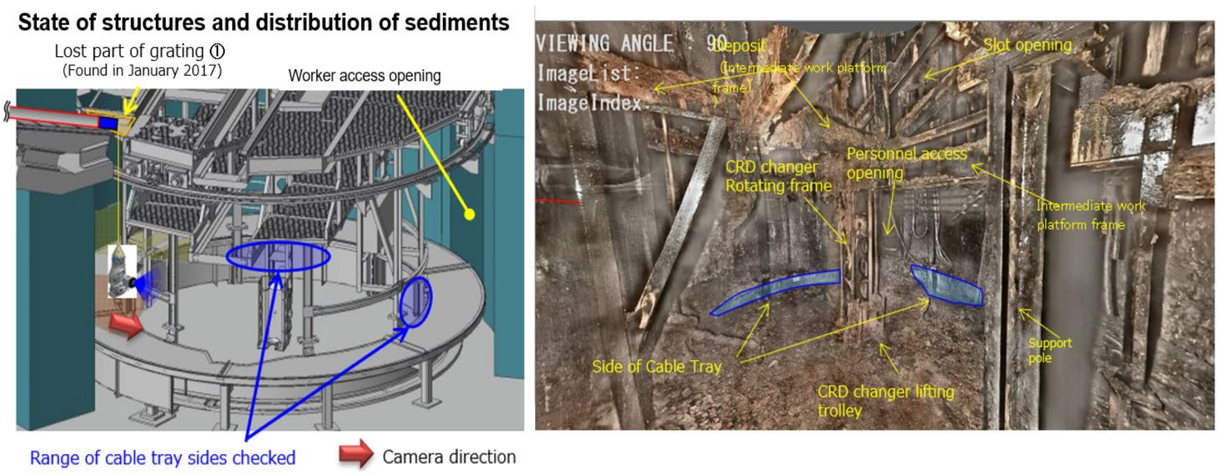


Figure 5 Unit 2, bottom of pedestal (part 1) [2]

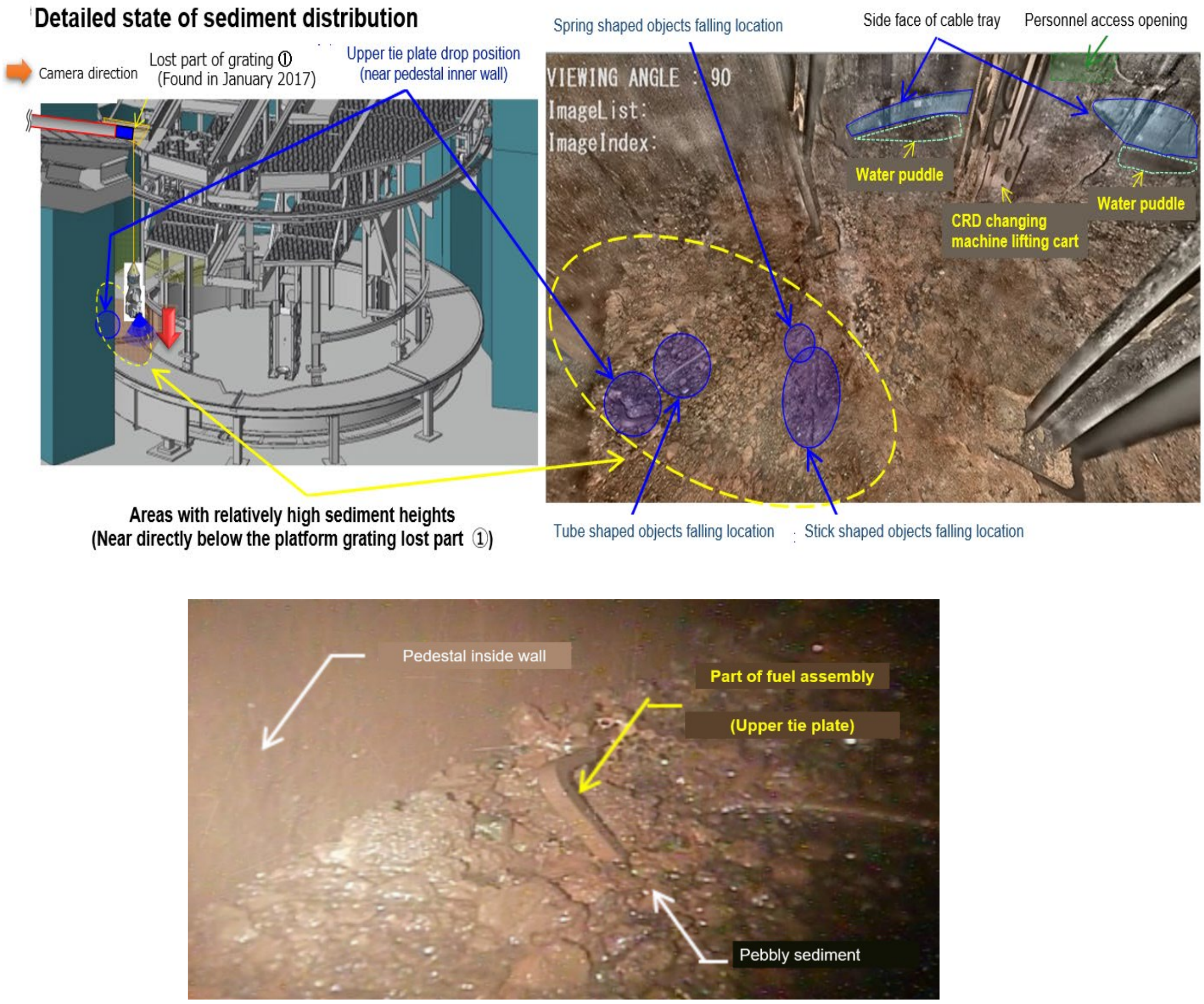


Figure 6 Unit 2, bottom of pedestal (part 2) [2]

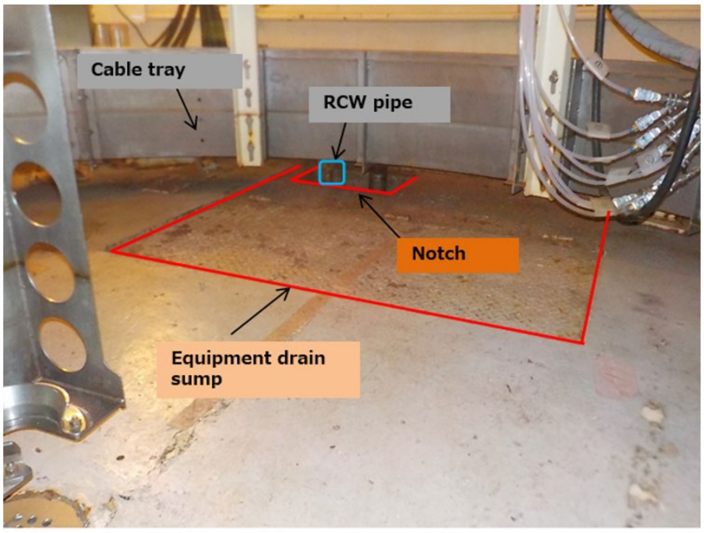


Figure 7　Unit 5 equipment drain sump area (similar structure in Unit 2)

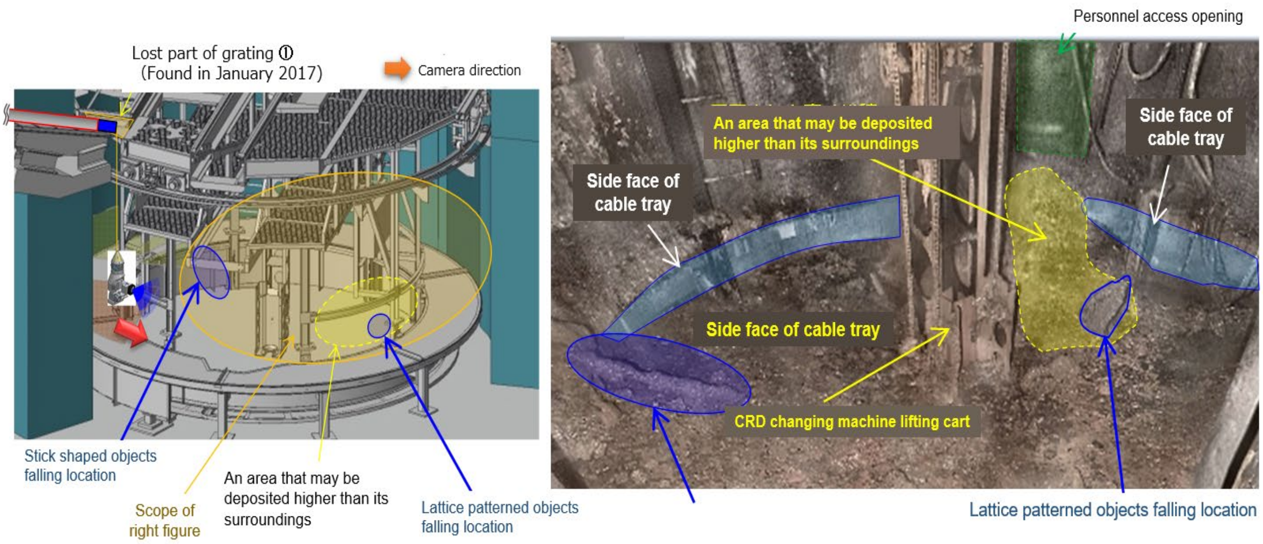
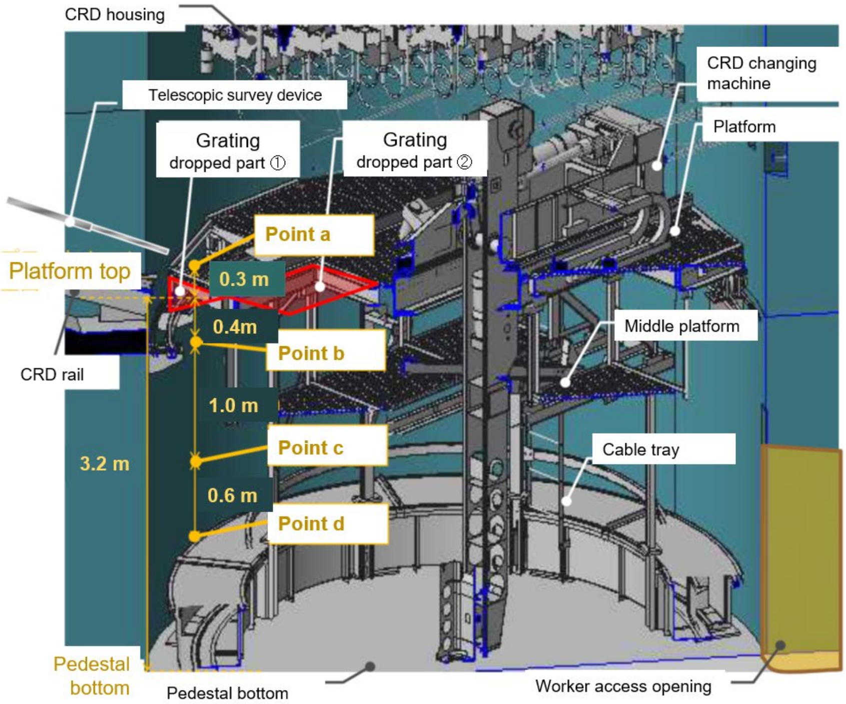


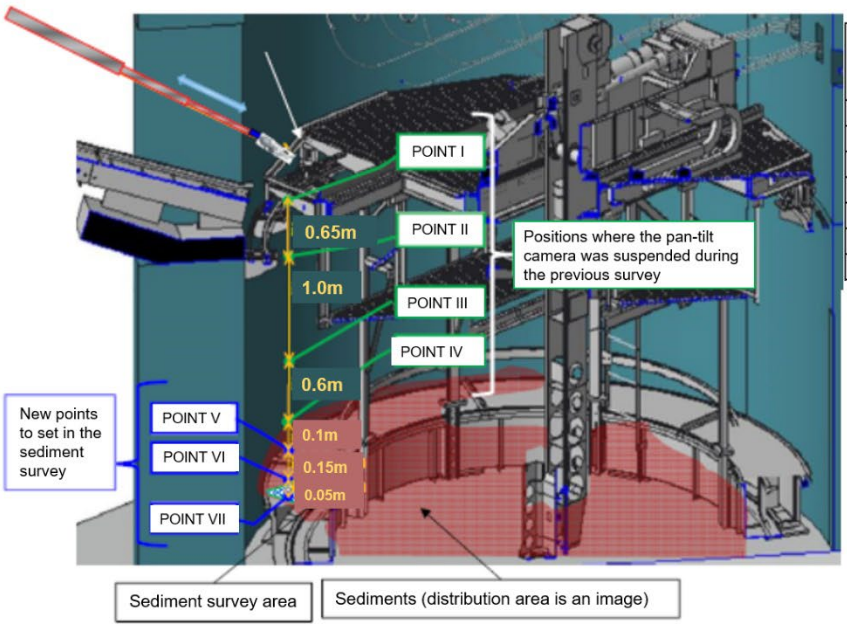
Figure 8　Unit 2, bottom of the pedestal (part 3) [2]



Measuring point	Dose rate *1,2 [Gy/h]	Temp.*2 [℃]
a	7	21.0
b	8	21.0
c	8	21.0
d	8	21.0

＊1: Calibrated by Cs-137 source
＊2: Errors: dosimeter ±7%; thermometer ±0.5℃

Figure 9 Unit 2, dose rate and temperature measured during investigation inside PCV [2]



Measuring point	Dose rate *1,2 [Gy/h]	Temp.*2 [℃]
I	6.4	23.2
II	6.8	23.1
III	6.5	23.1
IV	7.0	22.9
V	7.2	22.8
VI	7.5	22.9
VII	7.6	22.9

(Ref: Outside the pedestal*3)
Dose rate : Max. 43 [Gy/h]
Temp. : Max 23.7 [℃]

＊1: Calibrated by Cs-137 source
＊2: Errors: dosimeter ±7%; thermometer ±0.5℃
＊3: Reference values as measurements were taken with the instrument housed in the survey equipment.

Figure 10 Unit 2, dose rate and temperature measured during investigation inside PCV [3]

It is thought that the contamination spread throughout the entire RCW system in Unit 1 because the PCV pressure was high at the time when the RCW piping to cool the equipment drain sump was thought to have been damaged, i.e., when the RPV was damaged and fuel debris fell to the PCV floor.

Therefore, it is necessary to consider the possibility that the RCW piping was damaged when the fuel debris fell to the PCV floor, but the PCV pressure was not high after that time and contamination did not spread into the RCW system as a factor in the lack of contamination in Unit 2. Thus, the following section discusses when the fuel debris was thought to have fallen into the PCV and what kind of PCV pressure conditions existed after that time that could have allowed contamination to enter the RCW system.

The RCW system is a closed-loop design, and the surge tank, which is located at the highest point in the system to absorb volume changes due to temperature changes of the fluid in the system, is on the 4th floor of the R/B and the top of this tank is open to the atmosphere. The RCW piping leading to the equipment drain sump on the PCV (D/W) floor is the lowest elevation in the system, and the PCV pressure must be higher than the hydraulic head pressure on the RCW system side in order for contamination to spread into the RCW system if the piping were to break due to contact with fuel debris on the D/W floor. Since the height of the D/W floor is O.P. 5480 and the height of the bottom of the surge tank on the 4th floor of the R/B is O.P. 37450, the difference in height between the two is about 32m, which translates to a pressure of about 32 mH_2O if rectified to a water column. In reality, given this and other uncertainties such as pressure loss in the piping, it is considered that at least enough PCV pressure to overcome the water head pressure of about 32 mH_2O is required for contamination to spread in the RCW system.

Then, Figure 11 shows the measured dose rate from the RPV pressure and PCV pressure and the containment atmosphere monitoring system (CAMS) in Unit 2. During the accident, the maximum value of D/W CAMS among those measured was 138Sv/h at 16:10 on March 15, indicating that the dose rate increased rapidly between 13:00 and 15:25 on March 15. As detailed in Attachment 2-11, this increase in dose rate may have been caused by damage to the bottom of the RPV. In terms of pressure changes, there was a large pressure difference of about 0.3MPa between the RPV pressure and the D/W pressure at 13:00 on March 15, but both pressures equalized at 15:25 (the RPV pressure was lower than the D/W pressure because of the high temperature in the D/W due to the accident and the water level in the RPV pressure measuring pipe). One of the reasons for the RPV pressure and D/W pressure equalizing is the possibility of a large leakage from the RPV to the D/W. In other words, the bottom of the RPV may have been damaged between 13:00 and 15:25 on March 15.

In addition to the fact that no data were measured between 13:00 and 15:25 on March 15, because a gas phase leak from D/W to R/B is considered to have occurred at that time and the Suppression Chamber (S/C) was considered to have been externally cooled from the beginning of the accident because the Torus room was flooded by the tsunami, it is difficult to predict the D/W pressure at the time when the bottom of the RPV was damaged and the RCW piping and deposits including fuel debris would have contacted each other near the D/W floor.

The D/W pressure at 13:00 on March 15 was about 0.315MPa[gauge] when converted to gauge pressure, excluding the atmospheric pressure (about 0.1MPa[abs]), or about 31.5 mH_2O in the water column.

Compared to the water head pressure on the RCW system side, which is about 32 mH_2O, the above mentioned D/W pressure values are about the same. Since there is a possibility that the bottom of the RPV was damaged when the D/W pressure increased and the RCW piping came in contact with the sediment containing fuel debris shortly afterwards, or that the D/W pressure increased with the RPV damage and the RCW piping came in contact with the sediment containing fuel debris shortly afterwards, it remains possible that the D/W pressure exceeded the hydraulic head pressure of the RCW system at the time when the piping and the sediment containing fuel debris are thought to have contacted. Conversely, since the leakage from D/W to R/B had occurred by this time, and in addition, the S/C was thought to have been cooled externally by water that had entered the torus room, it is possible that the D/W pressure was below the water head pressure on the RCW system side by the time the deposits including fuel debris were thought to have contacted the RCW piping.

After this, the D/W pressure basically decreased monotonically and tended to approach atmospheric pressure, as shown in Figure 12.

Discussion was made on "the possibility that the RCW piping was damaged when the fuel debris fell to the PCV floor, but the PCV pressure was not high after that and contamination did not spread into the system" combined with the assumed accident progression and acquired plant data. However, this possibility still remains after all efforts.

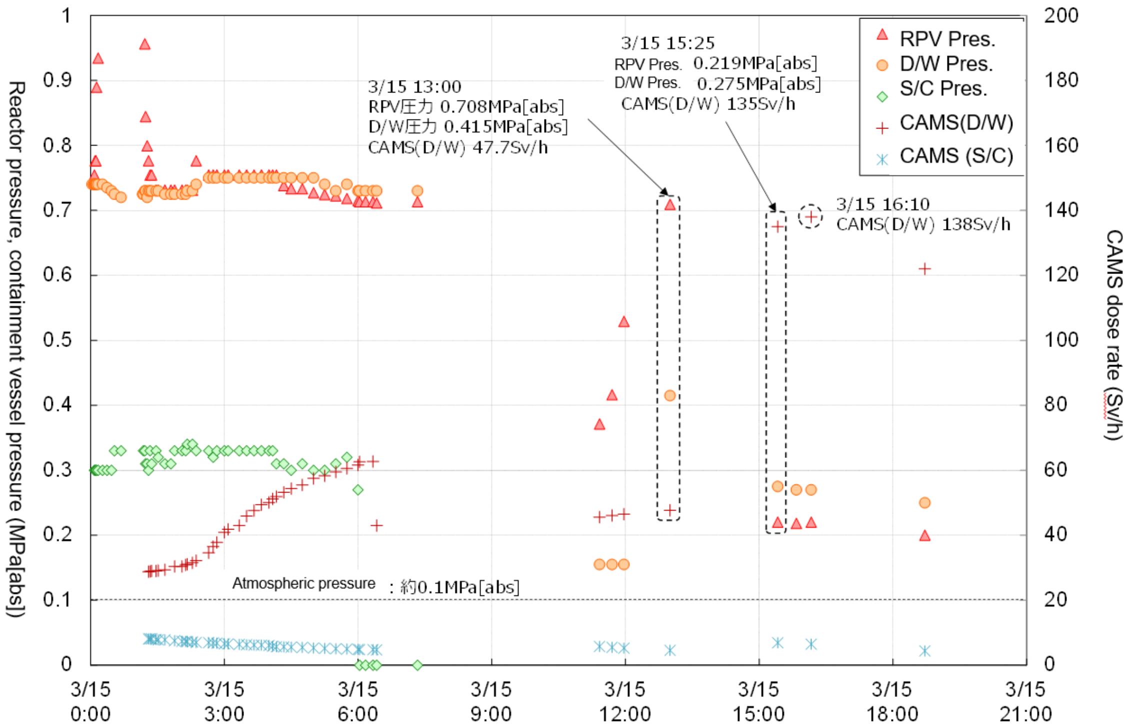


Figure 11 RPV pressure, PCV pressure, and CAMS measurements of Unit 2 (part 1)

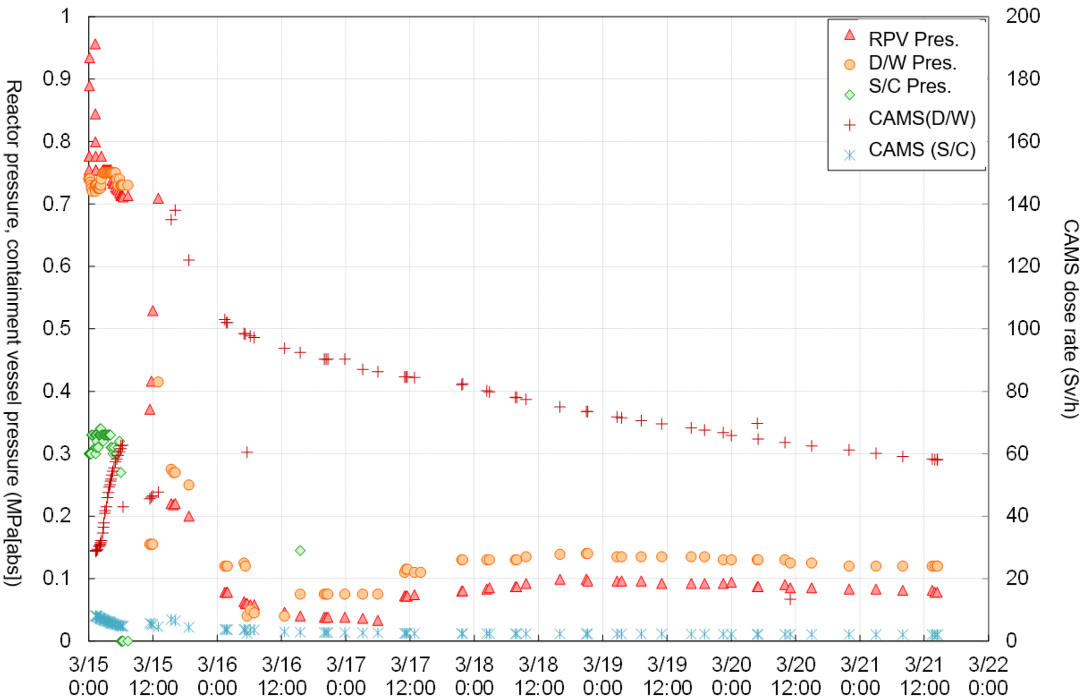


Figure 11 RPV pressure, PCV pressure, and CAMS measurements of Unit 2 (part 2)

- 5. Relationship to safety measures at the Kashiwazaki-Kariwa Nuclear Power Station (NPS)

Based on the previous discussion, it is assumed that the reason why no contamination was observed in the RCW system of Unit 2 is because, unlike Unit 1, the RCW piping that cools the drain sump was not damaged (although the same piping was damaged, it is still possible that contamination did not spread within the RCW system because the PCV pressure was not high). On the other hand, since contamination was observed in the RCW system of Unit 1, prevention of contamination spreading due to damage to the RCW piping that cools the drain sump is an important safety measure for restoration operations at the Kashiwazaki-Kariwa NPS.

At the Kashiwazaki-Kariwa NPS, RCW system piping that penetrates the PCV has PCV isolation valves (or check valves) installed both inside and outside the PCV at locations close to the PCV penetration (Figure 13). These valves are designed to detect a drop in the reactor water level or an increase in D/W pressure and automatically isolate, and by closing them before the RPV fails and molten fuel migrates to the lower D/W (check valves prevent backflow from inside the PCV to the outside), the spread of contamination to piping outside the PCV is prevented. In addition, the drive power supply for the PCV isolation valves described above is enhanced by a gas turbine generator, inter-unit power supply and power truck, which improve the reliability of the isolation operation. The D/W sump has a line for transferring sump water outside the PCV, and this line is equipped with isolation valves with automatic isolation functions inside and outside the PCV penetration, as in the RCW system.In addition, a corium shield is installed in the lower D/W to prevent molten fuel from entering the sump.

In addition to the above equipment measures, the operational procedure to cool molten fuel dropped into the lower D/W by filling the lower D/W with water and maintaining the water level before the RPV is damaged has been in place since before the Fukushima Daiichi NPS accident. In addition to the MUWC system that has been in place at Kashiwazaki-Kariwa NPS Units 6 and 7, a water injection method using fire trucks has been implemented to improve the reliability of the lower D/W water injection and reduce the risk of piping damage that could lead to the spread of contamination.

It is believed that the above measures will prevent the spread of contamination caused by damage to the RCW piping that cools the drain sump.

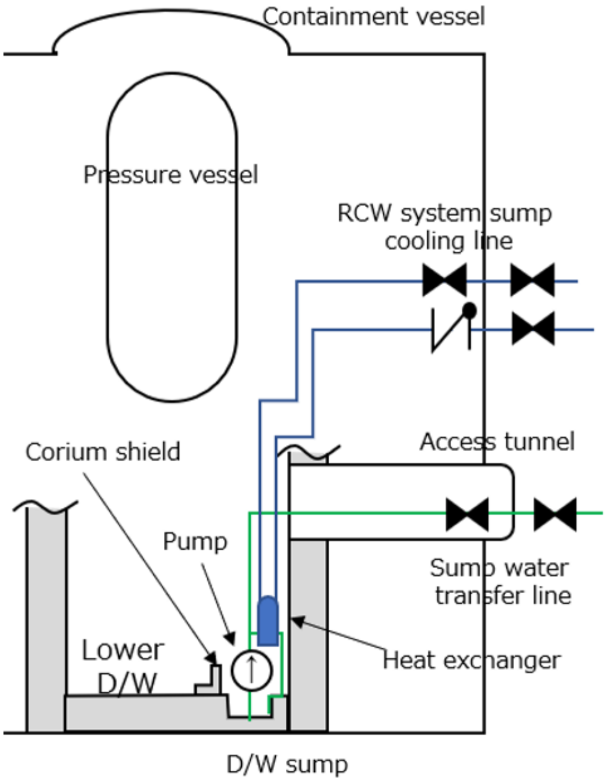


Figure 13 Isolation valves in RCW system and sump water transfer line

■ 6. Summary

The reasons why high dose rate were not observed in the RCW system in Unit 2, unlike in Unit 1 were examined. As a result, it is considered that the RCW piping in the pedestal was not damaged like other structures at the bottom of the pedestal and did not lead to a situation where radioactive materials were mixed into the RCW system, although it is quite possible that the RCW piping in the pedestal came into contact with deposits including fuel debris deposited at the bottom of the pedestal.

However, as an uncertainty at this time, there remains the possibility that contamination did not spread within the RCW system due to low D/W pressure, although the RCW piping was damaged.

Efforts will continue for the study of this possibility by utilizing information obtained as the decommissioning work progresses.

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