Attachment 2-16

Decrease in Unit 2 containment vessel pressure in the morning of March 15

This document is a study related to the containment gas phase leakage listed in "Unit 2-11" in the list of issues to be studied in Appendix 2, and is based on the study commissioned by TEPCO to TEPCO Systems, Inc.

■ 1 Introduction

As shown in Figure 1, the D/W pressure in Unit 2 remained above 0.7MPa[abs] from around 23:30 on March 14 to 07:20 on March 15, after which the measurement was temporarily interrupted and dropped to 0.155MPa[abs] when the measurement was restarted at 11:20 on the same day.

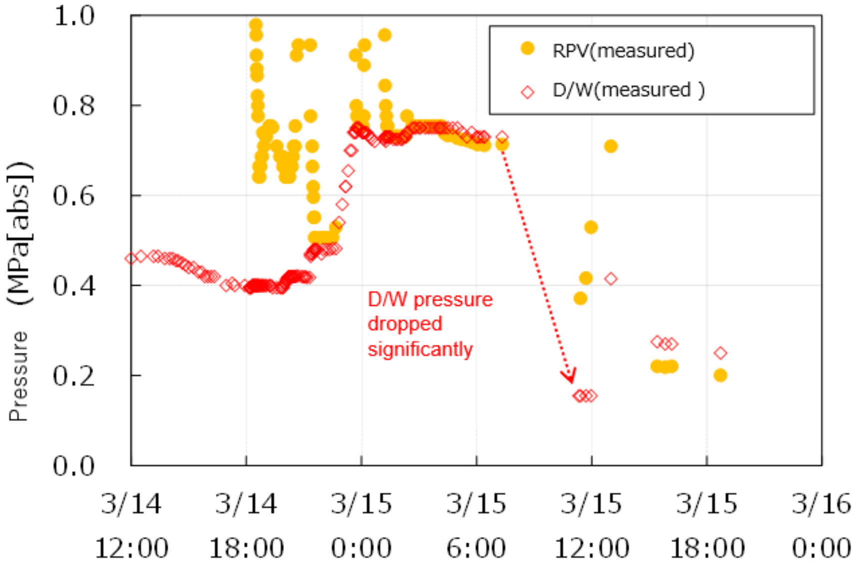


Figure 1 Trends in containment pressure (Reference: Reactor pressure)

The D/W pressure had reached a maximum of 750kPa[abs] since the increase at around 22:40 on the 14th, which is the maximum pressure experienced by the Unit 2 containment vessel during the accident in the recorded data. Since high radiation doses were measured around the shield plug in Unit 2 after the accident [1], and since leakage from the top head flange was likely to have occurred at any point in time, and since the displacement of the containment top head flange increases as containment pressure increases, increasing the possibility of leakage, leakage from the containment top head flange might have already occurred during the period when this pressure was high.

See "10. Supplement" in the main body of this report for the O.P. description.

Subsequently, the D/W pressure decreased after 07:20 on the 15th. Possible causes for this could be that the gas phase leakage from the containment vessel expanded for some reason or that the containment vessel was cooled for some reason, which led to the condensation of water vapor in the containment vessel. In the following, the feasibility of each scenario is examined.

■ 2 Examination of depressurization scenarios due to gas phase leakage from the containment vessel

The scenario in which the containment vessel depressurized due to the expansion of gas phase leakage from the containment vessel for some reason after 07:20 on the 15th, was examined.

Attachment 2-9 shows the results of the analysis to reproduce the reactor pressure and containment pressure from the forced depressurization of Unit 2 at around 18:00 on March 14 to 02:00 on March 15 using the thermal-hydraulic analysis code GOTHIC. As an extension of that analysis, an analysis to reproduce the measured values including the period of depressurization up to 11:20 on the 15th was conducted to evaluate the gas phase leakage area required for depressurization and to discuss the accident progression assumed from the results. Unlike the depressurization scenario described below, that analysis did not consider the increase in containment cooling.

From the perspective of estimating the gas phase leakage area required to reproduce depressurization, it was assumed that the depressurization period was long and the amount of water vapor generated in the containment vessel was small so that the leakage area was minimized. In other words, although the time when depressurization started after 07:20 on the 15th is unknown, it was assumed here that the containment leak area expanded at that time, when the last measured value was obtained before the depressurization. The amount of gas produced in the pressure vessel from 07:20 to 11:20 on the 15th is unknown, but it was assumed here that no gas was produced. The leakage point from the containment vessel was assumed to be the D/W. The thermal-hydraulic analysis code GOTHIC8.2 (QA) was used for the analysis. The conditions of the analysis are shown in Appendix 1.

The analysis reproduced depressurization from 730kPa[abs] of D/W pressure to 155kPa[abs] by setting 300cm^2 (constant during depressurization) as the containment leakage area (Figure 2). The water temperature of the entire S/C pool was relatively high, and the depressurization boiling of the S/C pool produced a large amount of water vapor, which tended to make depressurization difficult in this analysis. In Figure 2, the pressure drop rate is seen to change. The reason why the pressure drop rate decreases after the inflection point is because depressurization boiling is occurring in the S/C pool. A large leakage area is required to release the water vapor formed by this process.

If the leak was caused by a larger gap at the top head flange of the containment vessel due to high pressure, the leak opening would be expected to close as the containment vessel pressure decreases. In this scenario, where a large leakage area must be maintained during depressurization, it is necessary to consider that the leakage from the containment was caused by thermal damage to the seals and other parts due to high temperature.

In addition, according to the results of the structural analysis of the MARK-I containment vessel shown in Figure 3 [2], the opening area of the top head flange is about 210cm^2 even under the conditions of high pressure and high temperature (750kPa[abs], 400°C assumed), which is the extent that can be expected before depressurization, even if the silicone rubber of the sealing section is considered absent. Furthermore, at lower pressures, the displacement of the top head flange is smaller and the opening area decreases.

Therefore, in this scenario, where the leakage area of 300cm^2 must be maintained throughout the depressurization, it is necessary to consider that there was a reasonable amount of leakage from other areas than the top head flange.

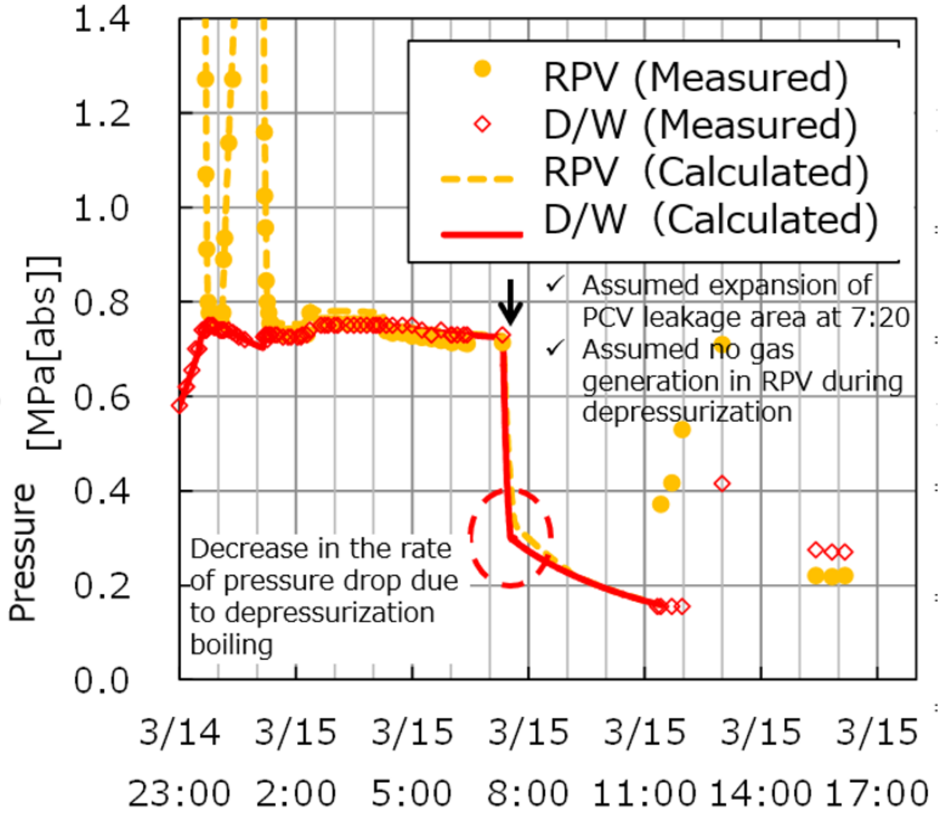


Figure 2 Analysis results given containment leakage area that reproduces D/W depressurization

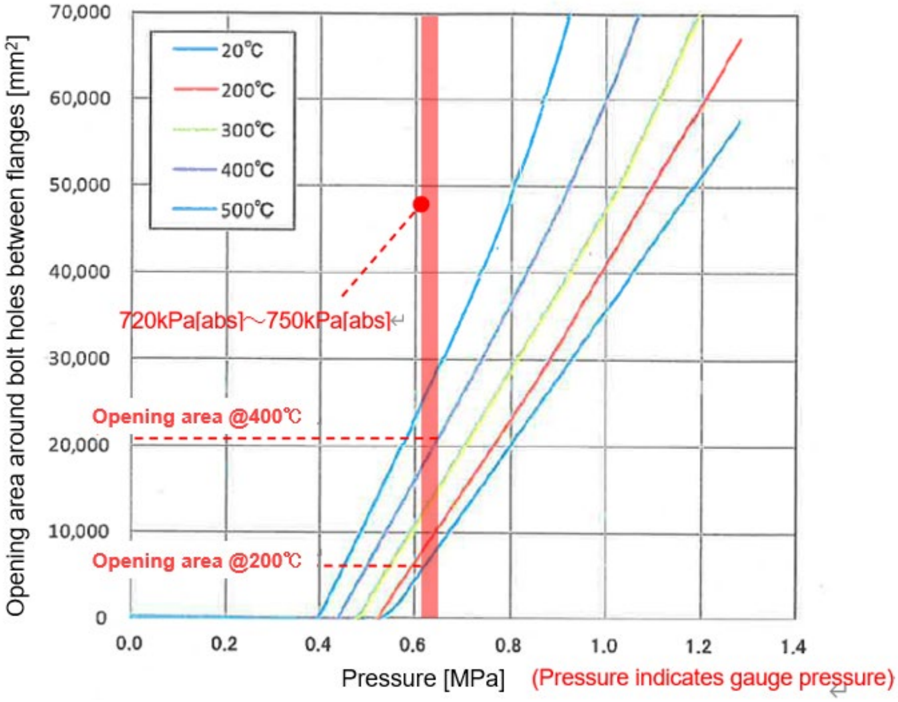


Figure 3 Results of evaluation of the opening area of the gap at the outermost circumference of the flange [2]

(Red characters and red colored areas are superimposed on the figures cited above.)

■ 3 Examination of the scenario in which depressurization due to condensation of water vapor in the containment vessel contributed to depressurization in addition to depressurization due to gas phase leakage from the containment vessel

As mentioned earlier, gas phase leakage from the containment vessel is considered to have occurred at some point after the D/W pressure increase at around 22:40 on the 14th. In addition to the gas phase leakage, a scenario was examined in which the containment vessel depressurized due to accelerated condensation of water vapor in the containment vessel after 07:20 on the 15th.

■ 3.1 Assumption of a scenario in which condensation of water vapor in the containment vessel is accelerated after 07:20 on the 15th

In order for condensation of water vapor to be accelerated, it is necessary to consider that there was a mechanism for heat removal from the containment vessel. Specifically, the containment could be cooled by containment spraying by an external water source, etc., or the amount of heat removal from the containment wall could have increased.

In Unit 2, it is thought that decay heat was brought into the S/C via the exhaust from the RCIC turbine during RCIC operation, but it has been confirmed that the containment pressure until the 14th was lower than the pressure estimated from the supply of that decay heat, and that the RCIC room and the basement floor of the turbine building were flooded soon after the accident; and the current water level behavior of the retained water in each building allows the conclusion to be made that water was moving between buildings. It was estimated that the torus room was flooded and the S/C was cooled from the outside (Attachment 2-2).

Based on this, the possibility is considered that the containment pressure drop after 07:20 on the 15th might have been caused by a change in the cooling situation from outside the S/C. As long as the water level in the torus room is lower than the S/C pool water level, the S/C wall in contact with the S/C gas phase section radiates heat to the air in the torus room, and the amount of heat radiated is determined by the natural convection heat transfer coefficient of the air in the outer S/C wall, making it difficult for cooling of the S/C wall to proceed. Therefore, the temperature of the S/C wall is the same as that of the S/C gas phase section, and condensation of water vapor in the S/C ga -phase section is considered to be unlikely to proceed. On the other hand, when the water level in the torus room exceeds the S/C pool water level, the S/C wall in the exceeded area is cooled by the torus room water from the outside, and the temperature difference between the S/C gas phase section and the inner wall increases, which may cause rapid water vapor condensation (Figure 4). When the S/C gas phase section is in a steam atmosphere, the amount of heat transferred per unit area and unit temperature difference can be 100 times greater with water than with air where the heat release destination from the S/C gas phase section is air or water. Therefore, it is necessary to sort out the relationship between the S/C water level and the torus room water level after 07:20 on the 15th.

・Water level in the torus room

As information on the water level in the basement floor of the reactor building, it was confirmed that the water level in and around the RCIC room was about the height of a pair of boots from around 01:00 to 04:00 on the 12th, and that the water level was on an upward trend [3]. The water level in the torus room, which is connected to the RCIC room by piping under the floor, may have been at the same level. Although the subsequent behavior of the water level in the torus room is unknown, it is possible that the water level would have risen continuously if there was an inflow of water from other buildings such as the turbine building.

・S/C water level

Based on the fact that the S/C water level had not reached the full level even after the post-accident water injection and the examination based on the actual S/C temperature measurements after the accident, it is assumed that a small-scale liquid phase leak occurred well below the S/C water surface or somewhere along the piping, possibly near or at the bottom of the S/C, although the timing is unknown (Attachments 2-8, 2-13 and 4). If there was leakage from the S/C pool, the possible leakage sites could include the torus room and the RCIC room, and it is conceivable that this leaked water might have contributed to the rise in the water level in the torus room.

As for the S/C water level, no actual measurements have been obtained since the recorder stopped functioning due to the arrival of the tsunami, but the height of the RCIC exhaust port is a clue for estimating the S/C water level at that time. As shown in Attachment 2-6, assuming that the RCIC exhaust stopped around 12:00 on the 14th in the analysis, the behavior of the measured reactor pressure is found to be well reproduced. If the S/C water level falls below the height of the RCIC exhaust port (about 2.9m from the bottom of the S/C) while the RCIC exhaust continues, the containment pressure would increase rapidly because the RCIC exhaust would be directly transferred to the S/C gas phase section. However, no such rapid rise in containment pressure has been observed during the period when the RCIC is thought to have been in operation. Therefore, even if there had been a leak from the S/C pool, the S/C water level would not have been below the lower end of the RCIC exhaust port by around 12:00 on the 14th. On the other hand, it is not possible to distinguish whether there was no leakage from the S/C pool at that time or whether there was leakage but the water level was still above the RCIC exhaust port, and even if there was no leakage from the S/C pool at that time. It is also possible that even if no leakage from the S/C pool occurred at that time, leakage could have occurred during the subsequent period until the containment vessel was depressurized after 07:20 on the 15th. Therefore, the water level behavior of the S/C pool is also unknown, but if there was a leak from the S/C pool, the S/C water level might have continuously decreased and the water level in the torus room might have continuously increased. Since both the amount of water brought into the containment vessel from an external water source (CST) due to RCIC operation and the amount of water transferred from the pressure vessel to the S/C via RCIC exhaust steam or SRV are limited, it is believed that the torus room water level might have exceeded the S/C pool water level regardless of whether or not there was a leakage from the S/C pool.

From the above, a possible scenario is "the water level in the torus room rose due to the inflow of water from other buildings and/or the leakage of water from the S/C pool. The water level in the torus room exceeded the level in the S/C pool after 07:20 on the 15th, which promoted cooling of the gas phase part of the S/C, and the condensation of water vapor was more advanced than before, resulting in a pressure drop.”

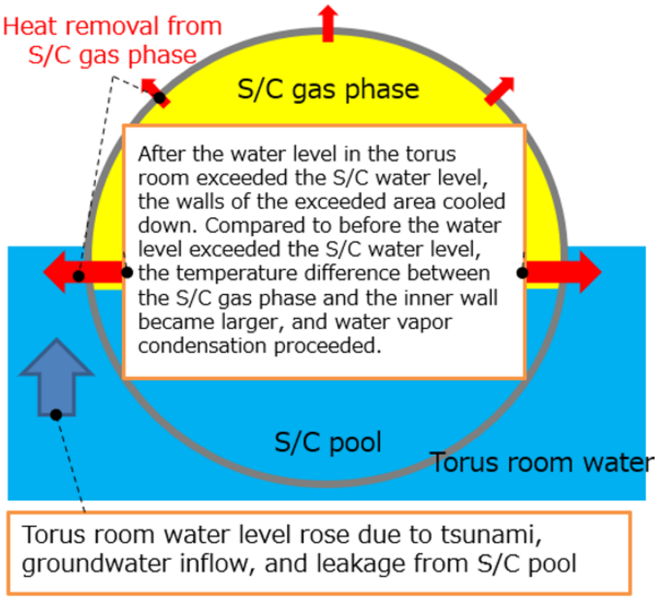


Figure 4　Image of rising water level in torus room

However, the following preconditions are necessary for this scenario to be valid.

① Most of the of non-condensable gas was discharged from the containment vessel before containment vessel depressurization after 07:20 on the 15th.

- ✧ Considering that the containment was depressurized by condensation of water vapor, non-condensable gas remained in the containment; therefore, it is necessary to consider that the amount of the non-condensable gas inside the containment from the stage before depressurization was small in order to depressurize to 155kPa[abs].
- ✧ In condensation of a mixture of water vapor and non-condensable gas, it is known that the greater the proportion of non-condensable gas, the lower the condensation heat transfer coefficient. For efficient condensation to occur, it is necessary to consider that the fraction of non-condensable gas was small.

② Temperature stratification must have occurred on the surface of the S/C pool at the stage before containment depressurization after 07:20 on the 15th.

- ✧ Based on the preconditions of ①, the containment vessel must have had a small amount of non-condensable gas, that is, the containment vessel must have been in a state of containing almost only water vapor, and the containment vessel pressure must have been maintained before depressurization. For this purpose, the temperature of the water surface of the S/C pool must be maintained at about the saturation temperature for the containment vessel pressure. On the other hand, if the temperature of the entire S/C pool is high, the amount of depressurization boiling would be large and it would be difficult to get depressurization, as shown in the results of the reproduced analysis shown in Section 2. Therefore, it is necessary to consider a situation where the temperature of the S/C pool surface is high, but the temperature of the pool as a whole is relatively low, that is, temperature stratification has occurred in the surface layer of the S/C pool.

■ 3.2 Examination of the feasibility of the scenario assumptions

It is examined whether the preconditions for the depressurization by the condensation scenario are satisfied; in other words “that most of the non-condensable gas in the containment vessel had been released and that thermal stratification had occurred on the surface of the S/C pool before depressurization after 07:20 on the 15th.”

First, regarding the possibility that most of the non-condensable gas in the containment vessel was released before the depressurization after 07:20 on the 15th, it is possible that the non-condensable gas in the S/C was transferred to the D/W via the vacuum break valve by the water vapor formed at the S/C water surface, and then most of it was discharged from the containment vessel via the top head flange of the D/W.

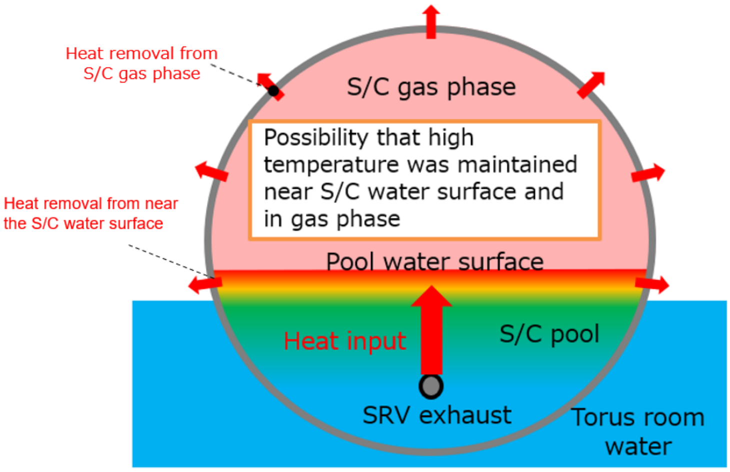
Next, regarding the possibility of temperature stratification in the surface layer of the S/C pool, at the time of the Great East Japan Earthquake, the reactor water level was maintained by the RCIC in Units 2 and 4 of the Fukushima Daini NPS while reactor depressurization was done by the SRV. At that time, a temperature difference occurred between the upper and lower portions of the S/C pool. In Unit 4, among others, the temperature difference occurred after RCIC isolation with the SRV open to maintain low reactor pressure. This suggests that temperature stratification can occur in the S/C liquid phase if the reactor pressure remains low and the SRV pumping rate remains small (the effect of SRV pumping to stir the S/C liquid phase is small).

In Fukushima Daiichi Unit 2, the reactor pressure decreased after the forced depressurization by SRV opening at around 18:00 on the 14th, and although it temporarily increased at around 21:00 and after 23:00 on the same day and at around 01:00 on the 15th, its pressure was lower than the rated pressure. Therefore, the SRV exhaust lacked momentum and was less effective in stirring the S/C pool, which might have caused the temperature difference between the bottom of the S/C pool and near the water surface to remain, and temperature stratification might have progressed in the same manner in Units 2 and 4 of the Fukushima Daini NPS.

The Mark-II type containment vessels used in Units 2 and 4 did not have a torus room outside the S/C and they were not designed to allow cooling of the S/C by stagnant water. Instead, in Fukushima Daiichi Unit 2, as mentioned above, cooling of the S/C is considered to have occurred due to water in the torus room. In the course of the water level in the torus room rising, when the water level in the torus room was lower than the S/C water level (Figure 5), the deeper part of the S/C pool than the surface layer was cooled, and the formation of a temperature difference with the pool surface layer might have been accelerated. Despite differences in the shape of the S/C pool and the SRV exhaust quencher, Fukushima Daiichi Unit 2 might have been even more prone to thermal stratification than Fukushima Daini Units 2 and 4, in that the lower part of the S/C is thought to have been cooled by water retained in the torus room.

As mentioned before, to maintain the containment pressure with less non-condensable gas before depressurization after 07:20 on the 15th, the temperature at the surface of the S/C water must be maintained at the saturation temperature for the containment pressure at that time. If the containment pressure before depressurization is 750kPa[abs], this can be achieved only with water vapor if the pool surface temperature is maintained at 168°C, which is the saturation temperature at that pressure. The SRV exhaust discharged into the S/C pool is expected to condense mostly to saturated temperature water, which rises due to the density difference with the surrounding water that is being cooled. If the amount of heat transferred to the S/C water surface is greater than the amount of heat removed from the vicinity of the S/C water surface and from the S/C gas phase, the S/C water surface temperature will be maintained at about the saturation temperature. If the amount of heat transferred to the S/C water surface is greater than the amount of heat removed from the S/C water surface and the S/C gas phase, it is possible that the temperature at the S/C water surface was maintained at about the saturation temperature and that water vapor was continuously generated to maintain pressure (Figure 5).

During the period before and after the depressurization after 07:20 on the 15th, no actual measurements of S/C water temperature, etc. were obtained. Therefore, no definite conclusion can be reached, but it is believed that the above situation can be established.



Assumes torus room water level was lower than S/C pool water level before depressurization

Figure 5　Image of temperature stratification of S/C pool before depressurization after 07:20 on the 15th

■　3.3　Evaluation of pressure behavior in the assumed scenario

Assuming that the water level in the torus room rose above the S/C pool water level after 07:20 on the 15th, an evaluation was made into how the containment pressure would change from 730kPa[abs] to 155kPa[abs] in 4 hours (the time required for depressurization is unknown, so the time from 07:20 to 11:20 when data were available was assumed) due to condensation by external cooling in the S/C gas phase. Then, the leakage area required to depressurize in 4 hours was evaluated.

In the evaluation, it was assumed that the containment vessel was filled with water vapor. It was also assumed that the decrease in energy in the containment before and after the depressurization from 07:20 to 11:20 on the 15th coincided with the balance of energy inflow into the containment (e.g., heat input from the pressure vessel and containment walls) and outflow from the containment (e.g., S/C external cooling, D/W gas phase leak) during that period. The evaluation conditions are shown in Table 1.

Since the behavior of the water level in the S/C pool and torus room is unknown, several cases were assumed as the water level difference between the S/C pool and torus room in this evaluation to confirm the impact. As other parameters, the amount of high-temperature water in the S/C pool (affecting the amount of depressurization boiling) and the condensation heat transfer coefficient of the inner wall of the S/C (affecting the amount of heat removal by external cooling) have large uncertainties and a large impact on the evaluation results, so sensitivity evaluations were conducted for these parameters. An image of the evaluation is shown in Figure 6.

The evaluation results are shown in Figures 7 and 8: the larger the water level difference between the S/C pool and the torus room, the more the condensation of the S/C gas phase part is promoted, and thus the leakage area required for depressurization decreases.

From Figure 7, if there is a small area of high temperature in the S/C pool, i.e., if temperature stratification occurs such that only the area near the S/C water surface is high, the amount of depressurization boiling will be less and the required leakage area will decrease.

Figure 8 shows that the larger the condensation heat transfer coefficient, the larger the condensation volume and the smaller the required leakage area. When water vapor condenses in an environment where only water vapor is present, the condensation heat transfer coefficient is very large, around 10kW/m^2-K or more. On the other hand, in condensation of a mixture of water vapor and non-condensable gas, it is known that the larger the ratio of non-condensable gas, the lower the condensation heat transfer coefficient. As an example, it has been confirmed that the condensation heat transfer coefficient is about 1.6kW/m^2-K when the mass ratio of water vapor to air is 10:1 and about 0.8kW/m^2-K when the mass ratio is 2:1, and that the condensation heat transfer tends to decrease as the ratio of non-condensable gas increases compared to the case of water vapor only [4].

Considering that the ratio of non-condensable gas is expected to increase with depressurization and that the concentration of non-condensable gas might increase near the wall where condensation occurs, it is necessary to consider that the ratio of non-condensable gas in the containment vessel at the stage after 07:20 on the 15th and before the containment vessel depressurization was reasonably low in order to maintain a high condensation heat transfer coefficient. The proportion of non-condensable gas in the containment vessel at the stage before containment vessel depressurization after 07:20 on March 15 must be considered to have been reasonably low in order to maintain high condensation heat transfer coefficient.

Table 1 Evaluation conditions (March 15, 07:20-11:20)

Item	Setting	Note
Period	4 hours	Assuming the period from 07:20 to 11:20 on the 15th
Pressure before change	730kPa[abs]	Set based on actual measurement values
Pressure after change	155kPa[abs]	Set based on actual measurement values
D/W	167℃	Assuming a saturation temperature of 730kPa[abs]

temperature		before depressurization: the change in D/W temperature during depressurization is considered small, and the same temperature is assumed before and after depressurization. The effect of D/W temperature on evaluation results is negligible.
Gas leakage from pressure vessel to D/W	Not taken into account	Since water vapor on the D/W side is considered to be drawn into the S/C pool and condensed as a result of depressurization due to condensation on the S/C side, the effect of gas leakage to the D/W on the evaluation results is thought to be limited and so not considered.
S/C pool water level (assumed constant during evaluation period)	5m	Considering the normal water level, the amount of water that is thought to have been injected from the CST before switching the RCIC water source and the water level that includes the amount of water held in the pressure vessel that has been transferred, it is assumed the S/C pool water level at the time of decompression from the bottom of the S/C is 5m. And it is assumed that since this is above the lower end of the vent pipe downcomer (2.875m from the bottom of the S/C), the steam in the D/W is drawn into the S/C liquid phase by the S/C depressurization and all of it condenses.
Water level difference between S/C pool and torus room (assumed constant during evaluation period)	0cm, 10cm, 100cm	Since the behavior of the rising water level in the torus room is unknown, the following water level differences are used: no water level difference (0cm); assuming that the torus room was flooded to the height of the basement floor of the turbine building in a short period of time (assuming an O.P. of 3400mm (since a water level of about 1.5m was confirmed on the basement floor of the turbine building on the 11th [3])), there is a water level difference of 100cm; and setting a water level difference between the two of 10cm.
Height of the area of saturated temperature in the S/C pool	0 to 5m	Since the temperature distribution of the S/C liquid phase is difficult to assume and is a source of uncertainty, the temperature distribution is simplified as shown in Figure 6, and the height of the region of saturation temperature is used as a sensitivity parameter to check the effect.
Condensation heat transfer coefficient	Cases in which the coefficient is set to 0 at 100% water vapor	Considering the possibility that the condensation heat transfer coefficient might decrease if non-condensable gas is present on the S/C wall, the effect is checked as a sensitivity parameter.

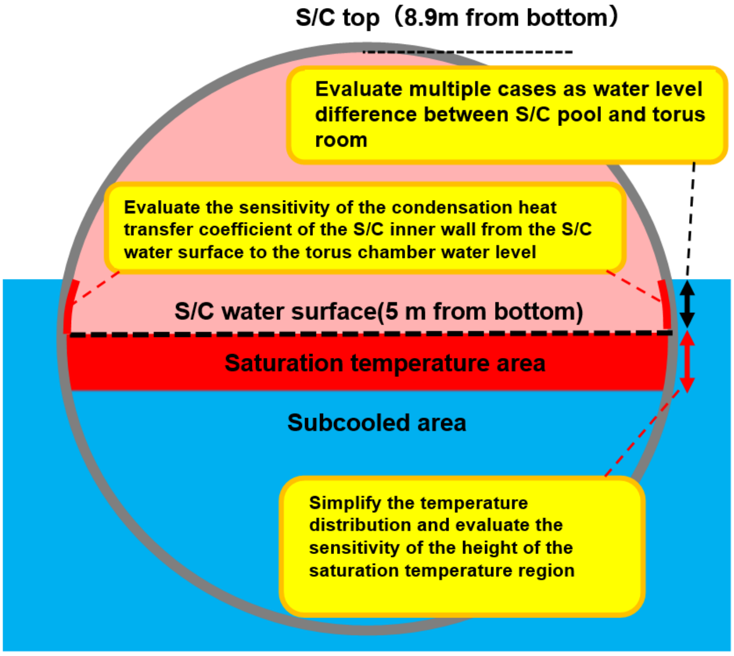


Figure 6 Evaluation image

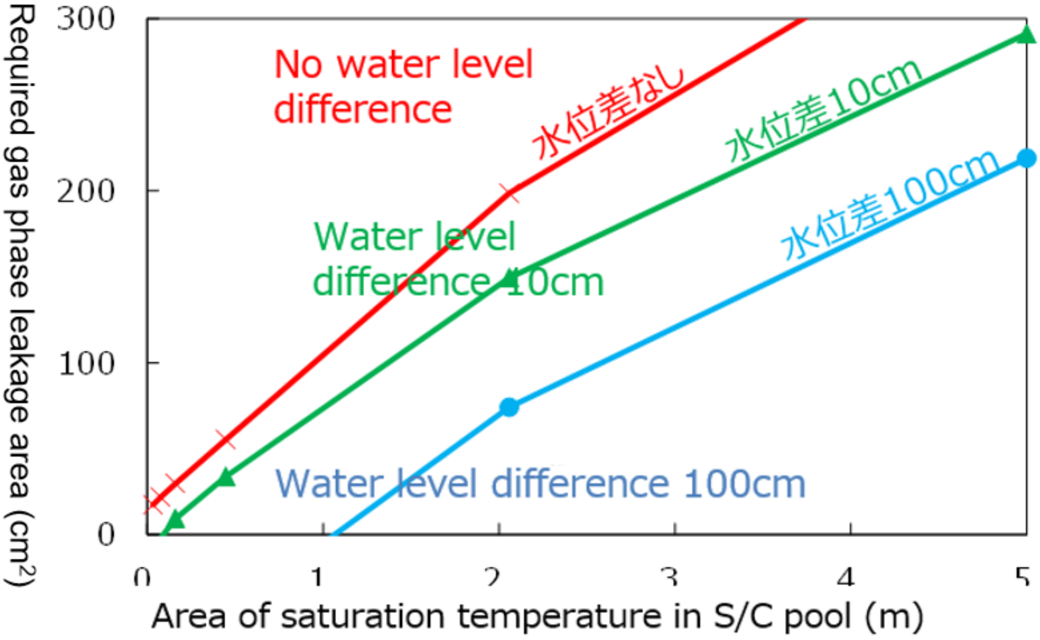


Figure 7 Changes in the required leakage area with respect to the height of the saturation temperature region of the S/C pool water

(assuming that there is no non-condensable gas in the containment vessel)

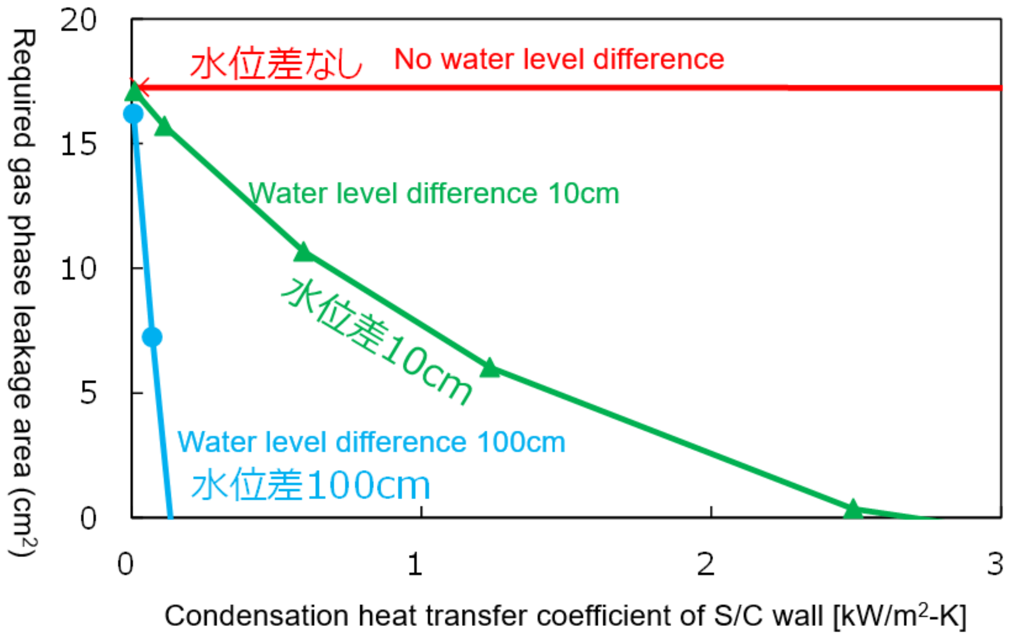


Figure 8 Changes in the required leakage area with respect to the condensation heat transfer coefficient of the inner wall of the S/C gas phase (assuming no boiling under reduced pressure)

■ 4 Examination of the feasibility of the scenario based on observed facts and existing estimates

From the viewpoint of consistency with observed facts such as measured plant parameters and information obtained from the site, the feasibility of the "depressurization scenario due to gasphase leakage from the containment vessel" and the "scenario in which depressurization due to gas phase leakage from the containment vessel plus condensation of water vapor in the containment vessel contributed to depressurization" were examined. Observed facts and existing estimates are given below. The results of the scenario feasibility study in terms of consistency with the observed facts and previous estimates are shown in Sections 4.1 to 4.10 and summarized in Table 2.

- ➢ D/W pressure behavior from about 00:00 to 07:20 on the 15th
- ➢ Decrease in D/W pressure from 07:20 to 11:20 on the 15th
- ➢ Increase and decrease in D/W pressure after about 12:00 on the 15th
- ➢ The current airtightness of the containment vessel of Unit 2
- ➢ High radiation dose rate around the shield plug of the 5th floor of the reactor building
- ➢ Relatively low dose rate at locations in the reactor building other than around the shield

plug that are considered to be migration pathways for radioactive materials

- White smoke from the blowout panel on the morning of the 15th
- Decreasing trend of S/C CAMS indication values after around 00:00 on the15th
- Estimation of liquid phase leakage from S/C
- Estimation of vacuum break valve leakage

Based on the comparison with the above observed facts and the previous estimations, in the depressurization scenario due to gas phase leakage from the containment vessel, it is necessary to consider that there was a large scale leakage besides at the top head flange due to thermal damage. However, in that case, regarding the D/W pressure increase and decrease after around 12:00 on the 15th, and the relatively high airtightness of the Unit 2 currently, it was found to be difficult to explain the relatively small contamination in the buildings, other than for the operating floor, in a way consistent with the observed facts. On the other hand, it was found to be easier to explain the consistency with the observed facts when considering that the condensation of water vapor in the containment vessel contributed to the depressurization.

■ 4.1 D/W pressure behavior from about 00:00 to 07:20 on the 15th

The D/W pressure was in the range of 0.7MPa[abs] to 0.75MPa[abs] from around 23:30 on the 14th to 07:20 on the 15th.

For the depressurization scenario due to gas phase leakage from the containment vessel, by assuming accident progression sequences such as SRV opening and closing, steam and hydrogen formation in the pressure vessel, leakage from the pressure vessel to the D/W, and leakage from the D/W to the reactor building, the reactor pressure and containment pressure including this period can be interpreted (Appendix 1). Based on this, the scenario that the containment pressure was maintained during this period, including non-condensable gas, by the inflow of water vapor generated in the pressure vessel into the D/W, while there was a gas phase leakage from the top head flange due to the pressure increase, is considered to be valid.

In the scenario of depressurization being contributed to by condensation of water vapor in the containment, it was necessary to consider that most of the non-condensable gas in the containment had been released and that strong thermal stratification (the status of the temperature increase only at the surface of the pool) had occurred in the S/C pool after 07:20 on the 15th and before depressurization in order for the D/W pressure to later decrease. Although this cannot be stated with certainty, the following scenario could be considered viable.

① Strong temperature stratification (the status of the temperature increase only at the surface of the pool) had occurred in the S/C pool due to the cooling of the lower part of the S/C by the rising water level in the torus room and the lack of momentum in the SRV exhaust. On the other hand, some of the heat from the SRV exhaust was transferred to the S/C water surface, and the area around the S/C water surface remained hot, maintaining the containment pressure by water vapor pressure.

② Water vapor produced at the surface of the S/C water caused non-condensable gas in the S/C to migrate to the D/W via the vacuum break valve, and then through the top head flange of the D/W, and most of this non-condensable gas was discharged from the containment vessel.

■ 4.2 Decrease in D/W pressure from 07:20 to 11:20 on the 15th

The D/W pressure was measured to be 0.73MPa[abs] at 07:20 on the 15th, after which the measurement was temporarily interrupted and it dropped to 0.155MPa[abs] when the measurement was resumed at 11:20 on the same day.

In the depressurization scenario due to gas phase leakage from the containment, a containment leak area of 300cm^2 (constant during depressurization) was required to reproduce the D/W pressure drop during this period. The size of the leak area could be interpreted by assuming that the thermal damage caused gas phase leakage from the large containment vessel, including all but the top head flange, to continue throughout depressurization. For the scenario of depressurization due to condensation of water vapor in the containment, the case was evaluated in which the water level in the torus room rose above the level of the S/C pool, and it was found that even a small gas phase leak from the containment could reproduce depressurization if most of the non-condensable gas in the containment had been released at 07:20 on the 15th and after, and if thermal stratification occurred on the surface layer of the S/C pool before depressurization. The results show that depressurization can be reproduced even when the gas phase leakage from the containment is small.

■ 4.3 Increase and decrease in D/W pressure after about 12:00 on the 15th

D/W pressure increased rapidly from 155kPa[abs] to 415kPa[abs] from around 12:00 to 13:00 on the 15th, then decreased relatively slowly until it was 120kPa[abs] at 01:24 on the 16th, and then remained almost constant until 05:15 the same day.

Based on this pressure behavior, the heat balance in the containment vessel was evaluated and it was found that in a depressurization scenario due to a gas phase leakage from the containment vessel, the heat required to reproduce the pressure change during this period exceeds the heat value of the fuel debris (integral value of decay heat + heat storage) in a situation where a 300 cm^2 leak opening is maintained in the containment vessel, and that is difficult to explain from the viewpoint of heat balance (Appendix 2).

On the other hand, in the scenario of depressurization due to condensation of water vapor in the containment, the amount of heat required to reproduce the pressure is less than the amount of heat from the fuel debris, although it depends on the water level difference between the S/C pool and the torus room, and it is found to be feasible in terms of heat balance (Appendix 2). In other words, while some of the heat from the fuel debris was transferred to the containment side due to evaporation of the injected water, the containment was also cooled by the rise in the water level in the torus room, which can be interpreted as an increase or decrease in containment pressure depending on the extent of the relationship.

■ 4.4 The current airtightness of the containment vessel of Unit 2

The containment pressure of Unit 2 after the accident was higher than that of other units and the containment vessel was considered to be airtight. The pressure was thought to be mainly caused by pressure loss due to leakage of sealed nitrogen. Even if it is assumed that all of the nitrogen contained in the containment vessel leaked out, the leak size that reproduces the containment vessel pressure is estimated to be about 1cm^2 or less (Appendix 3).

As mentioned above, in the depressurization scenario due to gas phase leakage from the containment vessel, it is difficult to explain the D/W pressure behavior after around 12:00 on the 15th when the leakage area of 300cm^2 is maintained. However, although the possibility that the leak has shrunk is not zero, it is unlikely that the leak, which was due to thermal damage and was maintained during depressurization, will shrink significantly thereafter.

On the other hand, in the scenario where condensation of water vapor in the containment vessel contributed to the depressurization, it is possible to explain that even if a leak occurred before the depressurization after 07:20 on the 15th, it was a leak due to high pressure, which shrank as the pressure decreased and the leak size was not maintained.

■ 4.5 High radiation dose rate around the shield plug of the operating floor

In the building, the high dose rate around the shield plug of the operating floor [1] suggests that the leakage was from the top head flange below the shield plug.

Since there was a period of high containment pressure of 0.7MPa[abs] or higher from around 00:00 on the 15th to before the depressurization after 07:20 on the 15th, it is possible that there was a leak from the top head flange during this period. In the depressurization scenario due to gas phase leakage from the containment, it is necessary to consider that a large leakage area was maintained during containment depressurization after 07:20 on the 15th, and the depressurization scenario with condensation of water vapor in the containment also allows for a small leakage from the containment, so both scenarios can be interpreted as causing contamination of the area around the shield plug by leakage from the containment top head flange before, during, or after depressurization.

■ 4.6 Relatively low dose rate at locations in the reactor building other than around the shield plug that are considered to be migration pathways for radioactive materials

With the exception of the area around the shield plug, no particularly high doses have been observed in the staircase area or other areas that are considered to be migration pathways for radioactive materials in the reactor building, although high doses have been observed in some containment boundaries, such as the X-6 penetration [1]. Therefore, there is no evidence that a large amount of radioactive material leaked outside around the top head flange.

In the depressurization scenario due to gas phase leakage from the containment vessel, it is necessary to consider that there was a reasonable amount of leakage from other sources than the top head flange, and it is difficult to explain the consistency with the above. On the other hand, in the scenario of depressurization due to condensation of water vapor in the containment vessel, it is possible to explain that no major leakage occurred around the top head flange.

■ 4.7 White smoke from the blowout panel on the morning of the 15th

White smoke was observed coming from the blowout panel on the morning of the 15th. The depressurization scenario due to gas phase leakage from the containment vessel assumes a large amount of leakage from the containment vessel, and the water vapor leaked from the containment vessel might have been observed as steam. In addition, the spent fuel pool water temperature is thought to have risen during this period [5], and it is possible that the steam produced from the pool was also included in the observation. Regarding the containment pressure behavior in Unit 2 until the 14th, it is estimated that water had accumulated in the torus room and cooled the S/C from a relatively early stage because the pressure was lower than that expected when decay heat was transferred to the S/C due to RCIC operation (Attachment 2-2). It is possible that the water in this torus room was heated by the heat transfer from the S/C and captured the steam produced from it. The white smoke could have been any of the above or a combination of them.

The scenario of depressurization contributed by condensation of water vapor in the containment is also considered to be consistent with the observed facts, as it allows for minute containment leakage. Therefore, this depressurization scenario can be basically explained in the same way as the depressurization scenario due to gas phase leakage from the containment.

■ 4.8 Decreasing trend of S/C CAMS indication values after around 00:00 on the 15th

The indicated value of the S/C CAMS (A system) increased from around 22:00 on the 14th to 00:00 on the 15th, and then decreased almost monotonically after 07:00 on the same day.

The scenarios assumed in this study are all based on the assumption that the SRVs were open after 01:00 on the 15th. This might lead to the possibility of radioactive materials migrating to the S/C. The consistency between this and the monotonically decreasing S/C CAMS is discussed below.

The S/C CAMS indicated value increases significantly when radioactive materials migrate to the S/C gas phase area (including the inner wall of the S/C steel plate), whereas when they are trapped in the S/C pool, the contribution to the indicated value is estimated to be relatively small due to the shielding effect by water (Attachment 2-11).

On the other hand, based on the behavior of the reactor pressure and D/W pressure, it is estimated that a large amount of hydrogen was formed in the pressure vessel at around 22:40 on the 14th, and that the major hydrogen formation had ended by 00:00 on the 15th (Attachment 2-9). Until around 00:00 on the 15th, the gas flowing into the S/C contained a large amount of hydrogen, and as a result of the incoming gas not being completely condensed in the S/C pool, radioactive materials contained in the gas might have migrated to the S/C gas phase section, causing the S/C CAMS indicator value to rise. On the other hand, after around 00:00 on the 15th, since hydrogen formation had been mainly completed, the gas flowing into the S/C was almost exclusively water vapor, which condensed almost completely in the pool, and radioactive materials were trapped in the pool water at that time and did not reach the gas phase section. On the other hand, the decay of radioactive materials that were already present in the gas phase may have caused the indicated value to decrease. Since such estimation is possible, it is considered that both scenarios are consistent with the observed facts.

■ 4.9 Estimation of liquid phase leakage from S/C

As a result of measuring the water level in the S/C in January 2014, it was confirmed that the S/C water level was linked at almost the same level as the stagnant water in the torus room (the water level in the S/C was slightly lower) and that a liquid phase leakage was occurring from the bottom of the S/C (including piping) (Attachment 4). Based on the behavior of the S/C thermometer readings after the accident, it is estimated the leakage area was 9cm^2 and the location of the leak opening was below O.P. 512, which is in good agreement with the actual measurements (Attachment 2-13).

Although the timing of the liquid phase leakage from the S/C is unknown, discussion is made about the impact on the feasibility of each scenario if the leakage had occurred during or before the period covered by this study.

If a liquid phase leakage from the S/C had occurred, the effects on the containment pressure would include (a) a pressure drop due to an increase in the containment space volume caused by the liquid-phase leak, (b) a pressure drop due to a gas phase leakage when the leak point is exposed, and (c) the S/C water level drop and the pressure drop due to an increase in the S/C external cooling caused by the water level increase in the torus room. As for (a), for the leakage area of 9cm^2, the speed of the increase of the space volume in the containment vessel with the decrease of the S/C water level is slow and the pressure decrease is also slow, so it is not directly related to the rapid depressurization seen after 07:20 on the 15th. Therefore, even if (a) were to occur, it would not have a significant impact on the feasibility of the scenarios considered in this study.

For (b), the leakage area that is most consistent with the behavior of the S/C thermometer readings after the accident is 9cm^2, which is small compared to the leakage area of 300cm^2 that reproduces the depressurization after 07:20 on March 15 in the scenario of depressurization due to gas phase leakage from the containment vessel. In addition, even in the scenario where depressurization is caused by condensation of steam in the containment vessel, as shown in Figures 7 and 8, the leakage area required for depressurization can vary greatly due to the difference in water levels between the S/C pool and torus room and uncertainty in the condensation heat transfer coefficient, so a change in leakage area of about 9cm^2 is still possible. This change would not significantly affect the feasibility of the scenario. Therefore, even if (b) were to occur, it would not significantly affect the feasibility of the scenarios considered in this study.

As for (c), as a precondition, it is not considered in the scenario where depressurization was caused by gas phase leakage from the containment vessel. On the other hand, in the scenario where condensation of water vapor in the containment vessel contributed to depressurization, if (c) had occurred, it might be easier to reproduce the D/W pressure drop after 07:20 on the 15th due to an increase in the amount of S/C external cooling. On the other hand, if the water level in the torus room rises significantly and the amount of S/C external cooling becomes too large, the increase and decrease in D/W pressure from around 12:00 on the 15th may require more heat than the fuel debris has (Appendix 2).

Considering this, the scenario in which condensation of water vapor in the containment contributed to depressurization can be interpreted by considering that the leakage from the S/C at that time, if any, had a relatively small impact on the S/C external cooling.

■ 4.10 Estimation of vacuum break valve leakage

Based on the behavior of the S/C thermometer readings after the accident, it is estimated that a leak (loss of the original function of the vacuum break valve to shut off the flow from the D/W to the S/C gas phase section) might have occurred in the S/C vacuum break valve (Attachments 2-8 and 2-13).

Although the timing of the vacuum break valve leak is unknown, from about 00:00 to 07:20 on the 15th, the indicated value of the D/W CAMS showed an upward trend, while the indicated value of the S/C CAMS had a downward one. Thus, there was no significant leakage from the D/W to the S/C gas phase section.

In the scenario of depressurization due to gas phase leakage from the containment, the containment pressure is maintained by leakage from the pressure vessel to the D/W from about 00:00 to 07:20 on the 15th before depressurization. Therefore, if the vacuum break valve were damaged, gas migration from the D/W to the S/C gas phase could occur. Therefore, this scenario can be interpreted by considering that no significant damage to the vacuum break valve occurred prior to 07:20 on the 15th. As for during depressurization, the currently estimated area of liquid phase leakage from the S/C is as small as 9cm^2, and the large leakage that would allow this scenario to be valid is interpreted as having occurred on the D/W side. In this case, the gas flow during depressurization would be from the S/C to the D/W to the reactor building, which is the original flow direction of the vacuum break valve, so the presence or absence of a leak at the vacuum break valve during depressurization would not affect the feasibility of this scenario.

In the scenario of depressurization being contributed to by condensation of water vapor in the containment, it is assumed that the temperature of the S/C water surface was maintained by SRV exhaust during the period from about0 0:00 to 07:20 on the 15th, and the containment pressure was maintained by the generation of water vapor from it. Under such circumstances, gas migration from the D/W to the S/C gas phase would not occur, so this scenario would hold true regardless of whether or not the vacuum break valve was damaged during this period. As for during depressurization, in this scenario, where depressurization occurs due to condensation on the S/C wall associated with external cooling, gas migration, mainly water vapor, from the D/W to S/C occurs. If there is no leakage at the vacuum break valve, the water vapor of the D/W is led to the S/C pool through the vent pipe downcomer and condenses there, so the effect on the amount of condensation on the S/C wall due to external cooling is small, and the effect on the feasibility of the scenario is negligible. If there is a leak at the vacuum break valve, water vapor from the D/W will directly migrate to the S/C gas phase section through the leak, and the amount of condensation on the S/C wall due to external cooling will increase by that amount. However, the effect of this is small compared to the effect of the high saturation temperature region in the S/C pool water and the uncertainty of the water level difference between the S/C pool and the torus room, as assumed in Figure 7 and elsewhere. Therefore, the presence or absence of a leak at the vacuum break valve during depressurization does not undermine the feasibility of this scenario.

Table 2　Consistency of observed facts for each scenario

Observed fact	Depressurization scenario due to leakage from containment vessel (＊)	Depressurization scenario contributed to water vapor condensation in containment vessel (＊)	Note
① D/W pressure behavior from about 00:00 to 07:20 on the 15th	Containment pressure was maintained by water vapor formed in the pressure vessel flowing into the D/W, including non-condensable gas, while there was gas phase leakage from the top head flange due to pressure increase	The rising water level in the torus room caused temperature stratification in the S/C pool surface layer, which maintained high temperatures near the S/C water surface, and the containment pressure was maintained by the water vapor pressure. Most of the non-condensable gas was released from the top head flange	See 4.1
② D/W pressure decrease from 07:20 to 11:20 on the 15th	Thermal damage caused massive gas phase leakage from the containment vessel, including all but the top head flange, which continued throughout depressurization	Water level in the torus room rose above the S/C pool level and depressurized mainly due to condensation of water vapor in the S/C.	See 4.2
③ Increase and decrease in D/W pressure after about 12:00 on the 15th	If the leakage opening is large, it is difficult to explain the increase in pressure from around 12:00 and the subsequent gradual decrease in pressure in terms of the containment heat balance	While some of the heat from fuel debris was transferred to the containment side due to evaporation of injected water, the containment vessel was cooled by the rising water level in the torus room, and the containment vessel pressure increased or decreased depending on the relative magnitude of the two.	See 4.3
④ Current tightness of the containment vessel of Unit 2	It is unlikely that a leak that was due to thermal damage and was maintained during depressurization will shrink significantly afterwards.	Containment leaks were primarily pressure-dependent in shape (e.g., top head flange pushed up by pressure) and shrunk as the containment was depressurized	See 4.4
⑤ High radiation dose rate around the shield plug of the operating floor	The area around the shield plug was contaminated by leakage from the containment vessel top head flange before, during, or after depressurization of the containment vessel after 07:20 on March 15 (common to both scenarios).		See 4.5

⑥ Relatively low dose rates at locations considered to be migration routes for radioactive materials in the reactor building	This is difficult to explain because it requires a certain amount of leakage from other than the top head flange.	No major leaks occurred outside of the top head flange	See 4.6
⑦ White smoke from the blowout panel on the morning of the 15th	Any one or a combination of them of: water vapor leaked from the containment vessel, water vapor generated from the spent fuel pool, and water vapor generated from the torus room was observed as steam (common to both scenarios).		See 4.7
⑧ Decreasing trend of S/C CAMS indicated value after 00:00 on the15th	The main hydrogen production in the pressure vessel ended and hydrogen in the SRV exhaust was low. When the SRV exhaust condensed in the S/C pool, the radioactive materials were captured and did not reach the gas phase, so the influence on the indicated value was small. Conversely, the indicated value decreased due to attenuation (common to both scenarios)		See 4.8
⑨ Estimation of liquid phase leakage from S/C	Even if a leak from the S/C had already occurred at that time, the effect of the leak itself on the containment vessel pressure drop rate was relatively small.	In addition to the left, the effect on S/C external cooling was relatively small.	See 4.9
⑩ Estimation of vacuum break valve leakage	The presence or absence of leakage from the vacuum break valve had little effect on the feasibility of the scenario (common to both scenarios)		See 4.10

∗ No underlining indicates scenarios that cannot be ruled out but are considered as possible scenarios to explain the observed facts.
Underlining indicates points that are difficult to explain in a way consistent with the observed facts.

■ 5 Summary

The D/W pressure of Unit 2 decreased from 0.73MPa[abs] to 0.155MPa[abs] from 07:20 to 11:20 on March 15. Assuming the possibility of depressurization due to gas phase leakage from the containment vessel and the possibility of depressurization contributed to condensation of water vapor in the containment vessel, the feasibility of each scenario was examined.

As a result, if it is considered that the depressurization was caused by gas phase leakage from the containment vessel, it is necessary to consider that there was a large-scale leakage other than at the top head flange due to thermal damage, and it is necessary to consider the increase and decrease of D/W pressure after around 12:00 on March 15, the fact that the current containment vessel of Unit 2 is relatively airtight, and the fact that the contamination in the building other than for the operating floor is relatively small. The relatively small contamination of the containment vessel of Unit 2 after 12:00 on the 15th was found to be difficult to explain in a way consistent with the observed facts.

On the other hand, it was found that it is easier to explain the consistency with the observed facts if it is considered that the condensation of water vapor in the containment vessel contributed to the depressurization. Although there is no conclusive evidence to conclude that the accident progressed in this way, there is a possibility that information can be obtained from future on-site investigations, etc. (For example, if a flooding trace in the torus room is visible, although information on the arrival time is lost, it is possible to determine the maximum extent of flooding, and thus it is possible that the condensation caused depressurization.) Examination of this issue in light of such future information will be continued.

References

[1] TEPCO, "Air dose rate in the building", (2013/3/22)

[2] (The former) Japan Nuclear Technology Institute, "Work related to the MARK I reactor containment elasto-plastic analysis for the development of severe accident response standards: FY2011 report," (2012) (unpublished report).

[3] TEPCO, "Fukushima nuclear accident investigation report, Appendix 2 (Mainly description of time-series events)," (2012/6/20).

[4] U.S.NRC, “Minimum Containment Pressure Model for PWR ECCS Performance Evaluation”, NUREG-0800 Rev. 3 (2007)

[5] TEPCO, “Fukushima nuclear accident investigation report attachment, Attachment 9-3”, (2012/6/20)

Reproduction analysis of reactor and containment pressures up to 11:20 on the 15th

Figure 1 shows the measured values of the reactor and the containment pressures. The possible reasons for the decrease in D/W pressure from 07:20 to 11:20 on the 15th are the expansion of the gas phase leakage from the containment vessel and the increase in the containment vessel cooling. To investigate the possibility of depressurization due to the expansion of gas phase leakage from the containment vessel, a reproducible analysis of the reactor pressure and the containment vessel pressure up to 11:20 on March 15 was conducted, and the gas phase leakage area required for depressurization was estimated. GOTHIC8.2(QA) was used for the analysis code.

It should be noted that this analysis does not take into account the increase in containment cooling (e.g., the increase in S/C cooling due to the flow of water from other buildings, or the changes in the torus room and S/C pool water levels due to liquid phase leaks in the S/C pool, etc.).

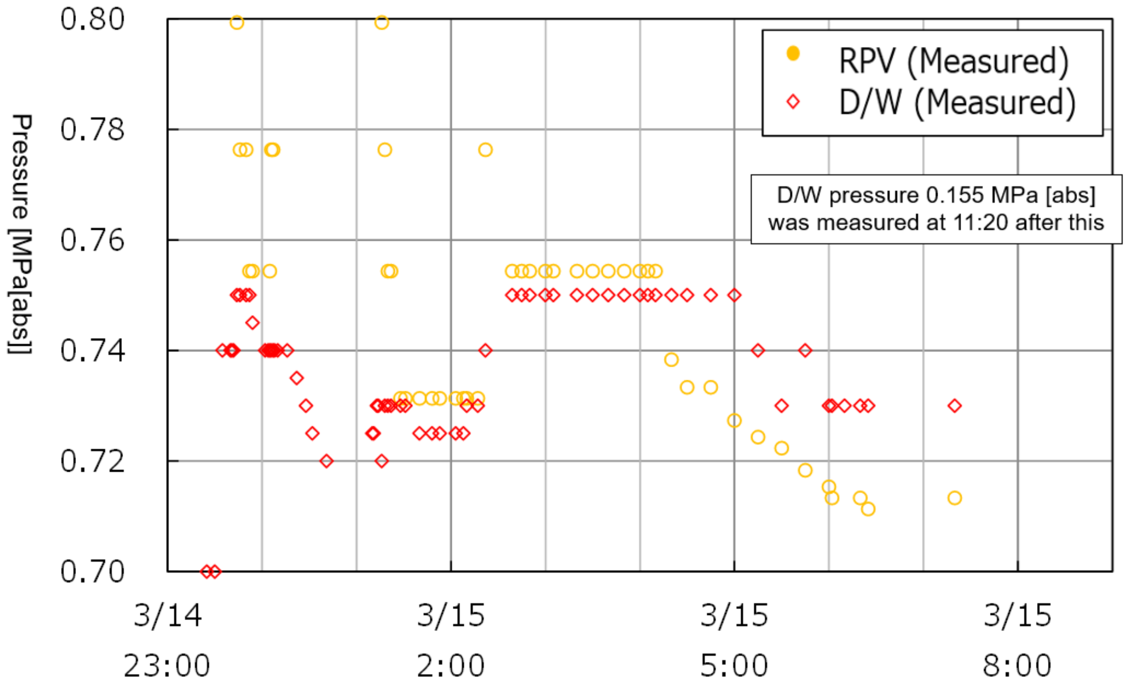


Figure 1 Actual measured reactor pressure and containment pressure (display range, 3/14 23:00 - 3/15 09:00; 0.7 - 0.8 MPa[abs])

1 Analysis system

Since this analysis is an extension of the reproduced analysis shown in Attachment 2-9, the analysis system is basically the same as that reduced analysis, and the leakage path from the RPV to D/W, which was not considered previously, is taken into account. Figure 2 shows the analysis system.

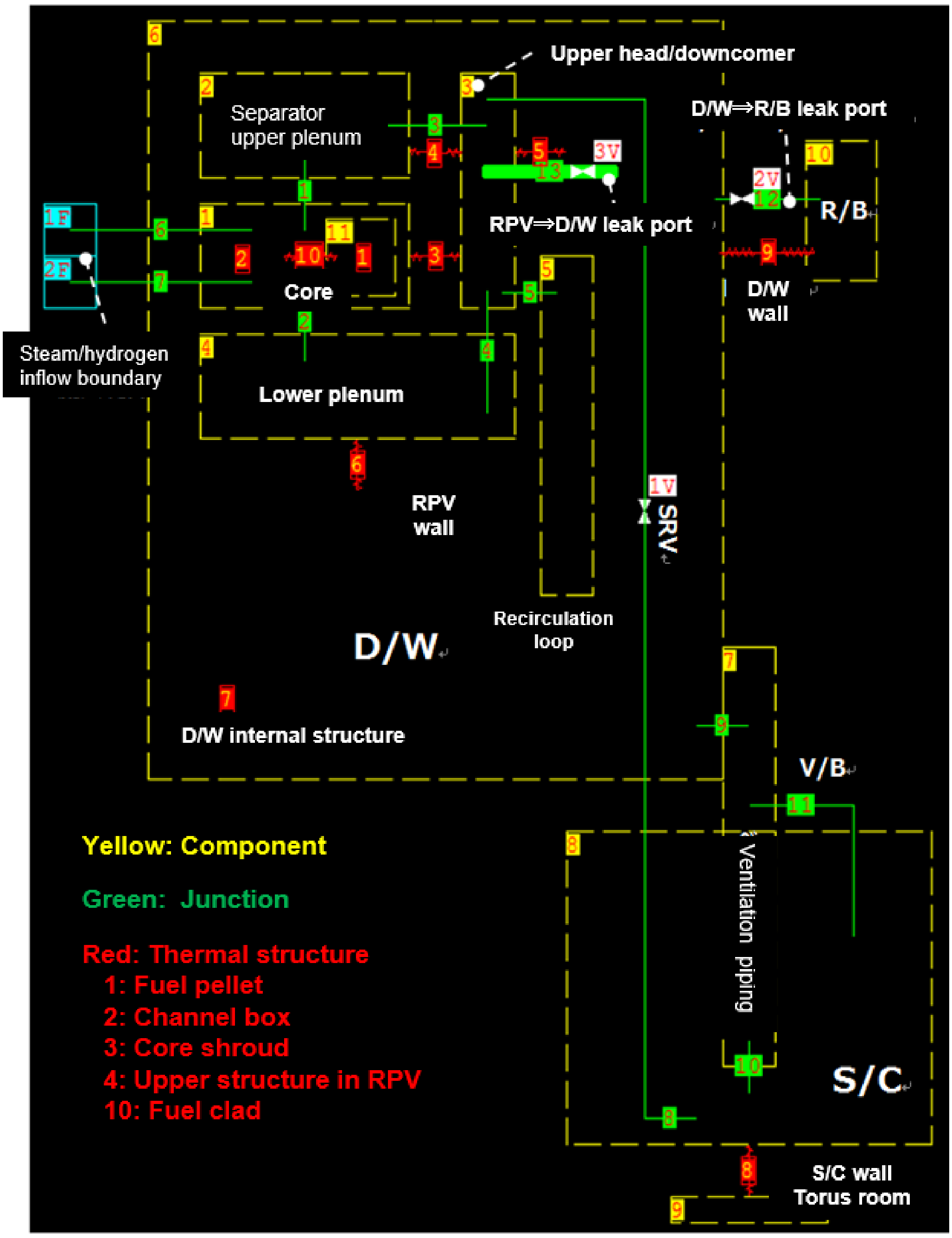


Figure 2 Analysis system

2 Analysis conditions

It is difficult to specify a single accident progression scenario because the reactor and the containment pressures are dependent on the opening and closing of the SRVs, steam and hydrogen formation in the pressure vessel, leakage from the pressure vessel to the D/W, and leakage from the D/W to the reactor building, etc. However, the following conditions were set as examples of possible accident progression scenarios.

The initial conditions and the analysis conditions up to about midnight on the 15th were basically the same as those of the analysis shown in Attachment 2-9. The setting of the analytical conditions after about midnight on the 15th and the concept of the analysis are shown below.

■ 2.1 SRV open/close status

The setup of the SRV open/close status is shown in Figure 3, and since the reactor pressure increased while the D/W pressure decreased during the period from around 00:00 to after 01:00 on March 15, it was assumed that the SRVs were closed at the start of the reactor pressure increase around 00:00 on March 15. Subsequently, at the timing of the start of the reactor pressure decrease after 01:00 on the 15th, SRVs were assumed to have been opened at this time, since there is a record of the SRVs being opened (Attachment 2-12). Since the differential pressure between the reactor pressure and D/W pressure remained almost constant after that, it was assumed that the SRVs remained open.

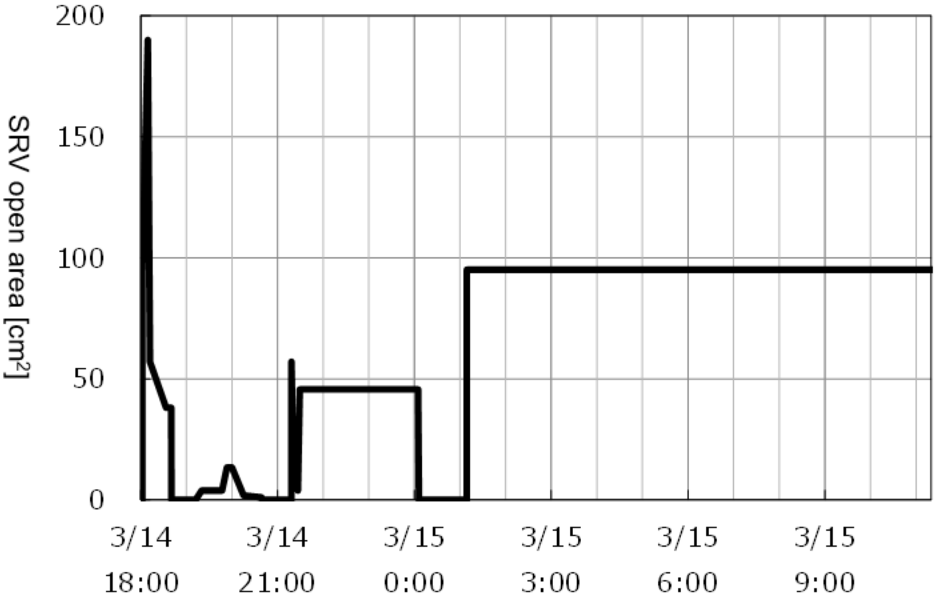


Figure 3 SRV open/close setting status

- 2.2 Formation of water vapor and hydrogen in the reactor pressure vessel

The settings of water vapor and hydrogen formation conditions in the RPV are shown in Figures 4 and 5.

For the formation of water vapor, the amount formed was set to reproduce the reactor pressure under the condition that the SRV was closed from around 00:00 to after 01:00 on March 15. The formation was then temporarily increased to reproduce a temporary increase in reactor pressure from around 02:00 to 02:40. After that, the amount of steam formation was decreased to simulate a decrease in reactor pressure at around 04:00[1]. After 07:20, it was assumed that no steam was formed, considering the possibility that the water in the RPV had been depleted. Regarding the additional formation of hydrogen, the formation amount was set so as to reproduce the D/W pressure rise behavior from about 02:00 to 02:40.

As for the setting of the temporary increase in the amount of steam and hydrogen formed from around 02:00 to 02:40, consideration could be given to the possibility of a temporary increase in the evaporation of the reactor water due to the fall of the fuel debris into the lower plenum.

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[1] As shown in Figure 1, the reactor pressure decreased significantly in a relatively short time around 04:00 and became lower than the D/W pressure. However, as long as there is no cause for the pressure increase on the containment vessel side, it is unlikely that the pressure relationship between the pressure vessel and the D/W would be reversed in this way. Although the possibility of fuel debris falling into the containment vessel is considered as a possible cause of the containment vessel side pressure increase, the trend of the D/W CAMS (A system) indicated values pointed to the fall of fuel debris into the containment vessel having not yet occurred at this time, and it is highly likely that it occurred between 13:00 and 16:10 on the 15th (Attachment 2-10).

On the other hand, the reactor pressure is measured by the pressure gauge at the end of the water level gauge pipe, and when the water level in the in the piping of the reference legdrops, the reactor pressure is measured as lower by the water head (up to about 1atm). Therefore, depending on the water level in the water level gauge piping, it is possible that the reactor pressure was measured as lower than the actual value. Based on this, the following situation of the accident progression was assumed.

(1) The water level in the piping on the side of the reference leg had been decreasing since the time before around 04:00, when the measured pressure values of the pressure vessel and D/W were almost the same, and the actual reactor pressure was higher

than the measured value and maintaining a constant differential pressure with the D/W pressure. This differential pressure was caused by the pressure loss of steam formed in the pressure vessel as it flowed out into the containment vessel.

(2) Around 04:00, the amount of steam formed in the pressure vessel decreased and the amount of leakage from the pressure vessel to the D/W decreased, resulting in a decrease in pressure loss at the leak position and in a relatively short time the pressure difference between the pressure vessel and the D/W decreased.

(3) On the other hand, D/W pressure gradually decreased with leakage into the reactor building.

Considering that the trend of the measured values might have captured the accident progress as described above, a drop in reactor pressure was simulated by decreasing the steam formation at about 04:00. In this way, it is possible to consider that the reactor water evaporation progressed.

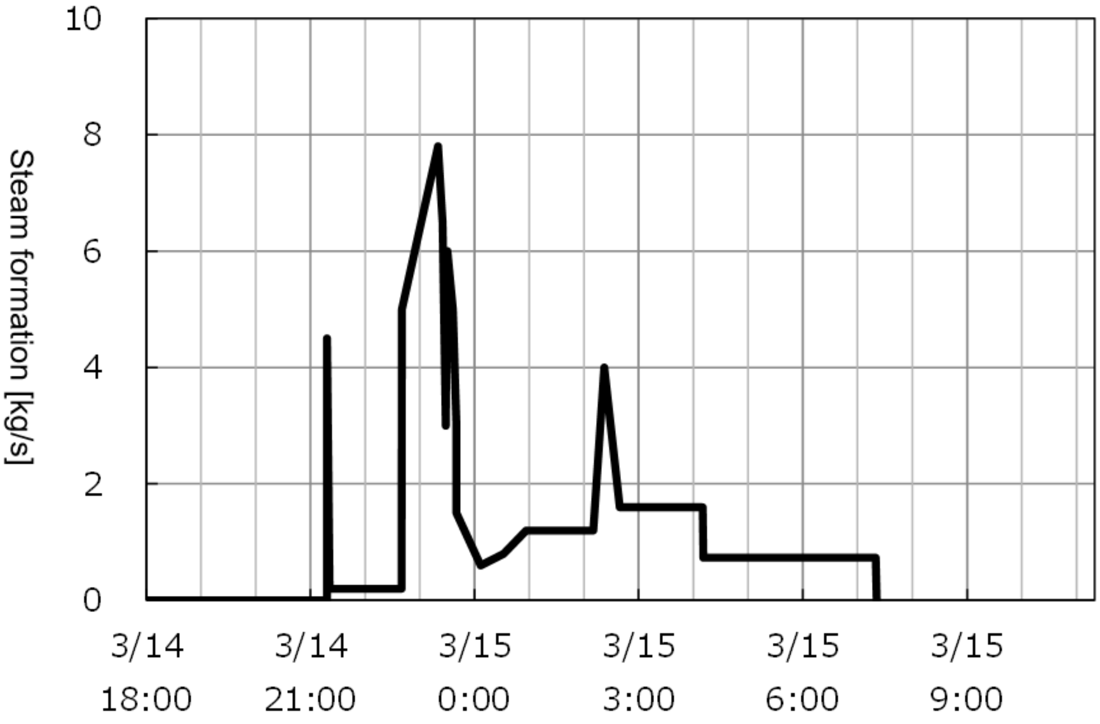

Figure 4 Setting of steam formation conditions in the reactor pressure vessel

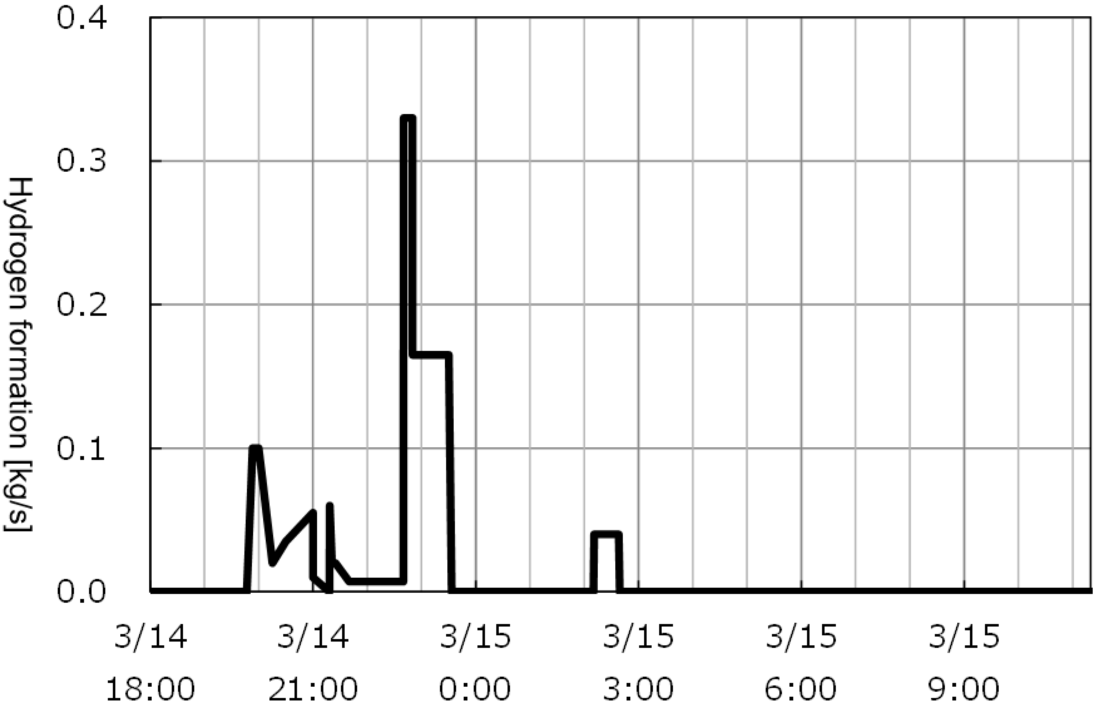

Figure 5 Setting of hydrogen formation conditions in the reactor pressure vessel

■ 2.3 Leakage situation from the reactor pressure vessel to D/W

Figure 6 shows the setting conditions of the leakage situation from the pressure vessel to D/W. From 23:25 to 23:54 on the 14th, the indicated value of D/W CAMS (A system) increased about 2.8 times (from 8.81Sv/h to 24.5Sv/h), while the indicated value of S/C CAMS (A system) increased about 1.4 times (from 6.61Sv/h to 9.10Sv/h). The core was already damaged by this time, and if there was no leakage from the RPV to the D/W, the FPs released from the fuel would have migrated to the S/C through the SRV and then to the D/W due to the pressure difference, so basically, the percentage increase in the CAMS indicated value on the S/C side would be larger. However, as shown above, the trend of the actual measured values is different. Therefore, the occurrence of a small leakage from the RPV to the D/W was assumed to happen at 23:30. The cause of the leak was thought to be the high temperature of the pressure vessel boundary due to insufficient fuel cooling, but since the specific leak location and leak area were unknown, 3cm^2 was set as an appropriate value. After that, the leak area was expanded after 01:00 on the 15th and again from 02:00 to 02:40 in order to reproduce the D/W pressure.

As for the setting conditions of the expansion of the leakage area, it is possible to interpret that as showing the inside of the RPV continued to be in a high temperature state, which caused the leakage area from it to the D/W to expand.

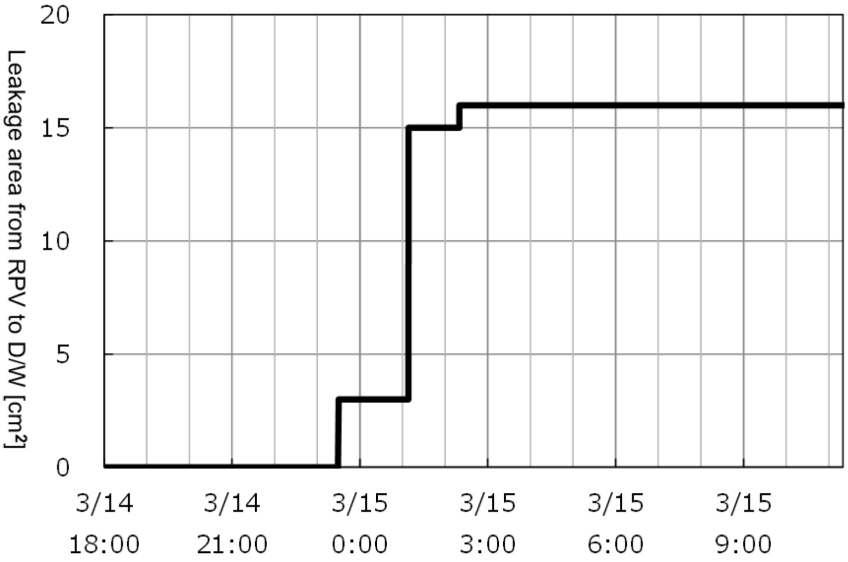

Figure 6 Setting conditions of the leakage situation from the RPV to D/W

■ 2.4 Leakage situation from D/W to the reactor building

Figure 7 shows the setting conditions of the leakage situation from the reactor pressure vessel to the D/W. Since the D/W pressure decreased after 23:50 on the 14th, it was estimated that the leakage from the D/W to the reactor building occurred around this time. The initial leak area was assumed to be the area that reproduced the drop in D/W pressure over 0:40 on the 15th. Since the change in the leakage area from then to 07:20 was unknown, it was assumed that the same leakage area continued. The leakage area was then increased significantly to 300cm^2 to reproduce the D/W pressure drop that occurred between 07:20 and 11:20.

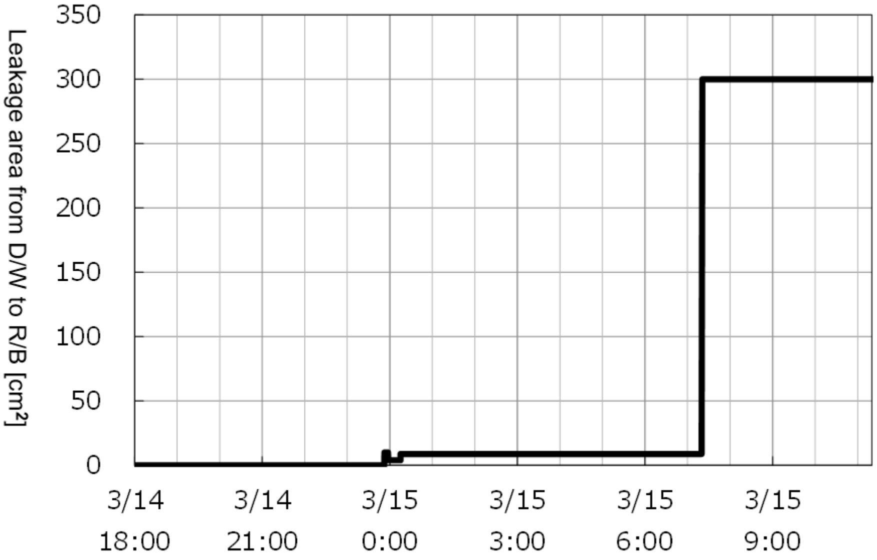

Fig. 7 Setting conditions of the leakage situation from the D/W to R/B

Increase/decrease in D/W pressure after about 12:00 on the 15th

The D/W pressure increased from 155kPa[abs] to 415kPa[abs] from about 12:00 to 13:00 on the 15th, then decreased relatively slowly until it was 120kPa[abs] at 01:24 on the 16th, and from then was almost a constant value until 05:15 on the 16th.

Regarding these changes in D/W pressure, it is believed that the fuel remained in the pressure vessel during the phase from about 12:00 to 13:00 on the 15th (see Attachment 2-10), and that the changes were caused by the relationship between the increase and decrease in heat in the containment vessel as described below.

(1) Increased heat in containment: The amount of heat transferred into the containment from the heat of the fuel (decay heat + heat storage) by evaporation of water injection, etc.
(2) Decreased heat in containment: the amount of heat released from the containment due to leakage of gas phase from the containment and/or cooling of the containment walls.

In other words, if the amount of heat required to reproduce the measured D/W pressure in the presence of the heat release in (2) exceeds the amount of heat that the fuel can hold in (1), then the scenario is physically unfeasible.

The amount of heat required to reproduce the measured pressure and the amount of heat that the fuel debris can hold were compared for the depressurization scenario due to vapor phase leakage from the containment vessel (scenario ①) and the depressurization scenario due to the contribution of water vapor condensation in the containment vessel (scenario ②). The evaluation method is the same as described in Attachment 2-16, Main Report 3.3. The evaluation conditions are shown in Tables 1 and 2.

The evaluation results are shown in Figure 1. In scenario ①, under the situation where a 300cm^2 leak is maintained in the containment vessel, the amount of heat required to reproduce the pressure change during this period exceeds the amount of heat that the fuel debris can hold, which is difficult to explain in terms of the heat balance. On the other hand, for scenario ②, the amount of heat required to reproduce the pressure is less than the amount of heat that the fuel debris can hold, depending on the water level difference between the S/C pool and the torus room, and this scenario is feasible from the viewpoint of heat balance.

For scenario ②, which assumes no difference in water levels between the S/C pool and torus room, the amount of heat required to reproduce the pressure is negative, but is shown as 0 on the graph. The reason why the amount of heat required to reproduce the pressure is negative is that the amount of heat released from the containment vessel in this case is small, and further heat release is required to reproduce the gradual pressure drop after 13:00 on March 15.

Table 1 Evaluation conditions common to all scenarios

Item	Setting	Note
Evaluation period	3/15 11:58 to 3/16 1:24	Set based on actual measurement values
Pressure change	155kPa[abs]⇒ 415kPa[abs]⇒ 120kPa[abs]	Set based on actual measurement values
D/W temperature	300℃	A higher temperature was set because it is believed that heat was transferred from the fuel debris. The impact on evaluation results is small.
S/C pool water level	5m	See Attachment 2-16, Table 1.
Decompression boiling ratio (% of saturated water in S/C liquid phase)	0	Since the S/C water temperature is considered to have tended to decrease due to external cooling, depressurization boiling during the evaluation period is ignored.
Condensation heat transfer coefficient	Value at 100% water vapor	Settings that are more difficult to establish due to the greater amount of heat required to reproduce the pressure in scenario ②.
Decay heat from fuel debris	7MW	Estimated value during the relevant period
Fuel debris weight	160 tons	Round number (about 300kg per fuel assembly x 548 fuel assemblies)
Fuel debris specific heat	300J/kg	Typical values of UO_2 and zircaloy
Fuel debris superheat (temperature difference from surrounding)	0 to 2850℃	Assume superheat up to near the UO_2 melting point (about 2850°C). Since the surrounding temperature is unknown, 2850°C is set as a higher superheat value.

Table 2　Evaluation conditions or each scenario

Item	Scenario ①	Scenario ②		
		A	B	C
D/W leakage area	300cm^2	None	None	None
Water level difference between S/C pool and torus room (assumed to be constant during the period)	None	100cm	10cm	None

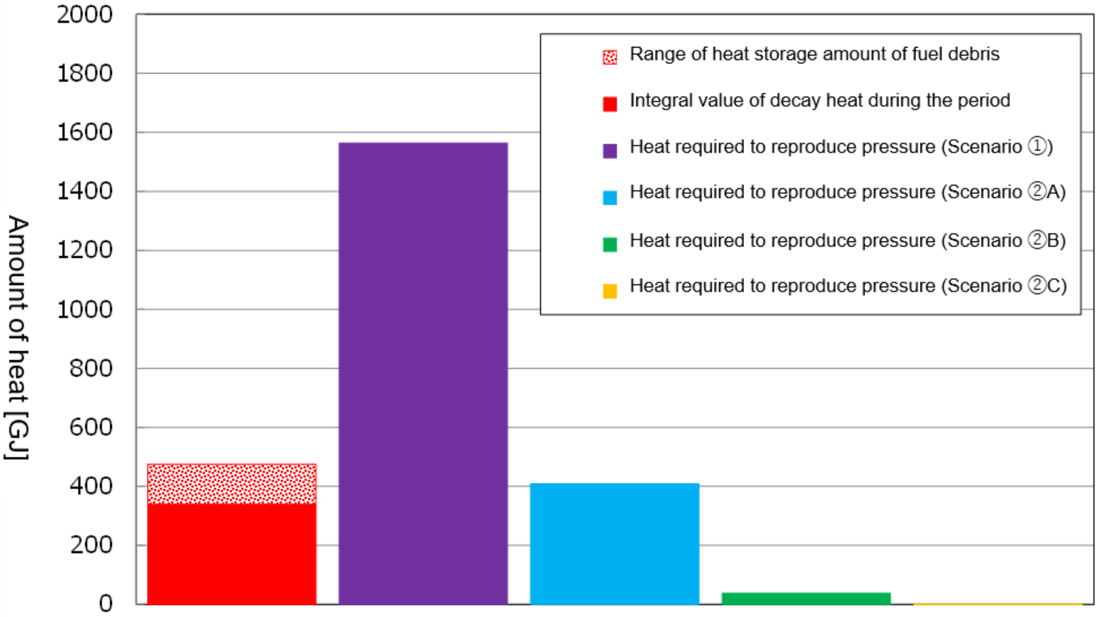

Figure 1 Heat required to reproduce pressure behavior from 11:58 on March 15 to 01:24 on March 16 vs. heat content of fuel debris (integral of decay heat + heat storage)

Simplified evaluation of containment gas-phase leakage area after the Unit 2 accident

After the accident, nitrogen has been sealed in the containment vessels of Units 1 to 3 as an inert atmosphere. The nitrogen is thought to have been either vented from the containment by the gas management system or through the containment gas-phase leakage port. The containment pressure is several kPa higher than the atmospheric pressure due to this nitrogen entrapment. Since this pressure difference with the atmospheric pressure is thought to correspond to the pressure loss that occurs when the gas passes through the gas-phase leak of the containment vessel, the flow rate of the gas discharged through the gas-phase leak of the containment vessel should be assumed. Then, from Bernoulli's theorem, the leakage area that reproduces the pressure difference can be easily calculated as follows.

$$A=\sqrt{\frac{f\rho Q^2}{2P}}$$

where

A: Leakage area（m^2）

f: Pressure drop coefficient（－）

ρ: Density of gas in containment vessel（kg/m^3）

Q: Gas flow rate discharged through the containment vessel gas-phase leakage opening（m^3/s）

P: Containment vessel pressure（Pa[gage]）

On the other hand, the net gas flow rate discharged from the containment by the gas management system is unknown because the amount of ambient air entrained outside the containment is added to the exhaust flow rate from the containment by the gas management system. Therefore, the leakage area was calculated assuming that the gas flow rate discharged from the containment by the gas management system was zero and that all nitrogen-filled flow was discharged through the containment gas-phase leakage port.

The containment pressure and nitrogen-filling flow rate were set based on the plant-related parameter summary table [1] as of January 1 for each of the years 2013 to 2019. For the pressure drop coefficient, a value of 1.5 was used as a general value for gas flowing through a narrow channel connecting two large spaces. For the density of gas in the containment vessel, 1.11kg/m^3 was assumed as the density of nitrogen at atmospheric pressure and 30°C. Since the unit of nitrogen inclusion in the summary table is normal-cubic meter (Nm^3), the value was converted to the equivalent value at 30°C and used.

The calculation results are shown in Table 1. For each time period, the estimated area of the leakage opening is less than 1cm^2, and the actual area of the leakage opening might be even smaller, considering that the exhaust from the containment vessel by the gas management system was ignored.

Table 1 Simplified calculation results of containment gas-phase leakage area in Unit 2 after the accident

Date	Containment vessel pressure （kPa[gage]）	Nitrogen-filled volume ＊ （m^3/h）	Estimated leakage area （cm^2）
January 1, 2013	5.71	18.56	0.62
January 1, 2014	7.73	17.48	0.50
January 1, 2015	7.06	17.41	0.53
January 1, 2016	3.71	17.70	0.74
January 1, 2017	4.11	16.51	0.65
January 1, 2018	4.27	14.13	0.55
January 1, 2019	2.94	11.71	0.55

＊ Values converted from Nm^3 to equivalent values at 30°C

[1] TEPCO, “Plant-related parameter summary table” (published on the TTEPCO website)