Attachment 3-11

Examination of water level in pressure suppression chamber of Unit 3

＊ This document was prepared based on the contents proposed and examined by TEPCO Systems, Inc. to help understand the accident progression after the reactor depressurization at about 09:00 on March 13, including the containment vessel venting listed in "Issue Unit 3-8," the gas phase leak from the pressure vessel listed in "Issue Unit 3-9," the gas phase leak from the containment vessel listed in "Issue Unit 3-10," and the hydrogen explosion in the list of issues for study in Attachment 2.

1. Introduction

As shown in Figure 1, actual S/C water level measurements were taken at Unit 3 by the operator from 17:15 on March 11 to 20:00 on March 12, but no further measurements were taken after that time [1].

As of 20:00 on March 12, when the last measured value was obtained, the alternative S/C spray by the DDFP, which was conducted to reduce the pressure in the S/C, and the HPCI, which was conducted to cool the core, were still in operation. The S/C water level was further increased and the HPCI turbine was driven by the steam extracted from the reactor. These factors would cause the S/C water level to rise further. On the other hand, the possibility of a drop in the S/C pool (S/C liquid phase section) water temperature and a gas phase leak from the containment vessel cannot be ruled out, and these could be factors that would cause the S/C water level to drop.

The S/C water level is important information for estimating the accident progression after the reactor depressurization at around 09:00 on March 13 and the contribution to the cooling of fuel debris after the pressure vessel damage. Therefore, focus was put on the S/C water level at the start of the S/C venting at around 09:00 on March 13 (hereinafter referred to as "first venting") and the S/C water level at the start of the first venting was estimated based on the obtained plant parameters (S/C water level and containment vessel pressure) (Section 2). Based on the estimated S/C water level, accident progression scenarios that explain the plant parameters were estimated, and their consistency with other observed facts was discussed (Section 3).

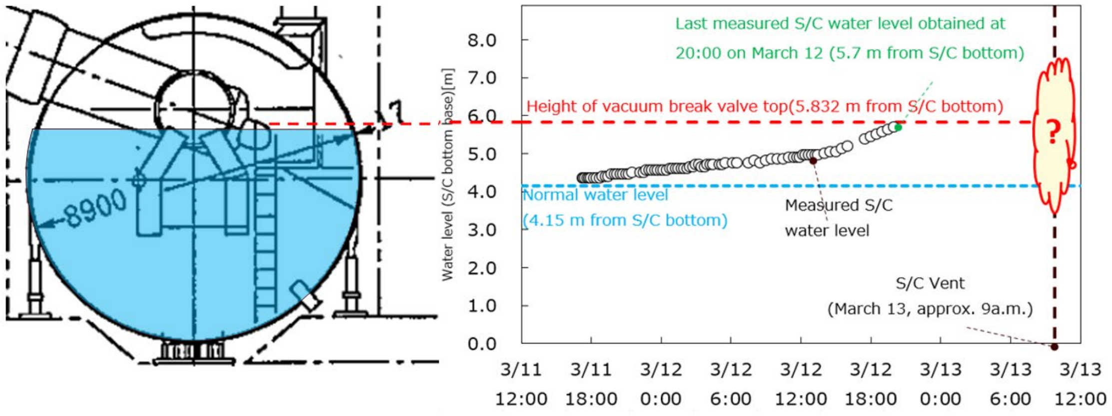


Figure 1 Measured S/C water level at Unit 3

■ 2 Estimation of S/C water level at the time of the first venting

■ 2.1 Estimation of accident progression scenarios related to S/C water level

As a preliminary step in the S/C water level evaluation, the accident progression scenario related to the S/C water level was estimated based on plant parameters. The measured D/W and S/C pressures and the pressure difference between them are shown in Figure 2.

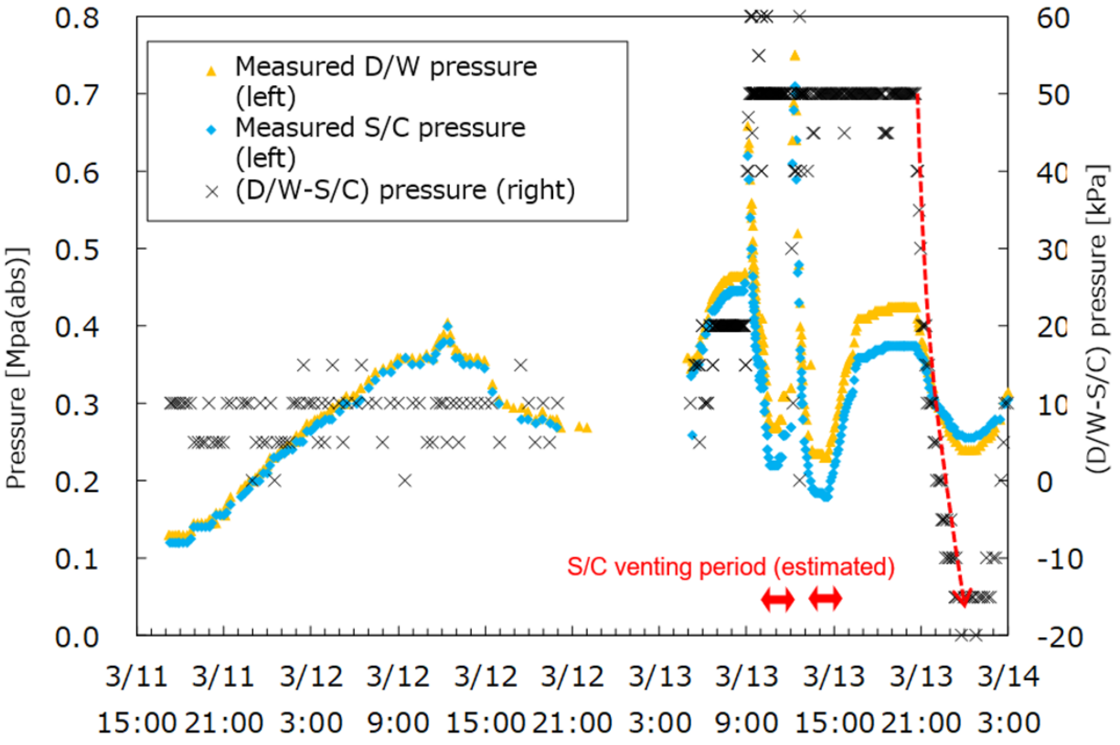


Figure 2 Pressure measurements of D/W and S/C and pressure difference between them

Based on Figure 2, the following three items were considered as relevant to the estimation of the S/C water level.

- Estimation 1: There were deviations in D/W and/or S/C pressure gauges, resulting in an overstatement of the pressure difference between the two.

  Figure 2 shows that from 17:20 on March 11 to 20:00 on March 12, D/W pressure was measured to be higher than S/C pressure in the range of 0 to 15kPa. On the other hand, as shown in Attachment 3-7, during this period of rising containment pressure, it was presumed that there was a factor on the S/C side that caused the pressure to rise due to water temperature stratification, and if so, the D/W pressure should be slightly lower than the S/C pressure. Therefore, it was thought that there were deviations in D/W and/or S/C pressure gauges, and as a result, the pressure difference between the two (D/W pressure - S/C pressure) was overstated.

- Estimation 2: From the start of the first venting until 20:40 on March 13, the water level in the vent pipe was pushed down to the bottom of the downcomer.

  The pressure difference between D/W and S/C increases from 20kPa to 50kPa before and after the start of the first venting. As shown in Figure 3, when the pressure on the S/C side decreases due to S/C venting, the gas in the D/W is drawn into the S/C and the water level in the vent pipe is considered to decrease to the lower end of the downcomer (hereinafter "vent clearing"). This was thought to have increased the pressure differential due to the increased water level difference between the inside of the vent pipe and the S/C. In addition, given that the pressure difference between D/W and S/C may have been overstated as described in Estimation 1, the actual measured pressure difference of 50kPa was considered to have been obtained by adding the overstated range of the pressure difference between the D/W and S/C to the water head difference due to the difference in water levels in the vent pipe and S/C in Figure 3.

  The pressure difference between the D/W and S/C after the start of the first venting was almost constant at 50kPa until 20:40 on March 13, although there were some changes. The fact that the pressure difference between the D/W and S/C has not changed suggests that the relationship between the water level in the vent pipe and the S/C level has not changed significantly during this period. In other words, the vent clearing condition is considered to have continued since the start of the first venting.

  The fact that the vent clearing state continued regardless of the continuation of S/C venting during this period can be qualitatively understood by considering that there were factors that caused the pressure to increase on the D/W side, such as gas phase leakage from the pressure vessel to the D/W.

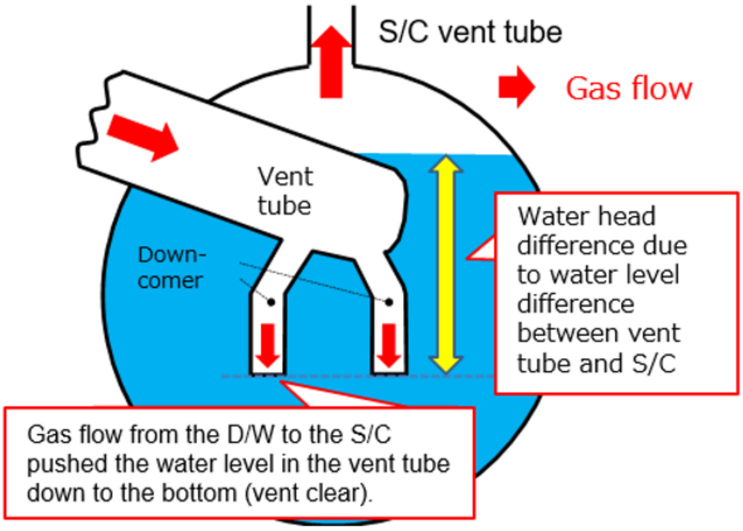


Figure 3 Estimation of state of the water level in the vent pipe and S/C after S/C venting

- Estimation 3: The S/C water level was above the vacuum break valve height at 20:40 on March 13. During the period of inversion of D/W and S/C pressures after 20:40, water on the S/C side was sucked up to the D/W side as the D/W side depressurized.

The containment pressures decreased from 20:40 on March 13 to 00:00 on March 14, and in the process the D/W pressure became lower than the S/C pressure (Table 1). The relatively large drop in the D/W pressure suggests that there were factors on the D/W side that caused the pressure drop, such as leaks into the reactor building. The pressure difference between the D/W and S/C during this period varied from 50kPa to -15kPa, which means that the relationship between the water level in the vent pipe and the S/C water level changed by 65kPa in terms of water head (approximately 7m if the water density was assumed to be 950kg/m^3).

If the S/C water level was lower than the vacuum break valve height, the vacuum break valve would open when the D/W pressure was a few kPa lower than the S/C pressure, and the S/C and D/W would equalize, so basically the D/W pressure would never be 15kPa lower than the S/C pressure, which is inconsistent with the actual measured trend (if the D/W pressure minus the S/C pressure was overstated based on Estimation 1, the actual differential pressure would be even larger). In such a case, the maximum rise in the water level in the vent pipe would be limited to less than 3m from the bottom of the vent pipe downcomer (2.875m from the bottom of the S/C) to the top of the vacuum break valve (5.832m from the bottom of the S/C), and the corresponding drop in the S/C water level would be within 0.2m. Therefore, the difference in water head change for 65kPa cannot be explained.

On the other hand, if the S/C water level was high and the vacuum break valve was submerged, even if the D/W side depressurized, gas could not flow from the S/C side to the D/W side and the two sides were not equalized, so a situation could occur where the D/W pressure exceeded the operating set pressure of the vacuum break valve and was lower than the S/C pressure. The water level in the vent pipe could be interpreted as a change in hydraulic head difference of 65kPa by considering that the water on the S/C side was sucked up to the D/W side due to the depressurization of the D/W side, causing the water level in the vent pipe to rise significantly. The S/C depressurization could be interpreted as the water on the S/C side being sucked up to the D/W side and the S/C water level decreasing by this amount, resulting in an increase in the space volume of the S/C and a decrease in pressure due to volumetric expansion.

Table 1: Measured containment pressures at 20:40 on March 13 and 00:00 on March 14

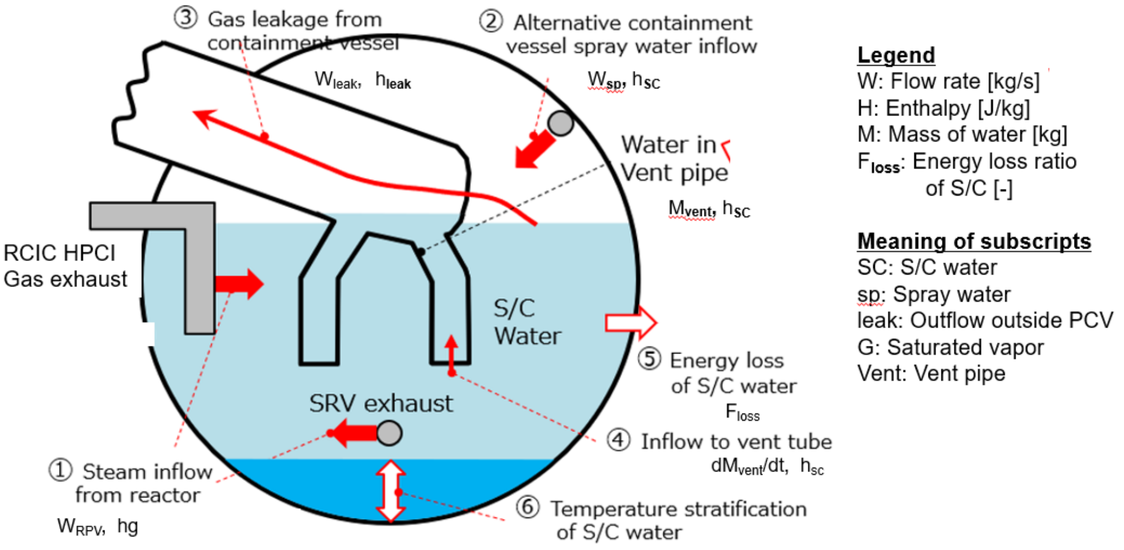
Time	D/W pressure	S/C pressure
3/13, 20:40	425kPa[abs]	375kPa[abs]
3/14, 00:00	240kPa[abs]	255kPa[abs]

■ 2.2 Evaluation based on measured S/C water level

Based on the measured S/C pool water level up to 20:00 on March 12 shown in Figure 1, the S/C water level behavior was evaluated until the time of the first venting, considering the steam inflow generated by decay heat and the assumed water injection rate of the containment vessel spray.

■ 2.2.1 Evaluation method

The S/C water level behavior was evaluated based on the mass and energy balance of the S/C pool water from the time of the earthquake to the first venting. An overview of the evaluation method is shown in Figure 4. In addition, details of the evaluation method, such as the setting method for items ① to ⑥ considered in Figure 4, are shown below.



Mass balance:

$$\frac{dM_{SC}}{dt} = W_{RPV} + W_{sp} - W_{leak} - \frac{dM_{vent}}{dt}$$

Energy balance:

$$\frac{dM_{SC}h_{SC}}{dt} = \left(W_{RPV}h_g + W_{sp}h_{sp}\right)\left(1 - F_{loss}\right) - W_{leak}h_{leak} - \frac{dM_{vent}h_{sc}}{dt}$$

Figure 4 Outline of the evaluation model

① Inflow of water vapor from the reactor

Until the reactor water level drops to the top of the active fuel length (TAF), all of the decay heat contributes to the evaporation of the reactor water, and the water vapor is assumed to flow into the S/C water through the RCIC HPCI gas exhaust or the SRV exhaust. The time at which the reactor water level reaches TAF was assumed to be 02:30

on March 13, based on the previous MAAP analysis (Attachment 3) and the results of various severe accident analysis codes in the BSAF project [2].

After the reactor water level reached TAF, the reactor water level was estimated to be near the bottom of the active fuel length (BAF) at 08:55 on March 13 in Attachment 3-9. The water in the core (above BAF and below TAF) and the water below TAF above the top of the jet pump outside the shroud was assumed to evaporate and flow out into the S/C pool. The period of the outflow was assumed to be 4.5 hours from 04:30 to 09:00 on March 13, when the reactor pressure increased and pressure oscillations began to occur, suggesting the operation of the SRVs.

② Inflow of spray water

The start time of the first alternative S/C spray and the spray flow rate were set to be the time when the measured S/C water level rose faster and the flow rate that reproduced the rate of increase, respectively.

Regarding the end time of the first alternative S/C spray, the completion of the switchover to the reactor alternative water injection line was communicated to the central control room at 03:05 on March 13, but the exact stop time is unknown, and the possibility that the spray water stopped flowing in due to factors other than the switchover of the water injection destination cannot be completely denied. Therefore, the effect on the S/C water level due to the time of the end of spray can be taken into account.

In addition, the alternative D/W spraying that started at 07:39 on March 13 was done so that the effect on the S/C water level due to the presence or absence of flow into the S/C side could be taken into account, since there was a possibility that water could flow into the S/C side through the vent pipe if water accumulated in the D/W floor area.

③ Gas phase leakage from containment vessel

The containment pressure up to the time of the first venting increased to 405kPa[abs] by 12:25 on March 12, then decreased slightly and increased to 470kPa[abs] from around 05:00 to 08:55 on March 13. Although these are all below the containment design pressure, the possibility of a gas-phase leak from the containment could not be completely ruled out, so the effect of such a leak from the containment on the S/C water level could be considered.

④ Inflow into the vent pipe

The water level of the vent pipe and the inflow from the S/C to the vent pipe were evaluated based on the evaluated value of the S/C water level and the pressure difference between the D/W and S/C. The pressure difference between D/W and S/C was obtained from the pressure difference between D/W and S/C based on actual measurements, excluding the overstatement range of the pressure difference obtained in the evaluation process.

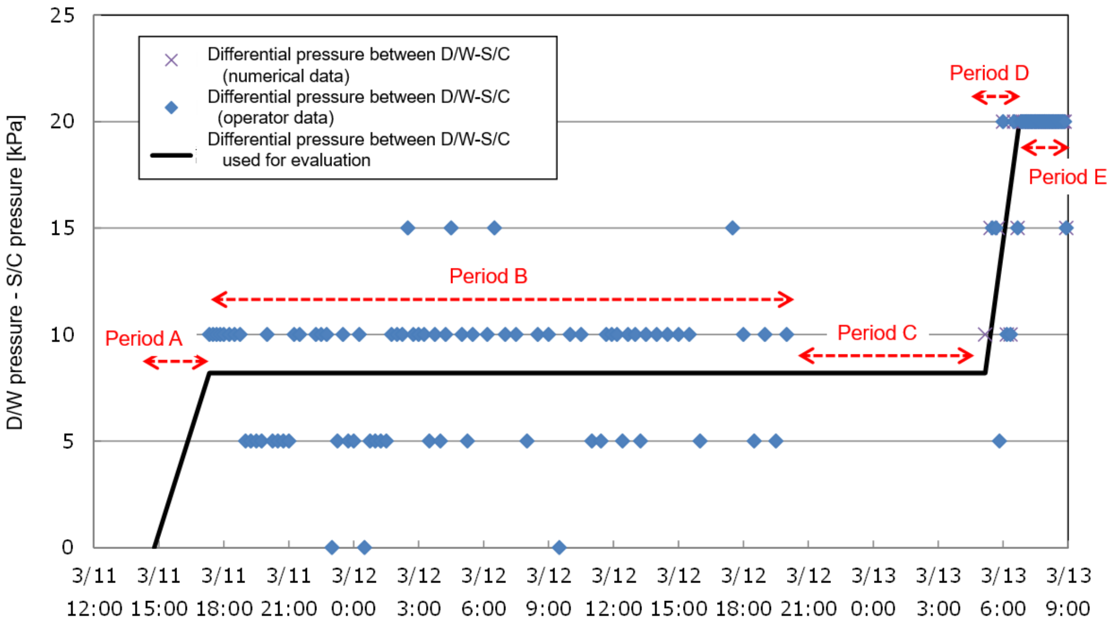


Figure 5 Pressure difference between D/W and S/C (measured values) and pressure difference used for evaluation

For the pressure difference between the D/W and S/C, where the measured values frequently changed in units of 5kPa, the values used in the evaluation were assumed to be the following for periods A to E in Figure 5.

- Since the pressure difference between D/W and S/C was not obtained for period A (until 17:20 on March 11), it was assumed that the pressure difference increased linearly from the condition at the time of the earthquake (assumed to be 0) to the average value of the pressure difference in period B.
- The pressure difference during period B (from 17:20 on March 11 to 20:00 on March 12) varied between 0kPa and 15kPa. At several points, 0kPa and 15kPa pressure differences were obtained, the cause of which is unknown, but the other pressure differences were either 5 or 10kPa. Given the fact that the measurements were taken in 5kPa increments, it could be assumed that for most of the period, the pressure differences were intermediate between 5kPa and 10kPa. Since the variation trend did not change significantly throughout the period, the pressure difference averaged over this period (8.2kPa) was assumed to be the pressure difference based on the measured values.

- The pressure difference was not obtained for period C (from 20:00 on March 12 to 05:10 on March 13), but based on the trend of the points for which data were obtained in Figure 5, it was assumed that the trend of the pressure difference in period B continued as it was.
- The pressure difference during period D (March 13, 05:10 to March 13, 06:40) varied between 5kPa and 20kPa. Overall, the pressure difference tended to increase, and later in period E, the pressure difference was almost constant at 20kPa. Based on these results, it was assumed that the pressure difference increased linearly from the average value of 8.2kPa in period C to 20kPa in period E.
- The pressure difference for period E (March 13 from 06:40 to 08:55) was constant at 20kPa except for one point at 08:55, which had the value of 15kPa, so 20kPa was assumed as the pressure difference for period E.

⑤ Energy loss ratio of S/C water

For items ① and ②, where energy flowed into the S/C water from outside, the effect on the S/C water level due to the energy loss of the S/C water (the percentage of the inflow energy that was lost due to heat dissipation to the torus room and to the S/C gas-phase section) could be considered. It was assumed that the cooling from the S/C wall was accelerated by the fact that the torus room was flooded in Unit 2 (Attachment 2-2), and although it was possible that a similar situation existed in Unit 3, there is no information in the accident response records for Unit 3 that supports the fact that the torus room was flooded (such as the fact that the torus room was filled with steam), and it was not considered.

⑥ Temperature stratification of S/C water

As shown in Attachment 3-7, temperature stratification of S/C water might have occurred during the time period in question. In order to consider the effect of this on the S/C water level, the S/C pool was divided into two regions, the upper and lower regions of high and low temperature, so that the effect of the boundary height (temperature stratification boundary height) between the two regions could be considered. It was assumed that the temperature of water below this height did not change, while the temperature of water above this height rose uniformly due to the inflow of energy.

2.2.2 Evaluation assumptions

- <u>Overstatement range of the pressure difference</u>

The overstatement range of the pressure difference was considered to be the difference in hydraulic head between the water level of the vent pipe after the start of S/C venting (estimated at the bottom of the downcomer in Estimation 2 of Section 2.1) and the S/C water level since it was possible to see how much the deviation was from the measured pressure difference of 50 kPa during the evaluation process of the S/C water level.

It is not clear whether this overstatement range of the pressure difference was originally in such a state or whether it was caused by the earthquake or the tsunami. In this evaluation, it was assumed that the pressure difference was zero at the time of the earthquake, increased linearly until 17:10 on March 11, when actual measurements began to be obtained, and remained constant thereafter.

This evaluation also assumed that the range of overstatement of the pressure difference between D/W and S/C has not changed since the actual containment pressure readings began to be obtained. The containment pressure gauges used are affected by ambient temperature, radiation, humidity, etc., and the errors of the gauges can expand, but since the pressure difference between D/W and S/C after the S/C vent, where these conditions would have changed significantly, showed almost constant values until 20:40 on the 13th, it was assumed that during the period of interest (to 00:00 on the 14th) the pressure gauge error did not increase significantly.

- <u>Consideration of the deviation between the indicated value of the S/C water level gauge and the actual water level</u>

The S/C water level gauge connects the piping from the S/C water and S/C vapor phase sections to the same differential pressure gauge, converts the differential pressure between the two into the water level, and outputs it as an indicated value. The evaluation value to be compared with the actual measured value of the S/C water level in the evaluation should not be the evaluated value of the S/C water level itself, but the value converted into the indicated value of the S/C water level meter. This is because the indicated value of the S/C water level gauge deviates from the actual water level due to the S/C temperature (changes in the S/C temperature cause changes in the density of the S/C water, resulting in a deviation between the value measured by the pressure gauge and the actual water level) and the water temperature in the water level gauge piping. The behavior of the S/C temperature can be determined by evaluation, but the behavior of the water temperature in the water level gauge pipe is difficult to evaluate, so the effect can be considered as one of the sensitivity parameters in the evaluation conditions.

- <u>Reliability of actual measured values of S/C water level</u>

It was confirmed that the indicated value of the S/C water level gauge could be reproduced well by taking into account the inflow of water vapor produced by decay heat in the reactor into the S/C until around 12:00 on March 12. This was believed to indicate that the actual measured values of the S/C water level during this period were also reliable to some extent.

In addition, as mentioned above, the S/C water level gauge connects the piping from the S/C water and S/C vapor phase sections to the same differential pressure gauge, converts the differential pressure between the two into a water level, and outputs it as an indicated value. In light of this, there was no particular factor that would cause the reliability of the instrument to deteriorate even after about 12:00 on March 12, when the DDFP was started up.

Based on the above, it was assumed that the actual measured value of the S/C water level was reliable for this evaluation.

■ 2.2.3 Evaluation conditions

The evaluation conditions are shown in Table 2. In the Base Case, the following conditions were applied: no inflow of alternative D/W spray into the S/C; the end time of the first alternative S/C spray was the time when the completion of the switch to the reactor alternative water injection line was communicated to the central control room; no containment gas phase leakage; no energy loss in the S/C water, no consideration of temperature stratification was made; and the water level gauge pipe water temperature was assumed to increase linearly with S/C temperature rise.

Several evaluation cases were conducted as sensitivity cases, in which only certain parameters were changed from the Base Case (corresponding to (i)-(vi) in Table 2). Sensitivity Case 1 was the case in which the alternative S/C spray system operated as per the actual operation records even after the S/C water level could no longer be measured, and furthermore, it was assumed that all the alternative D/W spray water injected flowed into the S/C side; Case 1 was positioned as a case in which the amount of spray water injected into the S/C was estimated to be large. On the other hand, Sensitivity Case 2 was the case in which the shortest spray time was assumed within the range in which the vent pipe water level was not higher than the S/C water level by more than the water level difference corresponding to the differential pressure of the vacuum break valve (about 35cm; Case 2 was positioned as the case in which the amount of water sprayed into the S/C was estimated to be small. Sensitivity Cases 3 through 6 confirmed the influence of uncertainties in factors other than the amount of water sprayed into the S/C.

Sensitivity Case 1: Only condition (i) was changed to "Setting (Sensitivity Case)

Sensitivity Case 2: Only condition (ii) was changed to "Setting (Sensitivity Case)"

Sensitivity Case 3: Only condition (iii) was changed to "Setting (Sensitivity Case)"

Sensitivity Case 4: Only condition (iv) was changed to "Setting (Sensitivity Case)"
Sensitivity Case 5: Only condition (v) was changed to "Setting (Sensitivity Case)"
Sensitivity Case 6: Only condition (vi) was changed to "Setting (Sensitivity Case)"

Based on the evaluation of Sensitivity Cases 1-6, the parameters that affected the results were identified and the evaluated value of the S/C water level at the start of venting was estimated.

Table 2 Evaluation conditions

Item	Setting (Base Case)	Setting (Sensitivity Case)	Basis for setting
S/C and vent pipe initial water level	4.15m from S/C bottom	Same as left	Chart
S/C initial water temperature	21℃	Same as left	Chart
RCIC/HPCI/Alternate S/C spray water injection temperature	10℃	Same as left	Note 1
Alternative D/W spray inflow into S/C	None	(i) All inflow	Note 2
End time of first alternative S/C spray	March 13, 3:05	(ii) March 12, 22:00	Note 3
Containment gas-phase leakage rate	No leakage	(iii) 100%/day	Assumption
S/C water energy loss ratio	No loss （F_{loss}=0）	(iv) 20% of heat input lost （F_{loss}=0.2）	Assumption
Temperature stratification boundary height	No temperature stratification	(v) S/C (1.6m from bottom)	Note 4
Water temperature of water level gauge pipe	21℃⇒50℃	(vi) 21℃ (constant)	Note 5

Note 1: The condensate storage tank, which is the water source for the RCIC/HPCI, and the filtered water tank, which is the water source for the alternative S/C spray, are both located outdoors and were assumed to be at the outdoor temperature.

Note 2: The flow rate of the alternative D/W spray was assumed to be approximately the same as the alternative S/C spray. On the other hand, the actual spray flow rate might have been lower because of the upward trend in D/W pressure during the period of alternative D/W spray implementation. In this sense, Sensitivity Case 1 can be positioned as a case with a higher spray flow rate, and thus a higher S/C water level is evaluated.

Note 3: If the vacuum break valve was not submerged, the vent pipe water level would not be higher than the S/C water level by more than the head (about 35cm) equivalent to the differential pressure (0.035kg/cm^2) of the vacuum break valve operation, so the earliest possible spray end time that satisfies this condition was set in the sensitivity case.

Note 4: The sensitivity case was set to the temperature stratification height at which the S/C water surface temperature became the saturation temperature of the pressure at 12:25 on March 12, when the peak S/C pressure was observed.

Note 5: The initial temperature was assumed to be about the same as the S/C water temperature; based on the situation where the operator was able to enter the torus room at 07:40 on March 13, it was assumed that the torus room temperature was below about 50°C at that time, and in the Base Case it was assumed to have risen linearly to 50°C by 09:00 on March 13. The sensitivity case was set to the case where the water temperature did not change.

■ 2.2.4 Evaluation results

A summary of the evaluation results is shown in Table 3, and the results for individual evaluation cases are shown in Figures 6 through 12.

In the course of the evaluation, the inflow start time of the alternative S/C spray and the spray flow rate (pressure loss in the spray piping) were determined so that the calculated value was consistent with the actual measured value of the S/C water level gauge indication. In addition, the overstatement range of the pressure difference between D/W and S/C was determined to be consistent with the actual measured value of 50kPa of the pressure difference between D/W and S/C after the first venting. These values are also listed in the table.

The S/C water level at the start of the first venting was 6.84 to 7.43m, more than 1m higher than the top of the vacuum break valve. Of the values to be determined during the evaluation process, the start time of the alternative S/C spray inflow was between 13:30 and 14:00 on March 12 (the reason why the start time of the spray inflow needed to be later than the DDFP startup time is discussed later in Section 2.2.5(2)). The maximum alternative S/C spray flow rate was around 100m^3/h. The overstatement range of the pressure difference between D/W and S/C was 5.9 to 11.7kPa, both results indicating that the actual pressure difference was smaller than the measured value. The validity of these evaluation results is discussed in Section 2.2.5.

Among all evaluated cases, the S/C water level was highest in Sensitivity Case 1 and lowest in Sensitivity Case 2, with the only difference between them being the amount of spray water injected. In Sensitivity Cases 3 through 6, in which the sensitivity of parameters other than spray was evaluated, there was no significant difference in S/C water level from the Base Case, suggesting that the amount of spray water injected was the dominant factor in the results of the S/C water level evaluation. Therefore, the range of results (6.84 to 7.43m) between Sensitivity Case 2 and Sensitivity Case 1, where the amount of spray water injection was over- or underestimated, was used as the range of S/C water level at the time of the first venting in this evaluation. Correspondingly, the overstatement range of the pressure difference between D/W and S/C determined by the S/C water level should be in the range of 5.9 to 11.7kPa.

Table 3　Summary of the evaluation results

Evaluation case	Result	Value to be sought in the evaluation process		
	S/C water level at start of first venting (Height from top of vacuum break valve)	Time of inflow start of alternative S/C spray	Maximum value of alternative S/C spray flow rate	Overstatement range of pressure difference between D/W and S/C
Base	7.32m（1.49m）	March 12 14:00	95.2m^3/h	6.9kPa
Sensitivity Case 1	7.43m（1.60m）	March 12 14:00	93.8m^3/h	5.9kPa
Sensitivity Case 2	6.84m（1.02m）	March 12 14:00	106.7m^3/h	11.7kPa
Sensitivity Case 3	7.32m（1.49m）	March 12 14:00	96.6m^3/h	6.9kPa
Sensitivity Case 4	7.28m（1.45m）	March 12 14:00	98.9m^3/h	6.7kPa
Sensitivity Case 5	7.35m（1.52m）	March 12 14:00	95.2m^3/h	7.2kPa
Sensitivity Case 6	7.36m（1.53m）	March 12 13:30	93.8m^3/h	6.6kPa

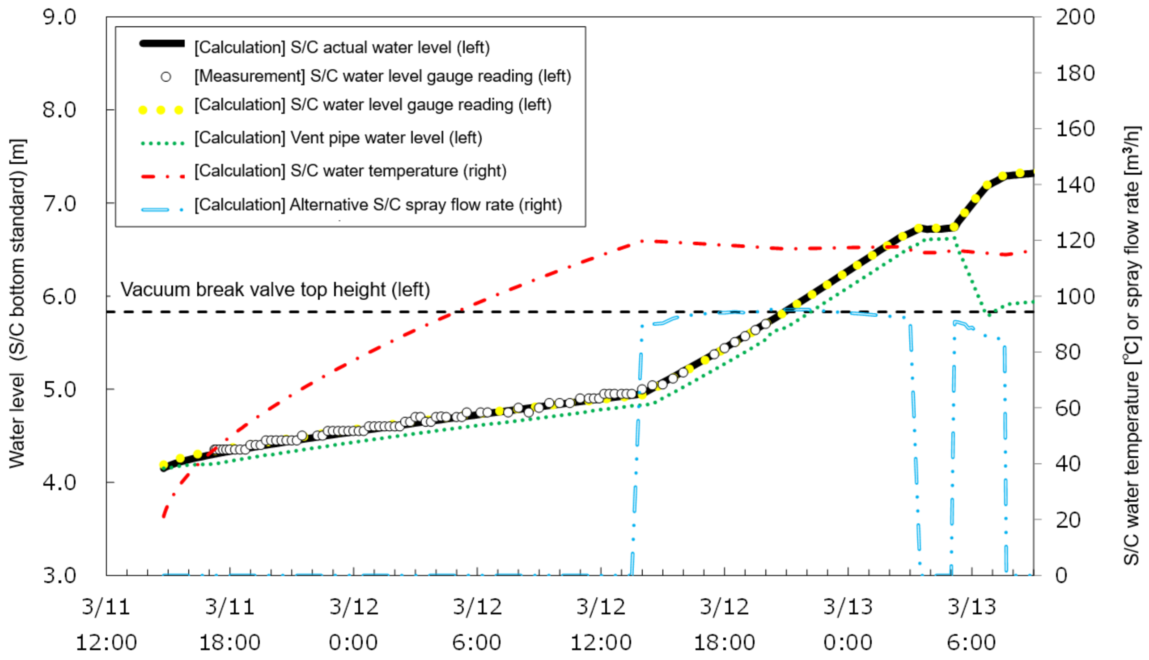


Figure 6　Evaluation result (Base Case)

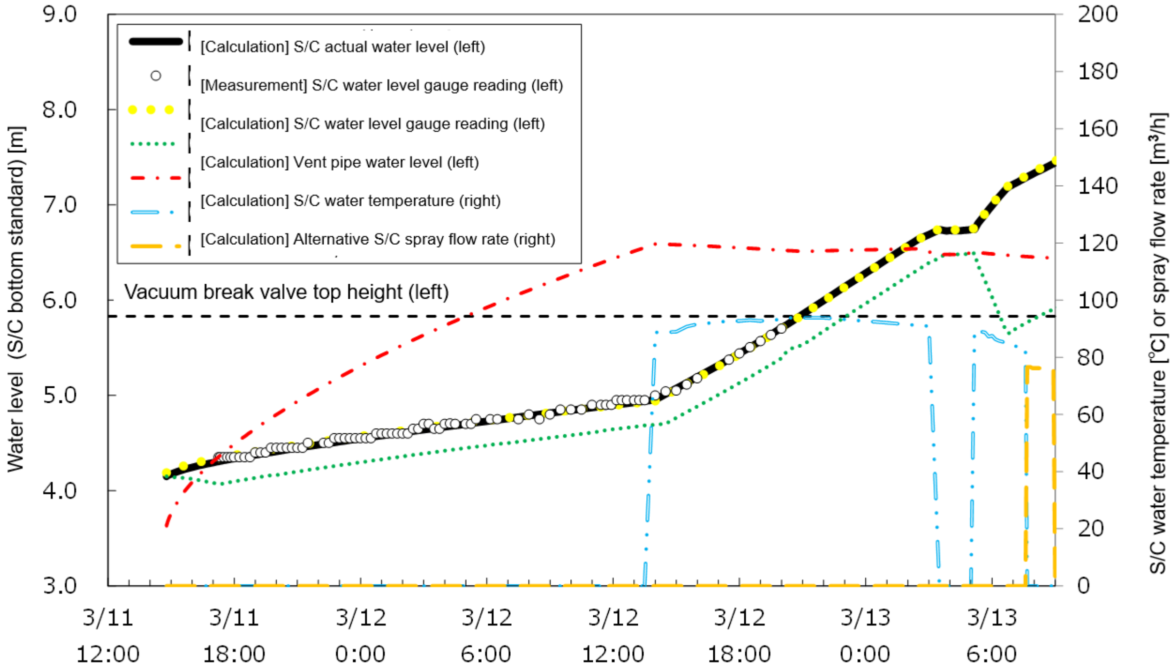


Figure 7　Evaluation result (Sensitivity Case 1: assuming inflow of alternative D/W spraying into S/C)

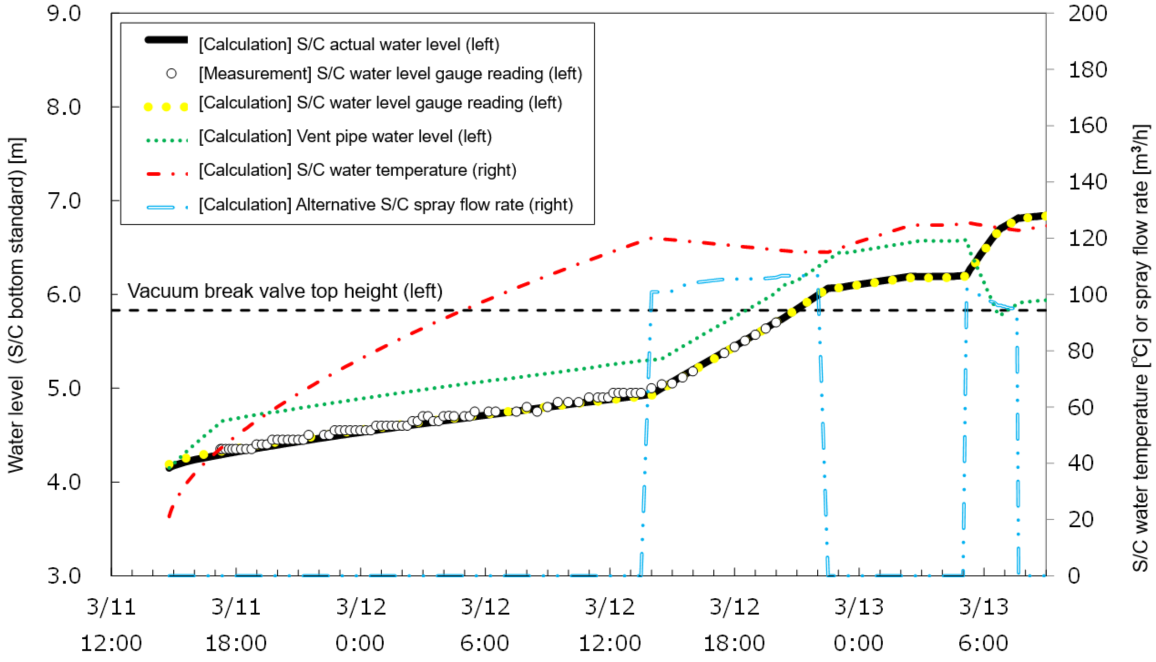


Figure 8 Evaluation result (Sensitivity Case 2: alternative spray end time, March 12, 22:00)

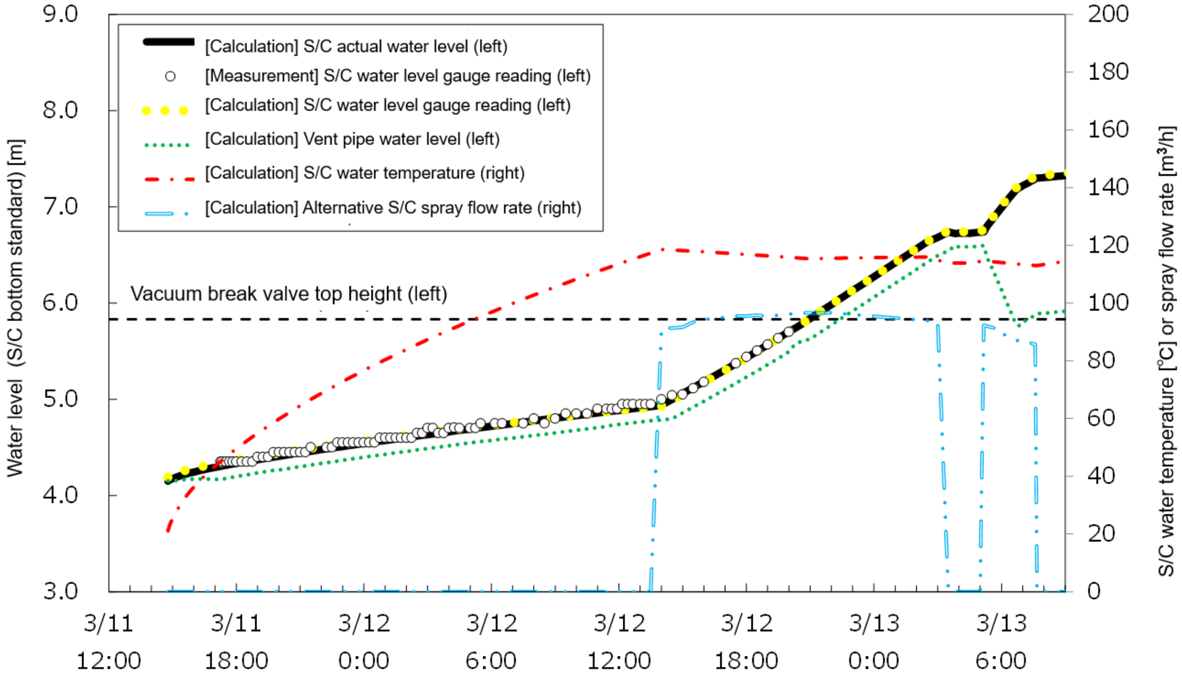


Figure 9 Evaluation result (Sensitivity Case 3: considering gas-phase leakage from the containment vessel)

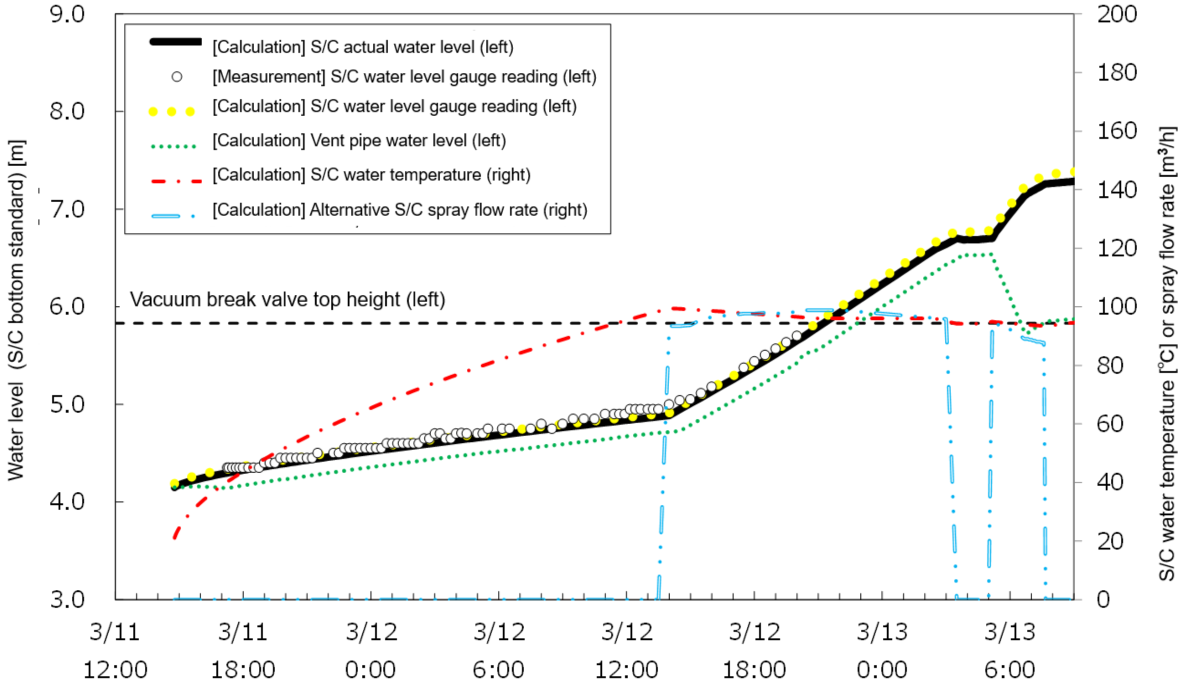


Figure 10 Evaluation result (Sensitivity Case 4: considering energy loss of S/C water)

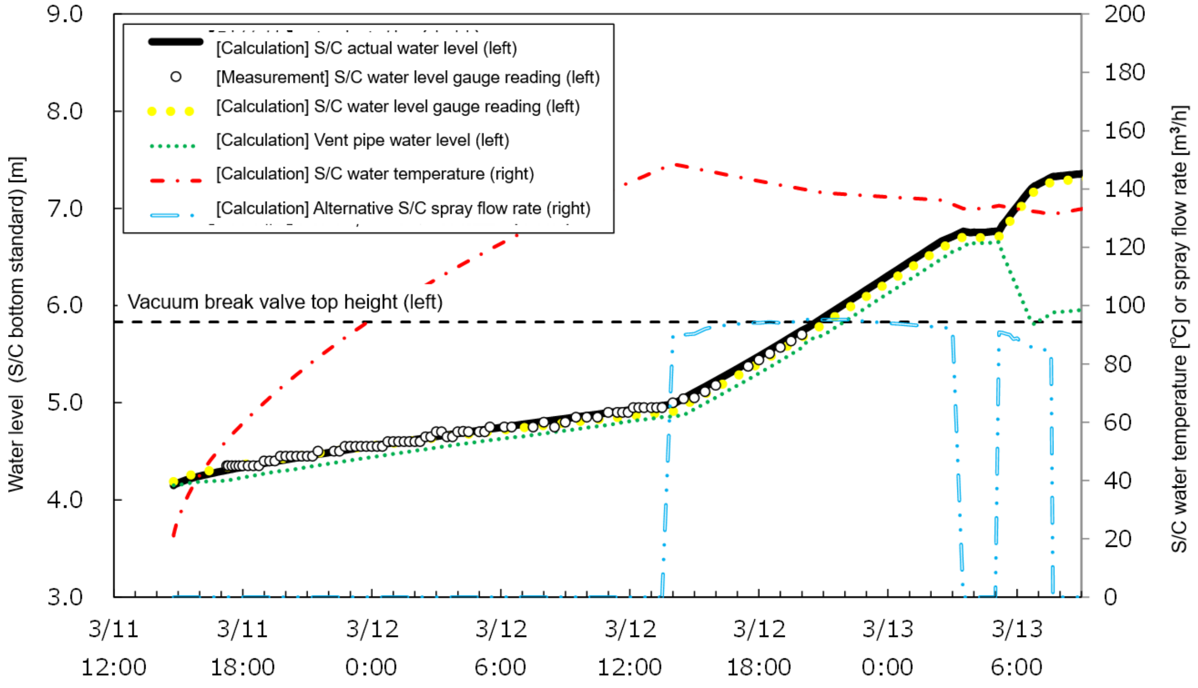


Figure 11 Evaluation result (Sensitivity Case 5: considering S/C temperature stratification)

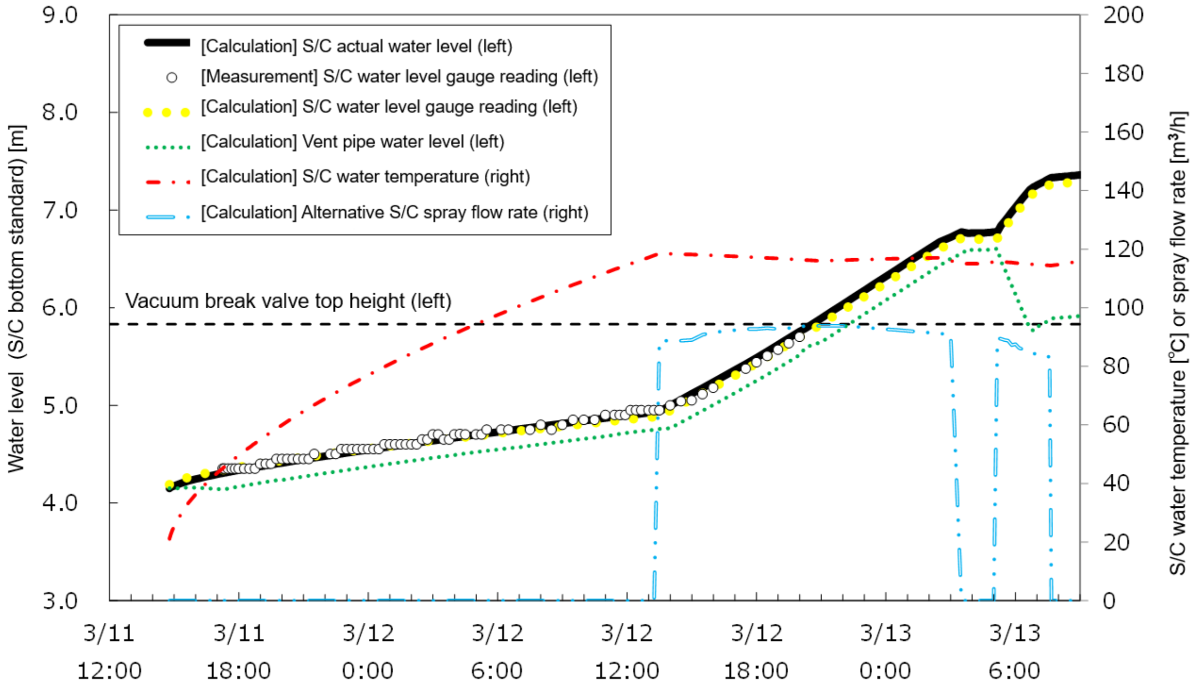


Figure 12 Evaluation result (Sensitivity Case 6: Considering water temperature changes in the water level gauge piping)

■ 2.2.5 Discussion of evaluation results

This section discusses the validity of the evaluation results presented in Section 2.2.4.

(1) Vent pipe water level after S/C water level exceeds top height of the vacuum break valve

In this evaluation, the relationship between the vent pipe water level and S/C water level did not change before and after the S/C water level exceeded the top height of the vacuum break valve. Since the pressure difference between the D/W and S/C was not obtained from 20:00 on March 12 to around 05:00 on March 13, the trend of the pressure difference until then was extrapolated as shown in Figure 5, which resulted in the evaluation. On the other hand, when the vacuum break valve is submerged, the function of equalizing pressure between D/W and S/C is lost, so the vent pipe water level will fall if the pressure on the D/W side is relatively higher, and the vent pipe water level will rise if the pressure on the S/C side is relatively higher, but since no pressure difference was obtained, the behavior of the vent pipe water level during this period is unknown. Therefore, it is possible that this evaluation does not trace the trend of the vent pipe water level during this period. However, the amount of water injected into the S/C itself is estimated from the actual S/C water level, and the estimation of the total amount of water including the vent pipe and S/C is not dependent on the behavior of the vent pipe water level during this period. The pressure difference between the D/W and S/C was obtained again after about 05:00 on March 13, and the extent to which water was in the vent pipe during the process, i.e., where the S/C water level was during the process, did not significantly affect the results of the evaluation of the S/C water level at the start of S/C venting which was the ultimate target to be obtained.

(2) Start time of the alternative S/C spray inflow is later than DDFP startup time

In order to reproduce the actual measured S/C water level in the evaluation, it was necessary to set the start time of the alternative S/C spray inflow about 1.5 to 2 hours later than the DDFP startup time of 12:06. The cause of this is not clear, but the S/C water level data [1] collected by the operator showed a constant value (4.95m from the bottom of the S/C) from 12:10 to 13:30 after DDFP startup, and if the injected water had accumulated in the S/C pool to the extent estimated from the subsequent rate of the rise of the S/C water level, the constant water level trend cannot be explained.

The containment pressure [1] was 390kPa[abs] for the D/W and 380kPa[abs] for the S/C at 12:10, immediately after the DDFP startup, but increased to 405kPa[abs] for the D/W and 400 kPa[abs] for the S/C at 12:25 when the next actual measurement was taken. Since different pressure data were collected over time, it is highly likely that the actual S/C water level was constant as well as the water level data at that time.

Furthermore, if the S/C spray had flowed in immediately upon the startup of the DDFP, the containment pressure would be expected to decrease, but the trend of the actual measured values was different.

From these observed facts, it is possible that the start time of the alternative S/C spray inflow was later than the DDFP start time for some reason.

The containment pressure dropped to D/W pressure of 390kPa[abs] and S/C pressure of 380kPa[abs] at 12:40, when the containment pressure was next measured. While it is possible that the S/C spray injection started a little later than the DDFP startup, this could have been caused by an increase in the alternative S/C spray flow rate to the extent that it had little effect on the S/C water level, resulting in a decrease in the S/C pressure. On the other hand, it cannot be ruled out that the pressure could have been reduced by factors other than the spray, such as the S/C water being agitated by the HPCI startup at 12:35, which caused the surface temperature of the S/C pool to drop. In either case, however, the conclusions of this evaluation are not significantly affected.

From the above, it is possible that the drop in containment pressure after around 12:30 on March 12 was a partial inflow of S/C spray, but given the fact that S/C pressure did not drop immediately after DDFP startup, it is possible that it took some time for the spray water to reach the S/C for some reason. The S/C pressure was not reduced immediately after the DDFP startup.

(3) Alternative S/C spray flow rate

In each evaluation case, the flow rate for the alternative S/C spray operation is about 100m^3/h. Since the DDFP used is capable of water injection of more than 100m^3/h in terms of performance, this is an achievable flow rate in terms of pump performance.

(4) Overstatement range of pressure difference between D/W and S/C

When the pressure difference between the D/W and S/C after the first venting is 50kPa, the range of pressure difference over-indication is 5.9kPa to 11.7kPa, and the evaluation results showed that the actual pressure difference between D/W and S/C was smaller than the measured value in both cases. The pressure difference between the D/W and S/C is proportional to the difference between S/C water level and vent pipe water level. A small pressure difference means a high vent pipe water level.

In Attachment 3-7, it is estimated that the likely cause of the increase in containment pressure up to about 12:30 on March 12 was due to temperature stratification in the S/C pool. In that case, water vapor generated in the S/C would migrate to the D/W through the vacuum break valve. The working differential pressure of this vacuum break valve is 0.035kg/cm^2 (about 3.4kPa). If the closing differential pressure was 0kPa, the water level in the vent pipe was higher than the S/C water level during the period when the vacuum break valve was operating, by the amount of water level difference (0 to about 3cm) corresponding to these differential pressures.

Looking at the evaluation results from this viewpoint, in the Base Case, the vent pipe water level was almost equal to the S/C water level, a direction consistent with the above assumption that the vacuum break valve was operating. In Sensitivity Case 1, the assumption of alternative D/W spray inflow into the S/C resulted in an increase in the S/C water level, and as a result, the range of pressure difference overstatement , such that the pressure difference between the D/W and S/C after the first venting was 50kPa, was smaller than in the Base Case. As a result, the vent pipe water level dropped slightly, a direction inconsistent with the above assumption that the vacuum break valve was operating. In Sensitivity Case 2, the vent pipe water level increased, contrary to Sensitivity Case 1, due to the earlier end time of the alternative S/C spray. The reason why the end time of the spray in this case was set at 22:00 on March 12 was because this was the time when the vent pipe water level was about 35cm higher than the S/C water level. Ending the spray earlier than this time would have resulted in a higher vent pipe water level, a difference that would have been physically impossible regardless of whether the pressure increase was on the S/C or D/W side. All other cases were not significantly different from the Base Case.

As described above, the vent pipe water level derived from the overstatement range of the pressure difference between D/W and S/C in the Base Case and Sensitivity Cases 1 through 6 covered the range of water levels expected when the vacuum break valve was activated. Since the S/C water level at the start of the first venting was used in the calculation, it is believed that the S/C water level at the start of the first venting is likely to be within the range of the evaluation results shown in Table 3.

(5) Differences between evaluation cases

Sensitivity Cases 1 and 2 differ from the Base Case in the estimated results of the final S/C water level at the start of the first venting because the assumption for the amount of water injected into the S/C during the period when actual measurements of the S/C water level are not available is different from that in the Base Case.

For the other sensitivity cases, differences from the Base Case were considered, including the period during which actual S/C water level measurements were obtained, but in the end, the amount of water injected from the alternative S/C spray was adjusted during the evaluation process to reproduce the value indicated by the S/C water level gauge, so the estimated results of the S/C water level at the start of the final first venting do not differ significantly from those of the Base Case. The difference in the maximum value of the alternative S/C spray flow rate after adjustment from the Base Case is only a few percent, and the impact of the differences considered in these sensitivity cases on the S/C water level is not considered to be that large in the first place.

Sensitivity Case 3 assumed a gas-phase leakage from the containment (100%/day) and it removes the mass and energy of the water vapor from the S/C water, but slightly increases the alternative S/C spray flow rate to be consistent with the measured S/C water level, resulting in little effect on the S/C water level evaluation results and only about 2°C decrease in S/C water temperature.

In Sensitivity Case 4, heat release from the S/C water (20% of the heat input is lost) was considered and the energy for this was removed from the S/C water. This has little effect on the results of the S/C water level evaluation, but the S/C water temperature is about 95°C at the start of the first venting, about 20°C lower than in the Base Case, indicating the need to appropriately assume heat release from the S/C water when evaluating S/C water temperature.

In Sensitivity Case 5, a temperature stratification boundary height was set, and mass and energy balances were calculated for the water above the boundary height while the water below the boundary height was left in its initial state. The results show that the S/C water temperature above the boundary height is higher than in the Base Case, but the adjustment of the alternative S/C spray flow rate has little effect on the results of the S/C water level evaluation. It should be noted that in order to confirm the effect of temperature stratification in this evaluation, an assumption was made that the boundary of temperature stratification existed and that its height was always constant, but it is unclear whether there was actually a clear boundary. It was also assumed that if the top of the S/C pool was cooled by the alternative S/C spray, temperature stratification would have been mitigated to a significant degree. Therefore, it is believed that the uncertainty in the results of the S/C water temperature assessment in this case is large, especially after the inflow of the alternative S/C spray, which is higher than the actual value.

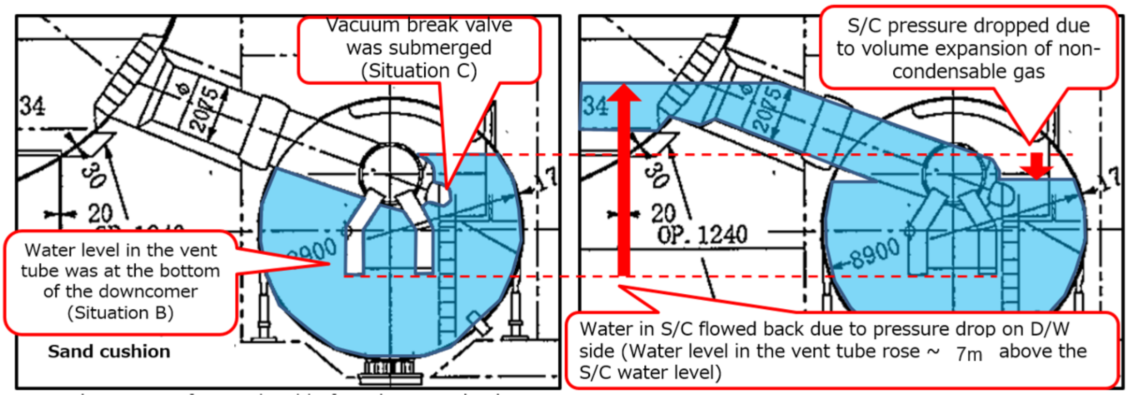
The reason why the inflow start time of the alternative S/C spray was 30 minutes earlier in Sensitivity Case 6 than in the other cases is that the water level gauge indication in the evaluation was slightly lower as a result of assuming that the water temperature in the water level gauge piping did not change from the initial period, and it was necessary to start the spray water injection earlier to reproduce the subsequent water level gauge indication.

■ 2.3 Evaluation based on actual measured containment pressure

Based on the actual measured values of containment pressure shown in Figure 2, the S/C water level at 20:40 on the 13th was evaluated. Also, the S/C water level at the start of the first venting was estimated by evaluating the change in the S/C water level since the start of the first venting.

■ 2.3.1 Evaluation of S/C water level at 20:40 on March 13

Figure 13 shows an image of the water level in the containment vessel from 20:40 on March 13 to 00:00 on March 14. Based on Estimations 1 to 3 shown in Section 2.1, the S/C water level at 20:40 on March 13 was evaluated to simultaneously reproduce the amount of depressurization due to the volume expansion of the S/C gas phase from 20:40 on March 13 to 00:00 on March 14 and the variation in the pressure difference between the D/W and S/C due to the migration of the volume expansion water to the D/W side.


Vacuum break valve was submerged (Situation C)

Water level in the vent tube was at the bottom of the downcomer (Situation B)

S/C pressure dropped due to volume expansion of non-condensable gas

Water in S/C flowed back due to pressure drop on D/W side (Water level in the vent tube rose ~ 7m above the S/C water level)

Figure 13 Image of water level in containment vessel from 20:40 on March 13 to 00:00 on March 14

(1) Evaluation procedures

The evaluation procedures are shown in (1) through (12) below. In addition, a conceptual diagram of the evaluation is shown in Figure 14.

① Assume the overstatement range of the pressure difference between D/W and S/C.

② Assume the S/C temperature.

③ Obtain the S/C water level before depressurization from the actual measured value of the pressure difference between D/W and S/C before depressurization (50kPa) and ① and ②.

④ Based on the relationship between water level and water volume on the S/C side, determine the volume of the S/C liquid phase section before depressurization.

⑤ Subtract the volume of the liquid phase from the total volume of S/C to obtain the volume of the gas phase of S/C before depressurization.

⑥ Find the volume of the S/C gas phase portion after depressurization based on the relationship between the S/C pressure before and after depressurization.

⑦ Subtract the volume of the gas phase from the total volume of the S/C to obtain the volume of the liquid phase of S/C after depressurization.

⑧ Find the S/C water level after depressurization based on the relationship between water level and water volume on the S/C side.

⑨ Obtain the volume of water sucked up to the D/W side from the difference in the volume of the S/C liquid phase section before and after depressurization.

⑩ Based on the relationship between the water level and water volume on the D/W side, obtain the water level on the D/W side after depressurization.

⑪ Find the increase in hydraulic head on the D/W side relative to the S/C side based on the range of decrease in water level on the S/C side and the range of increase in water level on the D/W side.

⑫ Change ② until the result agrees with the measured fluctuation of the pressure difference between D/W and S/C, 65kPa. If it agrees, repeat the above by changing ①.

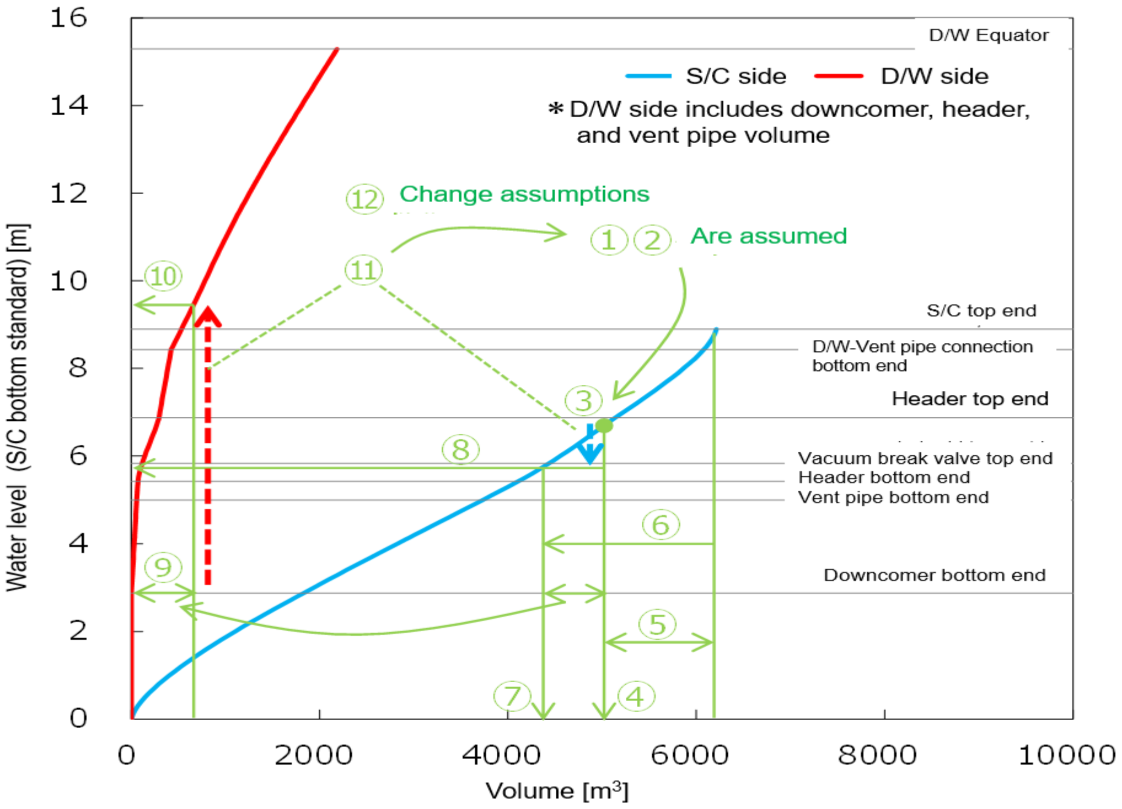


Figure 14 Conceptual diagram of the S/C water level evaluation at 20:40 on March 13

By evaluation procedure ③, the S/C water level before depressurization was obtained by Equation (1) based on Bernoulli's theorem:

$$H_{SC} = H_{DCbot} + \frac{\left(\Delta P_{mea} - \Delta P_{over}\right) \times 1000}{\rho_{SC} g} \tag{1}$$

where

H_{SC} : S/C water level before depressurization (S/C bottom reference) [m]

H_{DCbot} : Height of vent pipe downcomer bottom edge (S/C bottom reference), 2.875 [m]

ΔP_{mea} : Actual measured pressure difference between D/W and S/C, 50 [kPa]

ΔP_{over} : Overstatement range of pressure difference between D/W and S/C [kPa] (assumed in ①)

ρ_{SC} : S/C water density [kg/m^3] (value at S/C temperature assumed in ②)

g : Gravitational acceleration [m/s^2]

By evaluation procedure ⑥, the volume of the S/C vapor phase after depressurization was evaluated using the Equations (2) and (3), which relate to the change in pressure when the S/C vapor phase expands in volume. P_{steam} in Equations (2) and (3) is the saturated water vapor pressure at the S/C temperature assumed in (2), and is assumed to remain unchanged during depressurization. This is based on the assumption that the S/C vapor phase temperature does not change significantly during depressurization (as the S/C vapor phase temperature decreases, the saturated vapor pressure decreases, in which case evaporation from the S/C water surface occurs and the vapor phase temperature is expected to be maintained to some extent). In other words, it is assumed that the depressurization of the S/C occurs only due to the volumetric expansion of the non-condensable gas. The possible mechanism for the presence of non-condensable gas in the S/C gas phase after S/C venting could be the migration of hydrogen and nitrogen remaining in the D/W or the migration of newly produced hydrogen in the reactor to the S/C gas phase:

$$P_1 = P_{steam} + P_{NC} \tag{2}$$

$$P_2 = P_{steam} + \frac{V_1}{V_2} P_{NC} \tag{3}$$

where

P_1, P_2 : S/C pressure before and after depressurization [Pa]

P_{steam} : Water vapor partial pressure in S/C [Pa]

P_{NC} : Non-condensable gas partial pressure in S/C before depressurization [Pa]

V_1、V_2 : Volume of S/C gas phase before and after depressurization [m^3]

The water level on the D/W side was treated as continuously rising even after the vent pipe water level reached the connection between the D/W and vent pipe due to backflow from the S/C. This is because it was considered that some water had accumulated on the D/W floor due to condensation of water vapor migrating from the S/C to D/W and the alternative D/W spray by the DDFP from 07:39 to 09:00 on March 13.

(2) Evaluation results

The evaluation results are shown in Figure 15. The solid and dashed lines show the values when only the S/C pressure was considered to be understated and when only the D/W pressure was considered to be overstated as a factor of the overstatement width of the pressure difference between D/W and S/C, respectively. By looking at the figure, for example, if the overestimation range of the pressure difference between the D/W and S/C was 8 kPa, the S/C water level at 20:40 on March 13 is read as about 7.3m from the bottom of S/C, the S/C water level after depressurization is about 6.5m, the D/W water level after depressurization is about 8.9m, the S/C temperature is around 100°C, and so on.

In Figure 15, as the overstatement range of the pressure difference between the D/W and S/C increases, the S/C water level, which reproduces the actual measured differential pressure before depressurization, becomes lower. The volume of the S/C gas-phase section increases accordingly, the partial pressure of non-condensable gas is higher to reproduce S/C depressurization, the water vapor pressure is lower, and the S/C temperature is lower.

Figure 15 shows the results for the range where the S/C temperature solution was obtained, and the estimated value of the S/C water level before depressurization from this evaluation is in the range of the figure (approximately 6.8m to 8.3m from the bottom of the S/C). In this evaluation, the S/C water level exceeded the top height of the vacuum break valve (5.832m from the bottom of the S/C) before and after depressurization, which is consistent with the assumption of the evaluation that the S/C water level exceeded the vacuum break valve height.

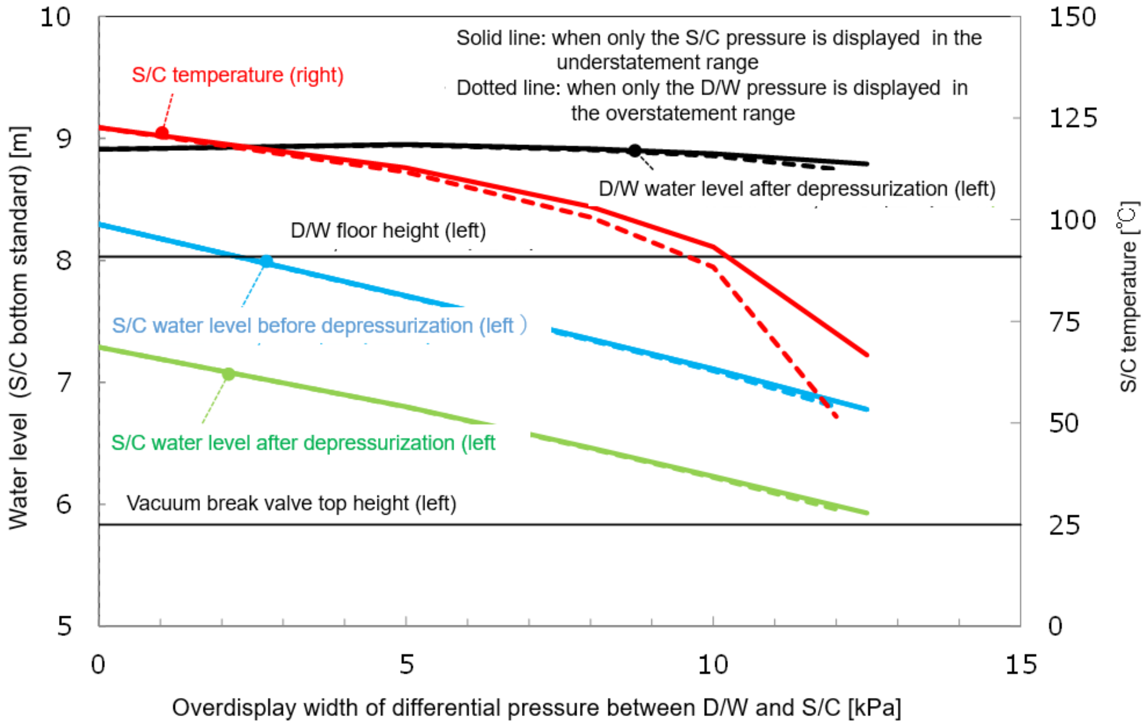


Figure 15 Evaluation results of S/C water level and S/C water temperature at 20:40 on March 13

- 2.3.2 Estimation of the range of fluctuation of the S/C water level from the start of the first venting to 20:40 on March 13

Based on the estimated range of S/C water level at 20:40 on March 13, the range of S/C water level at the start of the first venting was estimated. The reasons for the water level fluctuation from the start of the first venting are considered to be (1) the fluctuation of the S/C water level from the time the water level in the vent pipe was pushed down to the lower end after the start of the first venting to 20:40 on March 13, and (2) the rise of the S/C water level due to the water in the vent pipe being pushed to the S/C side at the start of the venting. Each of these were evaluated.

(1) Fluctuation of S/C water level after the water level in the vent pipe is pushed down to the lower end after the first venting starts

Estimation of the extent of the rise in the S/C water level

The reason for the rise in the S/C water level after the first venting is thought to be the inflow of water vapor produced by the decay heat and the water-Zr reaction heat into the S/C. Although the amount of water injected into the reactor was unknown, it is thought that the injected water evaporated and migrated into the S/C. Since the extent to which the heat from the decay heat and water-Zr reaction heat was actually transferred to the water and contributed to evaporation and the extent to which the produced water vapor flowed into the S/C are both unknown, it is difficult to estimate the lower limit of the rise in the S/C water level due to this heat. On the other hand, it is possible to estimate the upper limit of the S/C water level rise by assuming that the amount of water vapor produced when all the decay heat and water-Zr reaction heat contributed to water evaporation flowed into the S/C. In that case, the following equation is used to determine the increase in S/C water volume:

$$\Delta V_{SC} = \frac{Q_{decay} + n_{H^2}\Delta H}{\rho_{SC} h_{fg}} \tag{4}$$

where

ΔV_{SC} : Increase in S/C water volume [m^3]

ρ_{SC} : S/C water density [kg/m^3]

Q_{decay} : Integral value of decay heat from the start of the first venting to 20:40 on March 13 [J].

$n_H{}^2$: Integral value of hydrogen formation [mol]

ΔH : Heat of water-Zr reaction per mol of hydrogen, 293,000 [J/mol] [3]

h_{fg} : Latent heat of evaporation of water [J/kg]

To estimate the upper limit of the S/C water level rise, each parameter used in Equation (4) that depends on the accident progression scenario (ρ_{SC}, $n_H{}^2$, and h_{fg}) should be such a value that ΔV_{SC} is large within the range that can be obtained.

The S/C water density ρ_{SC} is the water density at the highest S/C temperature (about 123°C) in the range shown in Figure 6. As for the integral value of hydrogen formation $n_H{}^2$, as shown in Attachment 2-9, the amount of hydrogen formed when all the Zr in the Unit 2 reactor (including cladding, water rods, spacers, and channel boxes) would undergo a water-metal reaction is about 1900kg, and the same amount of hydrogen is assumed for Unit 3. The net amount of hydrogen that could be generated in the reactor is considered to be smaller than 1900kg, because the hydrogen that could be generated if only the Zr contained in the cladding is considered is about 1000kg, and the Zr in the surface layer of the structure is considered to be easily oxidized by contact with steam, while the interior is considered to be less susceptible to oxidation. The latent heat of evaporation h_{fg} of water is smaller at higher pressures. Since the reactor pressure at which water vapor is produced is at its highest value of about 3MPa after 12:00 on March 13, the latent heat of evaporation at this pressure was applied.

The increase in S/C water volume ΔV_{SC} in the above setup was approximately 400m^3. If this was excluded from the S/C water volume at the lower limit of the S/C water level (about 6.8m from the bottom of the S/C) at 20:40 on March 13, as estimated in Section 2.3.1, the S/C water level would be about 6.2m from the bottom of the S/C. Therefore, the S/C water level at the point when the water level in the vent pipe was pushed down to the lower end after the first venting started was estimated to be more than 6.2m from the S/C bottom.

Estimation of the S/C water level decrease range

Possible factors that might cause the S/C water level to drop after the first venting include depressurization and boiling of the S/C due to S/C venting, evaporation of water due to energy inflow from non-condensable gas that has passed through the S/C pool, and increase in water density due to a decrease in S/C temperature caused by heat release from the S/C, but information to estimate these is not available at this time, and it is difficult to estimate the extent of the decline in the S/C water level. Therefore, the upper limit of the S/C water level at the start of the first venting cannot be estimated from this evaluation.

(2) The range of rise in the S/C water level due to water in the vent pipe being pushed to the S/C side at the start of venting

In (1), the S/C water level was estimated to be 6.2m or higher when the water level in the vent pipe was pushed down to the lower end after the first venting started, and the D/W pressure before the depressurization of the pressure vessel at around 09:00 on March 13 is considered to have been higher than the S/C pressure even taking the overstatement range into account. The water level in the vent pipe at this time was lower than the S/C water level, which is considered to be less than 6.2m. If 6.2m is considered as a higher value, the water volume in the vent pipe would be approximately 170m^3. If this is removed from the S/C water volume at the S/C water level of 6.2m, the S/C water level would be approximately 5.9m from the bottom of the S/C.

In other words, considering the aforementioned lower limit of 6.8m for the S/C water level estimate at 20:40 on March 13 as a reference, the range of increase in the S/C water level from the start of the first venting at around 09:00 on March 13 as the sum of the amount of water pushed out from the vent pipe during venting (0.3m maximum) and the amount of water vapor inflow from the reactor (0.6m maximum), the maximum level difference was estimated to be 0.9m.

From the above, it was estimated that the S/C water level at the start of the first venting was approximately 5.9m or more from the bottom of the S/C, and that the vacuum break valve was submerged at this point.

- 2.4 Estimation of S/C water level at the time of the first venting based on the total evaluation results

The evaluation result of the S/C water level at the start of the first venting based on the S/C water level in Section 2.2 (6.84 to 7.43m from the bottom of the S/C) was included in the evaluation result based on the containment pressure in Section 2.3 (5.9m or more from the bottom of the S/C). It was also considered reasonable that the evaluation of Section 2.2 could narrow down the range more than the evaluation of Section 2.3, in that the overstatement range of the pressure difference between the D/W and S/C could also be identified from the vent pipe water level behavior. Therefore, the result of the evaluation in Section 2.2 (6.84 to 7.43m from the bottom of the S/C) was adopted.

On the other hand, with respect to the evaluation of Section 2.2, there is some uncertainty in the evaluation results because the reason why it was necessary to start the inflow of the alternative S/C spray later than the DDFP startup time is unclear, and there might be some influence on the S/C water level due to factors other than spraying (Section 2.2.3, Sensitivity Cases 3 to 6). Consequently, it is considered that there is some uncertainty in the evaluation results.

Therefore, the S/C water level at the start of the first venting was estimated to be around 7m from the bottom of the S/C, i.e., above the vacuum break valve, taking into account the uncertainty.

- 3 Estimation of accident progression scenarios

Based on the estimated S/C water levels, accident progression scenarios explaining the measured values of other plant parameters were estimated. The feasibility of the estimated scenarios was also discussed in terms of the consistency between the estimated accident progress scenarios and other observed facts.

- 3.1 Estimation of the accident progression scenario that explains plant parameters

Among the plant parameters measured during this period, the parameters most closely related to the S/C water level are the D/W pressure and the S/C pressure. Since the measured value of the S/C water level is explained by the evaluation in Section 2.2, an accident progression scenario that explains the behavior of the D/W and S/C pressures and the pressure difference between them is estimated, as shown in Figure 16.

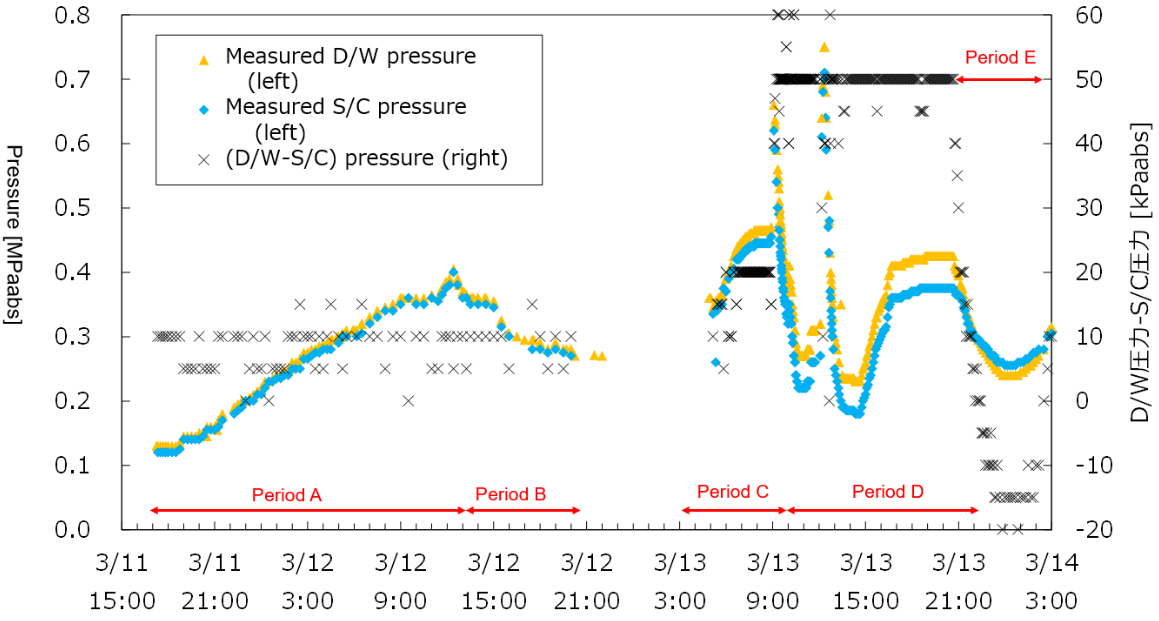


Figure 16 Actual pressure measurements of D/W and S/C and the pressure difference between them

<u>Period A: March 11 at about 17:00 to March 12 at 12:30</u>

During this period the containment pressure increased at a faster rate than estimated from the decay heat. This was thought to be caused by temperature stratification in the S/C pool (see Attachment 3-7). However, a quantitative interpretation of the measured D/W pressure ≥ S/C pressure for this period, including possible deviations in the measured values, has not been obtained.

In the present evaluation, the overstatement range of the pressure difference between the D/W and S/C was estimated to be between 5.9 and 11.7kPa. The average value of the pressure difference during this period was approximately 8.2kPa, suggesting that there could actually be a situation where the D/W pressure ≤ S/C pressure. This reinforces the previous estimation that the pressure increase was due to factors on the S/C side.

<u>Period B: March 12 from about 12:30 to 20:00</u>

About this time, operations affecting the S/C side, such as the implementation of alternative S/C spraying and HPCI startup, were taking place. Therefore, the drop in containment pressure during this period could be attributed to a drop in pressure on the S/C side due to the temperature stratification of the S/C pool mitigated by the S/C spray and other operations, resulting in a drop in the temperature of the S/C water surface and gas-phase section. However, when the pressure on the S/C side decreases, the vent should normally be cleared and the pressure difference between the D/W and S/C should increase, but in reality, the D/W pressure decreased while maintaining an almost constant pressure difference with the S/C, which was a point where the actual measurements were difficult to interpret (Attachment 3-7).

The reasons for this difference between the assumed and measured trends include scenarios such as a pressure drop on the D/W side or a leak in the vacuum break valve, etc. As for the pressure drop on the D/W side, the D/W pressure was below the design pressure at this stage, so a leak due to D/W damage, etc. is difficult to assume. Although it is difficult to assume a leakage due to damage to the D/W, the possibility cannot be ruled out that the pressure drop was caused by condensation of water vapor due to heat absorption by the structures in the D/W, combined with a drop in the amount of water vapor migrating from the S/C. Although no scenario has been determined at this stage, it is possible to envisage several scenarios explaining the pressure trend as described above.

Period C: March 13 at about 05:00 to 09:00

It was estimated that this was the period when the reactor water level was falling and core damage and melting was progressing (see Attachment 2-7). A report also mentions the possibility of small leaks to the S/C through the SRVs and small leaks to the D/W through in-core instrumentation, etc., as the reactor pressure was slowly decreasing from about 05:50 to 08:50 (see Attachment 3-4). However, the containment pressure at this time had the relationship D/W pressure > S/C pressure, and no clear interpretation was given as to why the pressure difference was almost constant after about 07:00.

As the evaluation estimated that the S/C water level was higher than the vacuum break valve during this period, it was difficult to interpret that the D/W and S/C were equalized by the operation of the vacuum break valve and that the pressure difference was overstated. In addition, regarding the pressure difference of 20kPa after about 07:00, even taking into account the estimated range of 5.9 to 11.7kPa of the over-display-width pressure difference, the pressure on the D/W side was still slightly higher than that on the S/C side. Therefore, it is estimated that although there were factors contributing to the pressure increase on the D/W side, the pressure difference with the S/C side had not increased enough for vent clearing, i.e. there were factors contributing to the pressure increase on the S/C side as well.

A possible scenario to explain this trend is that a small leak from the high temperature pressure vessel to the D/W occurred and that the pressure between the D/W and S/C was balanced due to a combination of this and the migration of the gas phase from the pressure vessel to the S/C side. On the other hand, noting that the water level in the vent pipe at this time was near the top of the vacuum break valve in the evaluation of Section 2.2, it is possible that for some reason a small leak occurred from the D/W side to the S/C side near the vacuum break valve or at its height, and gas leaking from the reactor to the D/W was transferred to the S/C side, as another possible scenario. Although the scenario has not been determined at this stage, it is highly likely that either scenario would have resulted in a small gas-phase leak from the pressure vessel to the D/W at this time.

From 08:50 to 08:55, the D/W pressure increased by 5kPa from 465 to 470kPa[abs] and the S/C pressure increased by 10kPa from 445 to 455kPa[abs] [1]. The larger pressure increase in the S/C suggests that the main cause of the pressure increase was on the S/C side. A possible reason for this could be the inflow of gas phase from the reactor through the SRV. In previous studies, focusing on the peak in reactor pressure seen just before the rapid depressurization of the reactor around 09:00, it has been estimated that steam formation might have occurred when some of the molten fuel migrated to the bottom of the pressure vessel, causing the pressure to rise and possibly triggering the SRV (see Figure 7 in Attachment 3-4).

As for the cause of the increase in D/W pressure from 465 to 470kPa[abs], it is possible that the measured value in increments of 5kPa increased by one step between 08:50 and 08:55 by chance as a result of continued minute gas phase leakage from the pressure vessel to the D/W, but it is also possible that D/W pressure increased for about one hour from around 08:00 given the fact that it remained constant, and the D/W pressure increased under the influence of the pressure increase on the S/C side, rather than a change in the leakage situation from the pressure vessel to the D/W.

On the other hand, noting that the pressure difference between the D/W and S/C dropped from 20 to 15kPa between 08:50 and 08:55, the vent pipe water level was considered to have increased by the amount of this pressure difference drop. A possible reason for the rise in the vent pipe water level is that the inflow of gas phase from the reactor through the SRVs described above increased the S/C pressure, pushing down the S/C water level and causing water to migrate into the vent pipe. This may have reduced the space volume on the D/W side of the vent pipe, including the gas-phase section, and compressed the gas, which may have increased the D/W pressure.

In the following, the range of increase in D/W pressure due to the rise in the vent pipe water level from 08:50 to 08:55 was estimated. The pressure difference between D/W and S/C during this period was assumed to decrease by 5kPa and the corresponding rise in the vent pipe water level was assumed to be 50cm. If this rises by 50cm, the space volume on the D/W side decreases by approximately 2%. If the D/W pressure increases at this rate, the D/W pressure will increase by approximately 10kPa during this period. In reality, however, some of the water vapor in the D/W condensed when compressed and did not contribute to the increase in pressure, so the increase in D/W pressure was expected to be smaller than this. This approximate result was consistent with the measured D/W pressure increase range of 5 kPa. Therefore, it is considered highly likely that the increase in D/W pressure during this period was contributed to by the compression of the D/W gas due to the rising water level in the vent pipe.

Period D: March 13 from about 09:00 to 20:40.

During this period, the first S/C venting was carried out at around 09:00 and the second venting after 12:00 (Attachment 3-8). Based on the operation records of personnel and the behavior of the containment pressure, it was considered that the vent valve closed at about 11:00 when the first venting took place and at about 14:40 when the second venting took place .

As shown in Estimation 2 in Section 2.1, the water level in the vent pipe was considered to have been pushed down to the bottom of the downcomer during this period, and the fact that the vent clearing condition continued not only during the S/C venting period suggested that there were factors for the pressure increase on the D/W side, such as gas-phase leakage from the pressure vessel to the D/W.

The scale of this gas phase leakage from the pressure vessel to the D/W might have been larger than the minute leakage expected in Period C. As the SRVs continued to be opened by the operators in Period D, there might have been gas inflow through the SRVs on the S/C side, and the fact that the vent-cleared condition continued in that situation suggested that there might have been a reasonable amount of gas-phase leakage on the D/W side. In other words, the gas-phase leakage to the D/W, which was minute in Period C, might have expanded at some point in Period D. There is room to consider the time, scale and factors of the occurrence (Appendix 3-12).

The high S/C water level at the time of S/C venting in Unit 3 might have had a significant effect on the removal of aerosols (scrubbing) in the S/C pool. If the S/C water level during venting is assumed to be 7m, this is approximately 3m higher than the normal water level of 4.15m. Experiments have confirmed that the removal efficiency of aerosols by pool scrubbing tends to increase with increasing water depth, with the amount of some aerosols released at a depth of less than 3m being reduced by a factor of several hundred to ten thousand [4]. Although quantitative evaluation is difficult, it is possible that such a large scrubbing effect was achieved during the S/C venting of Unit 3 and that the amount of aerosol-like radioactive materials released was suppressed.

Period E: March 13 from 20:40 to March 14 00:00

In previous examinations, the containment depressurization speed during this period was very slow compared to the first and second S/C venting, and the behavior of the pressure difference between the D/W and S/C led to the assumption that the cause of the containment pressure drop was not the S/C venting but a leak on the D/W side (see Attachment 3-8). However, no specific estimation was made as to how the water level in the containment had changed with regard to the pressure difference between the D/W and S/C.

This examination evaluated changes in the water level in the containment vessel due to the S/C water being sucked up during the depressurization on the D/W side in the period when the S/C water level was higher than the vacuum break valve. The results showed that after depressurization, the water level on the D/W side was likely to have risen to about 1m above the D/W floor. It is possible that the water migrating to the D/W side at this time might have contributed to the cooling of the fuel debris that fell from the pressure vessel into the pedestal. In addition, considering that the S/C gas phase section is a closed space during depressurization and that the water vapor pressure in the S/C gas phase would not change significantly during depressurization, the main cause of the depressurization on the S/C side during this period was considered to be the volume expansion of non-condensable gases. Therefore, either non-condensable gases of nitrogen or hydrogen remained in the containment vessel after the two S/C vents, or new hydrogen was formed in the reactor, or both, and these non-condensable gases must have migrated to the S/C side through the SRVs or vent pipes by 20:40 on the 13th.

3.2 Consideration of the feasibility of scenarios based on other observed facts

This section discusses whether the estimated S/C water levels and the accident progression scenarios estimated from them are feasible in light of the observed facts other than plant parameters. This section focuses on the current situation in the D/W of Unit 3.

As shown in Figure 17, the current water level in the D/W of Unit 3 is higher than in Unit 1, which suggests that the shell below the D/W has not been damaged by fuel debris contact. In this evaluation, it was estimated that there was about 1m of water from the floor in the D/W as of 00:00 on March 14 due to water sucked up from the S/C side, but as the containment pressure increased from around 01:00 to 07:00 thereafter, and the D/W CAMS indication value recorded a peak at 06:35 on the 14th, it was considered that fuel debris was falling from the pressure vessel into the pedestal around the time when this D/W water level rose. Although the water level is thought to have fluctuated with changes in containment pressure, it is possible that the water in the D/W cooled the fuel debris and the fuel debris did not reach the shell below the D/W due to spreading or MCCI, leaving the shell undamaged. On the other hand, a leak from the sand cushion drain pipe was observed in Unit 1, suggesting that some part of the shell below the D/W might have been damaged by contact with the fuel debris.

As shown in Figure 18, the height of the deposits in the Unit 3 pedestal was more than 2m. In contrast, the D/W water level at 00:00 on March 14 was at most 1m high, and it is considered that the water level was not high enough to flood all of the current deposits. However, it is possible that cooling by water might have worked on the fuel debris that fell below the water surface, and cooling by steam produced by the heat of the fuel debris below the water surface might have worked on the fuel debris deposited above the water surface. In addition, the water injection into the reactor continued, although it was temporarily interrupted by the hydrogen explosion in Unit 3 at 11:01 on March 14, and it is possible that the injected water flowed down from the damaged opening at the bottom of the pressure vessel through which the fuel debris had passed, cooling the fuel debris from above.

In addition, as mentioned above, the MCCI is not considered to have progressed far enough to reach the shell at the bottom of the D/W and that most of the fuel debris is considered to have fallen to the bottom of the pressure vessel; it is likely that most of the fuel debris is deposited in the pedestal. In addition to the fuel debris, the height of the deposits might have been increased by the folding of non-fuel debris structures in the pedestal, such as the CRD housing, the CRD exchanger and the platform grating.

As described above, the scenario that the water level formed in the D/W due to the depressurization on the D/W side as estimated in this study is also consistent with the current conditions in the D/W of Unit 3 (high water level and height of deposits in the pedestal) and is considered feasible.

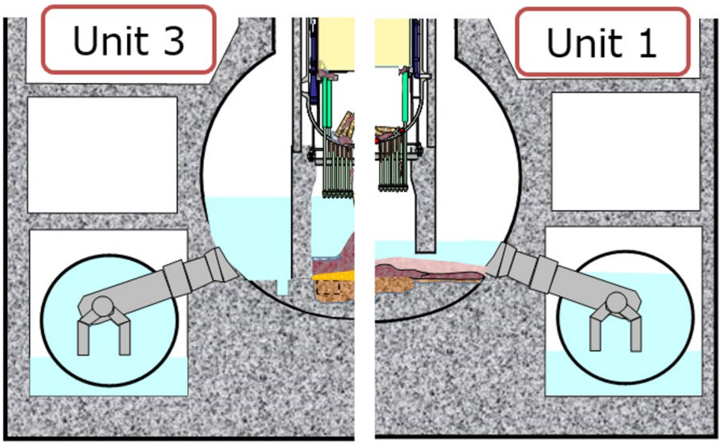


Figure 17 Current water level in the D/W

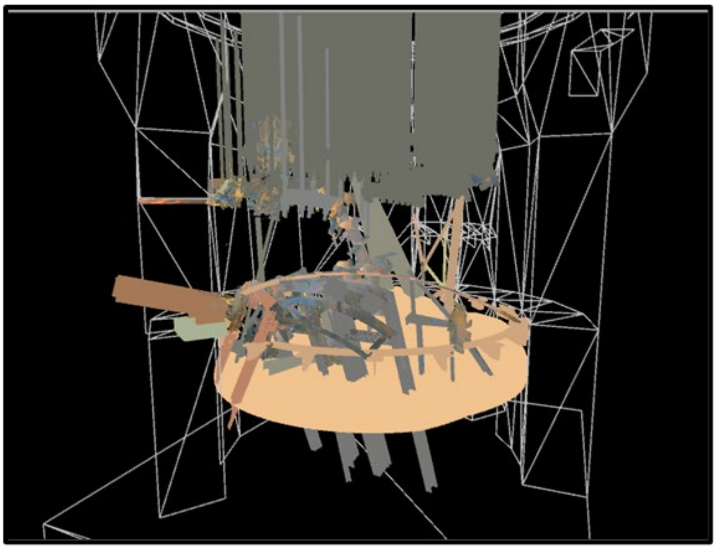


Figure 18　Results of 3D reconstruction of deposits from photos taken inside the Unit 3 pedestal

■ 4. Summary

The S/C water level at the start of the S/C venting at about 09:00 on March 13 was estimated to be about 7m, which was higher than the vacuum break valve. The accident progression scenario estimated from the said water level was also considered feasible in light of the current conditions in the D/W of Unit 3 (high level of water and high height of deposits in the pedestal).

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

From this examination, it was estimated that the S/C water level was around 7m at the start of the S/C venting of Unit 3 at about 09:00 on March 13 and was higher than the vacuum break valve. The vacuum break valve has the function of maintaining the integrity of the containment vessel by resolving the negative pressure in the D/W against the S/C when the D/W pressure drops due to containment vessel spray, etc. Therefore, submergence of the vacuum break valve must be avoided, and control of the S/C water level is important for this purpose.

Figure 19 shows the vacuum break valve at the Kashiwazaki-Kariwa NPS. In addition to the residual heat removal system, the Kashiwazaki-Kariwa NPS has a newly installed alternative circulation cooling system to remove heat from the containment vessel without raising the S/C water level by circulating water through a heat exchanger, as a response to the decay heat accumulated in the containment vessel, so there is no danger that the vacuum break valve is submerged. If the abovementioned equipment is not available, it is necessary to continue water injection and spraying from outside the containment for heat removal, and the S/C water level will rise, but the procedure is to stop the spraying and implement containment venting before the vacuum break valve is submerged.

In addition, even if the vacuum break valve is submerged, the procedure is to prevent containment damage due to negative pressure by stopping the containment spray before the containment becomes negatively pressurized if containment spraying is carried out after venting has been stopped, etc., and by supplying nitrogen gas in the containment in the medium to long term.

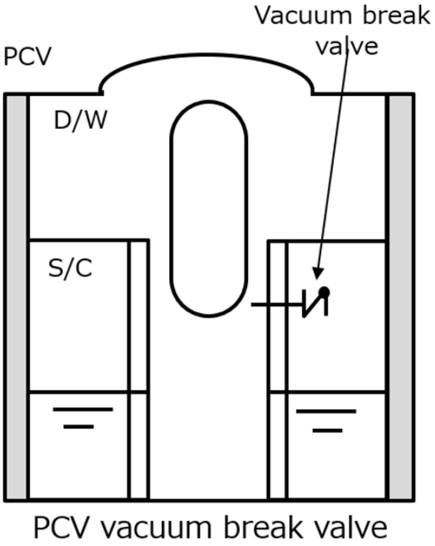


Figure 19 Vacuum break valve in containment vessels

References

[1] TEPCO, "Data collected by operators at Unit 3 after the Tohoku-Pacific Ocean Earthquake", (6 Aug 2014)

[2] OECD/NEA, “Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF Project) – Phase I Summary Report”, (2015/3)

[3] Nuclear Safety Research Association, "The behaviour of light water reactor fuels", (1998/7).

[4] NRA, "Aerosol removal effect experiment by pool scrubbing", 8th Meeting of the Study Group on Analysis of Accident at TEPCO's Fukushima Daiichi Nuclear Power Station, Document 4, p13 (28 Nov 2019).