Accident progression after the Unit 3 reactor depressurization

＊ This document is prepared based on the contents proposed and examined by TEPCO Systems, Inc. and describes the accident progression after the reactor depressurization at about 09:00 on March 13, including containment vessel venting (Issue Unit 3-8), gas phase leakage from the pressure vessel (Issue Unit 3-9), gas phase leakage from the containment vessel (Issue Unit 3-10), and the hydrogen explosion (Issue Unit 3-10) in the list of issues to be considered in Attachment 2.

■ 1. Introduction

Based on previous studies of the accident progression scenario for Unit 3, the following details were estimated.

- The reactor depressurization around 09:00 on March 13 was most likely caused by the automatic depressurization function (ADS) of the main steam safety relief valve (SRV) (Attachment 3-3).
- The increase in reactor pressure before about 09:00, about 10:00, and about 12:00 on the 13th may have been due to some of the fuel migrating to the lower plenum; by 12:00 on the 13th, six of the SRVs might not have remained open. In addition, leakage from the pressure vessel to the D/W might have occurred (Attachment 3-4, Attachment 3-11).
- The first vent opening operation at about 09:00 and the second one at about 12:00 on March 13 were clearly successful, and it is possible that leakage from D/W to the reactor building occurred at about 21:00 on March 13 (Attachment 3-8).
- The venting might have caused several hundred kilograms of hydrogen to migrate to the Unit 4 reactor building (Attachment 3-10).
- The S/C water level was high at the time of venting, and the vacuum break valve might have been submerged. Also, water on the S/C side might have migrated to the D/W side when the containment vessel pressure dropped between around 21:00 on the 13th to around 00:00 on the 14th (Attachment 3-11).

In order to examine these estimations from a quantitative viewpoint and to determine the specific timing of each event in them, the accident progression scenario up to 00:00 on March 14 was organized based on previous studies (Section 2), and then the analysis was conducted to reproduce the actual measured values such as reactor pressure and containment pressure (Section 3). Through the reproduction analysis, the amount of hydrogen formed in the reactor and its migration status, which are necessary conditions for considering the hydrogen explosion mechanism in the Unit 3 and Unit 4 buildings, were also examined.

■ 2. Development of the accident progression scenario

Based on the analysis of plant parameters and previous studies, an accident progression scenario from the time the reactor water level reached the top of active fuel (TAF) to 00:00 on the 14th was developed as shown in Figure 1. The underlined items in the figure are the parts where the timing of occurrence, etc., were refined. The rationale for each item is shown from Section 2.1.

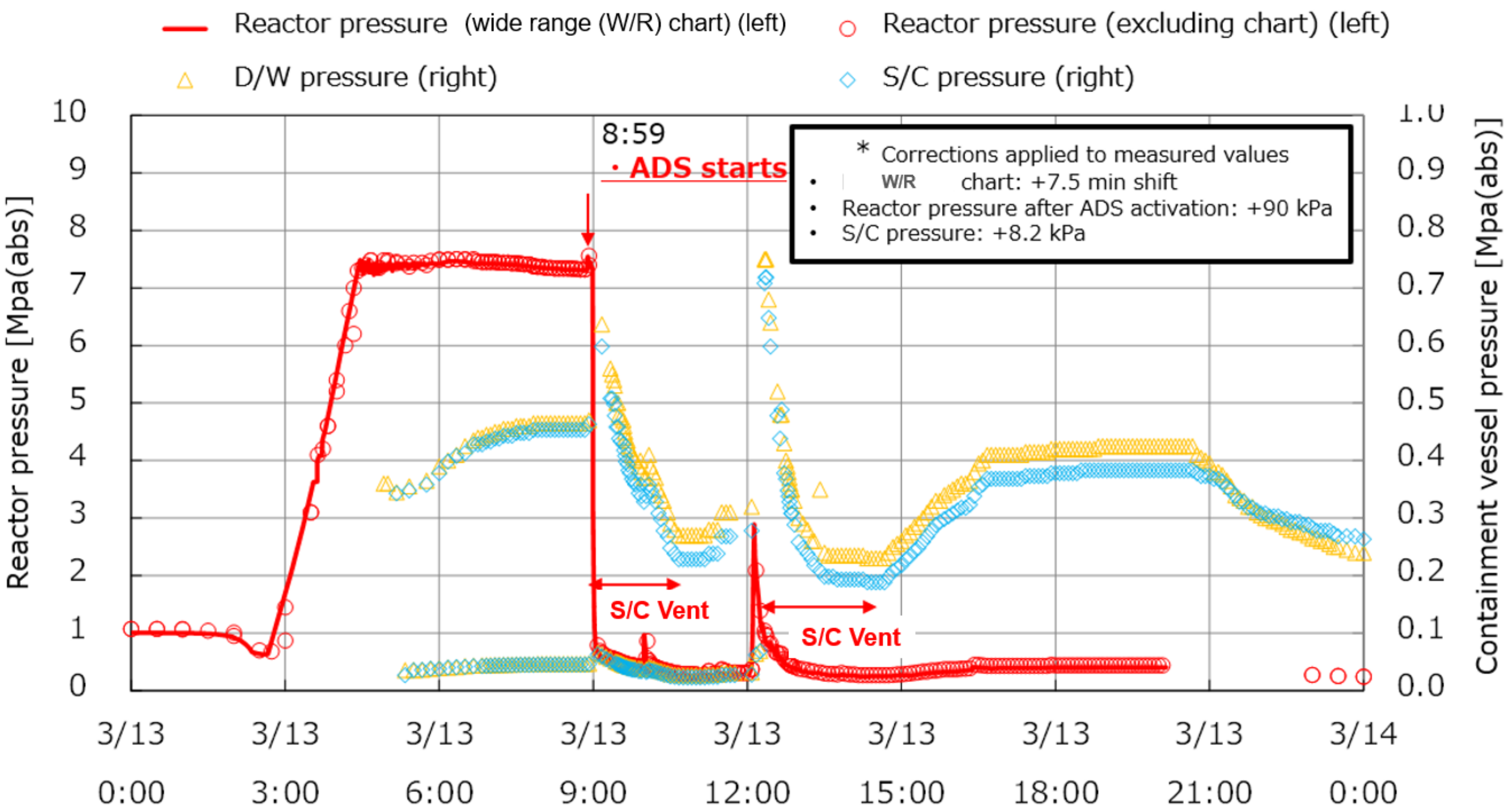

Figure 1 Developed accident progression scenario

■ 2.1 Correction of actual measured values

The actual measured values of reactor pressure, D/W pressure, and S/C pressure for Unit 3 are shown in Figure 2. The reactor pressure might have been understated because there were periods when it was significantly lower than the D/W and S/C pressures. In addition, as shown in Attachment 3-11, the pressure difference between the D/W and S/C might have been overstated. Corrections to these actual pressure measurements are discussed. In addition, the possibility of time deviations in the reactor pressure wide range chart is discussed.

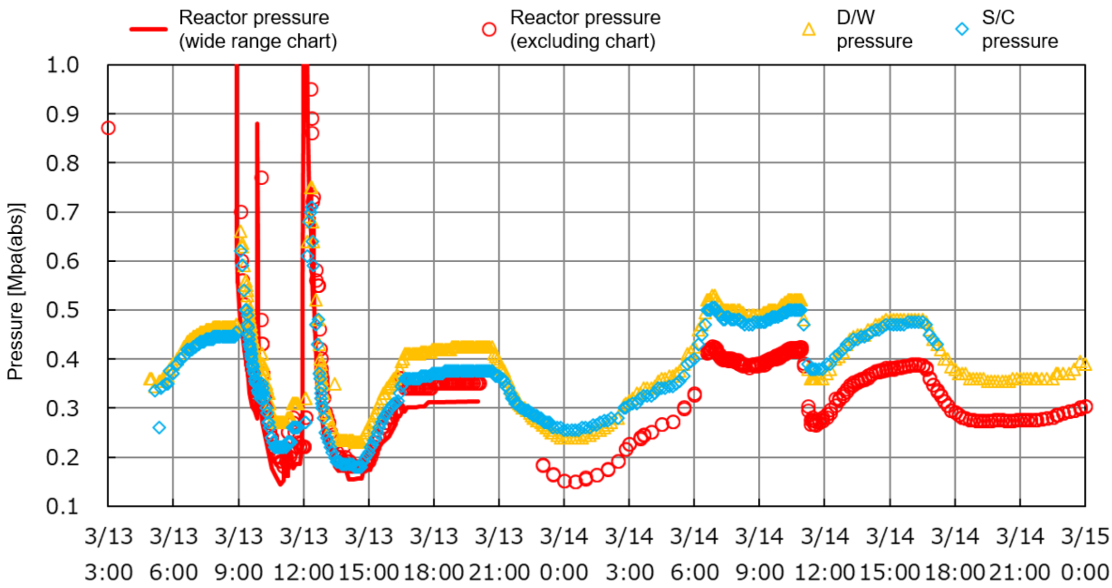

Figure 2 Measured reactor pressure and containment pressure of Unit 3 (uncorrected)
(Data in the chart are digitized and illustrated; the same applies to the following figures.)

(1) Correction of D/W pressure

Since March 21, 2011, D/W pressure has generally been near atmospheric pressure. The D/W pressure instrument was changed on July 16, 2011, but considering that the actual D/W pressure measurements before and after the instrument change were almost unchanged, the D/W pressure before the instrument change was considered to be generally correct, and therefore it was determined that no correction to the D/W pressure was necessary.

(2) Correction of S/C pressure

It was estimated that the containment pressure increased during the RCIC operation period until about 12:00 on the 12th due to temperature stratification in the S/C pool (Attachment 3-7). In that case, the pressure on the S/C side should be slightly higher than that on the D/W side, but the actual measured pressure on the D/W side was generally higher than that on the S/C side in the range of 5 to 10kPa. This suggests the possibility of deviations in the actual measured values of D/W and/or S/C pressures (Attachment 3-11). However, since the actual measured values of D/W pressure were generally considered to be correct as described in (1), it was decided to correct the pressure on the S/C side. The correction range was 8.2 kPa, which is the average value of the pressure difference during the period in question, added to the S/C pressure from the viewpoint of canceling out the pressure difference between the D/W and S/C during this period.

(3) Correction of reactor pressure after ADS activation

Figure 3 shows the difference between the reactor pressure (A system) and D/W pressure after 09:00 on March 13. When no correction was applied to the reactor pressure, the reactor pressure was below the D/W pressure, including during the first S/C venting period. In addition, the pressure difference has remained almost constant for a long period of time after around midnight on the 14th.

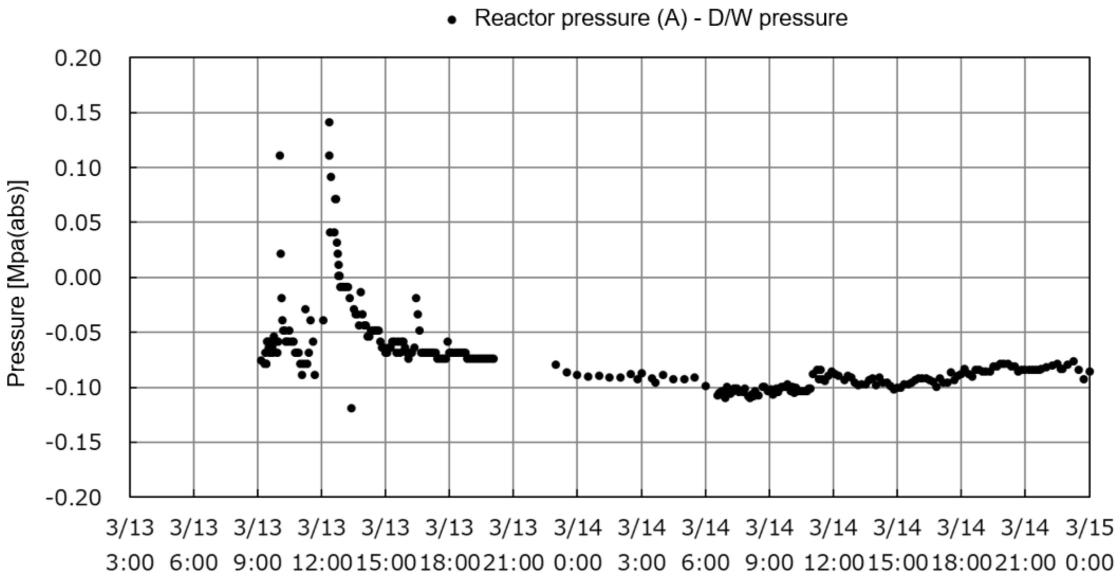

Figure 3 Difference between measured reactor pressure and D/W pressure

On the other hand, the rise in reactor pressure around 10:00 and 12:00 on the 13th suggested that water at some level was present in the pressure vessel, and that the lower head was not damaged at this time and the main heat source was in the pressure vessel. Therefore, it was unlikely that the reactor pressure fell below the D/W pressure during at least the first S/C venting period. In addition, the D/W CAMS(A) value reached its maximum value (170 Sv/h) at around 06:30 on March 14, and other actual measurements suggested that the lower head was damaged and fuel might have migrated from the pressure vessel. Therefore, it is difficult to imagine a situation in which an almost constant pressure difference between the reactor and the containment vessel is maintained for a long period of time with such a hole in the head. From the viewpoint of resolving the above inconsistency and minimizing the difference between the reactor pressure and D/W pressure after midnight on the 14th, a correction of +90 kPa was added to the reactor pressure after the ADS activation.

The possible causes of the reactor pressure deviation were the evaporation of the water column in the piping of the reference leg connected to the reactor pressure gauge and possible instrument deviation. The water column in the reference leg was estimated to have been empty up to the containment vessel penetration after the reactor depressurization due to the ADS operation at around 09:00 on March 13 (Attachment 3-9) except for a short period of time. The height of this water column was approximately 6m inside the containment vessel, and it was considered that the reactor pressure was understated by approximately 60kPa after 09:00 on March 13 due to the water head pressure. In this estimation, the correction range was set at 90 kPa, and the remaining approximately 30 kPa was attributed to instrument deviation.

(4) Time deviation of reactor pressure wide range chart

Figure 4 shows the reactor pressure wide range (W/R) chart data before and after the scram and the reactor pressure data from the transient recorder. Comparing the two, a time shift could be seen, and shifting the chart data by +7.5 minutes showed they agreed well with the trend of the transient data records. As shown in Figure 5, the data after 09:00 on the 13th also tended to agree well with other reactor pressure data (digital table data and operator-collected data) by shifting the reactor pressure wide range chart data by +7.5 minutes. Therefore, a correction of +7.5 minutes was added to the time of the reactor pressure wide range chart.

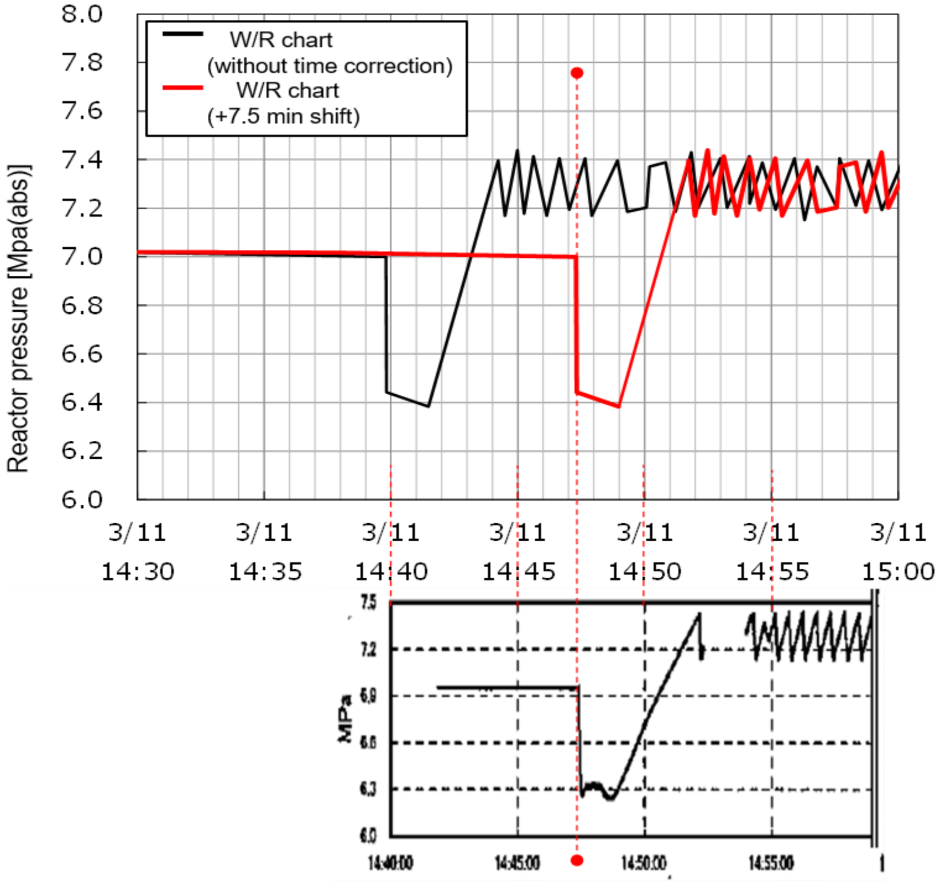

Figure 4 Relationship between reactor pressure wide range chart data before and after scram and reactor pressure data from transient recorder (only time correction applied)

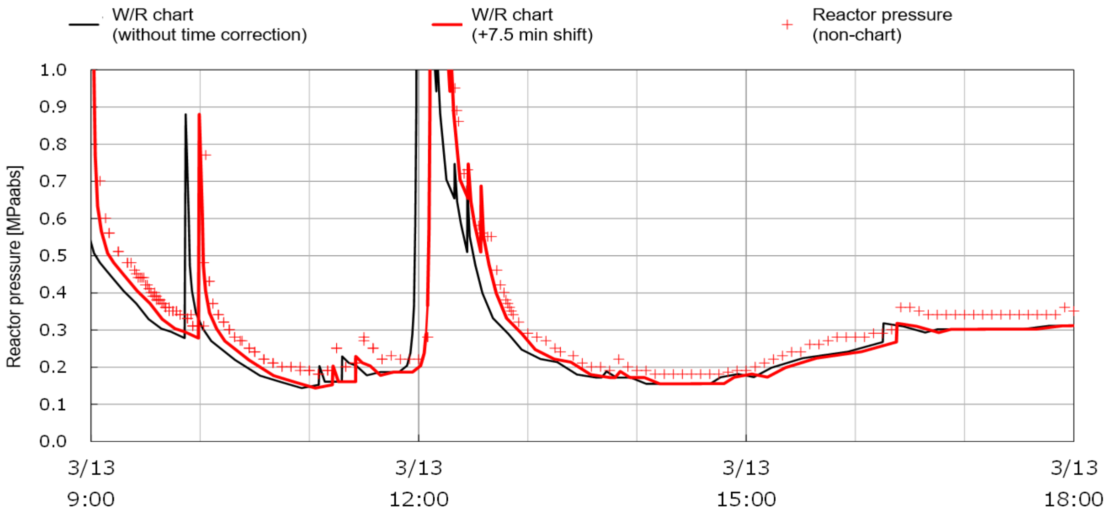

Figure 5 Relationship between reactor pressure wide range chart data and reactor pressure data other than chart data after 09:00 on the 13th (only time correction applied)

■ 2.2 Time of reactor water level reaching TAF

Figure 6 shows the behavior of the reactor pressure from 18:00 on the 12th to 03:00 on the 13th. The reactor pressure decreased due to the HPCI startup at 12:36 on the 12th, and then remained almost constant from about 22:00 on the 12th to 01:00 on the 13th. During this period of almost constant reactor pressure, the steam production from the decay heat and the extraction to drive the HPCI turbine were considered to be in equilibrium. This might have been caused by a decrease in the amount of steam produced or an increase in the amount of HPCI extraction.

Regarding HPCI operation at the time of the accident, the amount of water injected into the reactor was adjusted by returning part of the injected water to the CST, the water source, and by using a flow controller, in order to avoid battery depletion during startup and shutdown and to ensure a stable reactor water level. After 20:36 on March 12, when the reactor water level could no longer be monitored due to the loss of power, the HPCI flow rate setting was slightly increased to ensure that water was injected into the reactor, and the operating status was monitored by the reactor pressure and HPCI discharge pressure.

There is no record of any operation leading to an increase in the HPCI extraction volume at about 01:00 on the 13th, when the reactor pressure began to decrease.

Based on the circumstances at the time, it was highly likely that the pressure drop was caused by insufficient water injection by the HPCI, the reactor water level reached the TAF around 01:00 on March 13, and the amount of steam produced gradually decreased as the amount of water in the pressure vessel decreased thereafter, leading to the reactor pressure drop.

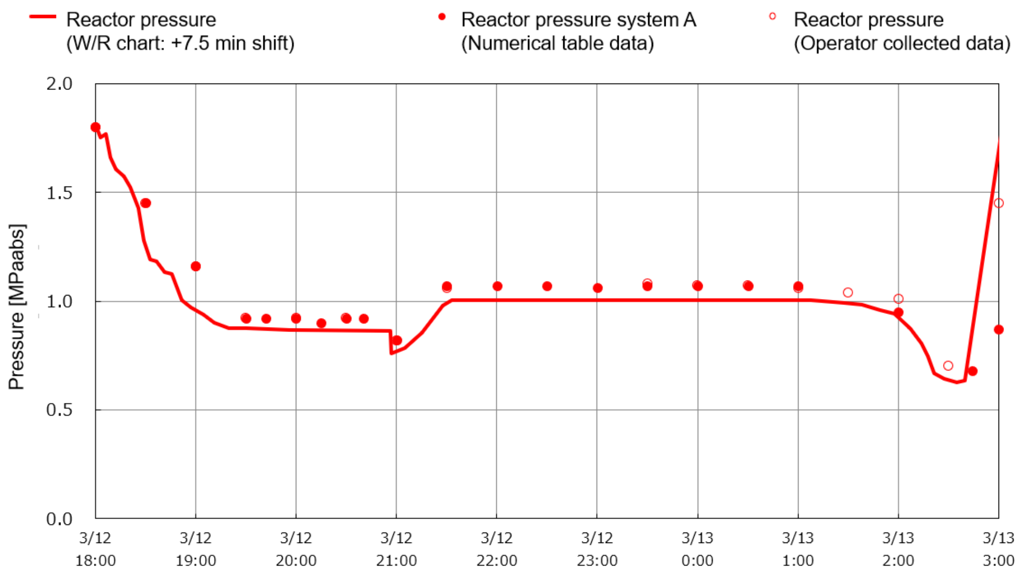

Figure 6 Reactor pressure from 18:00 on the 12th to 03:00 on the 13th

■ 2.3. ADS activation time

Figure 7 shows the reactor pressure from 03:00 to 09:00 on the 13th. The wide range (W/R) chart data were shifted by +7.5 minutes. The narrow range (N/R) chart data deviated from the actual data also because reactor pressure was below the measurement range at the time of HPCI startup, so the power supply was turned off to prolong the life of the DC power supply, which caused the shift from the actual time. Therefore, the narrow range chart data were shifted by +818 minutes to match the behavior of the other pressure data. Although there was a discrepancy of a few tens of kPa in each pressure value, the timing of the pressure change was in good agreement.

Figure 8 shows the reactor pressure at about 09:00 on the 13th. In the chart data after time correction, reactor depressurization started around 08:59. Therefore, the ADS activation time was set at 08:59.

As shown in Figure 7, there was a difference of up to 50 kPa in the numerical table data, operator-collected data, and wide range and narrow range chart data. This suggested that there could be a constant deviation of several tens of kPa in the measured reactor pressure, which might be related to the fact that an instrumental deviation of about 30 kPa had to be estimated in the correction of the reactor pressure after the ADS activation as mentioned above.

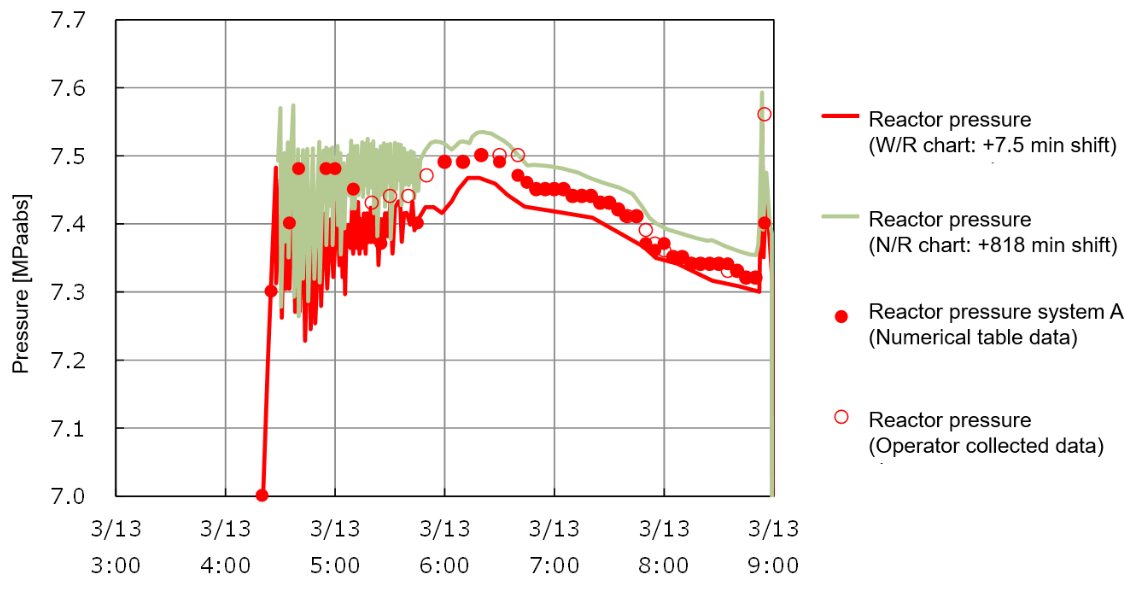

Figure 7 Reactor pressure data from 03:00 to 09:00 on the 13th (only time correction applied)

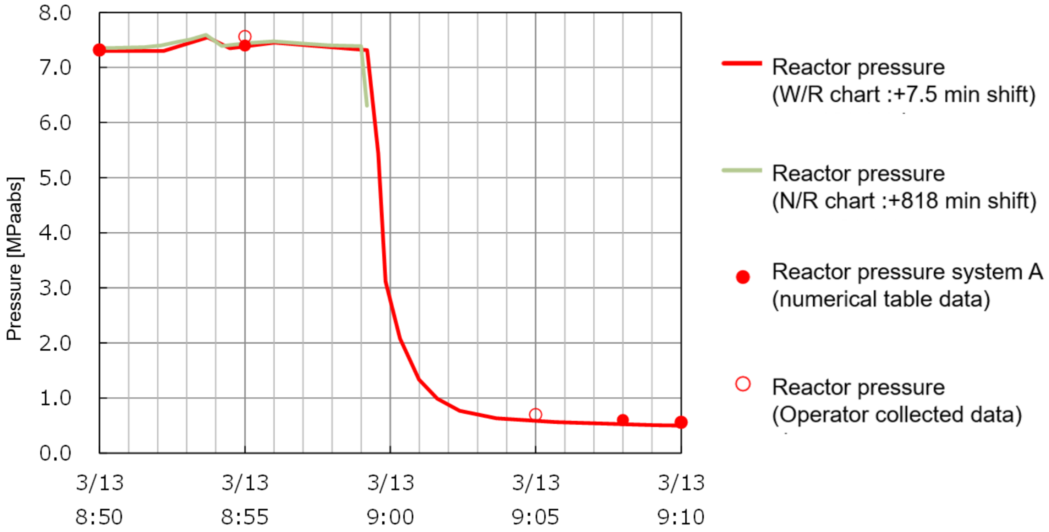

Figure 8 Reactor pressure before and after 09:00 on the 13th (only time correction applied)

■ 2.4. Gas phase leakage from pressure vessel to D/W

(1) Occurrence of small leakage

In Figure 7, the SRVs were activated from around 04:30 to 05:50, when the reactor pressure was fluctuating, and the gases formed in the reactor probably migrated to the S/C through the SRVs.

On the other hand, it was estimated that the vacuum break valve was already submerged by this time (Attachment 3-11). If the SRVs were activated in that condition and gas migrated to the S/C, the S/C pressure should have been higher than the D/W pressure, exceeding the operating set pressure of the vacuum break valve, unless there were factors causing the pressure to rise on the D/W side, because the vacuum break valve was not activated.

In reality, however, as shown in Figure 9, after 05:10, when the pressure difference between the D/W and S/C began to be obtained, the D/W pressure was still slightly higher than the S/C pressure after the S/C pressure is corrected. This suggested that there were some factors contributing to the pressure increase on the D/W side as well.

Furthermore, in Figure 7, the reactor pressure was slowly decreasing from after 06:00 to before 09:00, and the containment pressure was increasing during the same period, as shown in Figure 2.

One of these factors could be leakage from the pressure vessel to D/W. The small pressure difference between the D/W and S/C shown in Figure 9 and the gradual decrease in reactor pressure from after 06:00 to before 09:00 suggested that even if leakage from the pressure vessel to D/W had occurred at this time, it would have been relatively small.

Although it is debatable whether such a minute leakage could occur structurally and whether it could be sustained for a long time, one scenario assumed here is that a minute gas phase leakage from the pressure vessel to the D/W occurred by 05:10, when the pressure difference between the D/W and S/C began to be obtained.

During this period, the reactor water level was lowered and the gas phase inside the pressure vessel was considered to be hot, and if leakage from the pressure vessel to D/W had occurred, it was most likely due to the effects of this high temperature. Possible candidates for leakage points included the reactor instrumentation piping and SRV gaskets.

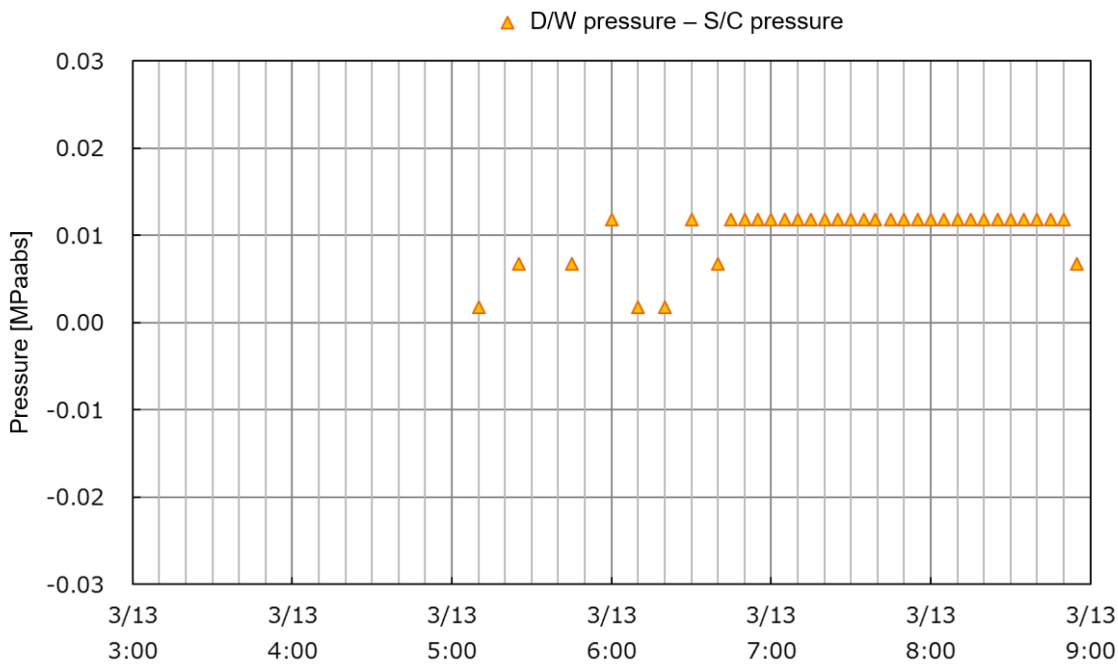

Figure 9 Pressure difference between D/W and S/C before ADS activation
(Correction: D/W pressure uncorrected / S/C pressure +8.2 kPa)

(2) Expansion of leakage at the same time as ADS activation

The ADS activation at 08:59 caused a large amount of gas to migrate into the S/C side, and S/C pressure was thought to have temporarily become higher than the D/W pressure. On the other hand, as shown in Figure 10, at 09:05, immediately after the ADS activation, S/C pressure was about 30 kPa lower than the D/W pressure (when the +8.2 kPa correction was added to the S/C pressure). Thus, although not shown in the data, the S/C pressure transitioned from being higher to being lower than the D/W pressure within just a few minutes from 08:59 to 09:05.

It was estimated that about this time, the containment pressure increased due to ADS operation, reaching the rupture disk design pressure and initiating the S/C venting (Attachment 3-8). Although it was assumed that D/W pressure gradually became dominant due to the release of gas from the S/C by venting, it was unlikely that this change would occur in just a few minutes. Therefore, as a cause of the pressure increase on the D/W side, it was assumed that there would be a reasonable leakage from the pressure vessel to the D/W side at about the same time as the ADS activation. The assumption of this expanded leakage was used here. The necessity of this assumption will be confirmed by the analysis described below.

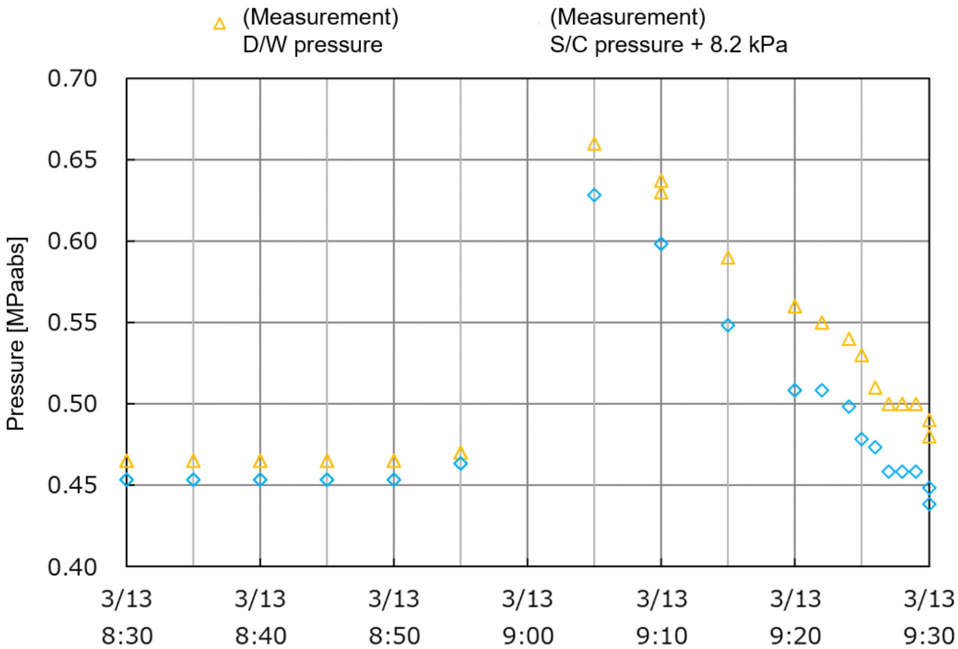

Figure 10 Containment vessel pressure before and after ADS activation

■ 2.5. Decrease in the number of open SRVs

As shown in Figure 11, the decreasing rate of the reactor pressure after the increase around 12:00 was slower than the decreasing rate around 09:00. Therefore, even if the ADS was activated around 09:00 to open six valves, it might not have been possible to keep all six valves fully open at that time (Attachment 3-4).

Also, at around 09:08 on the 13th, the status indicator lights on the SRV control panel showed that the SRVs (A) and (G) were in an intermediate open state (the red indicator light showing open was repeatedly flickering and both the red light and the green light showing closed were lit), and the remaining four valves did not show an open indication. Therefore, it seemed that it was already impossible to keep six SRVs open at this time.

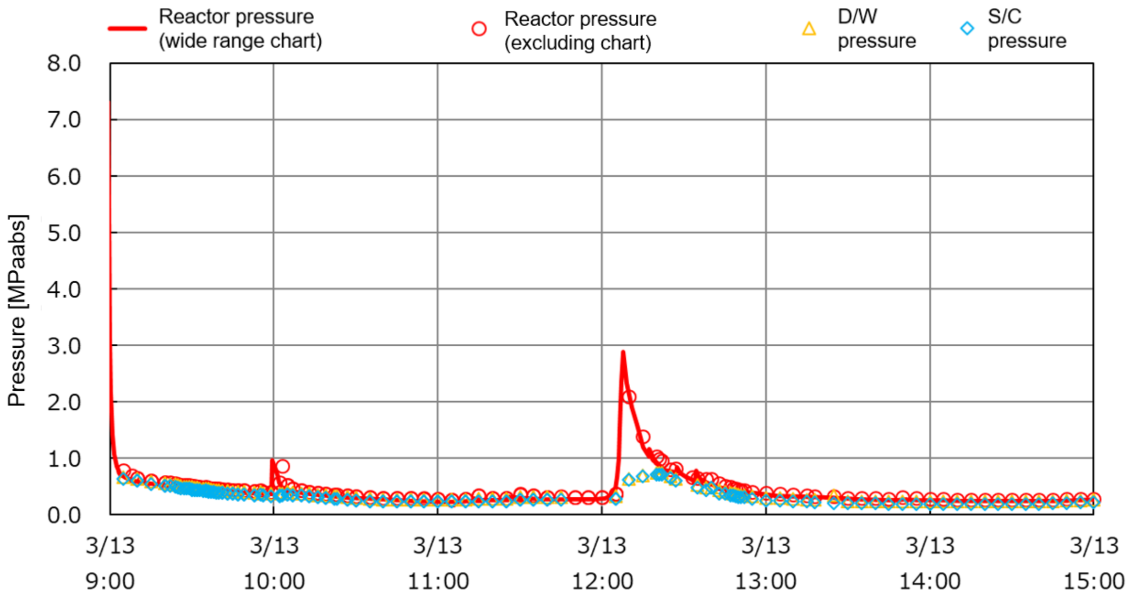

Figure 11　Reactor pressure after ADS activation

The following were possible factors that might cause SRVs to fail (Attachment 2-12).

① Deterioration of operating environment

② Insufficient N_2 gas supply pressure due to frequency of operation

③ Poor connection or insufficient capacity of temporary battery (i.e., insufficient power supply)

④ Effects of damage due to repeated operation

⑤ Mechanical factors due to the relationship between the N_2 gas supply pressure, reactor pressure, and containment vessel pressure

Regarding factor ① above, the environment inside the containment vessel might have been severe in terms of temperature, humidity, and radiation due to heat from the pressure vessel and gas phase leakage. For example, it is possible that the sealing material used in the solenoid valves, etc. deteriorated and N_2 gas used to drive the SRV leaked, making it impossible to open the SRV.

Regarding ②, since the accumulator capacity for the ADS is designed to allow the SRV to operate at least five times even when the supply from the N_2 cylinder is not available, it is considered that there was enough N_2 in the accumulator even after ADS operation, and the possibility of closure due to insufficient N_2 gas supply capacity can be ruled out.

Regarding ③, the reactor pressure did not decrease when the SRVs were remotely opened from the central control room at 03:00 on March 13, and it is possible that the power supply was insufficient at that time, but the DC power load was reduced by sequentially stopping the DC-driven pumps after that, and the ADS function of the SRVs was able to secure the necessary power supply capacity to operate (Attachment 3-3). It is conceivable that this lack of power supply capacity could have allowed the solenoid valves to be excited for only a short period of time, and that the six valves could no longer be kept open at around 09:08.

Regarding ④, it is not necessary to consider this as a factor that caused the SRV to shift to intermediate open or closed positions after ADS activation.

Regarding ⑤, even if there was no pressure difference between the pressure and the containment vessels, the solenoid valves of the ADS could be excited to fully open the SRV mechanically, so the possibility that SRVs were closed due to mechanical factors can be ruled out.

From the above, if the SRVs closed after the ADS was activated, the possible causes are ① deterioration of the operating environment and ③ lack of power supply.

■ 2.6 S/C venting period

Figure 12 shows the containment vessel pressure from 09:00 to 15:00 on March 13; the top of the graph matched the release of water vapor from the Units 3 and 4 exhaust stack in the live camera image [1] recorded hourly. Based on this figure, the assumptions for the first and second venting periods are discussed.

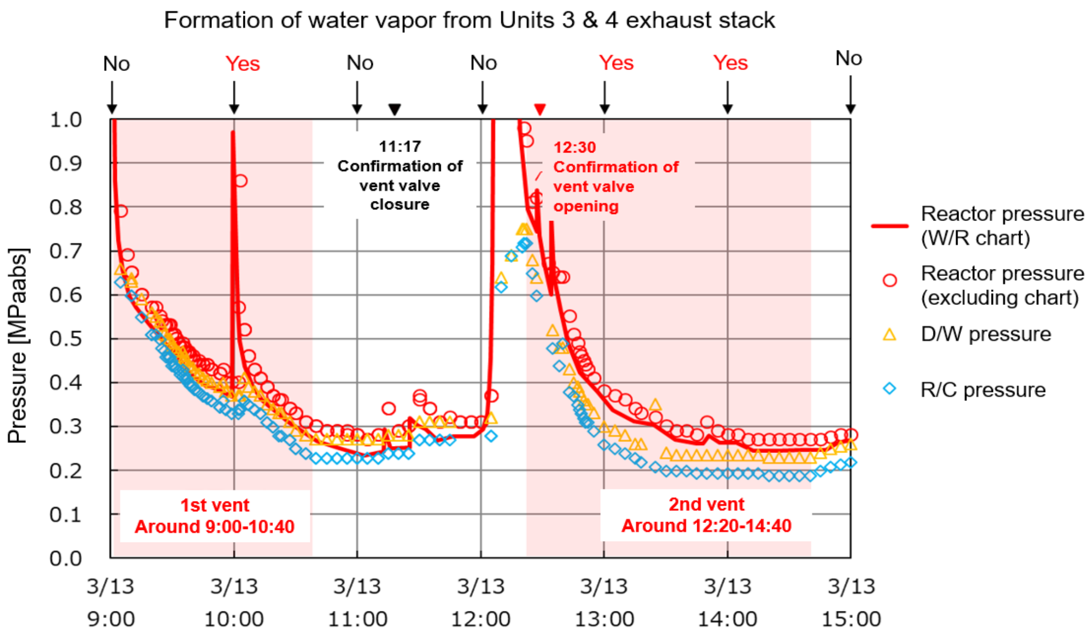

Figure 12 Containment vessel pressure behavior; presence or absence of water vapor release from the exhaust stack (Correction: chart +7.5 minute shift, reactor pressure +90 kPa, S/C pressure +8.2 kPa)

(1) The first venting period

The containment vessel pressure increased due to the ADS activation at 08:59, and the S/C venting was considered to have started when the containment vessel pressure reached the design pressure of the rupture disk; since steam emitted from the exhaust stack was not visible in the live camera image at 09:00, this image was considered to have captured the scene immediately before the venting. The first venting was considered to have started just after 09:00 because the reactor pressure drop that caused the rupture disk to exceed the operating set pressure took place at around 08:59, and the containment vessel pressure recorded after that showed a drop in pressure between 09:05 and 09:10.

Also, after 10:40, the containment vessel pressure, which had been continuously decreasing until then, became constant. One possible cause for this change was that the vent valve might have closed at 10:40, and a second possibility was that the vent valve was open at 10:40, but the pressure drop slowed down due to a larger amount of depressurization and boiling in the S/C pool. If there was depressurization boiling, the static value of the S/C pressure should be the same during the first and second venting, or higher during the second venting due to the heat input to the S/C. However, the former was 220 kPa[abs] and the latter was 180 to 190 kPa[abs] (both without correction), and the value during the second venting was lower. Therefore, the change in the rate of pressure drop at 10:40 was considered to be due to the vent valve being closed. Since the operation record states that "the large valve of the S/C vent (AO valve) closed due to a loss of cylinder pressure," it is considered that the cause of the closure was a loss of cylinder pressure.

(2) The second venting period

The second venting period was considered to have started at about 12:20, because the containment pressure has been decreasing since about 12:20, and steam released from the exhaust stack was not seen in the live camera video at 12:00, but was seen at 13:00.

In addition, the containment pressure turned from falling to rising at about 14:40, and steam released from the exhaust stack was seen in the same video at 14:00 but not at 15:00, making it highly likely that the vent valve was closed around 14:40.

■ 2.7 Migration of fuel debris into the lower plenum

As shown in Figures 5 and 7, the time corrected chart data showed large increases in reactor pressure at around 08:52, 09:59, and 12:05. As mentioned in Attachment 3-4, this is thought to capture the gas production as the fuel migrated to the lower plenum. It is also possible that small-scale migration might have occurred at other times when the reactor pressure was slightly increasing.

■ 2.8. Start of continuous gas phase leakage from D/W and depletion of lower plenum water

Figure 13 shows the containment vessel pressure from 15:00 on the 11th to 00:00 on the 14th, and the pressure on the D/W side was lower than the pressure on the S/C side during the period when the containment vessel pressure decreased after around 21:00 on the 13th. This suggests that a gas phase leakage from D/W occurred around this time (Attachment 3-8).

In addition, the containment vessel pressure was below the design pressure (about 490 kPa[abs]) until about 09:00 on the 13th for the available data. Since no pressure changes suggestive of leakage start were observed, no significant leakage was considered to have occurred by 09:00 on the 13th. Containment vessel pressure rose above the design pressure at around 09:00 and after 12:00 on the 13th, but the period was short. The S/C venting that followed the pressure increase reduced the pressure, and the containment vessel pressure has been increasing since the time when the S/C vent valve was considered to have been closed. Therefore, no indication of a continuous leakage from the containment vessel by 14:40 on the 13th can be read from the containment vessel pressure.

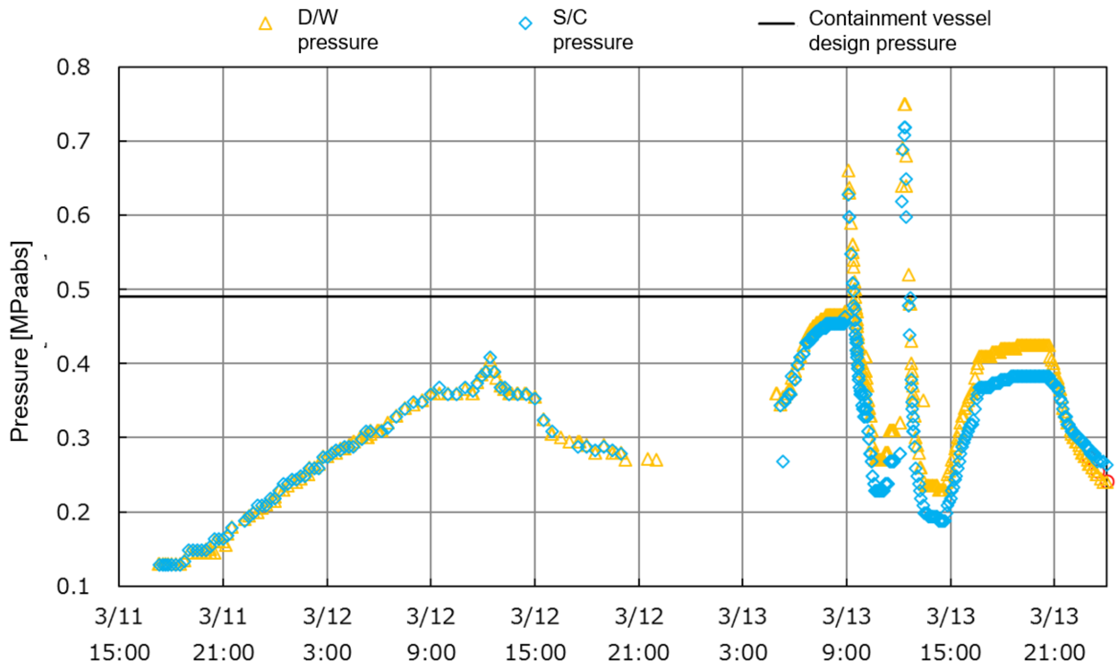

Figure 13 Containment vessel pressure (from 15:00 on the 11th to 00:00 on the 14th)

Figure 14 shows the containment vessel pressure and reactor pressure from 14:00 on the 13th to 00:00 on the 14th. At 16:40, the containment vessel pressure, which had been increasing until then, became almost constant until 20:40, and then began to decrease. There are two possible reasons for this: the start of gas phase leakage from D/W and the decrease in gas production (decrease in steam generation due to depletion of water in the pressure vessel).

Looking at the reactor pressure, it is considered that the reactor pressure was slightly higher than the D/W pressure during the period from 16:40 to around 20:00, although there could be some uncertainty due to correction. The pressure difference during this period is considered to correspond to the pressure loss caused by the leakage of gas formed in the reactor to the D/W side. On the other hand, if the containment pressure did not increase despite the leakage from the pressure vessel, it is highly possible that a gas phase leakage from the D/W occurred after 16:40. From the viewpoint of temperature, however, there is a possibility that the inside of the D/W was hot due to gas phase leakage from the pressure vessel, and thus it is possible that the rubber seals and other parts were damaged due to excessive temperature.

On the other hand, after around midnight on the 14th, the containment vessel pressure increased and D/W CAMS(A) recorded a peak value (170 Sv/h) at about 06:30 on the 14th, and other actual measurements were obtained that suggested damage to the pressure vessel lower head. In addition, although the amount of reactor water injected by the fire pumps at that time averaged about 36 m^3/h (=10 kg/s), which is larger than the amount of water evaporated by decay heat (~5 kg/s), it is highly likely that part of the fire pump water flowed into other systems and equipment and not all the water was injected into the reactor. Therefore, it is possible that the water level in the pressure vessel (including the water level in the lower plenum) could not be maintained or increased by water injection, and the amount of water held in the pressure vessel may have decreased under the conditions where the fuel was moving to the lower plenum. Based on the above, it is highly likely that the depletion of water in the lower plenum occurred prior to midnight on the 14th.

The depletion of water in the lower plenum reduces the amount of water vapor formed in the reactor, which can be a factor in the containment vessel pressure drop in situations where there is leakage from the containment vessel. Since this is consistent with the change in containment vessel pressure at about 20:40, it is assumed that the pressure drop from 20:40 was due to water depletion in the lower plenum.

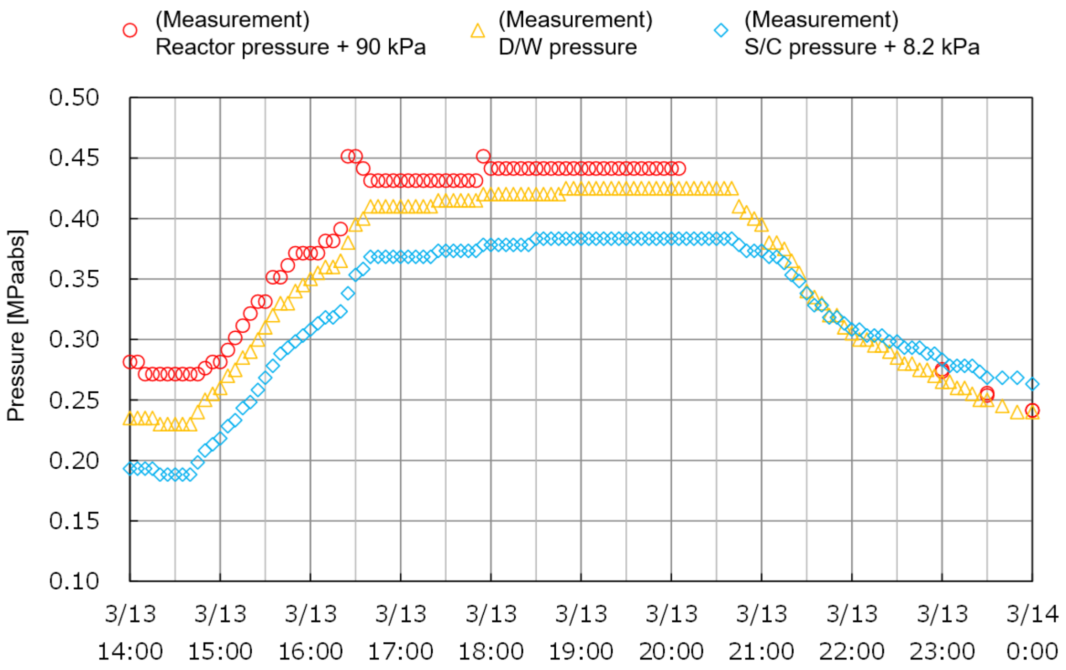

Figure 14 Containment vessel pressure and reactor pressure (from 14:00 on the 13th to 00:00 on the 14th)

■ 3. Examination of accident progression scenario through reproduction analysis of actual measurements

The accident progression scenario developed was examined from a quantitative viewpoint through reproduction analysis of actual measurements. Through this reproduction analysis, the range of parameters that are important for accident progression was evaluated.

■ 3.1. Concept of evaluation

After core damage, there are several parameters that have a large impact on the pressure behavior of the plant and that have a large uncertainty, such as gas formation including hydrogen in the pressure vessel, migration of gas to the containment vessel through SRVs, etc., and leakage from the containment vessel. Therefore, it is difficult to identify the most probable state of each parameter through reproduction analysis.

Based on this, the subsequent reproduction analysis focuses on specific parameters and adjusts other parameters within the developed accident progression scenario to reproduce the pressure behavior of the plant while evaluating the range (maximum and/or minimum values) of the parameters to be focused on. The evaluation procedure is as follows.

① Set other parameters in the direction of maximizing/minimizing the focus parameter.

② Perform reproduction analysis while changing the focus parameter.

③ Check the reproducibility of pressure (if not reproduced, return to ① or ②).

The parameters to be focused on are the amount of hydrogen formation and transfer, the area of gas phase leakage from the pressure vessel after ADS activation, and the period during which the six SRVs were kept open after ADS activation; these are considered particularly important for understanding the accident progression.

■ 3.2 Reproduction analysis

The thermal hydraulic analysis code GOTHIC v8.3 (QA) was used for the analysis. An overview of the analysis system is shown in Figure 15. The reactor pressure vessel, containment vessel, reactor building, and vent piping were simulated as fluid flow spaces. Leakage from the SRV, pressure vessel, and containment vessel was simulated by setting up these channels and valves. Arrows connecting each region indicate fluid migration pathways.

For containment vessel spray, reactor water injection, and hydrogen and steam formation in the reactor, external input values were given as inflow boundaries for the purpose of, for example, being able to adjust the amount of pressure that can reproduce the actual measured pressure.

In order to evaluate temperatures in the pressure vessel and containment vessel, reactor components such as fuel and control rods, walls of the pressure vessel and containment vessel, and concrete in the containment vessel were simulated, and decay heat and water-metal reaction heat corresponding to a set amount of hydrogen were given for the fuel.

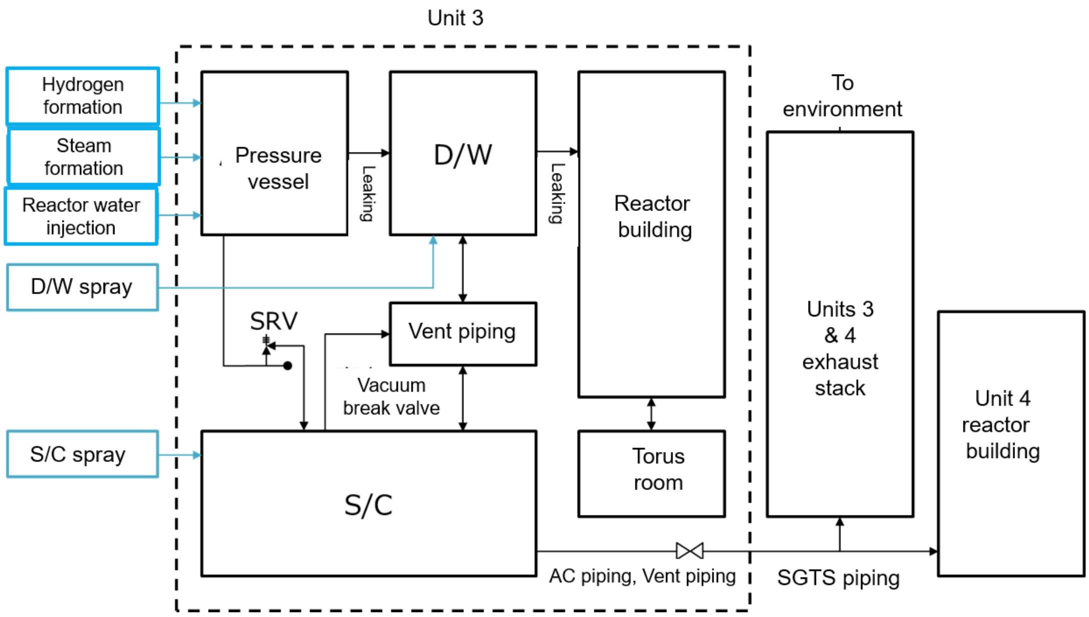

Figure 15 Outline of analysis system

(1) Evaluation of the range of hydrogen formation in the reactor and the amount of hydrogen migration

The amount of hydrogen formed in the reactor and the amount of hydrogen migrated into the reactor buildings are important when considering the mechanism of hydrogen explosions in the reactor buildings of Units 3 and 4. However, it is difficult to precisely evaluate how much hydrogen migrated into each of these reactor buildings, therefore as an example here, the hydrogen formation in the reactor was evaluated as large.

a) Analysis conditions

Analysis was conducted according to the developed accident progression scenario (Figure 1) from the time the reactor water level reached TAF to 00:00 on the 14th. The main analysis conditions other than those shown in Figure 1 and the basis for setting them are described below. Of these conditions, conditions ②, ③, and ④ were set so that the amount of hydrogen formation would be large while reproducing the actual pressure measurements.

① The state of the containment vessel at the time of reaching TAF

The pressure, temperature, gas composition, water level, etc. in the containment vessel at the assumed time of reaching TAF were evaluated by a separate analysis that reproduced the actual measured values of containment vessel pressure and S/C water level from the time of scram to the assumed time of reaching TAF.

In the analysis, water vapor generated by decay heat and S/C spray water were allowed to flow into the S/C to reproduce the measured values of the S/C water level. The containment pressure was reproduced by adjusting the water vapor balance in the S/C gas phase. At that time, heat transfer to the containment shell and concrete, and the control bleed-off flow rate from the recirculation pump to the D/W were also taken into account. In this way the water vapor and nitrogen transfer between S/C and D/W, as well as the temperature were estimated.

As a result, the containment pressure was about 270kPa[abs] at 01:00 on the 13th, the estimated time of reaching TAF, and the temperature was about 95°C on the D/W side and about 107°C on the S/C side. The S/C water level was about 6.3m above the S/C floor. These state quantities were set as the initial conditions in the containment vessel in the analysis after the TAF was reached.

② Water vapor formation in the reactor

The amount of water vapor formed during the core water level lowering process before the ADS operation was set assuming that the decay heat from the fuel below the water level in the core contributed to the evaporation of the reactor water, except for the period from the HPCI shutdown (02:42) to the SRV operation (around 04:30) when the reactor pressure increased significantly. The period from 02:42 to 04:30 was set according to the amount of steam formation that reproduced the increase in reactor pressure.

It is possible that a part of the decay heat contributed to the rise in the water temperature in the lower plenum during the increase in the reactor pressure and the decrease in the reactor water level after the HPCI shutdown, and that steam formation by depressurization boiling corresponding to the temperature increase might occur after the ADS is activated, but the extent of such steam formation is not clear. In this analysis, additional water vapor formation during this depressurization process after ADS activation was not considered from the viewpoint of increasing the relative contribution of hydrogen to the containment pressure increase and thus the amount of hydrogen formed.

For the water vapor formation due to fuel migration into the lower plenum, an amount that reproduces the reactor pressure peak was set.

For the reactor water injection (water injection by fire trucks), the amount and water injection period were adjusted to the extent that records were available. Specifically, it was assumed that 1.75 kg/s water injection reached the reactor from around 10:30 to 12:05 and after 13:12 on March 13. This adjustment was made from the viewpoint of suppressing the amount of water vapor formed in the reactor after the first S/C venting and reproducing the trend of a slow containment pressure increase after 10:40, when the vent valve was assumed to be closed, and from the viewpoint of simulating the trend of containment pressure decrease after the lower plenum water was depleted at around 20:40. Although the actual reactor water injection rate is considered to be dependent on the reactor pressure, a fixed amount was given here for simplicity. This amount of water injected was smaller than 10kg/s, which is the average of the fire pump discharge during the same period, and is consistent with the possibility that part of the fire pump discharge flowed into other systems and equipment, and not all of the water was injected into the reactor.

③ Gas phase leakage area from the pressure vessel and SRV opening area

Figure 16 shows the area of gas phase leakage from the pressure vessel and the SRV opening area.

For the gas phase leakage from the pressure vessel, a small leakage (0.6 cm^2) from the pressure vessel to the D/W at 03:30 was assumed to reproduce the increase in D/W pressure (270 kPa[abs] at 22:00 on the 12th to 360 kPa[abs] at 04:55 on the 13th). Since this was before the SRV was activated, the in-core instrumentation piping was assumed as the leakage location.

Regarding the post-ADS activation, the number of open SRVs decreased and an expansion of gas phase leakage in the pressure vessel occurred immediately after the ADS activation (based on the assumption of the same period as the ADS activation, the leakage from the SRV or main steam pipe was assumed) and the SRV full closure at 12:15 was an adjustment based on the assumption of a large amount of hydrogen formation in the developed accident progression scenario. Although both SRV (A) and (G) open/close indicator lights were observed to be lit around 09:08, for simplicity, this analysis assumed that SRV (G) was fully closed immediately after ADS activation, and only SRV (A) was assumed to be in an intermediate open state.

The enlargement of the SRV(A) opening area at around 10:00 was adjusted to reproduce the rate of decrease of the reactor pressure after its increase at about 10:00, based on the fact that the SRV(A) was operated to open at about 09:50.

The expansion of the pressure vessel gas phase leakage at 12:15 is an adjustment that became necessary to reproduce the actual measured reactor pressure as a result of the assumed SRV closure to increase the amount of hydrogen formation, as mentioned above. The necessity of this assumption of increased gas phase leakage depends on the state of SRV opening and closing, and there is some uncertainty.

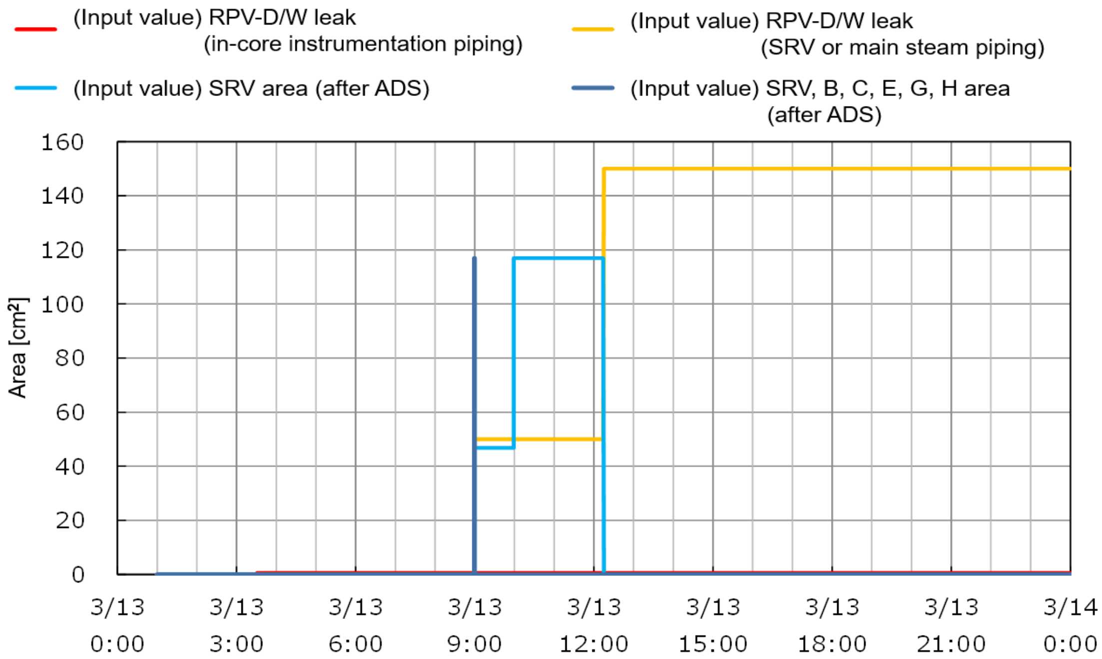

Figure 16 Gas phase leakage area from pressure vessel and SRV opening area (per valve) (evaluation case with a large amount of hydrogen formation)

④ Amount of hydrogen formation

Figure 17 shows the hydrogen formation settings. In addition to the settings for the large amount of hydrogen formation shown in ② and ③, continuous hydrogen formation during the S/C venting period and from the containment vessel was assumed. As a result, the cumulative amount of hydrogen formation up to midnight on the 14th was about 1,700kg, which was close to the hydrogen formation (about 1,900kg) that would be assumed if all the zirconium in the reactor core were oxidized.

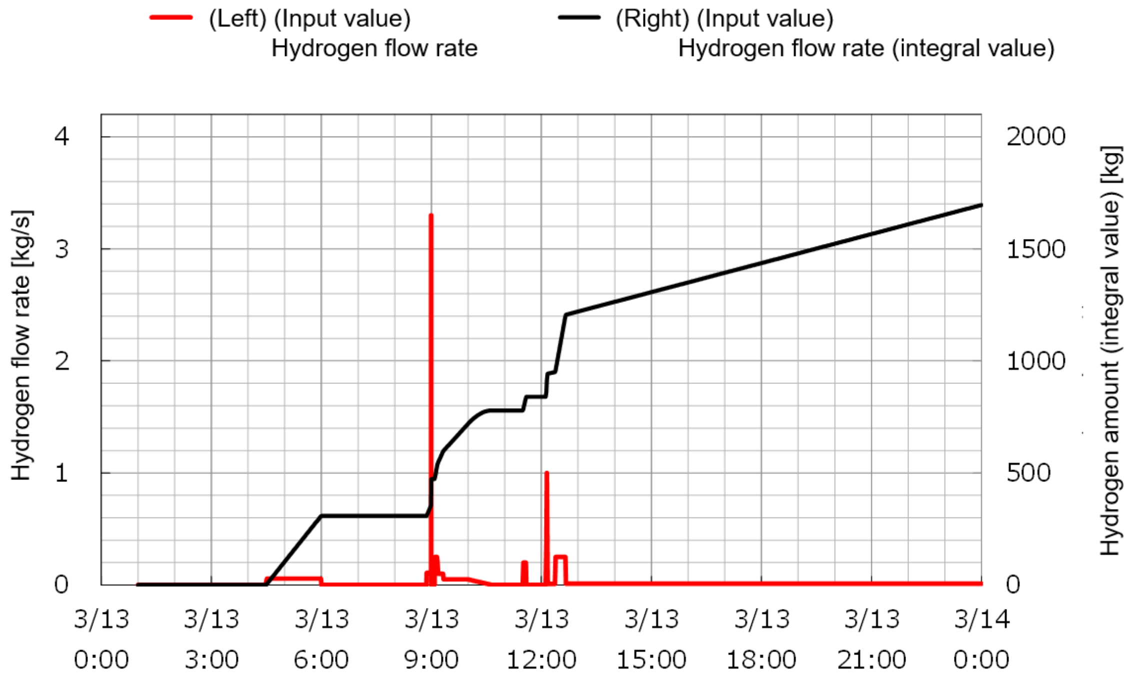

Figure 17 Hydrogen formation settings (evaluation case with a large amount of hydrogen formation)

b) Analysis results

①Analysis results of reactor pressure and containment pressure

Figure 18 shows the analysis results of the reactor pressure and containment vessel pressure. The above mentioned analytical conditions reproduced the measured pressure values generally well.

Figure 19 shows the analytical results of the pressure difference between D/W and S/C. The tendency for D/W pressure to be slightly higher than S/C pressure from about 05:00 to 09:00 on the 13th, the expansion of the pressure difference at around 09:00, the tendency for the pressure difference to be almost constant from about 09:00 to 20:40, and the tendency for the relationship between the two pressures to reverse after 20:40 were all reproduced quite well.

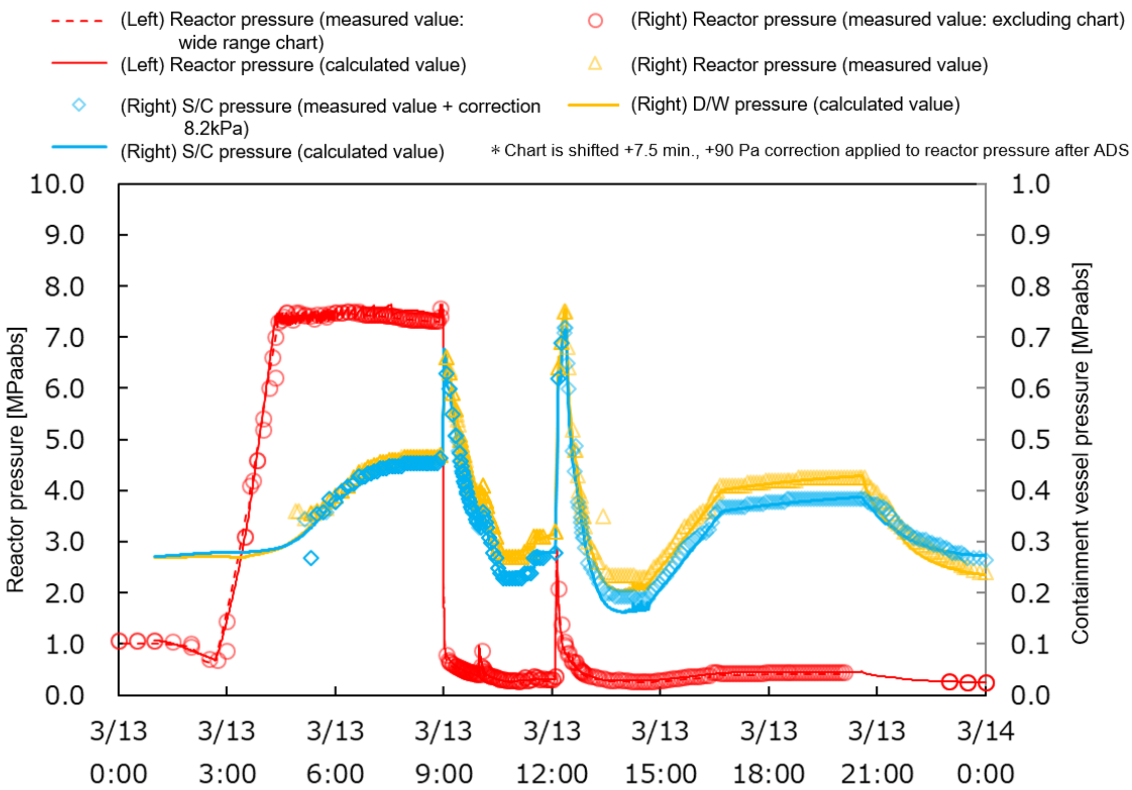

Figure 18: Analysis results of reactor pressure and containment vessel pressure (evaluated case with large amount of hydrogen formation evaluated)

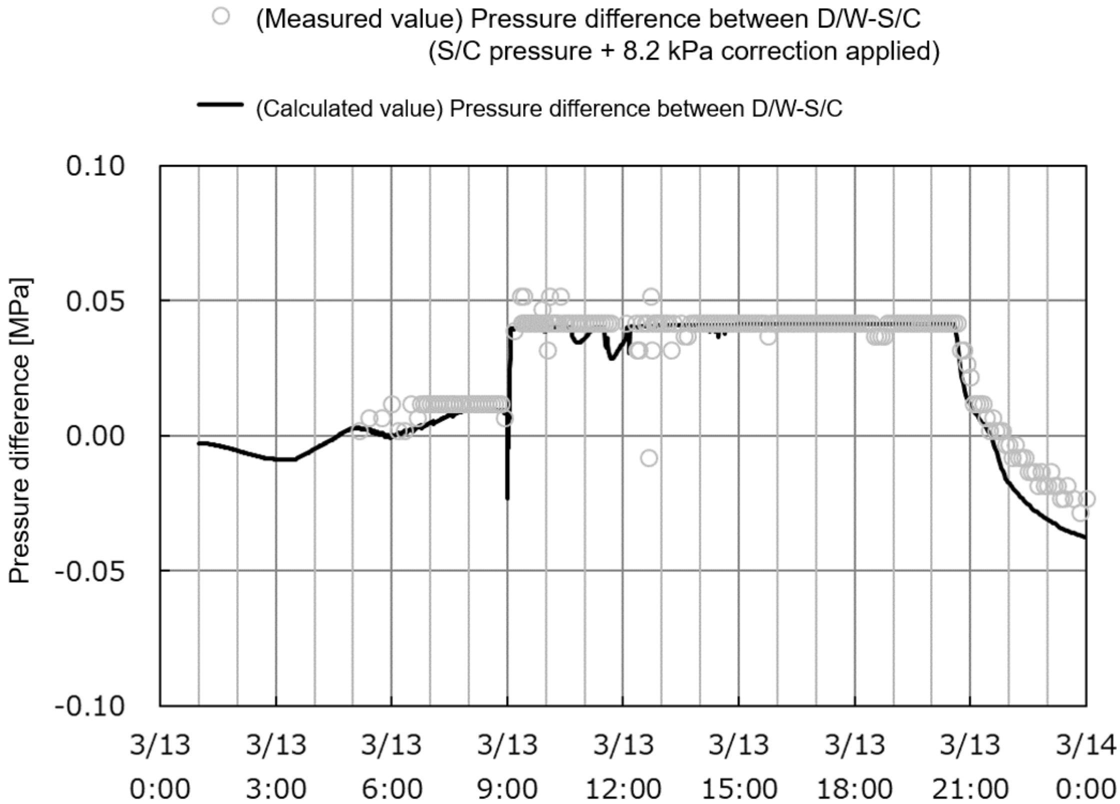

Figure 19: Analysis results of pressure difference between D/W and S/C (evaluation case with a large amount of hydrogen formation)

② Analysis results of hydrogen migration

Figure 20 shows the analysis results of hydrogen migration. In this analysis, the amount of hydrogen formation was assumed to be large, such as by assuming continuous hydrogen formation during the S/C venting period and even after the containment vessel leakage, so the amount of hydrogen migrating to each part was considered to be larger than the actual amount of hydrogen. It should be noted that this analysis does not take into account the backflow into the Unit 3 reactor building during S/C venting, but if backflow were taken into account, the amount of hydrogen migrating into the Unit 3 reactor building would increase slightly and the amount of hydrogen migrating into the Unit 4 reactor building would decrease slightly.

<u>Amount of hydrogen in the pressure vessel and containment vessel</u>

Until the ADS activation, a part of the hydrogen formed in the RPV was distributed in the RPV and the containment vessel as some of the hydrogen migrated to the containment vessel; after the ADS activation, due to the SRV opening and the expansion of gas phase leakage from the RPV, the hydrogen formed in the RPV was not accumulated in the RPV but migrated to the containment vessel, where it was released from the containment vessel by S/C venting.

However, the hydrogen formed in the containment vessel was not fully released by the end of the first S/C venting (10:40) due to the large influx of hydrogen assumed to be newly formed. The amount of hydrogen that formed slightly increased at 11:30 due to the assumption of additional hydrogen formation, and then further increased at 12:05 when the fuel debris migrated into the lower plenum. The hydrogen formation was further increased by the assumption of hydrogen formation at 12:05. Most of the hydrogen in the containment vessel was then released during the second S/C venting period (set from 12:23 to 14:40 based on containment vessel pressure reproducibility).

After 14:40, until the start of the leak from the D/W (16:40), the hydrogen that was formed migrated along the pressure vessel → D/W → S/C pathway, resulting in an increase in hydrogen amount in the S/C. Thereafter, there was almost no new inflow and it remained almost constant.

Amount of hydrogen that migrated into the Unit 3 reactor building

After 16:40, when the leakage from the containment vessel to the reactor building was assumed to occur, almost all of the hydrogen that was formed leaked into the reactor building of Unit 3, and the cumulative amount of hydrogen leaked until midnight on March 14 was approximately 300 kg.

Amount of hydrogen that migrated into the Unit 4 reactor building

The amount of hydrogen flowing into the Unit 4 reactor building from the two S/C vents was about 150 kg for the first venting and about 90 kg for the second venting, for a cumulative total of about 240 kg. The ratio of the amount of hydrogen flowing into Unit 4 to the total vented gas was about 24% for the first venting and about 14% for the second.

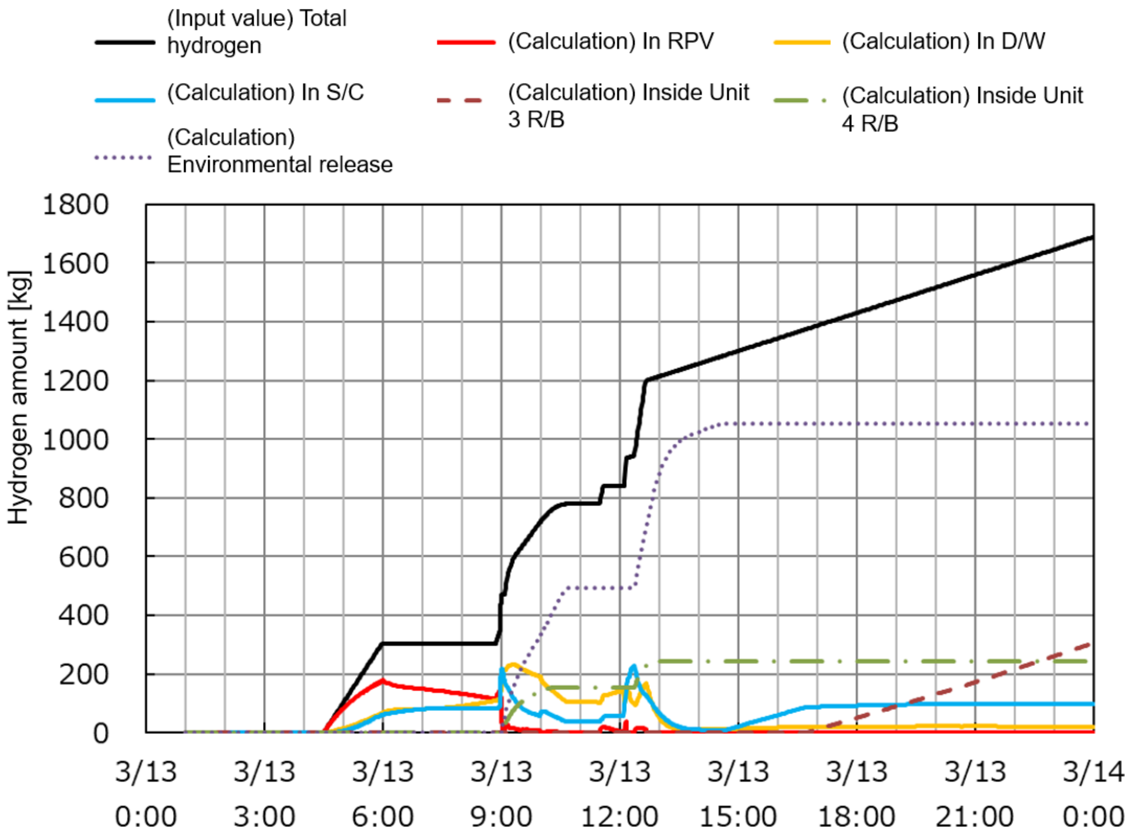

Figure 20 Results of analysis of hydrogen abundance at various locations (evaluation case with a large amount of hydrogen formation)

(2) Evaluation of the range of gas phase leakage area of the pressure vessel after ADS activation

The D/W pressure obtained at 09:05 immediately after ADS activation was several tens of kPa higher than the S/C pressure. In order to estimate the leakage expansion from the pressure vessel to the D/W, the minimum leakage area required to reproduce this pressure behavior was evaluated.

a) Analysis conditions

The following conditions were changed from those shown in Section 3.2 (1) a).

① Hydrogen formation

A hydrogen formation rate that reproduces the increase in containment vessel pressure was set. The period of hydrogen formation was assumed to have been completed by the time the SRV opening area was reduced as described in ③, although it is considered to be different from the actual hydrogen formation situation, so that the D/W pressure tended to be higher than the S/C pressure due to leakage mainly of water vapor even when the leakage area from the pressure vessel to the D/W was small. However, it was assumed that hydrogen formation was completed by the time of the SRV opening area reduction described in ③.

② Water vapor formation

Water vapor leakage to the D/W side contributes to the pressure increase in D/W, while water vapor migrating to the S/C side condenses in the S/C pool, therefore its contribution to the pressure increase in the S/C is small. From the viewpoint of reproducing the trend of measured values where the pressure on the D/W side is dominant, a large water vapor formation rate was assumed by assuming depressurization boiling of water in the pressure vessel during the depressurization process after ADS operation.

③ Number of SRVs open after ADS activation

In order to increase the amount of leakage to the DW side, a reduction of the SRV opening area immediately after ADS activation was assumed. The SRV opening area after this reduction was assumed to be an area that would not increase the pressure difference between the reactor and containment vessel too much, and the area for two SRV valves was set based also on the intermediate open indication of SRVs (A) and (G) at 09:08.

④ Gas phase leakage of pressure vessel

From the above settings, $30cm^2$ was set as the leakage area that roughly reproduces the pressure behavior.

b) Analysis results

Figure 21 shows the analysis results of the reactor pressure and containment vessel pressure from 08:55 to 09:05 on the 13th, which generally reproduced the relationship between the D/W and S/C pressures at 09:05. The reactor pressure was slightly overestimated compared to the wide range chart. If the gas phase leakage area of the pressure vessel was further reduced, from the viewpoint of reproducing the pressure difference between D/W and S/C at 09:05, the SRV opening area was further narrowed to reduce the pressure increase on the S/C side, after increasing the water vapor and the amount of hydrogen formed to reproduce the pressure increase on the D/W side. As a result, the depressurization rate of the pressure vessel was reduced, and the discrepancy between the measured and analyzed reactor pressure during the depressurization process was further widened.

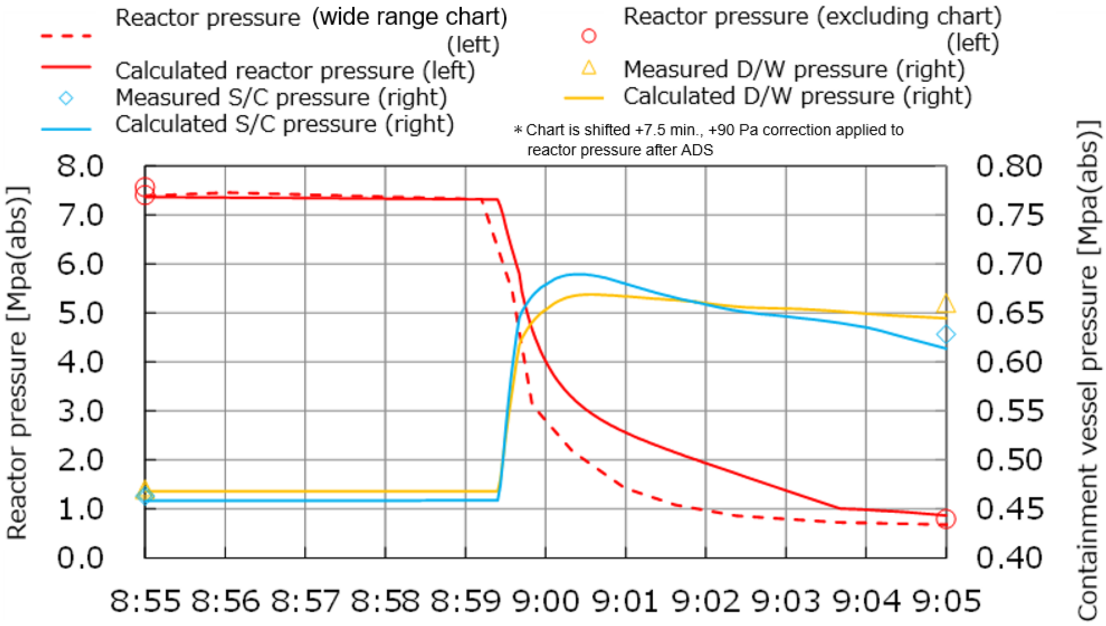

Figure 21 Analysis results of reactor pressure and containment vessel pressure (30 cm^2 pressure vessel gas phase leak)

(3) Evaluation of the range of the period during which the six SRVs were maintained open after ADS activation

To estimate the range of the period during which the six SRVs remained open based on the increase in reactor pressure after ADS activation, the cases in which six SRVs remained open (fully open) after ADS activation (hereinafter the "SRV6 valves maintained open case") and the case in which SRVs were fully closed immediately after ADS activation (hereinafter the "SRV fully closed case") were separately evaluated.

a) Analysis conditions

The following conditions were changed from those shown in Section 3.2 (1) a).

① Hydrogen formation

In both cases, water vapor was mainly formed in the pressure vessel when fuel debris migrated to the lower plenum at 09:59. This water vapor migrated into the D/W, while the hydrogen accumulated in the D/W migrated into the S/C due to this effect, resulting in a tendency for the containment vessel pressure increase to be excessive. Therefore, the reproducibility of containment vessel pressure was improved by reducing the amount of hydrogen formation itself and reducing the amount of hydrogen accumulated in the D/W. In addition, vent flow rate was decreased to reproduce the containment vessel pressure because the rate of decrease of the containment vessel pressure due to venting was increased by this change.

② Water vapor formation

In the SRV6 valves maintained open case, most of the gas formed in the reactor migrated to the S/C, making it difficult for the D/W pressure to rise. In order to reproduce the increase in reactor pressure to the extent possible even when the six SRVs were opened, the maximum setting of water vapor formation due to the migration of molten materials to the lower plenum was limited by the total amount of the reactor internals.

In the SRV fully closed case, as in Section 3.2 (2), water vapor formation during the depressurization process after ADS activation was not assumed. In the SRV fully closed case, the gas generated in the reactor mainly migrated to the D/W, and the D/W pressure tended to rise. As a result, even without additional water vapor formation during the depressurization process after ADS, the increase in containment vessel pressure after ADS activation and the relationship between D/W and S/C pressures at 09:05 were reproduced.

② Number of SRVs open after ADS activation

In the SRV6 valves maintained open case, it was assumed that six SRVs maintained the open state after ADS activation; in the case of the SRV fully closed case, it was assumed that SRVs were fully closed immediately after ADS activation.

③ Gas phase leakage from the pressure vessel after ADS activation

In both cases, values were set to reproduce the relationship between D/W and S/C pressures at 09:05.

b) Analysis Results

Figure 22 shows the analysis results of the reactor pressure and containment vessel pressure for the SRV6 valves maintained open case. The fuel migration at 09:59 to the lower plenum reproduced the reactor pressure peak, but the pressure drop after the peak was faster than the measured value due to the assumption that the six SRVs were open. Subsequent migration of all remaining fuel in the core to the lower plenum at 12:05 did not reproduce the subsequent increase in reactor pressure. This suggested that six open SRVs could not be maintained before 12:05.

Figure 23 shows the analysis results of the reactor pressure and containment vessel pressure in the SRV fully closed case. The fact that the peak of the reactor pressure was reproduced by the migration of fuel debris into the lower plenum indicated that even assuming full closure of the SRV immediately after the ADS activation, it is possible to reproduce the measured values depending on the scale of the gas phase leakage from the pressure vessel. Therefore, the possibility that the SRVs were fully closed immediately after the ADS activation cannot be ruled out.

From the above, it is estimated to be highly likely that the six SRVs could no longer be maintained open between immediately after the ADS activation and about 12:00.

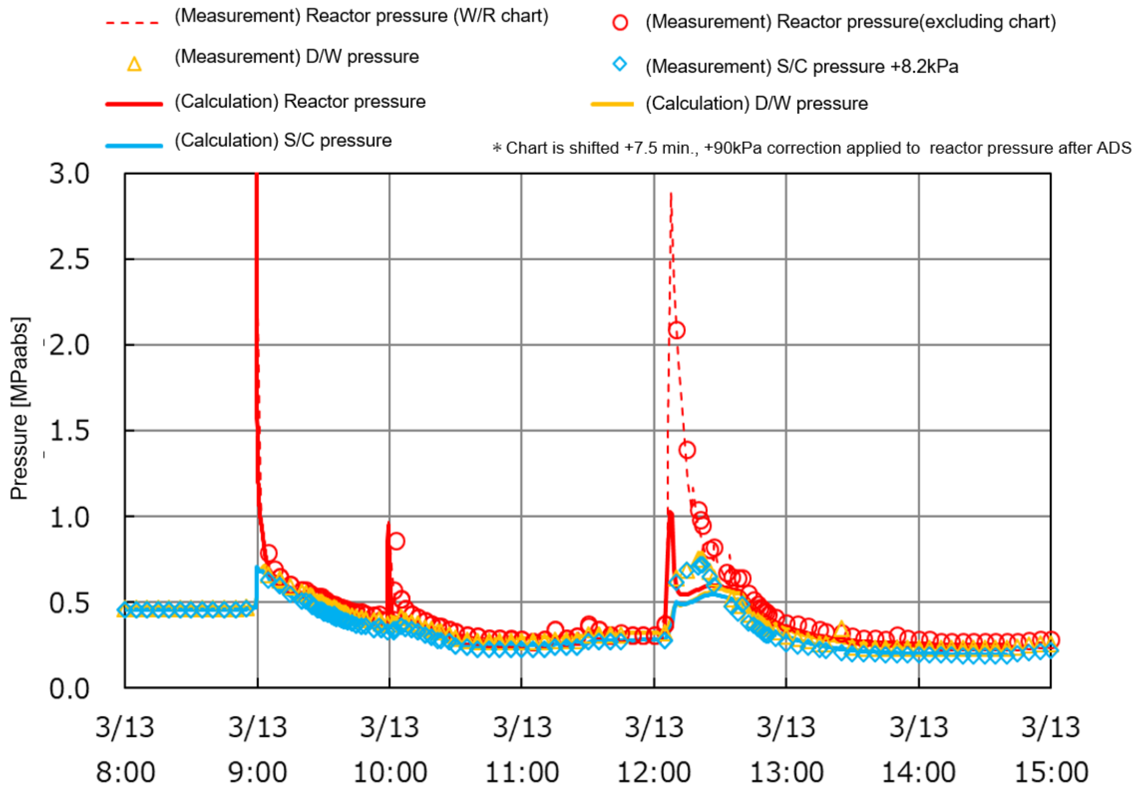

Figure 22 Analysis results of reactor pressure and containment vessel pressure (SRV6 valves maintained open case)

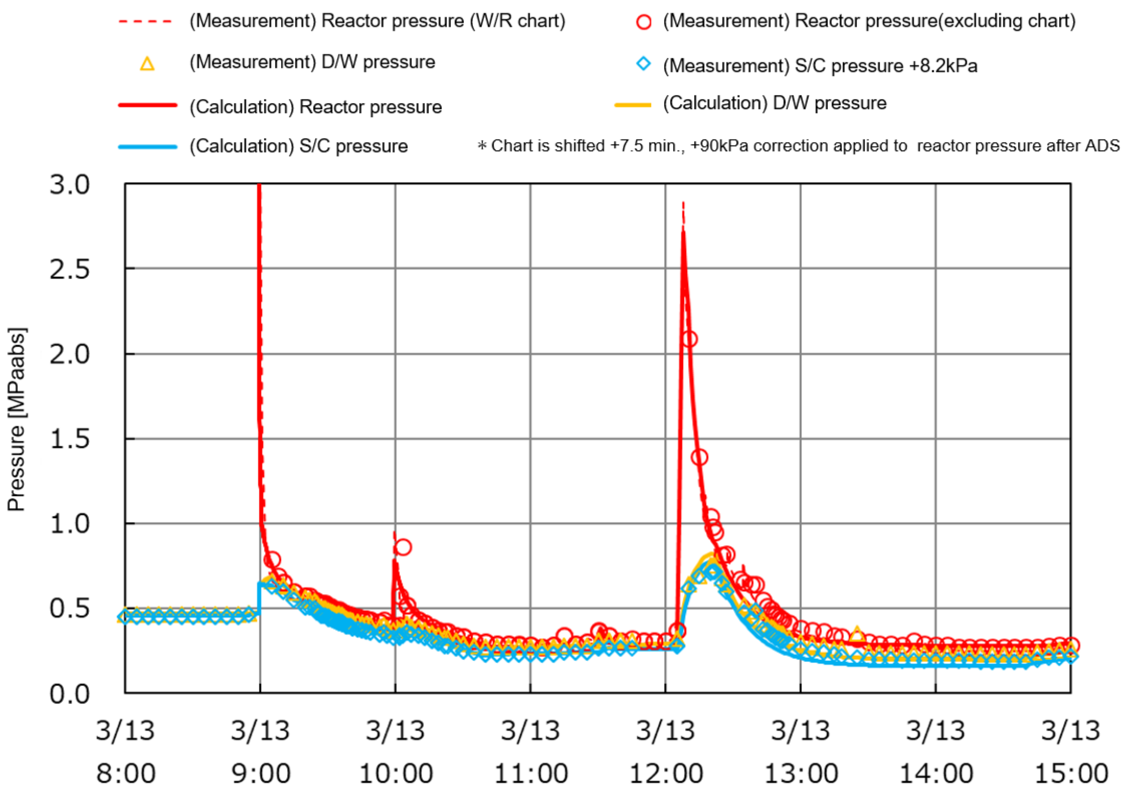

Figure 23: Analysis results of reactor pressure and containment vessel pressure (SRV fully closed case)

3.3 Discussion of the feasibility of the accident progression scenario

As shown in Figure 18, reactor pressure and containment vessel pressure could be reproduced well by the analysis according to the accident progression scenario shown in Figure 1. In the reproduction analysis, the amount of hydrogen migrating into the Unit 4 reactor building, the expansion of gas phase leakage from the pressure vessel at about 09:00 on March 13, and the decrease in the number of SRVs open after the ADS activation were estimated. The feasibility of these estimates is also discussed in terms of previous studies and observed facts.

(1) Amount of hydrogen migrating into the Unit 4 reactor building

In this evaluation, the amount of hydrogen flowing into the Unit 4 reactor building from the two S/C vents was about 150 kg for the first venting and about 90 kg for the second venting, for a total of about 240 kg. The ratio of the amount of hydrogen flowing into Unit 4 to the total vented gas was about 24% for the first venting and about 14% for the second.

This result is lower than that of the previous evaluation report (Attachment 3-10), both in terms of the amount of hydrogen and the percentage of inflow. The main causes are as follows.

- In the previous evaluation, the S/C water level at the start of venting was assumed to be half of the S/C height, resulting in a larger free space volume of the S/C being available than in reality and a larger hydrogen volume at the start of venting. On the other hand, in this evaluation, the estimation of the S/C water level was updated to a greater height based on the results of the study in Attachment 3-11, resulting in a smaller hydrogen volume at the start of the first venting. Unlike the previously reported evaluation, this assessment assumed hydrogen formation during venting, but even with the addition of this assumption, the amount of hydrogen formed during the first venting was smaller than in the previously reported assessment.
- In the previous evaluation, the containment vessel pressure tended to drop faster after S/C venting than the actual measured value. This was considered to be because the vent flow rate was overestimated. In the present analysis, the vent flow was reduced compared to the previously reported evaluation so that the containment vessel pressure drop reproduced the measured value. As a result, the pressure at the junction with the Unit 4 SGTS piping in front of the exhaust stack decreased, and the ratio of vented gas migrating to the Unit 4 side decreased.

This assessment was oriented toward consistency with the progression of the accident, such as the assumption of the S/C water level at the start of venting based on the measured S/C water level and containment vessel pressure behavior, and the vent flow rate that reproduced the rate of decline of containment vessel pressure. However, the consistency with the accident progression, such as the hydrogen explosion that occurred in the Unit 4 reactor building, is an issue to be further considered after this evaluation.

(2) Expansion of gas phase leakage from the pressure vessel about 09:00 on the 13th

Through the analysis, it was estimated that the expansion of gas phase leakage from the pressure vessel to the D/W was likely to have occurred at about the same time as the ADS activation.

In Attachment 3-9, it is estimated that the increase in the fuel range water level gauge reading immediately after the ADS activation was caused by evaporation of water in the reference leg of the water level gauge. This suggests that the containment vessel temperature might have increased due to the expansion of gas phase leakage from the pressure vessel, which is consistent with the above estimated results.

In Unit 3, high dose rates were measured at the shield plug position. This is thought to be due to a leak at the D/W top head flange; CAMS indicated values (D/W, 140 Sv/h; S/C, 4.28 Sv/h) were obtained at 04:10 on March 14, but not before, and it is not clear when the dose rate in the D/W increased. However, even to the extent that actual measurements are available for Unit 3, the S/C water level was near the vacuum break valve as of 20:00 on March 12, and it is estimated that the S/C water level was already higher than the vacuum break valve at about the time the core damage developed (Attachment 3-11). Under these circumstances, the radioactive material that migrated to the S/C side via the SRVs would be mostly trapped in the S/C pool by scrubbing, and no radioactive material would migrate from the S/C side to the D/W side through the vacuum break valve. Therefore, the high dose rate at the shield plug location is consistent with the assumption that there was a gas phase leak from the pressure vessel to the D/W.

(3) Decrease in the number of open SRVs after ADS activation

Through the analysis, it was estimated that the six SRVs were likely to no longer be able to maintain their open states between immediately after the ADS activation and at about 12:00.

As described in Section 2.5, among the factors that could have caused the SRVs to close after the ADS activation were the deterioration of the operating environment and the lack of power supply. As mentioned above, the rise in the fuel level indicator immediately after the ADS activation indicates an increase in containment vessel temperature, and it is possible that the SRVs could not remain open due to deterioration of the operating environment (e.g., deterioration of sealing materials used in solenoid valves, etc., and leakage of N_2 gas used to drive the SRVs) caused by increased gas phase leakage from the containment vessel.

In addition, since the power supply was not sufficient at the time of the accident, it is possible that the closure was due to a lack of power. The fact that SRVs (A) and (G) showed an intermediate open indication at 09:08 and the remaining four valves did not show they were open suggests that the open area of the SRVs might have shrunk relatively early after the ADS was activated. These observed facts are consistent with the present estimation results.

■ 4. Summary

The following is a summary of the examinations to date.

- Based on the behavior of plant parameters and previous studies, the accident progression scenario shown in Figure 1 was developed. The analysis according to this accident progression scenario was able to reproduce the actual measured values of reactor pressure and containment vessel pressure.
- The amount of hydrogen formed was evaluated to be large when reproducing the actual pressure measurements. As a result, the amount of hydrogen that migrated to the Unit

3 reactor building by 00:00 on March 14 was evaluated to be approximately 300 kg, and the amount of hydrogen that migrated to the Unit 4 reactor building was evaluated to be approximately 240 kg. The latter value is smaller than the previous evaluation (Attachment 3-10), and it is an issue to be further considered in light of the consistency with the accident progression scenario after this evaluation, such as regarding hydrogen explosions that occurred in the reactor buildings of Units 3 and 4.

- The leakage was estimated to have occurred at about the same time as the ADS activation, and it is highly likely that the gas phase leakage from the pressure vessel to the D/W was expanding. This is consistent with the increase in the fuel range water level gauge readings immediately after the ADS activation and the high dose rates measured at the shield plug location.
- It was estimated that the six open SRVs were likely unsustainable between the time immediately after the ADS activation and about 12:00. This is consistent with the increase in the fuel range water level gauge readings immediately after the ADS activation (possible non-operation due to deterioration of the operating environment, such as increase of containment temperature), the fact that there was an insufficient power supply at the time of the accident (possible non-operation due to lack of power), and the SRVs (A) and (G) showing intermediate opening as of 09:08.

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

This examination indicates that the SRVs might not have been able to stay open due to the high temperature inside the containment vessel caused by the leakage from the pressure vessel, and that a gas phase leakage might have occurred in the containment vessel. This suggests once again the importance of measures to cool the containment vessel and keep the SRVs open.

As shown in Figure 24, the Kashiwazaki-Kariwa NPS has installed an alternative containment vessel cooling system in addition to the residual heat removal system (RHR) spray as a means of cooling the containment vessel. In addition, the containment vessel bottom water injection system is installed to cool the molten fuel that has migrated to the containment vessel bottom and to suppress the containment vessel atmosphere temperature from rising due to the heat transfer from the molten fuel. The alternative spray and the containment vessel bottom water injection have been conventionally carried out using the condensate water makeup system (MUWC), but this has been enhanced by adding a method for carrying out water injection using a fire truck.

In addition, the following measures have been implemented to operate and maintain the

SRVs as open (Figures 25 and 26).

- In the event of loss of nitrogen in the accumulator, the nitrogen supply is secured by a cylinder in the high-pressure nitrogen gas supply system. In addition, a line independent of the high-pressure nitrogen gas supply system is installed to enable the operation of SRVs only by supplying nitrogen from the cylinder.
- The sealing material of the solenoid valve in the nitrogen supply line was changed to EPDM which has superior high temperature resistance.
- An alternative spray procedure was added to mitigate thermal effects on SRVs.
- In the case of loss of the permanent DC power, a supply method was added using storage batteries intended for accident management, portable DC power equipment (power supply vehicles), or portable storage batteries for SRVs.

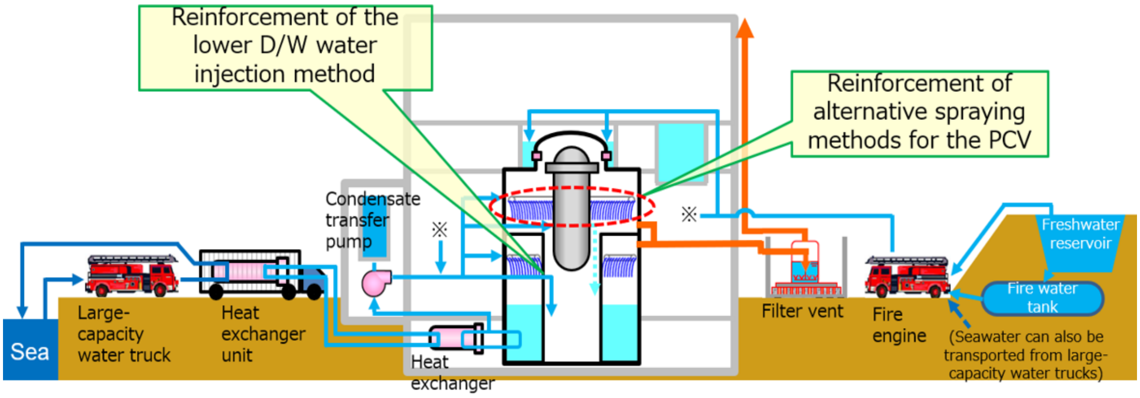

Figure 24 Measures to prevent PCV damage at the Kashiwazaki-Kariwa NPS (conceptual diagram)

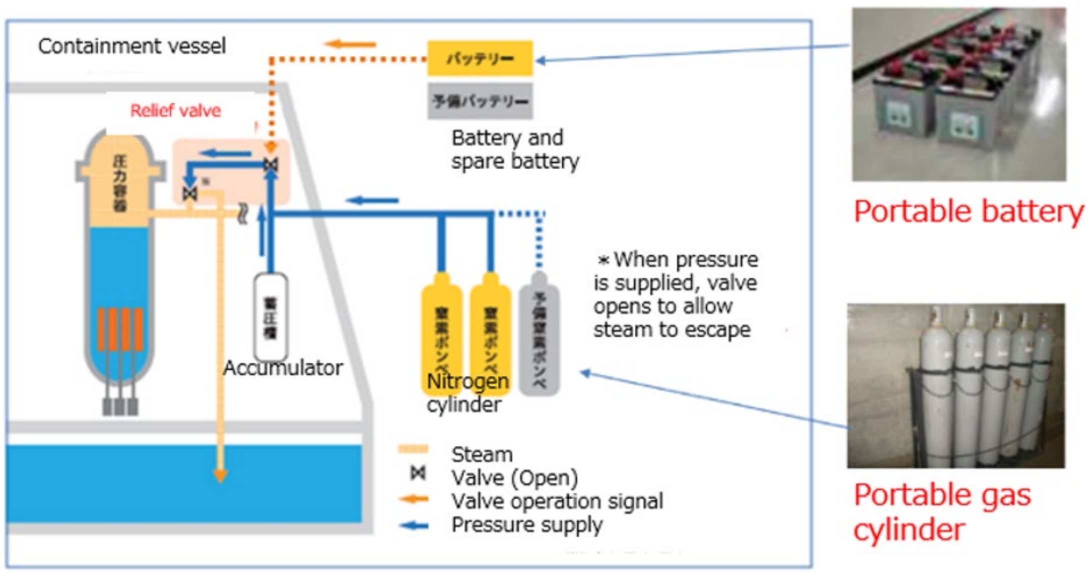

Figure 25 Measures to maintain SRV open (1/2)

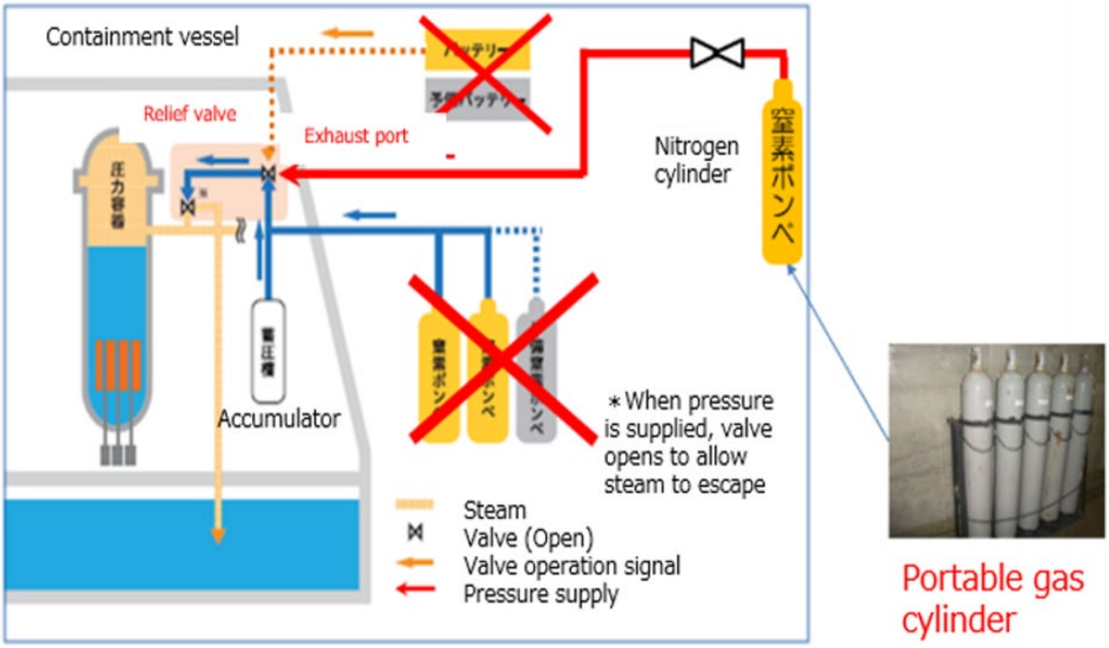

Figure 25　Measures to maintain SRV open (2/2)

Reference
[1] TEPCO HD, "Fukushima Daiichi live camera still images (for March 11 - May 31, 2011)".