Evaluation of the fraction of Unit-3 vent gas that flowed into Unit-4 reactor building

1. Introduction

The hydrogen explosion, which occurred on March 15, 2011, at the Unit-4 reactor building (R/B) of Fukushima Daiichi Nuclear Power Station, is believed to have been caused by part of the vent gas of Unit-3, released when the Unit-3 containment vessel (PCV) had been vented. The vent gas included hydrogen and it flowed in reverse to the Unit-4 R/B via the Unit-4 standby gas treatment system (SGTS).

In the evaluations to date [1][2][3], about 25 to 29% of the vent gas was considered to have flowed to the Unit-4 R/B, depending on the conditions that were assumed. However, some drawbacks were present in those studies, for example: dependence of pressure loss coefficient of friction on flow velocity was not taken into account [1][2]; and the whole piping configuration was not incorporated in the modelling [3]. It should be noted that, the amount of hydrogen which flowed into the Unit-4 R/B can be roughly estimated as the amount of hydrogen in the Unit-3 PCV calculated by the accident analysis code multiplied by the fraction above, but there are large uncertainties in the amount of hydrogen calculated by current accident analysis codes [4].

The fraction of vent gas, which had flowed to the Unit-4 R/B, was evaluated by a thermal-hydraulic code to deepen the understanding of mechanisms which had caused the hydrogen explosion at Unit-4. This code is capable of modeling the whole configuration of gas flow paths including piping based on the design data, and of evaluating the impact of pressure loss along the line depending on the flow gas velocities. Initial conditions such as the amount of hydrogen gas in the Unit-3 PCV at the time of venting were derived from the plant parameters measured at that time, not from the results of the accident analysis code.

2. Vent gas flow paths

Figure 1 illustrates the assumed vent gas flow paths from the Unit-3 PCV to the Unit-4 R/B. The following three reasons can be considered for the Unit-3 vent gas flows to Unit-4.

① The vent line had been modified from its form at the time of plant construction as an accident management (AM) measure; that is, by using most of the existing SGTS (connected to the Unit-4 ventilation ducts having openings in the building), it was able to serve as an AM measure.

② The Unit-3 and Unit-4 SGTS lines were joined together before reaching their common stack.

③ All valves in the Unit-4 SGTS line were automatically opened at the time of the station black-out (fail-open design).

It should be noted that no dampers were in place at the exit of the Unit-4 SGTS filter trains to prevent reverse flows. Dampers are not powerful enough to completely prevent reverse flows, but if they had been in place, they could have prevented significant reverse flows into the building.

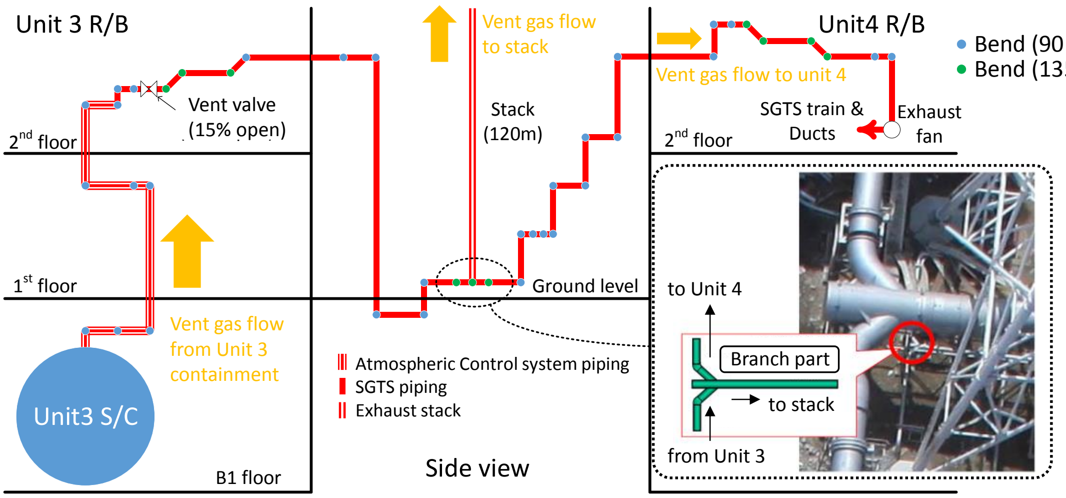


Figure 1 Vent gas flow paths from Unit-3 PCV to Unit-4 R/B

3. Analysis of the vent gas fraction that flowed into Unit-4 R/B

The amount of hydrogen and other conditions in Unit-3 PCV when the PCV had been vented were estimated based on plant parameters measured at that time. The results were used as initial conditions to analyze the fraction of vent gas which had flowed to Unit-4.

3.1. Estimation, based on measured values, of the Unit-3 in-containment conditions at the time of venting

Figure 2 presents plant parameters measured before and after the Unit-3 PCV venting. Besides the plant data in Figure 2, Unit-3 plant data readings recorded by shift operators at the time of the earthquake are available. Although they are slightly different in numerical values from what is shown in Figure 2, the data in Figure 2 were used in the current study. Pressures are expressed in absolute values throughout this attachment.

The drywell (D/W) pressure was 470 kPa[abs] at 08:55 on March 13, 2011. It increased to 637 kPa[abs] at 09:10 and decreased thereafter to 630 kPa[abs] at 09:15. The PCV is considered to have been vented before 09:15. In the current study, it was assumed that the PCV venting had started at 09:10, when the measured value had been recorded.

The PCV conditions (pressures, temperatures, gas compositions) at 09:10 were estimated in the following steps.

a. Pressures were estimated from the measured values.
b. Gas temperatures were estimated from the measured values.
c. Gas partial pressures were estimated based on estimated pressures and temperatures.

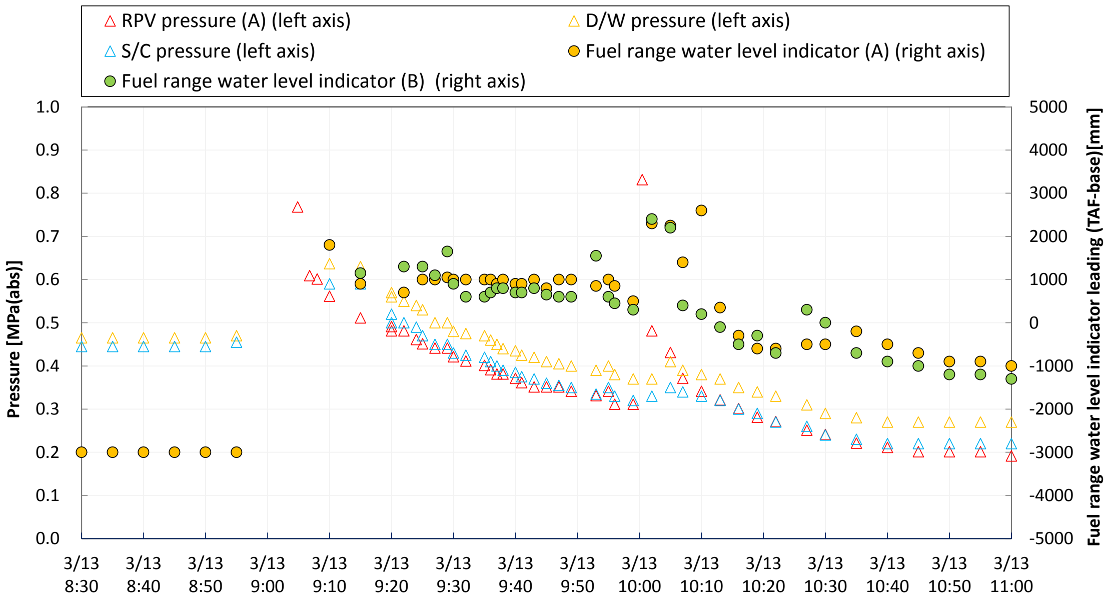


Figure 2 Plant parameters measured before and after PCV venting

The gaseous phase in the PCV was assumed to have contained, at the outset of PCV venting, nitrogen gas, which had filled the PCV during normal operation, steam and hydrogen, both of which had been produced in the process of the accident. Table 1 shows the in-PCV conditions at the outset of the assumed PCV venting. The grounds for the estimation are elaborated later for the D/W and suppression chamber (S/C).

Table 1 In-PCV conditions assumed at the outset of PCV venting

In D/W	Pressure	637 kPa[abs]
	Gas temperature	135 deg C
	Gas partial pressures (against total pressure)	Nitrogen: about 35% Steam: about 50% Hydrogen: about 15%
In S/C	Pressure	637 kPa[abs]
	Gas temperature	130 deg C
	Gas partial pressures (against total pressure)	Nitrogen: 0% Steam: 0% to about 42% Hydrogen: about 58% to 100%

(1) Grounds for estimation of in-D/W conditions at the outset of PCV venting

a. Estimation of pressure

The D/W pressure measured as 637 kPa[abs] at 09:10 was used as it was. There is room to argue on the reliability of absolute numerical values obtained by the D/W pressure indicator (Attachment 3-7), but the measured values were taken in the current study, because the overall impacts to reliability of the study outcome were considered small.

b. Estimation of gas temperature

The D/W gas temperature was estimated based on the fuel range water level indicator readings. Figure 2 shows the fuel range water level indicator readings remained roughly constant until about 10:00 after the venting had started and decreased gradually thereafter. The decrease of fuel range water level indicator readings after about 10:00 is considered to have been due to decompression boiling and the ensuing level decrease in the variable leg of fuel range water level indicator piping (see Attachment 3-9). Consequently, the water temperature in the variable leg at about 10:00 was estimated to be the saturation temperature 135 deg C at the reactor pressure 310 kPa[abs] measured at this timing. As no thermal insulators were installed on the water level indicator piping, the water temperature in the variable leg was assumed to be in equilibrium with the D/W gas temperature, hence 135 deg C, the same as the D/W gas temperature. Further assuming no big temperature changes in the D/W gas temperature during PCV venting, the D/W gas temperature was also assumed to be 135 deg C when the venting had started.

c. Estimation of gas partial pressures

The partial pressure of nitrogen was assumed to be about 223 kPa (about 35% of total pressure), as all the nitrogen in the S/C was assumed to have been transferred to the D/W due to the safety relief valve (SRV) operations before the venting and activation of the automatic depressurization system (ADS) (see Attachment 3-5). The partial pressure of steam was estimated to be about 318 kPa (about 50% of total pressure) as the saturated steam pressure for the D/W temperature estimated above of 135 deg C. The partial pressure of hydrogen was estimated to be about 96 kPa (about 15% of total pressure) by subtracting the above partial pressures of nitrogen and steam from the D/W pressure of 637 kPa[abs].

(2) Grounds for estimation of in-S/C conditions at the outset of PCV venting

a. Estimation of pressure

The S/C pressure was estimated as 637 kPa[abs], by assuming a situation that the S/C and D/W pressures had been in equilibrium as the result of vacuum breaker valves having been activated when gases had flowed into the S/C from the reactor by operations of the SRVs and ADS before the venting.

b. Estimation of gas temperature

The S/C gas temperature was estimated from the measured PCV pressures. The PCV pressures began to decrease from 09:10 due to venting but increased for a while at around 10:00. It is considered at this timing that part of the molten debris was relocated to the lower plenum and that steam and hydrogen were being produced (see Attachments 3-3, 3-4, and 3-9). These gases are considered to have raised the PCV pressures temporarily by being transferred to the PCV. Although this temporary pressure increase delayed the PCV pressure decrease, it decreased monotonously thereafter and from 10:40 the D/W pressure remained constant at 270 kPa[abs] and the S/C pressure at 220 kPa[abs], respectively. Two possibilities are considered for the D/W and S/C pressures to have remained constant: decompression boiling began in the S/C pool; or the vent line was closed. If decompression boiling had begun in the S/C pool, a large amount of steam should have been produced and therefore the PCV pressure decrease should have been slowed down. But no such trend could be noticed until 10:40 in the measured values of PCV pressures except the above-mentioned temporary increase. Therefore, the S/C pool water temperature at 10:40 can be considered to have been at or below the saturation temperature for the PCV pressure at that timing.

In the meantime, the large air-operated (AO (large)) valve on the vent line is confirmed to have been closed as of 11:17 due to loss of driving air pressure [1]. The AO (large) valve could have been closed as of 10:40. If that is the case, the S/C pressure could have been constant irrespective of the S/C pool water temperature. It is not possible, therefore, to estimate from the measured data to what extent the S/C pool water temperature was lower than the saturation temperature as of 10:40.

In the current study, the S/C gas temperature was set at a higher value by assuming the S/C pool water temperatures at 10:40 as the saturation temperature for the D/W pressure (270 kPa[abs]), i.e. 130 deg C. The S/C gas temperature was also assumed to be 130 deg C. Furthermore, the S/C gas temperature when the vent had started was also assumed to be 130 deg C, by considering that no big changes would have occurred during PCV venting.

c. Estimation of gas partial pressures

The S/C pressures increased from 445 kPa[abs] to 590 kPa[abs] between 08:55 and 09:10, as can be seen in Figure 2. As of 08:55, the reactor water level is estimated to have dropped to a level near the bottom of active fuel (BAF) (see Attachment 3-9). The S/C pressure increase is considered to have been caused by the hydrogen inflows from the RPV to S/C upon ADS activation during production of a large amount of hydrogen in the core region, where the temperatures had been elevated due to reactor water decrease. If this is the case, the S/C could have been in a gas-liquid non-equilibrium state (steam partial pressure < saturation vapor pressure), as the result of steam removal from the S/C to D/W by the hydrogen inflows to the S/C.

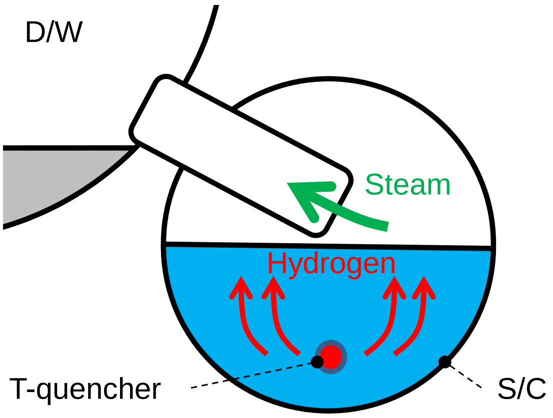


Figure 3 Steam behavior in the S/C when hydrogen gas flowed in

The following two extreme cases were assumed, as it is unknown to what extent the steam pressure was below the saturation vapor pressure.

Case A: S/C in a gas-liquid equilibrium state (steam pressure = saturation vapor pressure)

The nitrogen partial pressure was set at 0 by assuming that all of the nitrogen gas had moved to the D/W. The steam partial pressure was set at about 270 kPa (about 42% of total pressure) by assuming that the saturation vapor pressure at the S/C gas temperature had remained in the S/C. The hydrogen partial pressure was set at about 367 kPa (about 58% of total) by subtracting the steam partial pressure from the total.

Case B: S/C in a gas-liquid non-equilibrium state (steam pressure = 0)

The nitrogen partial pressure was set at 0 by assuming that all of the nitrogen gas had moved to the D/W. The steam partial pressure was also set at 0 by assuming that all of the steam had been pushed out of the S/C to the D/W by hydrogen. As a result, the gaseous phase in the S/C became filled by hydrogen (637 kPa).

It is considered that additional steam and hydrogen were produced at about 10:00 when part of the molten debris was relocated into the lower plenum, and caused the PCV pressure increase, as being pointed out in “(2) b. Estimation of gas temperatures”. This additional production of steam and hydrogen is not taken into account in the analysis in Section 3.2. But it is believed that this does not influence the conclusions of the current study because the gaseous volume fractions in the PCV have little influence on the vent gas fraction which flows to Unit-4 R/B.

3.2. Analysis of vent gas flows to Unit-4 R/B

The thermal-hydraulic analysis code GOTHIC was used to evaluate the fraction of Unit-3 vent gases and the amount of hydrogen gas flowing into Unit-4 R/B, with the influence of actual piping lengths, piping diameters and bending configuration being considered.

(1) Configuration for analysis

The Unit-3 PCV, vent lines of Unit-3 and Unit-4, and the stack were configured in the modelling for analysis. Figure 4 illustrates the configuration for GOTHIC analysis.

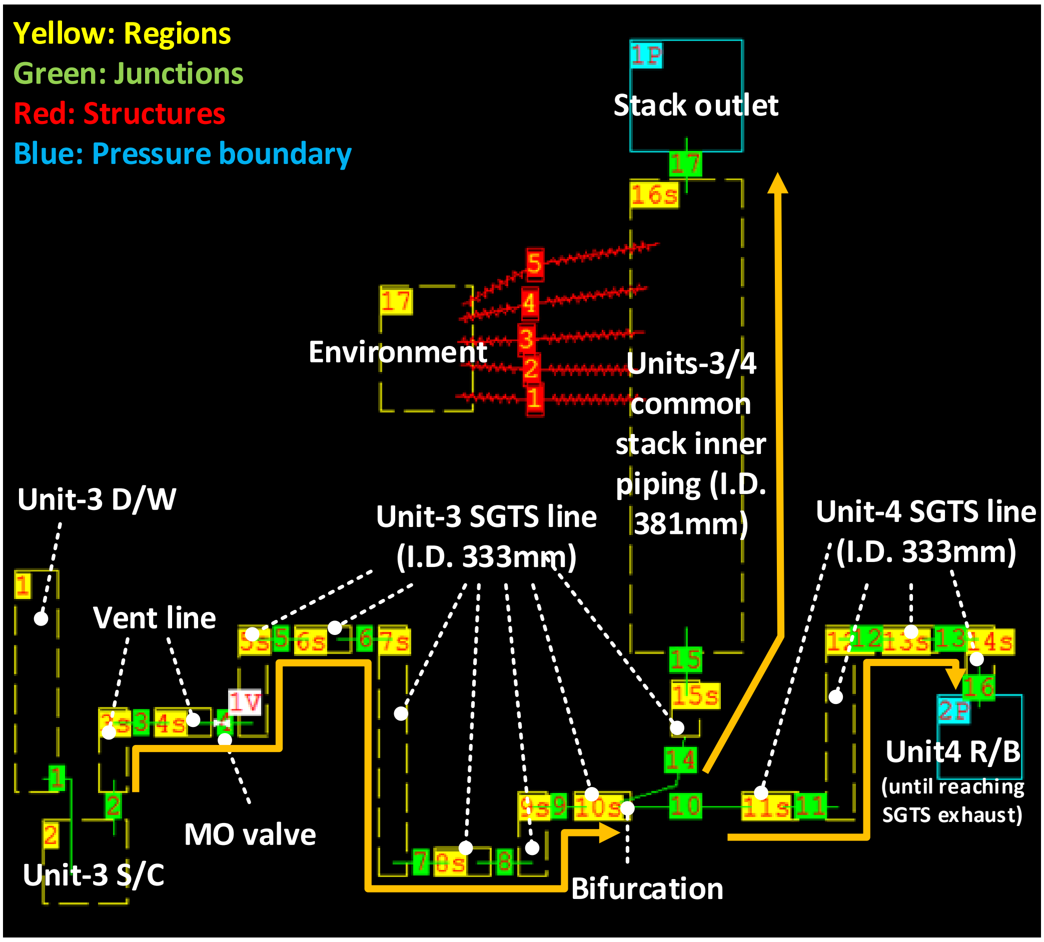


Figure 4 Configuration for GOTHIC analysis

Since check valves were installed at the outlet of the SGTS filter trains at Unit-3, this would have limited the reverse flow of vent gases back to Unit-3. Therefore, the vent gas reverse flow paths to the Unit-3 R/B were not included in the analysis. Concerning vent gas flow paths to Unit-4 R/B, the SGTS piping was connected to the ventilation ducts in the building via the SGTS filter trains in between. In the analysis, the configuration up to the SGTS filter train exit (near the SGTS exhauster) was incorporated in the modelling.

The PCV volume, diameters and lengths of venting lines and stack were taken from the design data. Venting line configurations were integrated in the analysis into simplified horizontal lines and vertical lines, although they were actually more complicated. The simplification facilitated modelling and saved computation time.

Fractions of vent gas flows to the stack and Unit-4 R/B depend on the pressure loses in the piping downstream from the bifurcation. Pressure losses in the piping have two components: frictional pressure losses due to friction between vent gases and piping inner walls; and localized pressure losses at pipe bends, and at pipe enlargement or reduction sections. To calculate the frictional pressure losses accurately, including velocity dependency, piping diameters and lengths were modelled from the design data. The localized pressure losses at pipe bends and pipe enlargement or reduction sections were calculated by simulating the paths in the form of respective pressure loss coefficients, while the localized pressure losses downstream from the Unit-4 SGTS filter train exit (SGTS filter train, ventilation ducts, etc.) were calculated by setting a localized pressure loss coefficient before reaching the Unit-4 R/B pressure boundary (near the SGTS exhauster).

The vent valve (MO valve) aperture was set at 15% based on the operational records [1]. As the pressure boundary conditions, atmospheric pressure was set on the Unit-4 R/B side, and the pressure loss due to the stack height was taken into account for the stack exit side.

On the other hand, heat releases to the environment were also taken into account by modelling the stack as heat structures in calculating the heat transfer in order to evaluate the impacts of condensed steam in the vent gases on the flow.

(2) Conditions for analysis

The time period of 09:10 to 11:00 on March 13 was chosen for analysis, this being from the time when the first venting had started at Unit-3 to the time when the PCV pressures had decreased and stabilized. The AO (large) valve on the vent line was assumed to have been open during this period.

Table 2 summarizes the key conditions for analysis. The initial conditions (pressures, air temperatures and gas compositions) of D/W and S/C were set from the estimations in Section 3.1. Two cases were analyzed: the case of small hydrogen inventory in the S/C at the time of vent initiation (Case A); and the case of large hydrogen inventory (Case B).

The S/C pool water level at the time of vent initiation is unknown, and was assumed in the analysis to have been at the S/C mid-height (roughly at the normal level). The S/C pool water level determines the free volume in the S/C, which, when combined with the partial gas pressures estimated in Section 3.1, determines the gas inventory in the PCV at the time of venting. The impacts of the assumed S/C pool water level on the results of analysis are discussed later in “(3) g. Hydrogen inventory having flowed into Unit-4 R/B.”

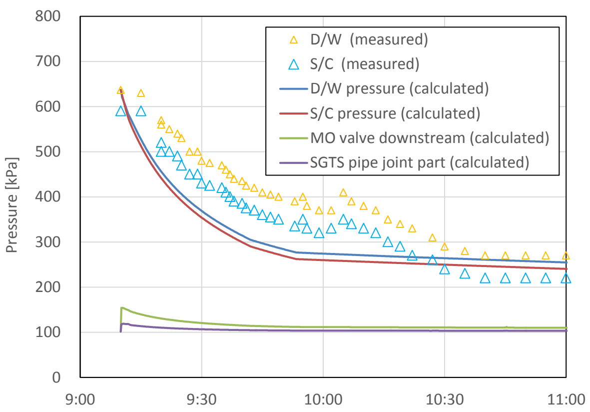
Table 2 Conditions for analysis

Item	Conditions for analysis	Remarks
Period analyzed	09:10 to 11:00 on March 13, 2011 (First venting at Unit-3)	From when the PCV pressure started to decrease to when it was roughly stabilized
D/W initial conditions	637 kPa[abs]; 135 deg C N_2 35%; Steam 50%; H_2 15% (Hydrogen inventory about 240 kg)	See Section 3.1 (1)
S/C initial conditions	637 kPa[abs]; 130 deg C; Water about 3000 m^3 <u>Case A: S/C in gas-liquid equilibrium</u> N_2 0%; Steam 42%; H_2 58% (Hydrogen inventory: about 670 kg in S/C, about 910 kg in PCV) <u>Case B: S/C in gas-liquid non-equilibrium</u> N_2 0%; Steam 0%; H_2 100% (Hydrogen inventory: about 1170 kg in S/C, about 1410 kg in PCV)	See Section 3.1 (2)
Initial conditions at other locations	Atmospheric pressure; 10 deg C; Air 100%	Pressure loss due to stack height taken into consideration at the stack exit pressure boundary

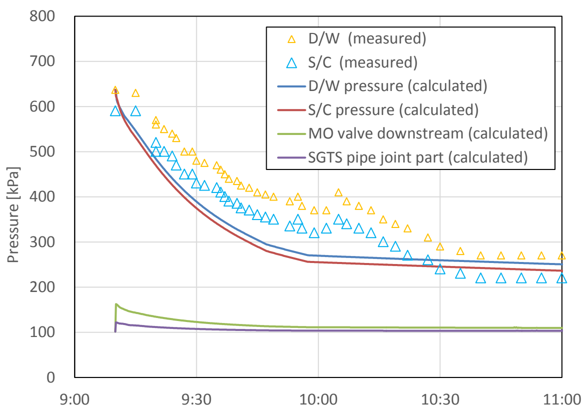
(3) Results of analysis

a. Pressures in PCV and vent lines

Figure 5 shows the measured PCV pressures, and the PCV and vent line pressures obtained from the analysis. In both Cases A and B, the PCV pressure decreasing trend and the lowest limit during the period are reproduced. Vent line pressures downstream from the MO valve (a narrowed section on the flow path) dropped very quickly and as a result the pressure at the SGTS line junction is about the atmospheric pressure (roughly 120 kPa or below).



Case A



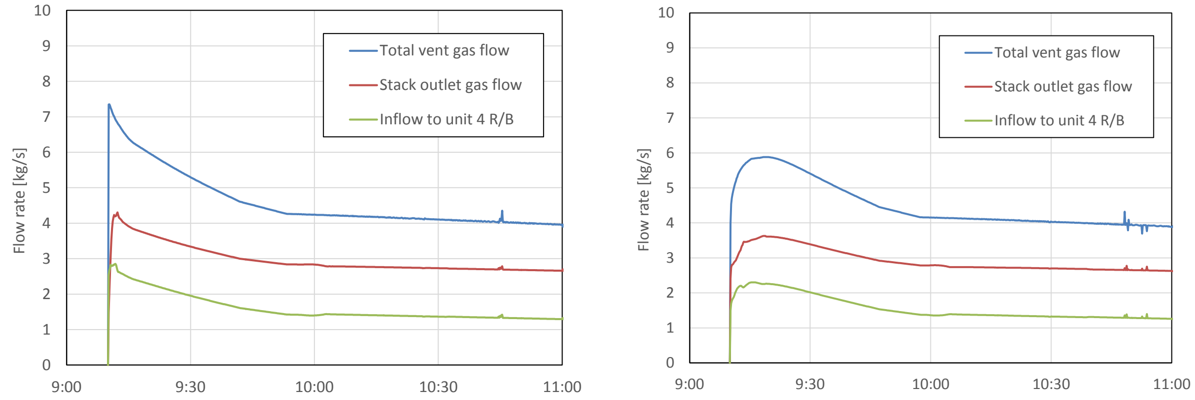
Case B

Figure 5 PCV pressures and vent line pressures

b. Vent gas flow rates

Figure 6 shows the vent gas flow rates at selected positions on the vent line. The fraction of vent gases which flowed into the Unit-4 R/B are discussed later in "(3) f. Fraction of vent gas having flowed into Unit-4 R/B."

It should be noted that the flow rate behavior just after the onset of venting is different in Case A and in Case B. In Case A, steam is contained in the S/C at the time of vent initiation, while in Case B the S/C is filled with lower density hydrogen and consequently flow rates just after the onset of venting are lower than in Case A. It is considered that the steam fraction increases in the S/C, thereafter, with hydrogen being released and the gas compositions approach the same value (see Figure 8) in both Cases A and B, irrespective of different initial conditions, and with the increasing density of the vent gases, the flow rates in Case B eventually approach the flow rates in Case A.

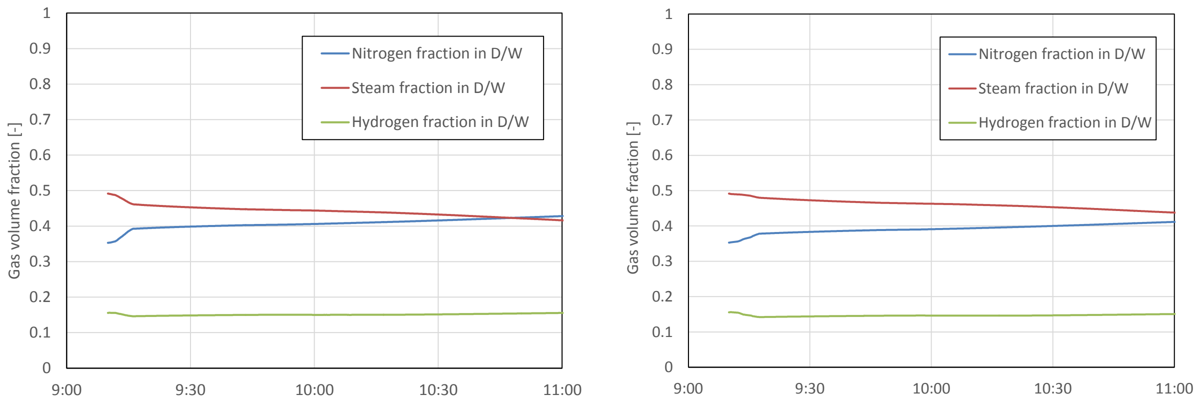


Case A　　　　　　　　　　　　　　　　Case B

Figure 6　Flow rates in vent lines

c.　Gas volumetric fractions in D/W

Figure 7 shows gas volumetric fraction changes in the D/W. No big changes are noticeable in the fraction of hydrogen in the D/W during the venting in either case. Since the D/W pressure is itself decreasing, the hydrogen is being released in the vent gas via the S/C in proportion to the pressure decrease.



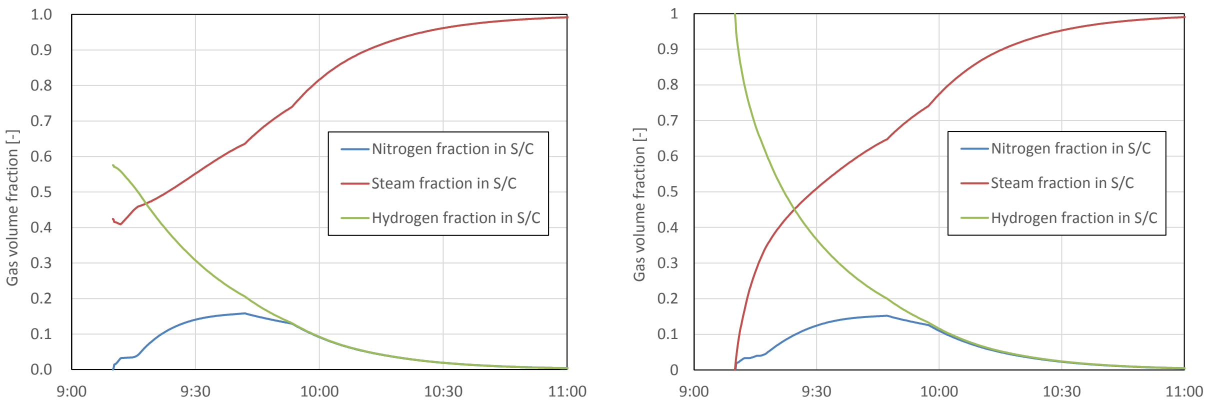
Case A　　　　　　　　　　　　　　　　Case B

Figure 7　Gas volumetric fraction changes in D/W

d.　Gas volumetric fractions in S/C

Figure 8 shows gas volumetric fraction changes in the S/C. During the venting, the D/W gases are vented via the S/C, and therefore the nitrogen volumetric fraction in the S/C increases temporarily at the beginning but is released together with hydrogen as the pressure decreases. The steam fraction increases with time because the steam continues being produced from the S/C pool to keep the saturation vapor pressure at the S/C temperature.

In both Cases A and B, hydrogen is almost completely released by about 11:00. In the current study, the AO (large) valve was assumed to have been open. But the figure shows that hydrogen in the S/C was almost completely discharged by about 10:40 even if the AO (large) value had been closed at that time.

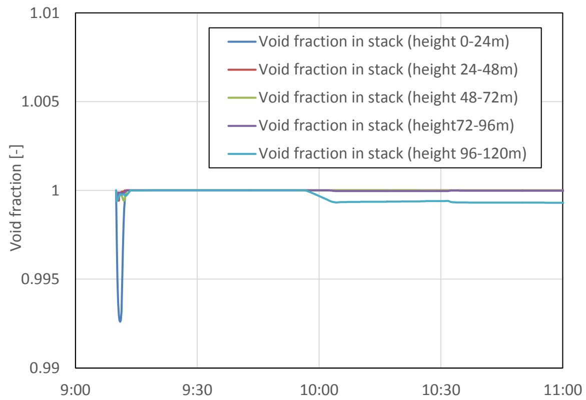


Case A　　　　　　　　　　Case B

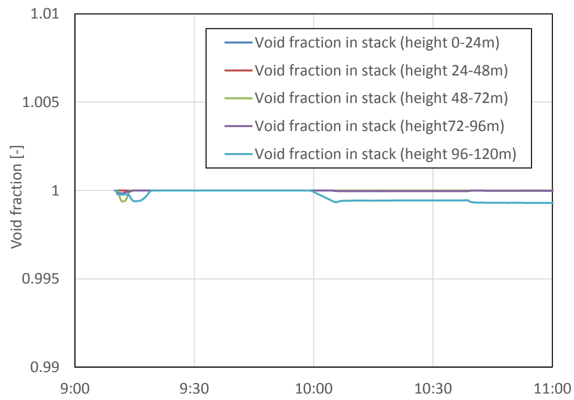
Figure 8　Gas volumetric fraction changes in S/C

e.　Gas volumetric fraction changes in the stack

Figure 9 shows gas volumetric fractions in the stack. Immediately after the vent initiation, the vent gases in the stack were condensed by transferring heat to the stack structures, but once the structures were warmed enough, heat transfer was minimized, and no more significant condensations occurred. In both cases, the gas volumetric fractions were constantly above 99% during the venting. The influence of condensation of vent gases on the vent gas flows is negligible.



Case A



Case B

Figure 9 Gas volumetric fraction changes in the stack

f. Fraction of vent gas having flowed into Unit-4 R/B

Figure 10 shows the fraction of vent gases that flowed into the Unit-4 R/B. The fractions were about 35% in both cases, irrespective of gaseous partial pressures in the PCV.

The earlier study of TEPCO [1] evaluated that about 29% of all the vent gases had flowed to Unit-4. The result of the current study is close to this earlier result but there is a discrepancy of several percent. The difference is considered to come mainly from the different approaches to obtain the pressure losses at the piping bend section. In the earlier study, the piping bend section was modelled as a sharp elbow as illustrated in Figure 11 (A), while in the current study it was modelled as a curved bend as in Figure 11 (B) to simulate the section as realistically as possible. The pressure losses at this section are lower in the current study than in the earlier study. As seen in Figure 1, the SGTS line of Unit-4 had many bends. As the result, the vent gas flows to Unit-4 are considered to have been facilitated more in the current study than in the earlier study.

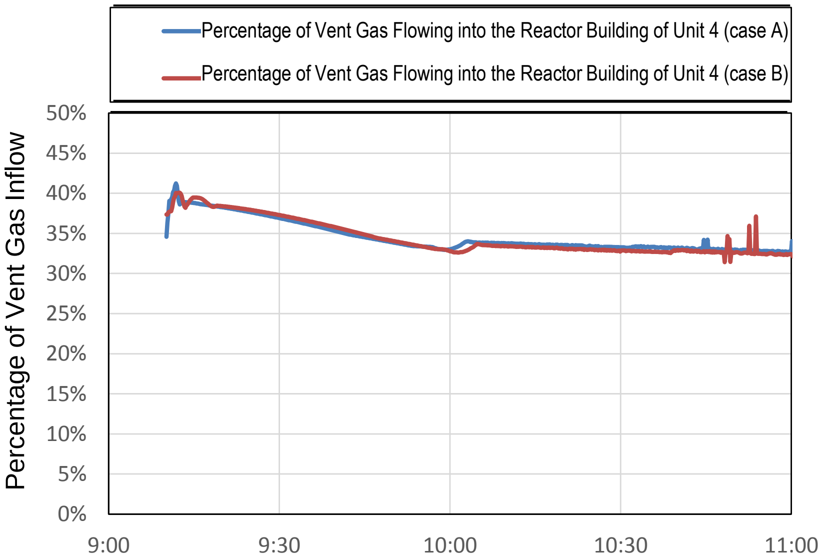


Figure 10 Fraction of vent gas that flowed into Unit-4 R/B

(A) Elbow (B) Bend

Figure 11 Modelling of piping bend section

g. Hydrogen inventory having flowed into Unit-4 R/B

Figure 12 presents the total amount of hydrogen that flowed into the Unit-4 R/B; about 300 kg in Case A, and about 500 kg in Case B. The initial steam fraction in the S/C is considered to have been between the steam fractions of Case A and Case B. The real amount of hydrogen that flowed into the Unit-4 R/B can be also considered to have been between the total amounts above in Case A and Case B.

It should be noted that the S/C pool water level at the time of venting could have been higher than the S/C mid-height (roughly at the normal level) assumed in the current study. As shown in Figure 13, the S/C water levels were recorded until 20:00 on March 12 (about 13 hours before the venting). The S/C water level could have even increased from the last recorded level, because the S/C spray continued after the final recording and the steam from the RPV might have condensed. The S/C water levels might have decreased, on the contrary, if the S/C water temperatures decreased or gaseous leakage occurred from the PCV. It becomes necessary to clarify the scenario based on the examination of reliabilities of measured S/C water levels, and consistency with PCV pressures and other parameters.

If the S/C water level is to change, the S/C free volume is to change, the hydrogen amount to reproduce the measured PCV pressures is to change, and hence the amount of hydrogen, about 300 to 500 kg, estimated above has uncertainties.

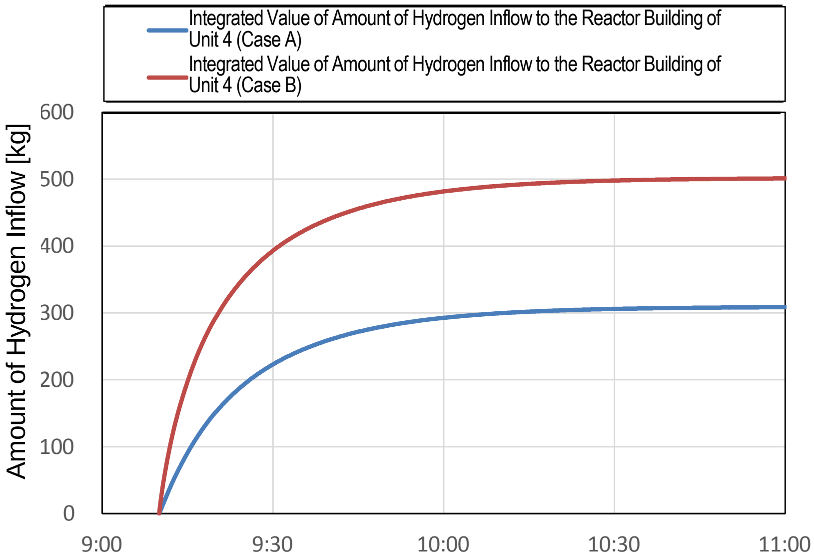


Figure 12 Total amount of hydrogen flows into Unit-4 R/B

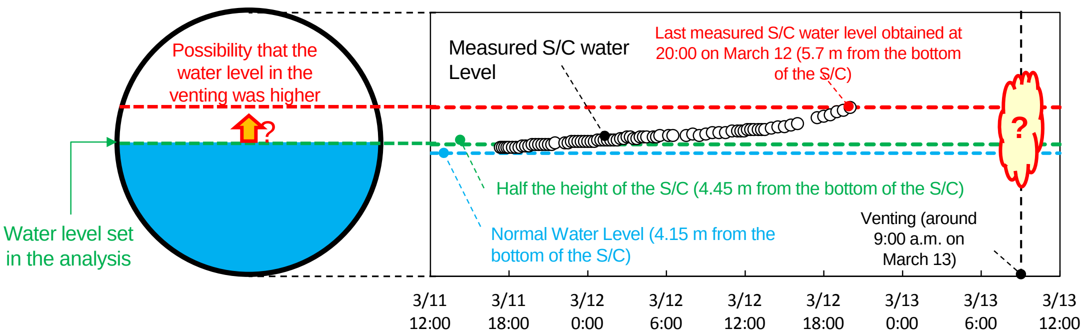


Figure 13 S/C water levels at the time of venting

4. Conclusion

Upon estimating in-PCV conditions at Unit-3 based on measured plant parameters, Unit-3 vent gas behavior was analyzed using a thermal-hydraulic analysis code. About 35% of the hydrogen-rich vent gases was estimated to have flowed into the Unit-4 R/B.

The high likelihood was reconfirmed that these hydrogen-rich vent gases had caused the explosion of Unit-4 R/B.

5. Implications of safety measures at the Kashiwazaki-Kariwa Nuclear Power Station

The current study has reaffirmed that measures are required to prevent the vented gas flows in reverse to buildings upon PCV venting (independence of vent lines must be secured).

The filtered vent lines to be newly installed at the reactor units at Kashiwazaki-Kariwa Nuclear Power Station share no lines with other units and each line is isolated from any other lines of its own unit (Figure 14). Thus, the vent line independence is secured, and no vent gas flows into the R/B will occur upon the PCV venting.

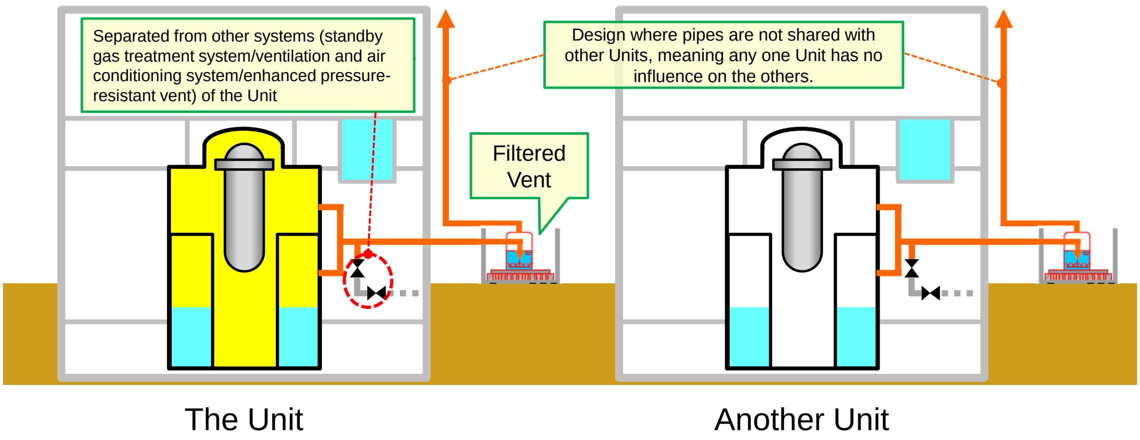


Figure 14 PCV vent lines at Kashiwazaki-Kariwa Nuclear Power Station

References

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[3] Masao Ogino (JNES), “Study on the Issues about Hydrogen Explosion at Fukushima Dai-ichi NPS”, Technical Workshop on TEPCO’s Fukushima Daiichi NPP Accident Handouts, Tokyo, Japan (July 24, 2012)

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