Analysis of the hydrogen explosion at the Unit-1 Reactor Building

1. Introduction

A hydrogen explosion occurred on March 12th, 2011 at the Unit-1 Reactor Building (hereafter the “R/B” in this Attachment). Among possible leak paths for hydrogen to the R/B, it is considered to be likely that hydrogen leaked out to Floor 5 from the top head flange of the containment vessel (hereafter “PCV”) via the shield plug, and exploded, since the dose rate of R/B Floor 5 was relatively high. This additional study was conducted to confirm the above scenario.

In the study, the hydrogen explosion was analyzed with the sites of both hydrogen leakage and ignition, and other factors as parameters. The analysis results were compared with the R/B damage conditions for estimating the hydrogen explosion development at Unit-1. A separate case was also analyzed[1], in which hydrogen was assumed to have leaked to Floor 4 from the isolation condenser (hereafter “IC”) piping, since a possibility of IC piping having been damaged was pointed out at the Discussion on Individual Issues of Fukushima Accident Investigation in Niigata Prefecture Technical Committee [Impacts of Seismic Motion on Equipment of Importance[2]]. Figure 1 is an image of hydrogen leak paths assumed in this study.

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[1] Direct leaks from IC piping outside the PCV to the R/B were assumed in the analysis, without specifying a damage mode. Other probable leak paths, if the IC piping is damaged, will be from the heat transfer tubes in the IC tanks (damaged by the ground motion), or from the piping near the reactor pressure vessel (RPV) in the PCV (damaged by elevated temperatures, for instance). In such damage cases, the hydrogen leaks directly to outside the R/B or inside the PCV, respectively. In either case, no hydrogen explosion could be caused.

[2] The results of this study have been reported to the 9th to 11th sessions of Discussion on Individual Issues of Fukushima Accident Investigation in Niigata Prefecture Technical Committee [Impacts of Seismic Motion on Equipment of Importance]

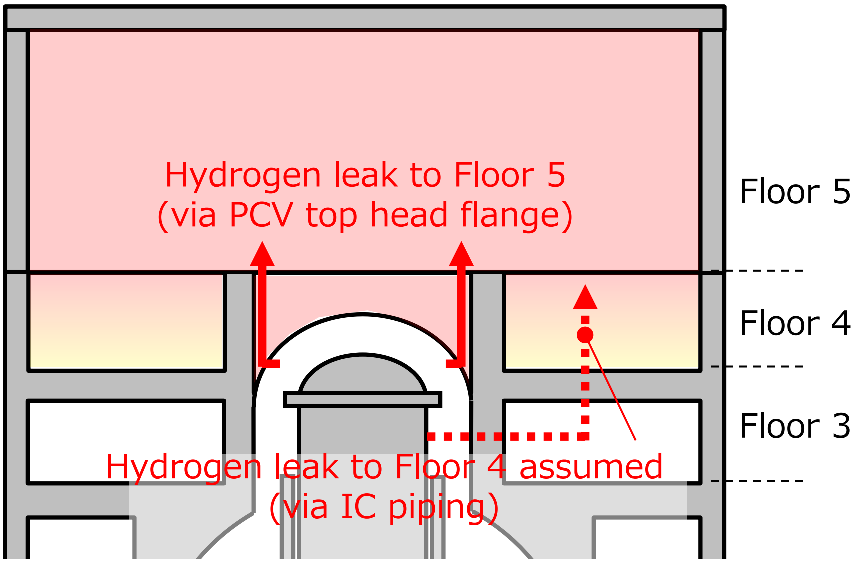


Figure 1 Image of hydrogen leak paths to the R/B

2. Hydrogen explosion analysis

Hydrogen explosions occurred at Unit-1, Unit-3 and Unit-4 of the Fukushima Daiichi Nuclear Power Station. In none of these explosions are the sites and amounts of hydrogen leaked, and the sites of the ignition known. It is extremely difficult to reproduce by analysis the explosion development in detail at the times of the explosions. But it would be possible to estimate a probable scenario of the hydrogen explosions, which could explain the explosion development not inconsistent with the R/B damage conditions. With this background, several cases of analysis were conducted, in which the sites of hydrogen leaks and ignition were changed as a parameter. Specific features of each case were derived and compared with the R/B damage conditions. This is the background of analyses in the current study addressing the hydrogen explosion at Unit-1.

Two scenarios were assumed: hydrogen leaked only from the shield plug on Floor 5 of the R/B; and hydrogen also leaked, in addition, from the IC piping on Floor 4 as pointed out by the Discussion Panel. In each scenario, spreading of the hydrogen leaked in the R/B and its eventual explosion were analyzed. Two sites of ignition were assumed, on Floor 5 and on Floor 4 (see Table 1 in 2.2 Conditions for analysis for details). The hydrogen propagation and explosion analysis code FLACS [1] was used. In the analysis, the site of leakage was assumed first, the hydrogen propagation was analyzed; the site of ignition was then assumed, and the explosion was analyzed.

It should be noted that leaked gases other than hydrogen, such as steam, were not considered in the analysis. Actually, steam is considered to have leaked, too. When the steam fraction in the leaked gas increases, the scale of the explosion becomes generally smaller. Therefore, if the scale of the actual explosion at Unit-1 is in the same order as the analysis results, the amount of hydrogen actually leaked will be more than the amount assumed in the analysis. Further, possible impacts of deformed structures on the explosion blast paths were not considered in the analysis except for some selected structures which might have significant impacts on the explosion development. These items not considered in the analysis may have some influences on the explosion conditions, but that would not affect the conclusions of this study, as the study aims at obtaining overall characteristics of the explosion.

2.1. Configuration for analyses

The whole R/B (from Basements to Floor 5) was included in the analysis to evaluate the explosion impacts in the whole R/B. The analysis included a certain space outside the R/B, too, so that the impacts of the air blast from the R/B could be taken into account.

Figure 2 and Figure 3 present plan views of Floor 5 and Floor 4 of the R/B, where major structures were placed (equipment hatch cover and south corridor wall on Floor 5; IC tank, ventilation ducts, etc. on Floor 4), so that the impacts of structures present on the explosion development could be taken into account. The equipment hatch is a hole penetrating the R/B from Floor 1 to Floor 5 for transferring equipment when needed, and the hatch on the floor of Floor 5 was closed with a cover at the time of the explosion. As major flow paths for hydrogen diffusion and combustion propagation, stair case openings, ventilation ducts, fuel pool ducts and gaps around the equipment hatch were modeled in the analysis. The mesh width of 50 cm was set in the analysis so that the distribution of hydrogen concentrations and the explosion could be appropriately evaluated.

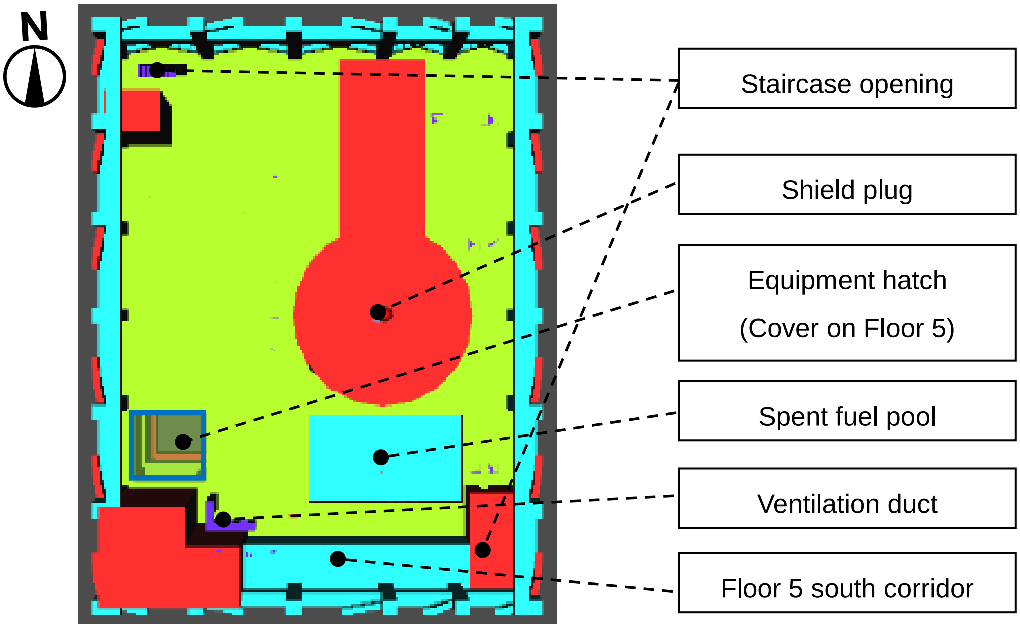


Figure 2 Plan view of R/B Floor 5

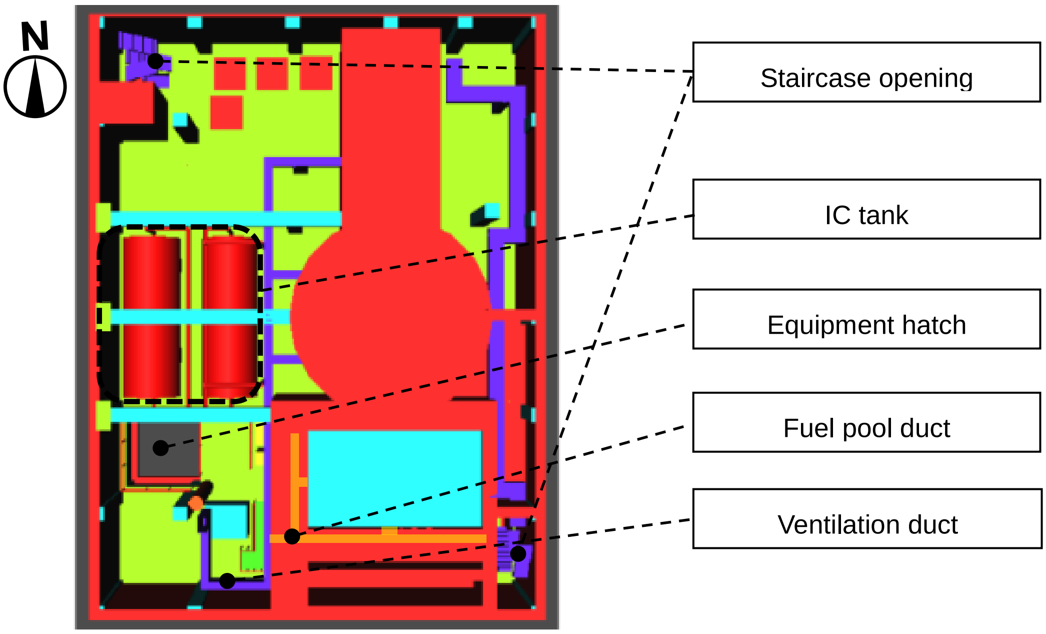


Figure 3 Plan view of R/B Floor 4

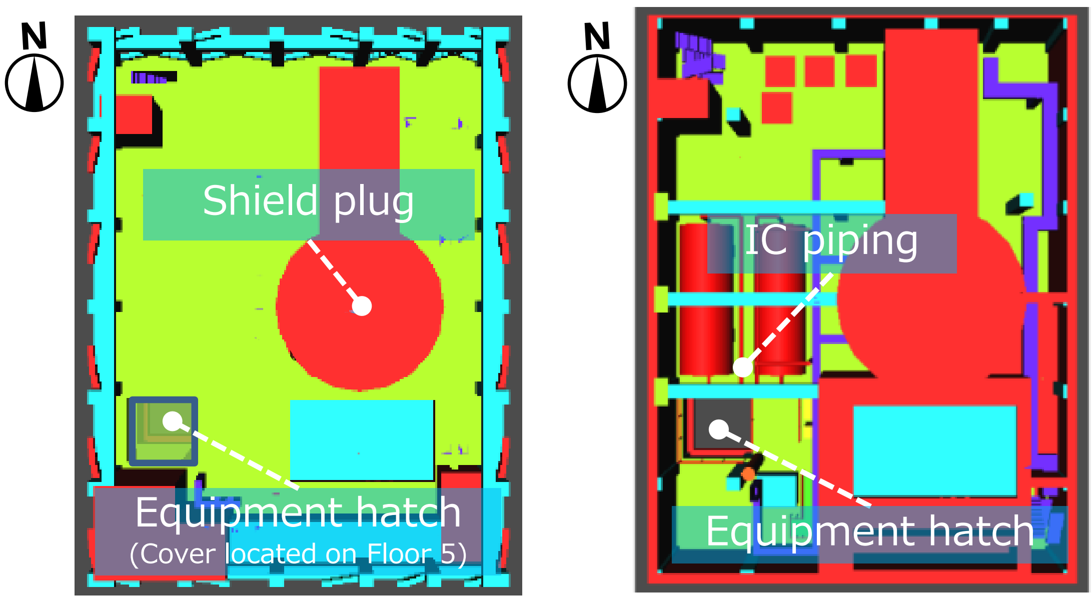
2.2. Conditions for analysis

(1) Cases of analysis

Table 1 presents the cases of analysis. Figure 4 illustrates the sites of leakage and ignition that were assumed.

Table 1 Cases of analysis

	Case ① Leak on Fl. 5 Ignition on Fl. 5	Case ② Leaks on Fl. 5+4 Ignition on Fl. 4	Case ③ Leaks on Fl. 5+4 Ignition on Fl. 5	Case ④ Leak on Fl. 5 Ignition on Fl. 4
Site of Leakage	Shield plug on Fl. 5	Shield plug on Fl. 5 ＋IC piping on Fl. 4	Shield plug on Fl. 5 ＋IC piping on Fl. 4	Shield plug on Fl. 5
Amount of Hydrogen Leaked	About 134 kg	About 154 kg (Case ①＋20 kg from IC piping on Fl. 4)	About 154 kg (Case ①＋20 kg from IC piping on Fl. 4)	About 210 kg
Site of Ignition	Right above shield plug on Fl. 5	Near ceiling on Fl. 4 (Right under equipment hatch cover)	Right above shield plug on Fl. 5	Near ceiling on Fl. 4 (Right under equipment hatch cover)



(A) R/B Floor 5 (B) R/B Floor 4

Figure 4 Sites of leakage and ignition assumed

Amounts of hydrogen leaked in each case in Table 1 were set from the results of hydrogen distribution analyses. The methodology is as follows.

Two cases were defined concerning the amounts of hydrogen leaked from the shield plug on Floor 5, based on the results of hydrogen distribution analysis; about 134 kg in

Cases ① to ③; and about 210 kg in Case ④. The former (about 134 kg) was set for a situation in which the hydrogen was distributed mostly on Floor 5 only, while the latter (about 210 kg) was set for a situation in which the hydrogen migrated down to Floor 4 in amounts adequate for ignition, but not to Floor 3 and below. The basis for this setting was that no significant damage to structures due to a hydrogen explosion was recognized on Floor 3 and below.

The amount of hydrogen leaked from the IC piping on Floor 4 in Cases ② and ③ was set as 20 kg. If gas leaks occur from the IC piping on Floor 4, the gas leaks from the RPV to the R/B. However, as shown in Attachment 1-3, no signs of such a leak were noticed in the plant parameters at an early stage of the accident progression. The amount of hydrogen leaked from the IC piping was estimated at about 40 to 200 kg based on: the leak size of 0.3 cm^2 assumed as the value, which gave no impacts on plant parameters; the amount of hydrogen generated in the core being assumed as 800 kg, by referring to the results by the accident analysis code; and the correlation between the reactor pressure and leak size given in the MAAP analysis results (Attachment 3). It was straightforward, however, that, if this amount of hydrogen (about 40 to 200 kg) had leaked from the IC piping on Floor 4, the hydrogen concentration would become very high on Floor 4, and the analysis results would be inconsistent with the R/B damage conditions. Consequently, the amount of 20 kg, less than the above value, was set as the amount leaked.

(2) Damage conditions of structures

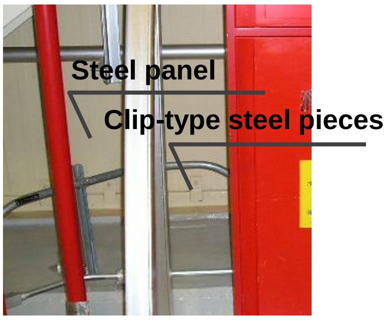
The hydrogen explosion at Unit-1 R/B blew off the Floor 5 side wall and dropped the ceiling. The cover of the equipment hatch was in place on Floor 5 at the time of the accident, but the cover has not been located to date. Since the presence or absence of the Floor 5 side wall and equipment hatch cover are considered to have a large impact on the explosion development, their damage during the course of the explosion was addressed in the analysis. Explained below in a. and b. are setting of the damage conditions of structures.

Concerning the ceiling of Floor 5, its impacts on the explosion development are considered minor for the following reasons: the ceiling slab dropped as a single body, and that was confirmed on site as the actual damage situation, and it seemed unlikely to have been blown off due to internal pressures; the ceiling on Floor 5 had higher resisting strength against inner pressures than the side wall, and therefore was likely to have been damaged later than the side wall; and the explosion was considered to have terminated the pressure build-up as soon as the side wall was blown off and the R/B pressures decreased.

a. Floor 5 side wall

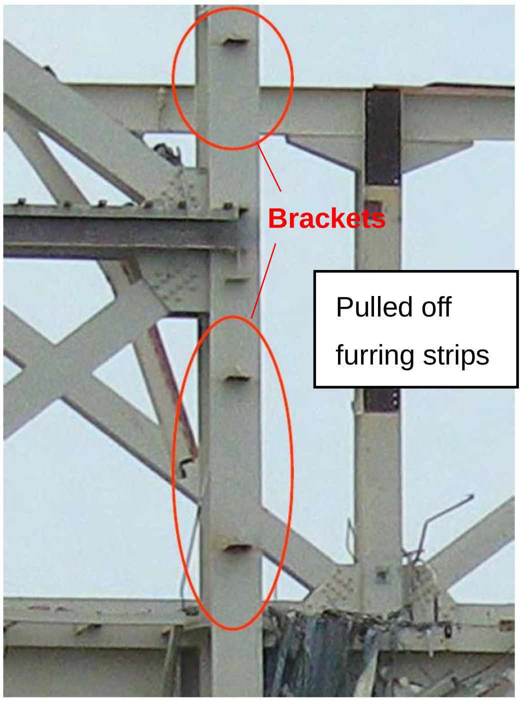
Figures 5 (A) to (C) show joints of the Floor 5 side wall and the R/B. The side wall of Floor 5 was made of steel panel and fixed to furring strips by dedicated clip-type steel pieces (A). The end of furring strips was fixed to brackets by two M-16 bolts (B) (C). After the hydrogen explosion, almost all furring strips were found to have been pulled off. This indicates that the bolts fixing the furring strips and brackets were damaged by the increased internal pressure (pressures of Floor 5) due to the hydrogen explosion.

As the bolt breakdown criteria, the internal pressure of 16 kPa was set. This value was derived by converting the bolt shear capacity obtained from tensile strengths of bolt material. In the analysis, the Floor 5 side wall was assumed to be damaged as soon as the Floor 5 internal pressure exceeded the criterion.



(A) Steel panel – furring strips

(B) Bolt hole at furring strip end



(C) Brackets

Figure 5 Joints between Floor 5 side wall and R/B structures

b. Equipment hatch cover

The equipment hatch cover was a foldable type as illustrated in Figure 6. It weighed 1.5 tons and its load capacity was 200 kg, the value at the weakest point which was at the hinge area at the center of the hatch cover lower face (in reality, the hinge area could break when the load of 1.5 to several times this value was added on the whole cover). The cover was opened or closed by connected wires and a winch. The cover side ends overlapped the Floor 5 floor surface and the cover could be smoothly operated for opening/closing using the wheels attached to its side ends. The hatch cover, as shown in Figure 7, was blown away and has not been found.

In the analysis, the hatch cover was assumed to have been opened and blown away by the pressure difference between Floor 4 and Floor 5. In a case of higher pressure for Floor 4 than for Floor 5, the cover was assumed to open when the pressure difference reached an adequate value to lift up the cover. In a case of higher pressure for Floor 5 than for Floor 4, the cover might be deformed and opened by the pressure applied from Floor 5[3], but such a pressure value is not known. Four different pressure values were applied to the cover from above in a sensitivity analysis: 10%, 30%, 50% and 80% of the pressure to destroy the Floor 5 side wall. In the 80% pressure analysis, the cover did not open before the Floor 5 side wall broke and almost no blast appeared on Floor 4 and below. This situation is inconsistent with the actual R/B damage conditions as described later. In all other cases, the explosion development was similar. In the analysis, the pressure difference to open the hatch cover was set at about 5 kPa, 30% of the pressure to destroy the Floor 5 side wall. This value is equivalent to about 70 times the allowable load capacity (200 kg mentioned above) of the hatch cover. The cover is considered to have been deformed accordingly.

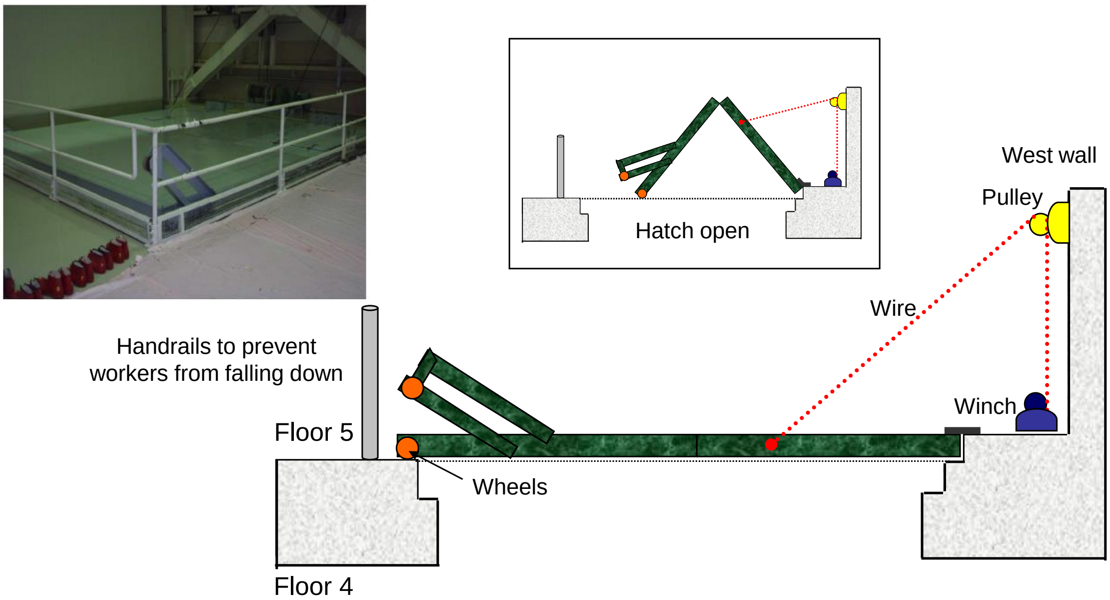


Figure 6 Configuration of equipment hatch (image)

[3] The cover might not be significantly deformed and to have been opened wide even when the hinge was damaged. But with application of further loads, the cover deformation would be enlarged.

Figure 7 Equipment hatch after hydrogen explosion
(view from Floor 4 to Floor 5)

2.3. Results of analysis

Table 2 summarizes key features of analytical Cases ① to ④ defined in Table 1.

Table 2 Key features of each analytical case

Site of Leakage	Ignition on Floor 5	Ignition on Floor 4
Shield Plug (Fl. 5)	Case ① Equipment hatch cover opened, followed by Fl. 5 side wall being damaged, blast mainly on Fl. 4 and above	Case ④ Similar to Case ①, but slightly larger explosion scale
Shield Plug (Fl. 5) + IC Piping (Fl. 4)	Case ③ Similar explosion development, as in Case ①, followed by similar blast as in Case ②	Case ② Sharp pressure increases on Fl. 4, violent blasts on Fls. 5, 4, 3 and even 2.

Detailed results of each case are described below, in which characteristic scenes of the explosion were selected and are shown. See the TEPCO homepage for an animated film showing changes of pressures, hydrogen concentrations, temperatures and velocity in the course of the Unit-1 explosion[4].

[4] URL: http://photo.tepco.co.jp/date/2017/201702-j/170217-01j.html (in Japanese only)

(1) Case ①: Leak on Floor 5, ignition on Floor 5

Figure 8 shows the distribution of hydrogen at the time of ignition. Hydrogen is distributed mainly on Floor 5 and part of it is migrating to Floor 4 via staircase openings and gaps around the equipment hatch cover, and other openings such as ventilation ducts, for example.

The analysis results are shown in Figures 9 (A) to (E). On Floor 5 combustion developed (A) and the pressure increased (B), resulting in the equipment hatch cover being opened and downward blasts being driven to Floor 4 and below through the equipment hatch depending on the pressure difference. On Floor 3 and below small blasts occurred in the horizontal direction from the equipment hatch (C). In the meantime, the pressure on Floor 5 increased, breaking the side wall, which had low resisting strength against inner pressures, and generating horizontal blasts (D). Once the Floor 5 side wall was damaged, the Floor 5 pressure dropped, pressures on Floor 4 and below became relatively higher and the upward blasts through the equipment hatch occurred with some time delay (E).

In Case ①, the site of ignition on Floor 5 was set at the shield plug. Sensitivity calculations with different sites of ignition on Floor 5 also gave similar results regarding the explosion features.

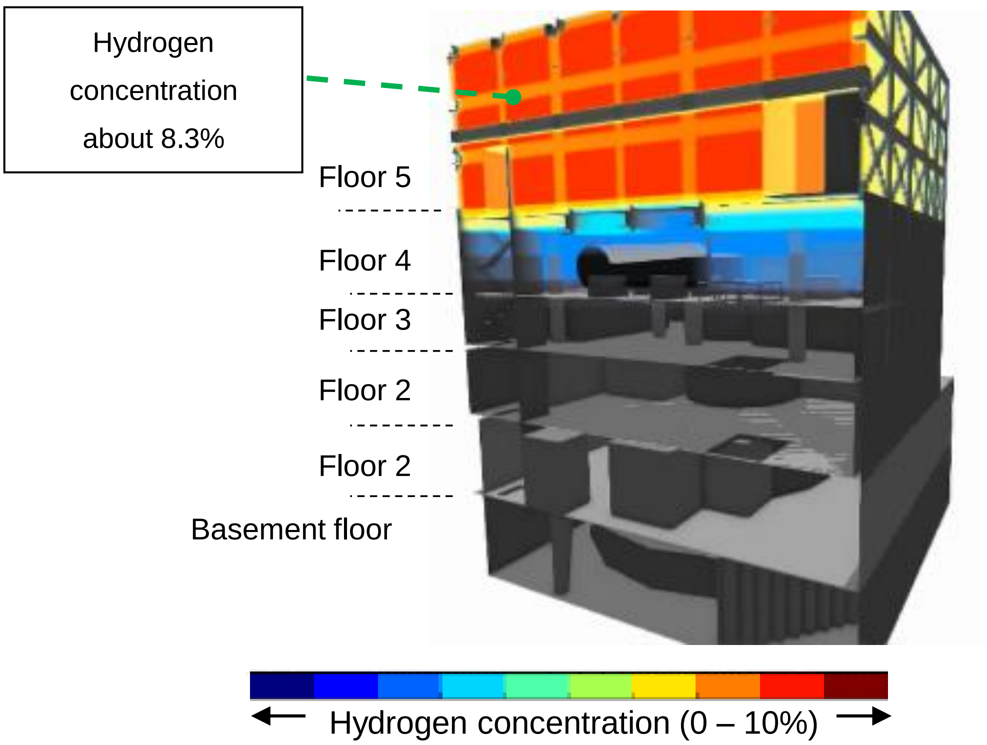


Figure 8 Distribution of hydrogen concentrations at the time of ignition
(Case ①: Leak on Floor 5, ignition on Floor 5)

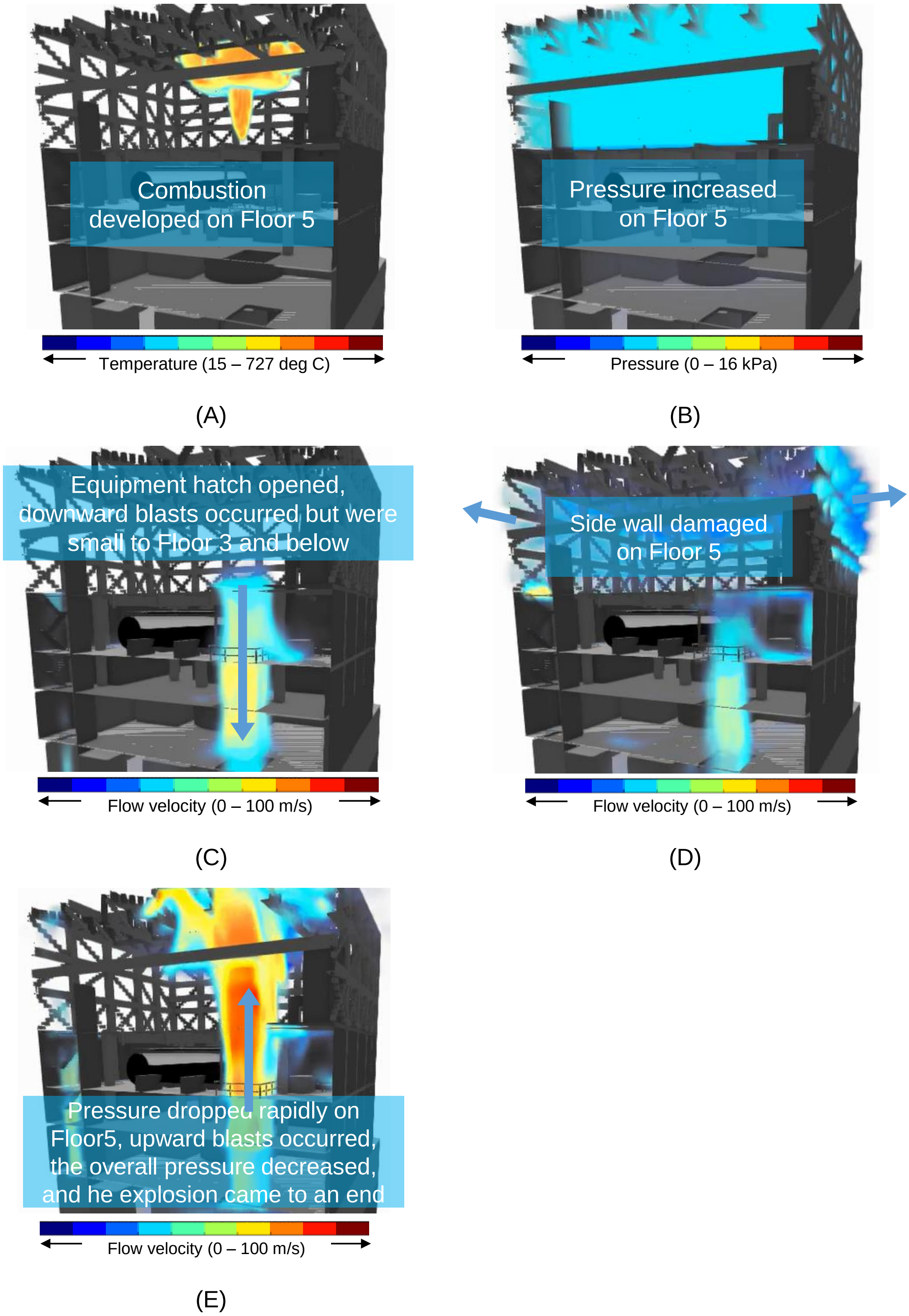


Figure 9 Results of hydrogen explosion analysis

(Case ①: Leak on Floor 5, ignition on Floor 5)

(2) Case ②: Leaks on Floor 5 and Floor 4, ignition on Floor 4

Figure 10 shows the distribution of hydrogen at the time of ignition. The hydrogen concentration on Floor 5 is the same as that of Case ① in Figure 9, although differently colored (a different color bar range was used). On Floor 4, the hydrogen concentrations on the ceiling area are relatively high near the site of leak from IC piping.

The analysis results are shown in Figures 11 (A) to (E). Upon ignition, combustion developed rapidly in the west area of Floor 4 where hydrogen concentration was high (A), and the pressure rose rapidly (B). The equipment hatch was opened by the pressure difference between Floor 4 and Floor 5; strong blasts started on Floor 4, where ignited, and moved toward the hatch opening, which was the gas escape path (C). Concurrently, strong horizontal blasts occurred on Floor 3 and below from the equipment hatch (D). On Floor 5, the ceiling and side wall broke almost simultaneously due to the violent blasts and strong upward and horizontal air flows occurred almost simultaneously (E).

When compared with the results of Case ①, the pressure rose more sharply and the blasts moved more rapidly through the R/B in Case ② (the color bar covers 0 – 100 m/s in Figure 9 for Case ①, while the color bar in Figure 11 covers 0 – 200 m/s for Case ②).

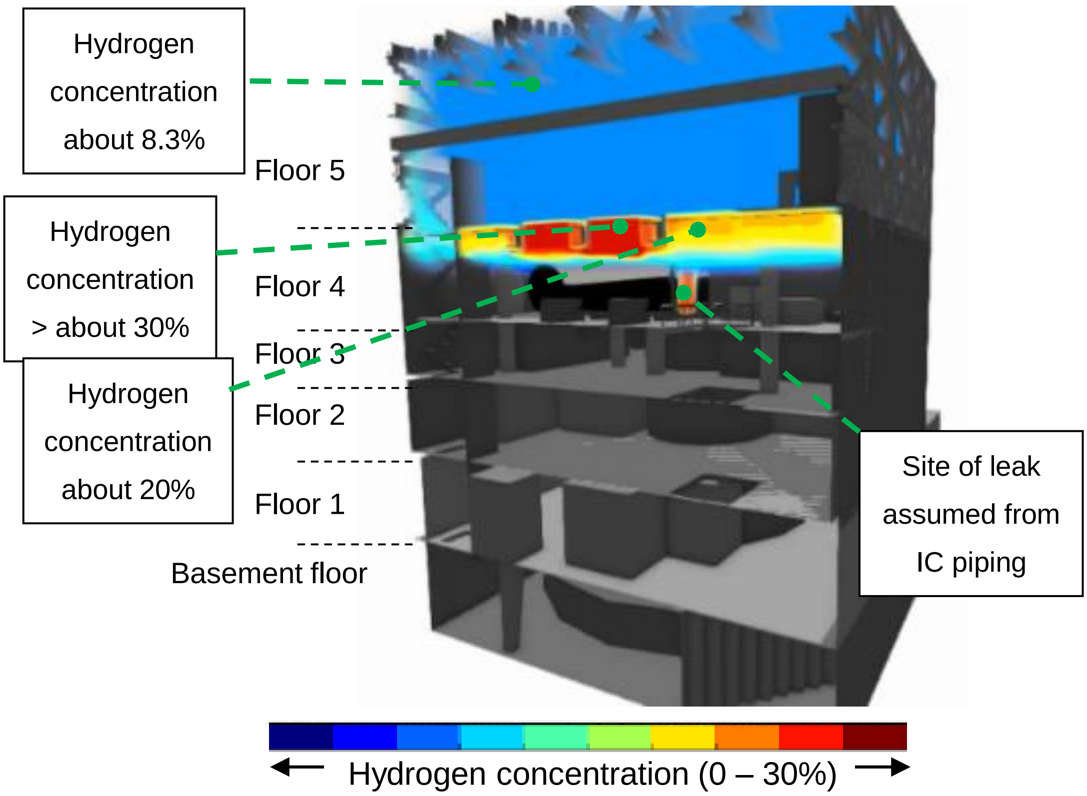


Figure 10 Distribution of hydrogen concentrations at the time of ignition
(Case ②: Leaks on Floor 5 and Floor 4, ignition on Floor 4)

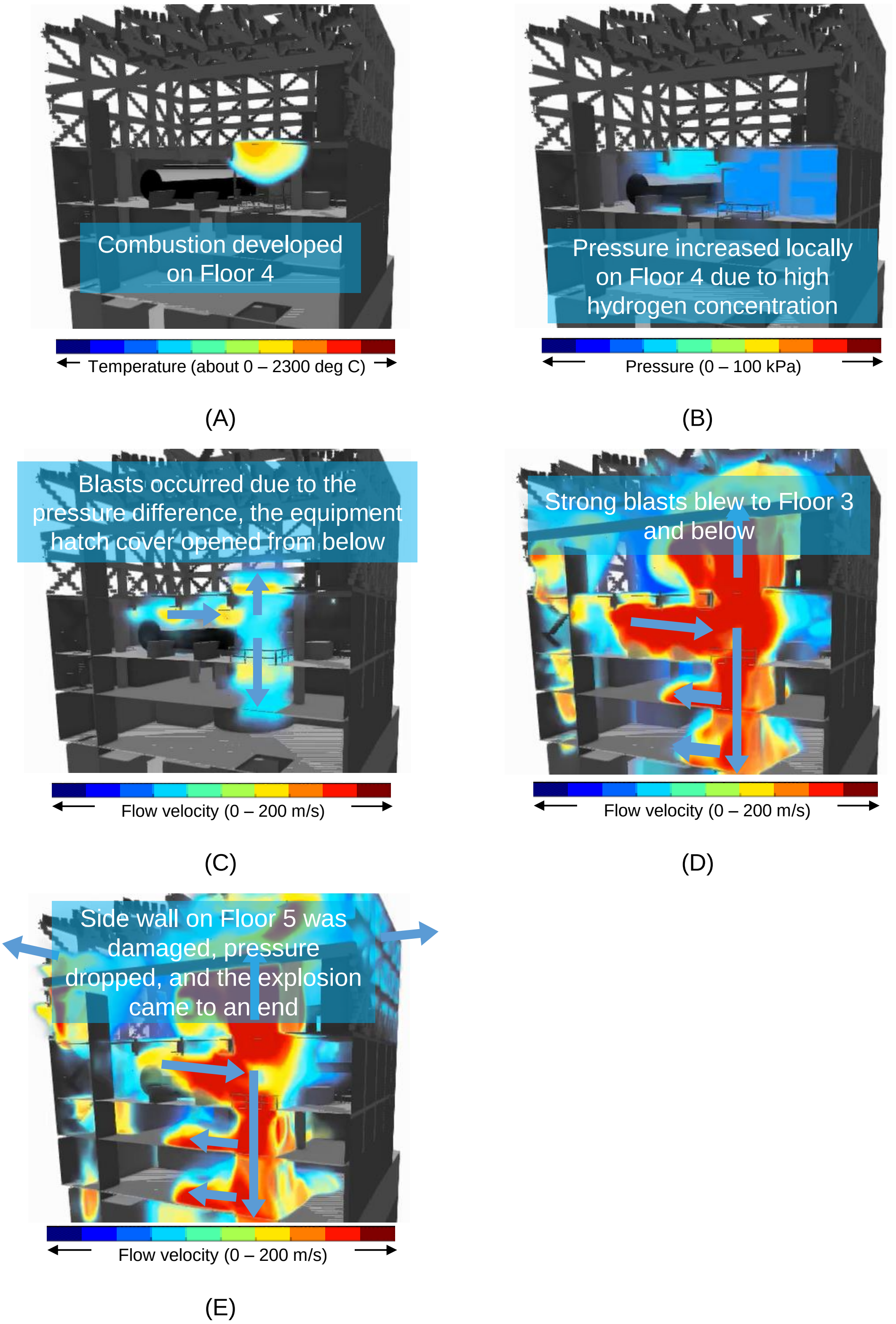


Figure 11 Results of hydrogen explosion analysis

(Case ②: Leaks on Floor 5 and Floor 4, ignition on Floor 5)

(3) Case ③: Leaks on Floor 5 and Floor 4, ignition on Floor 5

The distribution of hydrogen concentrations at the time of ignition was the same as that of Case ② (Figure 10), but the site of ignition was moved to the shield plug on Floor 5 in Case ③.

Since the distribution of hydrogen concentrations on Floor 5, where the site of ignition was assumed, is the same as that of Case ①, the explosion developed similarly to Case ① (Figures 9 (A) to (E)). Figures 12 (A) to (D) show the development after that. For a while after the development shown in Figure 9, hydrogen remained near the ceiling on Floor 4 in high concentration (A). A flare on Floor 5 ignited that hydrogen on Floor 4 (B), the pressure on Floor 4 increased locally (C), and violent blasts similar to those in Case ② were added (D). Consequently, upward blasts occurred twice through the equipment hatch.

In Case③, the site of ignition on Floor 5 was set at the shield plug. Sensitivity calculations with different points of ignition on Floor 5 also gave similar results regarding the explosion features.

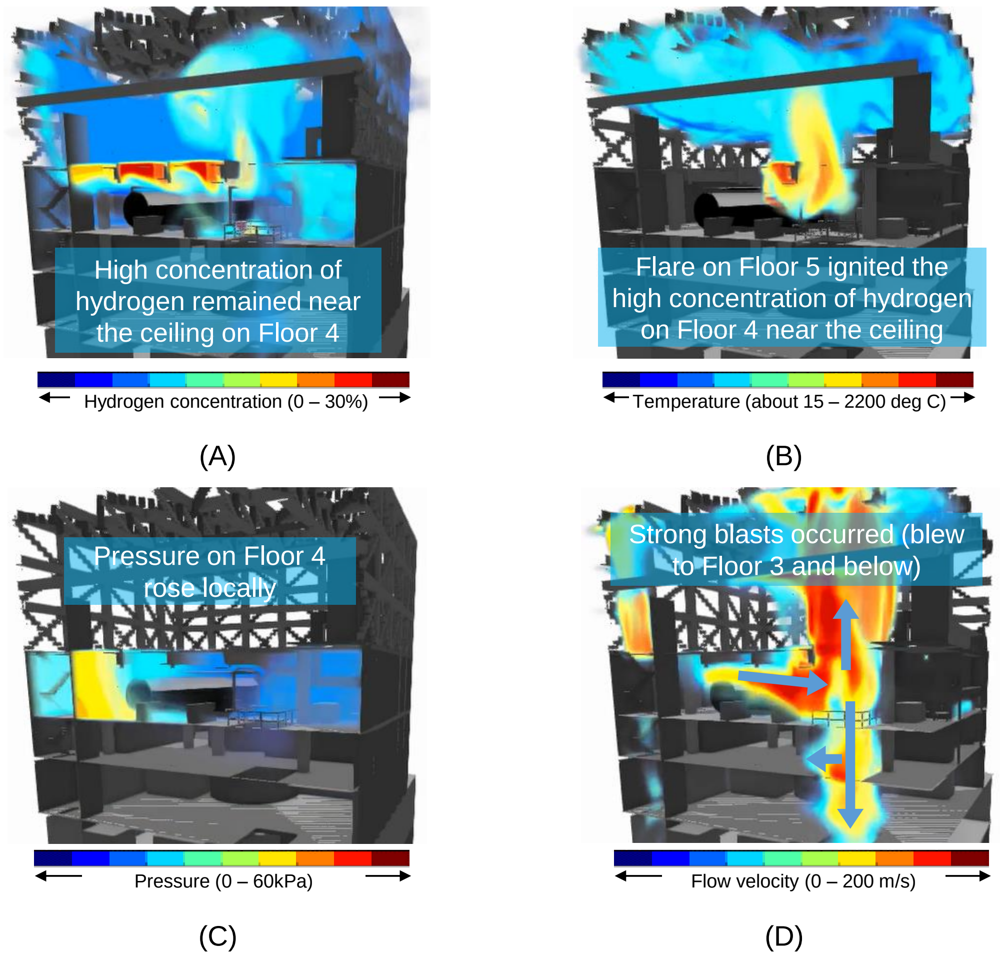


Figure 12 Results of hydrogen explosion analysis

(Case ③: Leaks on Floor 5 and Floor 4, ignition on Floor 5)

(4) Case ④: Leak on Floor 5, ignition on Floor 4

Figure 13 presents the hydrogen distribution at the time of ignition. The amount of hydrogen leaked was increased from about 134 kg in Case ① to about 210 kg in Case ④. The hydrogen migrated to Floor 4, and that amount was enough to develop combustion there, but almost none moved to Floor 3 and below.

Figures 14 (A) to (D) present the analysis results. After ignition on Floor 4, combustion developed on Floor 4 and propagated to Floor 5 through the gaps around the equipment hatch (A). The hydrogen concentration on Floor 4 was relatively lower than that on Floor 5, and combustion developed slowly on Floor 4. Combustion developed mainly on Floor 5 (B). Consequently, the pressure on Floor 5 increased earlier than on Floor 4 (C), the equipment hatch was opened by the force from above, and downward blasts were generated (D). Hereafter, the explosion developed in a manner similar to that in Case ① shown in Figures 9 (D) and (E).

The amount of hydrogen leaked was larger than that in Case ① and the hydrogen concentration was higher, too. Therefore, the scale of the explosion (blast velocities) was somewhat bigger, but the features of the explosion were similar to those in Case ①.

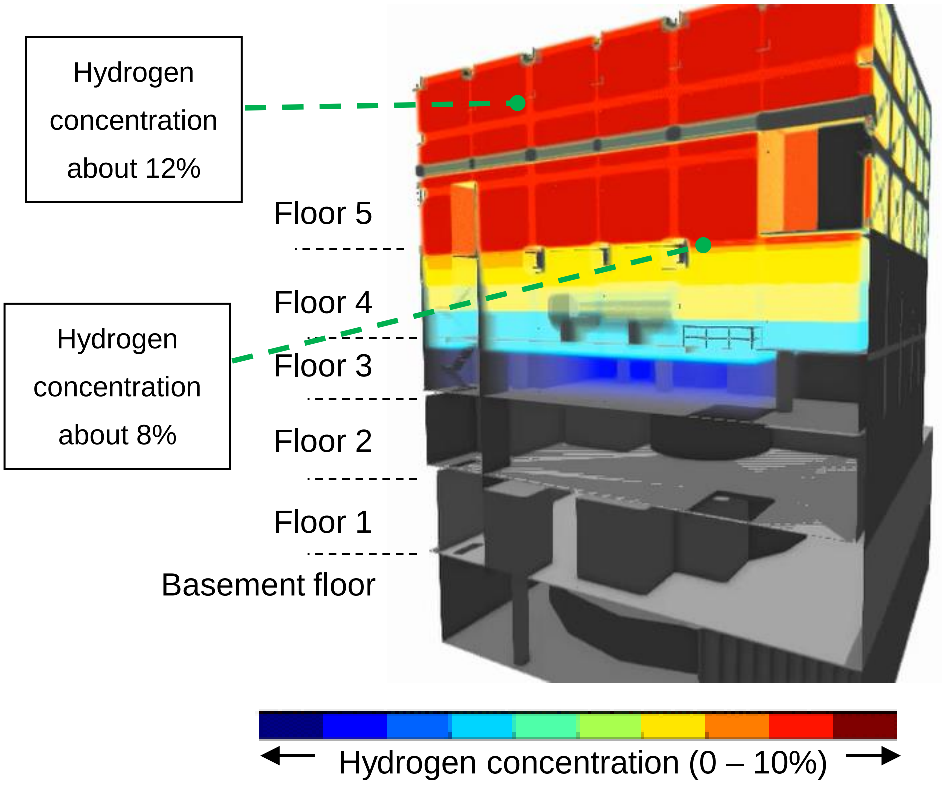


Figure 13 Distribution of hydrogen concentrations at the time of ignition
(Case ④: Leaks on Floor 5, ignition on Floor 4)

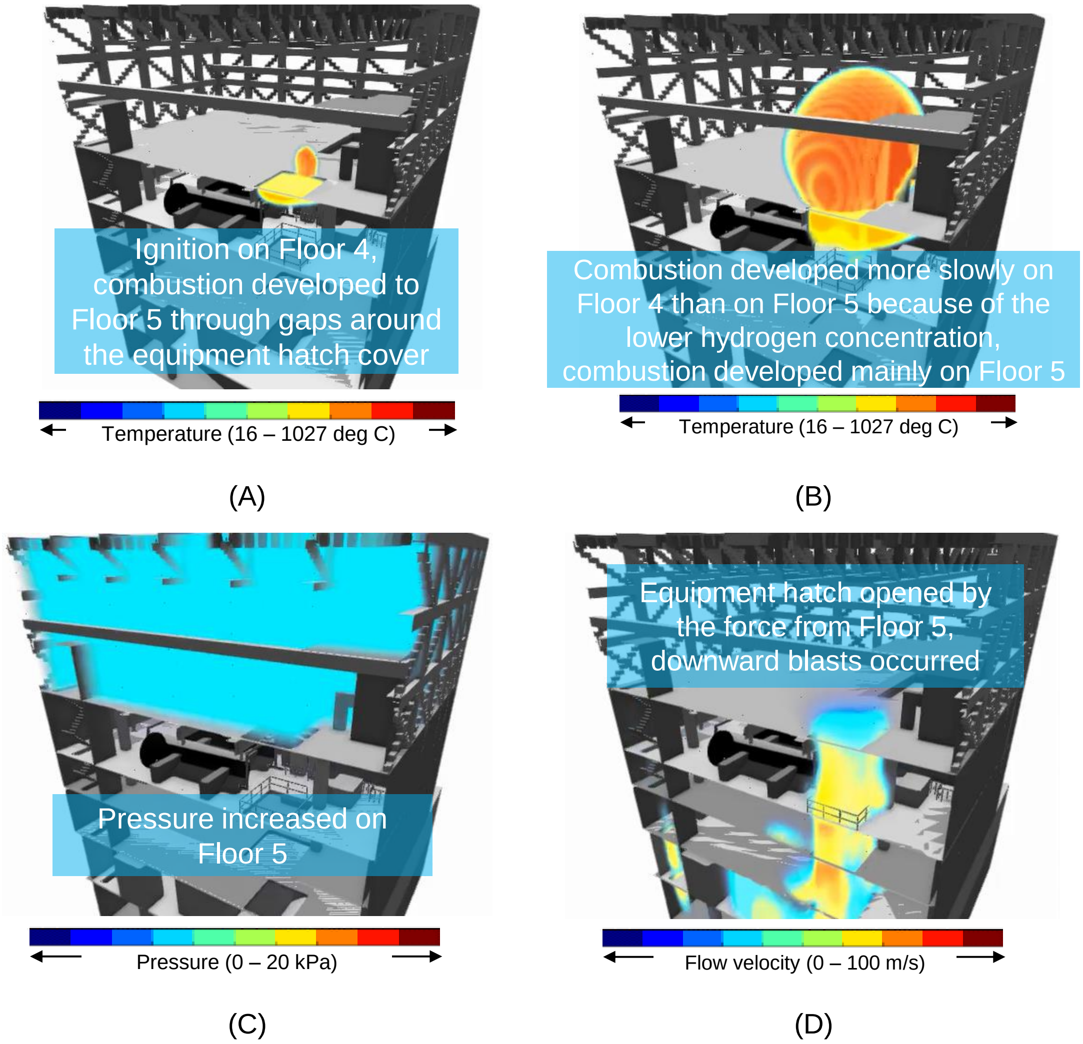


Figure 14 Results of hydrogen explosion analysis

(Case ④: Leak on Floor 5, ignition on Floor 4)

3. Comparison between the analysis results and damage conditions

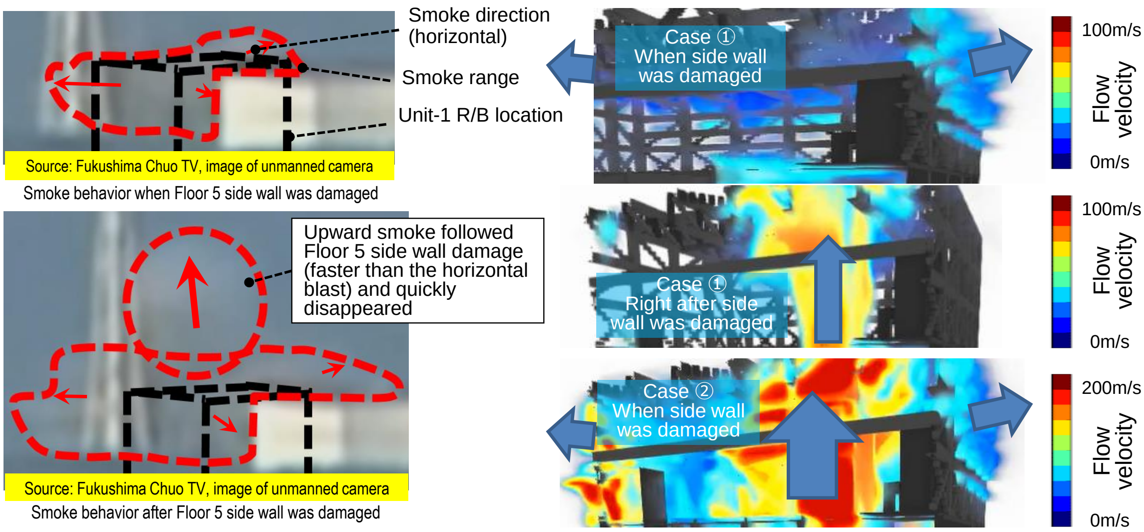
In order to derive a likelier scenario, the characteristics of analysis results in Section 2 were compared with the actual damage R/B conditions at key selected locations.

3.1. R/B Floor 5

On Floor 5 of the R/B after the explosion, the side wall was blown off and the ceiling slab fell to the floor. The Floor 5 floor surface was mostly covered by the fallen slab and the floor surface damage conditions are unknown. Damage at other positions is also difficult to identify as to whether it was due to the explosion or due to the fallen slab.

On the other hand, an unattended video camera recorded the situation at the time of the hydrogen explosion. Figure 15 compares the situation of smoke development recorded in the video (A) with the results obtained by the analysis (B). In (A), there were horizontal blasts when the side wall was damaged, and a while later upward blasts of high speed were observed. The analysis results shown in (B) tell different development scenarios after the side wall on Floor 5 was damaged: in Case ①, upward blasts of high speed followed the horizontal blasts with a delay, similar to the video records; in Case ②, upward blasts occurred simultaneously with the horizontal blasts; in Case ③, a second upward blast followed after the first one in Case ① as mentioned above in 2.3 (3).; and in Case ④, the development was similar to that of Case ①.

The following findings are drawn from the comparison. The video may have recorded the upward blasts after the side wall had been damaged as indicated in Case ① and Case ④, in which hydrogen leaks were assumed to have occurred on Floor 5. On the other hand, in Case ② and Case ③, in which leaks on Floor 5 and Floor 4 were assumed, the development was different from what was seen in the video records; the timings of horizontal and upward blasts in Case ②, and the number of upward blasts in Case ③.



(A) When hydrogen exploded (video film) (B) Blasts estimated in analysis

Figure 15 Blast images at the time of the hydrogen explosion and analysis

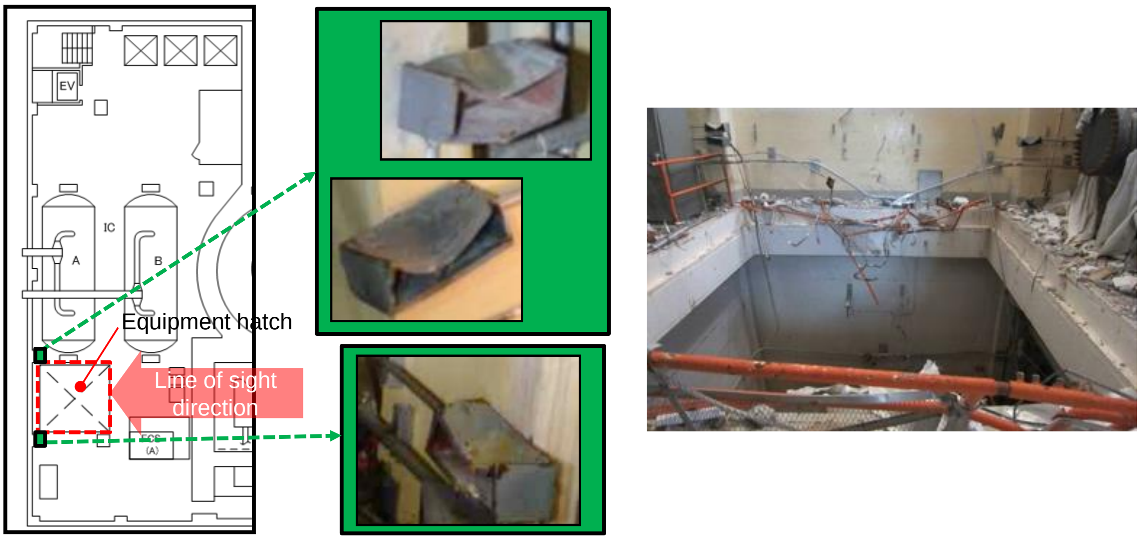
3.2. R/B Floor 4

The main damage on Floor 4, being considered to have been due to the hydrogen explosion, includes: (1) a deformed pull box and damaged handrail near the equipment hatch; (2) stripping off of thermal insulators and their covers from the south side of the IC tank; and (3) deformed MCC, temporary toilet, ventilation duct, etc.; but (4) damage on the

Floor 4 east side was minor. The characteristics of analysis results were compared with the R/B damage conditions at each location[5].

(1) Deformed pull box and damaged handrail near the equipment hatch

Figure 16 shows the damage conditions near the equipment hatch. The pull box in (B) seems crushed from above.



(A) Fl. 4 west plan view (B) Deformed pull box (C) Damaged handrail

Figure 16 Deformed pull box and damaged handrail near equipment hatch

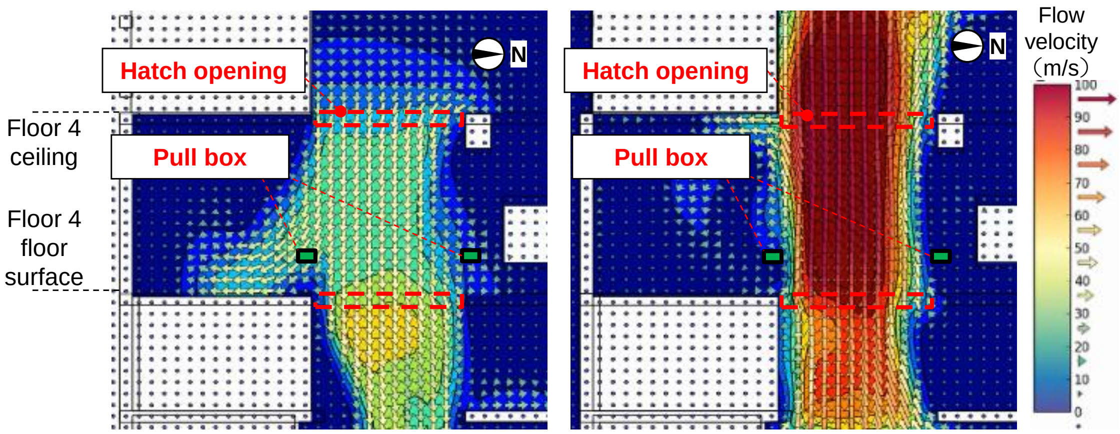
Figure 17 shows the blast analysis results in Case ①. The figure presents velocity vectors in the vertical direction near the equipment hatch. The line of sight direction is the same as in Figure 16 (A). Figure 17 (A) indicates that downward blasts right after the equipment hatch cover was damaged expanded to outside the hatch area and reached the pull box location near the wall. The pull box might have been deformed downward by this blast as seen in Figure 16 (B). On the other hand, the upward blast in Figure 17 (B) after the Floor 5 side wall was damaged mostly passed through the equipment hatch area. Therefore, the pull box outside the hatch area might have escaped the upward blast and deformation. The handrail in Figure 16 (C) might have been deformed either by the blasts after the equipment hatch cover damage or by the blasts after the Floor 5

5 The ceiling of Floor 4 was damaged on the northwest side, but this damage is considered not to be by the increased pressure due to the hydrogen explosion but by the shocks caused by the falling ceiling slab and other materials on Floor 5, because the damage was localized.

side wall damage. In Case ④ blast velocities are somewhat bigger than in Case ①, but the development of the explosion is similar to that of Case ①.

Figure 18 shows the blast analysis results in Case ② and Case ③, indicating that, in these cases, strong horizontal blasts collided against the pull box, after the high concentration hydrogen on Floor 4 had been ignited. The damage condition of the pull box shown in Figure 16 (B) indicates no marks of horizontal blasts.

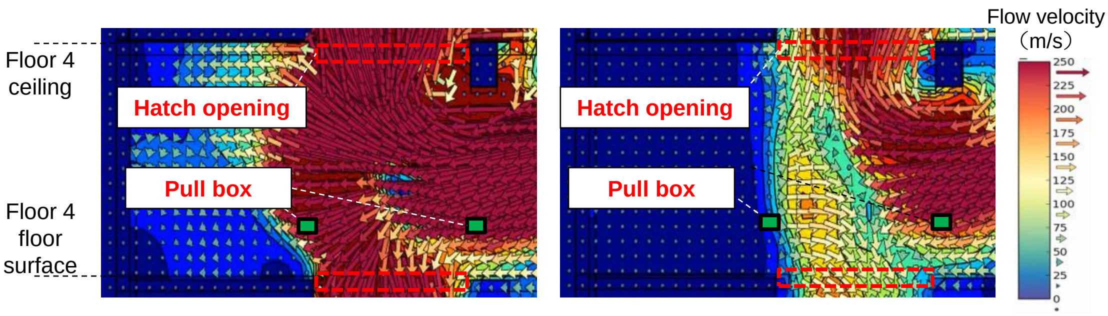
From these comparisons, it is concluded that: the deformed shape of the pull box near the equipment hatch on Floor 4 is consistent with the blast directions in Case ① and Case ④ when hydrogen leaks on Floor 5 were assumed; whereas, it is inconsistent with the blast directions in Case ② and Case ③ when hydrogen leaks on Floor 5 and Floor 4 were assumed.



(A) Right after the equipment hatch opened

(B) Right after the Floor 5 side wall was damaged

Figure 17 Blast velocity distribution at the pull box position (Case ①)



(A) Case ②
(right after the equipment hatch opened)

(B) Case ③
(right after high concentration of hydrogen that remained on Floor 4 was ignited)

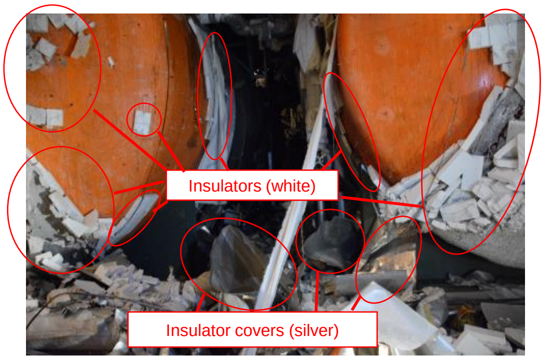
Figure 18 Maximum blast velocity at the pull box location

(2) Stripping-off of thermal insulators and their covers from the south side of IC tank

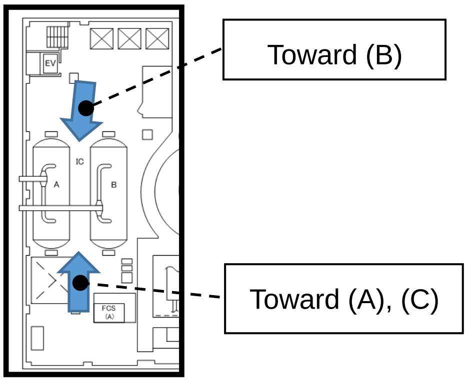
Damage conditions of IC tank thermal insulators and covers are shown in Figures 19 (A) to (C). Figure 19 (D) gives the directions in which the camera was pointed. The IC tank body looked orange-colored. The IC tank was originally covered by white-colored thermal insulators (C) having silver-colored insulator covers (B). On the IC tank south side, the insulator covers were peeled off, exposing the insulators (A). On the IC tank north side, the insulator covers remained intact (B). It should be noted that part of the insulator and their covers had flaked off and remained in the vicinity of the IC tank south side (C).

(A) IC tank south side (1)

(B) IC tank north side



(C) IC tank south side (2)



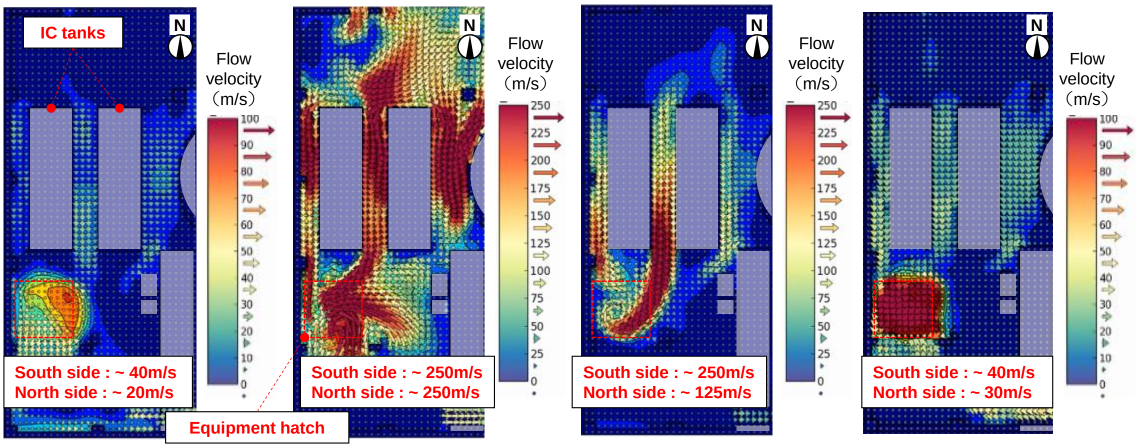
(D) Floor 4 west plan view

Figure 19 Damage conditions of IC tank insulators and insulator covers

Figure 20 shows the analysis results of the maximum blast velocities in the vicinity of the IC tank, presenting velocity vectors on the horizontal cross section at the IC tank central elevation. In Case ② and Case ③, the maximum blast velocities on the IC tank south side and north side are as high as about 125 m/s to 250 m/s, while in Case ① and Case ④ they are about 40 m/s on the IC tank south side and about 30 m/s on the north side. It is not certain whether the blast velocity on the IC tank south side is strong enough to strip the insulator covers off, but the velocity on the IC tank north side is comparatively lower than that on the south side. This relation coincides with the difference in the damaged conditions of the insulator covers on the IC tank south and north sides.

If violent blasts as seen in Case ② and Case ③ are assumed, stripped off insulators and their covers may be scattered over some distance by the blast pressures. In reality, however, part of the stripped off insulators and their covers remain in the vicinity of the IC tank, as seen in Figure 19 (C). The blast velocities may have been not that violent.

From these comparisons, it can be understood that: the damaged conditions of insulators and their covers seem to be consistent with Case ① and Case ④, when hydrogen leaks were assumed on Floor 5; while blast velocities may be too big in Case ② and Case ③, when hydrogen leaks were assumed on Floor 5 + Floor 4.



(A) Case ①　　(B) Case ②　　(C) Case ③　　(D) Case ④

Figure 20 Maximum blast velocities on the horizontal cross section at the IC tank central elevation

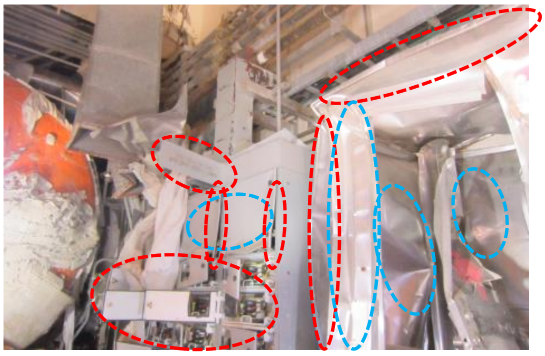
(3) Deformed MCC, temporary toilet and ventilation duct

Damaged conditions of the MCC, temporary toilet and ventilation duct, are shown in Figures 21 (A) and (B). Figure 21 (C) gives the directions in which the camera was pointed. Locations encircled in red in the figure are deformed outward and those encircled in blue are deformed inward.

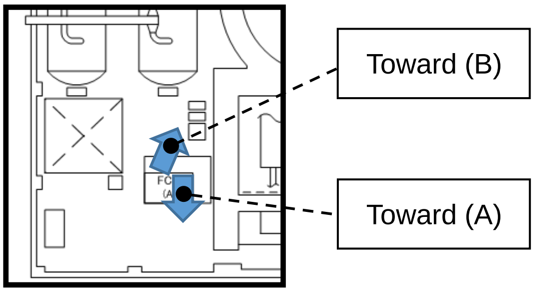
Figure 22 gives the analysis results of pressure distribution at the elevation of the ventilation duct. At the timing when the R/B pressure rapidly increased by the hydrogen combustion (A), the pressure in the duct could not follow the R/B pressure changes and remained lower. On the contrary at the timing when the R/B pressure rapidly dropped due to the Floor 5 side wall damage (B), the in-duct pressure exceeded the R/B pressure. Thus, a pressure difference was generated between locations inside and outside the ventilation duct.

A similar pressure difference could have been generated in hollow structures of the ventilation ducts, MCC and temporary toilet, and consequently inward and outward deformations as was seen in Figure 21 might have been caused in the course of the R/B pressure increase and decrease. Figure 22 shows the results in Case ① as an example, but the above correlation (pressure difference between inside and outside the ventilation duct) is commonly observed in all cases and none of them is considered inconsistent with the damage conditions.

(A) Ventilation duct

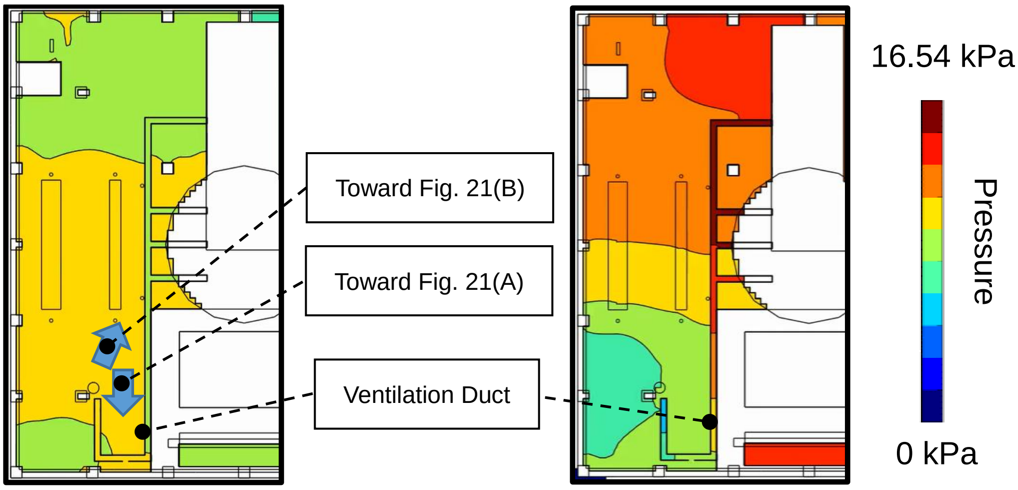


(B) MCC, temporary toilet



(C) Floor 4 southwest plan view

Figure 21　Deformed ventilation duct, MCC and temporary toilet



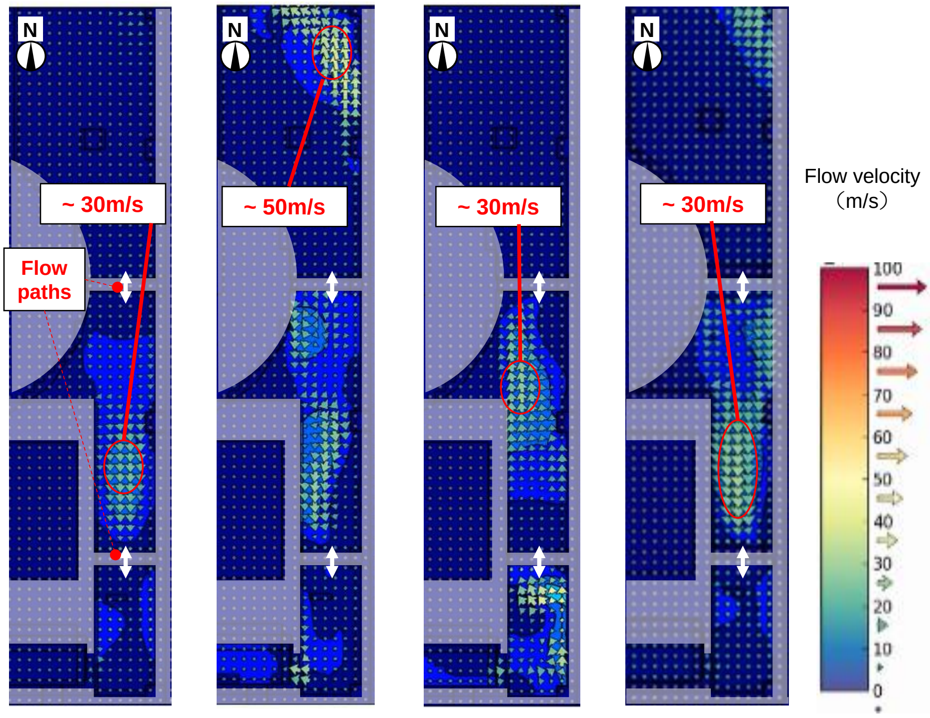
(A) Right after hatch cover was opened (B) Right after Floor 5 side wall was damaged

Figure 22 Pressure distribution at the elevation of the Floor 4 ventilation duct (Case ①)

(4) Damage on Floor 4 east side

Damage on the east side area on Floor 4 was minor as compared with that on the west side area, as mentioned earlier. The ceiling in the east side area was lower and it was harder for the leaked hydrogen to flow in from Floor 5 or Floor 4 west side. As a result, hydrogen concentration was low and no hydrogen combustion occurred in any of the analysis cases.

Figure 23 shows the analysis results of maximum blast velocity in the east side area on Floor 4. In this east side area, the access paths were relatively narrow and the resultant maximum blast velocities were less than those in the west side area. This is not inconsistent with the damage conditions.



Case ①　　Case ②　　Case ③　　Case ④

Figure 23　Maximum blast velocities in Floor 4 east side area

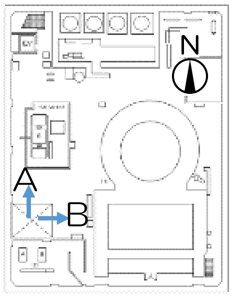
3.3.　R/B Floor 3 and below

Figure 24 shows conditions around the equipment hatch on Floor 3 and below. Some damage can be noticed (encircled in red) on relatively thin structures. But almost no damage is noticeable on other structures. The damage is less than that on Floor 4 in the west side area discussed in Section 3.2 and no strong blast marks are noticeable.

Figure 25 presents the analysis results of maximum velocity of blasts moving down to Floor 3 and below. Velocity vectors on the vertical planes around the equipment hatch are shown in the figure. The direction in which the camera was pointed is the same as that in Figure 16 (A). The maximum velocities in the analysis of blasts moving into Floor 3 and below in Case ② and in Case ③ are much higher than in Case ① and Case ④. Blasts in Case ② and Case ③ could be too strong from the viewpoint of the blast velocities moving in.

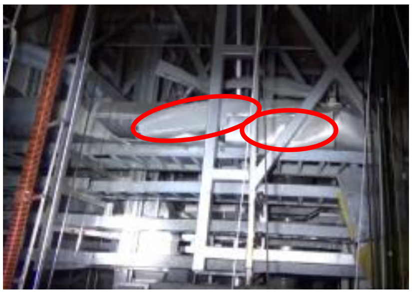
(A) Fl. 3 equipment hatch north

(B) Fl. 3 equipment hatch east

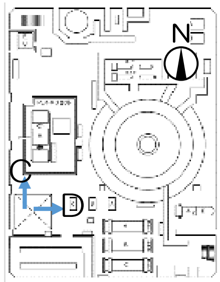


Floor 3 plan view

(C) Fl. 2 equipment hatch north

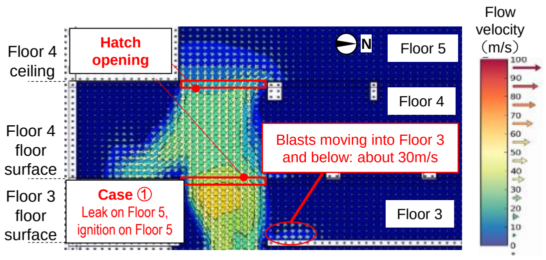


(D) Fl. 2 equipment hatch east

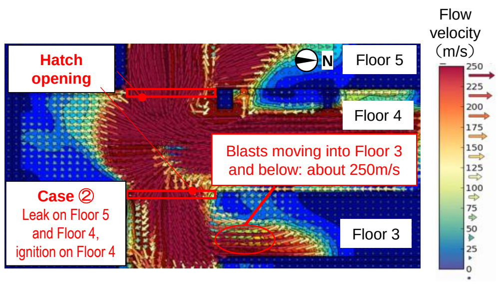


Floor 2 plan view

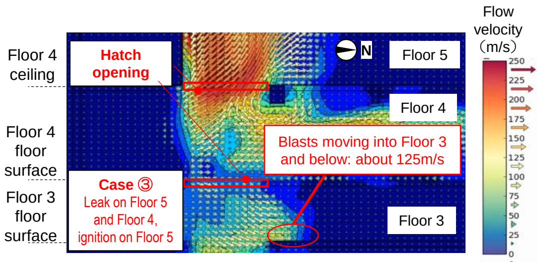
Figure 24　Conditions around equipment hatch on Floor 3 and below



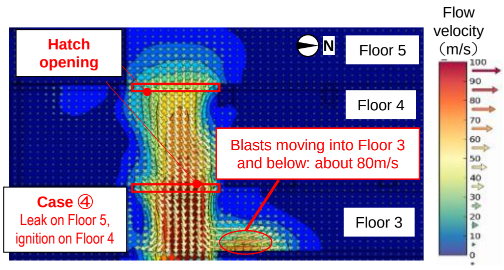
(A) Case ①



(B) Case ②



(C) Case ③



(D) Case ④

Figure 25 Maximum velocities of blasts moving to Floor 3 and below

3.4. Summary of comparisons between the analysis results and R/B damage conditions

Table 3 summarizes the comparison discussed above between analysis results and actual R/B damage conditions. Circle marks ○ in the table indicate that the analysis is not inconsistent with damage conditions, while triangle marks ▲ indicate that the cause of the discrepancy between analysis and actual conditions is difficult to explain.

Table 3 Comparison between analysis results and R/B damage conditions

Floor	Damage Conditions	Comparison with Analysis Results: Cases ①, ④ Leak on Fl. 5	Comparison with Analysis Results: Cases ②, ③ Leaks on Fl. 5+4
5	Side wall blown off	○ (See 2.3)	○ (See 2.3)
	Equipment hatch cover opened	○ (See 2.3)	○ (See 2.3)
	Smoke flow after side wall damaged	○ (See 3.1)	▲ (See 3.1)
4	Damage around equipment hatch (Handrail damaged; Pull box deformed; Insulators stripped off on IC tank south side)	○ (See 3.2)	▲ (See 3.2)
	Ventilation duct/MCC/Temporary toilet deformed	○ (See 3.2)	○ (See 3.2)
	Insulator covers on IC tank north side remained intact	○ (See 3.2)	▲ (See 3.2)
	Minor damage in the east side	○ (See 3.2)	○ (See 3.2)
3 and below	Minor damage except around equipment hatch	○ (See 3.3)	▲ (See 3.3)

4. Conclusion

Comparisons were made between the R/B damage conditions and analysis results, concerning the hydrogen explosion at Unit-1 of the Fukushima Daiichi Nuclear Power Station. It was concluded from the study that the possibility the hydrogen had leaked on Floor 4, for instance from the IC piping, was low and that the possibility the hydrogen had leaked on Floor 5 instead was more likely, as having been assumed to date. The conclusion is consistent with the field survey results [2] (no damage confirmed on the equipment and piping around the IC, and other findings).

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

The current study reaffirmed the possibility that hydrogen had leaked from the PCV top head flange at Unit-1 of the Fukushima Daiichi Nuclear Power Station. Therefore, it is necessary to take measures to prevent hydrogen leaks from the PCV. Measures are also required to keep hydrogen concentration in the R/B low enough to prevent hydrogen explosions, even when leaks have occurred, including localized accumulations.

As preventive measures against PCV leaks, the following steps will be taken at the Kashiwazaki-Kariwa Nuclear Power Station in order to prevent PCV damage due to overheating and overpressure: strengthening PCV seal materials, strengthening alternative means of PCV spray, implementing top flange cooling, implementing alternative circulation cooling and a filtered vent, etc. It should be noted that pipes penetrating the PCV are designed to be automatically isolated by the isolation valves, as soon as anomalies in accident conditions are detected.

As preventive measures against hydrogen explosions, hydrogen concentration measuring instruments are being installed for early leak detection at locations where leaks can occur (R/B top floor above the PCV top head, and at a small cell for the equipment hatch or airlock). Measures will be taken to control excessive hydrogen leaks to the R/B by depressurizing the PCV through implementation of a filtered vent as soon as a set hydrogen concentration limit is exceeded on the R/B top floor. Further, installation of passive autocatalytic recombiners (PARs) on the R/B top floor, hydrogen discharge from the R/B via the top vent, and other means are being considered. Figure 26 outlines the concept of these measures. Even when hydrogen leaks from the equipment hatch or airlock, hydrogen is led to the top floor via ventilation ducts and others. With these measures, it is estimated the hydrogen concentration in the R/B will not reach the combustion limit.

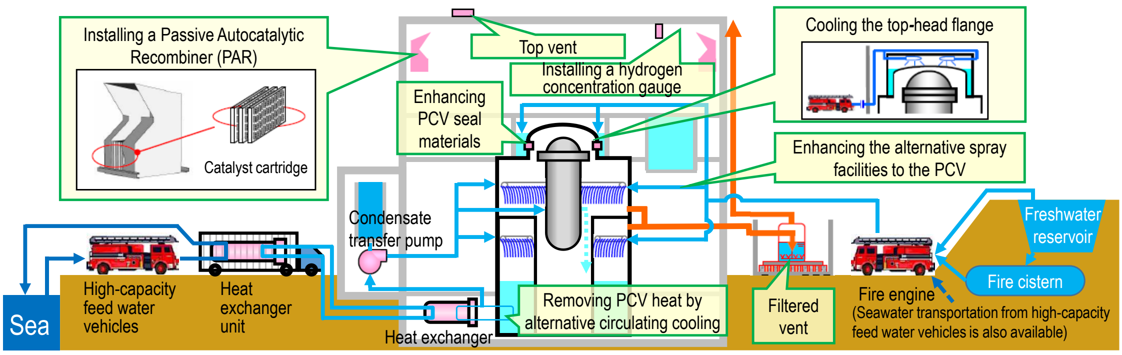


Figure 26 Preventive measures against PCV leaks and hydrogen explosions at Kashiwazaki-Kariwa Nuclear Power Station

References

[1] Hansen, O.R. et al., "Validation of FLACS-hydrogen CFD consequence prediction model against large scale H_2 explosion experiments in the PFLAME facility," 1st International Conference on Hydrogen Safety, Pisa, Italy (2005)

[2] Tokyo Electric Power Company, “Evaluation of operating conditions of Isolation Condenser, Unit 1, Fukushima Daiichi Nuclear Power Station”, (November 22nd, 2011)