# Leaks from Unit-3 PCV and steam release in a large amount

## 1. Background

At Unit-3 the suppression chamber (S/C) vent line configuration was completed at 08:41 on March 13th and the dry well (D/W) pressure decrease was confirmed at 09:24 on March 13th. The Emergency Response Center (ERC) at the Fukushima Daiichi Nuclear Power Station (NPS) concluded that the Unit-3 primary containment vessel (PCV) had been vented. The S/C vent valves (large, small) were operated to open thereafter when the PCV pressure increased.

The D/W pressures (measured) repeated ups and downs over this period. But chronologically many of the vent timings do not correspond to the timings of D/W pressure drop. The following incidents are reported in Reference [1] concerning the difficulty of venting operations at that time: when the vent valves opened by the opening operation, they remained open, but it was very hard for them to keep the opened position; they closed unintentionally after a while due to insufficient driving air pressure from the temporary compressors, defective circuits for activating the vent valves, difficulty of keeping the solenoid activated because of failed small generators, etc. The D/W pressures repeated ups and downs corresponding to the steam and hydrogen gas generation by the injected water, venting operations and other causes, but it remained at approximately the atmospheric pressure after it increased temporarily on March 21st. In other words, it has been explained that gaseous leaks occurred eventually from the PCV. However, it is unclarified which opening operations did work and which did not, although it is known to have been hard to keep the valves open. This means that the opening operation of vent valves does not necessarily mean gaseous release by venting from the PCV. The records made public to date have a risk leading to a misunderstanding that gaseous release always occurred when the vent valves were operated to open.

Photos taken on the occasion of dust sampling in the upper part of the reactor building (R/B) on August 24th, 2011 confirm steam leaks from the shield plug peripheries, distorted dryer separator (DS) pit gate surroundings and other spots in the area. It is understood therefore that the leaks from the PCV occurred through the gaps generated by the seal material deterioration of the PCV upper head just below the shield plug.

This document examined the relations between the venting functionality (success/failure), leaks from the PCV and steam leaks from the upper part of the building observed at Unit-3. The examination was based on the R/B conditions observed on March

15th onward, PCV pressure changes in response to the vent valve opening operations, and the investigation results of scrubbing effects in the S/C assuming the release of radioactive materials via vent lines (the items are defined as Unit-3/Issue-8, -10 and -11, separately).

This examination was done based on the discussions with researchers and engineers of the Institute of Applied Energy, Toshiba and Hitachi-GE Nuclear Energy.

[1] Responses at the Fukushima Daiichi and Daini Nuclear Power Stations, Annex 2 to the Fukushima Nuclear Accident Analysis Report, Tokyo Electric Power Company, June 20, 2012

## 2. Reactor building conditions observed on March 15th onward

In order to know the R/B conditions after the earthquake, (i) information from filming by a live camera and (ii) photos taken by the Fukushima Daiichi NPS personnel using their digital cameras are available, although the relevant records are insufficient. The information from the live camera films will be more or less exact in time but the resolution is not so good because of the far distance at which the filming was done. Photos by the digital cameras, on the other hand, have good resolutions because they were taken close to the R/B, but the time information has uncertainties because it is referenced to built-in clocks of the individual cameras. The errors in time information of digital cameras, however, will not be as big as a day unit except when the clock is backdated by being reset due to battery depletion or other reasons. In the current evaluation, the time information of the live camera was assumed to be accurate and the photo information by digital cameras was used unless big discrepancies were found in times from those of the live camera.

### 2.1. Photos by the live camera

**Photos at 10:00 on March 11th**

Figure 1 shows the photo recorded by the live camera at 10:00 on March 11th. This photo shows the Fukushima Daiichi NPS in sound conditions before the earthquake. A chimney type structure seen in the far left is the Unit-5/6 stack, a chimney type structure to its right is the Unit-3/4 stack and the last chimney type structure is the stack of the turbine building (T/B) ventilation system. The Unit-1/2 stack stands just behind the Unit-3/4 stack and is not visible in this photo. Occasionally the Unit-1/2 stack is visible in later live camera feed, because the live camera photo angle changes perhaps due to aftershocks.

A building near the T/B ventilation system stack is the radioactive waste treatment building (RW/B). A building behind the Unit-3/4 stack is the Unit-4 R/B, but Unit-1 to Unit-4 are almost on a single straight line from the live camera point, as seen in the enlarged photo, and it is difficult to compare Unit-1 to Unit-3 from the live camera feed.

<u>Photos at 10:00 on March 13th</u>

Unit-3 is considered to have been successfully vented at about 09:20 on March 13th and Figure 2 shows a photo live camera taken at 10:00, about 40 minutes after the venting. As can be seen in the enlarged photo of the Unit-3/4 stack, steam was being discharging by venting. Meanwhile, no extraordinary conditions are recognized for the R/B.

<u>Photos at 13:00 and at 15:00 on March 13th</u>

Figure 3 shows photos by the live camera at 13:00 and 15:00 on March 13th. It is recorded elsewhere that the vent valve closure was confirmed at 11:17 and the vent valve opening (second opening operation) was confirmed at 12:30. Therefore, the steam release as confirmed in the live camera photo of 13:00 is considered as the result of the successful venting. No clear steam release can be recognized in the photo of 15:00.

<u>Photos at 07:00 and at 10:00 on March 14th</u>

Figure 4 shows photos by the live camera at 07:00 and 10:00 on March 14th. In the records operation of the vent valve (small valve) was completed at 06:10 (fourth operation time). Steam release cannot be recognized clearly in either of these live camera photos. There is a possibility, though, that the steam released by the small vent valve operation was limited and not recognizable in live camera photos.

<u>Photos at 07:00 on March 15th</u>

Figure 5 shows photos by the live camera at 07:00 on March 15th. At this timing, steam release from the Unit-3/4 stack cannot be recognized, but from the enlarged photos around the R/Bs, steam release, probably from the top of the R/B of an unknown unit, can be recognized.

<u>Photos at 16:00 on March 15th</u>

Figure 6 shows photos by the live camera at 16:00 on March 15th. At this timing, steam release from the Unit-3/4 stack cannot be recognized, but from the enlarged photos around the R/Bs, steam release, probably from the top of R/B of an unknown unit, can be recognized.

Photos at 17:00 on March 15th

Figure 7 shows photos by the live camera at 17:00 on March 15th. In the records, the small generator for opening operations of vent valves was replaced and opening operation was done for the fifth time, but no clear steam release can be recognized in the live camera photos. Like in the photos at 16:00 (Figure 6), steam release, probably from the top of an R/B, can be recognized.

Photos at 10:00 on March 16th

Figure 8 shows photos by the live camera at 10:00 on March 16th. At this timing, steam release from the Unit-3/4 stack cannot be recognized yet. But steam release probably from the top of an R/B can be recognized. In the earlier photos, the shape of the RW/B was clearly visible, but at this timing the RW/B was partially invisible due to the released steam. Therefore, the steam released at this timing from the R/B, i.e., leaks from PCV, can be considered as significantly large scale.

2.2. Photos taken by digital cameras

It should be noted that the time information in this section 2.2 was taken from the built-in clock of the digital camera and may not be precise.

Photo at 07:31 (built-in clock time) on March 15th

Figure 9 shows a photo taken by a digital camera in the morning of March 15th. It confirms that steam release from the top of Unit-3 R/B had started by this timing. The photo by the live camera at 07:00 on March 15th (Figure 5) also shows steam release. Therefore, the date information in the digital camera photo is roughly correct.

Photo at 08:58 (built-in clock time) on March 15th

Figure 10 shows a photo of the Unit-2 R/B taken in the morning of March 15th. It is known that the blowout panel of the Unit-2 R/B opened at the time of the Unit-1 R/B hydrogen explosion and steam was being released though this blow-out panel. It is reported in Reference [1], too, that white smoke (like steam) was confirmed to be rising at 08:25 on March 15th from around the 5-th floor of the Unit-2 R/B. Therefore, this date information can be regarded as roughly correct.

Photo at 09:51 (built-in clock time) on March 16th

Figure 11 shows a photo taken in the morning of March 16th. It confirms that the steam release from the top of the Unit-3 R/B was still continuing. The amount of steam being released seems larger than that on the previous day. This is consistent with the live camera feed of 10:00 on March 16th. Therefore, this date information can be regarded as roughly correct.

## 2.3. Deliberation from the photos observed

Live camera photos confirm steam release from the Unit-3/4 stack twice: the first (1st) and the second (2nd) vents on March 13th. It can be concluded that Unit-3 was vented at least at these occasions. The third (3rd) vent operation of opening was at night and the result could not be confirmed by the live camera. The fourth (4th) opening operation of vent valves was early in the morning of March 14th. Steam release could not be confirmed, although its possibility remains: the amount of steam flow in the vent line was too little to recognize, because the vent valve operated for opening was the small vent valve. At the fifth (5th) opening operation of vent valves in the evening of March 15th, no steam release could be confirmed from the stack photos, either. The last sixth (6th) opening operation was at dawn on March 16th, and live camera photos cannot confirm the steam release.

From the digital camera photos, steam release is confirmed in the morning of March 15th from the top of the Unit-3 R/B. At this timing, leaked gases from the PCV (including steam and radioactive materials) are considered to have been in a situation to be directly released to the environment. Meanwhile in the morning of March 15th, steam release from the blow-out panel of the Unit-2 R/B was also confirmed and radioactive materials were being released from Unit-2, too (Attachments 2-9 and 2-10).

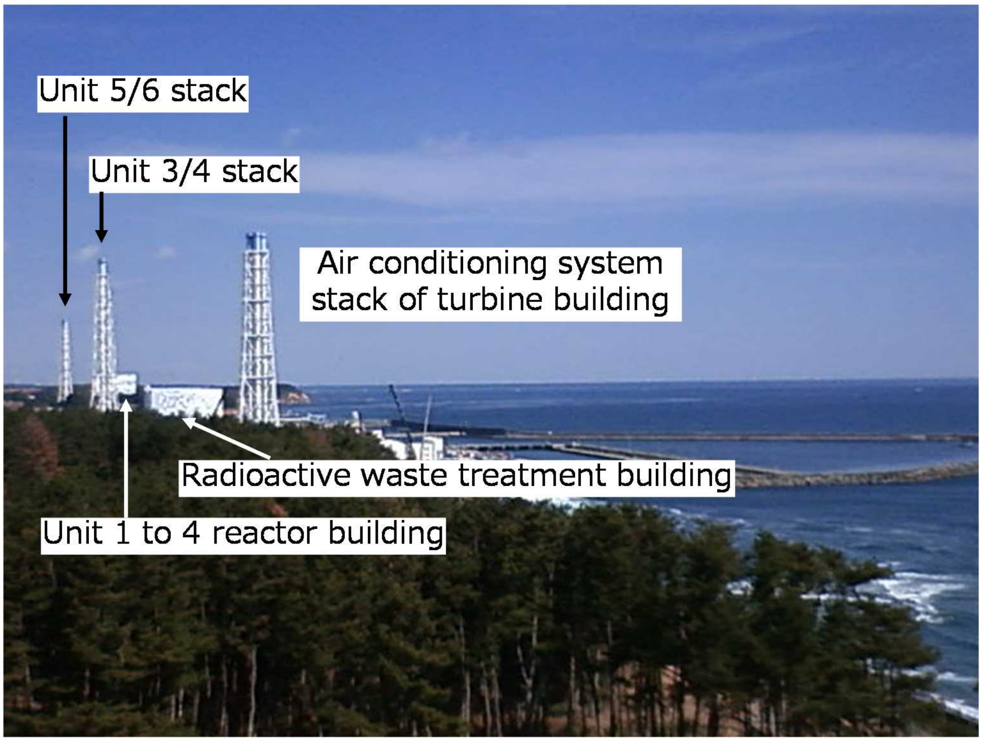


Figure 1 Photos by the live camera at the Fukushima Daiichi NPS (taken at 10:00 on March 11th) (Top: Full screen view of the live camera, Bottom: Enlarged R/B surroundings)

Figure 2 Photos by the live camera at the Fukushima Daiichi NPS (taken at 10:00 on March 13th) (Top: Full screen view of the live camera, Center: Enlarged Unit-3/4 stack, Bottom: Enlarged R/B surroundings)

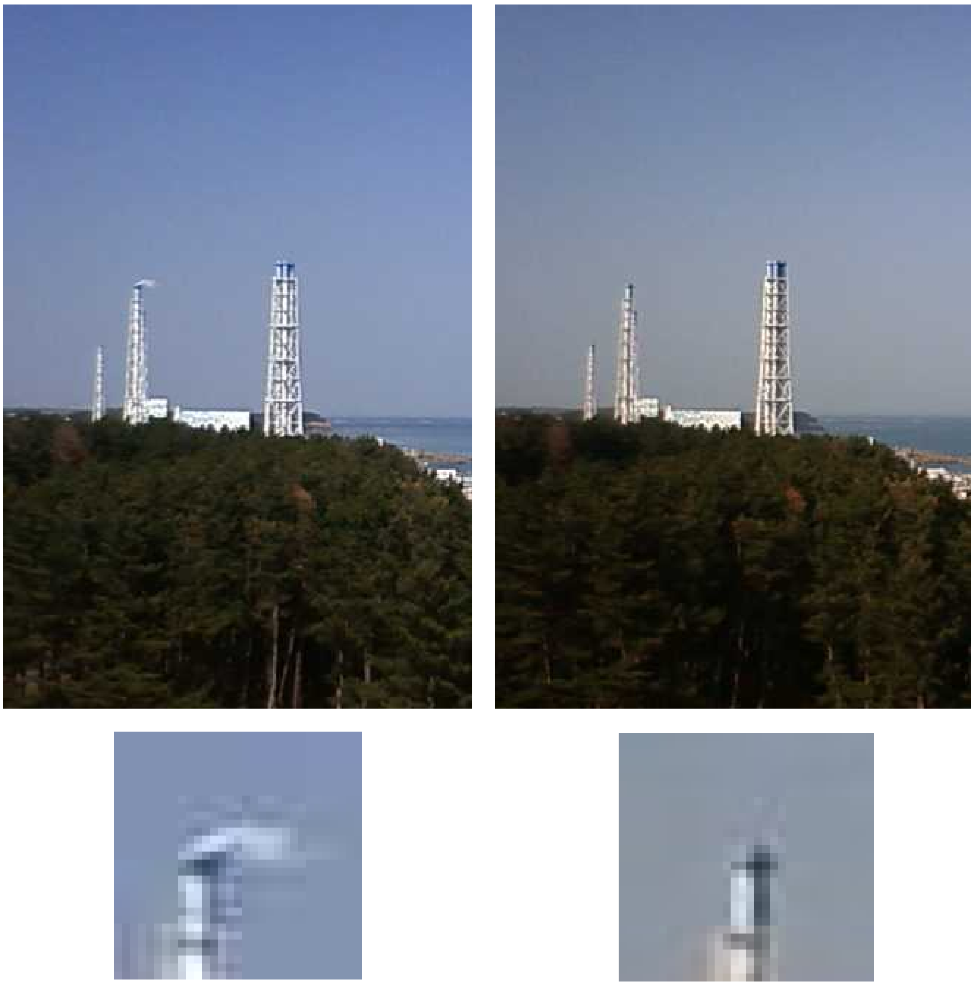

Figure 3 Photos by the live camera at the Fukushima Daiichi NPS (Part) (Left: taken at 13:00 on March 13th, Right: taken at 15:00 on March 13th) (Top: Live camera photos (excerpt), Bottom: Enlarged Unit-3/4 stack)

Figure 4 Photos by the live camera at the Fukushima Daiichi NPS (Part) (Left: taken at 07:00 on March 14th, Right: taken at 10:00 on March 14th) (Top: Live camera photos (excerpt), Bottom: Enlarged Unit-3/4 stack)

Figure 5 Photos by the live camera at the Fukushima Daiichi NPS (taken at 07:00 on March 15th) (Top: Full screen view of the live camera, Center: Enlarged Unit-3/4 stack, Bottom: Enlarged R/B surroundings)

Figure 6 Photos by the live camera at the Fukushima Daiichi NPS (taken at 16:00 on March 15th) (Top: Full screen view of the live camera, Center: Enlarged Unit-3/4 stack, Bottom: Enlarged R/B surroundings)

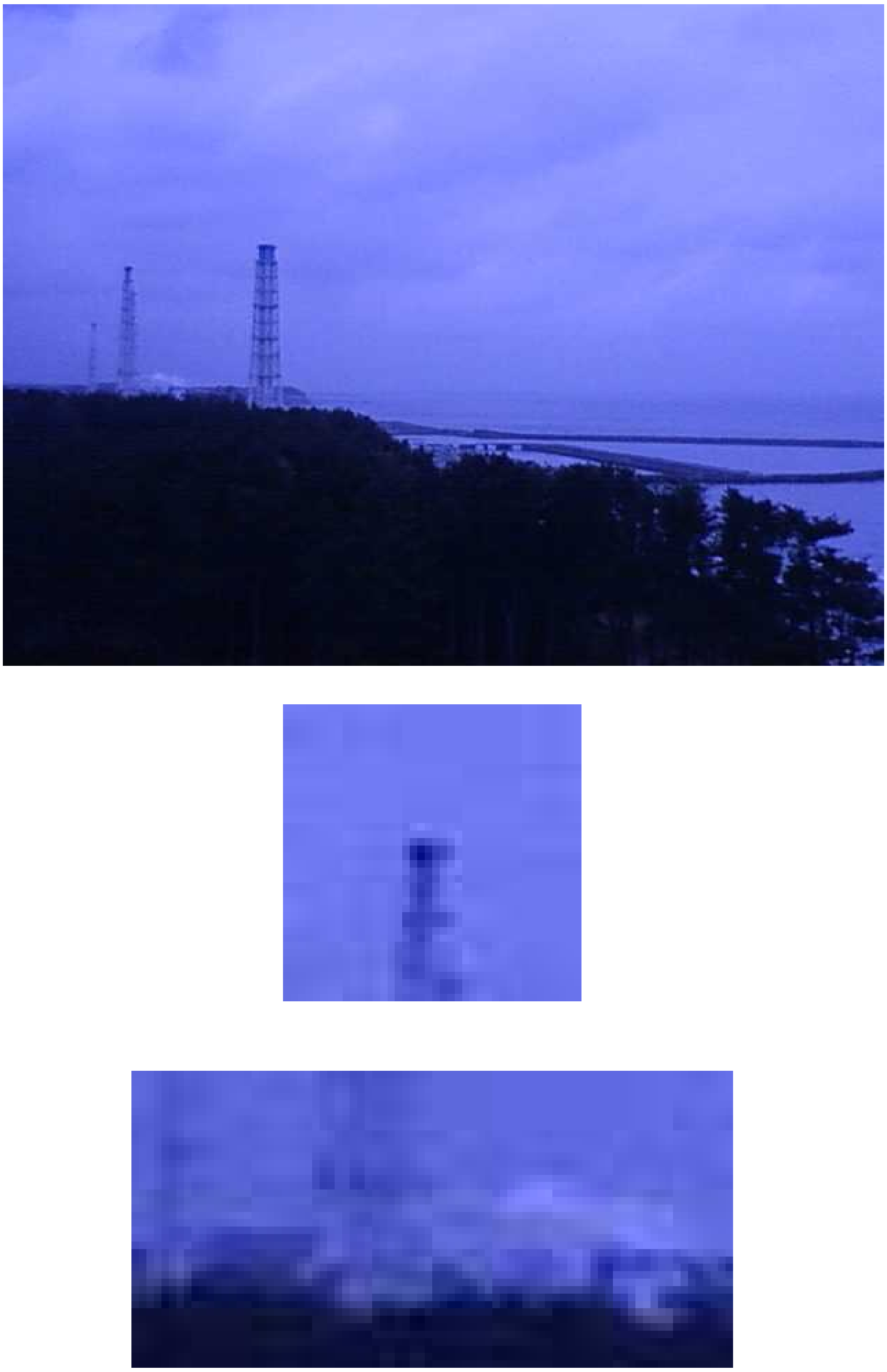

Figure 7 Photos by the live camera at the Fukushima Daiichi NPS (taken at 17:00 on March 15th) (Top: Full screen view of the live camera, Center: Enlarged Unit-3/4 stack, Bottom: Enlarged R/B surroundings)

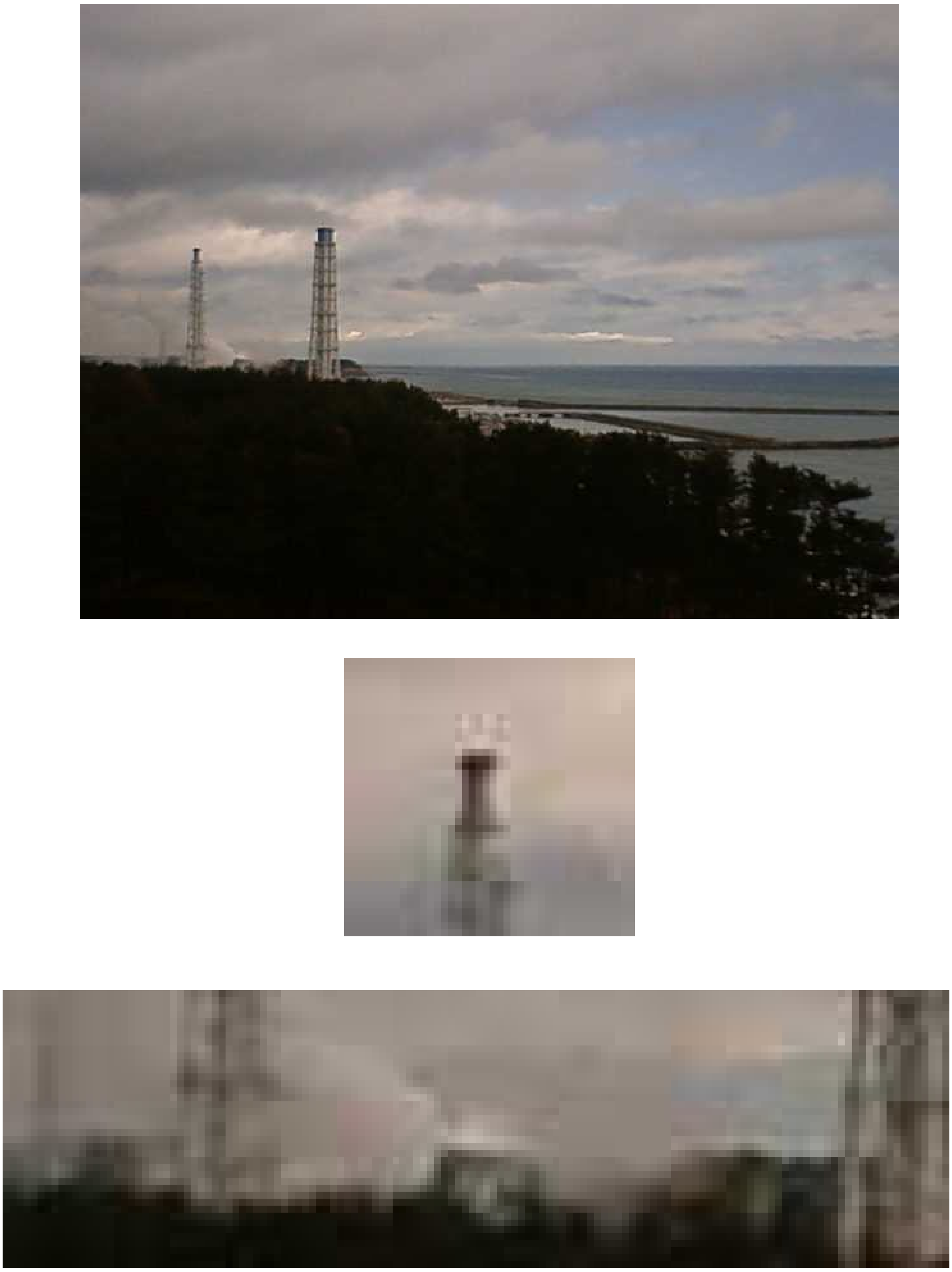

Figure 8 Photos by the live camera at the Fukushima Daiichi NPS (taken at 10:00 on March 16th) (Top: Full screen view of live camera, Center: Enlarged Unit-3/4 stack, Bottom: Enlarged R/B surroundings)

Figure 9 Steam release from Unit-3 (photographed at 07:31 on March 15th)

Figure 10 Steam release from Unit-2 (photographed at 08:58 on March 15th)

Figure 11 Steam release from Unit-3 (photographed at 09:51 on March 16th)

3. Examination into the PCV pressure changes in response to vent valve opening operations

As afore-mentioned, the vent valve opening operations assume that once opened, the vent valves remain opened. No intentional action to close the valves is taken. In the meantime, a difficulty to keep the valves open is also reported. It is further reported that the PCV pressure did not decrease even upon vent operation. Thus, the opening operations of vent valves do not necessarily mean gas releases by venting. It should be noted that it is not possible to judge directly whether the PCV could be successfully vented or not unless the steam release from the stack could be confirmed, nevertheless it has been judged some times to date by the PCV pressure decrease or increase whether the vent valves had been opened or closed. In other words, even when the PCV pressure was increasing, it could be due to more gas inflow or gas generation in the PCV than to the amount of possible gas release via vent tubes, or even when the PCV pressure was decreasing, it could be due to gas releases from the PCV through paths other than the vented gas from the stack.

From such considerations, this document examines the PCV pressure behavior at the timings of opening operation of vent valves, referring to that of the 1$^{st}$ and 2$^{nd}$ vent operations as reference cases when the gas release from the PCV had been certainly confirmed.

3.1. PCV pressure changes from 06:00 on March 13$^{th}$ to 09:00 on March 14$^{th}$

Figure 12 presents the PCV pressure changes over this time span. At Unit-3, the high pressure coolant injection system (HPCI) lost its water injection function before its manual shutdown (Attachment 3-3). Therefore, it is interpreted that the core was damaged by about 05:00 on March 13$^{th}$ and a large amount of hydrogen gas was being generated. This means the continuous PCV pressure increase till just before 09:00 is considered to be due to the inflow of non-condensable hydrogen gas into the PCV. At about 09:00 when the reactor was depressurized, the hydrogen gas in the reactor vessel was instantly released to the PCV and the PCV pressure increased high enough to activate rupture discs for venting.

At this first (1$^{st}$) venting, the PCV pressure dropped fairly rapidly, about 0.4MPa in 90 minutes, that is, from 0.637MPa(D/W) and 0.590MPa(S/C) at 09:10 to 0.270MPa(D/W) and 0.220MPa(S/C) at 10:40.

At the second (2$^{nd}$) venting, too, the PCV pressure dropped fairly rapidly, about 0.5MPa in 75 minutes, that is, from 0.750MPa(D/W) and 0.700MPa(S/C) at 12:20 to 0.235MPa(D/W) and 0.190MPa(S/C) at 13:35. The vent valves were judged based on the

PCV pressure decrease to have opened, approximately when the reactor pressure increased rapidly to about 3MPa on the chart readings. The rapid PCV pressure increase prior to this timing could be explained by a scenario that, if the reactor pressure increase was this rapid, the PCV pressure could have increased even if the vent valves had been opened. On the other hand, it was highly probable the vent valves were in closure positions, because there is a record that the cylinders for vent valve operation were being replaced. Whatever the situation was, the PCV pressure decreasing speed can be evaluated as above once the highest and lowest PCV pressures are known.

From these two cases, fairly rapid PCV pressure decrease is anticipated when vented, i.e., 0.25MPa to 0.4MPa per hour.

From 19:00, at the mid-point of this time span, temporary compressors were connected for driving vent valves upon observing the PCV pressure increase. When the D/W pressure decreased at about 21:10, the vent valves were concluded to have opened (3$^{rd}$ venting). The PCV pressure decrease this time was very slow when compared with those of the 1$^{st}$ and 2$^{nd}$ vents: about 0.2 to 0.15MPa in 200 minutes from 0.425MPa(D/W) and 0.375MPa(S/C) at 20:40 to 0.240MPa(D/W) and 0.255MPa(S/C) at 24:00.

The relation between the D/W pressure and S/C pressure should draw more attention. At this timing the heat source is considered to exist in the D/W. It is reasonable, therefore, that the D/W pressure is higher than the S/C pressure. If gases are vented via the S/C, the gases move from the D/W to the S/C and then are released from the stack. In order to move gases from the D/W to the S/C, some pressure difference is required for the water to spill over in the S/C downcomer pipe. It is physically reasonable that there is a difference of about 0.05MPa between the D/W and S/C pressures until about 21:00. But, the pressures were reversed at 22:30 as 0.285MPa(D/W) and 0.290MPa(S/C) and at 24:00 the S/C pressure exceeded that of the D/W by 0.015MPa. If the PCV pressure had decreased by venting, gases must have moved from lower pressure points to higher pressure points, which is physically impossible.

It would be more natural, therefore, to interpret as follows: the cause of the PCV pressure decrease at the occasion assumed as the 3$^{rd}$ venting should be shifted to the D/W side, not by venting. Leaks from the D/W would be most probable from the PCV upper head due to deterioration of seal materials by the high temperature environment.

In the second half of this time span, the 4$^{th}$ opening operation of vent valves is recorded (completed at 06:00 on March 14$^{th}$). The vent valve operated for opening this time was the small valve. Even if the valve was opened, the affordable flow was limited. Therefore, two possibilities exist for no clear PCV pressure decrease: a possibility of failure of the vent valve to open; and a possibility of too low flow even when the valve was opened, and these caused the pressure increase eventually. At any rate the leak from the D/W is considered to have been continuing through the leak path which was already present at the 3rd vent operation and it could not become closed for no reason.

### 3.2. PCV pressure changes from 09:00 on March 14th to 12:00 on March 15th

The pressure changes over this time span are shown in Figure 13. During this period, Unit-3 experienced the hydrogen explosion at 11:00 on March 14th. This explosion occurred due to the hydrogen gas leaked to the R/B. It is consistent with the actual accident progression to assume that the leak from the PCV to the R/B started by the time of the 3rd vent operation.

It should be noted that the PCV pressure dropped largely at the hydrogen explosion occurrence. The reason of this pressure decrease is not clarified. The D/W and S/C pressures are reversed again. If leaks occurred from the PCV, it would be from the D/W.

### 3.3. PCV pressure changes from 12:00 on March 15th to 18:00 on March 16th

The pressure changes over this time span are shown in Figure 14. During this period, the 5th vent operation was implemented according to the records. The relevant part of Annex 2 to Reference [1] is cited below.

> At 16:00, closure of large and small S/C vent valves (air-operated) confirmed due to failure of the small generator being used for activating the valves. Thereafter at 16:05 the new small generator replaced the old one and activated the large S/C vent valve (air-operated) for opening operation.

Although the opening operation of vent valves was taken, the result is not clarified. As a matter of fact the PCV pressure decrease of about 0.1MPa during 5 hours was lower than the anticipated rate by venting: from 0.415MPa(D/W) at 16:00 to 0.335MPa(D/W) at 21:05, although no data are available for the S/C pressures. From the morning of March 15th, steam release was continuously recognized from the top of Unit-3 R/B as shown in Item 2 above. Therefore, the PCV pressure decrease of this low rate probably comes from the direct release from the PCV.

### 3.4. Deliberation from the PCV pressure changes

From the PCV pressure changes from March 13th through March 16th, it is highly likely that the gas release through the Unit-3/4 stack was only at the 1st and 2nd vents.

It was only toward the end of March that water injection to the reactor started in a stable manner. The fuel debris around March 16th is considered to have been not under good cooling conditions. Therefore, the PCV pressure repeated ups and downs in a balance between overheating and PCV leaks, once the PCV gas release by venting became impossible.

If all opening operations of vent valves after the 3rd (inclusive) had failed, the hydrogen explosion of Unit-4 can be concluded to have occurred due to the hydrogen gas released by the 1st and 2nd vents and flowed into Unit-4 in a reverse flow (*). This means there is a need to examine if the amount of hydrogen gas that flowed into Unit-4 was sufficient to cause the hydrogen explosion.

(*) It was recorded that TEPCO personnel tried to approach the spent fuel pool of Unit-4 at about 10:30 on March 14th in order to check its conditions but gave up entering the R/B because of high dose rate. From investigations of the R/B contamination thereafter, the source of this high dose rate is considered to be rare gases. Rare gases are non-condensable gases released selectively in the venting. Therefore, it can be regarded as certain that the gases released at least by the 1st (and 2nd) vent operations flowed in a reverse flow to Unit-4.

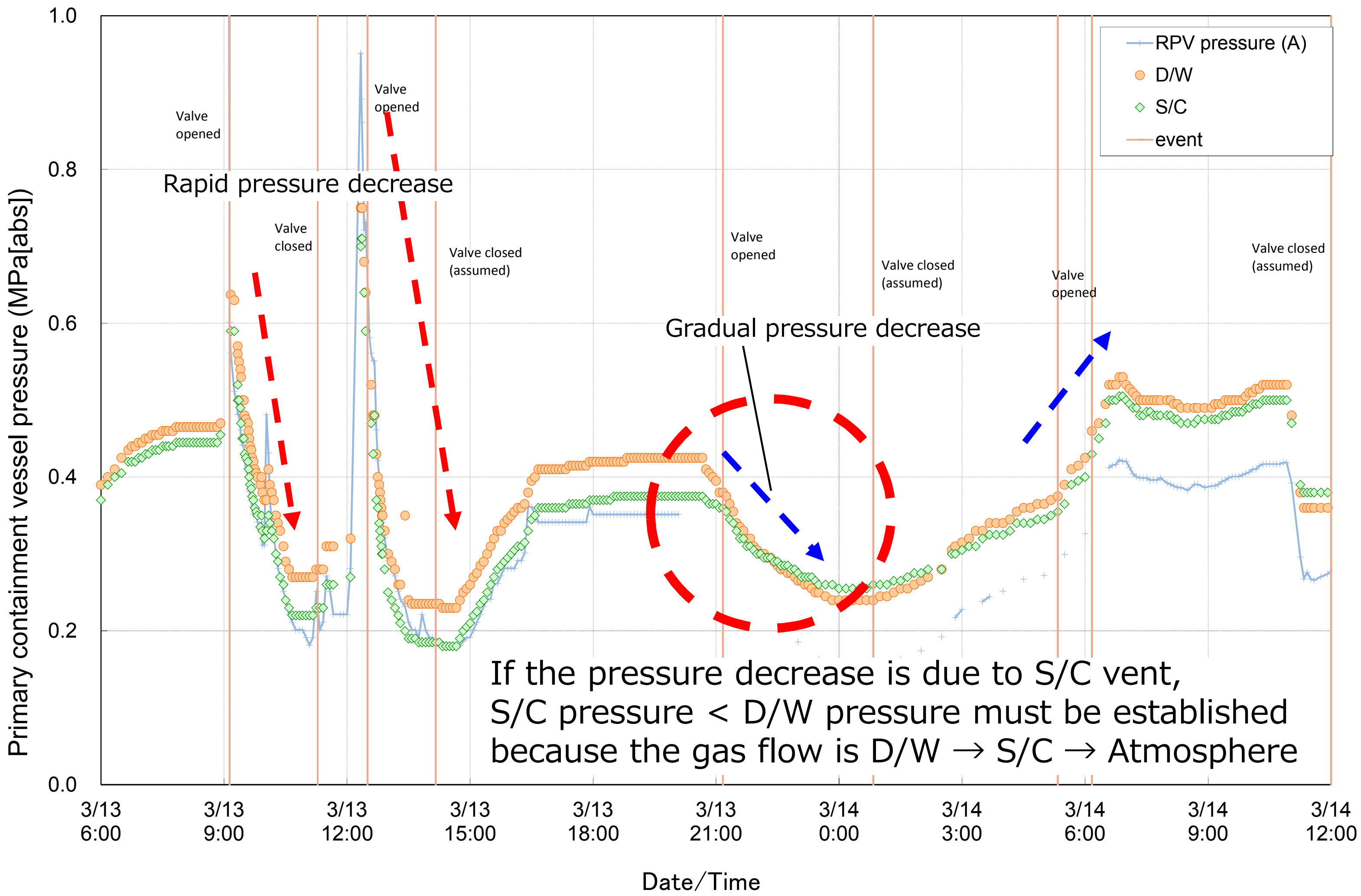


Figure 12 PCV pressure changes at Unit-3 (from 06:00 on March 13th to 12:00 on March 14th)

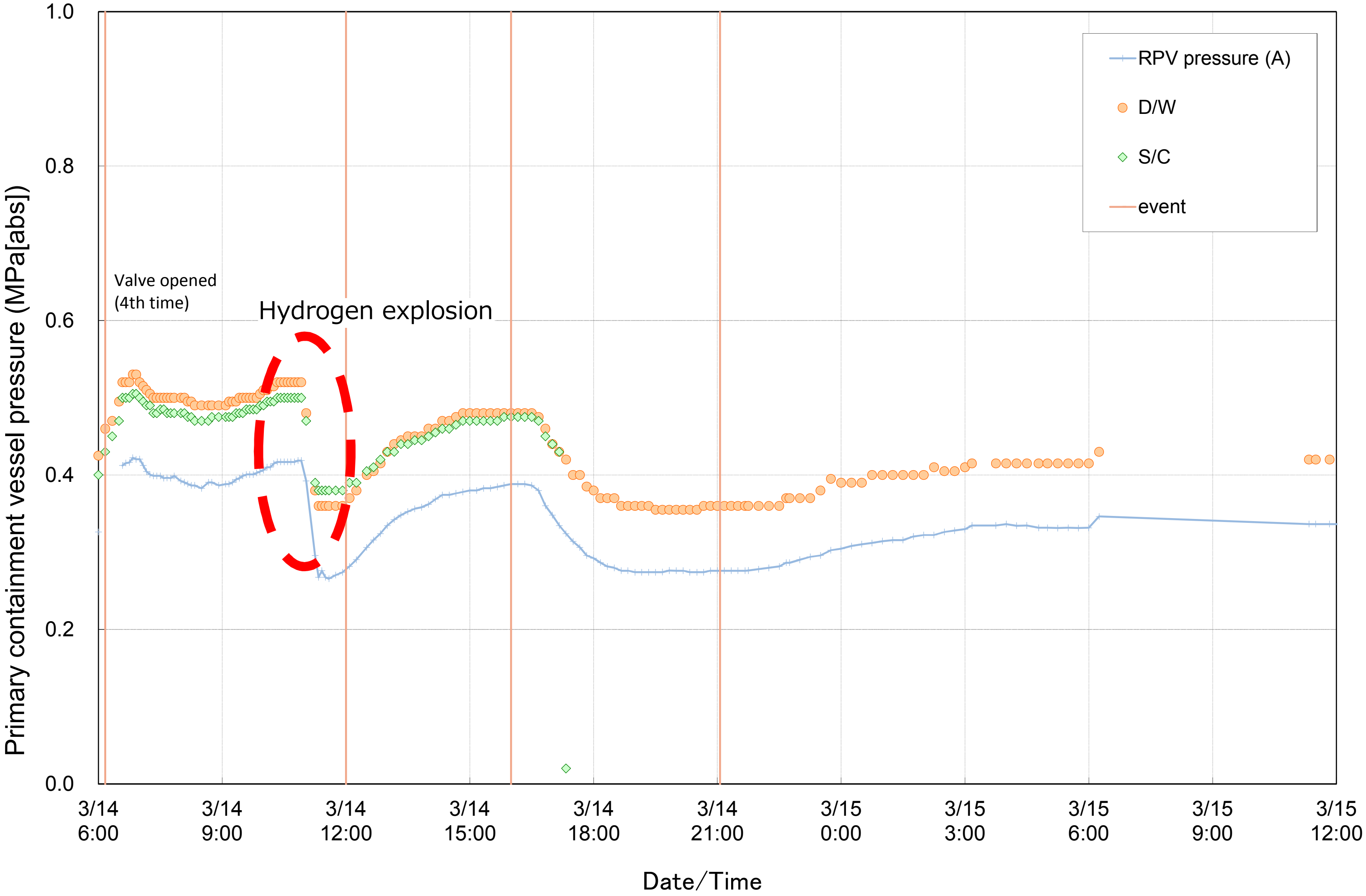


Figure 13 PCV pressure changes at Unit-3 (from 09:00 on March 14th to 12:00 on March 15th)

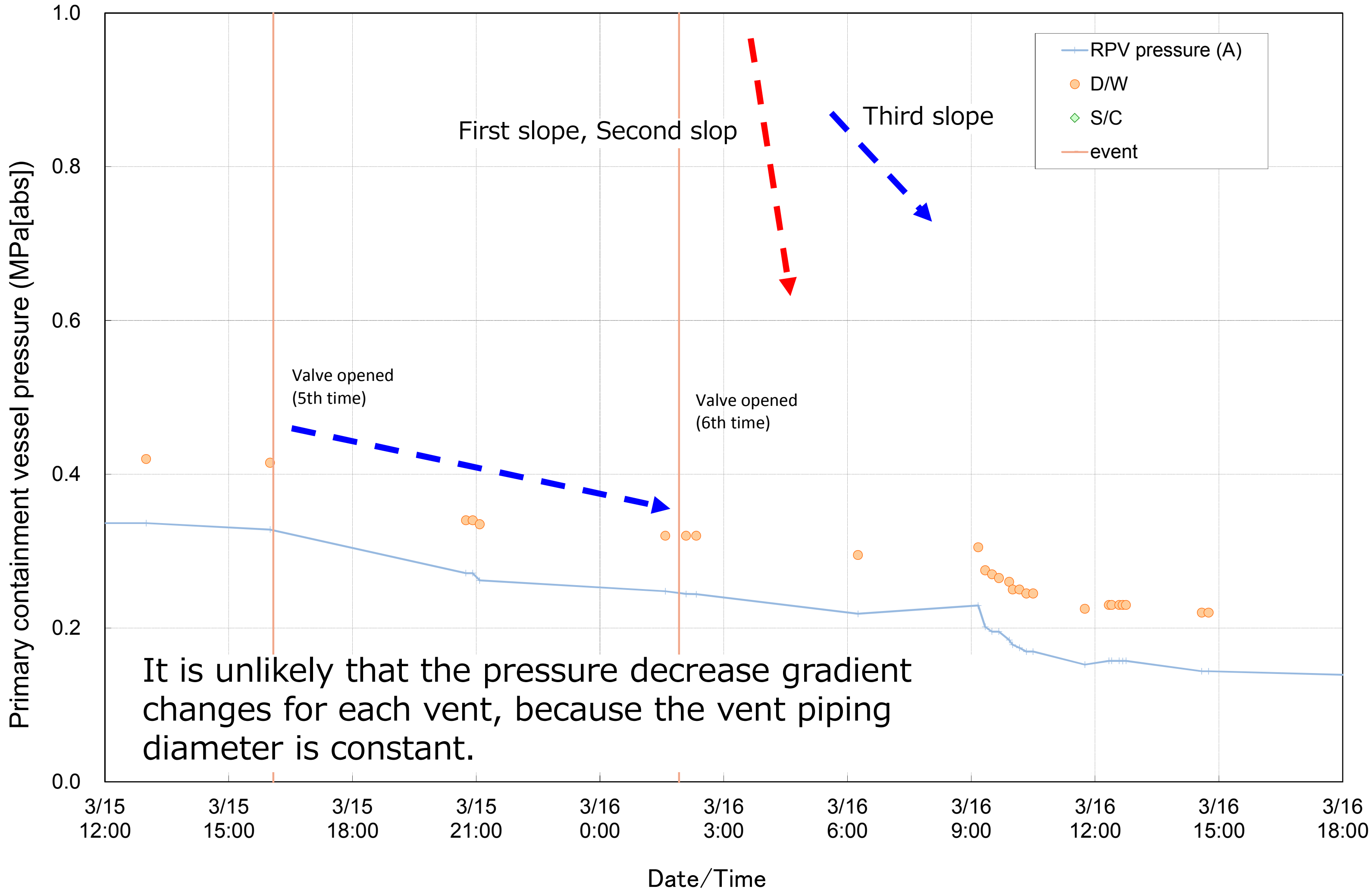


Figure 14 PCV pressure changes at Unit-3 (from 12:00 on March 15th to 18:00 on March 16th)

4. Conclusions

The following points can be concluded from the examinations above.

- Opening operations of vent valves of Unit-3 were clearly successful only at the first venting at about 09:00 and at the second venting at about 12:00 on March 13th.
- At the third opening operation of vent valves at about 21:00 on March 13th, the D/W and S/C pressures reversed and the PCV pressure decrease is unlikely to be achieved by venting.
- An assumption that leaks were continuing from the D/W to the R/B at the time of the third opening operation of vent valves is consistent with the hydrogen explosion at 11:00 on March 14th.
- By the morning of March 15th at the latest, the Unit-3 PCV was in the condition in which steam and radioactive materials were directly released to the environment.
- In the morning of March 15th, the Unit-2 PCV was also in the condition in which steam and radioactive materials were directly released to the environment through the blow-out panel due to the leaks from the PCV (the environmental pollution was caused mainly by the release from Unit-2, according to TEPCO's estimation).
- At the fifth opening operation of vent valves of Unit-3 at about 16:00 on March 15th, the PCV pressure decrease was gradual and likely due to leaks from the PCV.
- The information from photos and other sources suggests that the hydrogen release from Unit-3 on March 16th was fairly sizable (nearly on the scale of that on March 15th).

5. Relation with the safety measures being taken at the Kashiwazaki-Kariwa NPS

As similar results can be seen in Attachment 3-6, it is considered that the PCVs of Unit-1 to Unit-3 of Fukushima Daiichi NPS developed into a situation in which radioactive materials were more or less continuously being discharged to the environment and that this discharge path was the dominant discharge path rather than the path by venting. Therefore, it is essential to maintain the PCV integrity and ensure its confinement function.

Under the severe conditions that existed in the Fukushima Daiichi NPS accident, high temperature steam might have deteriorated silicon gum seals used in the containment vessel top flange or hatches (gaskets) causing the loss of confinement function. From this concern, the following measure has been taken at the Kashiwazaki-Kariwa NPS:

additional backup seal material was coated on the flange outside of such gaskets in order to strengthen their resistance to steam at elevated temperatures. Also being considered is the replacement of silicon-based seal material with a more temperature-resistant seal material (improved ethylene-propylene rubber materials), because silicon-based seal materials have a tendency to deteriorate upon exposure to high temperature steam.

The seal material for the containment air-lock equalizer valves, fluororesin, may experience deterioration in its seal performance when exposed to radiation under severe accident conditions. In order to ensure the integrity (of the confinement capability) under severe accident conditions, the next measure was taken: a blind flange was newly mounted on the R/B side opening of the piping which connected the equalizer valves across the outer side door of the air-lock. The blind flange was equipped with a seal with high tolerance to environmental conditions. An alternative seal material is also being explored for use in equalizer valves, which is more resistant to radiation than fluororesin and to high temperatures.