# Estimation of accident progression at Unit-1 based on the air dose rate monitoring data

## 1. Introduction

Radioactive materials released from nuclear fuel in the course of the nuclear accident at the Fukushima Daiichi Nuclear Power Station (NPS) were released to the environment via the containment vessel (PCV) vent, direct leaks from the PCV, explosions at reactor buildings (R/Bs), etc. Off-site releases of radioactive materials from the accident, their depositions to the soil, and other behaviors were evaluated in terms of the quantities of radioactive materials released, the reasons for highly contaminated areas being found in the northwest direction from the Fukushima Daiichi NPS, and other relevant matters, and the results were reported in "Estimation of the amount of radioactive materials released to the atmosphere at the nuclear accident at the Fukushima Daiichi Nuclear Power Station," (May 2012) [1]. In the evaluation, the sources of released radioactive materials at each timing were attributed to specific units, if that was possible, for instance, due to explosions, venting, etc. Meanwhile, after March 13, when core damage occurred at multiple units and radioactive materials were released, the source unit was estimated based on the knowledge of the accident progression available at the time of the evaluation. The estimated amount of $^{137}$Cs released in the evaluation was roughly similar to the results obtained by other organizations. The results of the $^{137}$Cs deposition evaluation were roughly similar to the deposition amounts evaluated from $^{137}$Cs concentrations in soil obtained by the Ministry of Education, Culture, Science and Technology (MEXT). Thus, a certain degree of understanding has been established concerning the amount of radioactive materials discharged, in particular the amount released off-site causing radioactive contamination. However, all the causalities of radioactive material discharge and accident progression at each unit are not clarified (Common/Issue-7).

Air dose rate changes on-site and off-site at the time of the accident are the result of the release of radioactive materials, and related to the progression of the accident that caused the release. Therefore, by estimating the release behavior of radioactive materials from air dose rate changes, it will be possible to obtain information relevant to accident progression that caused these air dose rate changes. From this viewpoint, the air dose rate changes were analyzed.

The current study focused on understanding the Unit-1 accident progression, which had resulted in the release of radioactive materials, by analyzing the air dose rate changes from about 00:00 to about 08:00 on March 12.

## 2. Air dose rate monitoring data on and off the power station site

### 2.1. Air dose rate monitoring data on and off the power station site

Figure 1 and Figure 2 show the air dose rate monitoring data on-site and off-site [2] from 00:00 to 08:00 on March 12.

The air dose rates on site were being monitored by monitoring cars, because the routinely used monitoring posts (hereafter "MPs") had been out of service due to loss of the power supply[1)]. The air dose rate measurements were being conducted during the time period of interest at two positions, near the Main Gate and MP-8, both about 1 km from Unit-1, as can be seen in Figure 1. It can be seen in Figure 1 that the air dose rates on site remained stable at a low level until about 04:00 on March 12, but significant changes began at and after about 04:00.

The off-site air dose rates were being measured at the Fukushima Prefectural MPs and they continued after the earthquake, too. From Figure 2, it can be seen that the off-site air dose rates remained stable at a low level until about 04:30 on March 12, but significant changes began at and after about 04:30.

Around this time of significant changes occurring in both on-site and off-site air dose rates, Unit-2 and Unit-3 were not in a situation in which fuel damage and ensuing release of radioactive materials were likely to occur, because the reactor core isolation cooling (RCIC) system was in operation at both units, and the reactor water levels were kept above the top of active fuel. On the other hand, Unit-1 was already in a serious condition, with all its reactor cooling and heat removal capabilities having been lost (see the Main Body of the Progress Report for estimated conditions of each unit during the time period of interest). Therefore, the air dose rate change behavior during the time period of interest in the current study, from about 00:00 to about 08:00 on March 12, is believed to have reflected the behavior of radioactive material transfers and releases from Unit-1.

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1) Monitoring data at a small number of MPs could be collected for a limited time at the Main Control Room. The shift operators collected the data to supervise the situation. ("Fukushima Daiichi Nuclear Power Plant Data Sheets at the time of the Tohoku District-off the Pacific Ocean Earthquake," Collection by Shift Operators, December 16, 2014, TEPCO Homepage) (in Japanese)

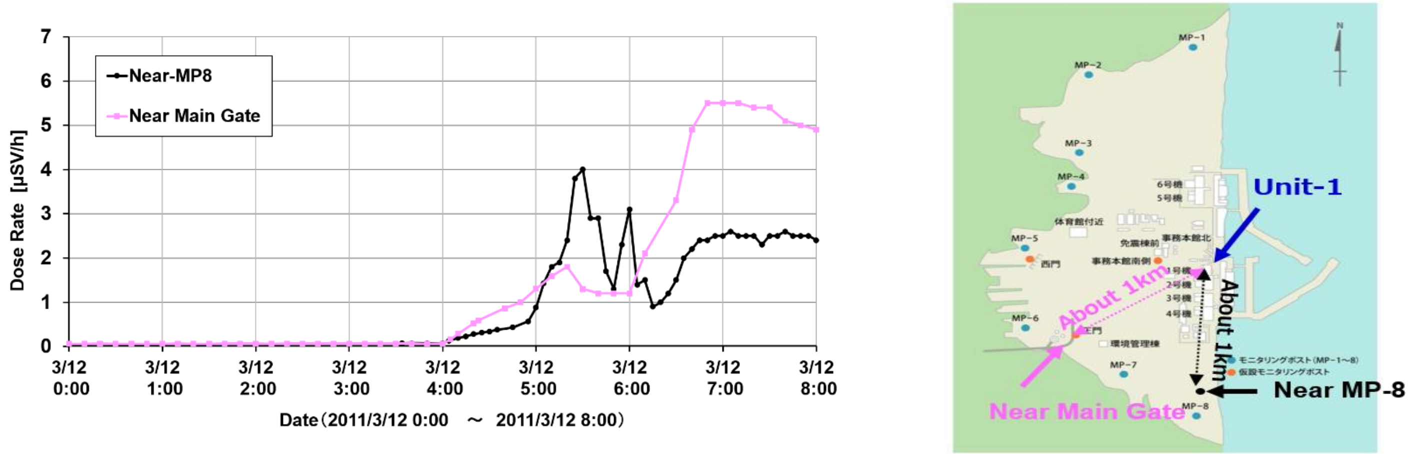


Figure 1 Air Dose rate monitoring data on-site [1]

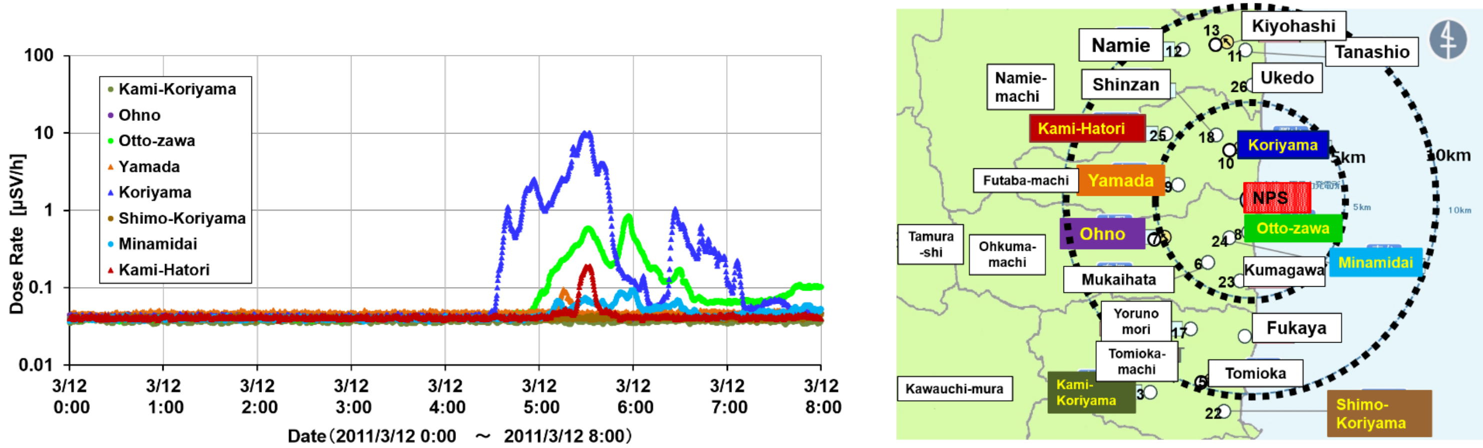


Figure 2 Air dose rate monitoring data off-site [2]

## 2.2. Transfer and release of radioactive materials from the PCV

Radioactive materials that were discharged from the fuel in the wake of fuel cladding failure and fuel damage are transferred to the containment vessel (PCV) either to the suppression chamber (S/C) via safety relief valves (SRVs) or to the drywell (D/W) by leaks from the reactor vessel (RPV). Radioactive materials leaked out to the PCV are released to the environment by (a) the PCV venting or (b) via further leaks to the R/B.

### (a) PCV venting

The PCV venting is done to release the gases in the PCV from the stack to the environment via the S/C or the D/W in order to remove heat (depressurization) from the PCV and prevent its damage. Radioactive materials contained in the gases are released to the environment, but usually they go through the S/C water pool first where they can be trapped and the amount to the environment can be controlled. The PCV venting via the S/C was the path chosen at the time of the accident at Fukushima Daiichi NPS, too, as intended in the design. In the PCV venting, the stack is the release point of the radioactive materials to the environment.

### (b) Leaks to inside the reactor building

When radioactive materials are released to the environment via the R/B, their paths are subject to the conditions. The amount of leakage from the PCV to R/B changes, subject to the accident progression. The PCV is leak-tight, but not perfectly leak-tight. A limited amount of gases in the PCV may leak out to the R/B at a rate below the design leak rates. With the increasing PCV pressures, the amount of the leaks will gradually increase. When the PCV reaches a condition of over-pressures and over-temperatures, the PCV pressure boundaries at relatively weak positions (such as top head flange seals) can be degraded and broken, and significant gas leaks to inside the R/B start.

From the R/B to the environment, radioactive materials may take two paths for release: via the stack or directly from the R/B. The R/B is usually kept at a negative pressure by the stand-by gas treatment system (SGTS), and when radioactive materials transfer from the PCV to R/B, they go through SGTS filters before being released to the environment via the stack. Thus, the concentrations of radioactive materials in the R/B atmosphere are controlled and the amount released to the environment can also be limited. If the radioactive materials cannot be completely trapped by the SGTS filters, their release point to the environment becomes the stack. In reality at the Fukushima Daiichi NPS, the SGTS lost its operability at Units-1 to 3 due to the station black-out. The R/Bs could not maintain their negative pressure, and radioactive materials were released to the environment from the non-leak-tight R/Bs. In other words, when the SGTS is inoperable, the R/B becomes the release point of radioactive materials.

The time period of interest in the current study, from about 00:00 to about 08:00 on March 12, was before the PCV venting and when the SGTS was inoperable at Unit-1. Radioactive materials are considered to have been transferred to the R/B from the PCV and to the environment. Only the R/B can be estimated to have been the release point of radioactive materials. It is important, therefore, to examine the transfer and release behavior of radioactive materials in the R/B.

### 2.3. Characteristics to note in the air dose rate changes

The air dose rates change according to radioactive decays of radioactive materials released to the environment, as was described in Section 2.2. There are two patterns which change air dose rates in the time period of interest in the current study: (A) direct and skyshine radiations from the radioactive materials retained in the R/B; and (B) cloudshine radiation from plumes released from the R/B[2)].

#### (A) Direct and skyshine radiations from the radioactive materials retained in the R/B

Radiation from the radioactive materials released to the R/B penetrates the building outer walls and roofs. Radiation is attenuated when going through outer walls or roofs, but enough radiation goes through them to increase air dose rates in the environment, depending on the amount of radioactive materials being retained in the R/B, and thicknesses of the walls and roofs. Radiation penetrability was relatively higher at the R/B Floor 5 outer walls, which were thinner than those in lower floors, and Unit-1 R/B had thinner walls overall than the other unit R/Bs. The radiation, which penetrated the roofs or outer walls reaches the objects in the pattern of direct radiation or skyshine radiation, with the latter reaching the objects after being scattered by the air. Figure 3 presents schematic images of direct and skyshine radiations, and an example of air dose rate changes due to them. The air dose rates due to direct and skyshine radiations are independent of wind direction at all measurement points. The air dose rates change less with a longer distance from the radiation source to the measurement points. The scale

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[2)] There is another pattern of radiation, groundshine radiation. Groundshine radiation occurs from radioactive materials deposited in the soil when radioactive materials are spread by the plumes. After the air dose rate peaks due to the passing plumes, they gradually decrease according to the attenuation curve of the radioactive materials deposited. In the time period of interest in the current study, no such behaviors are noticed. Therefore, only two patterns of radiation were discussed in the current study.

of the changes depends on the shielding conditions, too, but when a change is noticed at one position, it changes everywhere at the same timing. Consequently, when radioactive materials transfer to the R/B, dose rates at all measurement points increase, as illustrated in the graph, depending on the amount of radioactive materials in the R/B. The dose rate changes as a function of the amount of radioactive materials transferred from the PCV to the R/B, release to the environment from the R/B, kinds of radioactive materials retained in the R/B and their attenuation, and other factors.

(B) Cloudshine radiation from plumes released from the R/B

Radioactive materials released from the R/B to outside diffuse in the form of plumes. Radiation emitted upon decay of radioactive materials in clouds is called cloudshine radiation. Figure 4 presents a schematic image of cloudshine radiation, and an example of air dose rate changes due to it. Plumes of the released radioactive materials diffuse over large distances, depending on the wind velocities and atmospheric conditions, but mainly on the wind conditions. Air dose rates vary from one measurement point to another, strongly depending on the direction from the radioactive material release point. When a measurement point is located downwind, the air dose rate increases as the plumes approach the point and decreases as they leave it, as illustrated in Figure 4. In other words, a peak as seen in this figure is characteristic of air dose rate changes due to cloudshine. The peak height and width are determined by the amount of radioactive materials released, wind directions, wind velocities, kinds of radioactive materials and other factors. As the plumes diffuse faraway, cloudshine radiation is detectable, even outside the plant site, too, while direct and skyshine radiations are harder to detect.

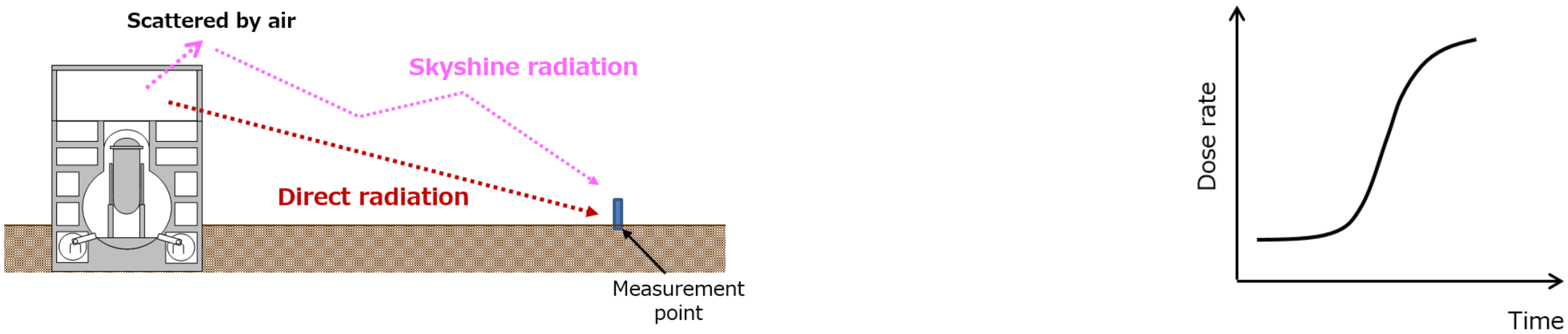



Figure 3 (A) Direct radiation and skyshine radiation; air dose rate changes due to direct radiation and skyshine radiation

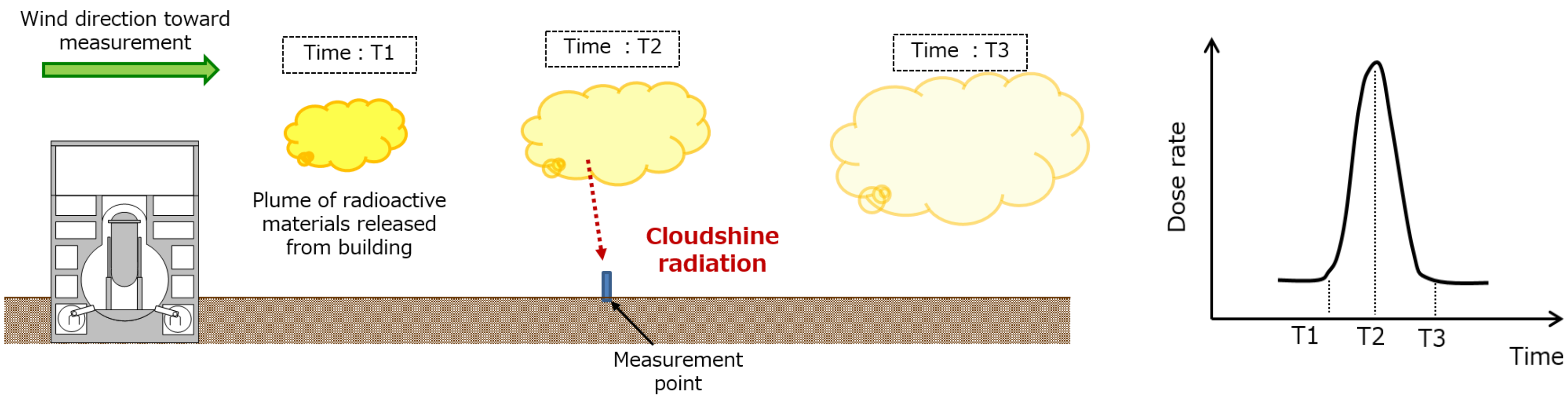
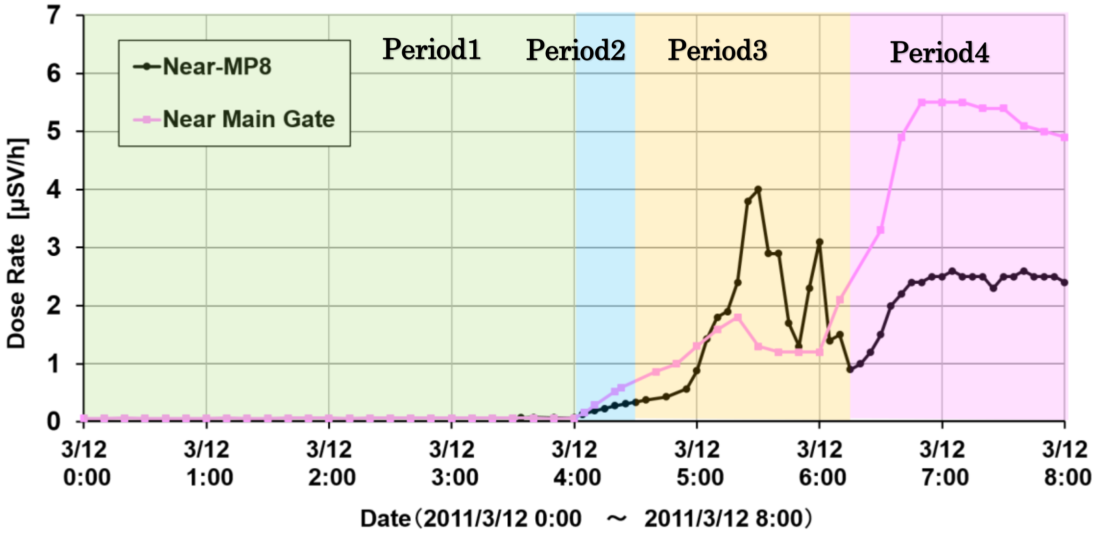



Figure 4 (B) Cloudshine radiation; air dose rate changes due to cloudshine radiation

3. Estimation of accident progression at Unit-1

3.1. Estimation of radioactive material transfer and release behaviors based on the air dose rate change behavior

The time period of interest in the current study was segmented into four sub-periods shown in Figure 5, and the transfer and release behaviors of radioactive materials were estimated based on the air dose rate changes on-site and off-site.



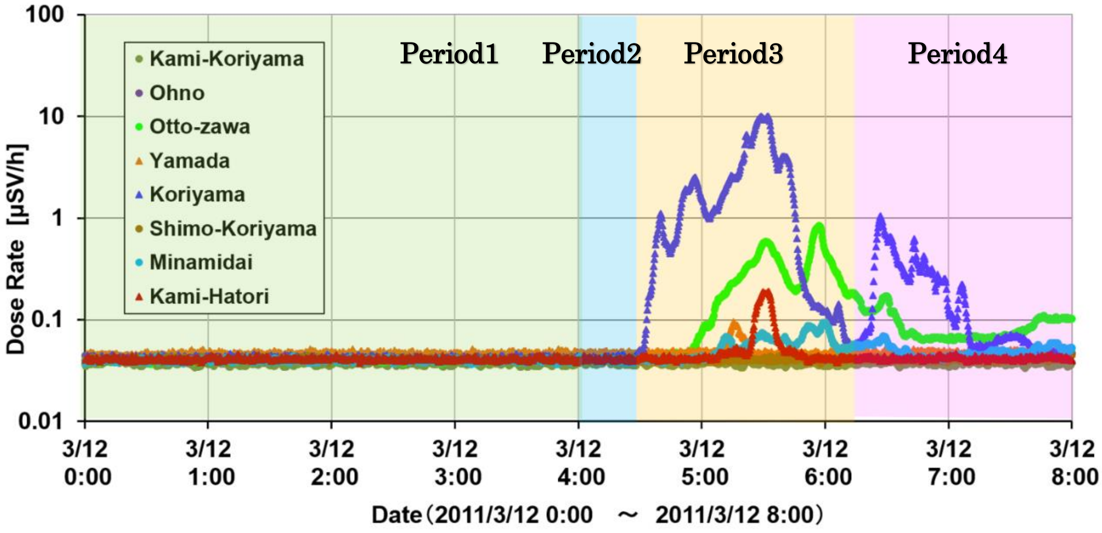




Figure 5 Air dose rates monitoring data and time sub-periods

(Top: On-site, Bottom: Off-site; the MP locations can be seen in the map of Figure 2)

| | |
|---|---|
| Period 1 (before about 04:00) | There were no noticeable changes in the on-site and off-site air dose rates. Therefore, radioactive material transfer to the R/B and environment from the PCV is estimated to be not so much that the air dose rate change would be noticed outside the R/B. |
| Period 2 (about 04:00 to 04:30) | Air dose rates on-site near the Main Gate and MP-8 increased simultaneously, but there were no peaks, a typical mode of Pattern A radiation (direct and skyshine radiations). The amounts of radioactive materials transferred to the R/B from the PCV are estimated to be so much that the air dose rate change would be detected near the Main Gate and Point MP-8. |
| Period 3 (about 04:30 to a little after 06:00) | Air dose rate peaks, characteristic of Pattern B (cloudshine radiation), were noticeable on-site and off-site. The first peak was noticeable at a little after 04:30 at an MP near Koriyama (data shown by the blue triangles of Figure 5), but it was too early to conclude this was when the release from the R/B had started, because no information was available on the air dose rate changes on the east side (seaside). The air dose rate changes in Pattern B are significant, but Pattern A (direct and skyshine radiations) is considered still to be continuing. Therefore, radioactive release from the R/B to the environment is estimated to have started at the latest by 04:30. |
| Period 4 (a little after 06:00 to about 08:00) | Air dose rates on-site near the Main Gate and at MP-8 increased almost simultaneously and then remained almost flat thereafter. This is considered to indicate the characteristics of Pattern A (direct and skyshine radiations). It is recognized that the air dose rates are higher after they stabilized than the earlier levels. Additional transfer of radioactive materials is estimated to have occurred from the PCV to R/B. In the meantime, the air dose rate changes off-site showed peaks, the Pattern B (cloudshine radiation) characteristic. It can be estimated that radioactive materials continued to be released from the R/B to the environment. |

## 3.2. Interpretation of estimated transfer and release behaviors of radioactive materials based on the Unit-1 PCV pressure change behavior

The correlation is reviewed in this section between the transfer and release behaviors of radioactive materials estimated from the air dose rate change behavior discussed in Section 3.1, and the Unit-1 PCV pressure change behavior.

Figure 6 compares the on-site air dose rate changes and the Unit-1 PCV pressure changes. The D/W pressure at 0.84 MPa[abs] at 02:45 decreased to 0.78 MPa[abs] at 04:19, and 0.77 MPa[abs] at 04:35 (① in Figure 6). Thereafter, it increased from 0.74 MPa[abs] at 06:00 to 0.79 MPa[abs] at 06:30 (② in Figure 6). While the PCV pressures were changing (① and ②), the on-site air dose rates were increasing, too. These increasing trends of air dose rates highlight the characteristics of Pattern A (direct and skyshine radiations), as seen in Period 2 and Period 4 in Section 3.1. It is considered that radioactive materials transferred from the PCV to the R/B during time period ① and further transferred during time period ②.

During the time period ①, when the PCV pressure was decreasing, fire engines were injecting water into the reactor at about 04:00. But it is estimated that the amount of water injected was limited because of the high reactor pressure (see Attachment 1-5) and therefore the PCV cooling and heat removal were very ineffective. Consequently, the PCV pressure decrease is considered to have been the result of PCV pressure boundary damage and ensuing gas leaks. This estimation is consistent with the estimation that radioactive materials transferred at about 04:00 in a quantity large enough to contribute to the air dose rate increase on site near the Main Gate and at MP-8 (Period 2).

Additional transfer of radioactive materials is estimated to have occurred during time period ② from the PCV to the R/B. If the increasing trend of air dose rates is assumed to have been caused simply by the increased amount of leaked gases due to an enlarged leak area of the PCV, the PCV pressure should have decreased as was the case in period ① (it should be noted that the water injection resumed at 05:46 by fire engines is considered to have been very ineffective in changing the PCV pressures, as was the case at about 04:00). The PCV pressures actually increased during period ②, on the contrary. In other words, some unknown event is considered to have occurred in the PCV, and increased its pressures by overcoming the decreasing trend due to gas leaks from the PCV, which had already started during period ①. This new event during period ② is considered to have increased the amount of leaked gases from the PCV, and that increased the amount of gas transfer to the R/B and then increased the air dose rates accordingly.

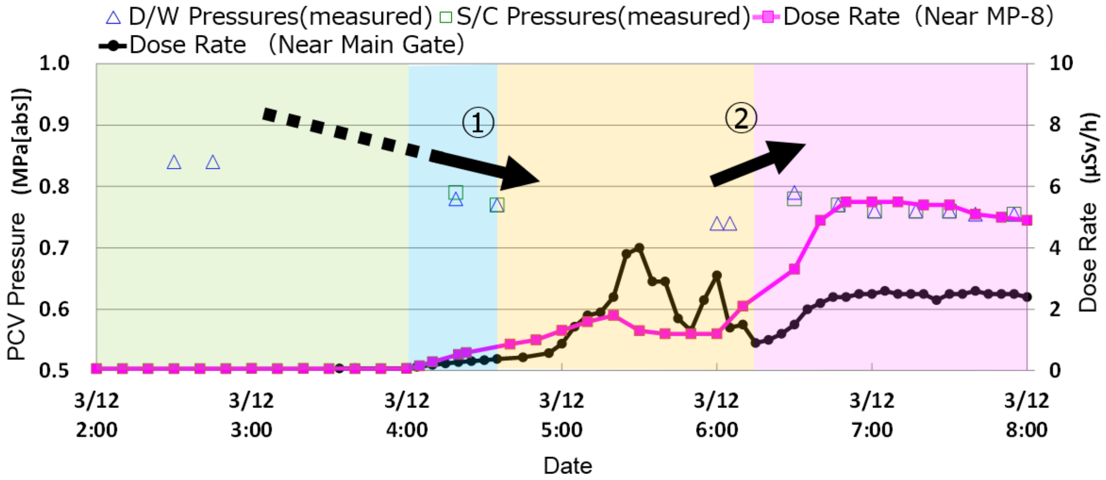



Figure 6 On-site air dose rate changes and Unit-1 PCV pressures

## 3.3. Estimation of accident progression at Unit-1

An accident progression scenario of Unit-1 has been estimated as below, based on the estimation of radioactive material transfer and release behaviors from the air dose rate changes in Section 3.1 and the deliberation on the correlation between the air dose rate changes and the PCV pressures in Section 3.2.

| | |
|---|---|
| Estimation (1) | No significant leaks of radioactive materials occurred from the PCV to the R/B and further to the environment as to be noticeable outside the R/B until about 04:00 on March 12. |
| Estimation (2) | At about 04:00, the amount of radioactive materials transferred from the PCV to the R/B was so much as to be noticeable outside the R/B. |
| Estimation (3) | By about 04:30, at the latest, radioactive materials leaked from the R/B to the environment. |
| Estimation (4) | At about 06:00, some unknown event occurred in the PCV, increased the PCV pressures and contributed to the increased transfer of radioactive materials to the R/B. |

## 3.4. Comparison of Unit-1 accident progression scenarios of the current study and studies to date

The Unit-1 accident progression scenario estimated in Sections 3.1 to 3.3 based on the air dose rate change behavior was compared with another accident progression scenario derived in the earlier study based on the changes of water level indicator readings (Attachment 1-6).

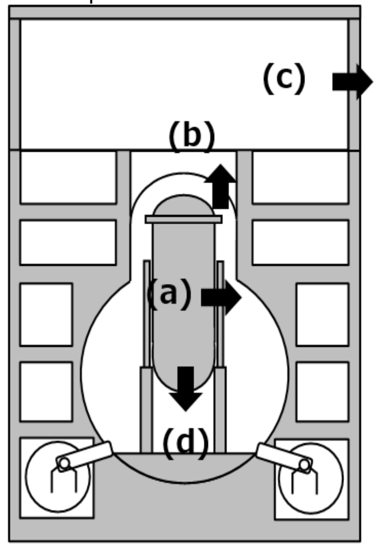
Table 1 compares the two scenarios of this study and the earlier study. The accident progression scenario in the latter estimated that, as of March 11, the fuel had melted, radioactive materials had transferred from the RPV to PCV and molten fuel had been relocated from the core region to the RPV (bottom head). In other words, radioactive materials were already transferred to the PCV and no inconsistency is noticeable between this earlier scenario and Estimations (1) and (2) derived in the current study: <Estimation (1)> No significant leaks of radioactive materials occurred until about 04:00 on March 12 from the PCV to the R/B as to be noticeable outside the R/B; and <Estimation (2)> At about 04:00, the amount of radioactive materials transferred from the PCV to the R/B was so much as to be noticeable outside the R/B. The accident progression scenario in the earlier study further estimated that the RPV bottom head had been damaged at about 06:00 on March 12, and molten fuel had been relocated to the PCV. This estimation is consistent with <Estimation (4)> in the current study, that is, "Some unknown event occurred at about 06:00 which increased the PCV pressures," since the high temperature molten fuel increases the PCV pressures, when it relocated to the PCV.

The Unit-1 accident progression scenario estimated in the current study based on the air dose rate change behavior is concluded to be consistent with the accident progression scenario derived in the earlier study.

Table 1 Comparison of accident progression scenarios estimated from the air dose rate monitoring data (current study) and the scenario from the water level indicator readings (earlier study)

| Date/Time | Scenario in the earlier study (Attachment 1-6) | Scenarios estimated based on the air dose rate change behavior and PCV pressure change behavior |
|---|---|---|
| March 11 | • Fuel melted, radioactive materials relocated from the RPV to the PCV ((a) in the right figure)<br>• Molten fuel relocated from the core region to the RPV (bottom head) | <Estimation (1)><br>No significant leaks of radioactive materials occurred from the PCV to the R/B and further to the environment as to be noticeable outside the R/B until about 04:00 on March 12. |
| At about 04:00 on March 12 | | <Estimation (2)><br>At about 04:00, the amount of radioactive materials transferred from the PCV to R/B was so much as to be noticeable outside the R/B ((b) in the right figure |
| At about 04:30 on March 12 | | <Estimation (3)><br>By about 04:30, at the latest, radioactive materials leaked from the R/B to the environment. ((c) in the right figure |
| At about 06:00 on March 12 | • RPV (bottom head) damaged ((d) in the right figure) | <Estimation (4)><br>At about 06:00, some unknown event occurred in the PCV, increased the PCV pressures and contributed to the increased transfer of radioactive materials to the R/B ((d) in the right figure |

Transfer paths of radioactive materials




(a) RPV (via piping connected) to PCV
(b) PCV to R/B
(c) R/B to environment
(d) RPV (via bottom head) to PCV

4. Conclusion

The Unit-1 accident scenario was estimated to obtain better understanding of the accident progression, which had led to the release of radioactive materials to the environment. The estimation focused its attention on the early phase of the accident and analyzed the air dose rate change behavior on-site and off-site as well as the PCV pressure change behavior.

When analyzing the air dose rate change behavior, the transfer and release behaviors of radioactive materials were estimated by identifying the respective significant pattern of air dose rates in several time periods of interest, i.e., either the direct and skyshine radiations from radioactive materials transferred from the PCV to the R/B, or the cloudshine radiation from the plumes of radioactive materials released from the R/B to the environment.

The air dose rate change behavior was also interpreted from the viewpoint of the PCV pressure change. The following accident progression scenario was concluded to be reasonable.

| | |
|---|---|
| Estimation (1) | No significant leaks of radioactive materials occurred from the PCV to the R/B and further to the environment as to be noticeable outside the R/B until about 04:00 on March 12. |
| Estimation (2) | At about 04:00, the amount of radioactive materials transferred from the PCV to the R/B was so much as to be noticeable outside the R/B. |
| Estimation (3) | By about 04:30, at the latest, radioactive materials leaked from the R/B to the environment. |
| Estimation (4) | At about 06:00, some unknown event occurred in the PCV, increased the PCV pressures and contributed to the increased transfer of radioactive materials to the R/B. |

Upon comparison of the accident progression scenario derived in the current study with the scenario derived in the earlier study, no inconsistency was noticed.

References

[1] Estimation of the amount of radioactive materials released to the atmosphere at the nuclear accident at the Fukushima Daiichi Nuclear Power Station, TEPCO, May 2012
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