Estimation of reactor water levels at the time when core damage and core melt progressed at Unit-3

This document was prepared based on the proposal and evaluation by TEPCO Systems Corporation concerning the behavior of readings of water level indicators of Unit-3, both listed in Attachment 2 “List of issues” as “Common/Issue-3” and “Unit-3/Issue-2”.

1. Introduction

At Unit-3, readings of the wide range water level indicators were recorded until about 20:30 on March 12, 2011. After recording capability was lost once, the wide range and fuel range water level indicators resumed recording at around 04:00 on March 13. As at Unit-1 and Unit-2, the water level indicators might have given incorrect readings, while temperatures were elevated in the reactor pressure vessel (RPV) and containment vessel (PCV). But it is possible to estimate the reactor water level behavior, which is significant in accident progression, by analyzing the readings based on the characteristics of the water level indicators mentioned in Attachment 1-2. With this background, the actual reactor water level changes were estimated based on measured values of plant parameters including water level indicator readings between 04:00 and 14:00 on March 13, 2011, when the core damage and core melt had developed at Unit-3.

2. Estimation of reactor water level behavior from measured values

Figure 1 shows the measured plant parameters from 04:00 to 14:00 on March 13, 2011. Actual behavior of reactor water levels during the Periods ① to ⑤ in the figure were estimated based on the measured parameters in each period.

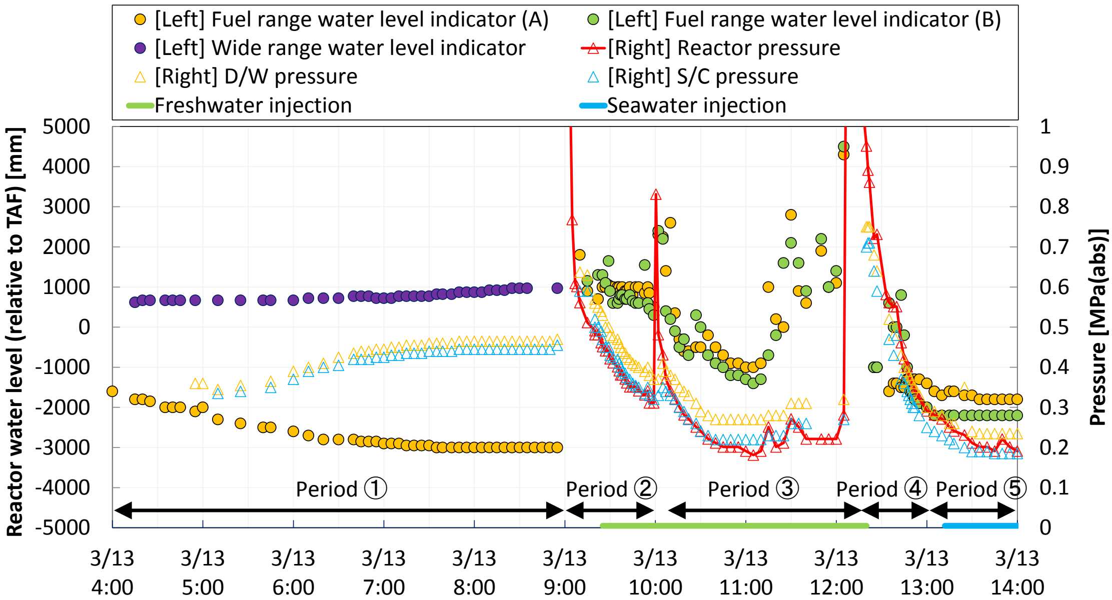

Figure 1 Plant parameters measured (04:00 to 14:00 on March 13, 2011)

Table 1 presents the estimated results of actual reactor water levels during the Periods ① to ⑤. Table 1 also gives the estimated water levels in water level indicator piping as relevant information. Sections 2.1 to 2.5 elaborate on the grounds of the estimation in each period.

Table 1 Estimated results of actual reactor water levels

Period	Actual reactor water level	Reference leg water level (relevant information)	Variable leg (fuel range) water level (relevant information)	Grounds given in
Period ① About 04:00 to 09:00	Decreasing in the core region, down to reach near BAF at 08:55	Filled, or almost filled	Filled	Sec. 2.1
Period ② About 09:00 to 10:00	Down to reach below about BAF-1.6m by decompression boiling	Down to reach a level near PCV penetrations	Being maintained	Sec. 2.2
Period③ About 10:00 to 12:00	Remained below about BAF-1.6m	Being maintained	Gradually down until about 11:00, then gradually up	Sec. 2.3

Period ④ About 12:00 to 13:00	Being maintained	Up to some extent and again down to reach a level near PCV penetrations	Filled until about 12:30, then down gradually to reach a level near PCV penetrations	Sec. 2.4
Period ⑤ About 13:00 to 14:00	Being maintained	Being maintained	Being maintained	Sec. 2.5

2.1. Period ① (from 04:00 to about 09:00)

The estimated actual reactor water level and water level indicator piping water levels (Table 1)

- ➢ Reactor water levels: Decreasing in the core region, down to reach a level near BAF at 08:55
- ➢ Reference leg water levels: Filled or almost filled
- ➢ Variable leg (fuel range) water levels: Filled

Period ① corresponds to the period when the reactor water level was considered to have been gradually decreasing after the HPCI water injection capability had been lowered. Readings of the fuel range water level indicator (A) remained constant at TAF (top of active fuel) – 3000mm, which suggests that the reactor water level had been lowered below TAF. It should be noted that these readings of TAF-3000mm are not the lower limit of the indicator measurement range, and therefore they are considered to have reflected the actual pressure difference between the fuel range water level indicator piping (reference leg and variable leg). It should be further noted that, while the readings remained constant, this pressure difference also remained constant, and therefore, the heads of the reference leg and variable leg would have been changing in a similar manner.

Between 07:35 and 08:55, when the readings of the fuel range water level indicator remained constant, the in-PCV temperatures were about 130 to 140 deg C according to the MAAP analysis (Attachment 3: “MAAP Analysis” in this document always refers to the information given in Attachment 3). By combining this condition with the reactor pressure, the readings of the fuel range water level indicator can be corrected to about TAF-2700mm. This corrected water level corresponds to about BAF (bottom of active fuel) +1m, which means that the cooling water in the reactor contacted the fuel as high as about 1 m. But there is no reason for the reactor water level to stop decreasing at this period, because no water injection was being conducted (see Attachment 3-4). Nevertheless, the readings of fuel range water level indicator remained constant.

In the meantime, the readings of the wide range water level indicator gradually increased in Period ①: TAF+620mm at 04:15, TAF+670mm from 04:20 to 06:00 and as high as TAF+970mm by 08:55. Figure 2 illustrates the piping arrangement of wide range and fuel range water level indicators in the PCV.

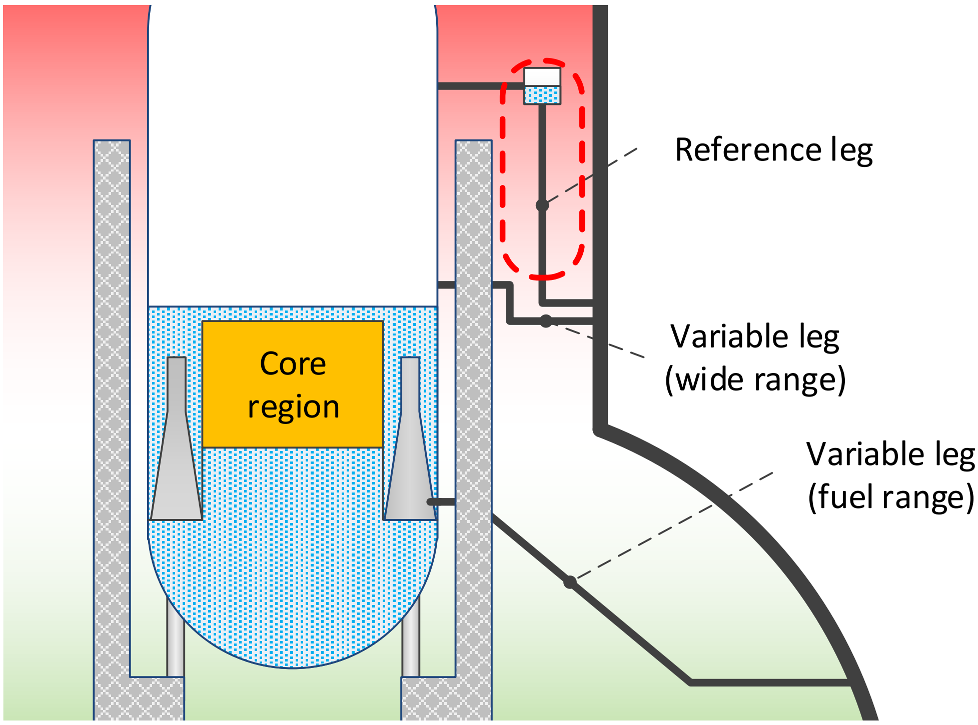

Figure 2 Piping arrangement of wide range and fuel range water level indicators in the PCV

The wide range water level indicator converts the head difference between the reference leg and variable leg (wide range) in Figure 2 to its readings. The reactor water level during this period is believed to be below TAF. Therefore, the connection part of the variable leg (wide range) is considered to have been uncovered. On the other hand, since the PCV penetrations for the reference leg and variable leg (wide range) are on the same level, the readings of the wide range water level indicator are believed to correspond to the water head of the portion enclosed in the red dashed line in Figure 2. The water head of the subject portion to reproduce the readings at 08:55 can be estimated to be about 48 kPa from the structural configuration of the wide range water level indicator. It should be noted that the water level decrease in the piping of the water level indicators on the building side (outside the PCV) would be negligible, because, as mentioned later in Section 2.5, no indications are confirmed during Period ⑤ which point to water level decreases in the piping of the water level indicators downstream from PCV penetrations (reactor building side).

The water head depends on the water levels in the piping and the water densities (water temperatures). Water levels and water temperatures in the piping were not measured, and so water temperatures were identified which could reproduce the wide range water level indicator readings at 08:55 by changing water level in the reference leg as a parameter. These results are given in Table 2. Water temperature in the reference leg is believed to be close to any one of the situations in Table 2, when the PCV gas temperature of about 130 to 140 deg C by MAAP analysis is taken into consideration.

Table 2 Reference leg conditions to reproduce the wide range water level indicator readings at 08:55

Water level	Water temperature
Filled (top)	219 deg C
10 cm below top	207 deg C
20 cm below top	194 deg C
30 cm below top	180 deg C
40 cm below top	164 deg C
50 cm below top	146 deg C
60 cm below top	125 deg C

Water level and temperature of the fuel range water level indicator reference leg are also considered to be close to any one of the situations in Table 2, since the reference legs of the fuel range and the wide range water level indicators were installed at similar positions, and their routings were similar, too.

The water temperature in the variable leg affects readings. As seen in Figure 2, variable legs of the fuel range and the wide range water level indicators were installed at different elevations. They might have been in a different temperature environment, even if they were in the same D/W environment. At Unit-3, the D/W was being sprayed at this timing. The D/W spray nozzle was located at a high position of the spherical-shaped part in the D/W. As Figure 2 illustrates, the variable leg (fuel range) was also positioned at an elevated point in the spherical-shaped part in the D/W and could be effectively cooled by the D/W spray. The water temperature of the variable leg (fuel range) might have been lowered more than that in the reference leg.

In order to identify possible influence on the water level indicator readings by water temperature in the variable leg (fuel range), the reactor water levels were estimated which could reproduce the fuel range water level indicator readings at 08:55 under the respective conditions of the reference leg given in Table 2. The in-PCV temperature was changed by 30 deg C above (+) or below (-) the MAAP estimate of 130 to 140 deg C. The results were from TAF-3400mm to TAF-3600mm (Table 3). Since these levels were near the bottom of active fuel (BAF), the reactor water level was estimated to have been near BAF before reactor depressurization at about 09:00 on March 13, 2011.

Table 3 Reactor water level at 08:55 reproducing fuel range water level indicator readings

Water temperature in variable leg	Reactor water level
100 deg C (Lowest MAAP estimate -30 deg C)	About TAF-3600mm
135 deg C (Average MAAP estimate)	About TAF-3500mm
170 deg C (Highest MAAP estimate +30 deg C)	About TAF-3400mm

One possible scenario in this Period ① is the following. When the reactor water level was lowered to near BAF, the reactor water level decrease would have been relaxed, because the heat transfer area from fuel to water as well as the decay heat per unit fuel length were reduced. Meanwhile, the fuel range water level indicator showed constant readings from 07:35 to 08:55 and the wide range water level indicator showed gradually increasing readings during the same period. Since both water level indicators give higher readings at higher PCV temperatures, the PCV temperature is considered to have been actually increasing during this period. A scenario could be that the actual reactor water level was gradually lowering, decreasing readings of the fuel range water level indicators were canceled by the effect of increasing PCV temperature, and the fuel range water level indicator readings apparently remained constant.

2.2. Period ② (from about 09:00 to about 10:00)

The estimated actual reactor water levels and water level indicator piping water levels (Table 1)

- Reactor water level: Decreased down to reach a level below about BAF-1.6m due to decompression boiling
- Reference leg water levels: Decreased down to reach a level near PCV penetrations
- Variable leg (fuel range) water levels: Continued being filled

Figure 3 shows plant parameters measured in Period ②. The reactor is estimated to have been depressurized at about 09:00 by the automatic depressurization system (ADS) (Attachment 3-3). The suppression chamber (S/C) is estimated to have been vented at a similar timing (Attachment 3-8).

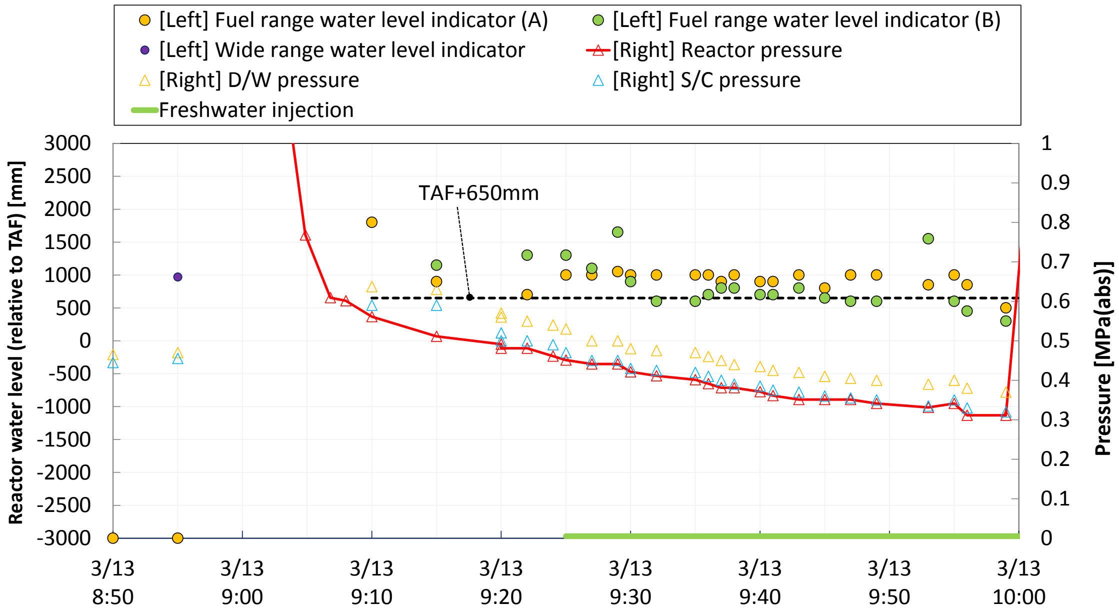

Figure 3 Plant parameters measured (Period ②)

As seen in Section 2.1, the reactor water level before depressurization is estimated to be near BAF. The reactor water level after depressurization is estimated to have cut under the level of the connection part of the variable leg (fuel range) (about BAF-1.6m), by taking the reactor water inventory before depressurization and the water level decrease due to decompression boiling into account. In the meantime, the fuel range water level indicator readings jumped, after depressurization at around 09:00, from TAF-3000mm at 08:55 to about TAF+1000mm during about 09:00 to 10:00.

The fuel range water level indicator provides the highest reading in a situation in which the reactor water level is below the connection part of the water level indicator (fuel range) piping, when the reference leg is dried out above the PCV penetrations and the variable leg (fuel range) is filled. For this situation, the readings should be about TAF+650mm. As this reading is close to the measured value (about TAF+1000mm), the water levels in the piping are considered to have been in a situation like this.

2.3. Period ③ (from about 10:00 to about 12:00)

The estimated actual reactor water levels and water level indicator piping water levels (Table 1) ➢ Reactor water level: Remained below about BAF-1.6m ➢ Reference leg water levels: Remained at a level near PCV penetrations ➢ Variable leg (fuel range) water levels: Gradually decreased until about 11:00 from filled level, then gradually increased

Figure 4 shows plant parameters measured in Period ③. In this period, the fuel range water level indicator readings decreased, and then turned to increase. A spike-shaped pressure increase was recorded twice, at about 10:00 and at about 12:00, while the PCV pressure and RPV pressure were decreasing due to S/C venting.

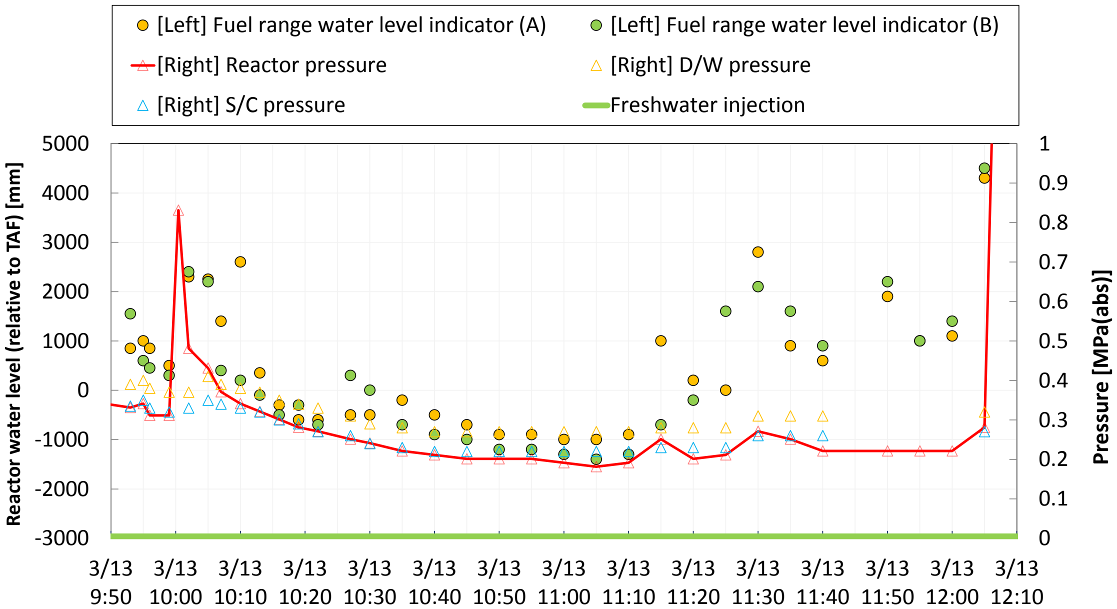

Figure 4 Plant parameters measured (Period ③)

The fuel range water level indicator readings were in a decreasing trend until about 11:00. The reactor water level around this time is considered to have been lowered below the connection part of the variable leg (fuel range) (about BAF-1.6m), as seen in Section 2.2. Two possibilities are considered for the readings to drop: the reference leg water level increases; and the variable leg (fuel range) water level decreases. The first possibility may be excluded, because it is considered difficult to increase the water level in the reference leg while the reactor was being depressurized. Therefore, the lowering of readings would have been due to a gradual decrease of the variable leg (fuel range) water levels by decompression boiling and other reasons.

Thereafter until about 11:40, the fuel range water level indicator readings increased. Two possibilities are considered for the readings to rise: the reference leg water level decreases: and variable leg (fuel range) water level increases. The first possibility may be excluded, because the reference leg is considered to have been almost dried out above the PCV penetrations, as mentioned in Section 2.2, and further water decrease is considered unlikely. Therefore, it is likely that the rising readings in this period were due to the increased water level in the variable leg (fuel range). The variable leg (fuel range) water level could have increased by the reactor water level recovering to the level of the connection part of the variable leg, steam condensing in the variable leg, or some other reasons. In any case, the reactor water level is estimated roughly to have been below the level of the connection part of the variable leg.

It should be noted that the fuel range water level indicator readings temporarily increased by about 2 m at 10:00 to 10:10, and by about 3 m at 12:05. At these timings, water injected by the diesel-driven fire pumps and fire engines might have reached the reactor, but that was unlikely to be so much as to increase the reactor water level by several meters in several minutes.

This period is considered as the period when the molten fuel dropped to the lower plenum and the steam production increased in the reactor, because the reactor pressure increased and decreased in this period. Temporary increases of water level indicator readings could have been caused by the pressure difference due to temporary steam flows in the reactor between the two connection parts of the reference leg and the variable leg (fuel range). To sum up, the situation in the reactor could have been as follows.

(1) Steam was produced when the molten fuel dropped down to the lower plenum.

(2) The pressure at the connection part of the variable leg (fuel range) became higher against that at the connection part of reference leg due to the pressure drop of the steam flow.

(3) The resulting bigger pressure difference was transmitted to the pressure difference gauge as the pressure difference between the reference leg and variable leg.

(4) The fuel range water level indicator responded with higher readings.

Another possibility is that the increased readings of the fuel range water level indicator were caused when the reactor water level temporarily exceeded the level of the connection part of the variable leg (fuel range) by the sharply increased lower plenum water levels (two-phase water level including bubbles) due to abrupt heat transfer to the water from the fallen molten debris.

It should be noted that similar discrete increases of reactor pressures and water level indicator readings are noticeable at about 11:15 and 11:30. Similar situations as above could have occurred at these timings. The scale of the increase of reactor and PCV pressures at these timings was smaller than that at about 10:00 and 12:00. Therefore, the amount of fallen molten debris seems relatively limited.

2.4. Period ④ (from about 12:00 to about 13:00)

The estimated actual reactor water levels and water level indicator piping water levels (Table 1)

- Reactor water levels: Remained below about BAF-1.6m
- Reference leg water levels: Increased to some extent from a level near PCV penetrations, and again decreased to near the PCV penetration level.
- Variable leg (fuel range) water levels: Remained filled until about 12:30, and then gradually decreased to a level near PCV penetrations.

Figure 5 shows plant parameters measured in Period ④.

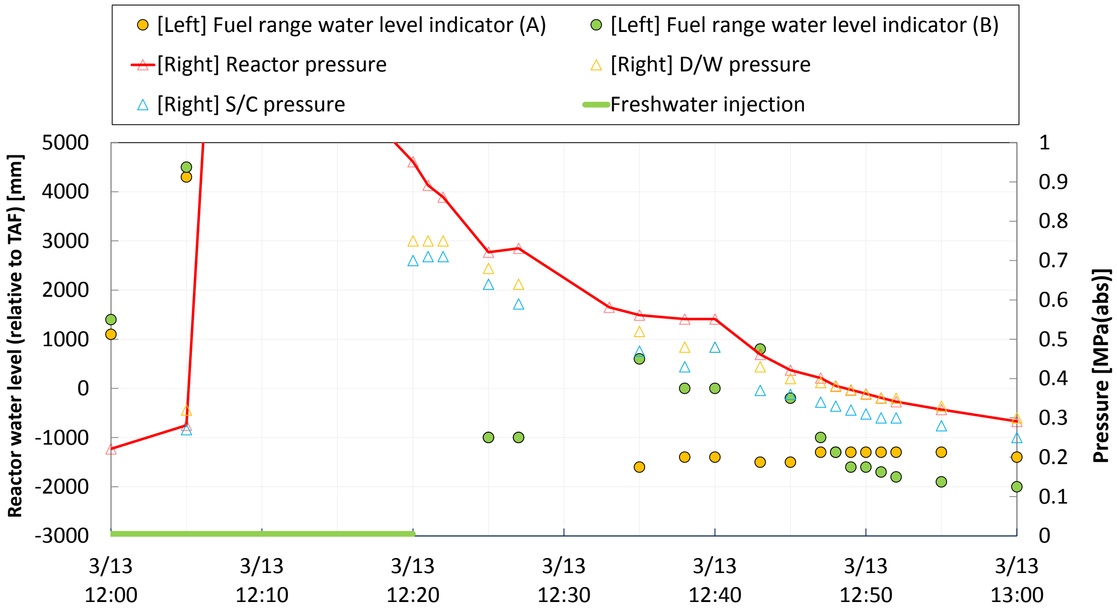

Figure 5 Plant parameters measured (Period ④)

No readings are recorded by the fuel range water level indicators from a little after 12:00, when the reactor pressure increased to about 2.8 MPa[abs], to 12:25 when it decreased down to 0.7 MPa[abs].

The readings of fuel range water level indicator (B) increased once between 12:27 and 12:35. The reason for these increased readings can be considered as the water level decrease in the reference leg, since the reactor water level is believed to have been decreasing due to decompression boiling and other reasons, and the water level in the variable leg (fuel range) is unlikely to increase during reactor depressurization. At 12:00, the reference leg is believed to have been dried out above the PCV penetration level. The water level in the reference leg could have been increased once between 12:00 and 12:25 (the reactor pressure increased, the saturation temperature in the water level indicator piping exceeded the PCV temperatures, steam was condensed in the reference leg, and thus the water level was increased). The water level in the reference leg is considered to have been lost again thereafter falling to the level near the PCV penetrations due to decompression boiling and other reasons.

The readings of fuel range water level indicator (B) decreased thereafter. The situation could be similar to the situation between about 10:00 and 11:00 in Period ③, in which the water level in the variable leg (fuel range) was lowered due to decompression boiling and other reasons.

The readings of fuel range water level indicator (A) between 12:35 and 13:00 remained almost constant, being different from those of fuel range water level indicator (B). Different ambient temperatures around water level indicators (A) and (B) could be the reason for different readings between the two. The reference legs of water level indicators (A) and (B) are positioned on almost opposite sides of the RPV, and the variable leg is shifted at about 100 degrees in a different direction. If the temperatures in the PCV were not uniformly distributed, readings of water level indicators (A) and (B) could have been different.

2.5. Period ⑤ (from about 13:00 to 14:00)

The estimated actual reactor water levels and water level indicator piping water levels (Table 1)

- Reactor water levels: Remained below about BAF-1.6m
- Reference leg water levels: Remained near the PCV penetration level.
- Variable leg (fuel range) water levels: Remained near the PCV penetration level.

Figure 6 shows plant parameters measured in Period ⑤.

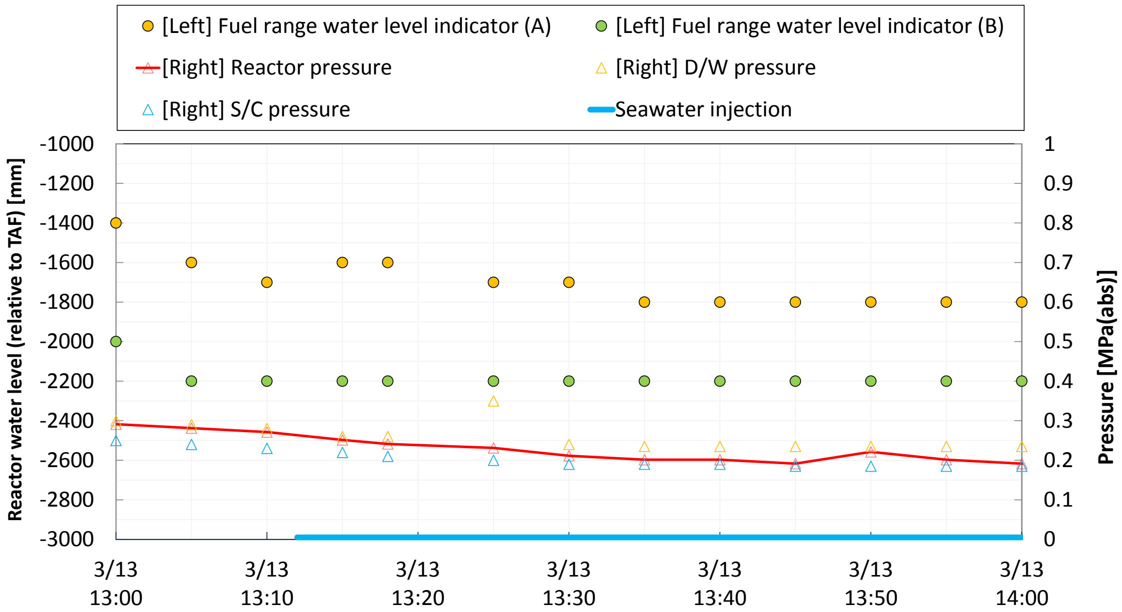

Figure 6 Plant parameters measured (Period ⑤)

In a situation that the reactor water level is below the level of the connection parts of the variable leg, and both reference leg and variable leg (fuel range) are dried out above the PCV penetrations, the readings of fuel range water level indicator (A) should be about TAF-1750mm and of water level indicator (B), about TAF-2250mm. This difference comes from the different elevation of PCV penetrations for the variable leg (fuel range) (A) and (B); the penetration for (B) is located about 50 cm lower than that for (A).

The measured fuel range water level indicator readings were TAF-1800mm at 13:35 to 14:00 by (A), and TAF-2200mm at 13:05 to 14:00 by (B). The readings were roughly consistent with the above theoretical values. Therefore, the actual situation in the reactor would have corresponded to the situation of the reactor water levels and water level indicator piping described above. The reactor water levels are believed to have cut under the level of the connection part of the variable leg (fuel range). Therefore, even if the injected water could have reached the reactor, the amount of water delivered is considered to have been insufficient to recover the water level to as high as the level of the connection part of the variable leg (fuel range).

3. Conclusions and future issues

Behavior of reactor water levels was estimated based on the plant parameters measured between 04:00 and 14:00 on March 13, 2011. As a result, it was estimated that, by the time the Unit-3 reactor was depressurized at about 09:00, the reactor water level had already dropped to near BAF and then further decreased due to decompression boiling by reactor depressurization. It was further estimated that, despite water injection thereafter by the fire engine pump and diesel-driven fire pump, the reactor water level could not have been recovered to as high as the core level. It was also estimated that the water level indicators had given higher readings than the actual levels, as was the case at Unit-1 and Unit-2. These estimations are consistent with other relevant estimations to date concerning the accident progression scenario (Attachments 3 and 3-3).

The above conclusions are consistent with the conclusions in the “Estimation of reactor water levels at the time when core damage and core melt progressed at Unit-2” (Attachment 2-14). Therefore, safety measures required thereto are the same as given in Attachment 2-14.

Knowledge will be acquired concerning the current distribution of fuel debris by examining water level indicator readings after the periods examined in this report. The study will continue.