Estimation of reactor water levels at the time when core damage and core melt progressed at Unit-2

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

1. Introduction

At Unit-2, readings of the fuel range water level indicators had been intermittently recorded during accident progression. As at Unit-1 and Unit-3, 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 very significant in accident progression, by analyzing the readings based on the water level indicator characteristics 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 over the night of March 14, 2011, when the core damage and core melt had developed at Unit-2, the timing having been monitored to date.

2. Estimation of reactor water levels from measured values

Figure 1 shows the plant parameters measured from 18:00 on March 14 to 00:00 on March 15, 2011.

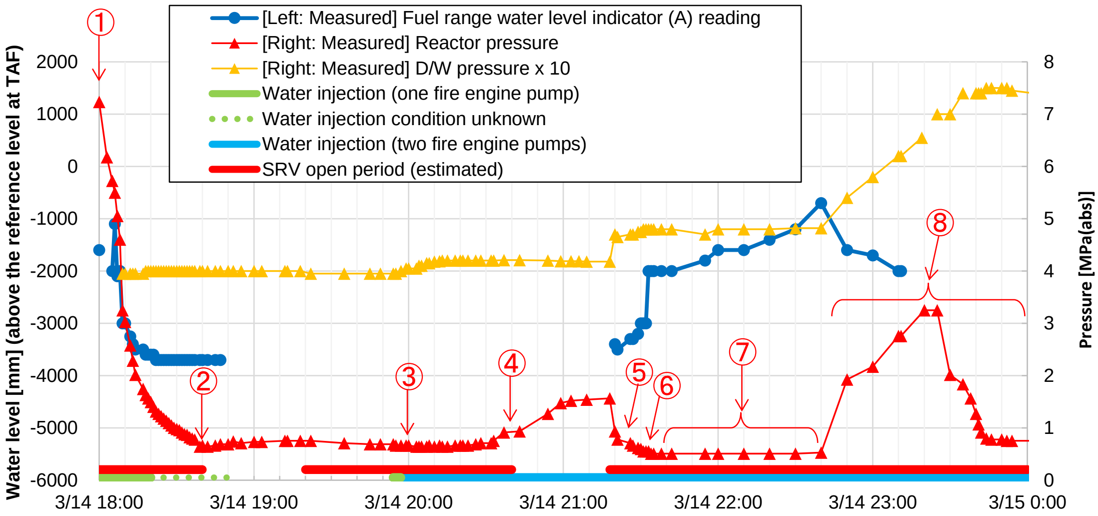


Figure 1 Measured plant parameters

Figure 1 shows the water injection conditions that were recorded and the period of the safety relief valve (SRV) having been open as estimated from the study to date (Attachments 2-9 and 2-12). From about 18:40 to about 19:20, the SRV aperture is unknown, but the SRV is considered to have been closed or almost closed, because if the SRV were assumed to have been open, the trend of reactor pressure increase over that period is difficult to explain. In the figure, the period is excluded from the "SRV open." It should be noted that throughout this attachment, all the pressures are expressed in absolute values.

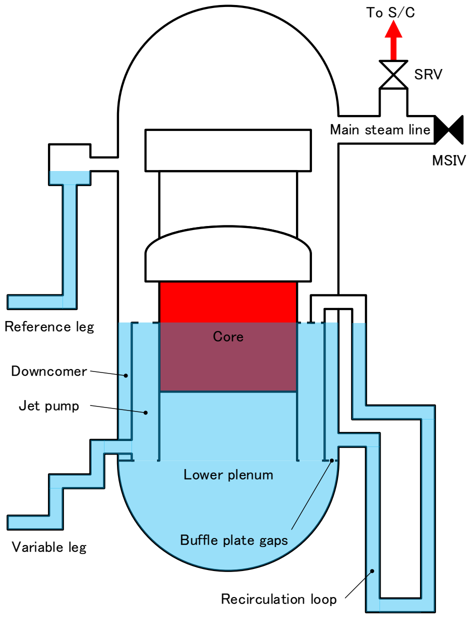
Circled numbers in Figure 1 specify the timings of significance in estimating the reactor conditions. For each number, estimated reactor conditions are summarized in Table 1, which gives the grounds of reactor water level estimation as well as those for estimation of reactor conditions other than water levels. The following are considered as a possible scenario from Table 1.

Estimation 1: The reactor water level decreased to below the bottom of active fuel (BAF) when the reactor pressure decreased from about 18:00 to 18:40;

Estimation 2: The water injection led to recovery of the reactor water level between about 21:40 and 22:40, but not to the BAF; and

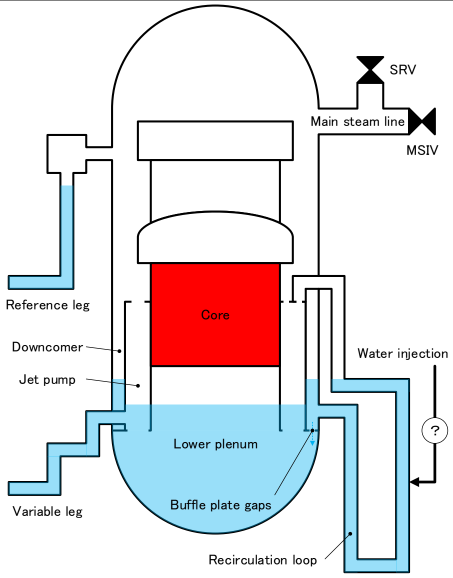
Estimation 3: The water level indicator piping on the reference water chamber side (reference leg) dropped significantly from about 21:20 to 21:30 but was almost constant from about 21:30 to 22:40.

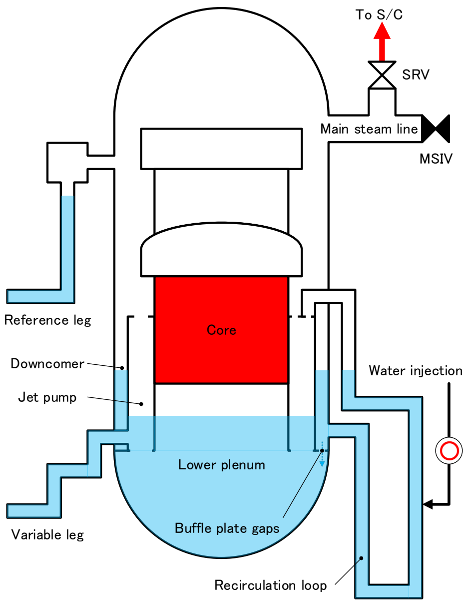
Table 1 Reactor conditions estimated at each timing

<table>
<tr><th>No.</th><th>Timing</th><th>Estimated reactor conditions</th><th>Grounds for estimation</th></tr>
<tr>
<td>①</td>
<td>About 18:00</td>
<td>


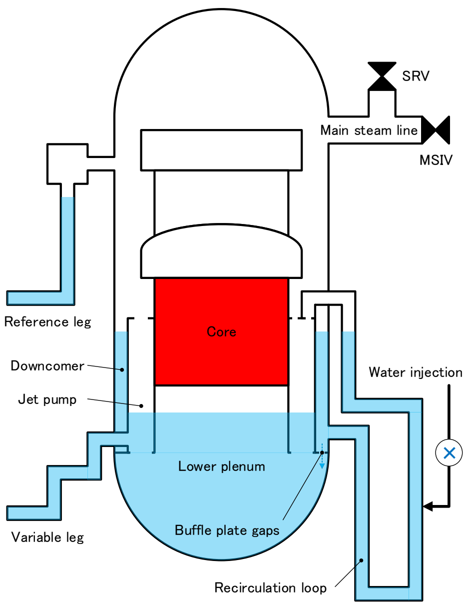
○ Water levels
• Reactor: about TAF-1100mm
• Downcomer: about TAF-1100mm
• Reference leg: full
• Variable leg: full
○ Water injection/SRV conditions
• Injection: reactor pressure too high for the water to reach the reactor
• SRV: open
</td>
<td>
• Corrected value of fuel range water level indicator readings (TAF-1600mm) at 18:00

Drywell (D/W) gas temperature was high, water density in water level indicator piping was considered low. Most likely, the fuel range water level indicator gave lower readings than the actual reactor water level. For correction, measured reactor pressure and D/W gas temperature are needed, but the D/W gas temperature is unavailable. The analysis value of D/W gas temperature was used for correction (Attachment 2-1). Corrected reactor water level is about TAF-1100mm. This includes uncertainties of measured values and estimated D/W gas temperature.
Note Downcomer water level was considered to be like that of the reactor, about TAF-1100mm. This corresponds to the elevation of the jet pump top throat.
</td>
</tr>
</table>

②	About 18:40	 〇 Water levels • Reactor: below BAF • Downcomer: below jet pump throat • Reference leg: near full • Variable leg: full 〇 Water injection/SRV conditions • Injection: unknown • SRV: closed (or almost closed)	• Reactor pressure decreased • Fuel range water level indicator readings lowered Decompression boiling started in the reactor due to depressurization, and water level indicator readings were lowered. From about 18:20 while being depressurized, the readings remained at TAF-3700mm, this being the lower limit of measurement. The actual reactor water level is considered to have been even lower due to decompression boiling when estimated from the readings before depressurization. Note When the downcomer water level cuts under the jet pump throat level, the flow path is limited to the very small baffle plate gaps between the downcomer and lower plenum. Water levels in the reactor and downcomer do not necessarily change together (discussed later in Table 5). Note From about 18:30, reactor pressure dropped to below 1 MPa[abs]. Only one fire engine pump may have injected water into the recirculation loop, but that is not certain. Fire engine fuel is reported at 19:20 to have run out (Attachment 1-4).

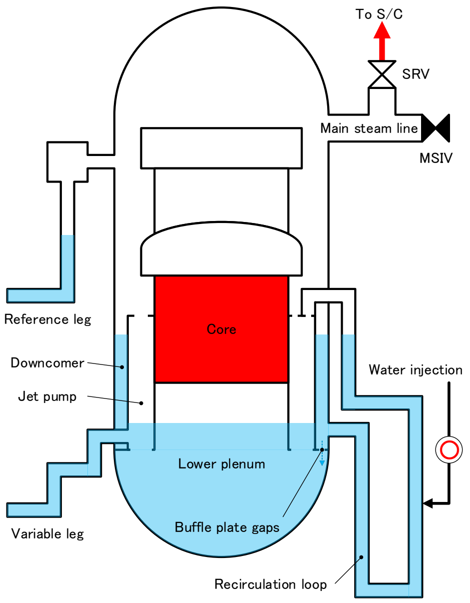
<table>
<tr>
<td>③</td>
<td>About
20:00</td>
<td>

○ Water levels
• Reactor: below BAF
• Downcomer: below jet pump throat
• Reference leg: near full
• Variable leg: full
○ Water injection/SRV conditions
• Injection: reached the reactor in a limited amount
• SRV: slightly open</td>
<td>• Reactor pressure relatively stable below fire pump discharge pressure

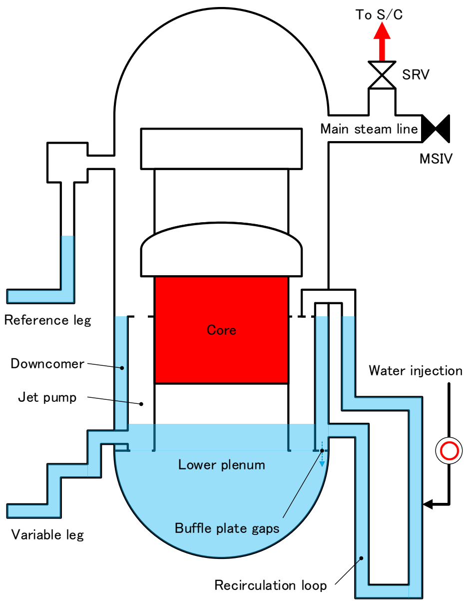
Two fire engine pumps started at 19:54 and 19:57 to inject water into the reactor (recirculation loop). Average discharge flow rates of fire engine pumps are known, but the amount of water that reached the reactor is unknown, because part of the water discharged was delivered to other equipment via branch lines (Attachment 1-4). It is unlikely that the reactor water level recovered to BAF during several minutes of injection. The reactor water level was estimated to be below BAF.
Note No operational records are left on the SRV having been opened, but it was estimated to have been slightly open, since the reactor pressure gradually decreased and PCV pressure gradually increased (Attachment 2-9).</td>
</tr>
<tr>
<td>④</td>
<td>About
20:40</td>
<td>

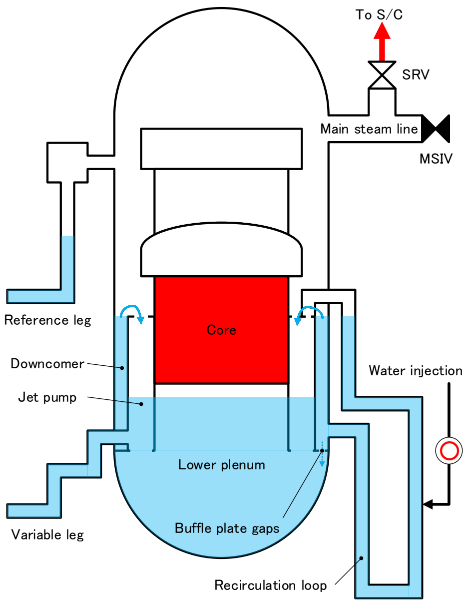
○ Water levels</td>
<td>• Reactor pressure increased to above fire engine pump discharge pressure
• PCV pressure almost constant

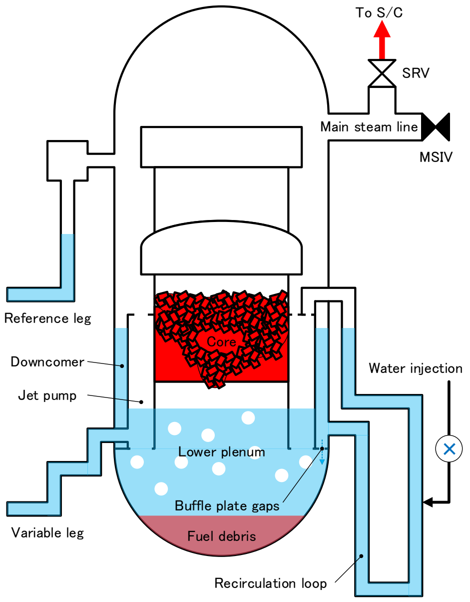
By this timing, the reactor pressure exceeded 1MPA, the fire engine pump discharge pressure, and no more water could reach the reactor. As the amount having been delivered to the lower plenum is unknown, the reactor water level was set as unknown.
Note Reactor pressure began to increase, but PCV pressure did not change. The SRV was considered to</td>
</tr>
</table>

		• Reactor: unknown • Downcomer: between reactor water level and jet pump throat • Reference leg: below full • Variable leg: full ○ Water injection/SRV conditions • Injection: reactor pressure too high for the water to reach the reactor • SRV: closed	have closed around this timing (Attachment 2-9). Note Reactor pressure increased to about 1.6 MPa[abs] by about 21:20 when the SRV was opened for depressurization. This pressure increase is impossible only by the temperature increase in the reactor. Reactor water evaporated by the heat from the core is considered to have increased reactor pressure. The following three heat transfer paths are possible, but the actual one is unknown. (1) Heat transfer when the reactor water level recovered to BAF. (2) Heat transfer by molten objects having fallen to the lower plenum. (3) Heat transfer to downcomer water via the core shroud.
⑤	About 21:20 to 21:30	 ○ Water levels • Reactor: unknown • Downcomer: between reactor water level and jet pump throat	• Fuel range water level indicator readings sharply increased • Reactor pressure decreased to below fire engine pump discharge pressure Part of the water injected could have reached the reactor, as the reactor was depressurized from about 1.6 MPa[abs] to 0.5 MPa[abs] between about 21:20 and 21:30, when the SRV was opened. It should be noted that water level indicator readings sharply increased when the reactor pressure dropped. Such sharp increases may occur when the reactor water level is actually increased by water injection, or when the reference leg water level is decreased. If

		• Reference leg: below full (lower than the level before ⑤) • Variable leg: full ○ Water injection/SRV conditions • Injection: reached reactor to some extent • SRV: open	the reactor water level had actually increased by water injection, more water should have reached the reactor between 21:40 and 22:40, when the reactor pressure was lower, but the increase of readings during this time span was slower. This is inconsistent with the observation. On the other hand, if the reference leg water level were assumed to have decreased due to decompression boiling and other factors, the grounds for the constant readings between 21:30 and 21:40, when the reactor pressure decreased to the minimum, can be interpreted as being the stabilized reference leg water level upon termination of decompression boiling. Therefore, the sharp increase of water level indicator readings from about 21:20 to 21:30 was estimated to have been due mainly to the decreased water level in the reference leg by decompression boiling. By considering that the water level indicator readings did not represent the actual reactor level, the reactor water level was set as unknown. The water level indicator reading dropped for one minute from 21:20 to 21:21. This could have been due to the decreased reactor water level or to the increased reference leg water level. As the reference leg water level is unlikely to increase while the reactor pressure was decreasing, the reactor water level is considered to have decreased due to decompression boiling.

⑥	About 21:30 to 21:40	 ○ Water levels • Reactor: unknown • Downcomer: near jet pump throat • Reference leg: below full (about the same as that at 21:30) • Variable leg: full ○ Water injection/SRV conditions • Injection: reached reactor due to low reactor pressure • SRV: open	• Water level indicator readings remained constant • Reactor pressure dropped to below fire engine pump discharge pressures Over this time span, water level indicator readings remained constant. Since the reactor pressure decreased by this time to about 0.5 MPa[abs], water seems to have reached the reactor. The following two possibilities are considered for the readings to be constant, but neither is certain. The reactor water level was set unknown as in timing ⑤. (1) Water could reach the reactor (recirculation loop) but not the core shroud, because the downcomer water level was below the jet pump throat. (2) All the water could reach the core shroud as the downcomer water level had reached the jet pump throat, but this was canceled by the water loss due to decompression boiling in the core shroud.

⑦	About 21:40 to 22:40	 ○ Water levels • Reactor: below BAF, but increasing • Downcomer: near jet pump throat • Reference leg: below full (about the same as that at 21:30) • Variable Leg: full ○ Water injection/SRV conditions • Injection: reached reactor due to low reactor pressure • SRV: open	• Water level indicator readings: gradually increasing • Reactor pressure: stable below fire engine pump discharge pressures • PCV pressure: almost constant The water level indicator readings gradually increased by about 1.3 m per hour. Two possibilities are considered for this: the reactor water level increased by water injection; or the reference leg water level decreased. The water level in the reference leg seems unlikely to decrease from the following two reasons. (1) The reactor pressure was constant at about 0.5 MPa[abs] at this timing. The saturation temperature was, therefore, constant, too. (2) Since the PCV pressure also remained almost constant, no big change is considered to have occurred in PCV temperatures. Consequently, the possibility is low that the reference leg water level decreased by evaporation, i.e., the water level indicator reading increase at this timing is highly likely to have recorded the reactor water level increase. Meanwhile, the reactor water level seems not to have reached BAF. If the level had reached BAF, the reactor and PCV pressures would have increased by the production of a large amount of steam and hydrogen by the contact between the increased water amount

			and high temperature in-core structures. In reality, no big changes are recorded on the reactor and PCV pressures.
⑧	About 22:40 to 24:00	 ○ Water levels • Reactor: below BAF • Downcomer: between reactor water level and jet pump throat elevation • Reference leg: below full (increase/decrease unknown) • Variable leg: full ○ Water injection/SRV conditions • Injection: reactor pressure too high for the water to reach the reactor • SRV: open	• Reactor pressure: sharp increase • PCV pressure: sharp increase • Water level indicator readings: sharp decrease For 10 minutes from 22:40 to 22:50, water level indicator readings dropped sharply, while the reactor and PCV pressures increased sharply. If the reactor water level had reached BAF immediately before and molten objects dropped to the lower plenum thereafter (within timing ⑧), it is possible to understand that the large amount of steam and hydrogen produced by the contact of molten objects and water increased the reactor and PCV pressures, and that the water in the lower plenum evaporated by the heat transferred from the molten objects lowered the water level indicator readings. The reactor water level was, therefore, estimated to be below BAF. Note It is also possible to consider that the reference leg water level increased at this timing and contributed to the water level indicator reading decrease. This is because the increased reactor pressure caused the reactor water saturation temperature to increase to above the reference leg water temperature and as a result the water in the reference leg might have condensed. In the meantime,

			a large amount of non-condensable gas (hydrogen) is considered to have been produced (Attachment 2-9) at this timing. At Unit-1, hydrogen gas had flowed into the isolation condenser piping and prevented steam condensation there (Attachment 1-7). The possibility of the same phenomenon occurring in the reference leg cannot be excluded. Should it occur, steam condensation (water level increase) in the reference leg is prevented.

3. Evaluation of reactor water levels

Survey analyses were made concerning the reactor water levels which were consistent with the reactor conditions mentioned above in Section 2 and could reproduce the water level indicator readings combined with the behavior of water levels in the water level indicator piping. The survey analyses covered the time span from 18:00 on March 14 to 00:00 on March 15, 2011, when the core damage and core melt are considered to have progressed.

3.1. Evaluation flow

Water level indicator readings can be derived from the water levels and water densities in the core shroud and in the indicator piping (reference leg and variable leg). The water level in the core shroud (reactor water level) and water density can be derived from the mass and energy balance of reactor water by assuming several parameters such as the amount of water injected, amount of heat transfer from the core to reactor water, etc. On the other hand, it is difficult to estimate the water levels and water densities in the water level indicator piping. This is because of the difficulty of estimating temperature distributions of the D/W atmosphere around the water level indicator piping, and its changes with elapsed time. Therefore, the following steps (Figure 2) were taken to estimate the range of realistic reactor water levels which could be consistent with the reactor conditions shown in Section 2 and could reproduce water level indicator readings.

(1) Assume parameters which affect the in-shroud water level and water density, and the water level indicator piping water densities, other than water injection conditions.

(2) Assume water injection conditions (reactor pressures vs. amount of water injected).

(3) Calculate the reactor water level and water densities from (1) and (2).

(4) Obtain the water level indicator piping water level, which reproduces the water level indicator reading, by combining the water level indicator reading and the reactor water level and water densities obtained in (3) above.

(5) Examine the consistency of the reactor water level from (3) and the water level indicator piping water level behavior from (4) with the estimation obtained in Section 2. If not consistent, steps (2) to (5) are repeated with different water injection conditions. By this repetition, the amount of water injected is determined, which is consistent, under the assumed parameters set in (1), with the reactor conditions estimated in Section 2 and reproduces the water level indicator readings.

(6) Repeat steps (2) to (5) after changing each parameter within a realistic range in step (1).

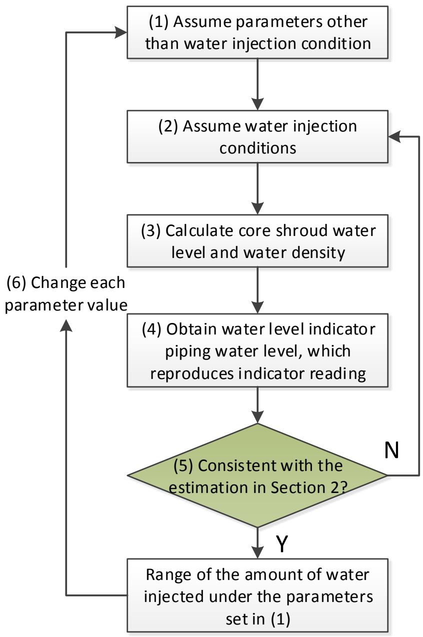


Figure 2 Flow of analysis

Section 3.2 gives the parameter setting logic of steps (1) and (2), Section 3.3 describes the calculation methods of steps (3) and (4), and Section 3.5 elaborates on decision criteria.

3.2. Parameter setting logic

Table 2 to Table 4 present parameters which affect the reactor water level and density, and the water densities in the water level indicator piping. Table 5 explains the logic of these parameter settings. Circled parameter numbers in Tables 2 to 4 coincide with the parameters in Table 5 for convenience. “Initial” in these tables means 18:00 on March 14, 2011.

Table 2 Parameters affecting reactor water level

Parameters	Remarks
②-1 Initial water level	-
②-2 Reactor pressure	Affecting the amount of decompression boiling
②-3 Initial water temperature	Affecting the amount of decompression boiling
②-4 Amount of reactor water evaporation by heat transfer	Affecting the amount of reactor water reduction
②-5 Water injection conditions to the reactor	Affecting the amount of reactor water increase
②-6 Time duration of water injection	Affecting the amount of reactor water increase
②-7 Baffle plate gap area	Affecting the amount of water injection to the reactor through the downcomer

Note) “Initial” means 18:00 on March 14, 2011

Table 3 Parameters affecting in-shroud water density

Parameters	Remarks*
③-1 Initial water temperatures	—
③-2 Reactor pressures	Affecting water temperature decrease by lowering saturation temperatures
③-3 Water temperature increase due to heat transfer	Affecting water temperature increase
③-4 Water injection conditions to the reactor	Affecting water temperature decrease
③-5 Time duration of water injection	Affecting water temperature decrease
③-6 Injected water temperatures	Affecting water temperature decrease
③-7 Baffle plate gap area	Affecting the amount of relatively low temperature water from the downcomer

* Impact on water temperature is remarked on, as water density is subject to it.

Note) “Initial” means 18:00 on March 14, 2011

Table 4 Parameters affecting fuel indicator piping water densities

Parameter	Remarks*
④-1 D/W gas temperatures	Assumed to be equal to the temperatures in the piping

* Impact on water temperatures is remarked on, as water densities are subject to it.

Table 5　Parameter setting logic

Parameter	Setting	Logic
Initial water level (②-1)	TAF-1500mm to TAF-500mm	The same initial water levels were set in the core shroud and downcomer. As seen in Table 1, the reactor water level at that time is estimated to be near the jet pump throat elevation based on the corrected water level indicator readings. But, the D/W gas temperatures need to be considered when correcting the water level indicator readings. The initial water levels were set here as TAF-1500mm to TAF-500mm. These are the levels which roughly reproduce the initial values of water level indicator readings even when uncertainties of ±100 deg C are assumed in the D/W gas temperatures from the MAAP result (170 to 180 deg C: Attachment 3).
Reactor pressure (②-2, ③-2)	Measured values	Measured values available.
Initial water temperatures (②-3, ③-1)	In core shroud: saturation temperature Downcomer: between the initial temperature that reproduces water level after decompression boiling in the downcomer when no decompression boiling occurs in the recirculation loop, and the	The initial water temperature in the core shroud was set as the saturation temperature for the reactor pressure. In the downcomer, the water temperature was believed to be kept near saturation temperature, too, due to the heat transferred via the core shroud. In the recirculation loop, which connects with the downcomer, the water temperature may be lowered by heat transfer to the D/W. The extent of the temperature decrease is unknown, but the water level decreases in the downcomer due to decompression boiling change and the amount of water injection to reproduce water level indicator readings changes accordingly. With this background, the recirculation loop water temperature was set as the temperature between the saturation temperature and the temperature for no decompression boiling at all.

	saturation temperature	
Amount of evaporation of reactor water due to heat transfer from the core (②-4)	In core shroud: Amount (G) of gas produced in RPV, which reproduces reactor pressure behavior $\times(1-F_{DC})$ Downcomer: $G \times F_{DC}$ F_{DC}: Fraction of the amount of evaporation of downcomer water out of total evaporation amount due to heat from the core (0 to 1).	The amount of evaporation of reactor water was estimated based on the amount of gas produced in the RPV (Attachment 2-9), which reproduces reactor pressure behavior. Part of the evaporation amount comes from the water in the core shroud, and the rest from water in the downcomer. The evaporation of downcomer water is caused by the heat transferred from the core via the core shroud. Therefore, no evaporation of downcomer water was considered when its level is below BAF. Further, evaporation from the downcomer after 22:40 was not considered, either, because a large amount of molten fuel is estimated to have fallen to the lower plenum (Attachment 2-9), the heat source in the core dropped after about 22:40, heat transfer to the downcomer decreased, the amount of evaporation decreased, and consequently, the impact on the evaluation of the amount of water injection required to reproduce water level indicator readings becomes limited. For the time periods other than above, the fraction of 0 to 1 was set for evaporation of water from the downcomer out of total evaporation amount.
Water temperature increase due to heat transferred from core to reactor water (③-3)	Same amount of heat evaporating reactor water was assumed to contribute to the water temperature increase	The amount of heat transferred to reactor water from the core is unknown. This is because it is unknown what amount of reactor water had reached saturation temperature, although evaporation is estimated to have occurred and increased the reactor pressure. In the current study, the same amount of heat to evaporate the reactor water mentioned above was assumed to have contributed to the water temperature increase. Although not accurate, the water level increase due to water density change by the increased reactor water temperature with this assumption would have little impact on the final reactor water level.
Water	In the equation on	The amount of water injected was set as a function of

injection conditions to the reactor (②-5, ③-4)	the right, P_0 is 0.6 to 1 MPa ΔH is 0 MPa and C is set so as to satisfy Estimations 1, 2 without specifying the range	reactor pressure. Their relationship is considered to be expressed roughly in the form: $$Q = \sqrt{\frac{P_0 - P_{RPV} - \Delta H}{c}}$$ where Q=amount of water injected, P_{RPV}=reactor pressure, P_0=lowest reactor pressure to reach 0 water injection (hereafter water injection limit pressure), ΔH=head from fire engine pumps to the reactor water injection point, and c=drag coefficient in the injection line. From 16:30 on March 14, two fire engine pumps were injecting water in series: one pumped up seawater to the R/B Floor 1 elevation and the other pump on the second fire engine was injecting water into the reactor [1]. Therefore, ΔH is considered to be relatively low. Meanwhile, the Unit-2 water injection line had branch lines such as the one to the condenser and it is likely that they affected the pressure distributions in the line (Attachment 1-4). This influences P_0 and c, but the extent is not known. In the current study, ΔH was set as 0, and P_0 and c were treated as sensitivity parameters. As it is considered that water was injected by 22:40 to some extent, P_0 was set as 0.6 to 1 MPa, while c was chosen, without specifying the range, so that estimations in Section 2 could hold. In addition, the amount of water being injected by two fire engine pumps (after 19:54) was assumed to be two times that by a single pump (before 19:20) for the same reactor pressure.
Fire engine operating time (②-6, ③-5)	As on the right	Before 19:20, fire engine pumps were set to have been in service from the beginning of the evaluation. They were set to have stopped between 18:20 and 18:50, as it had been recorded that they had stopped 30 to 60 minutes before 19:20 (Attachment 1-4). Concerning the water injection after 19:54, they were set to have

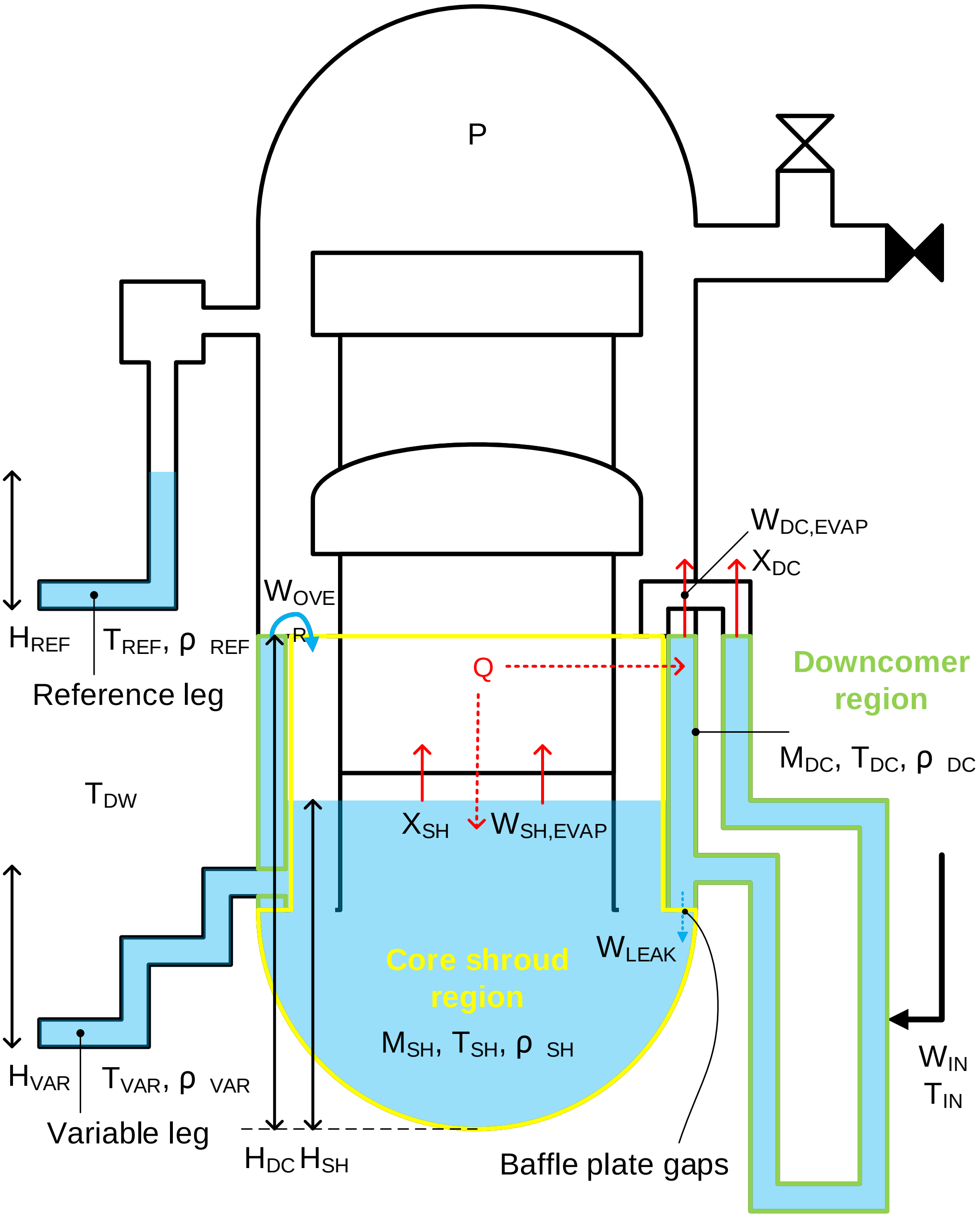
		started at that timing.
Injected water temperature (③-6)	10 to 30 deg C	Unknown, but assumed as 10 to 30 deg C.
Baffle plate gap area (③-7)	0 to 2.2 cm^2	The baffle plate manhole on the boundary between the downcomer and lower plenum may not have been leak-tight. The gap area was chosen, which had been estimated from the relationship between the recirculation pump inlet pressure changes and amount of water injection flow rate during December 2011 and February 2012.
D/W gas temperature (④-1)	80 to 280 deg C	For simplicity, the D/W gas temperature was assumed uniform in the D/W and constant over time. The temperature range of 80 to 280 deg C was for considering the uncertainties of D/W gas temperature evaluation by MAAP (about 170 to 180 deg C: Attachment 3) over this time. The impact of D/W gas temperature on the evaluation result is considered limited, as it affects only water densities in the water level indicator piping water.

Note 1) “Initial” means 18:00 on March 14, 2011.

Note 2) Parameter numbers in the first column correspond to the numbers of Tables 2 to 4.

3.3. Calculation methods

This section explains the methods to calculate the reactor water level and water densities in step (3) in the evaluation flow of Section 3.1, and the water levels in water level indicator piping in step (4), which can reproduce water level indicator readings. Figure 3 shows the configuration for evaluation. For practicality in the evaluation, the core shroud region includes the reactor vessel lower plenum and jet pumps, while the downcomer region includes the recirculation loops.



Legend
P : Pressure
M : Mass
T : Temperature
ρ : Density
W : Flow rate
H : Height
X : Evaporation rate by decompression boiling
Q : Heat

Meanings of suffixes
SH : Core shroud
DC : Downcomer
IN : Water injection
EVAP : Evaporation
OVER : Overflow via jet pump throat
LEAK : Leaks via baffle plate gaps
REF : Reference leg
VAR : Variable leg
DW : Drywell

Figure 3 Configuration for evaluation

The reactor water mass balance and energy balance are calculated at each timing when the reactor pressure was recorded in the core shroud and downcomer regions (recirculation loop included).

○ Mass balance of reactor water in the downcomer and in the core shroud

The following equations were used to estimate mass balance by reactor water masses in the downcomer and in the core shroud at one timing when the reactor pressure had been recorded, and then to estimate mass at the next timing when the reactor pressure had been recorded. The suffixes indicate the number of timing when the pressure was recorded. Time point "n" corresponds to when the reactor pressure was recorded at the "n-th" time. In the equation, X_{DC} and X_{SH} are evaporation fractions of reactor water due to decompression boiling (decompression boiling ratio), while $W_{DC,EVAP}$ and $W_{SH,EVAP}$ are the amounts of evaporation due to heat transfer from the core to reactor water. The "dt" in the equation is the time interval from time point "n" to "n+1."

$$M_{DC}{}^{n+1} = M_{DC}{}^{n}\left(1 - X_{DC}\right) + \left(W_{IN}{}^{n} - W_{LEAK}{}^{n} - W_{OVER}{}^{n} - W_{DC,EVAP}{}^{n}\right)dt$$

$$M_{SH}{}^{n+1} = M_{SH}{}^{n}\left(1 - X_{SH}\right) + \left(W_{LEAK}{}^{n} + W_{OVER}{}^{n} - W_{SH,EVAP}{}^{n}\right)dt$$

Calculation processes of each parameter follow.

Decompression boiling ratio

The decompression boiling ratio X_{DC} or X_{SH} is calculated by the following equation if the water temperature at step n exceeds the saturation temperature at step n+1, otherwise it is zero.

$$X_{(DC,SH)} = \left(h_f{}^{n} - h_f{}^{n+1}\right) / \left(h_g{}^{n+1} - h_f{}^{n+1}\right)$$

Here, h_f is the saturated water enthalpy and h_g is the saturated steam enthalpy.

Water injection rate

The water injection rate W_{IN} is determined subject to the reactor pressure based on the preset injection conditions.

Water leak rate via baffle plate gaps

The water leak rate via baffle plate gaps W_{LEAK} is calculated by using Torricelli's theorem. The following equation is used to calculate W_{LEAK} when the water level in the downcomer is higher than that in the core shroud, in which A is the gap area of the baffle plates and ρ_{DC} is the water density in the downcomer.

$$W_{LEAK}{}^{n} = A\rho_{DC}{}^{n}\sqrt{2g\left(H_{DC}{}^{n} - H_{SH}{}^{n}\right)}$$

When the water level in the downcomer is lower than that in the core shroud, the following equation is used for calculating W_{LEAK}.

$$W_{LEAK}{}^{n} = -A\rho_{DC}{}^{n}\sqrt{2g\left(H_{SH}{}^{n} - H_{DC}{}^{n}\right)}$$

<u>Outflow rate to the lower plenum via jet pump throat</u>

The outflow rate W_{OVER} is calculated as the amount of water that overflowed the jet pump throat.

<u>Evaporation rate due to heat transfer from the core to reactor water</u>

The evaporation rates $W_{DC,EVAP}$ and $W_{SH,EVAP}$ are obtained by the following equations, in which F_{DC} is the fraction of heat transferred to the downcomer water out of the heat Q transferred to the reactor water from the core. Settings of Q and F_{DC} are explained in Table 5 as “Amount of evaporation of reactor water due to heat transfer from core to reactor water (②-4).

$$W_{DC,EVAP}{}^{n} = F_{DC}Q^{n} \Big/ \left(h_{g}{}^{n} - h_{f}{}^{n}\right)$$
$$W_{\mathrm{SH},EVAP}{}^{n} = \left(1 - F_{DC}\right)Q^{n} \Big/ \left(h_{g}{}^{n} - h_{f}{}^{n}\right)$$

○ Energy balance in the downcomer and in the core shroud

Water temperatures in the downcomer and in the core shroud can be obtained from the energy balance. The energy balance is calculated by the following equation, in which h is the enthalpy, when the downcomer water level is higher than that in the core shroud. When the water temperature obtained from the enthalpy calculation exceeds the saturation temperature, the saturation temperature is used.

$$M_{DC}{}^{n+1}h_{DC}{}^{n+1} = M_{DC}{}^{n}h_{DC}{}^{n} + \left\{W_{IN}{}^{n}h_{IN}{}^{n} - \left(W_{LEAK}{}^{n} + W_{OVER}{}^{n} + W_{DC,EVAP}{}^{n}\right)h_{DC}{}^{n} + Q^{n}F_{DC}\right\}dt$$
$$M_{SH}{}^{n+1}h_{SH}{}^{n+1} = M_{SH}{}^{n}h_{SH}{}^{n} + \left\{\left(W_{LEAK}{}^{n} + W_{OVER}{}^{n}\right)h_{DC}{}^{n} - W_{SH,EVAP}{}^{n}h_{SH}{}^{n} + Q^{n}\left(1 - F_{DC}\right)\right\}dt$$

On the contrary, when the downcomer water level is lower than that in the core shroud, the leaks via the baffle plate W_{LEAK} transfer water to the downcomer from the in-shroud region. The following equation is used for the energy balance, with consideration being taken that W_{LEAK} is negative and the enthalpy of reactor water transferred is the enthalpy of the water in the shroud.

$$M_{DC}{}^{n+1} h_{DC}{}^{n+1} = M_{DC}{}^{n} h_{DC}{}^{n} + \left\{ W_{IN}{}^{n} h_{IN}{}^{n} - W_{LEAK}{}^{n} h_{SH}{}^{n} - \left(W_{OVER}{}^{n} + W_{DC,EVAP}{}^{n} \right) h_{DC}{}^{n} + Q^{n} F_{DC} \right\} dt$$
$$M_{SH}{}^{n+1} h_{SH}{}^{n+1} = M_{SH}{}^{n} h_{SH}{}^{n} + \left\{ W_{LEAK}{}^{n} h_{SH}{}^{n} + W_{OVER}{}^{n} h_{DC}{}^{n} - W_{SH,EVAP}{}^{n} h_{SH}{}^{n} + Q^{n} \left(1 - F_{DC} \right) \right\} dt$$

Once the masses and temperatures of the water in the downcomer and core shroud can be calculated, water densities (ρ_{SH}, ρ_{DC}) and water levels (H_{SH}, H_{DC}) are calculated in their respective regions.

○ Water temperatures in the variable leg and reference leg

The water temperatures T_{VAR} and T_{REF} in the variable leg and the reference leg are set, as a simplified approach, as either the saturation temperature at the reactor pressure or D/W gas temperature, whichever is lower.

○ Mass balance in the variable leg

When the reactor water level exceeds the level of the connection part of the variable leg, the variable leg is assumed to be filled. Otherwise, the water mass in the variable leg is calculated by the following equation, in which X_{VAR} is the decompression boiling ratio and $W_{VAR,EVAP}$ is the amount of evaporation by the heat transferred from the PCV.

$$M_{VAR}{}^{n+1} = M_{VAR}{}^{n} \left(1 - X_{VAR} \right) - W_{VAR,EVAP}{}^{n} dt$$

Methods of calculating each parameter in the above equations are as follows.

<u>Decompression boiling ratio</u>

The decompression boiling ratio X_{VAR} is calculated in the same way as that in the core shroud and downcomer.

<u>Amount of evaporation by heat transferred from the PCV</u>

The $W_{VAR,EVAP}$, amount of evaporation by the heat transferred from the PCV, is obtained by the following equation, when the water temperature in the variable leg is the saturation temperature, otherwise it is zero. In the equation, Q_{VAR} is the amount of heat transferred from the D/W to the water in the variable leg, c_{VAR} is the heat transfer coefficient and A_{VAR} is the heat transfer area.

$$W_{VAR,EVAP}{}^{n} = Q_{VAR}{}^{n} \Big/ \left(h_g{}^{n} - h_f{}^{n} \right)$$

$$Q_{VAR}{}^{n} = c_{VAR} A_{VAR} \left(T_{DW}{}^{n} - T_{VAR}{}^{n} \right) dt$$

Water densities in the water level indicator piping (ρ_{VAR}, ρ_{REF}) and the water level in the variable leg H_{VAR} now can be calculated.

○ Water level in the reference leg

The water level in the reference leg H_{REF} can be calculated from the pressure difference between the reference leg and the variable leg (DP) obtained from the water level indicator readings as follows: subtract the influence of water head inside the variable leg, inside the core shroud, and in the water level indicator piping outside the PCV (ambient temperatures assumed) from DP; divide this by the water density in the reference leg ρ_{REF} and the acceleration of gravity.

3.4. Decision criteria

Table 6 presents the decision criteria for evaluating the consistency between the results in the evaluation flow in Section 3.1 (5) and the three estimations presented in Section 2. The water level in the reference leg, which reproduces the water level indicator readings from 21:40 to 22:40, was found never to remain constant when the reactor water levels were calculated. For this reason, the criterion 3b is defined with a certain margin. The margin was taken as 50 cm, and relatively large, for estimating a realistic reactor water level with a certain range, not for taking the measurement accuracies into account.

Table 6 Decision criteria for consistency

Estimation	Criteria
Estimation 1	1: The reactor water level at 18:40 was below BAF.
Estimation 2	2: The reactor water level had not recovered to BAF between 21:40 and 22:40.
Estimation 3	3a: Reference leg water level decreased between 21:18 and 21:34. 3b: Reference leg water level change between 21:34 and 22:40 (maximum - minimum) was no more than 50 cm.
Others	4: The amount of water injected to the reactor did not exceed the estimated amount discharged by the fire engine pumps (about 80 m^3/h)

3.5. Evaluation results

Table 7 gives the evaluation results of water injection rate to the reactor. The results show the ranges of the water injection rates which satisfy the decision criteria in Section 3.4 over the time between 21:40 to 22:30 (when the reactor pressure remained constant at about 0.51 MPa[abs]) with the parameters being set in Section 3.2 for the water injection limit pressures (minimum reactor pressure to limit the injection rate to zero) of 0.6 to 1.0 MPa assumed.

Table 7 Water injection rates for respective water injection limit pressures (at about 0.51 MPa[abs] reactor pressure)

Water injection limit pressure	Water injection rate to the reactor (at about 0.51 MPa[abs] reactor pressure)
1.0 MPa	2.4 to 5.9 kg/s（8.6 to 21.2 m^3/h）
0.9 MPa	2.6 to 6.5 kg/s（9.4 to 23.4 m^3/h）
0.8 MPa	2.8 to 6.9 kg/s（10.1 to 24.8 m^3/h）
0.7 MPa	3.3 to 8.0 kg/s（11.9 to 28.8 m^3/h）
0.6 MPa	4.6 to 9.3 kg/s（16.6 to 33.5 m^3/h）

Figure 4 shows the ranges of water injection rates to the reactor as summarized in Table 7, and the range of water injection conditions to the reactor when two fire engine pumps were in operation estimated from the equation given in the “water injection conditions to the reactor” (②-5, ③-4) in Table 5. The graph shows that the water injection rate to the reactor was limited for reactor pressures higher than 0.5 MPa against the average discharge flow rate of about 80 m^3/h of the fire engine pumps at that time (21:40 to 22:30 on March 14). The balance of water discharged is considered to have flowed into other equipment.

It should be noted that in Figure 4 the water injection rate has a big range for each of the reactor pressures. This comes mainly from the water injection limit pressures and the ranges of the parameters in Table 5, among which the average downcomer temperatures at time zero have the biggest influence. The amount of evaporation of downcomer water by decompression boiling changes significantly, subject to the average downcomer temperatures at time zero, and as a result the amount of water to be injected to fill the downcomer region changes significantly (relevant to decision criterion 3b). It will be possible to reduce the range and consequently the uncertainty in the water injection rate if the water temperature in the recirculation loop at 18:00 on March 14, 2011 can be appropriately estimated.

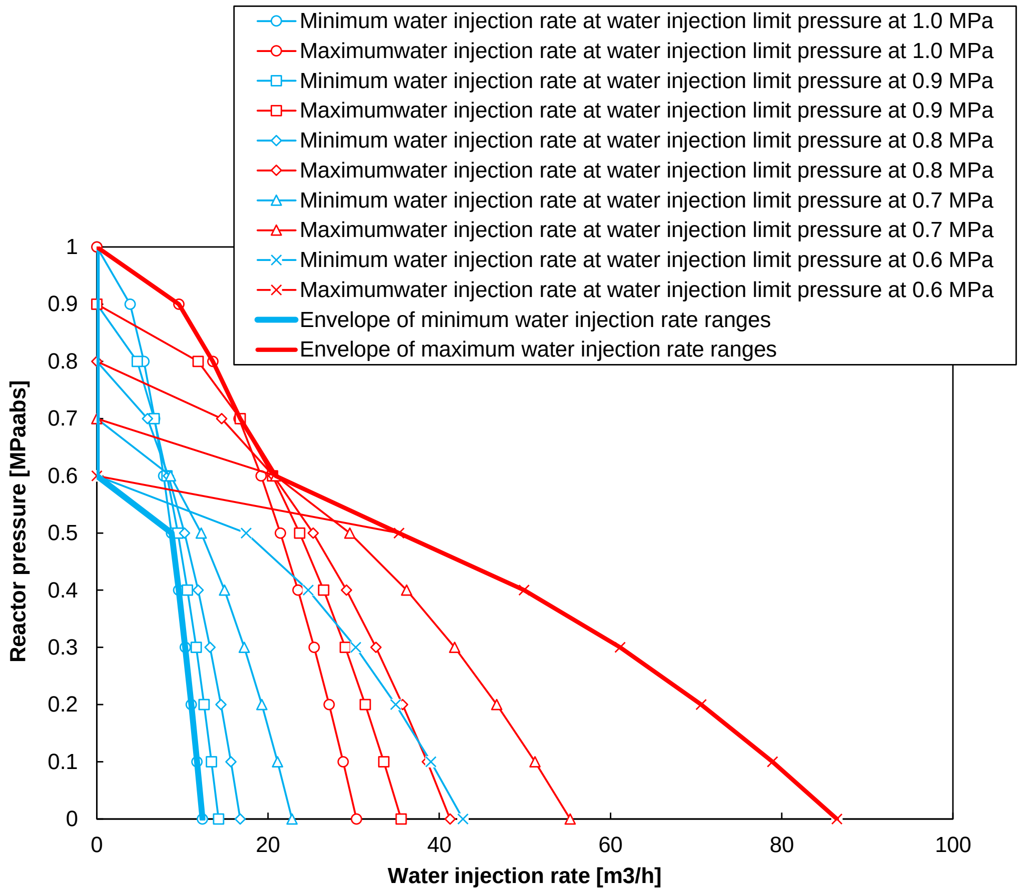


Figure 4 Range of characteristics of water injection to the reactor using two fire engine pumps

Figure 5 and Figure 6 give the evaluation results for the cases of minimum and maximum water injection rates among the cases given in Table 7. Figure 7 gives the ranges of minimum and maximum values of the reactor water level and downcomer water level at each time point of evaluation for all cases in Table 7. The figure shows that the reactor water level did not recover to BAF even before the time period corresponding to decision criterion 2 (before 21:40), once the water level had dropped below BAF due to the forced depressurization at 18:00.

On the other hand, the reactor pressure was increasing from about 20:30 to 21:20. Even if the reactor water level was below BAF as evaluated in this study, this pressure increase could have been caused by falling molten debris to the lower plenum or by other reasons. But no clear scenario is yet available to explain this pressure increase, because the pressure increase observed was a slow development in the situation of the reactor water level being below BAF. To sum up, the results of this study are considered to suggest a scenario in which the reactor level changed at low levels.

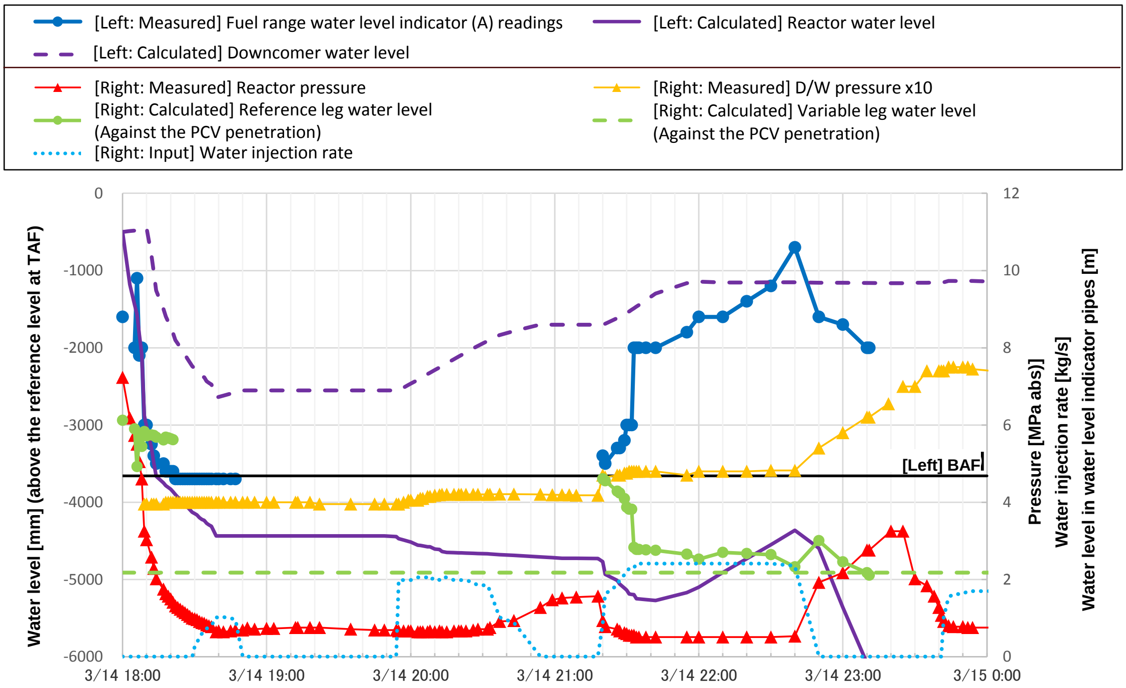


Figure 5 Evaluation results: Minimum water injection flow rates

(Water injection limit pressure, 1 MPa; Water injection flow rate to reactor from 21:40 to 22:30, 2.4 kg/s)

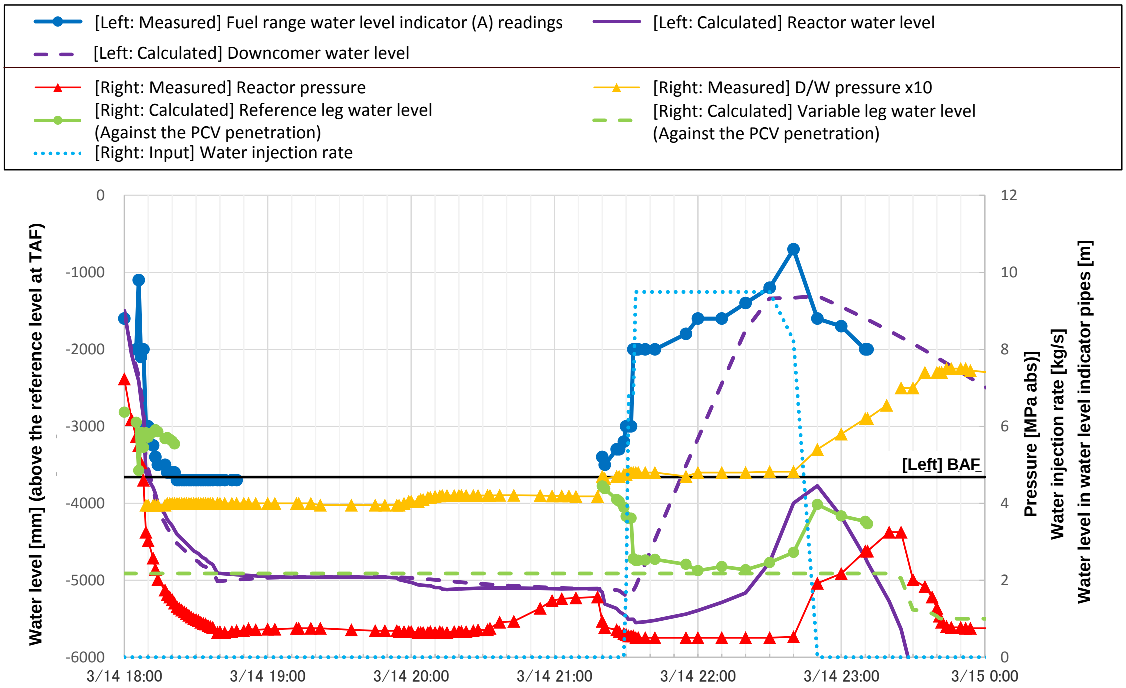


Figure 6 Evaluation results: Maximum water injection flow rates

(Water injection limit pressure, 0.6 MPa; Water injection flow rate to reactor from 21:40 to 22:30, 9.3 kg/s)

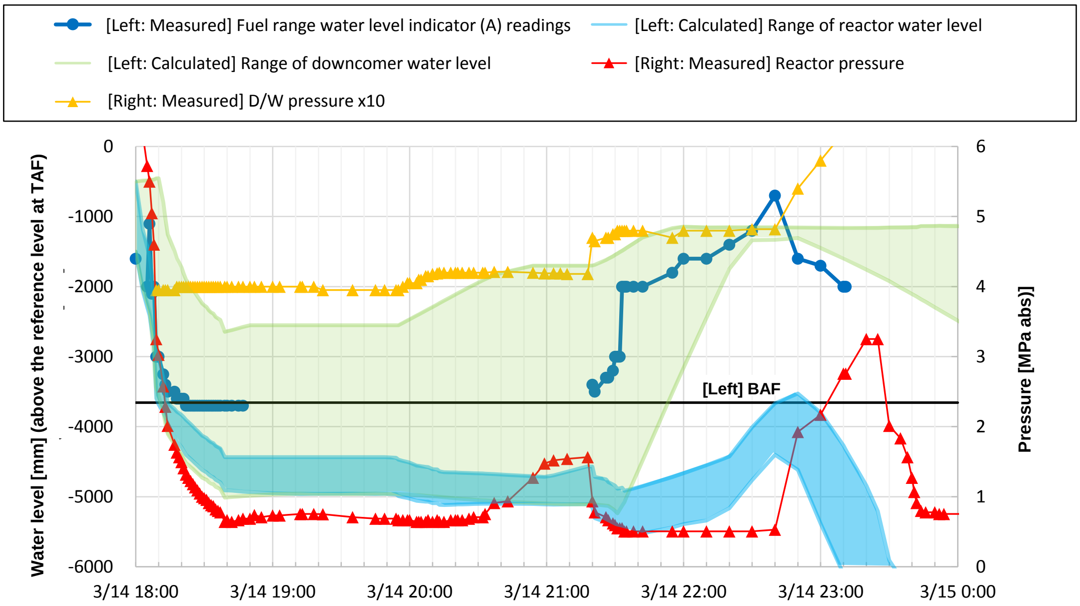


Figure 7 Estimated ranges of reactor water level and downcomer water level

4. Conclusion

Reactor conditions of Unit-2 at the time when the core damage and core melt had progressed (the night of March 14, 2011) were estimated based on measured plant parameters, and therefrom the conditions of water injection to the reactor and probable ranges of reactor water level were evaluated.

In the study, the reactor water level did not reach BAF between 20:30 and about 21:20, and the results failed to provide a clear scenario to explain the reactor pressure increase during that time. Therefore, the results of this study are considered to suggest a scenario in which the reactor water level changes were low.

The reactor water level (the water inventory in the RPV) represents key information to evaluate hydrogen generation, fuel melt behavior and cooling conditions for fuel debris relocated in the lower plenum. The estimated reactor water level will be provided to the continuing estimation of accident progression.

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

This study led to the estimation that, despite water injection to the reactor by fire engine pumps, the reactor water was not sufficient to cover the core. Measures are required to ensure that sufficient water can be injected into the reactor. In addition, fuel range water level indicators are estimated to have indicated higher readings than the actual levels, as was seen at Unit-1 and Unit-3. Approaches are required to measure the reactor water level appropriately. As reflections of these lessons, the measures summarized in Table 8 and illustrated in Figure 8 are being taken at Kashiwazaki-Kariwa Nuclear Power Station.

Table 8 Safety measures at Kashiwazaki-Kariwa Nuclear Power Station related to findings of the current study

Measures to ensure water injection to the reactor in sufficient amounts	Enhancement of items to maintain the depressurization function	Add power sources, nitrogen gas supply, and depressurization means.
	Diversification of water injection means	Add high pressure alternative cooling (remote and manual); and low pressure alternative cooling (stationary and transportable).
	Prevention of bypass flows of injected water to branch lines other than reactor	Install check valves or other devices on branch lines.
Measures to obtain reliable reactor water level values	Evaluation of water level indicator reliabilities	Install thermometers in the reference leg (condensing chamber). Prepare for actions for “Reactor level unknown” when loss of reference leg water level is recognized.
	Implementation of a means to estimate reactor water levels	Estimate the reactor water level using water injection flow rates, temperatures around the reactor, and other values as supplementary information.

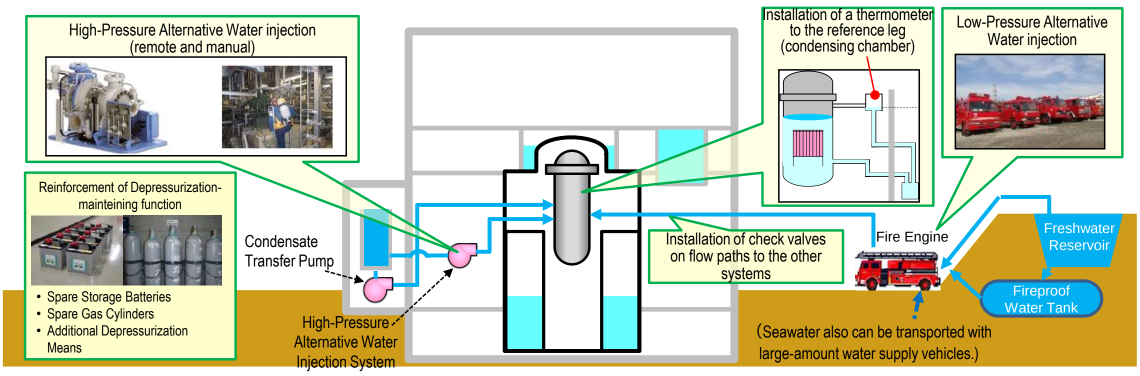


Figure 8 Schematic of safety measures at Kashiwazaki-Kariwa Nuclear Power Station related to findings of the current study

Reference

[1] Tokyo Electric Power Company, “Report on initial responses to the accident at Tokyo Electric Power Co.'s Fukushima Daiichi Nuclear Power Plant” (December 22, 2011)