Findings from the latest analyses using MAAP5

1. Latest analysis of Unit-1 by MAAP5.01

1.1. Plant conditions and event chronology

Table 1-1 summarizes key plant conditions, while Table 1-2 shows the key event time line as primary conditions for analysis. The incidents therein integrate the chronological records made public since May 2011, including two earlier documents (in Japanese): one is "Plant data compilation of the Fukushima Daiichi Nuclear Power Station when the Tohoku–Chihou-Taiheiyou-Oki (Great East Japan) Earthquake occurred" reported to the Nuclear and Industry Safety Agency (NISA) on May 16th, 2011; and the other is "First-hand responses to the accident at the Fukushima Daiichi Nuclear Power Station)" made public on December 22nd, 2011.

Table 1-1 Plant conditions of Unit-1

Item	Conditions
Initial reactor output	1380 MWt (rated)
Initial reactor pressure	6.92MPa [abs] (operating pressure measured just before the earthquake) *
Initial reactor water level	4376mm (distance above TAF) *
RPV nodalization	See Figure 4 in Attachment 1
Active core nodalization	5 (radial), 10 (axial)
Cladding temperature to burst	727 deg C (1000K)
Criteria for core melting	Melting points of each core component material or the average melting temperature of mixed materials considering eutectic reactions.
Containment vessel model	See Figure 5 in Attachment 1
Containment vessel volumes	D/W volume: 3410m^3 S/C volume: 2620m^3
Suppression pool water volume	1750m^3
Decay heat	ANSI/ANS5.1-1979 model (Parameters adjusted for consistency with the decay heat evaluated by ORIGEN2 incorporating fuel loading history)

*) The parameters are based on the measured data recorded by the transient recorder.

・Reactor pressure; 6.82MPa[gage] (narrow range indicators A, B, C)

・Reactor water level; (3427+(949+956.5+940)/3) mm

(The average of narrow range indicator subsystems-A, B, C)

Attachment 3-2

Table 1-2 Event chronology at Unit-1

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
1	3/11	14:46	Earthquake	A	—
2		14:48 (14:47:33)	Reactor SCRAM	A	"Fukushima Nuclear Accident Analysis Report" section 7.1, TEPCO, 2012. 6.20
3		14:48 (14:48:03)	MSIV closed	B	The data in the transient recorder (*1) show the MSIV closing time was around 14:48 although there was a small difference between the time for main steam flow rate to drop to zero and the time for the valve position signal to change to closed. In the analysis, considering the recorded data, the MSIV closure time of 14:48:03 was assumed so that the measured reactor pressure transient could be well reproduced.
4		14:52	IC (A) (B) automatic start-up	A	Transient recorder data (*1)
5		ca.15:03	IC (A) stopped	A	Transient recorder data (*1)
6		ca.15:03	IC (B) stopped	A	Transient recorder data (*1)
7		15:05	CCS torus cooling (A) in service	A	Transient recorder data (*1), also reported in "investigation of causes of damage situation of power facilities inside and outside of Fukushima Daiichi Nuclear Power Station", TEPCO, 2011.5.23 (CCS operation eventually stopped due to station blackout)
8		15:10	CCS torus cooling (B) in service	A	Same as No.7
9		15:17	IC (A) restarted	A	Transient recorder data (*1)
10		15:19	IC (A) stopped	A	Transient recorder data (*1)
11		15:24	IC (A) restarted	A	Transient recorder data (*1)
12		15:26	IC (A) stopped	A	Transient recorder data (*1)
13		15:32	IC (A) restarted	A	Transient recorder data (*1)
14		15:34	IC (A) stopped	A	Transient recorder data (*1)
15		15:37	Station blackout	A	Shift supervisor logbook, "4. Operator diaries" reported on 2011.5.16

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
16	3/11	18:18	IC (A) valves 2A, 3A opened / steam generation confirmed	C	IC function loss assumed in the analysis after station blackout, although subject records are left in “7. Summary of operational actions”, reported on 2011.5.16 (*2)
17		18:25	IC (A) valve 3A closed	C	Same as No.16.
18		20:50	Alternative water injection lines composed and diesel-driven fire pump (DDFP) started up (stand-by for injection after reactor depressurization)	C	“First action of Fukushima Daiichi Nuclear Power Station Accident,” TEPCO press release on 2011.12.22 Injected water by DDFP estimated not to have reached the reactor pressure vessel (RPV) due to high reactor pressure
19		21:30	IC (A) valve 3A opened / steam generation confirmed	C	Same as No.16.
20	3/12	01:48	DDFP stoppage confirmed	C	“Initial actions taken at the accident of Fukushima Daiichi NPS,” TEPCO press release on 2011.12.22 Injected water by DDFP estimated not to have reached the RPV due to high reactor pressure (7.0MPa[abs] (checked by the pressure indicator installed in the reactor building) at 20:07 on 3/11 and 0.9MPa[abs] (on the recovered MCR indicators) at 02:45 on 3/12, the changes in between unknown)
21		04:00	Freshwater injected	C	“First action of Fukushima Daiichi Nuclear Power Station Accident,” TEPCO press release on 2011.12.22 Fresh water of 1300 liters was injected See Attachment 1-5 regarding analysis condition (*3)
22		04:02	Freshwater injection by fire engines completed	C	See Attachment 1-5 regarding analysis condition(*3)
23		05:46	Freshwater injection by fire engines resumed	C	“7. Summary of operational actions”, reported on 2011.5.16 See Attachment 1-5 regarding analysis condition(*3)
24		14:30	PCV pressure decrease confirmed upon AO valve operation on S/C	B	“7. Summary of operational actions”, reported on 2011.5.16 PCV venting at 14:30 confirmed based on PCV pressure decrease, but the

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
			side for PCV venting at 10:17		opening of vent valve assumed at 14:11 in the analysis for simulating the measured PCV pressure changes
25	3/12	14:53	Freshwater injection completed	A	“7. Summary of operational actions”, reported on 2011.5.16 See Attachment 1-5 regarding analysis condition(*3)
26		15:27	PCV venting valve closed	B	Vent valve closure assumed at 15:27 in the analysis for simulating the PCV pressure changes measured.
27		15:36	Unit-1 reactor building exploded	A	“7. Summary of operational actions”, reported on 2011.5.16
28		19:04	Seawater injection started by fire engines	C	“Initial Response of Tohoku-Chihou-Taiheiyo-Oki Earthquake at Fukushima Daiichi and Fukushima Daini Nuclear Power Station,” TEPCO press release on 2011.8.10 See Attachment 1-5 regarding analysis condition(*3)
29		21:45	Seawater injection stopped	C	“Initial Response of Tohoku-Chihou-Taiheiyo-Oki Earthquake at Fukushima Daiichi and Fukushima Daini Nuclear Power Station,” TEPCO press release on 2011.8.10 See Attachment 1-5 regarding analysis condition(*3)
30		23:50	Seawater injection resumed	C	See Attachment 1-5 regarding analysis condition(*3)
31	3/14	01:10	Seawater injection stopped	C	See Attachment 1-5 regarding analysis condition(*3)
32		20:00	Seawater injection resumed	C	See Attachment 1-5 regarding analysis condition(*3)

*1) The data in the transient recorder were used as the grounds of the event time, which included 10 ms cycle data recorded from 14:42:03 to 15:17 on March 11th (reported on 2011.5.16) and 1 minute cycle data recorded from 12:00:59 to 15:36:59 (2013.7.17).

*2) The IC operating situation after the station blackout remains unclear. In the analysis, the IC was assumed to have lost its functions, since there is not sufficient evidence showing its functioning.

*3) The timings and amounts of water injected were set, based on the action records of operation in Attachment 1-4 and the examination results in Attachment 1-5. Analysis input for water injection rate is described in Attachment 1-1.

1.2. Definition of conditions based on plant data observed

The following conditions were set for analysis based on the plant data observed.

(1) Leaks from RPV in the gaseous phase

At Unit-1, the pressure of the primary containment vessel (PCV) was measured as 0.6MPa[abs] at 01:05 on March 12th and 0.84MPa[abs] at 02:30, while the pressure of the reactor pressure vessel (RPV) was measured as 0.9MPa[abs] at 02:45 also on March 12th. It is possible that the PCV and RPV pressures might have been balanced at an earlier time. The RPV pressure was confirmed to have been 7.0MPa[abs] at 20:07 on March 11th, which is approximately the closure pressure of the safety mode of the main steam safety relief valve (SRV) actuated by spring force. This might indicate that the measured pressure was just when the SRV was closed during SRV operation cycling, but it might also indicate that the reactor was depressurized by some reason other than SRV actuation.

In the earlier analysis reported in May 2011, the reactor pressure decreased due to RPV rupture and its observed pressure could not be reproduced. The high PCV pressure observed at 01:05 or 02:30 on March 12th could not be reproduced, either, under the condition of continued steam release to the suppression chamber (S/C) from the SRV.

Therefore, in the current analysis, it was assumed, based on the arrangement of core internals and design information of equipment that steam had leaked from the RPV to the drywell (D/W) due to the temperature increase in the reactor caused by overheated fuel and fuel melting.

Two possible leak paths from RPV exist: one is the in-core instrumentation dry tubes; and the second is the main steam piping flange gaskets. The in-core instrumentation dry tubes could be damaged by elevated fuel temperatures, releasing steam directly to the D/W. The main steam piping flange gaskets could lose their seal capability in the environment of about 450 deg C. In the analysis, gaseous leaks ($0.00012m^2$, $0.0015m^2$) were assumed at the timings when the core maximum temperature reached 1,427 deg C (SUS melting temperature) (about 4.4 hours after the earthquake) and when the in-reactor gas temperature reached about 450 deg C (about 5.6 hours after the earthquake), respectively.

These assumptions are purely for analysis, and it is not certain yet whether or not the leaks really occurred, or the leaks occurred from the in-core instrumentation dry tubes or main steam piping flange gaskets, as assumed in the analysis.

(2) Leaks from PCV in the gaseous phase

Leak holes as in the following were assumed in the analysis in order to roughly simulate the PCV pressures observed.

- A leak due to pipe damage on the RCW piping (0.0018 m^2) at the time of RPV rupture, and the leak area decreased to 0.0012 m^2 at 21.0 hours after the earthquake (assumed partially blocked due to fuel debris)
- A leak upon PCV temperature increase (total leak area increased to 0.00195 m^2 at 24.7 hours after the earthquake (following venting valve closure), 0.0024 m^2 at 51.2 hours after the earthquake (leak area enlarged)).

At about 24.7 hours after the earthquake when a leak due to the overheated PCV was assumed, the PCV temperature was calculated as exceeding about 300 deg C, far above the PCV design temperature (138 deg C). It is known from earlier research (*) that piping flange gaskets might be damaged at this elevated temperature. Therefore, if a leak from the PCV really occurred, gasket damage due to PCV overheating could be one cause. Concerning the assumption of enlarged leak areas about 51.2 hours after the earthquake, increased number of leak holes could also be a cause, because the PCV temperatures also change at elevated temperatures in the analysis.

However, these assumptions are purely for analysis, and it is not certain yet whether or not the leaks really occurred, or whether the leaks simply seem to have occurred from instrumentation errors.

(*) K. Hirao, T. Zama, M. Goto et al., “High-temperature leak characteristics of PCV hatch flange gasket,'' Nucl. Eng. Des., 145, 375-386 (1993).

(3) Operating conditions of the isolation condensers (ICs)

The isolation condensers (ICs) were assumed (*) not working in the analysis after the station blackout, since their operation conditions after station blackout are not yet clear.

Before the station blackout, intermittent operation of either IC kept the reactor pressure under control, that is, below the SRV working pressure (about 7.4 MPa[abs]).

(*) When the IC water levels on the shell side were confirmed by the local level indicators on October 18th, 2011, they were at 65% (Channel A) and 85% (Channel B) (Normal level is 80%).

The temperature chart of IC cooling water recorded that the temperature of Channel B stayed at about 70 deg C and that of Channel A increased to about 100 deg C, the saturation temperature, at about the same time as the tsunami arrival. This indicates that in Channel B evaporation caused only a slight water level change, while in Channel A heat exchange after the tsunami arrival decreased its water level.

It is not clear, though, concerning Channel A, how long and to what extent, the ICs could maintain their capability after the tsunami arrival on the following grounds: (i) the aperture of isolation valve on the PCV inner side is not known; (ii) the IC heat removal capability deteriorates when incondensable hydrogen gas generated by zirconium-water reactions due to overheated fuel stays on the IC cooling tube surfaces; and (iii) the IC heat removal capability also deteriorates by decreased steam flow to the ICs from the reactor due to decreased reactor pressure, as the reactor pressure dropped at an unknown time but before 02:45 on March 12th, 2011.

Therefore, the assumption in the May 2011 analysis of ICs not working after station blackout seems reasonable.

(4) Amounts of water injected to reactor

The amounts of water injected to the reactor were evaluated, as discussed in Attachment 1-5, in consideration of water discharged by fire engines under the conditions of constant discharge pressure and losses via bypass flow paths. The input values in the current analysis are given in Attachment 1-1. The reactor water levels observed are not used in the analysis, because the water level indicators are considered to have shown higher values than reality due to water evaporation in the water level indicators, as discussed in Attachment 1-2.

(5) Decay heat

Decay heat used in the current analysis is based on the ANSI / ANS5.1-1979 model with the parameters adjusted to keep consistency with the decay heat evaluated by ORIGEN2 incorporating the fuel loading history.

1.3 Results of MAAP analysis

Table 1-3 gives the key results of MAAP analysis.

Table 1-3 Summary of MAAP analysis results of Unit-1

Item	Results
The time when the core began to be uncovered (when the in-shroud water level decreased to TAF)	about 3 hours after the earthquake (about 18:00 on March 11th)
The time when the core damage started (when the maximum core temperature reached 1200 deg C)	about 4 hours after the earthquake (about 18:40 on March 11th)
The time when the RPV was ruptured	about 15 hours after the earthquake (about 05:40 on March 12th)

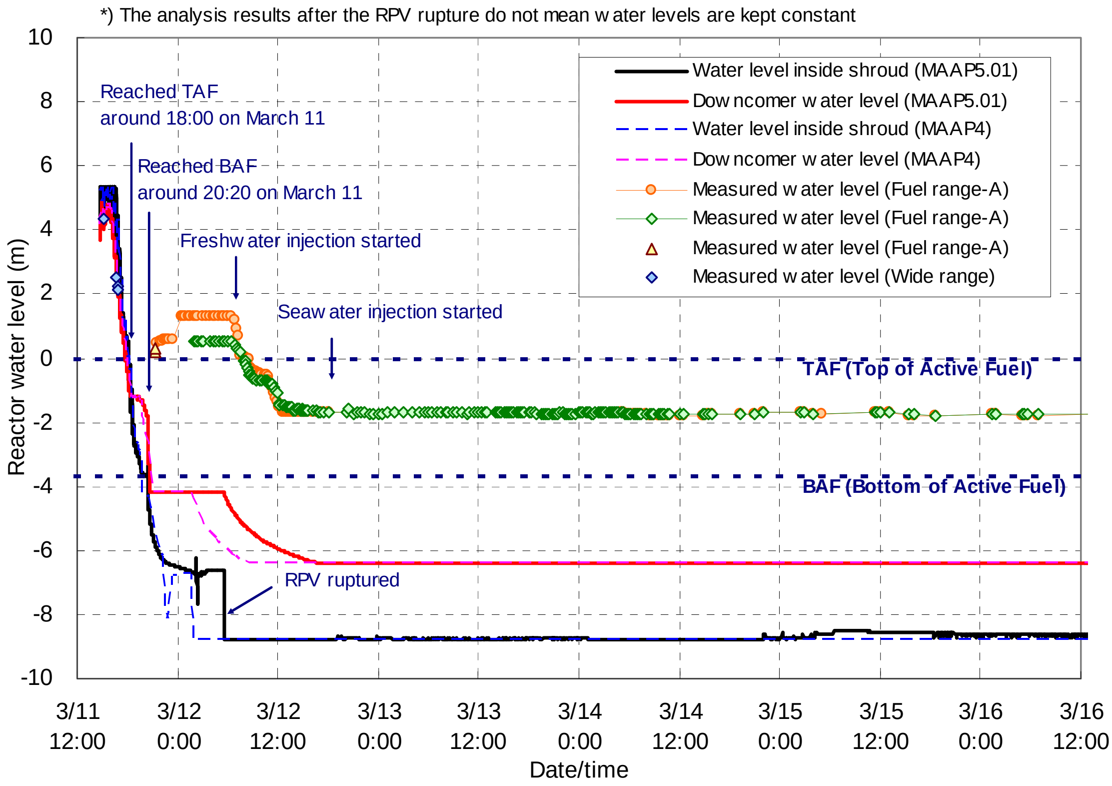


Figure 1-1 Reactor water level changes of Unit-1

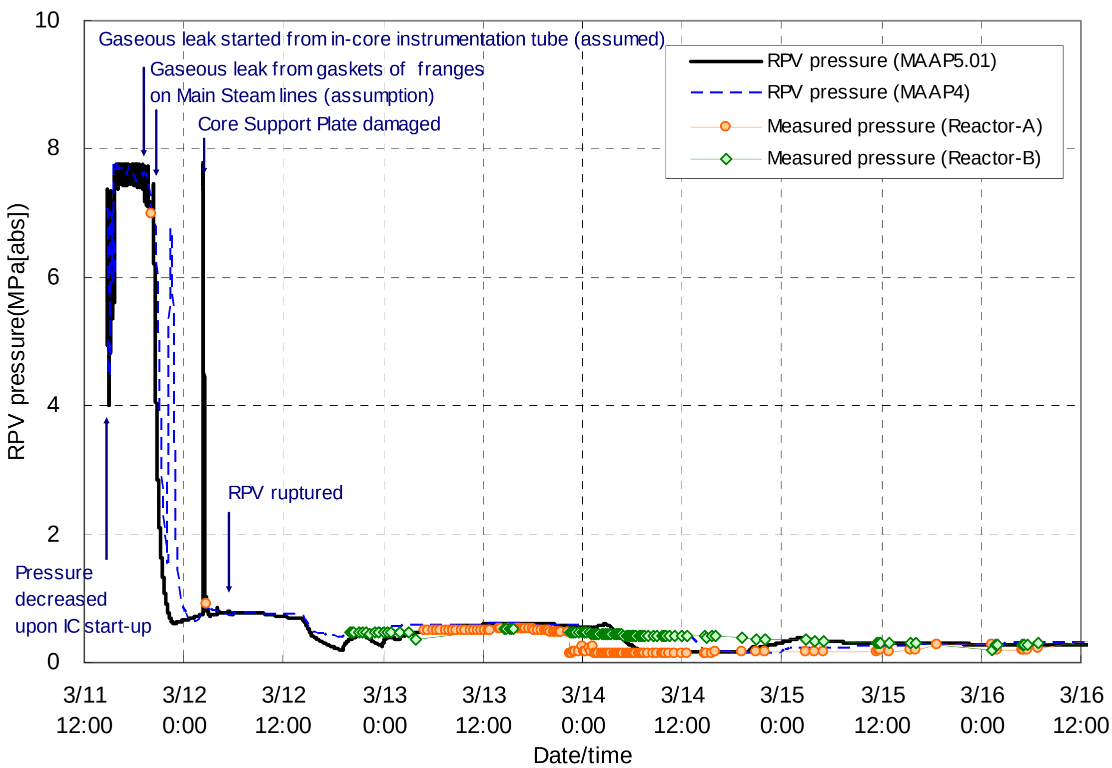


Figure 1-2 RPV pressure changes of Unit-1

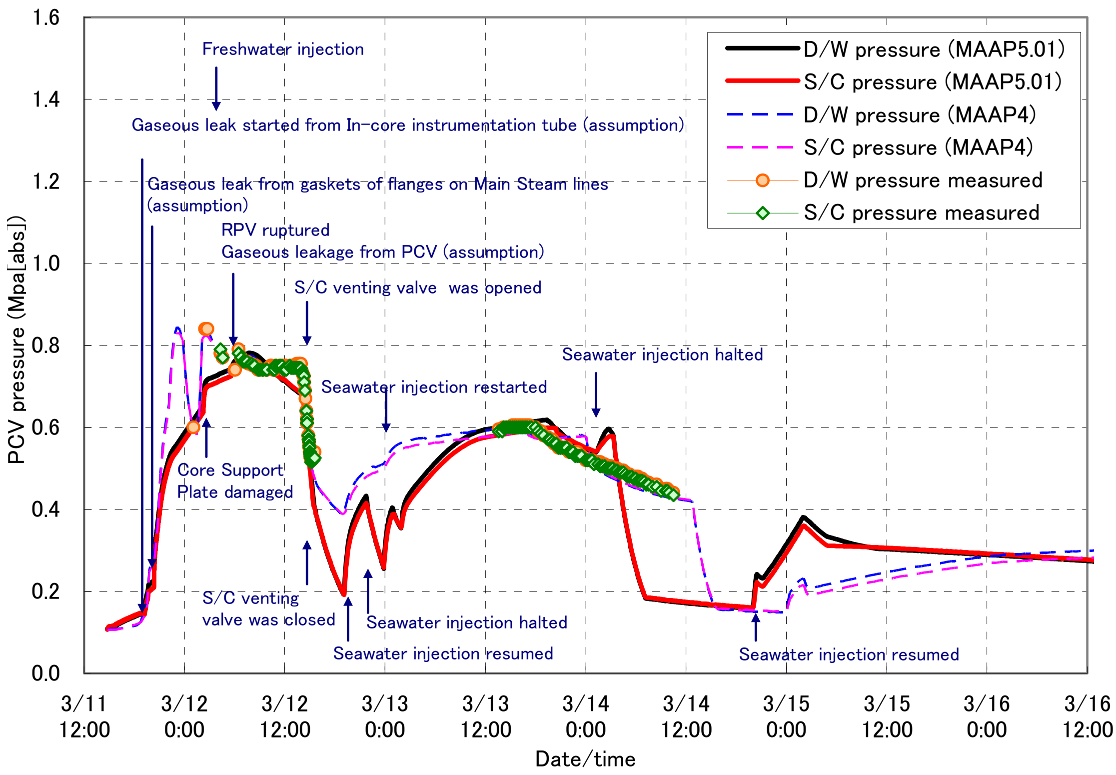


Figure 1-3 PCV pressure changes of Unit-1

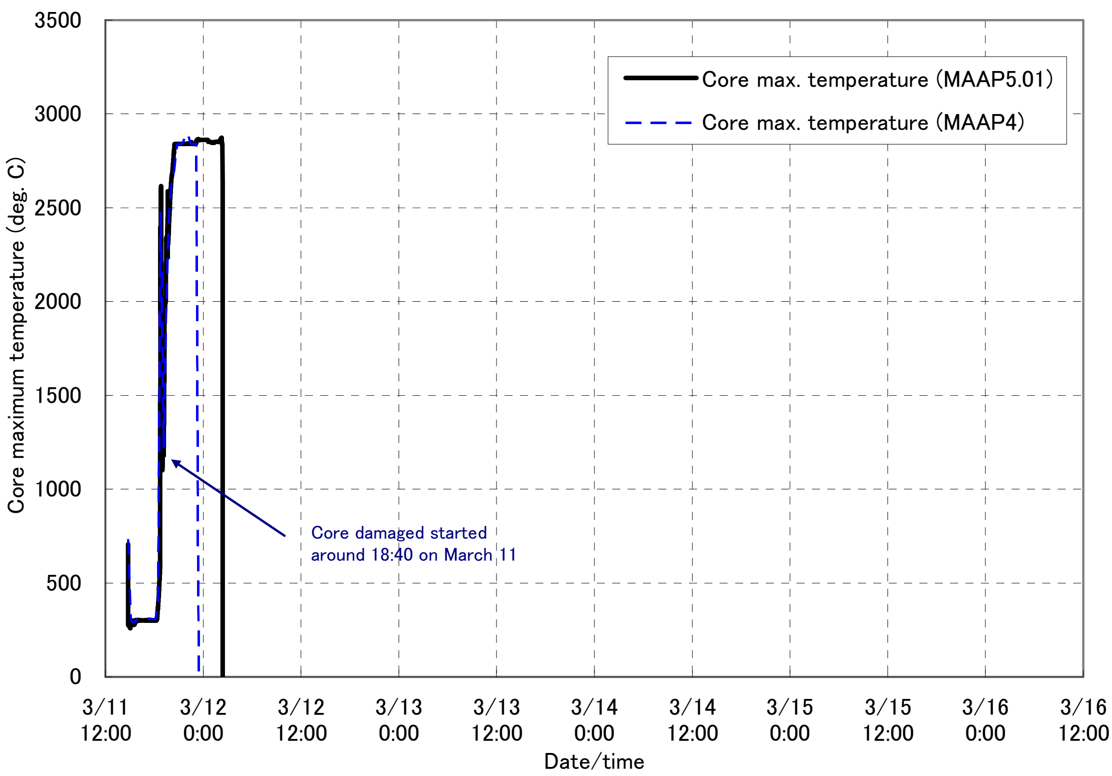


Figure 1-4 Core temperature changes of Unit-1

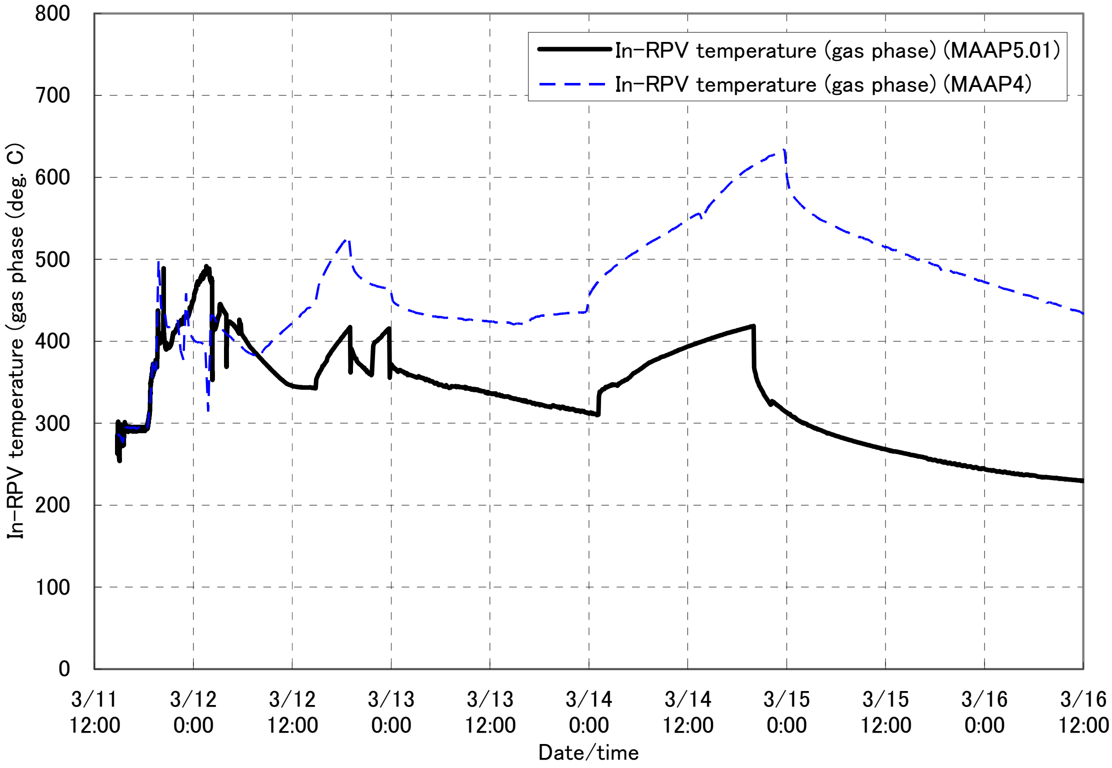


Figure 1-5 Gaseous temperature changes in RPV of Unit-1

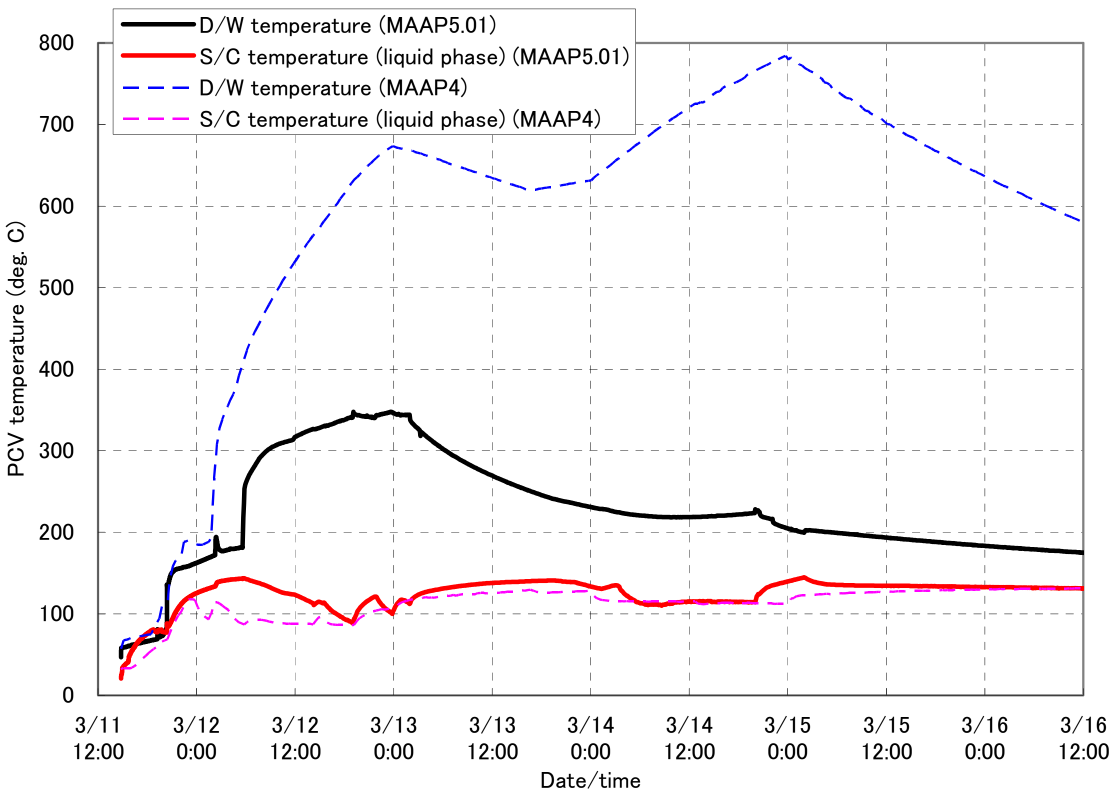


Figure 1-6 PCV temperature changes of Unit-1

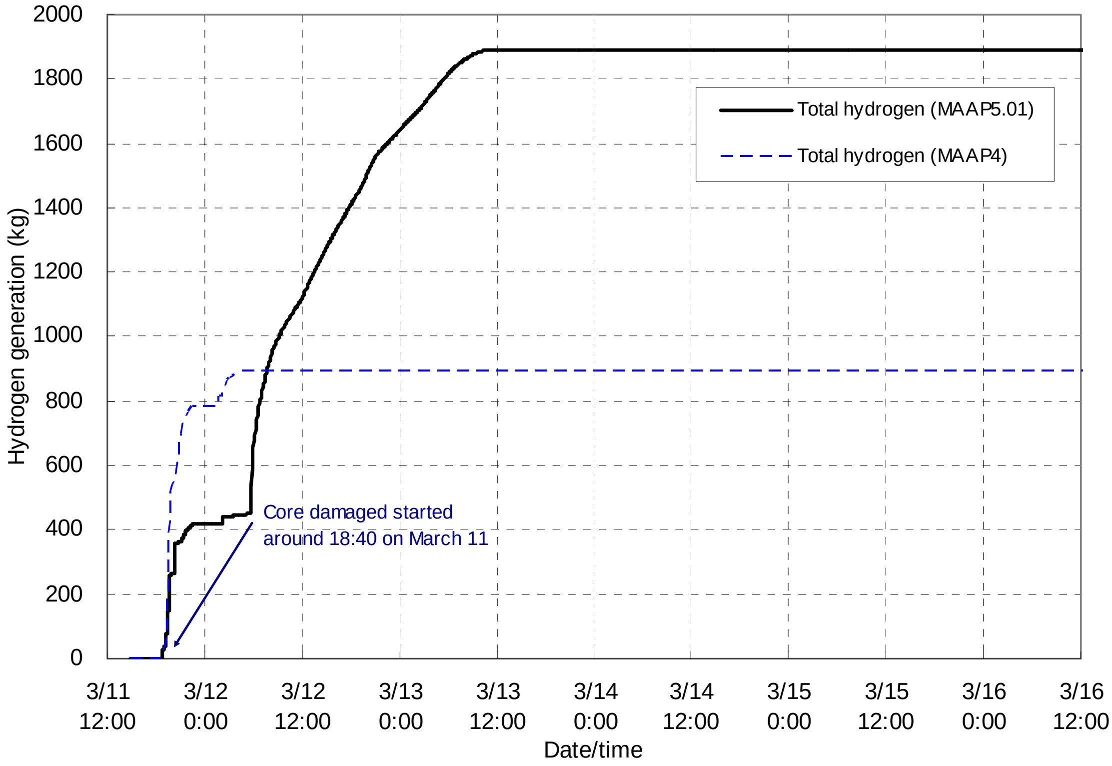


Figure 1-7 Hydrogen gas generation at Unit-1

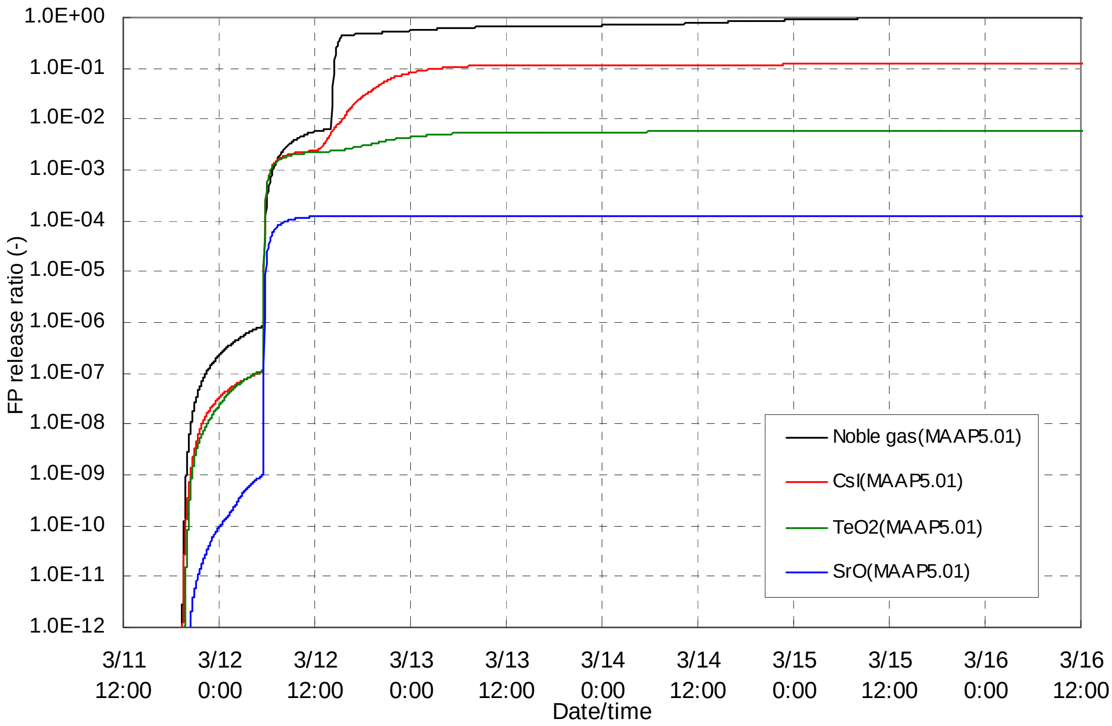


Figure 1-8 FP release ratio at Unit-1 (1/4)

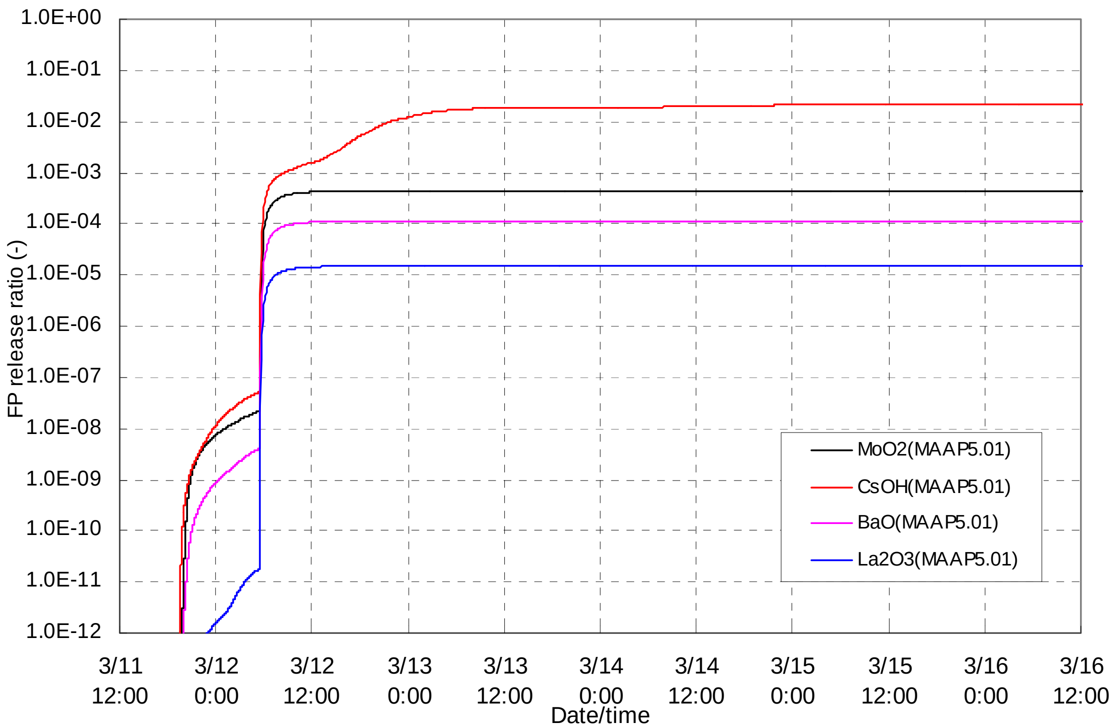


Figure 1-9 FP release ratio at Unit-1 (2/4)

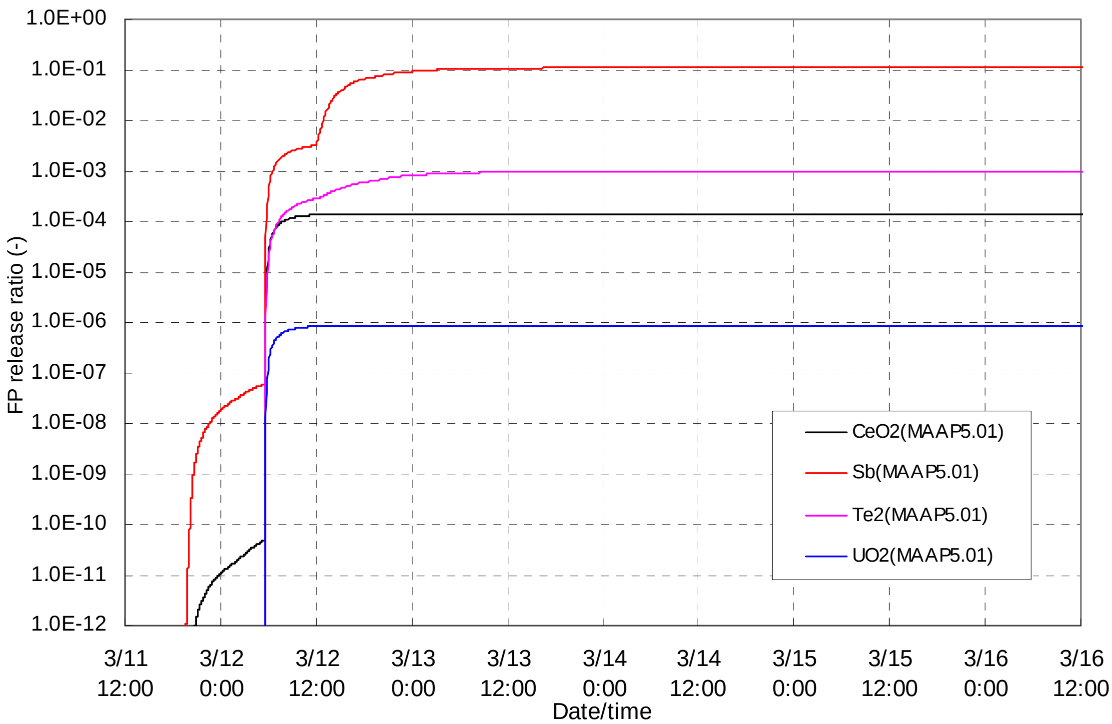


Figure 1-10 FP release ratio at Unit-1 (3/4)

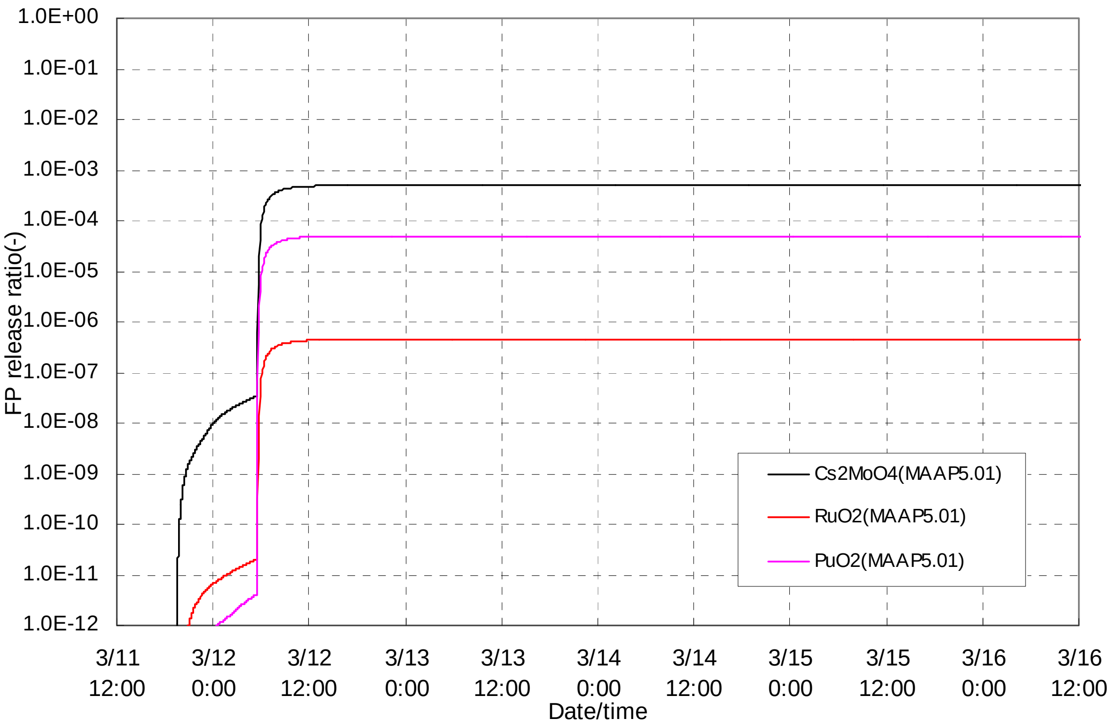


Figure 1-11 FP release ratio at Unit-1 (4/4)

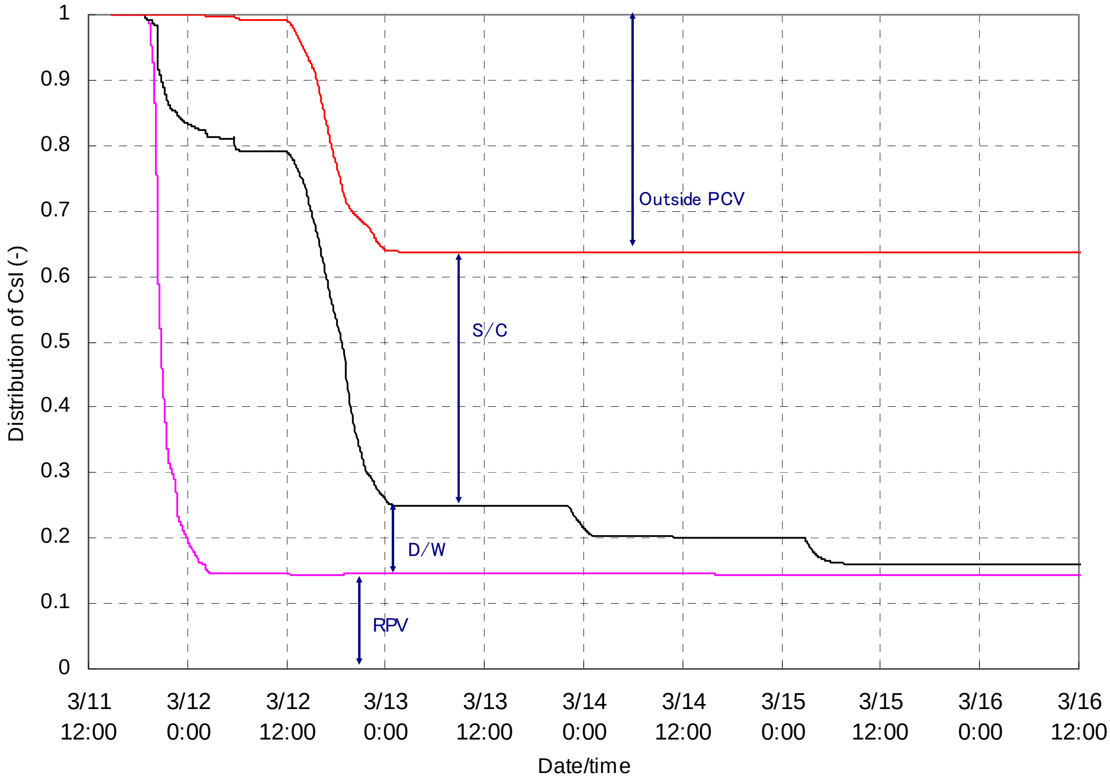


Figure 1-12 Distribution of FPs at Unit-1 (1/2)

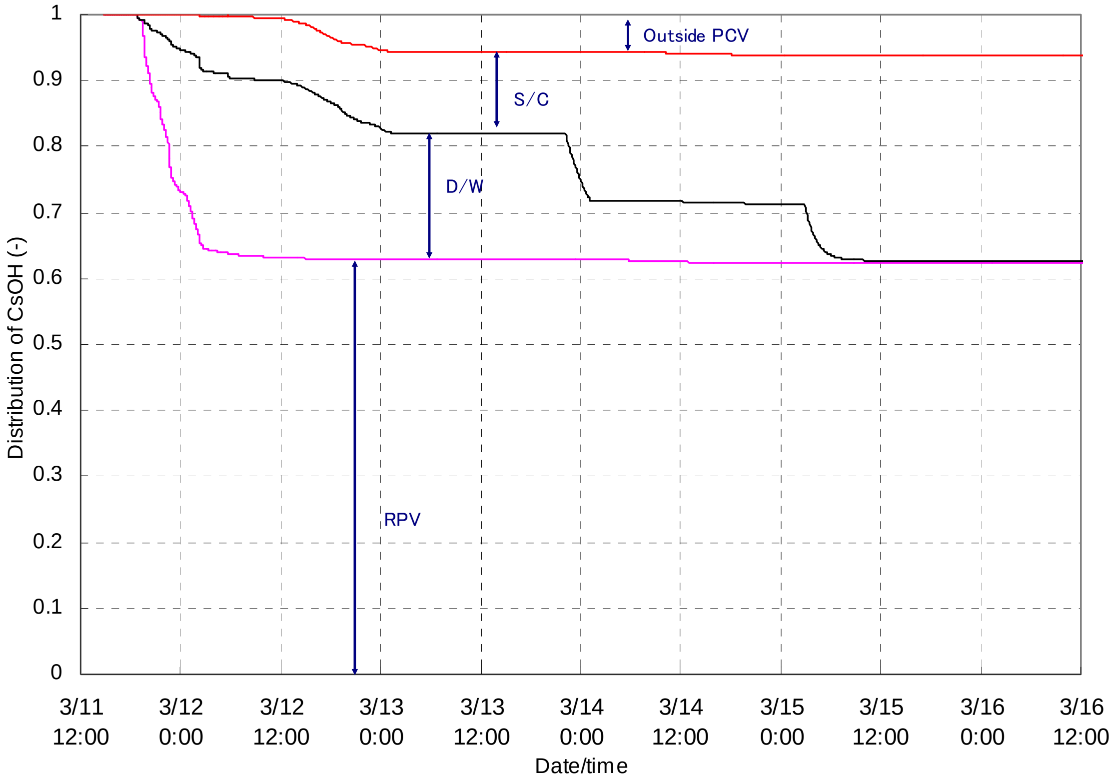
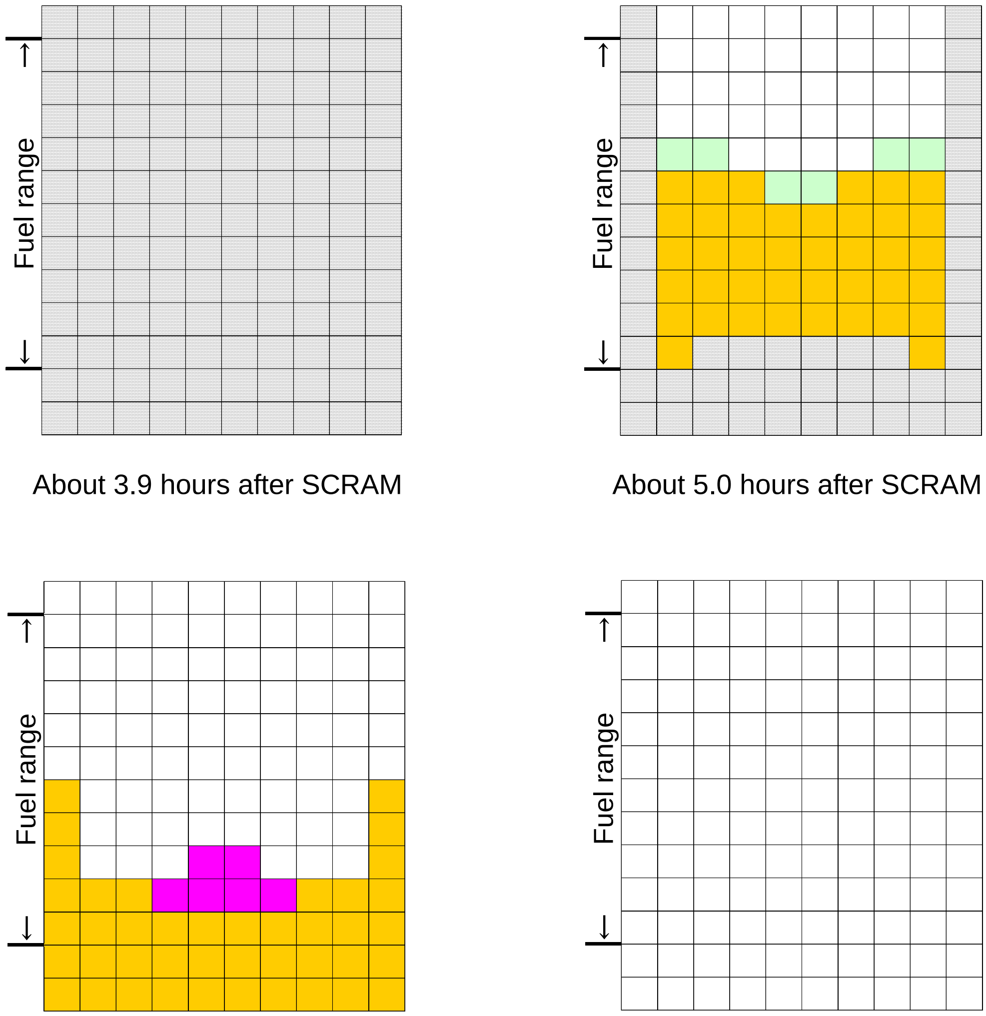


Figure 1-13 Distribution of FPs at Unit-1 (2/2)



About 3.9 hours after SCRAM

About 5.0 hours after SCRAM

About 11.5 hours after SCRAM

About 12.0 hours after SCRAM

Core damage configuration model

- : Empty (No fuel)
- : Normal fuel
- : Collapsed fuels piled up (Fuel rod shapes were kept)
- : Fuel rod diameters increased due to molten fuel flowing down on their surfaces and solidifying there
- : Fuel rod diameters further increased and blocked the downward flowing path
- : Molten core pool formed

Figure 1-14 Core status of Unit-1

2. Latest analysis of Unit-1 by MAAP5.01

2.1 Plant conditions and event chronology

Table 2-1 summarizes key plant conditions, while Table 2-2 shows the event time line as primary conditions for analysis. The incidents therein integrate the chronological records made public since May 2011, including two earlier documents (in Japanese): one is “Plant data compilation of the Fukushima Daiichi Nuclear Power Station when the Great East Japan Earthquake occurred” reported to the Nuclear and Industry Safety Agency (NISA) on May 16th, 2011; and the other is “First-hand responses to the accident at the Fukushima Daiichi Nuclear Power Station” made public on December 22nd, 2011.

Table 2-1 Plant conditions of Unit-2

Item	Conditions
Initial reactor output	2381 MWt (rated)
Initial reactor pressure	7.03MPa [abs] (normal operating pressure)
Initial reactor water level	About 5274mm (normal water level, distance above TAF)
RPV nodalization	See Figure 6 in Attachment 1
Active core nodalization	7 (radial), 24 (axial)
Cladding temperature to burst	727 deg C (1000K)
Criteria for core melting	Melting points of each core component material or the average melting temperature of mixed materials considering eutectic reactions.
Containment vessel model	See Figure 7 in Attachment 1
Containment vessel volumes	D/W volume: 4240m^3 S/C volume: 3160m^3
Suppression pool water volume	2980m^3
Decay heat	ANSI/ANS5.1-1979 model (Parameters adjusted for consistency with the decay heat evaluated by ORIGEN2 incorporating fuel loading history)

Table 2-2 Event chronology at Unit-2

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
1	3/11	14:46	Earthquake	A	—
2		14:47	Reactor SCRAM	A	Shift supervisor logbook, "4. Operator diaries" reported on 2011.5.16
3		14:50	RCIC manually started	A	"First-hand responses to the accident at the Fukushima Daiichi Nuclear Power Station", TEPCO Press release, 2011.12.22
4		14:51	RCIC automatically tripped (L-8)	A	"Initial Response of Tohoku-Chihou-Taiheiyo-Oki Earthquake at Fukushima Daiichi and Fukushima Daini Nuclear Power Station", TEPCO Press release, 2011.8.10
5		15:02	RCIC manually started	A	"7. Summary of operational actions", reported on 2011.5.16
6		15:07 to 15:25	S/C pool cooling by RHR	A	Process computer data and Shift supervisor logbook, "4. Operator diaries" reported on 2011.5.16
7		15:25 to 15:37	S/C spray by RHR	A	Process computer data and Shift supervisor logbook, "4. Operator diaries" reported on 2011.5.16
8		15:28	RCIC automatically tripped (L-8)	A	"7. Summary of operational actions", reported on 2011.5.16
9		15:39	RCIC manually started	A	"Initial Response of Tohoku-Chihou-Taiheiyo-Oki Earthquake at Fukushima Daiichi and Fukushima Daini Nuclear Power Station", TEPCO Press release, 2011.8.10
10		15:41	Station blackout	A	"7. Summary of operational actions", reported on 2011.5.16
11	3/12	ca. 4:20 to 5:00	Switching water source of RCIC from CST to S/C pool	B	"7. Summary of operational actions", reported on 2011.5.16 In the analysis, the time to switch was assumed so that measured reactor pressure change was well reproduced, to be 4:20 March 12th

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
12	3/14	13:25	Loss of RCIC function was judged from the decreasing reactor water level	B	"7. Summary of operational actions", reported on 2011.5.16 13:25 was the time to judge that RCIC had stopped. In the analysis, the timing of RCIC functional deterioration was assumed so that measured reactor water level around 18:00 on March 14th, just before the reactor depressurization, was well reproduced. Note that measured water level should be corrected under the actual reactor pressure and D/W temperature.
13		16:34	Operation to open one SRV started for reactor depressurization	A	"7. Summary of operational actions", reported on 2011.5.16 It is thought that the SRV did not open by this operation. Therefore, in the analysis, the SRV opening was not assumed
14		16:34	Working for seawater injection through fire protection line started	A	"7. Summary of operational actions", reported on 2011.5.16 (*1)
15		ca.18:00	Reactor pressure started to decrease by opening one SRV and depressurization was confirmed	A	"7. Summary of operational actions", reported on 2011.5.16
16		19:20	Fire engines were found to have halted due to depletion of fuel	A	"7. Summary of operational actions", reported on 2011.5.16 (*1)
17		19:54	Restarting 1st fire engine	A	"7. Summary of operational actions", reported on 2011.5.16 (*1,*2)
18		19:57	Restarting 2nd fire engine	A	"7. Summary of operational actions", reported on 2011.5.16 (*1)
19		21:20	Opening other 2 SRVs and reactor pressure decreased and reactor water level increased	A	"7. Summary of operational actions", reported on 2011.5.16 (*1) In the analysis, no SRV opening was assumed at this timing

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
20	3/14	23:25	Leak from RPV to D/W in the gaseous phase was assumed	B	In the analysis, it was assumed that the leak from RPV to D/W in the gaseous phase was formed in the time period when measured D/W pressure started to significantly increase
21	3/15	1:10	Opening one SRV	B	“First-hand responses to the accident at the Fukushima Daiichi Nuclear Power Station”, TEPCO Press release, 2011.12.22 In the analysis, no SRV opening was assumed at this timing
22		2:22	Operation to try to open SRV started	B	“First-hand responses to the accident at the Fukushima Daiichi Nuclear Power Station”, TEPCO Press release, 2011.12.22 In the analysis, no SRV opening was assumed at this timing
23		Around 6:00 to 6:10	Impact sound occurred S/C pressure indicator showed 0 MPa[abs]	B	It had been judged that the impact sound came from Unit-4 explosion, stated in “Fukushima Nuclear accident analysis report (Interim report)”, TEPCO press release, 2011.12.2. Regarding the S/C pressure dropping to 0 MPa[abs] at the timing, the possibility can not be denied that S/C was somewhat damaged and S/C pressure actually decreased, considering the instrumentation error. However, no leakage was assumed in the analysis because D/W maintained its pressure.
24		7:20	Leak from D/W in the gaseous phase was assumed	B	In the analysis, it was assumed that leak from D/W in the gaseous phase was formed because D/W pressure dropped.

*1) From the record that fire engines were found to have halted at 19:20 on March 14th, although it is not clear how long fire engines were running, there may be a possibility that water had been injected to reactor after the reactor depressurization. But in the analysis, sea water injection was assumed to start when the fire engine was restarted at 19:54 on March 14th and the increase in measured reactor water level was observed.

*2) Timings and flow rate of water injected were defined so as not to exceed the average flow rate of water injection described in Attachment 1-4. Analysis input for water injection rate is described in Attachment 2-3.

2.2 Definition of conditions based on plant data observed

(1) Assumption concerning operational conditions of RCIC

After the earthquake, operators controlled reactor water level by repeating manual actuation of reactor core isolation cooling system (RCIC) followed by automatic shutdown due to water level high signal. Station blackout occurred due to ensuing tsunami after they manually started RCIC at 15:39 on March 11th, which was 3rd start-up. Then RCIC operation was continuing for about 3days without control power due to the loss of DC power supply.

As shown in Attachment 2-4, the turbine steam control valve will fully open upon the loss of control power, or DC power, for RCIC. According to the process computer data recorded around the arrival of tsunami, it was observed that reactor water level increased and reactor pressure decreased from about 15:45 on March 11th although some data among the records showed abnormality. Once reactor water level measurement was resumed by connecting temporary battery in 22:00 on March 11th, measured water level constantly indicated upper value of measurement range. It is thought, as shown in Attachment 2-1, that actual water level would reach around main steam nozzles. Furthermore the transition of measured reactor pressure was lower than the normal operational pressure while the rated pressure was expected with SRV cycling under RCIC operation. It is thought, as shown in Attachment 2-1, that RCIC turbine was driven by two-phase flow due to the high water level reaching main steam nozzles as a result of uncontrolled RCIC operation.

Therefore, in the analysis, RCIC operational conditions were assumed as in the following.

- After the loss of DC power, RCIC water injection rate was set larger than rated design value in order to simulate the increasing reactor water level recorded by process computer
- After reactor water level reached main steam nozzles, RCIC water injection rate was set as 30t/h, about one third of rated design value, and two-phase flow was extracted for RCIC turbine with the energy corresponding to decay heat, in order to simulate the low reactor pressure transient.
- Regarding RCIC functional deterioration, RCIC turbine steam flow was adjusted so as to simulate the increasing reactor pressure observed from about 9:00 on March 14th

The discussion about RCIC operational situation was described in Attachment 2-1.

It is noticed that RCIC mechanical turbine overspeed trip mechanism will work according to its design if turbine control valve turns fully open upon the loss of DC power during operation like Unit-2 situation. The reason why Unit 2 RCIC could continue its operation and the actual timing to lose its control power are still unclear.

(2) Containment vessel pressure behavior observed from 00:00 on March 12th to 12:00 on March 14th

Containment vessel pressure was expected to increase by the exhausted steam from RCIC operation into S/C but pressures measured of the D/W and S/C increased more slowly than the prediction by the analysis over the time period from about 00:00 on March 12th to about 12:00 on March 14th, 2011. In the analysis, in order to simulate this pressure behavior, it was assumed that the containment vessel heat had been removed by the water retained in the torus room which was gradually inundated by tsunami. The detail was described in Attachment 2-2.

(3) Amounts of water injected to the reactor

Regarding RCIC water injection after the station blackout, RCIC operational conditions were assumed as described above.

- After the loss of DC power, RCIC water injection rate was set larger than rated design value in order to simulate the increasing reactor water level recorded by process computer
- After reactor water level reached main steam nozzles, RCIC water injection rate was set as 30t/h, about one third of rated design value, and two-phase flow was extracted for RCIC turbine with the energy corresponding to decay heat, in order to simulate the low reactor pressure transient.

After the loss of RCIC function, measured water level was decreasing and lowered below TAF before reactor was depressurized by opening SRV at about 18:00 on March 14th. The water level rapidly dropped upon the depressurization and lowered below BAF. Then sea water injection by fire engines started at 19:54 on Mach 14th, after the depressurization.

Moreover intermittent increases in reactor pressure were observed around 21:00 and 23:00 on Mach 14th, and 01:00 on March 15th although reactor had been depressurized by opening SRV, and the increase in D/W pressure was also observed. Although actual opening and closing behaviors of SRVs are still unclear, possible causes for SRV to fail to operate would be insufficient driving gas pressure under the high back pressure or D/W pressure, or insufficient voltage to energize solenoid valve under the high temperature condition. Therefore the increase and decrease in reactor pressure would not necessarily be caused by the close and open of SRVs.

Considering these situations, it was assumed in the current analysis that one SRV was kept open and water injection rate from fire engines was adjusted so as to simulate the increase in RPV and D/W pressure. This is also because it is inferred that the water injection from fire engines induced water – zirconium reaction followed by the increase in RPV and D/W pressure. And during this process, it was assumed that water injection into the reactor was interrupted when reactor pressure exceeded 1.1 MPa[gage].

As found in calibrating the reactor water level indicators, the water level indicators did not show correct values and actual water level was below the measurement range. Consequently the reactor water level was assumed as unable to keep the level sufficient to cover the core region. The water injection rates in the analysis were set so that the reactor water level stayed below the fuel region. And also the water injection rate was set so as not to exceed its daily average discharge flow rate from fire engines (Attachment 1-4, 2-3).

(4) Leaks from RPV in the gaseous phase

Leak holes were assumed in the analysis in order to roughly simulate the PCV pressures observed. Gaseous leaks from RPV to D/W with the area of 0.005454m^2, corresponding to expected leakage from in-core instrumentation tube, were assumed at the timing when D/W pressure significantly increased (at 23:25 on March 14th, about 81 hours after the earthquake).

These assumptions are purely for analysis, and it is not certain yet whether or not the leaks really occurred, as assumed in the analysis.

(5) Leaks from PCV in the gaseous phase

Leak holes were assumed in the analysis in order to roughly simulate the PCV pressures observed. Gaseous leaks from D/W with the area of 0.013m^2 were assumed at the timing when D/W pressure significantly dropped (at 07:20 on March 15th, about 89 hours after the earthquake).

These assumptions are purely for analysis, and it is not certain yet whether or not the leaks really occurred, or whether the leaks simply seem to have occurred from instrumentation errors.

(6) Decay heat

Decay heat used in the current analysis is based on the ANSI / ANS5.1-1979 model with the parameters adjusted to keep consistency with the decay heat evaluated by ORIGEN2 incorporating fuel loading history.

2.3 Results of MAAP analysis

Table 2-3 gives the key results of MAAP analysis.

The current analysis gives following characteristics compared to the previous results by

MAAP4 (Separate Volume 1).

- The reactor water level increased earlier because of the increasing RCIC water injection rate after the station blackout.
- After the reactor depressurization, water injection from fire engines into the uncovered core induced the water-zirconium reaction, which resulted in the increase in reactor and containment vessel pressure with one SRV kept opened. However, the simulated increase was still smaller than the observed increase. There are many unclear issues regarding actual SRV workings and water injection rate from fire engines. Further investigation is needed.
- Moreover, RPV was not ruptured in the analysis result, which is strongly affected by water injection rate from fire engines and the uncertainties in its analysis conditions.

Table 2-3　Summary of MAAP analysis of Unit-2

Item	Results
The time when the core began to be uncovered (when the in-shroud water level decreased to TAF)	about 75 hours after the earthquake (about 18:10 on March 14th)
The time when the core damage started (when the maximum core temperature reached 1200 deg C)	about 77 hours after the earthquake (about 19:20 on March 14th)
The time when the RPV was ruptured	- (not ruptured in the current analysis)

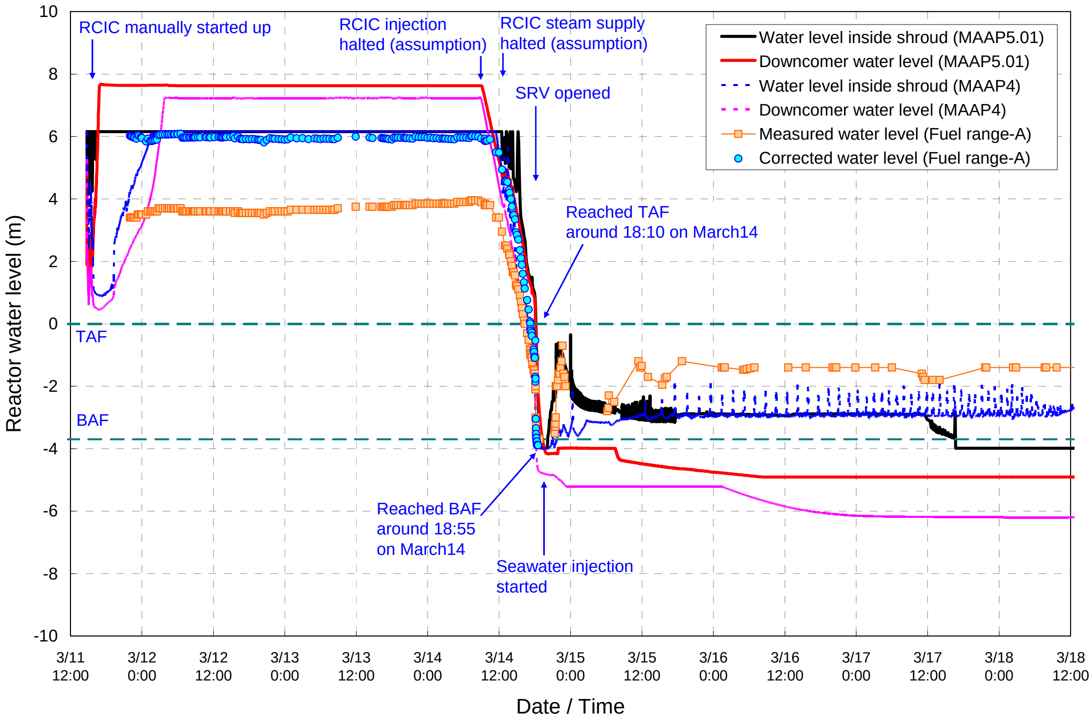


Figure 2-1 Reactor water level changes of Unit-2

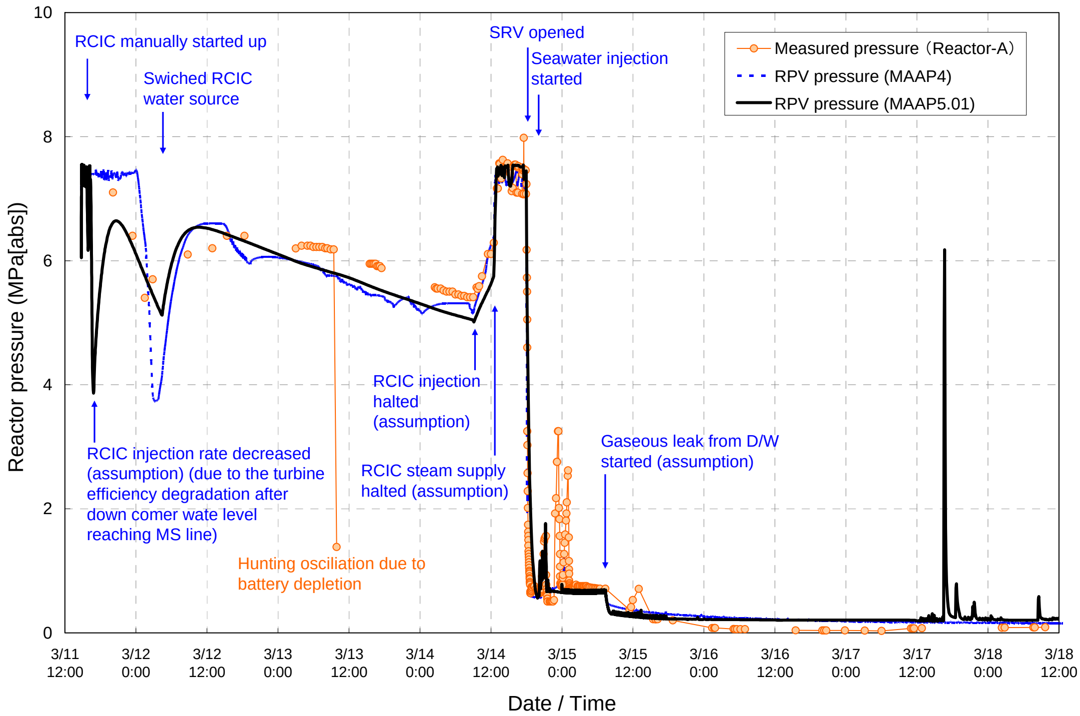


Figure 2-2 RPV pressure changes of Unit-2

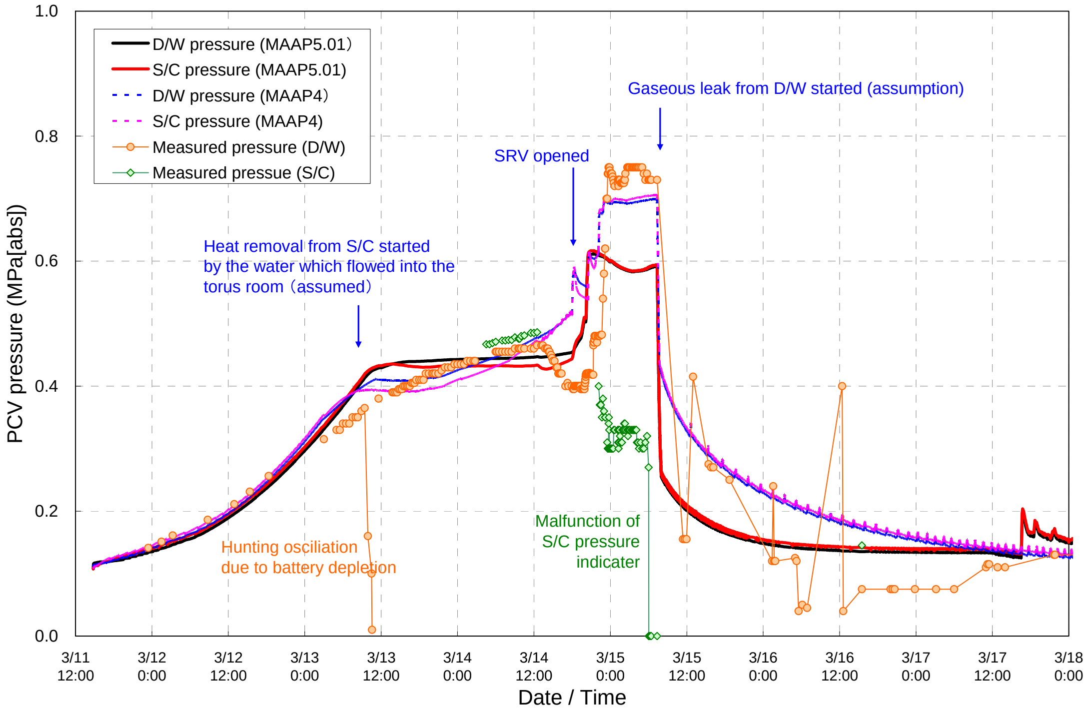


Figure 2-3 PCV pressure changes of Unit-2

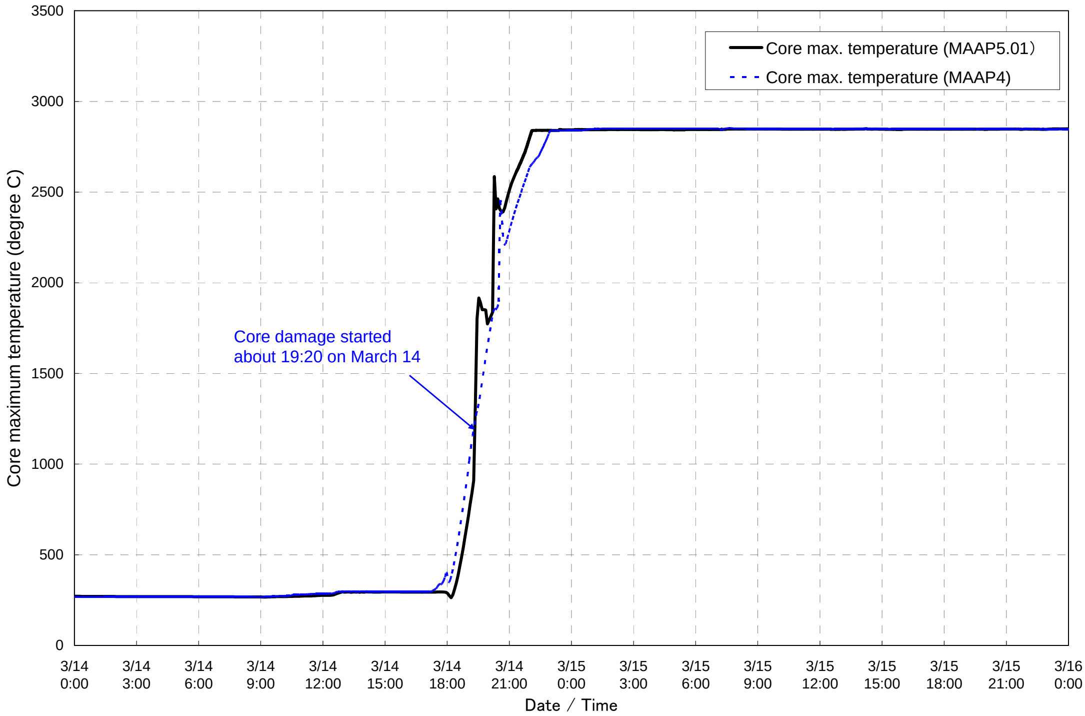


Figure 2-4 Core temperature changes of Unit-2

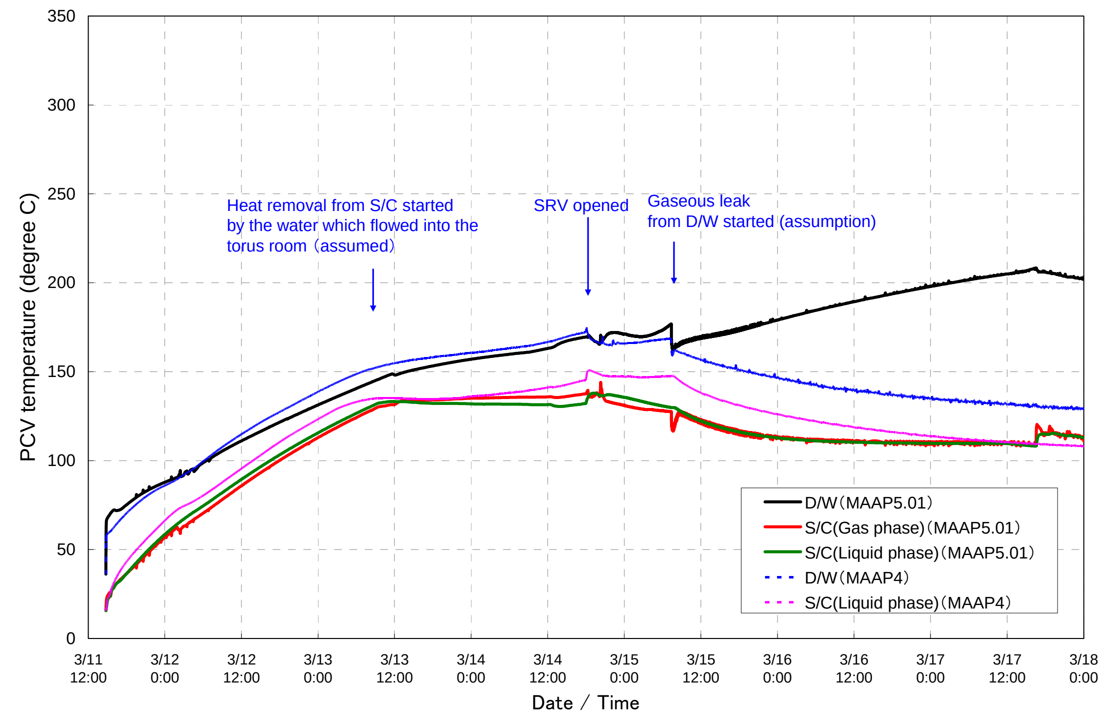


Figure 2-5 PCV temperature changes of Unit-2

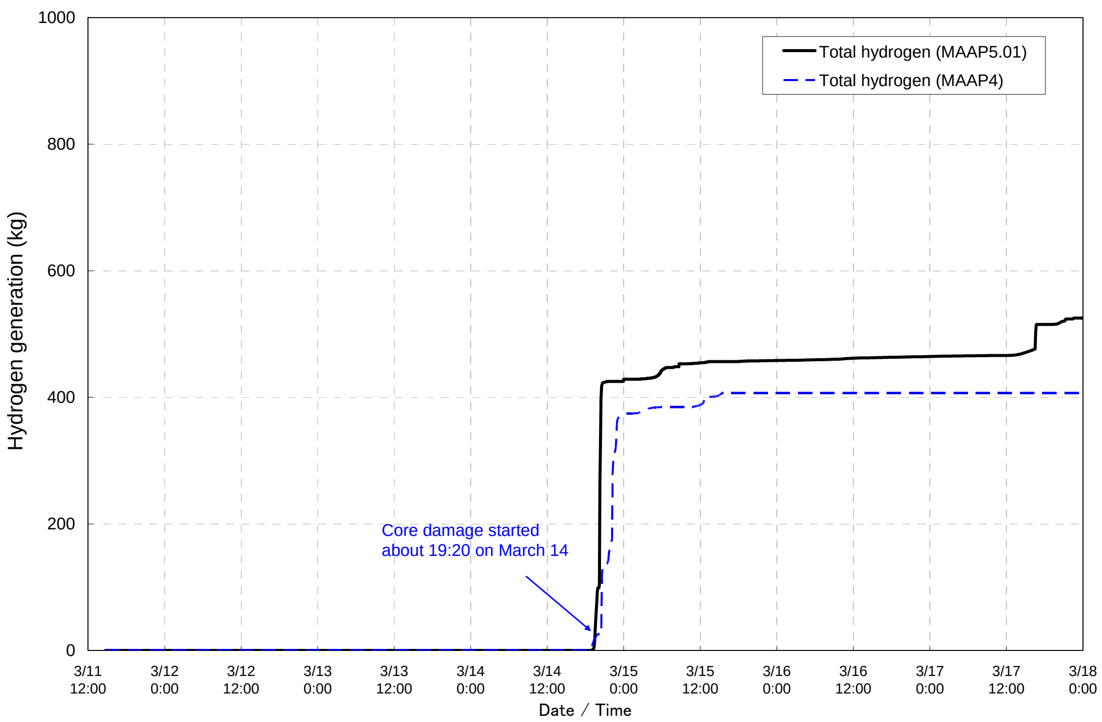


Figure 2-6 Hydrogen gas generation at Unit-2

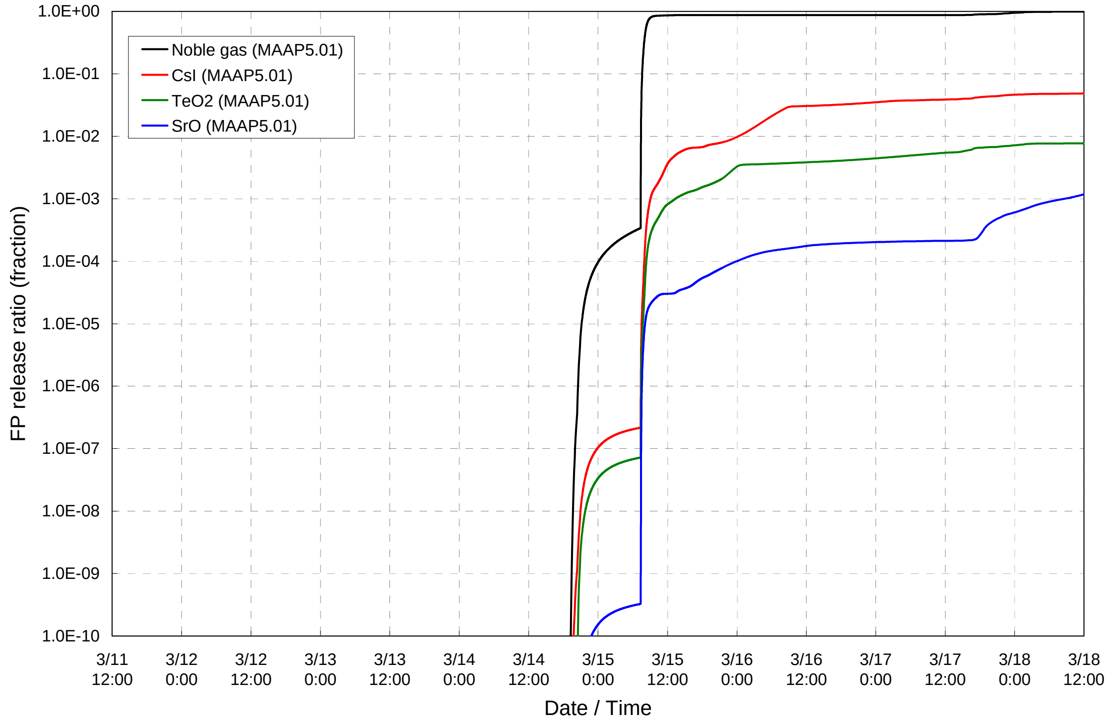


Figure 2-7 FP release ratio at Unit-2 (1/4)

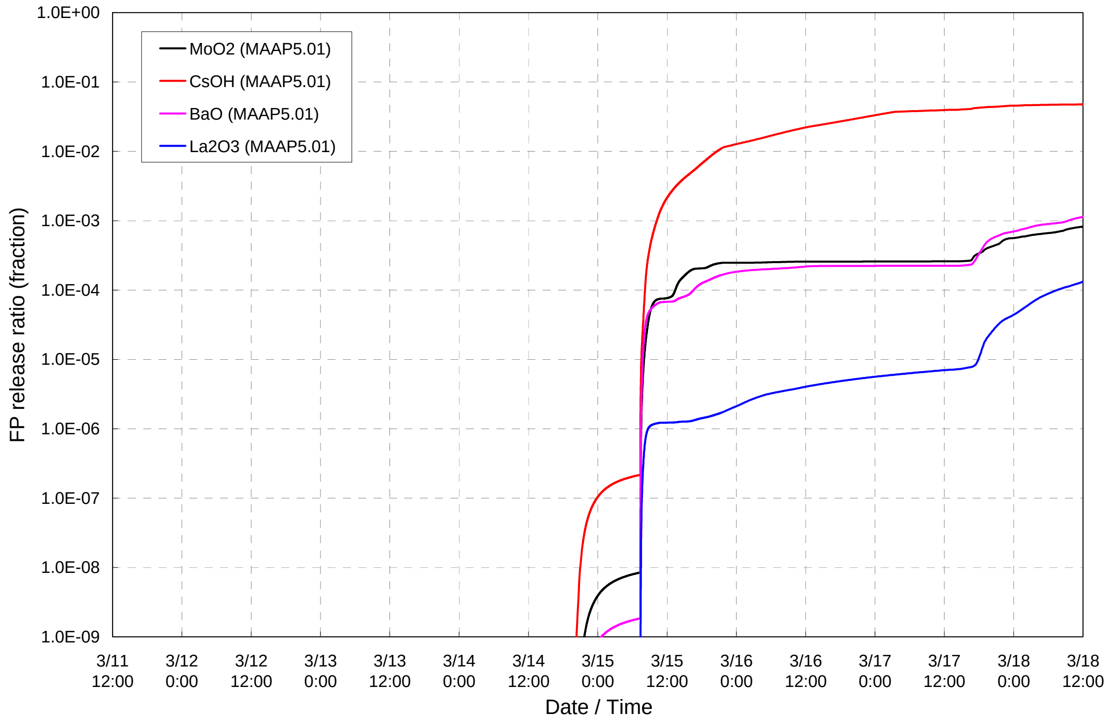


Figure 2-8 FP release ratio at Unit-2 (2/4)

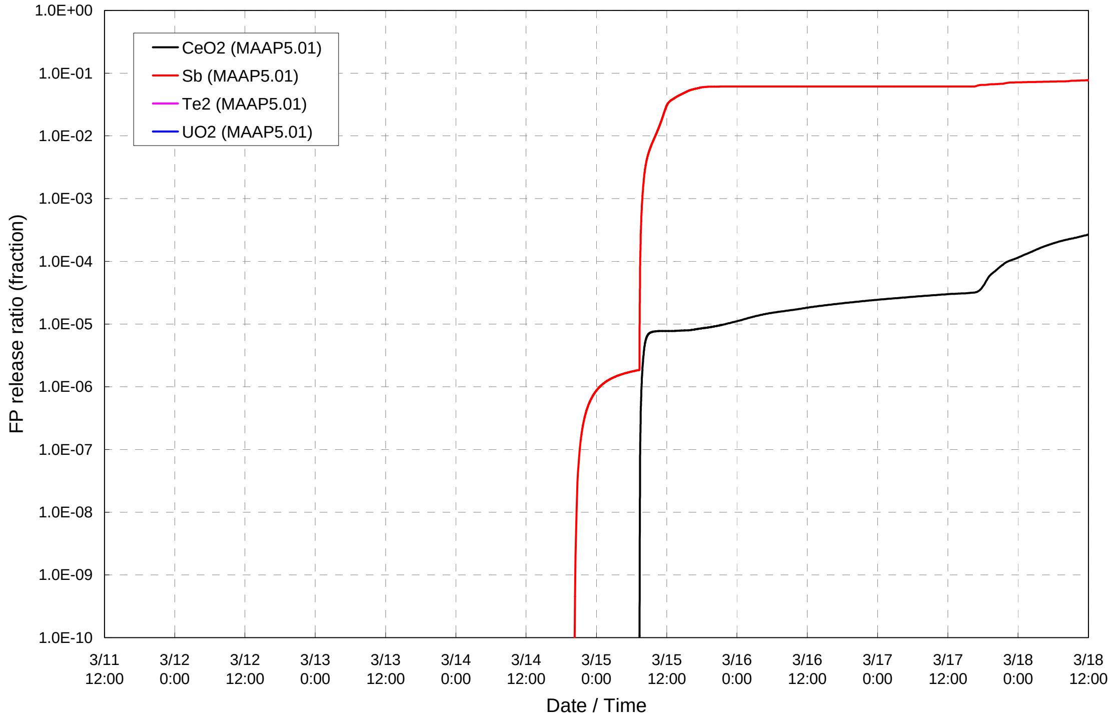


Figure 2-9 FP release ratio at Unit-2 (3/4)

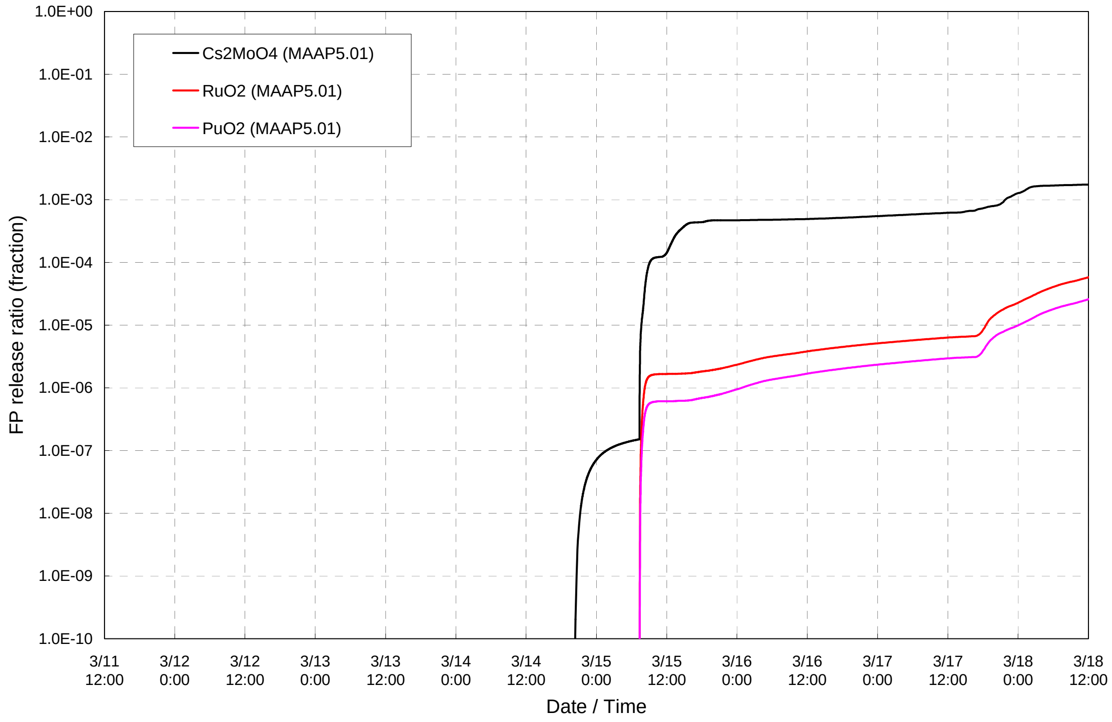


Figure 2-10 FP release ratio at Unit-2 (4/4)

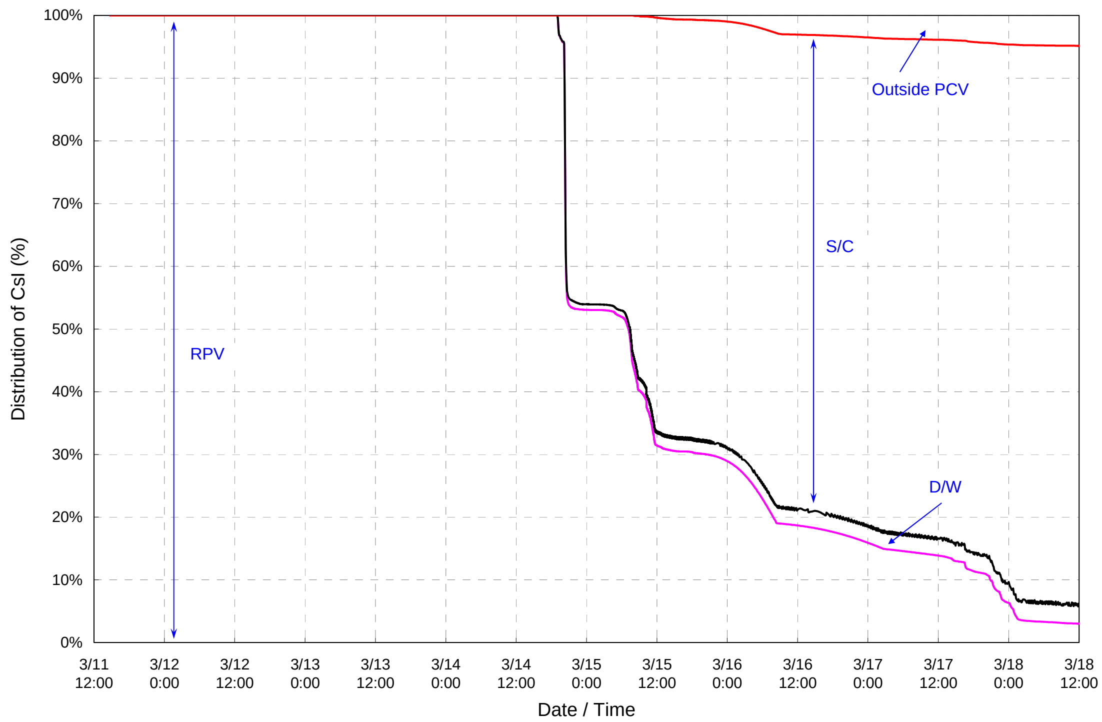


Figure 2-11 Distribution of FPs at Unit-2 (1/2)

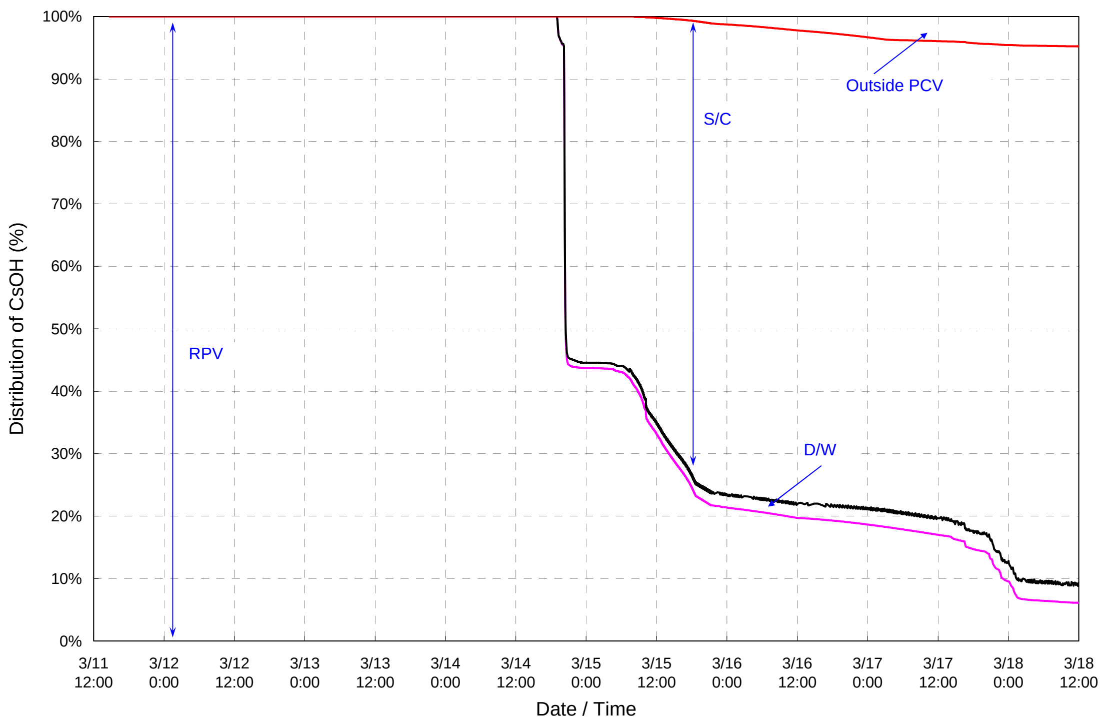
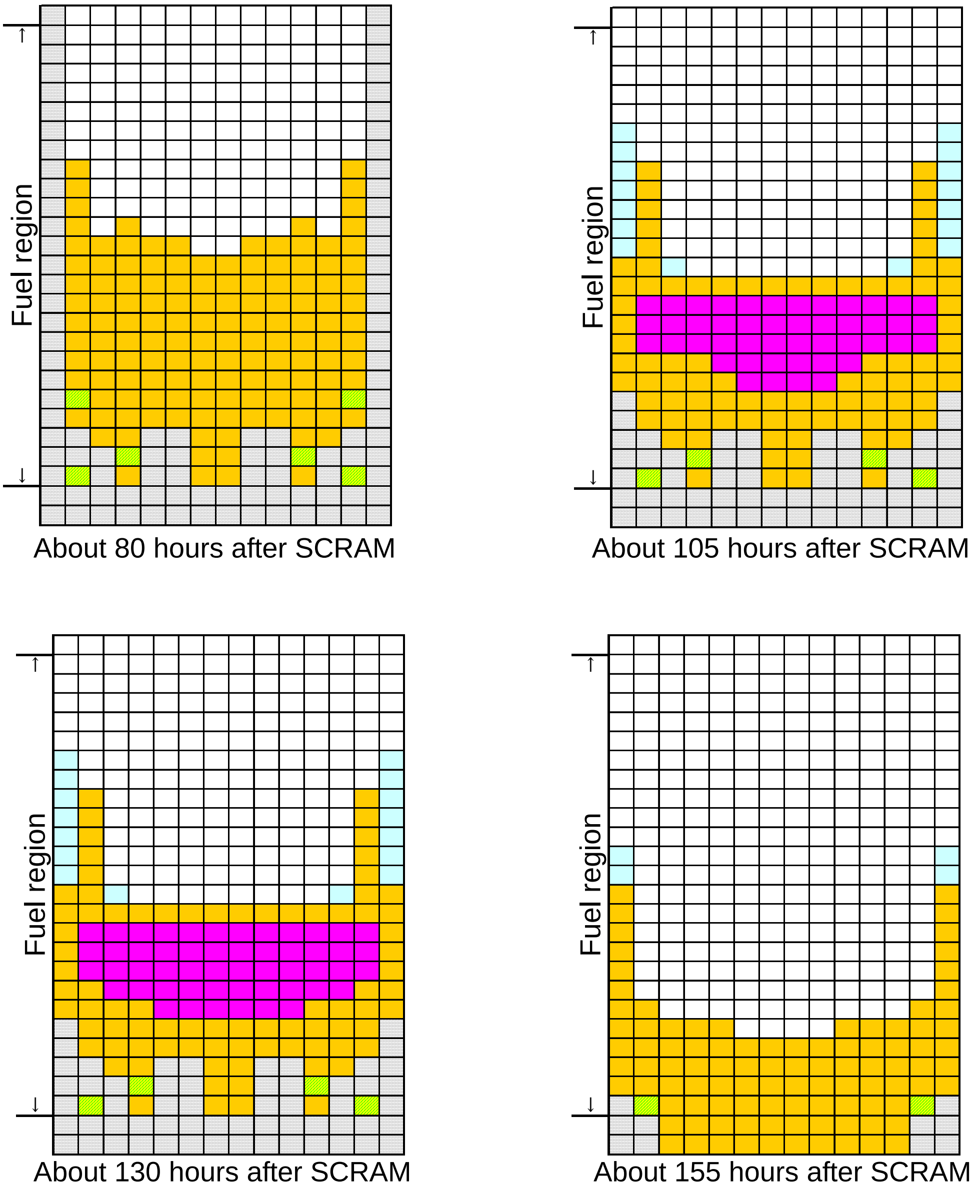


Figure 2-12 Distribution of FPs at Unit-2 (2/2)



Core damage configuration model

- : Empty (No fuel)
- : Normal fuel
- : Collapsed fuels piled up (Fuel rod shapes were kept)
- : Fuel rod diameters increased due to molten fuel flowing down on their surfaces and solidifying there
- : Fuel rod diameters further increased and blocked the downward flowing path
- : Molten core pool formed

Figure 2-13 Core status of Unit-2

3. Latest analysis of Unit-3 by MAAP5.01

3.1 Plant conditions and event chronology

Table 3-1 summarizes key plant conditions, while Table 3-2 shows the event time line as primary conditions for analysis. The incidents therein integrate the chronological records made public since May 2011, including two earlier documents (in Japanese): one is “Plant data compilation of the Fukushima Daiichi Nuclear Power Station when the Great East Japan Earthquake occurred” reported to the Nuclear and Industry Safety Agency (NISA) on May 16th, 2011; and the other is “First-hand responses to the accident at the Fukushima Daiichi Nuclear Power Station” made public on December 22nd, 2011.

Table 3-1 Plant conditions of Unit-3

Item	Conditions
Initial reactor output	2381 MWt (rated)
Initial reactor pressure	7.03MPa [abs] (normal operating pressure)
Initial reactor water level	About 5274mm (normal water level, distance above TAF)
RPV nodalization	See Figure 6 in Attachment 1
Active core nodalization	7 (radial), 24 (axial)
Cladding temperature to burst	727 deg C (1000K)
Criteria for core melting	Melting points of each core component material or the average melting temperature of mixed materials considering eutectic reactions.
Containment vessel model	See Figure 7 in Attachment 1
Containment vessel volumes	D/W volume: 4240m^3 S/C volume: 3160m^3
Suppression pool water volume	2980m^3
Decay heat	ANSI/ANS5.1-1979 model (Parameters adjusted for consistency with the decay heat evaluated by ORIGEN2 incorporating fuel loading history)

Table 3-2 Event chronology at Unit-3

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
1	3/11	14:46	Earthquake	A	―
2		14:47	Reactor SCRAM	A	Shift supervisor logbook, “4. Operator diaries” reported on 2011.5.16
3		15:05	RCIC manually started	A	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22
4		15:25	RCIC automatically tripped (L-8)	A	“7. Summary of operational actions”, reported on 2011.5.16
5		15:38	Station blackout	A	Shift supervisor logbook, “4. Operator diaries” reported on 2011.5.16
6		16:03	RCIC manually started	A	“7. Summary of operational actions”, reported on 2011.5.16
7	3/12	11:36	RCIC automatically tripped	A	“7. Summary of operational actions”, reported on 2011.5.16
8		12:06	Alternative S/C spray by DDFP started	A	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22
9		12:35	HPCI automatically started (L-2)	A	“7. Summary of operational actions”, reported on 2011.5.16
10	3/13	02:42	HPCI manually stopped	A	“7. Summary of operational actions”, 2011.5.16
11		03:05	Alternative S/C spray by DDFP was stopped. Completion of switchover to alternative water injection into the reactor reported to MCR	B	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22 Preparation for switching over of injection line was being done before stopping HPCI, but it was not clear when the switchover was completed. It was assumed to have been completed at this time. In the analysis, however, water injected was assumed to have failed to reach the reactor, since the RPV pressure was high during the subject time period.
12		05:08	Alternative S/C spray by DDFP started (switched over from the alternative water injection line into the reactor)	A	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
13	3/13	07:39	Alternative D/W spray by DDFP started (switched over from the alternative S/C spray)	A	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22
14		07:43	Alternative S/C spray by DDFP halted	A	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22
15		08:40 to 09:10	Alternative D/W spray by DDFP halted Switched over to alternative water injection line into the reactor	B	“First action of Fukushima Daiichi Nuclear Power Station Accident”, TEPCO Press release, 2011.12.22 In the analysis, D/W spray was assumed to have stopped at 08:55, when PCV pressure increased significantly
16		ca. 09:08	Reactor depressurized by SRV	A	“7. Summary of operational actions”, reported on 2011.5.16
17		09:20	PCV pressure decrease by venting confirmed	A	Although the vent line was configured at 08:41 by operating the AO-valve on the S/C side, which is stated in “7. Summary of operational actions, 2011.5.16,” venting was assumed to have started at 09:20, when PCV pressure decrease was confirmed.
18		09:25	Freshwater injection started by fire engines	A	“7. Summary of operational actions”, reported on 2011.5.16 (*1) It was assumed in the analysis that water injection into the reactor by DDFP started when the RPV pressure decreased (Item 16), because the alternative injection line was configured before (Item 15). After water injection started by fire engines (item 18), water injection from fire engines only was assumed because of its higher discharge pressure.
19		11:17	Closure of AO-valve of S/C venting line confirmed due to loss of driving gas pressure	A	“7. Summary of operational actions”, reported on 2011.5.16

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
20	3/13	12:20	Freshwater injection terminated due to water inventory depletion in fire protection pools. Switching over to seawater injection started	A	"First action of Fukushima Daiichi Nuclear Power Station Accident", TEPCO press release, 2011.12.22 It was assumed in the analysis that water was not injected by DDFP during the interruption of water injection by fire engines because operating situation was unclear.
21		12:30	S/C vent valve opened for PCV venting	A	"7. Summary of operational actions", reported on 2011.5.16
22		13:12	Seawater injection line configured and injection started	A	"7. Summary of operational actions", reported on 2011.5.16 (*1)
23		14:10	S/C vent-valve closure assumed	B	Due to D/W pressure increase, PCV venting, which started at 12:30 on 3/13, was assumed to have stopped at this timing.
24		21:10	AO-valve opening judged for PCV venting	B	"First action of Fukushima Daiichi Nuclear Power Station Accident", TEPCO press release, 2011.12.22 In the analysis, it was set at 20:30 when PCV pressure started to decrease
25	3/14	00:50	S/C vent-valve closure assumed	B	Due to D/W pressure increase, PCV venting, which started under Item 24, was assumed to have stopped at this timing.
26		01:10	Water injection halted to make up the water source pit	A	"7. Summary of various operations implemented", reported on 2011.5.16
27		03:20	Water source pit make-up done Seawater injection resumed	A	"7. Summary of various operations implemented", reported on 2011.5.16 (*1)
28		05:20	Small S/C vent valve (AO) opening started for PCV venting	A	"First action of Fukushima Daiichi Nuclear Power Station Accident", TEPCO Press release, 2011.12.22

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
29	3/14	06:10	Small S/C vent valve (AO) opening completed for PCV venting	A	"First action of Fukushima Daiichi Nuclear Power Station Accident", TEPCO Press release, 2011.12.22 Small S/C vent valve (AO) opening started at 05:20 and completed at 06:10 on 3/14, but in the analysis PCV venting was implemented at 05:20 on 3/14 for PCV venting
30		11:01	Unit-3 reactor building exploded	A	"7. Summary of various operations implemented", reported on 2011.5.16
31		11:01	Seawater injection halted (in response to explosion)	A	"Initial Response of Tohoku-Chihou-Taiheiyo-Oki Earthquake at Fukushima Daiichi and Fukushima Daini Nuclear Power Station", TEPCO Press release, 2011.8.10
32		12:00	S/C vent valve closure assumed for PCV venting	B	In view of D/W pressure increase, venting assumed to have ended, which started under Item 28
33		15:30	Seawater injection resumed	A	"Fukushima Nuclear Accident Analysis Report", TEPCO, 2012.6.20 (*1)
34		16:00	S/C vent valve opening assumed for PCV venting	B	In view of D/W pressure decrease, venting assumed to have been resumed
35		19:20 to 19:54	Seawater injection halted (fire engines found to have been out-of-service from 30 min to 1hour before 19:20)	A	"Addendum and correction to Plant data compilation of the Fukushima Daiichi Nuclear Power Station when the Great East Japan Earthquake occurred" (in Japanese), TEPCO Press release 2013.7.17 (*1)
36		21:04	S/C vent valve closure assumed for PCV venting	B	In view of D/W pressure increase, venting assumed to have ended, which started under Item 34
37		21:14 to 3/15 02:30	Seawater injection halted and resumed at 02:30 on 3/15	A	"Addendum and correction to Plant data compilation of the Fukushima Daiichi Nuclear Power Station when the Great East Japan Earthquake occurred" (in Japanese), TEPCO Press release 2013.7.17 (*1)

Chronology				Category & Remarks‡	‡: A, recorded for incidents and reference documents are available; B, estimated from records or from reasonable grounds; C, assumed in analysis
No	Date & Time		Events		
38	3/15	16:05	S/C vent valve closure assumed for PCV venting	A	"7. Summary of various operations implemented", reported on 2011.5.16
39	3/16	01:55	S/C vent valve for PCV venting opened	B	"7. Summary of various operations implemented", reported on 2011.5.16, records venting was implemented at this timing, but no venting was assumed in the analysis because D/W pressure remained unchanged
40	3/17	21:00	S/C vent valve for PCV venting confirmed to have been closed	B	"7. Summary of various operations implemented", reported on 2011.5.16, records confirmation of vent valve closure, but closure was not assumed in view of D/W pressure changes
41		21:30	S/C vent valve opened for PCV venting	B	"7. Summary of various operations implemented", reported on 2011.5.16, records valve opening, but opening was not assumed in view of D/W pressure changes
42	3/18	05:30	S/C vent valve for PCV venting confirmed to have been closed	—	"7. Summary of various operations implemented", reported on 2011.5.16, records the subject venting, but this is outside the time of the current analysis
43	3/18	ca. 05:30	S/C vent valve opened for PCV venting	—	"7. Summary of various operations implemented", reported on 2011.5.16, records the subject venting, but this is outside the time of the current analysis
44	3/19	11:30	S/C vent valve for PCV venting confirmed to have been closed	—	"7. Summary of various operations implemented", reported on 2011.5.16, records the subject venting, but this is outside the time of the current analysis
45	3/20	ca. 11:25	S/C vent valve opened for PCV venting	—	"7. Summary of various operations implemented", reported on 2011.5.16, records the subject venting, but this is outside the time of the current analysis

*1) Timings and flow rate of water injected were defined so as not to exceed the average flow rate of water injection described in Attachment 1-4. Analysis input for water injection rate is described in Attachment 3-2.

3.2 Definition of conditions based on plant data observed

(1) Amounts of water injected to the reactor

Water injection to Unit-3 reactor continued after the station blackout by use of the RCIC and HPCI, as described in Table 3-2. When the HPCI was started up, the reactor pressure decreased to about 1MPa(abs). The reactor pressure changed at a low level thereafter. This is probably because the HPCI continuously extracted steam for driving itself while it was being operated with flow control (Attachment 3-1). In the analysis, the amounts of water injected to the reactor were set so that the reactor pressure and water level measured could be more or less simulated. Furthermore, a possibility of insufficient water injection to the reactor due to insufficient driving power before the HPCI was manually stopped was also considered when setting the amounts of water injected to the reactor (Attachment 3-2).

The following assumptions were made in setting the amounts of water injected to the reactor after 09:25 on March 13th, when freshwater injection started.

As found in calibrating the water level indicators of Unit-1, the water level indicators did not show correct values. Consequently the reactor water level was assumed as unable to keep the level sufficient to cover the core region. The water injection rates in the analysis were set so that the reactor water level stayed below the fuel region, and further, so that PCV pressures could be approximately simulated. And also the water injection rate was set so as not to exceed its daily average discharge flow rate from fire engines (Attachment 3-2).

(2) Decay heat

Decay heat used in the current analysis is based on the ANSI / ANS5.1-1979 model with the parameters adjusted to keep consistency with the decay heat evaluated by ORIGEN2 incorporating fuel loading history.

3.3 Results of MAAP analysis

Table 3-3 gives the key results of MAAP analysis.

The current analysis gives significantly different characteristics of water injection to the reactor from that of previous results by MAAP4 (Separate Volume 1). This difference led to significant changes in analysis results. The following three points are particularly to be noted.

- The reactor water level decrease significantly advanced, and it reached near the TAF by the time when the operators manually stopped the HPCI at about 02:42 on March 13th. The core was not covered already by around this time.
- As a result, the timing of core damage also advanced. By the time when the water

level decrease according to the water level indicators in the fuel range ended at about 07:30 on March 13th, fuel melting was already in progress. (Maximum core temperature in the analysis reached 2200 deg C at 05:30.)

- The accident progression developed faster, the time when fuel could not be cooled was prolonged, and eventually the reactor vessel was ruptured.

Table 3-3 Summary of MAAP analysis of Unit-3

Item	Results
The time when the core began to be uncovered (when the in-shroud water level decreased to TAF)	about 36 hours after the earthquake (about 02:30 on March 13th)
The time when the core damage started (when the maximum core temperature reached 1200 deg C)	about 38 hours after the earthquake (about 05:10 on March 13th)
The time when the RPV was ruptured	about 64 hours after the earthquake (about 07:10 on March 14th)

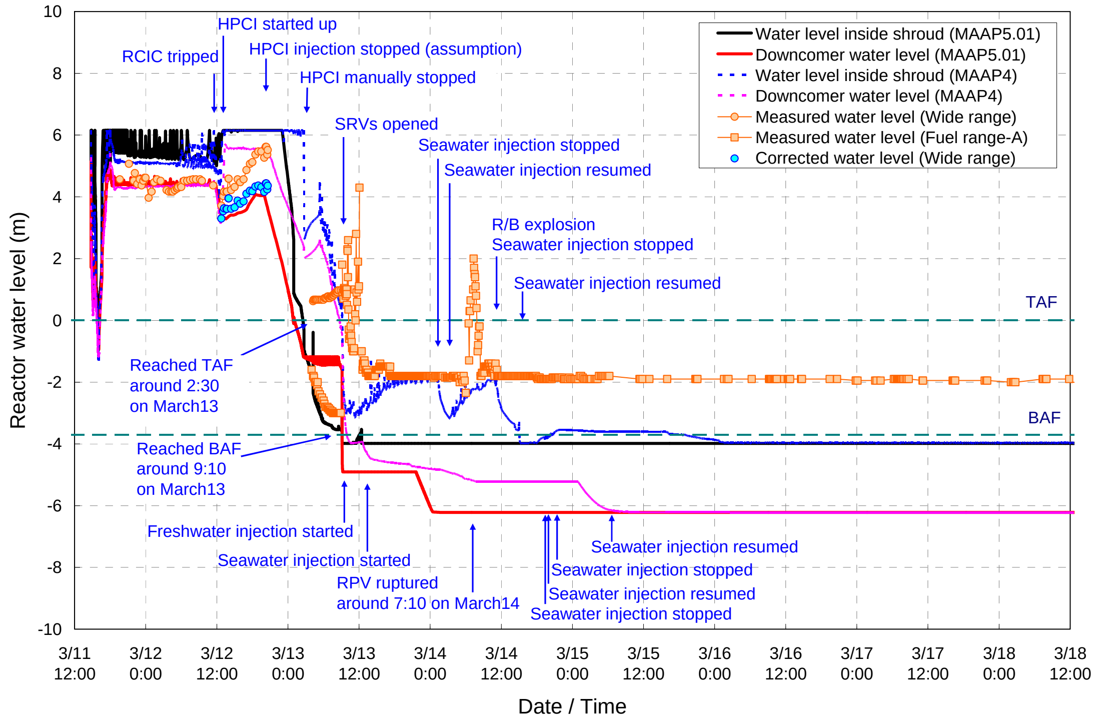


Figure 3-1 Reactor water level changes of Unit-3

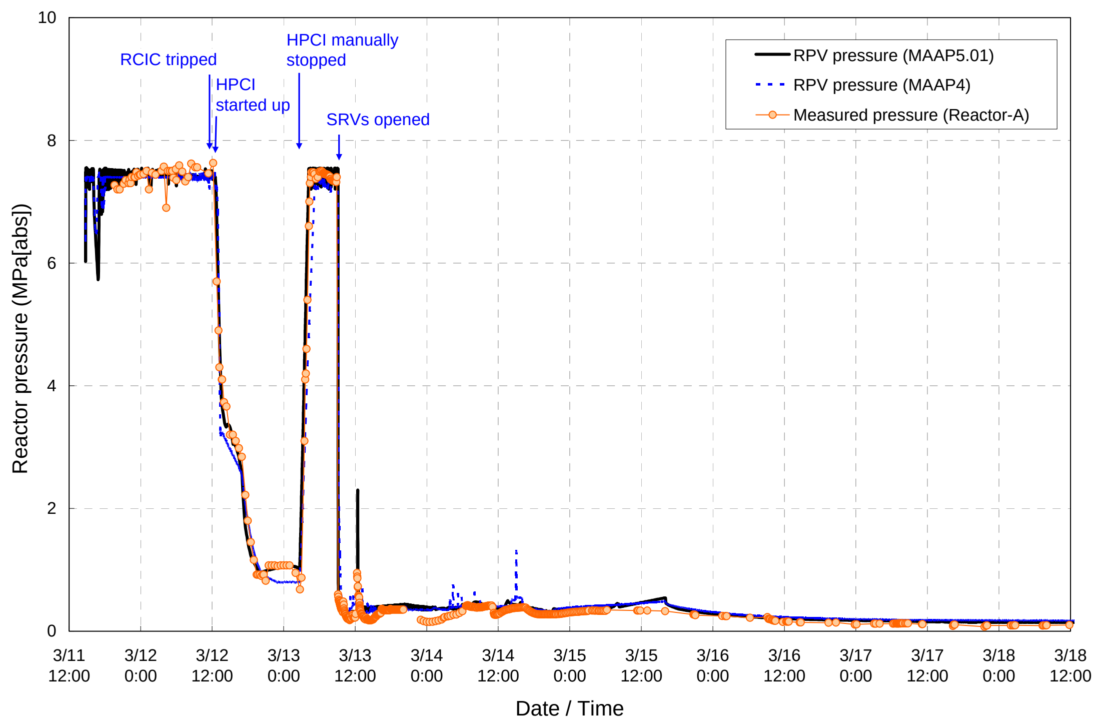


Figure 3-2 RPV pressure changes of Unit-3

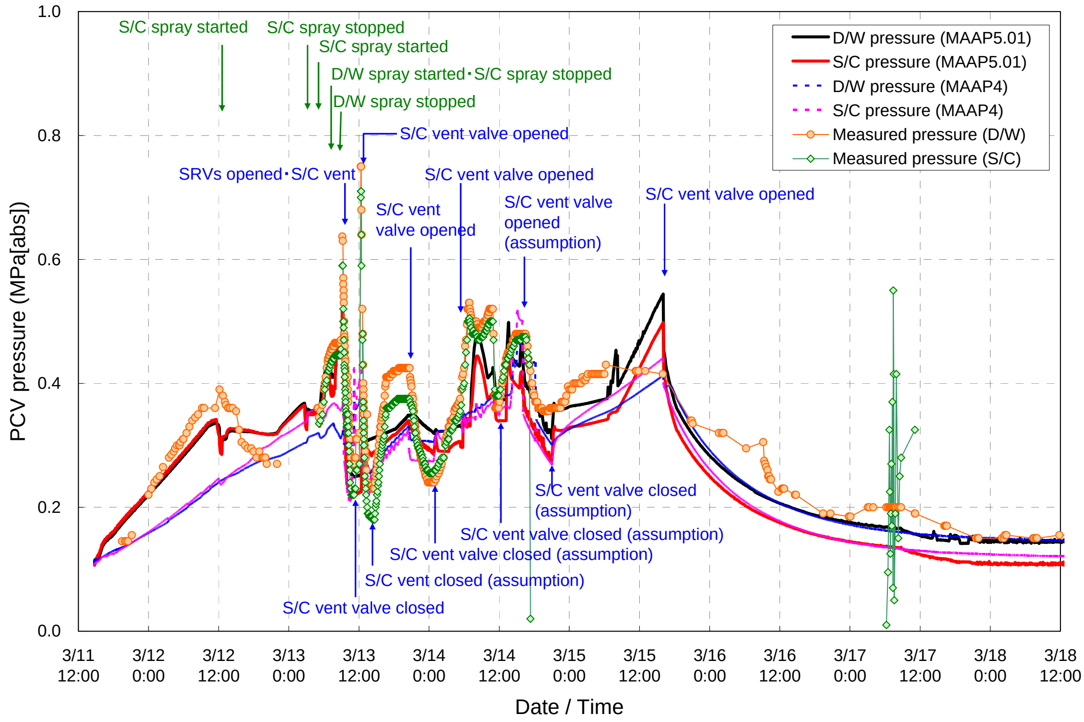


Figure 3-3 PCV pressure changes of Unit-3

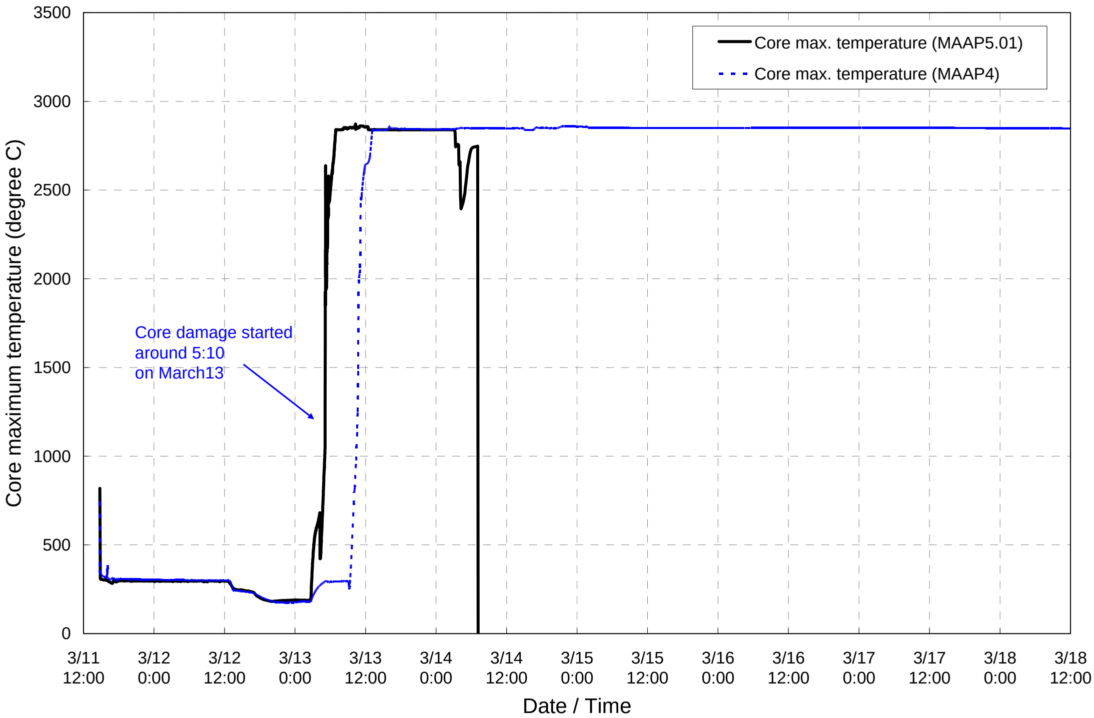


Figure 3-4 Core temperature changes of Unit-3

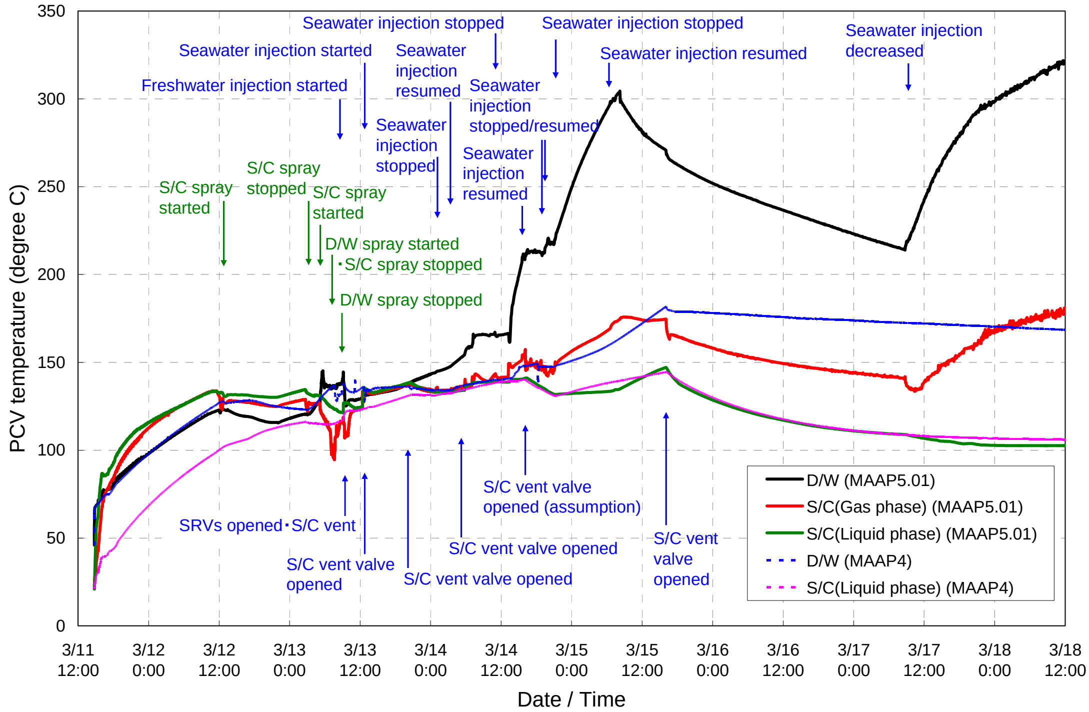


Figure 3-5 PCV temperature changes of Unit-3

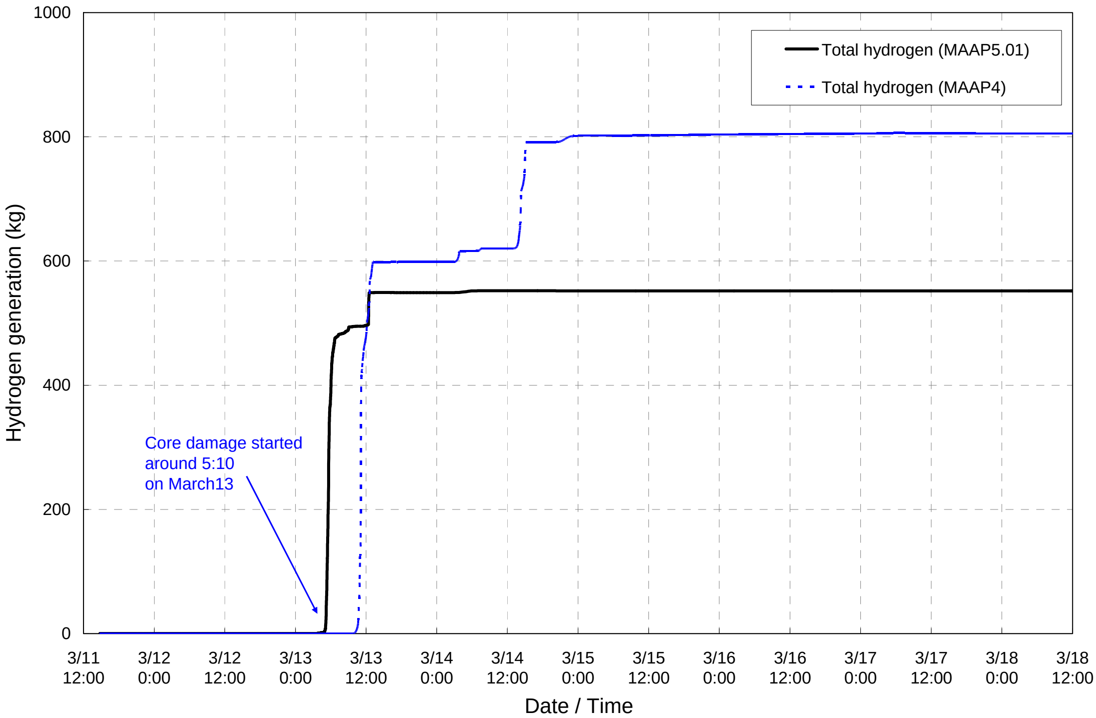


Figure 3-6 Hydrogen gas generation at Unit-3

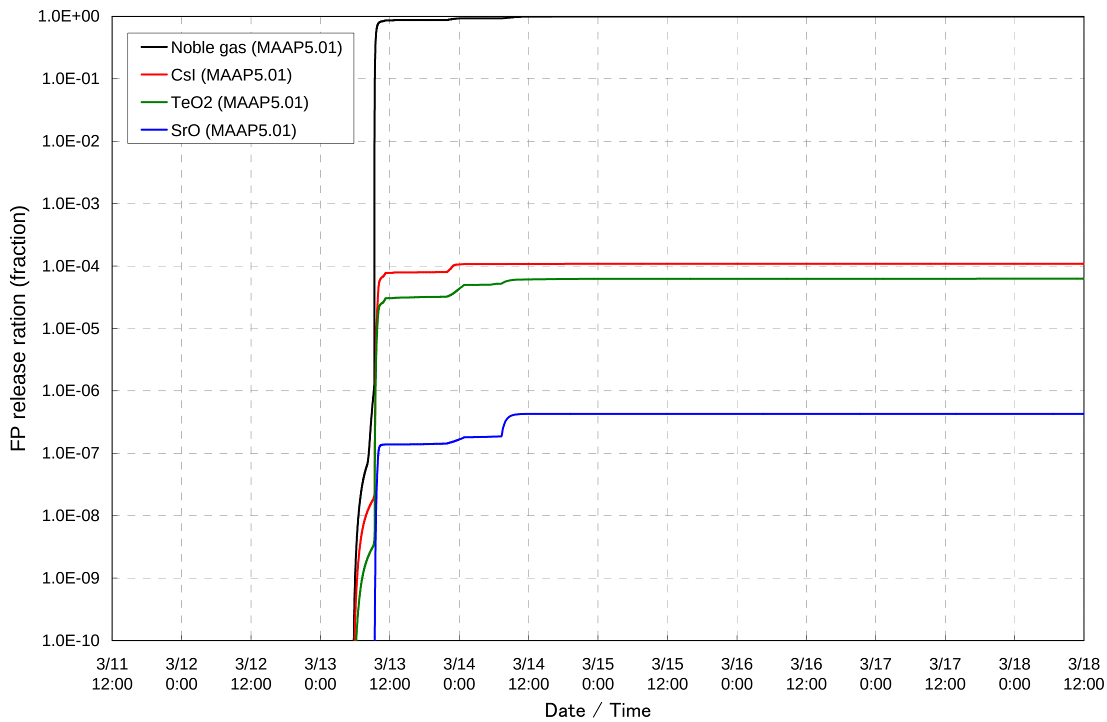


Figure 3-7 FP release ratio at Unit-3 (1/4)

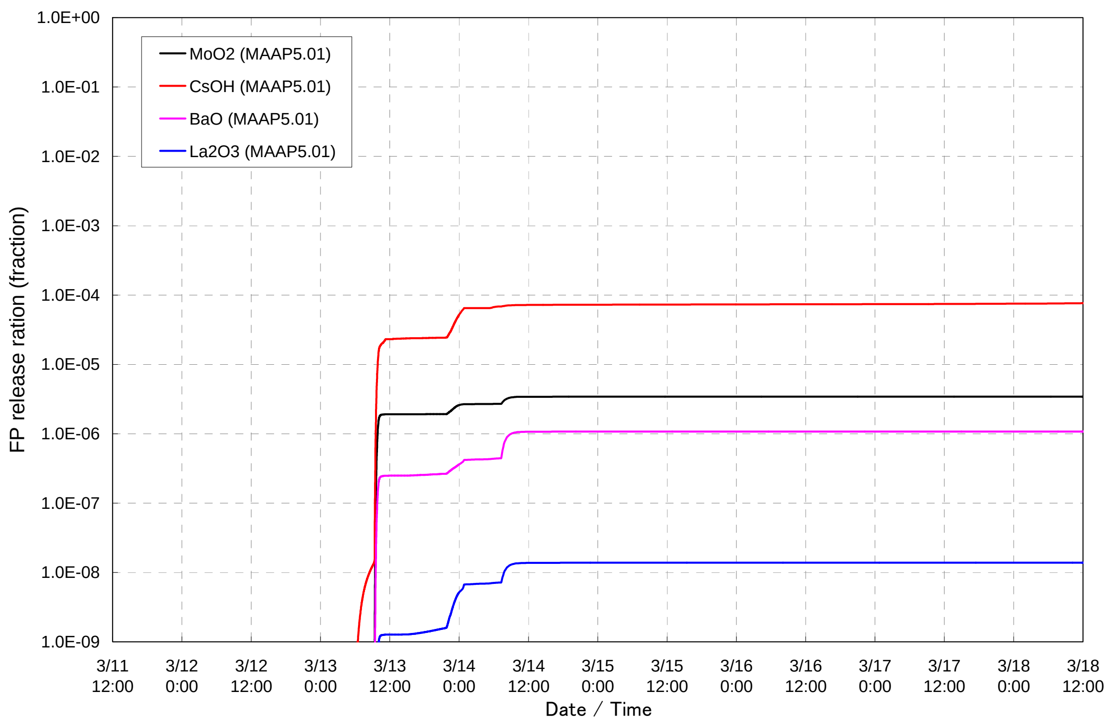


Figure 3-8 FP release ratio at Unit-3 (2/4)

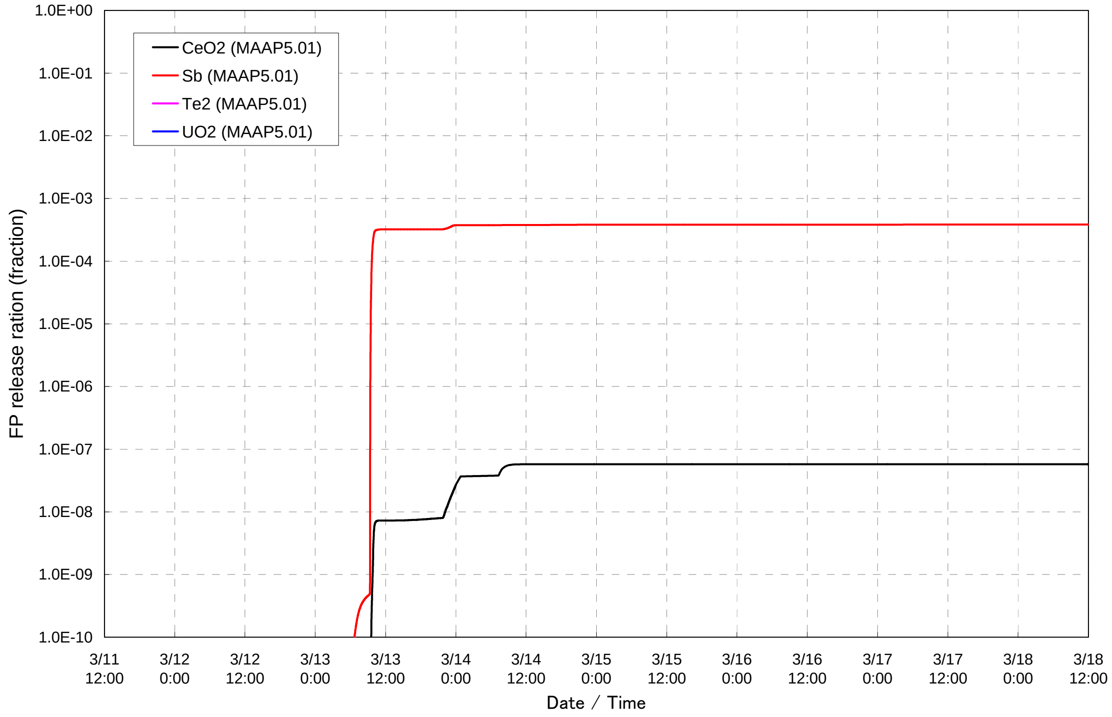


Figure 3-9 FP release ratio at Unit-3 (3/4)

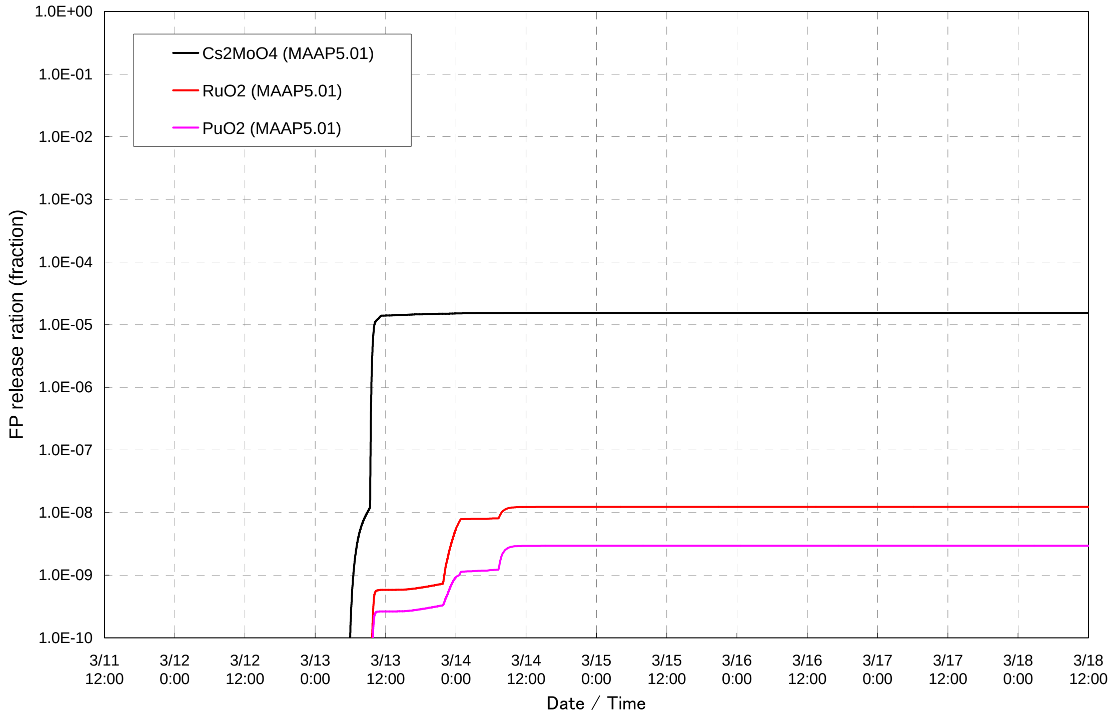


Figure 3-10 FP release ratio at Unit-3 (4/4)

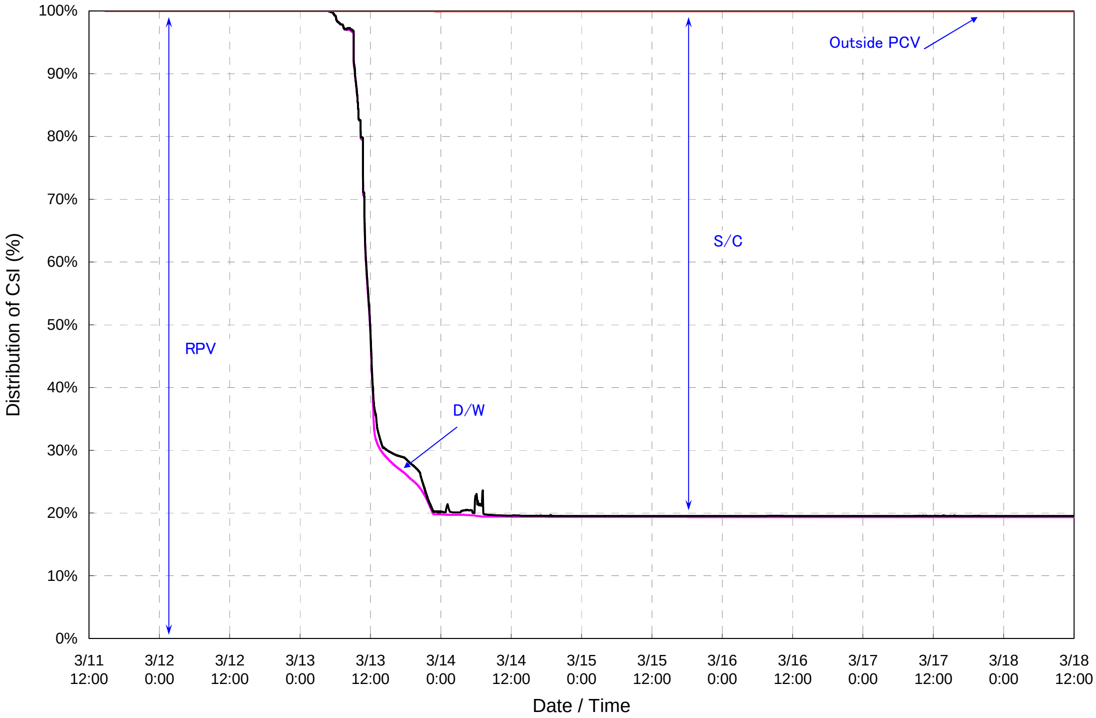


Figure 3-11 Distribution of FPs at Unit-3 (1/2)

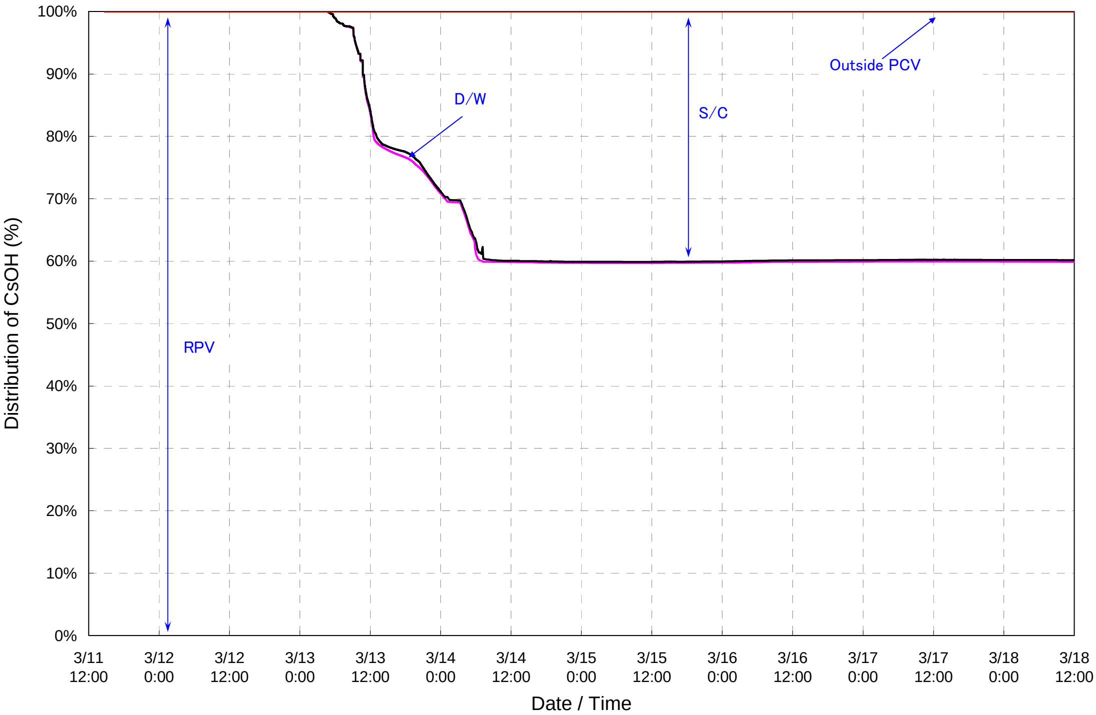


Figure 3-12 Distribution of FPs at Unit-3 (2/2)

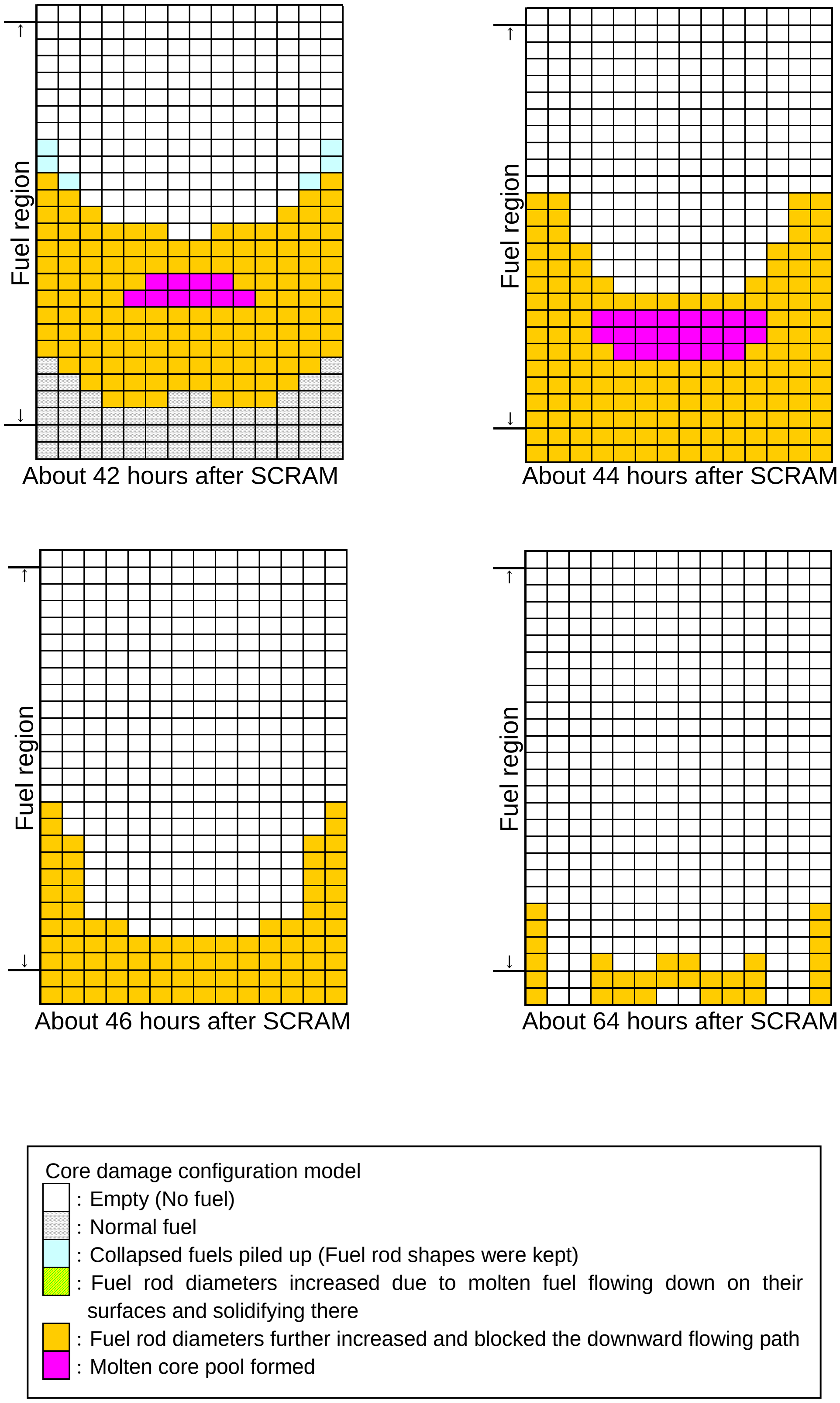


Figure 3-13 Core status of Unit-3