TEPCO's Activities on the Investigation of Fukushima Daiichi Accident

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TEPCO
TOKYO ELECTRIC POWER COMPANY

1. introduction

- On March 11th 2011, the Great East Japan Earthquake and subsequent tsunami hit the north east area of Japan including the Fukushima Dai-ichi nuclear power station (NPS).
- After the earthquake, Fukushima Dai-ichi unit 1, 2, and 3 in normal operation are automatically shutdown by seismic SCRAM logic.
- However, due to subsequent tsunami of 15m height, plants lost electric power and safety equipment.
- In the end, three plants fell into severe accident, a massive amount of radioactive materials are released to environment.
- In this presentation, I will explain BWR plant design relating accident progressions with reference to basic safety functions for nuclear power plant (NPP),
  and I will show you the Fukushima Dai-ichi accident progression chronologically and our investigation activities.

1. Damage Caused by GEJE

Houses Swept Away by Tsunami in Iwate

Stranded Cruise Ship in Iwate

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1. Tsunami attack to the Fukushima Daiichi NPS

1. introduction

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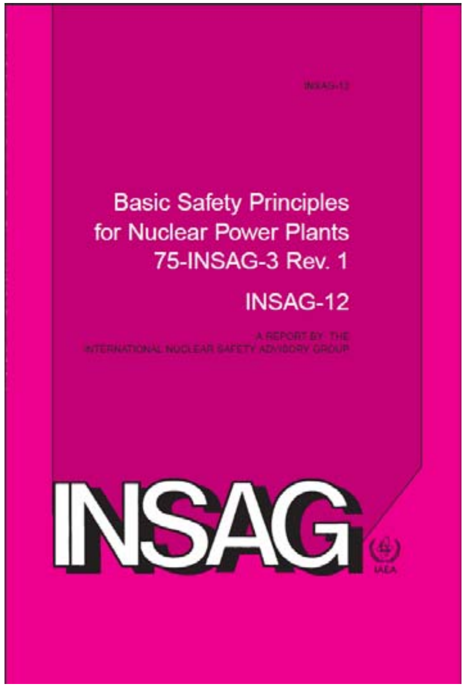
- After the earthquake, Fukushima Dai-ichi unit 1, 2, and 3 in normal operation are automatically shutdown by seismic SCRAM logic.
- However, due to subsequent tsunami of 15m height, plants lost electric power and function of safety equipment.
- In the end, three plants fell into severe accident, a massive amount of radioactive materials are released to environment.
- In this presentation, I will explain BWR plant design relating accident progressions with reference to basic safety functions for nuclear power plant (NPP),
  and I will show you the Fukushima Dai-ichi accident progression chronologically and our investigation activities.

2. Basic safety functions for NPP

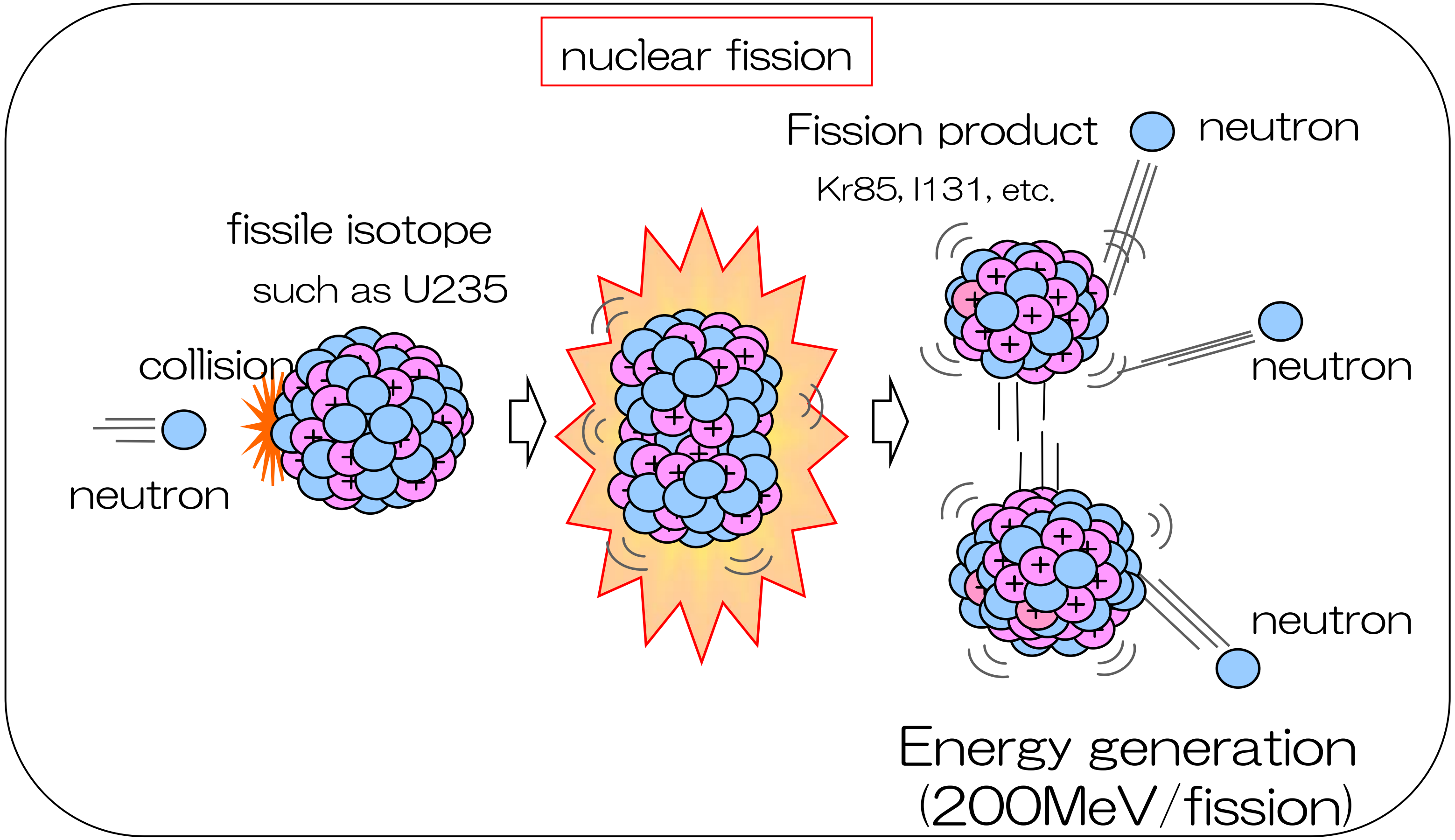
- controlling the power (shutdown)
- cooling the fuel (cooling)
- confining radioactive material (containment)



http://www-pub.iaea.org/MTCD/publications/PDF/P082_scr.pdf

2. Energy generation by nuclear fission

When fissile isotope, such as U235, collides with neutron and captures it, nuclear fission occurs. Fissile isotope split into two small isotopes, such as Kr85, I131, etc., and two or three neutrons. Isotopes generated after fission event are called fission product (FP). These fission events release about two hundred million eV (200 MeV) of energy for each fission event.



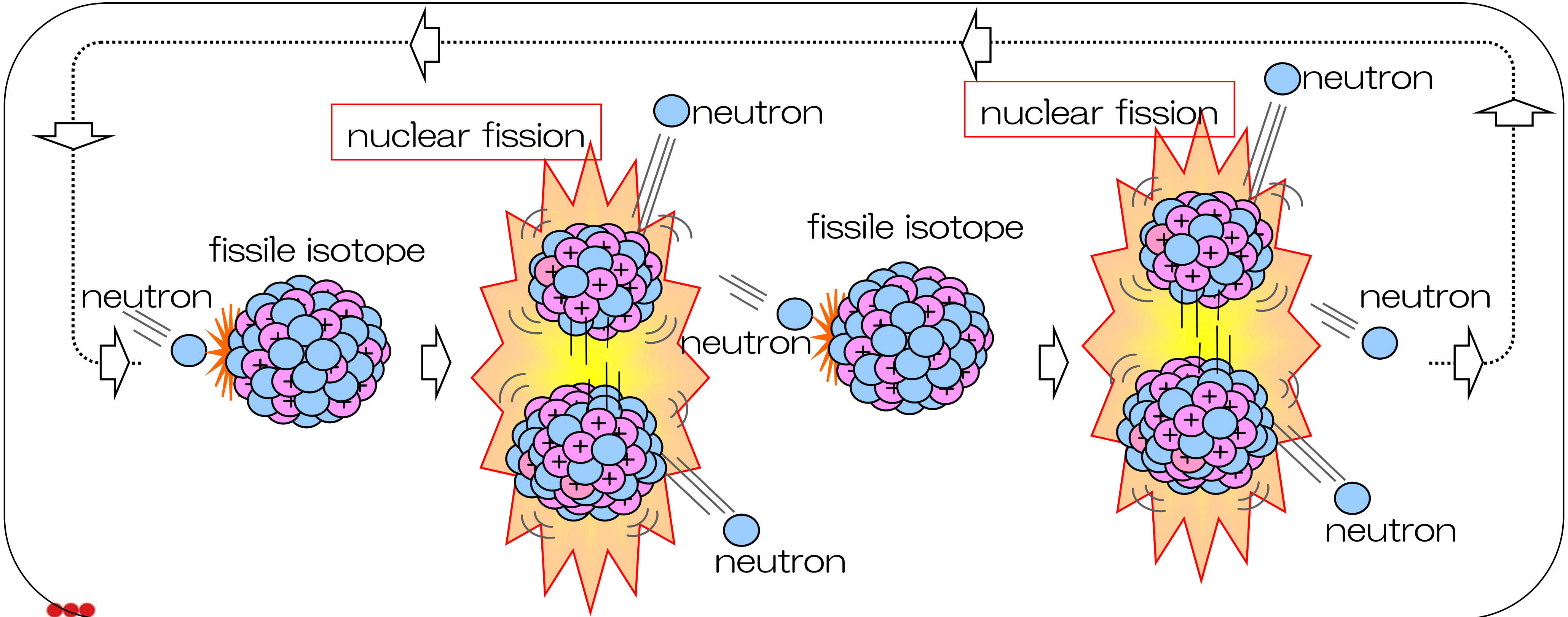
2. Nuclear chain reaction and criticality

Nuclear chain reaction

The state that nuclear fission continuously occurs by the neutrons generated previous fission events.

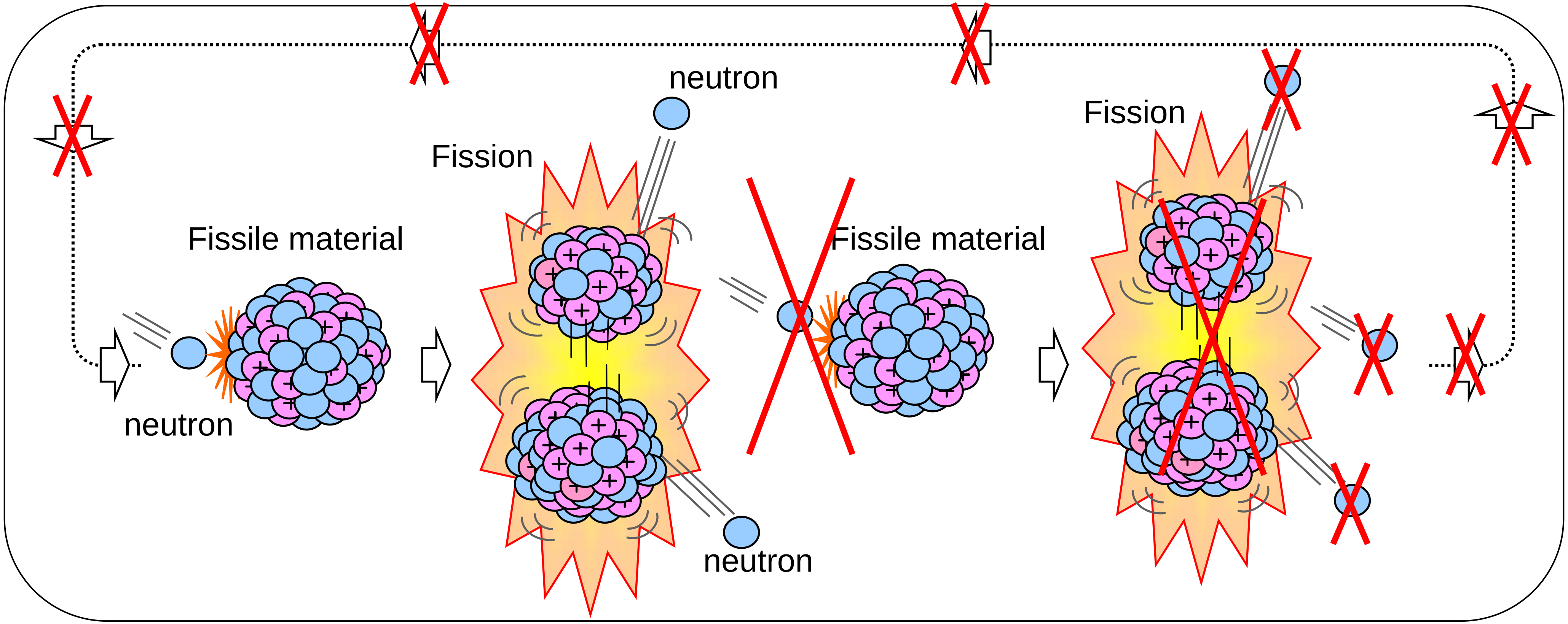
Criticality

When a nuclear chain reaction of fissile material is self-sustaining, the state is said to be in a criticality, in which there is no increase or decrease in power, temperature, or neutron population.



3. “Controlling the power” (shutdown)

- Controlling the power means “terminating the chain reaction.”



- After “terminating the chain reaction”, there is no energy generation by nuclear fission.
- What is the heat required to be removed after shutdown ?

3. Decay heat : energy generated after shutdown

Decay heat

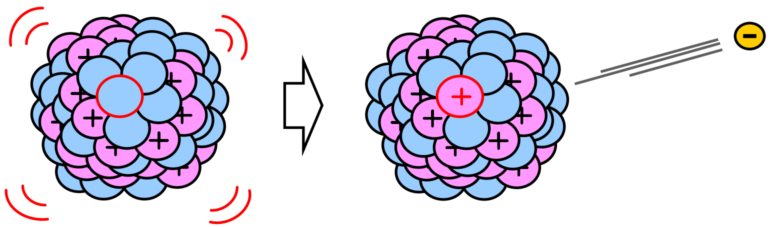
Fissile nucleus with large atomic number contains many neutrons. For example, atomic number of uranium two three five is ninety two, but number of neutrons is one hundred and forty three. This is why fission products have many neutrons compared to stable isotopes and are relatively unstable. Therefore, fission products decay to stable isotopes with releasing some energy. This energy discharged from FP is called decay heat.

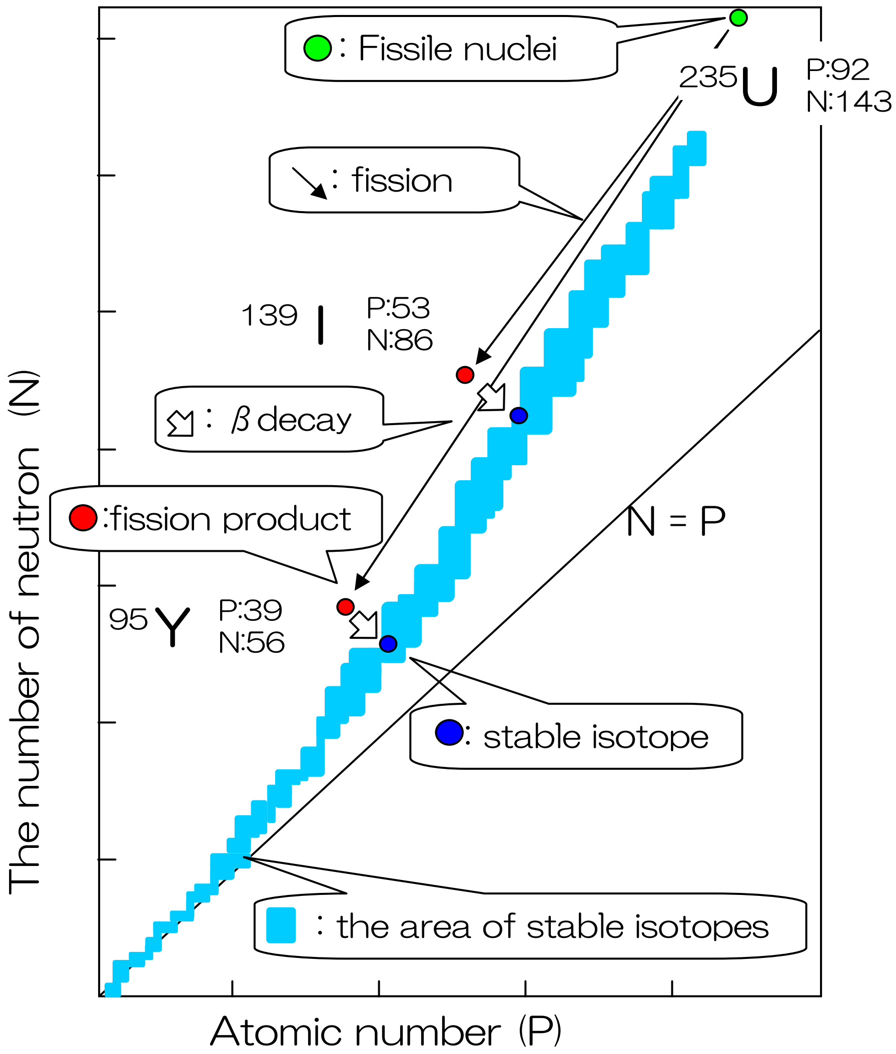
→Continuous removal of the decay heat is required after shutdown.

Example of decay（beta decay）

A neutron transform into positron and electron.

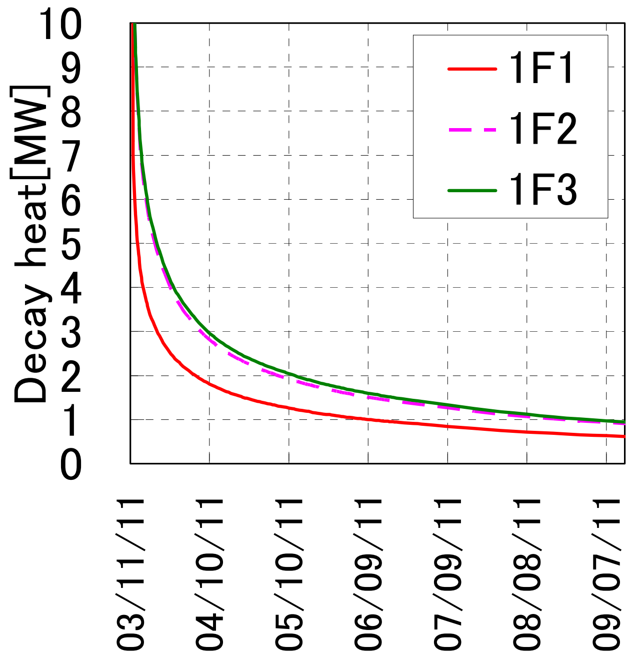
→Nuclei comes closer position to the light blue area.





4. “Cooling the fuel” (cooling)

- Cooling the fuel means “removal of the decay heat.”
- Continuous removal of the decay heat is required after shutdown.
- Decay heat is decreasing monotonically;
  - 0 second after shutdown : about 5.5% of core power
  - 1 minute after shutdown : about 3.4% of core power
  - 1 hour after shutdown : about 1.3% of core power
  - 1 day after shutdown : about 0.5% of core power
  - 1 year after shutdown : about 0.03% of core power
  - 2 years after shutdown : about 0.01% of core power



- In Fukushima Dai-ichi BWR plants, there are many equipments for “cooling the fuel”;

<u>Operable under high pressure condition</u>

- IC (unit 1) : Isolation Condenser (passive cooling system)
- RCIC (unit 2,3) : Reactor Core Isolation Cooling system (turbine driven)
- HPCI : High Pressure Coolant Injection system (turbine driven)

<u>Operable under only low pressure condition</u>

- LPCI : Low Pressure Coolant Injection system (motor driven)
- CS : Core Spray system (motor driven)

4. Impact of Loss of AC or DC power

Loss of AC power：SBO(Station Black Out)

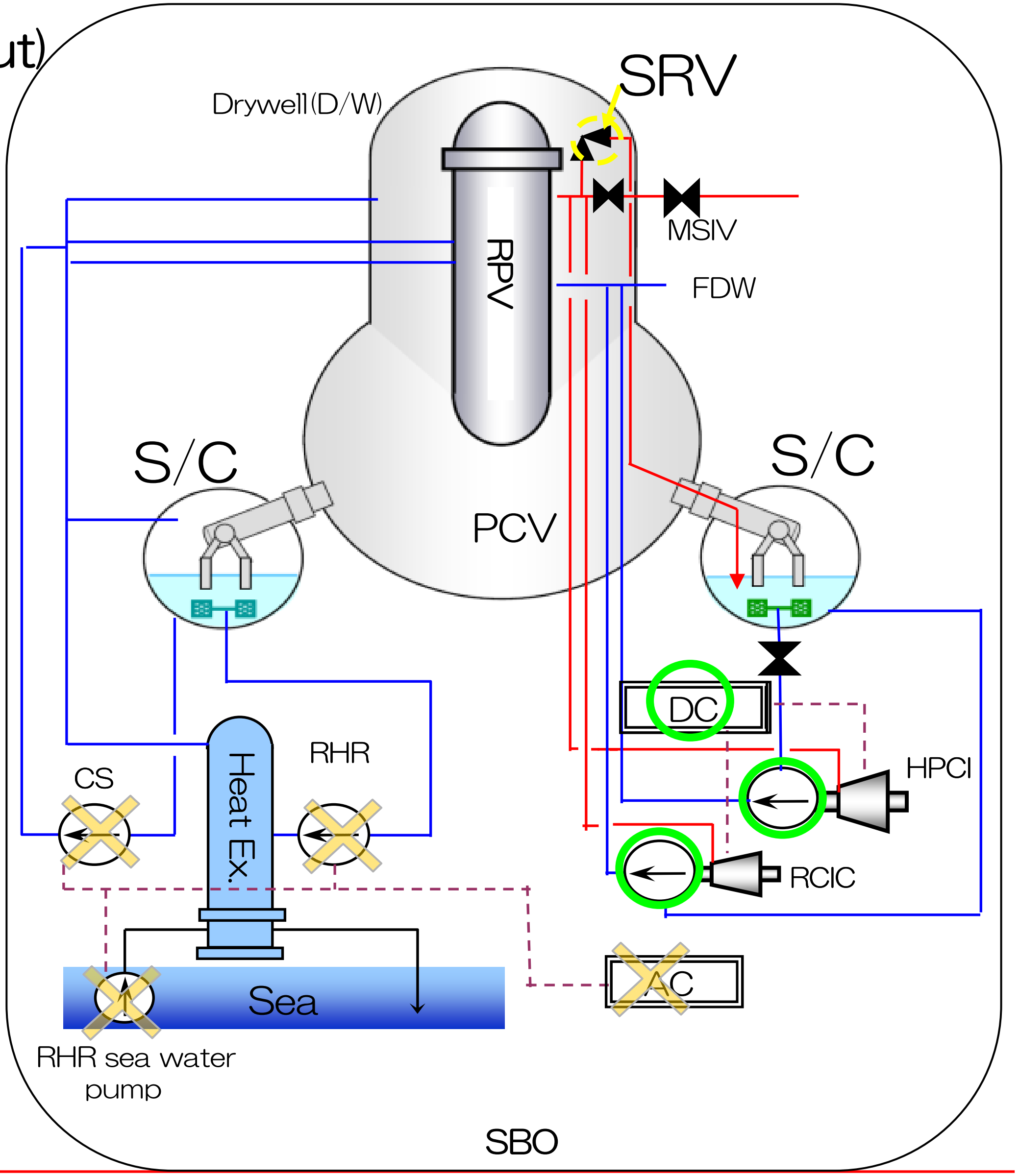
- SBO is the condition that both loss of offsite power and function failure of D/G at the same time. Only DC power is available.
- Motor driven pumps were NOT operable.
- DC power is used to control the turbine driven pumps, valve operation, and measurement instrument.

→RCIC, HPCI, IC are operable under SBO

Loss of AC and DC power：Total SBO

- Total SBO is the condition that both AC and DC power are NOT available.
- All RPV injection systems became out of control or never start up.
- Measurement systems can NOT work.

→Operator can NOT operate any system and can NOT know plant condition until restoring AC or DC power.

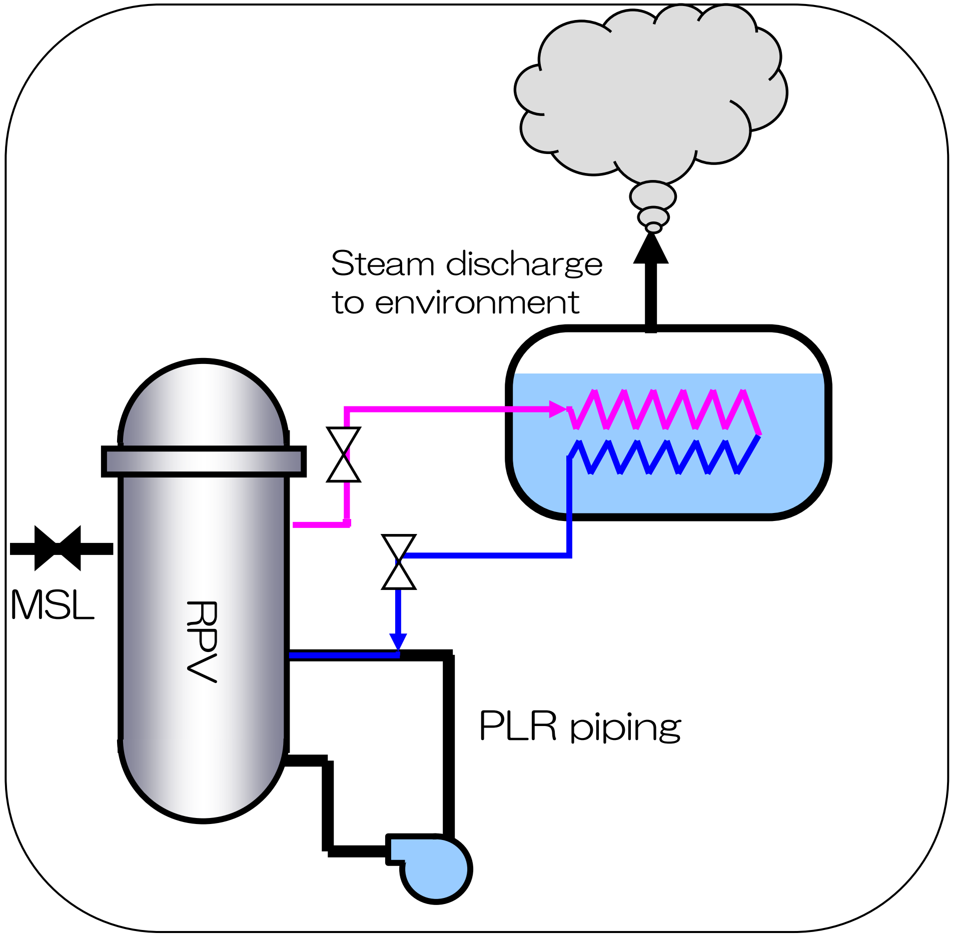


4. Passive Cooling system operable in unit 1

Isolation Condenser：IC

- Designed to use during reactor core isolation (Isolation means main steam isolation valve is close position.)
- Operable in DC only condition
- High pressure steam will be condensed in the heat exchanger, then condensate water go back to RPV.
- Steam generated in shell side is discharged to environment.
- Operable for 8 hours
- Designed to remove the decay heat 5 minutes after SCRAM.

→If the decay heat decrease to less than decay heat 5 minutes after SCRAM, RPV pressure decrease due to overcooling.
operator controlled the RPV pressure by opening/closing operation in unit 1.



4. Turbine driven RPV water injection system

Reactor Core Isolation Cooling system : RCIC

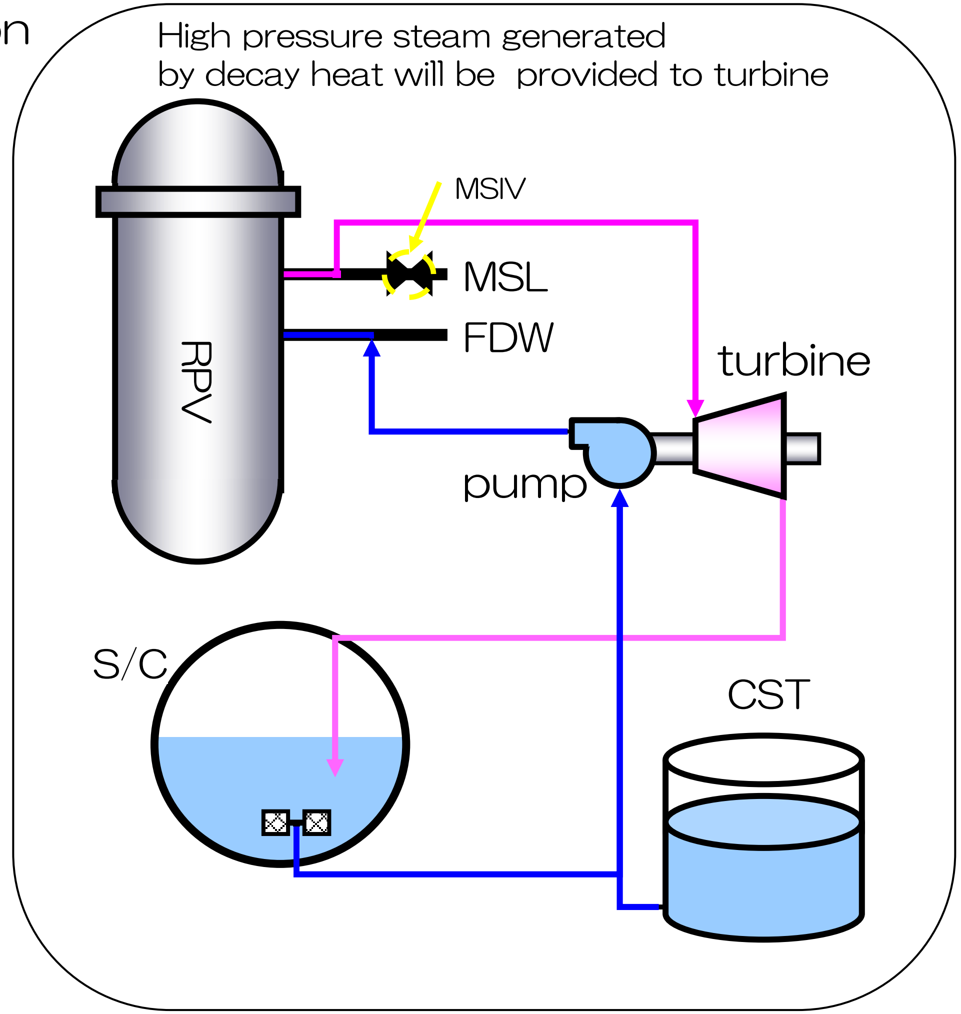
- Designed to be used during reactor core isolation (Isolation means main steam isolation valve is close position.)
- Operable in DC only condition
- Designed to remove the decay heat 15 minutes after SCRAM.

→If the decay heat decrease less than decay heat 15 minutes after SCRAM, RPV water level increase.

High Pressure Coolant Injection system : HPCI

- Designed to be used in medium and small break LOCA
- Operable in DC only condition
- Injection ability is ten times larger than RCIC, because HPCI have to makeup more water in LOCA condition.

→More steam was consumed to drive turbine. It is difficult to control the RPV water level and RPV pressure not in LOCA condition.



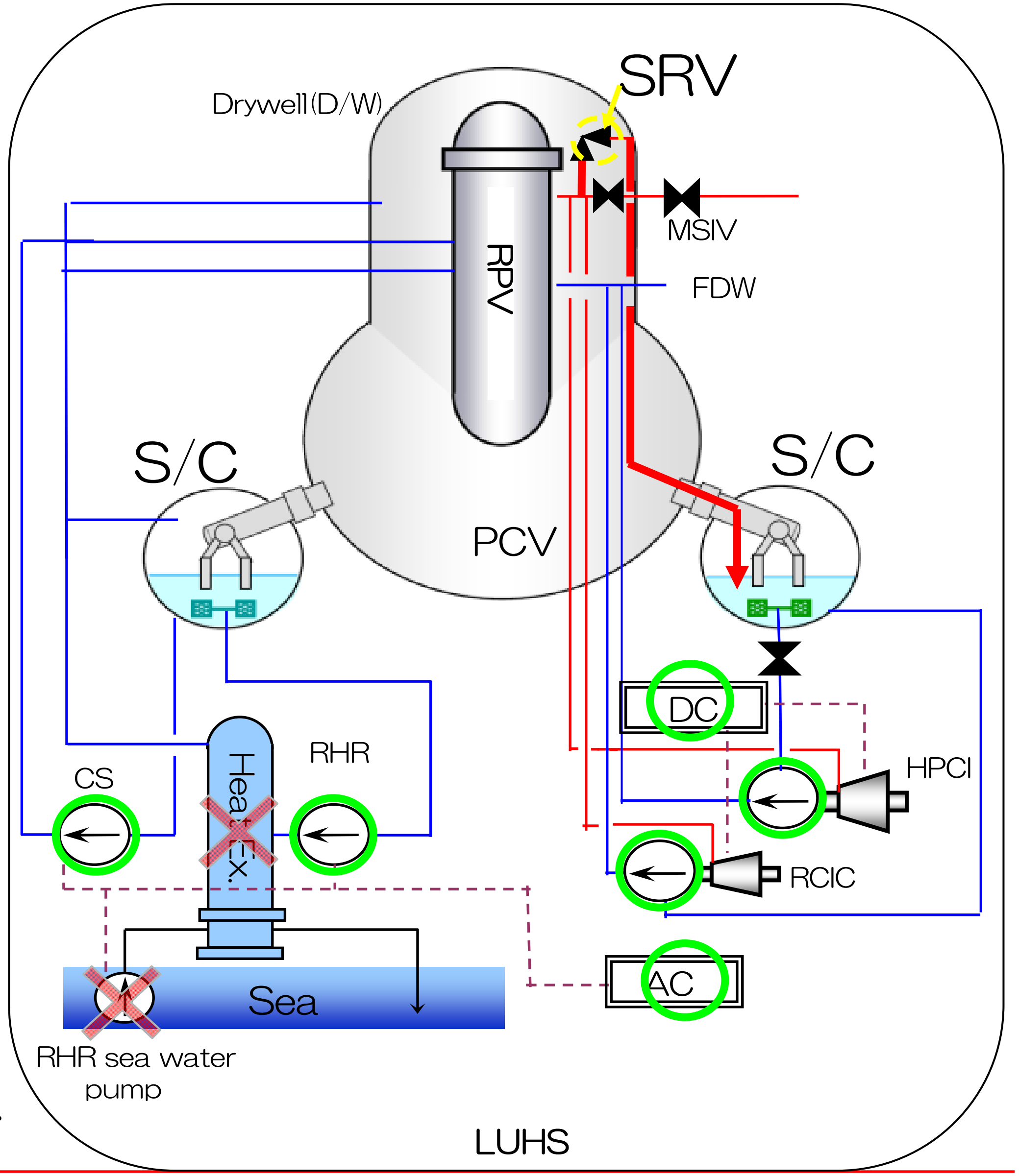
4. Loss of Ultimate Heat Sink : LUHS

- Decay heat removed from RPV will be transported to Suppression Chamber(S/C) through Safety Relief Valve(SRV).
- Energy stored in the S/C will be released to the sea by means of heat exchanger in RHR (Residual Heat Removal system).

- LUHS means the condition in which the decay heat could not be removed from S/C.
- In case of LUHS, even if we could continue cooling the core, decay heat remains inside the PCV boundary.

→Temperature and pressure of the PCV increase gradually.

In unit 1, accident progression was so fast that we don't need to consider LUHS.
On the contrary, LUHS played an important role for the accident progression for unit 2/3.

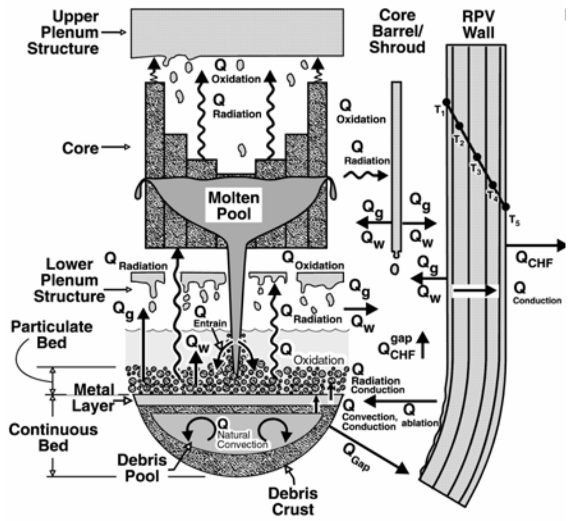


5. “Confining radioactive material” (containment)

✓ “Confining radioactive material” means maintain the integrity of containment.

After loss of “cooling the fuel”

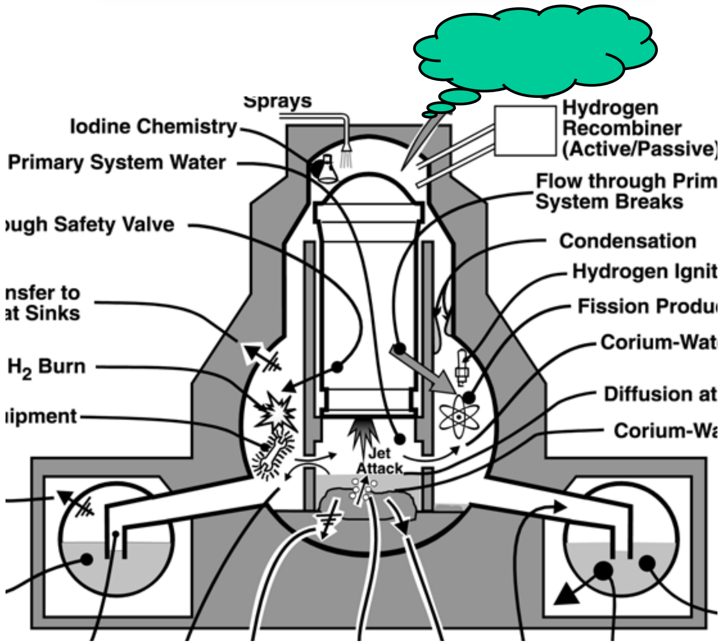
- fuel overheating
- break of the physical barrier
- release of radioactive material



✓ If we lose the cooling function, we can not avoid release of radioactive material because of the decay heat.

✓ From next slide, I will show you how we lost the function of equipments for “cooling the fuel.”

✓ And I will explain key topics to understand the accident progressions from our investigation activities.



Courtesy of EPRI

Unit 1 Accident progression

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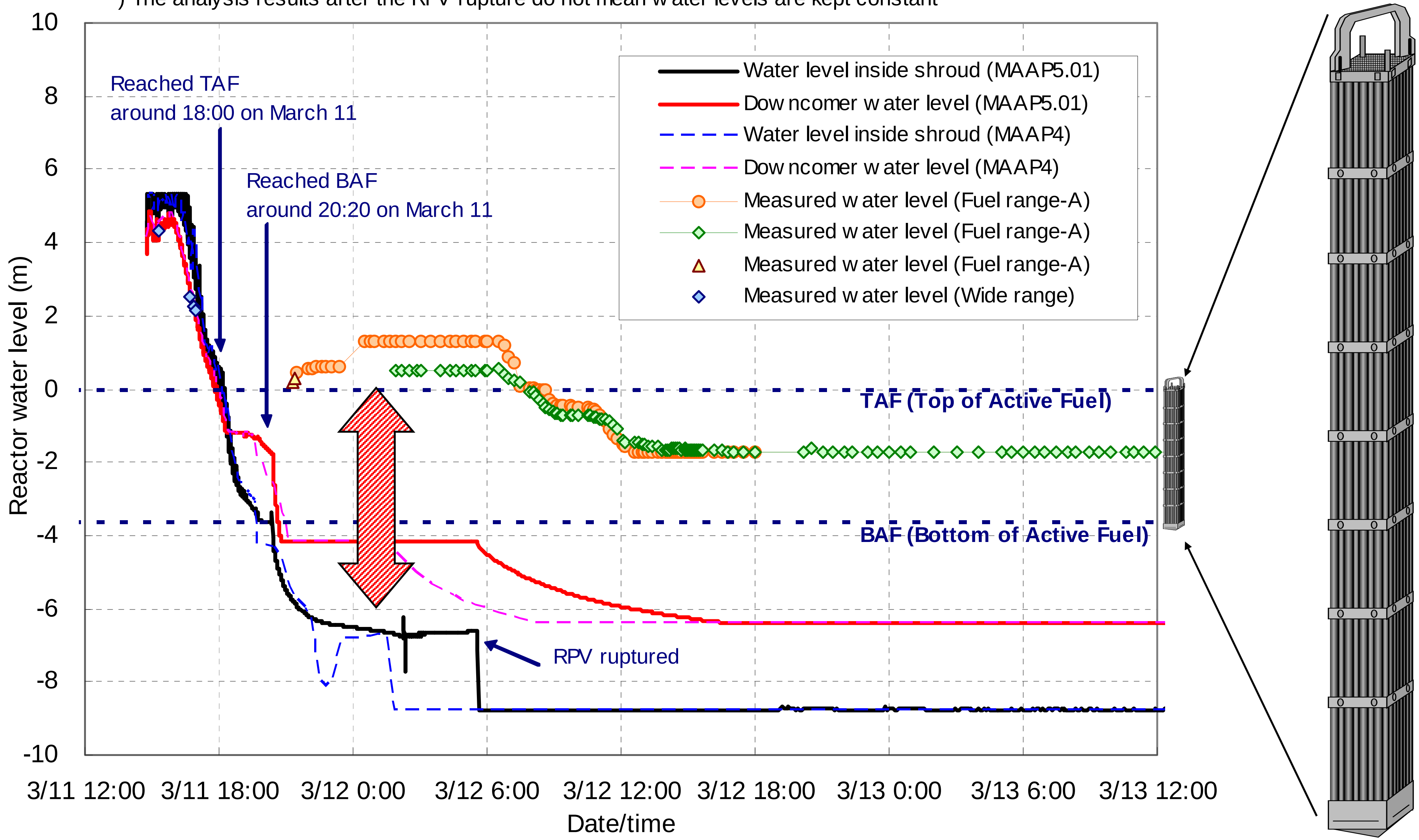
6. Chronological accident description of unit 1

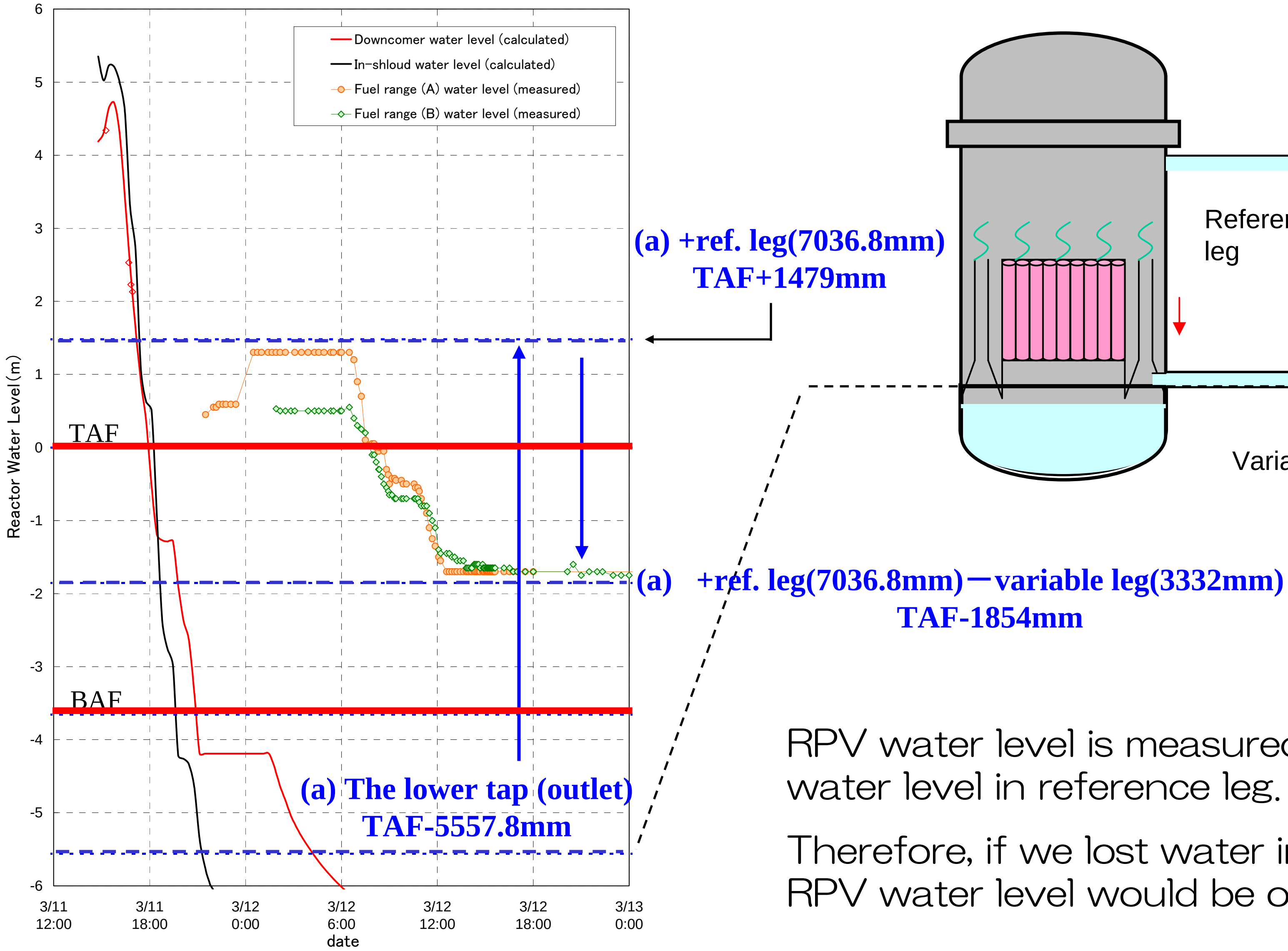
- 3/11 14:46
  - Earthquake : Reactor was automatically shutdown.
    Decay heat was continuously generated.
  - Loss of off-site power : However, DG was automatically started.
    Therefore, AC and DC power were available in this period.
- 14:52 – 15:34
  - IC cooling : Reactor was cooled by IC with start-stop operation so that RPV cooling down rate did not exceed 55 degree-C/hr. Unit 1 was operated to achieve cold shutdown.
- 15:37
  - Tsunami hit : AC and DC were lost. **IC was not in operation at this time.**
- After tsunami hit
  - **We could not restart due to loss of DC**. RPV water inventory decrease due to boiling.
- Around 18:00 (from MAAP calculation)
  - Core uncovery : Starting fuel heat up
- Around 18:40 (from MAAP calculation)
  - Reactor core damage : Peak clad temperature became above 1200 degree-C
- Around 3/12 05:40(from MAAP calculation)
  - RPV bottom damage : Corium (melted fuel) slumping to PCV pedestal
- After core damage
  - Radioactive materials were released to environment

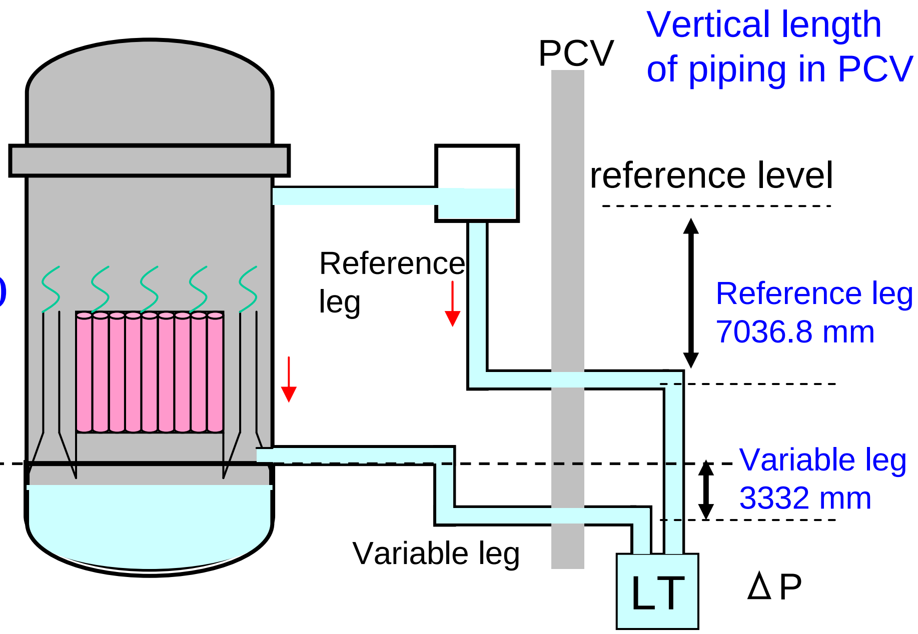
6. RPV water level in unit 1

*) The analysis results after the RPV rupture do not mean w ater levels are kept constant



6. Reactor Water Level

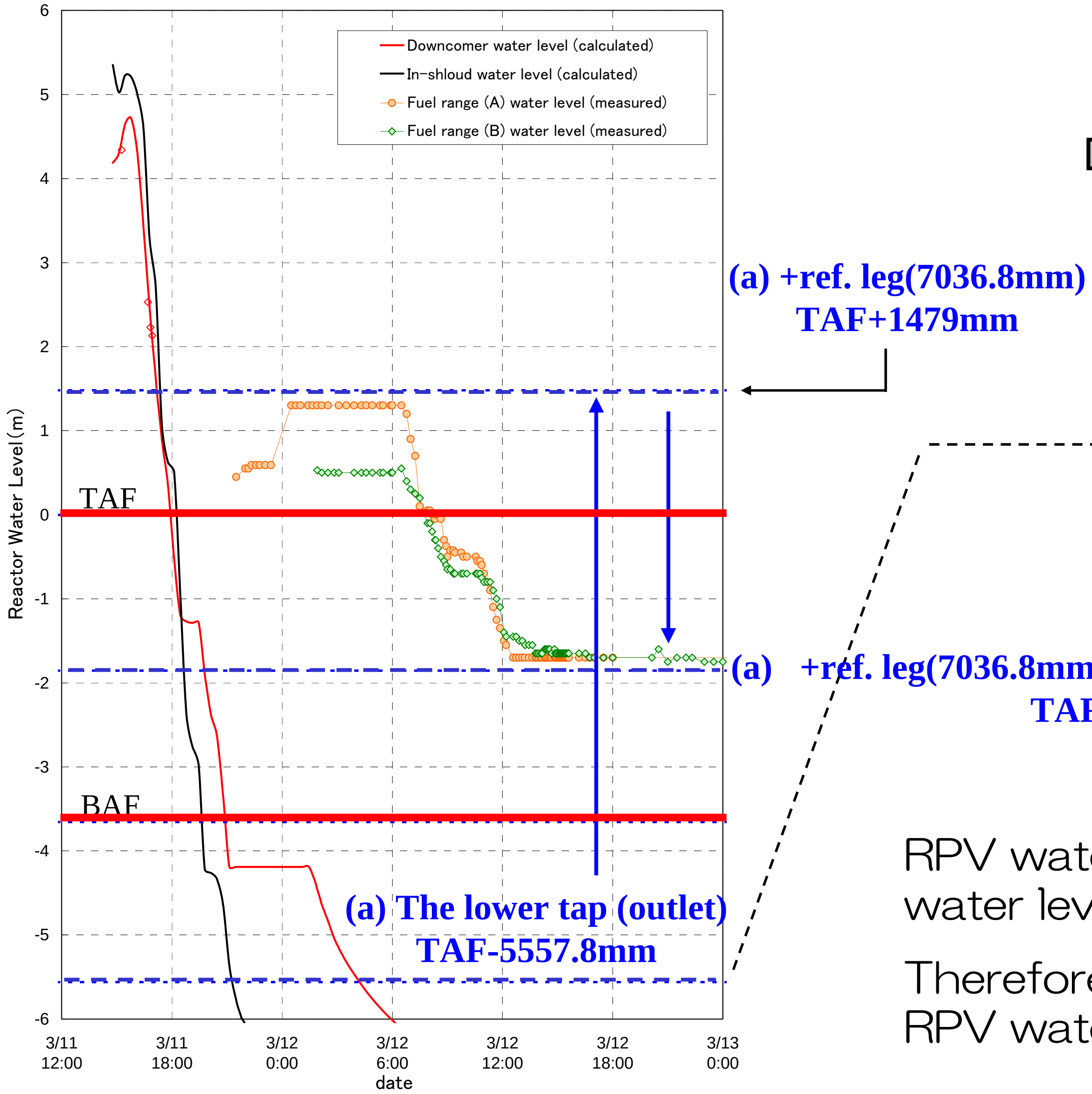


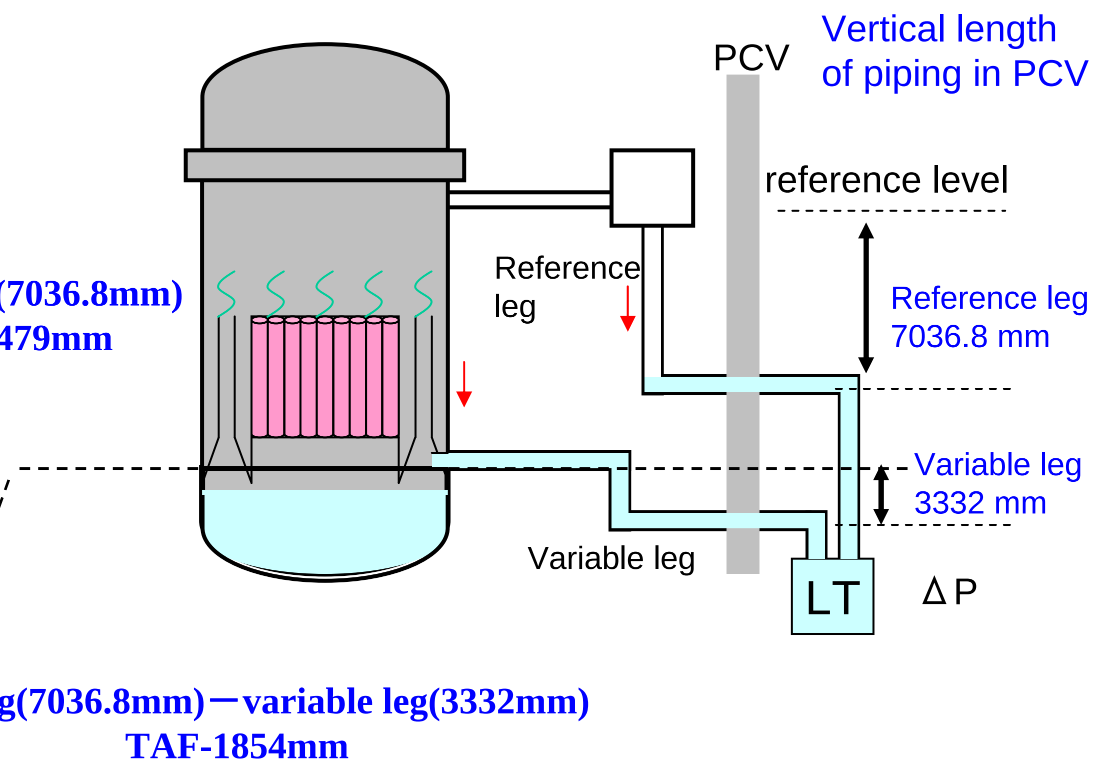


RPV water level is measured by comparing the water level in reference leg.

Therefore, if we lost water in the reference leg, RPV water level would be overestimated.

6. Reactor Water Level





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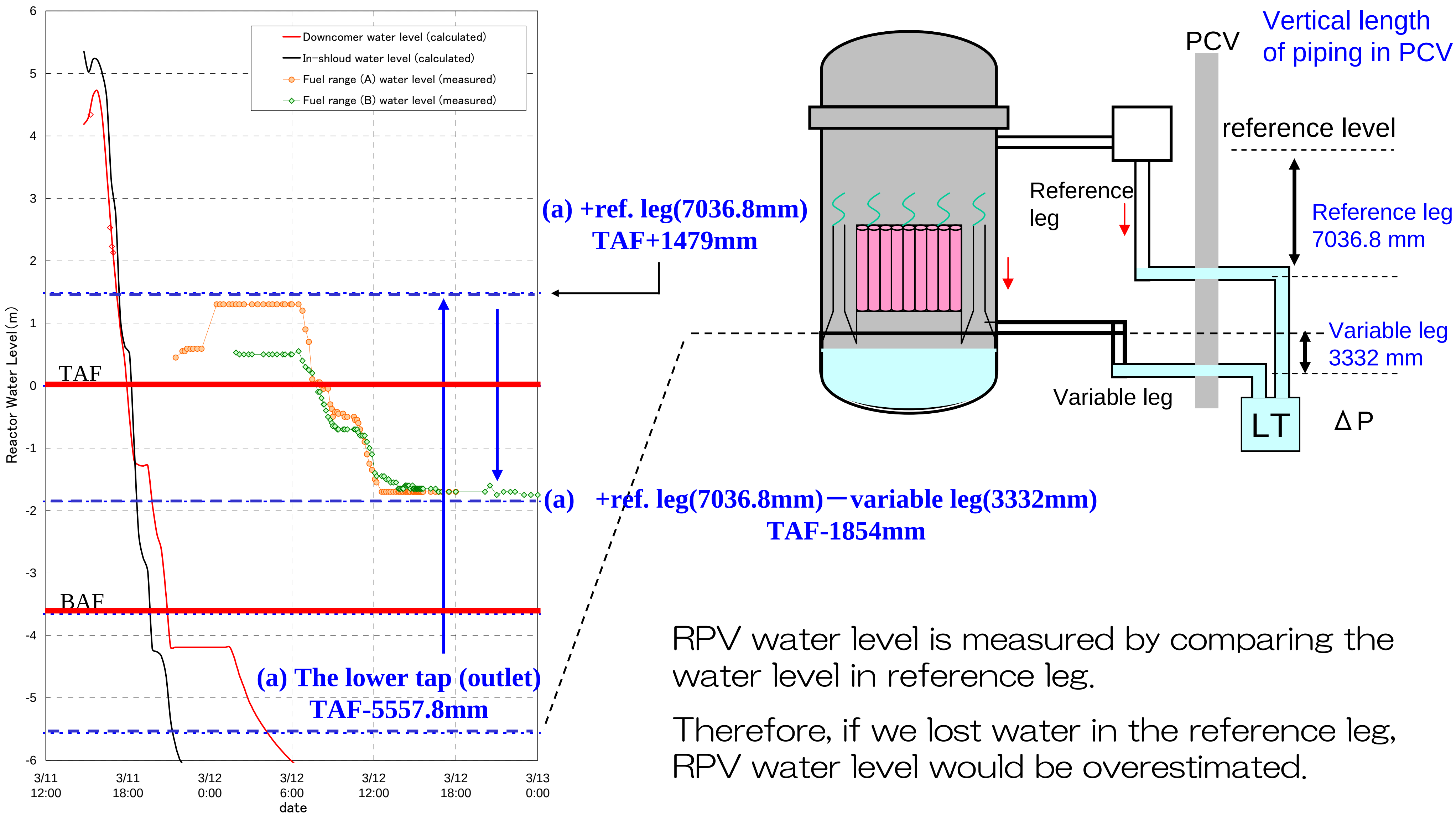

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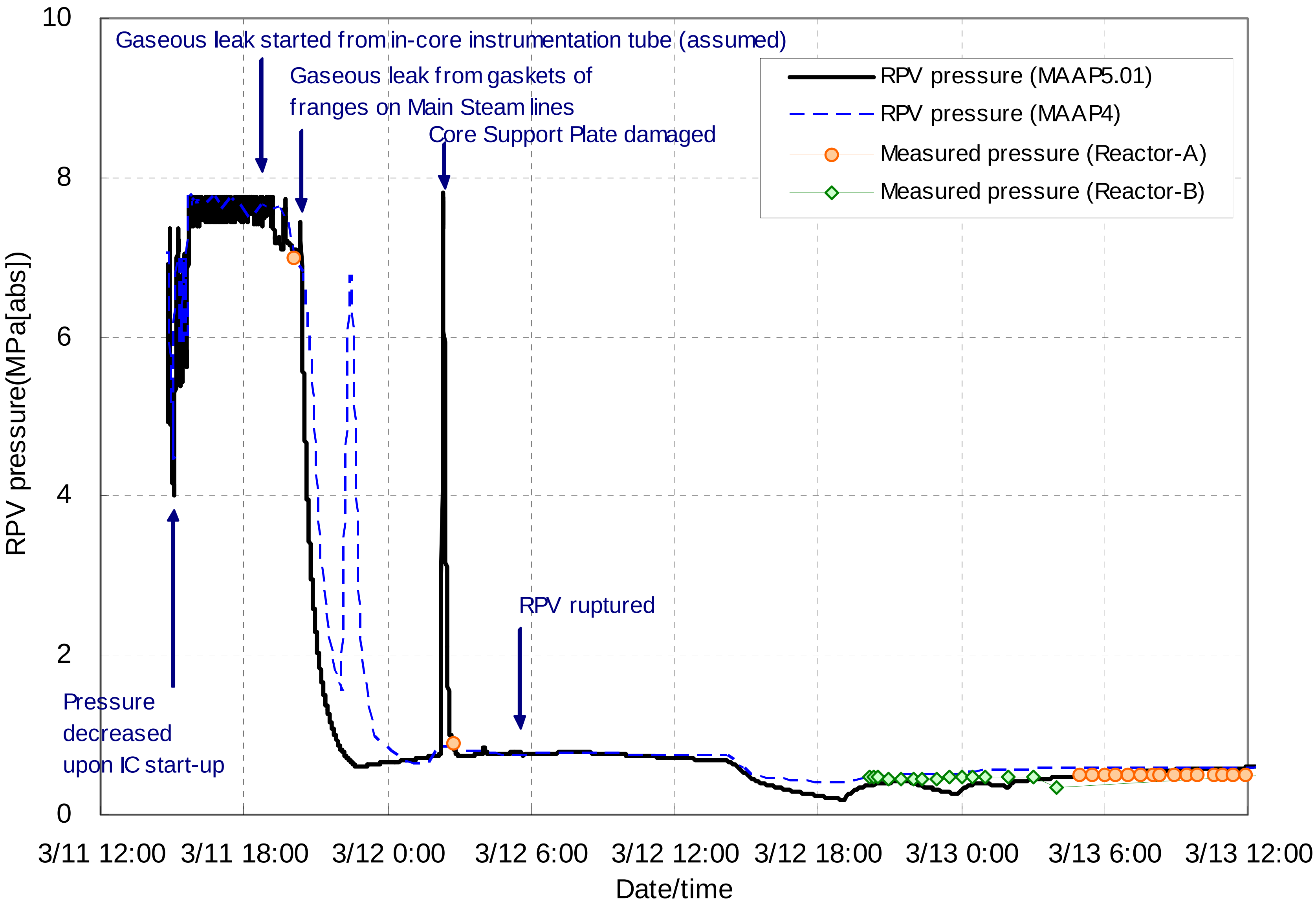
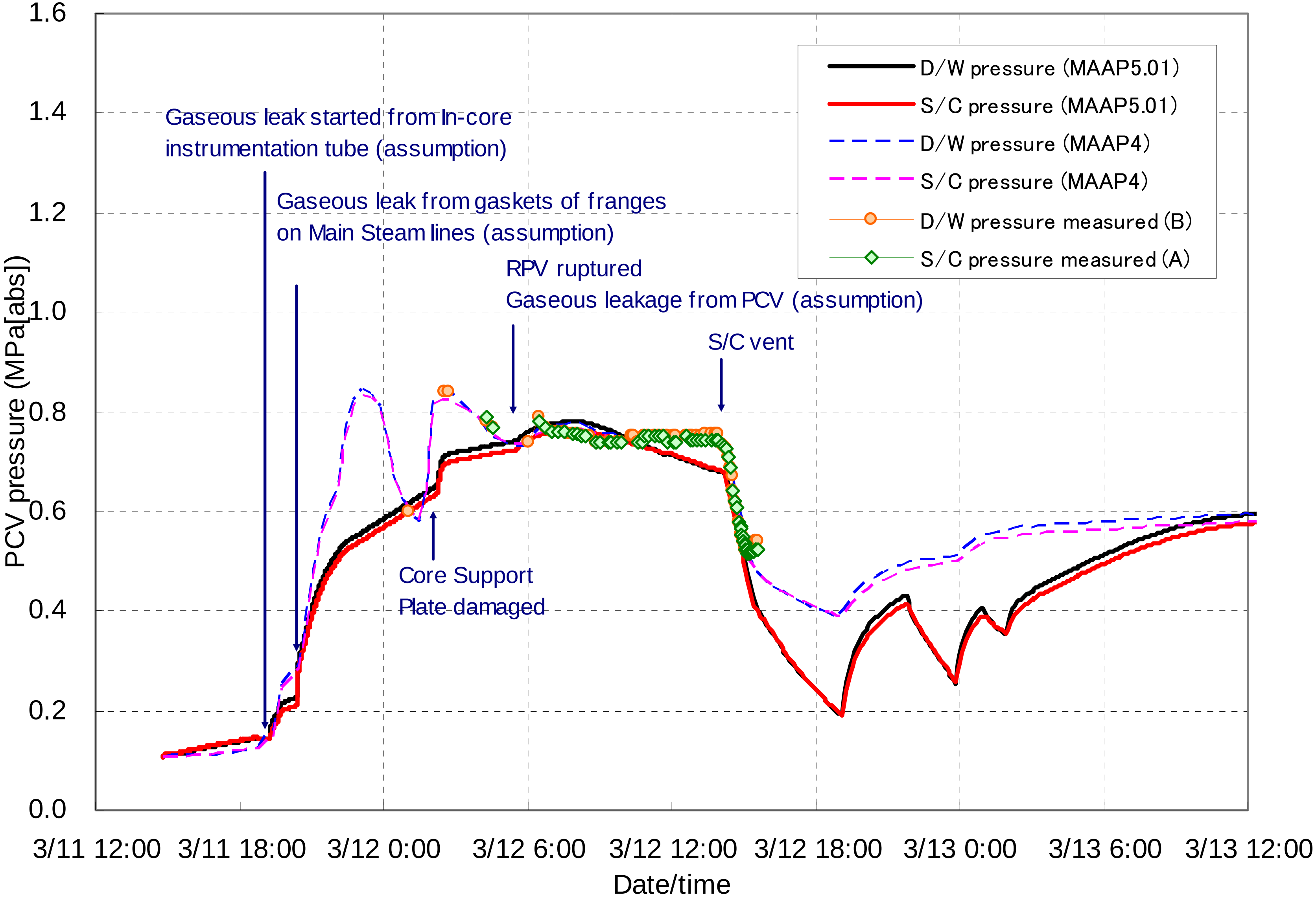
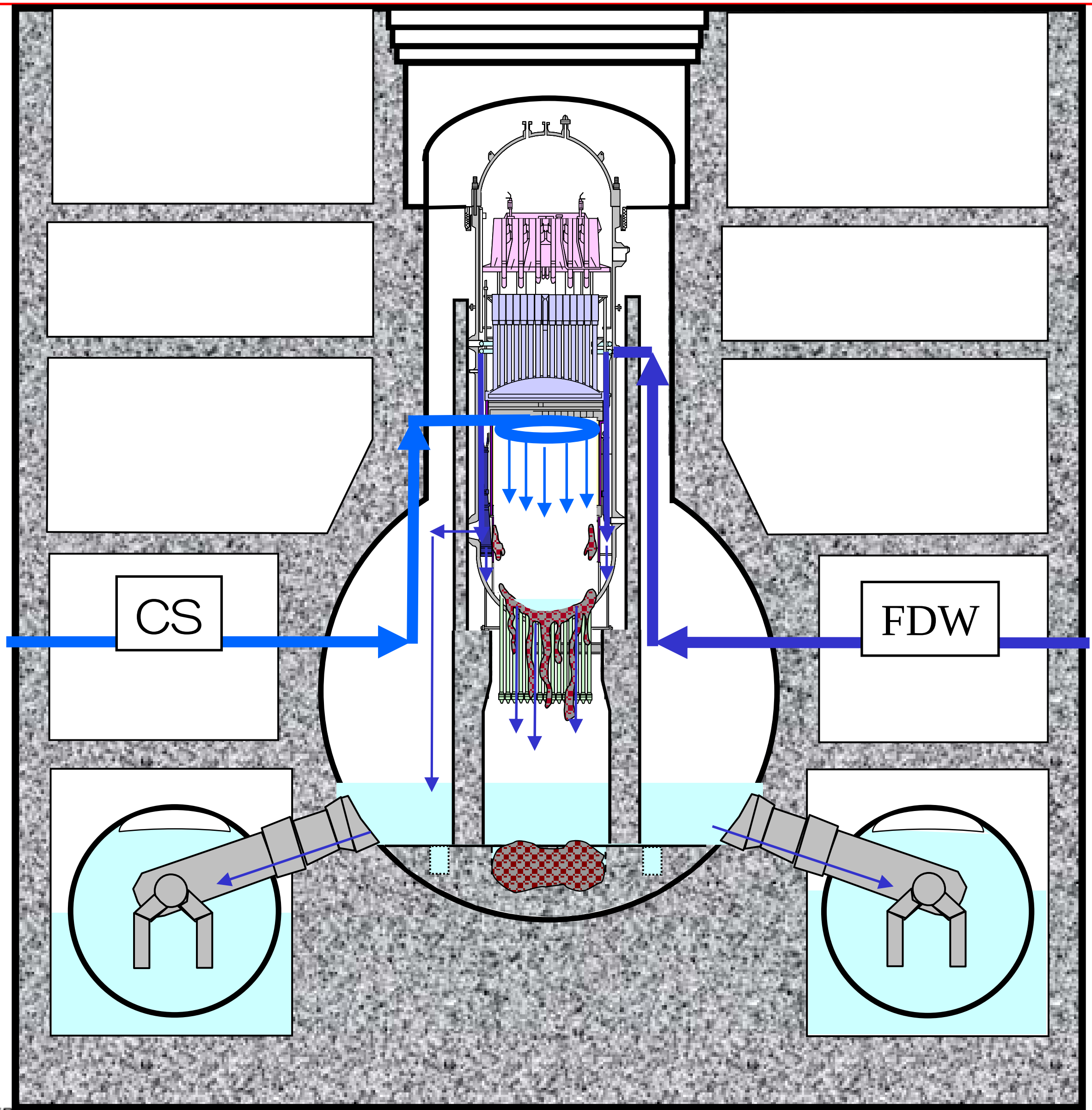
6. RPV pressure in unit 1



6. PCV pressure in unit 1



6. Estimation of the status of unit 1



6. Discussions on damage by Earthquake

・Due to the earthquake, Fukushima Daiichi NPS lost all external power. AC power was secured by EDG.

・About after 50 minutes, Unit1-3 went into both SBO.

Some insists it is not clear whether SBO in unit 1 was caused by tsunami or earthquake.

Ex. "The tsunami was, therefore, not the cause of the loss of the power in system A of Unit 1, which occurred at 15:35 or 15:36[155] according to the NAIIC hearings.[156]" from NAIIC report.

<u>We think SBO was caused by tsunami for the following reason.</u>

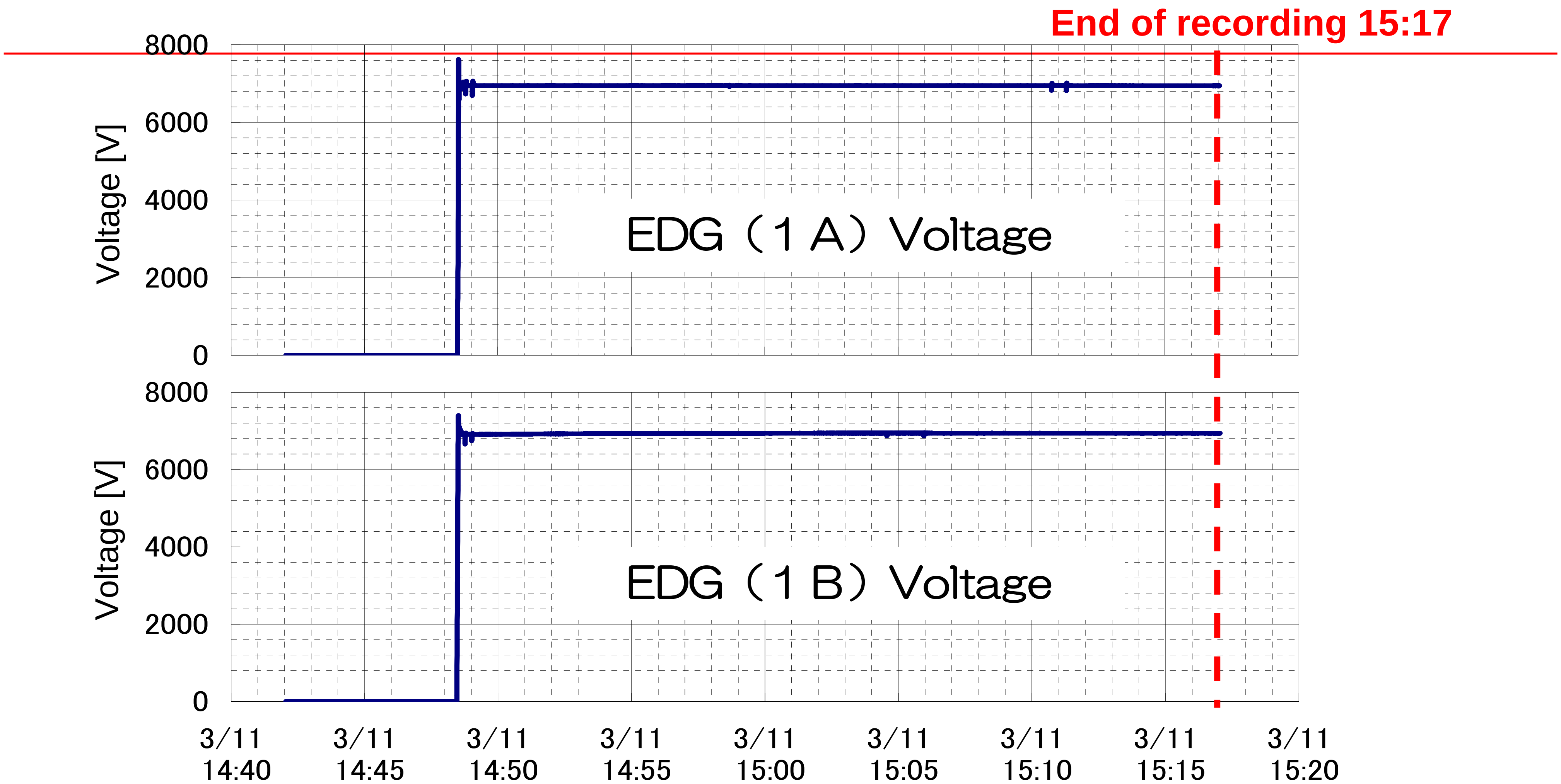
During recording time(14:42~15:17) of the transient recorder(TR), EDG had started up and operated normally.
(→No data was recorded after 15:18 until the arrival of the tsunami)

✓From the time of end of recording data to the tsunami arrival time, there had not been any big aftershocks

✓All calculated values of EDG are below the evaluation criteria

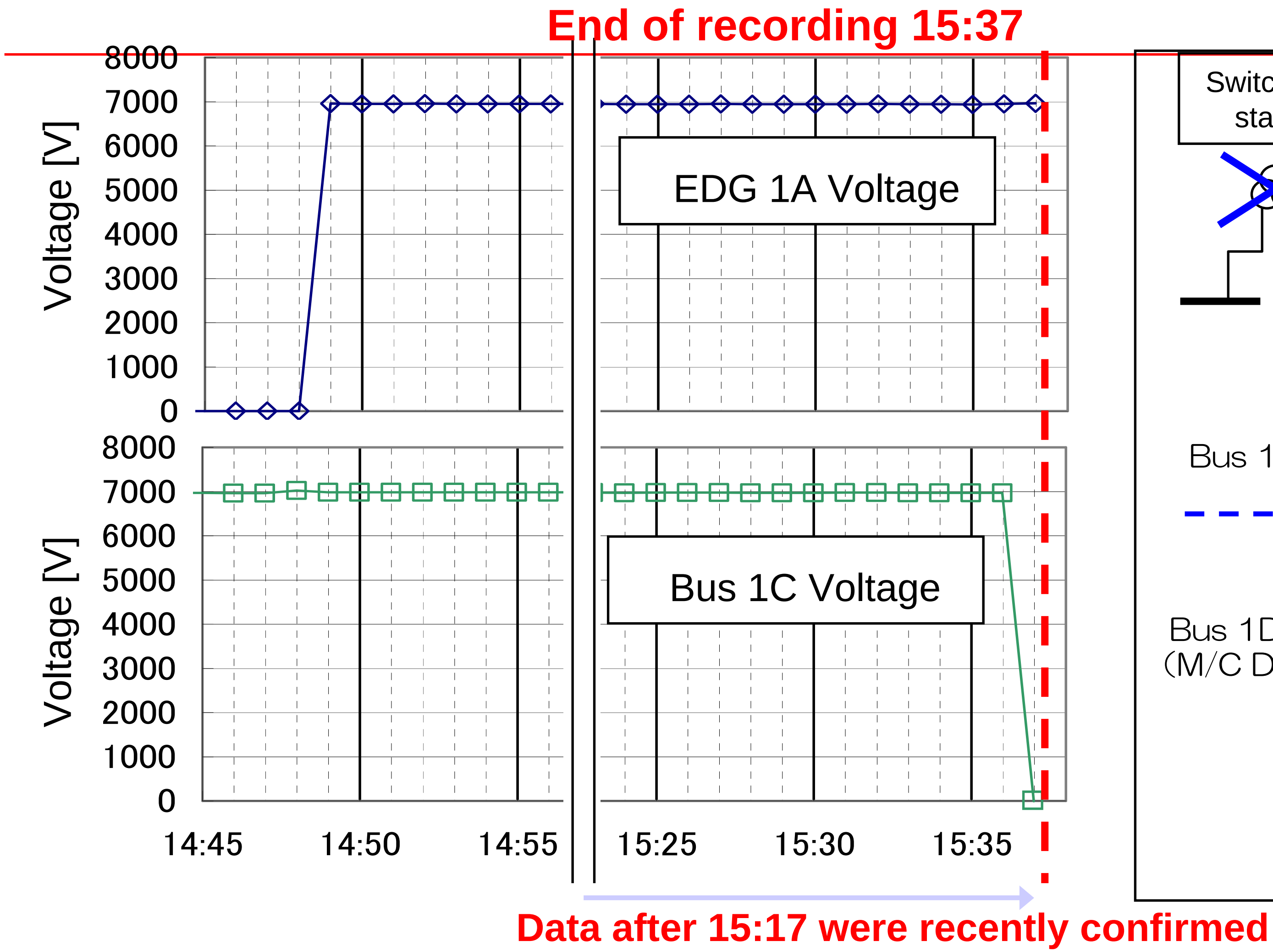
<u>In May 2013, the data recorded by TR for another purpose was found.</u>

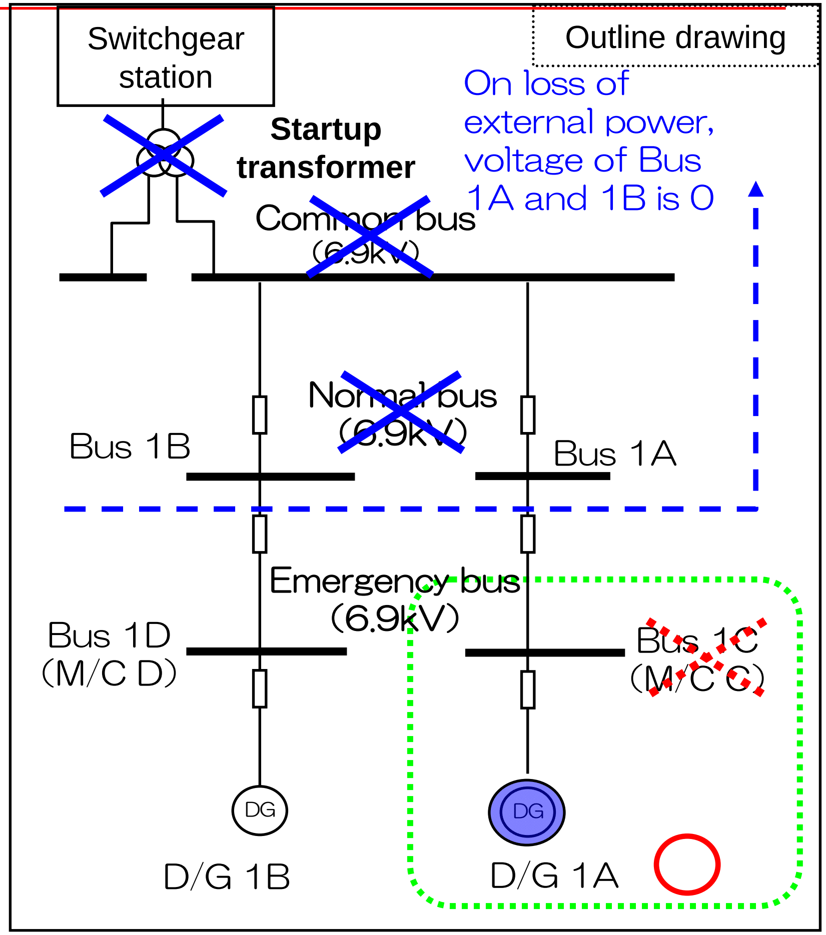
6. State of start up and operation of EDG（～15:17）



- The transient recorder recorded that EDG(A) (B) had operated normally until recording stop time. In addition, aftershocks with seismic intensity 4 occurred six times and with seismic intensity 3 occurred twice during the recording time.

6. State of EDG operation（Time around Tsunami arrival）

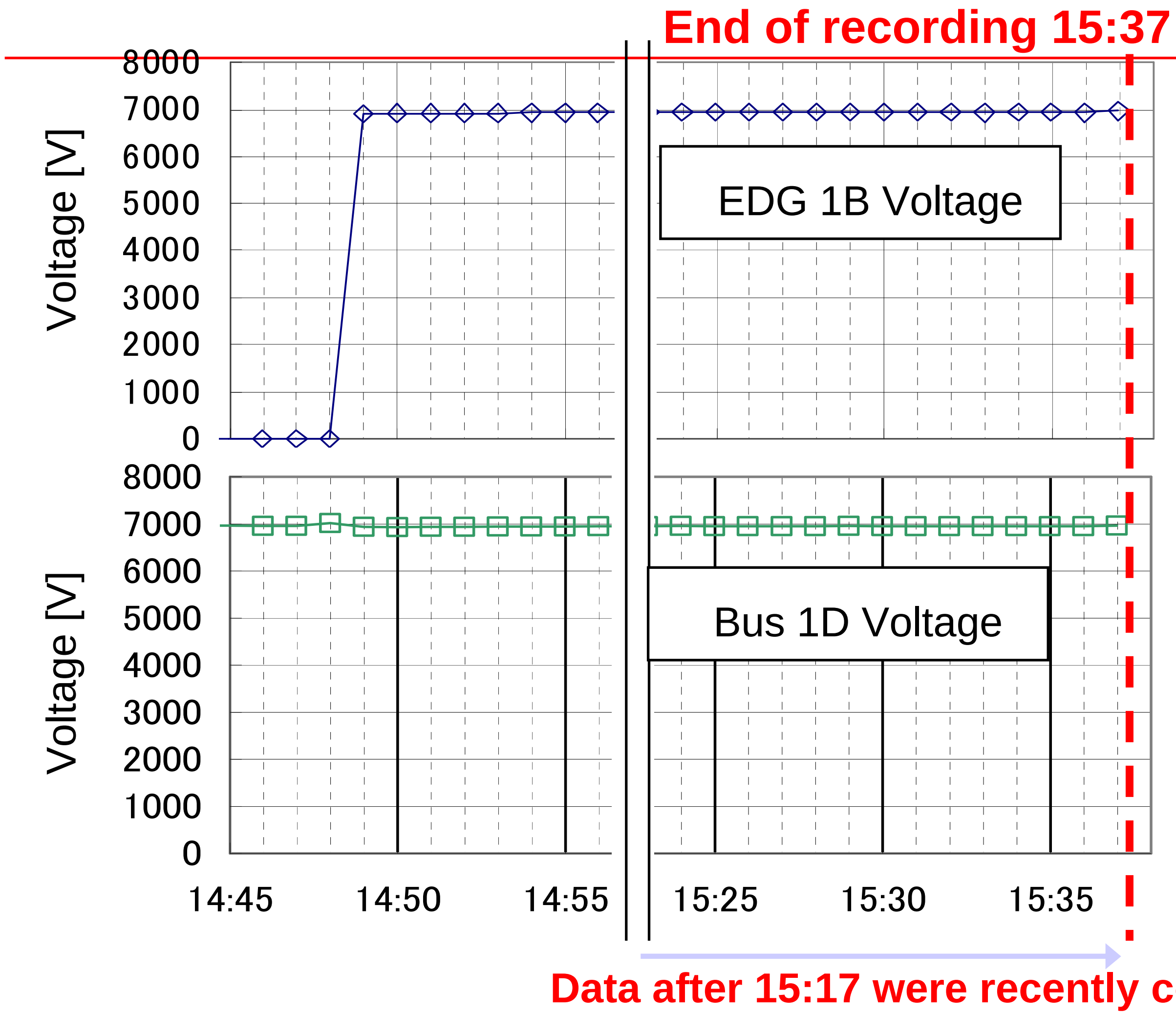


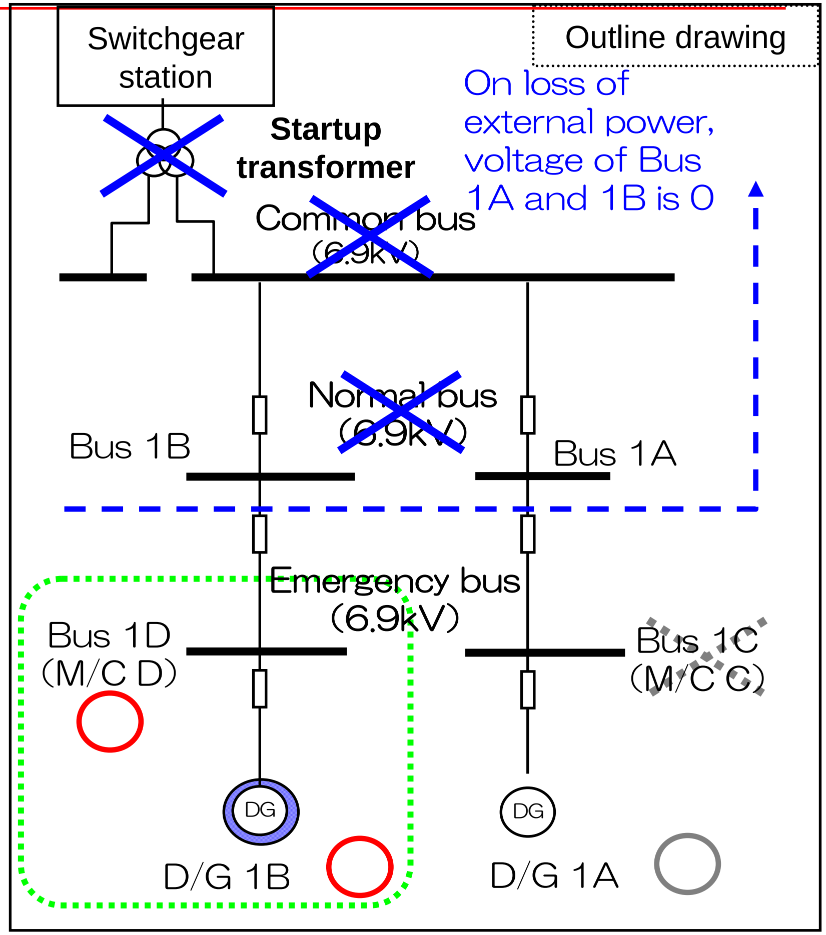


Voltage data at 15:37 shows EDG 1A at rated voltage, Bus 1C at 0 V

→ Bus 1C lost its function earlier than EDG 1A

6. State of EDG operation（Time around Tsunami arrival）



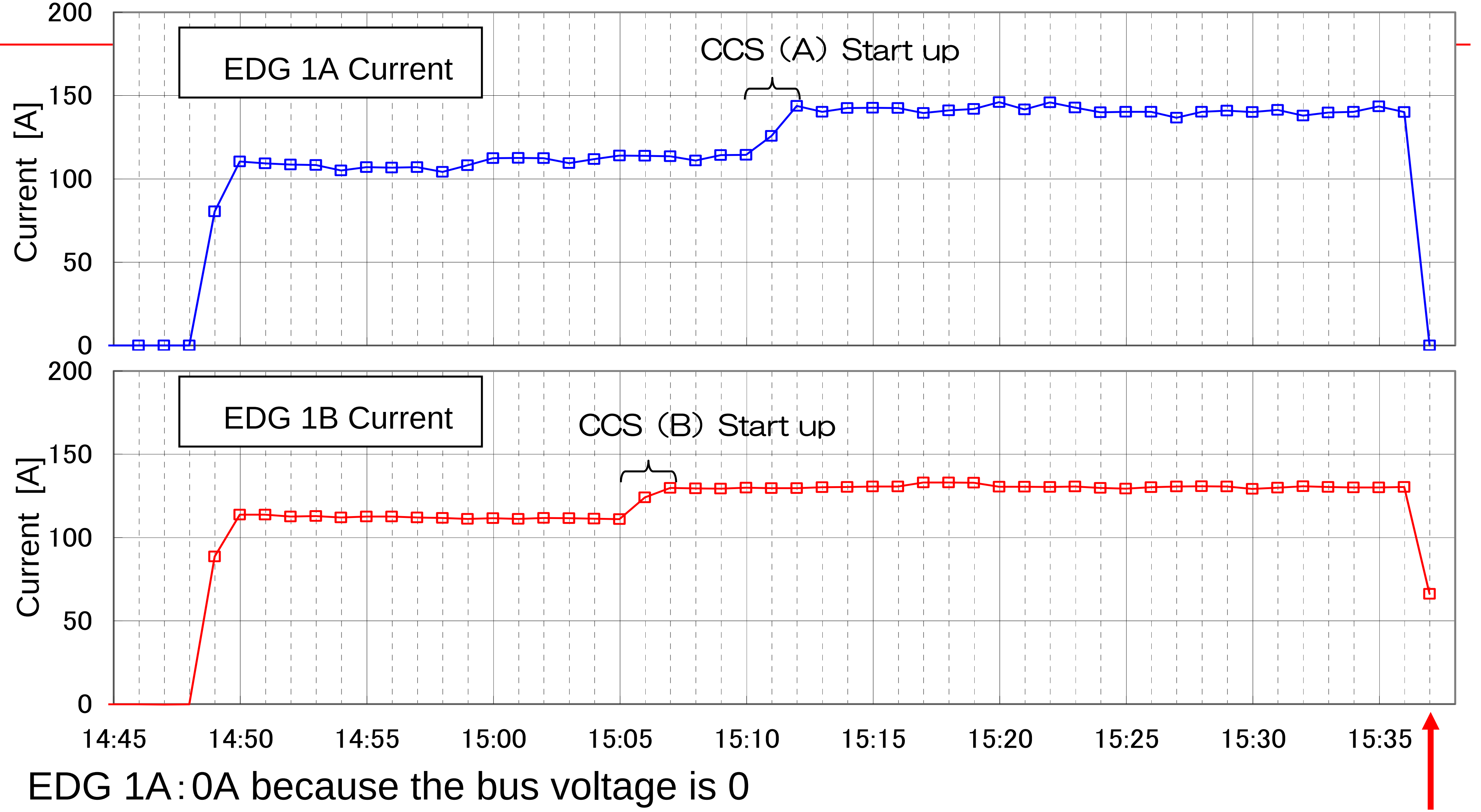


Voltage data at15:37

Both EDG1 B and Bus 1D at rated voltage

→　It is not clear which lost function first, EDG or Bus.

6. EDG 1A, 1B　Current data



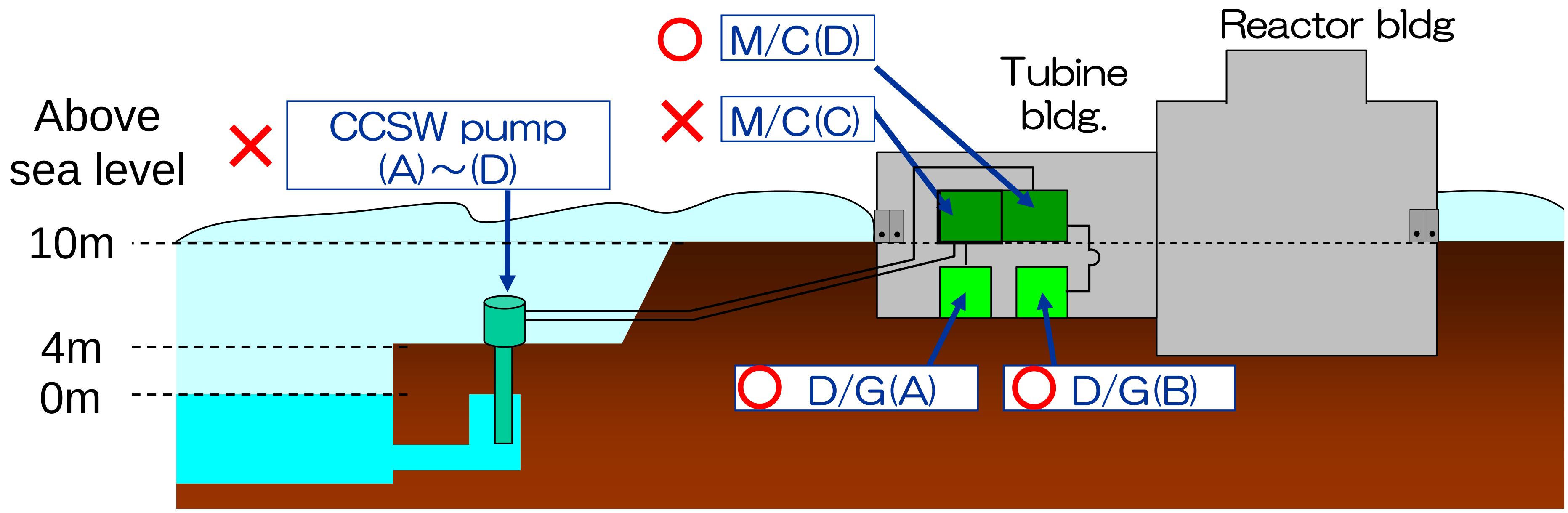
EDG 1A：0A because the bus voltage is 0

EDG 1B：Voltage decrease

→**Load equipment of EDG stopped due to the tsunami**

6. Function loss time of equipment by the tsunami

15:36～15:37



- All CCSW pumps were stopped between 15:36-15:37.

 →Equipment was gradually affected from seaside by the tsunami.
- M/C 1C Voltage is 0 V, likely being damaged by tsunami water.
- D/G maintained normal voltage.

6. Progression of tsunami flooding event

Around 15:35

The tsunami pass through tide gauge at 1.5 km offshore

↓

15:36～15:37

Function loss of CCSW pump（Outside）
Function loss of M/C 1C

↓

After 15:37

✓Function loss of followings
- D/G 1A
- D/G 1B
- M/C 1D
- Direct current power source

- Tripping time of EDG is after the arrival of the tsunami and it was after 15:37.

6. Summary of the loss of function of EDG

Findings from transient recorder data recently confirmed.

✓Both EDG(A) and EDG(B) had been keeping the rated voltage until just before the tsunami arrived.

✓After the tsunami had arrived, the voltage of bus (C) of alternating current diminished earlier than that of EDG(A).

✓Sea water pumps tripped between 15:36 and 15:37

As we have reported so far

・EDG at unit 1 had kept their function just before the tsunami.
SBO at unit 1 was caused by the tsunami.

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Unit 2 Accident progression

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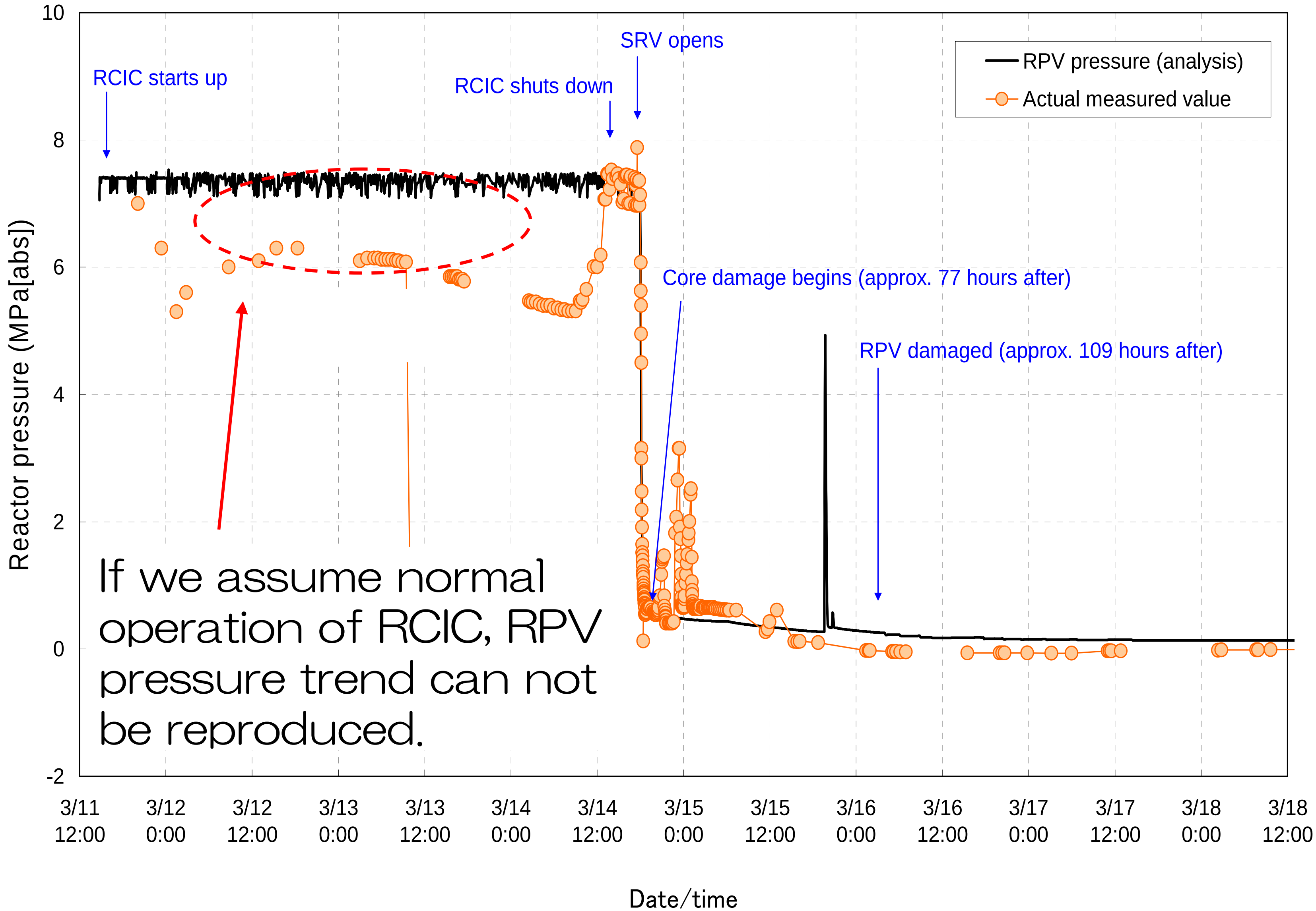
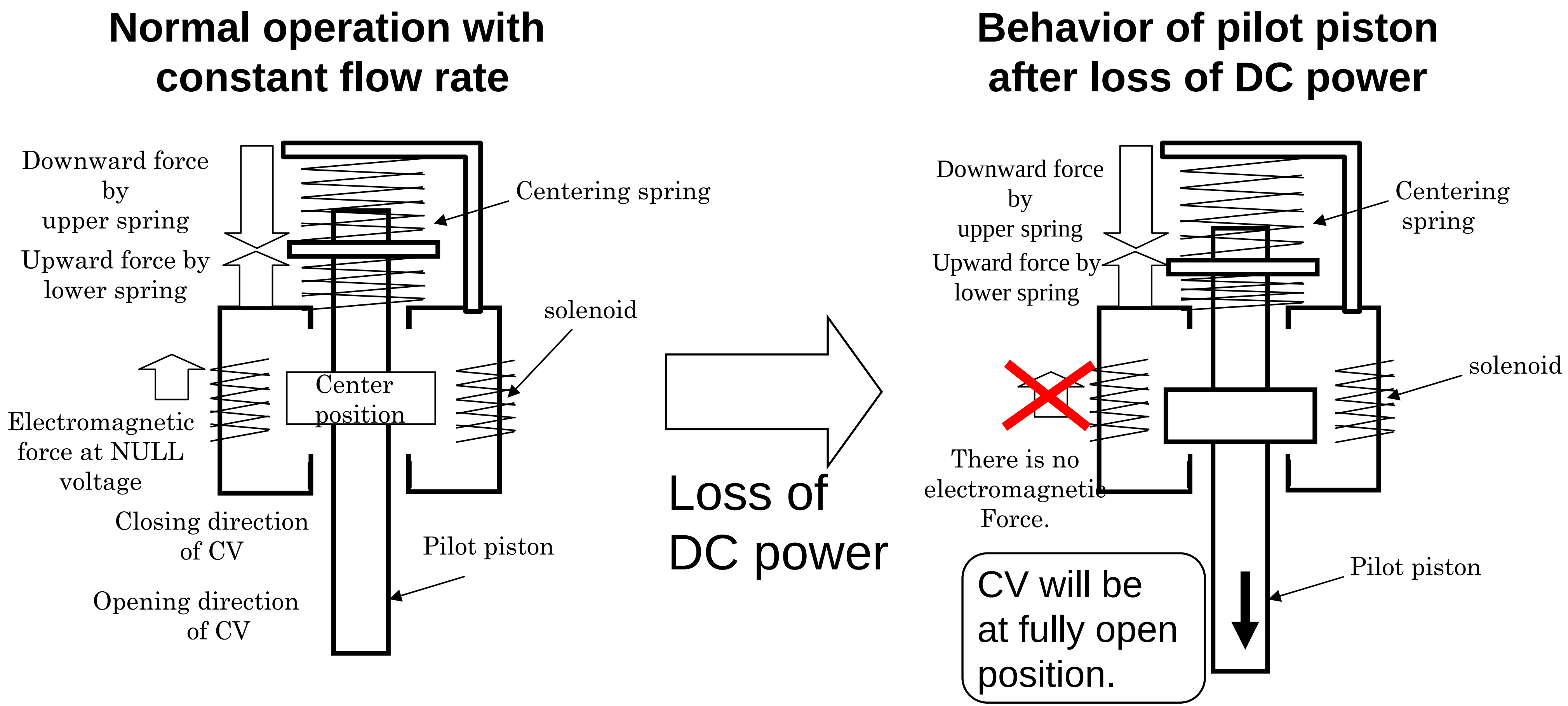
7. Chronological accident description of unit 2

- 3/11 14:46
  - Earthquake : Reactor was automatically shutdown.
    Decay heat was continuously generated.
  - Loss of off-site power : However, DG was automatically started.
    Therefore, AC and DC power were available in this period.
- 14:50 – 15:41
  - RCIC injection : Reactor was cooled by RCIC, even though RCIC was tripped several times due to RPV water level too high.
- 15:37
  - Tsunami hit : AC and DC were lost. **RCIC had been in operation since 2 minutes before loss of power.** RCIC continued injecting the water to RPV with no controlling.
- Around 3/14 9:00
  - **RCIC operation was terminated due to some reason**
- After termination of RCIC
  - RPV water inventory decreased due to boiling.
- Around 17:00 (from MAAP calculation)
  - Core uncovery : Starting fuel heat up
- Around 19:20 (from MAAP calculation)
  - Reactor core damage : Peak clad temperature became above 1200 degree-C
- After core damage (can NOT specify from MAAP calculation)
  - RPV bottom damage : Corium (melted fuel) slumping to PCV pedestal
  - Radioactive materials were released to environment

7. RCIC operation after loss of control (loss of DC)

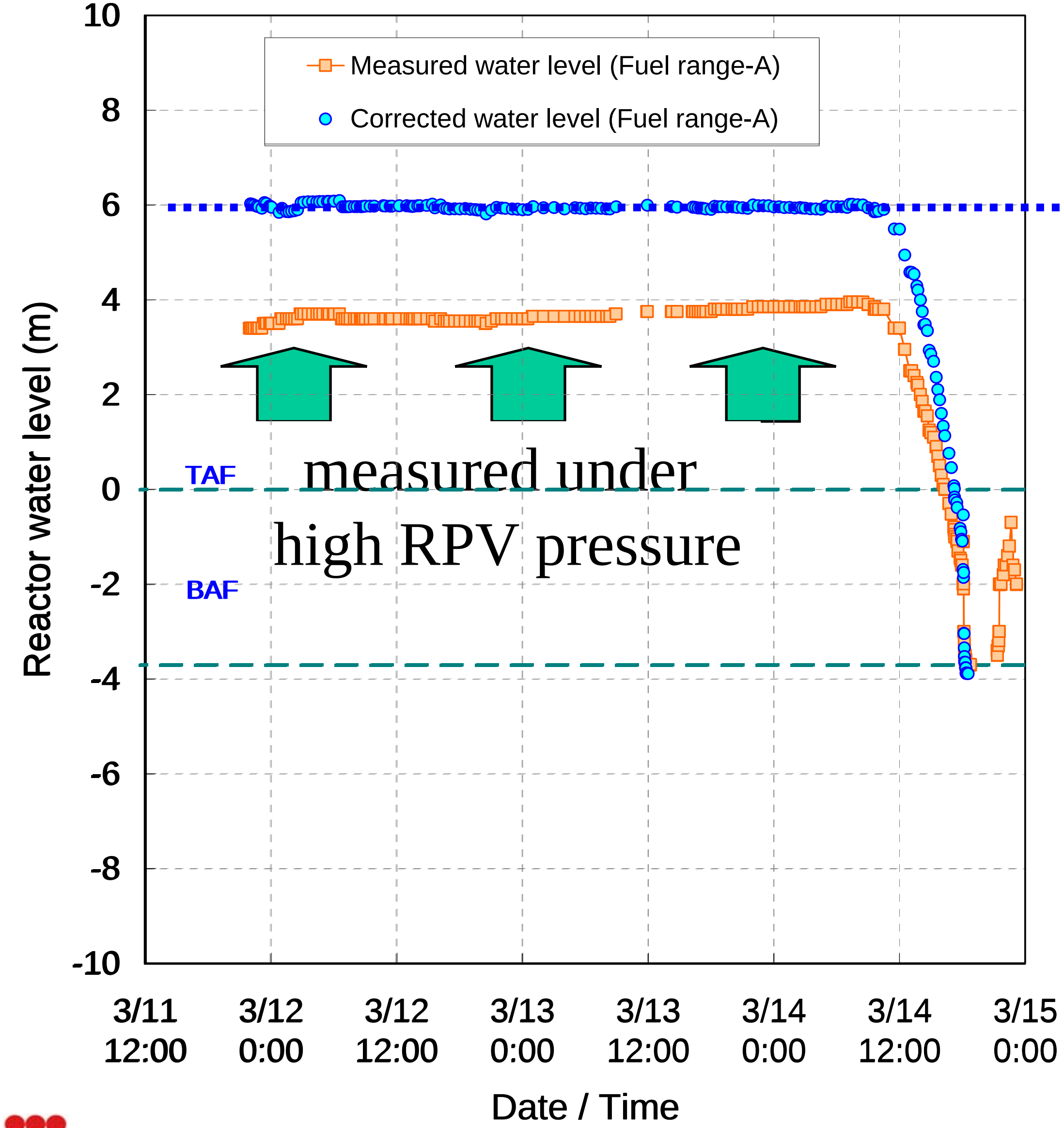


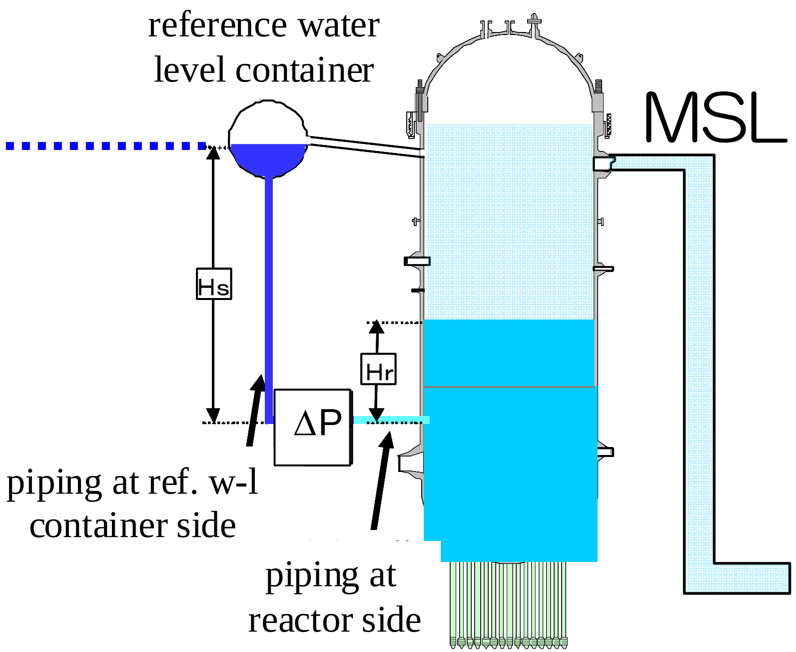
7. CV position after loss of DC power



After loss of DC power, flow rate of uncontrolled RCIC will gradually increase.

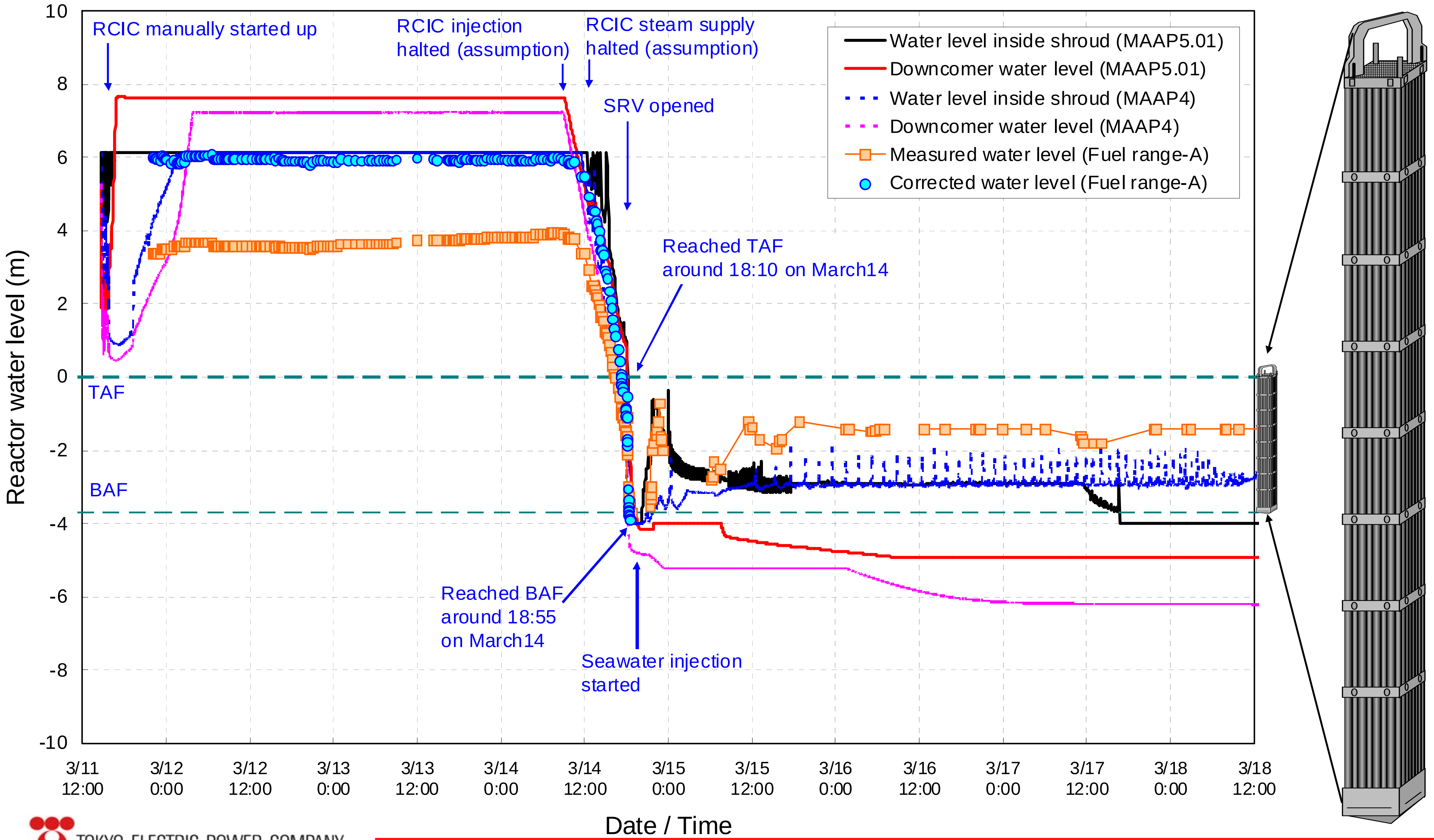
7. Status of RCIC operation in unit 2





After correction, values of measured water level agree with maximum water level. Actual water level may be higher than that. Therefore, Two phase fluid will flow into RCIC turbine.

7. RPV water level in unit 2



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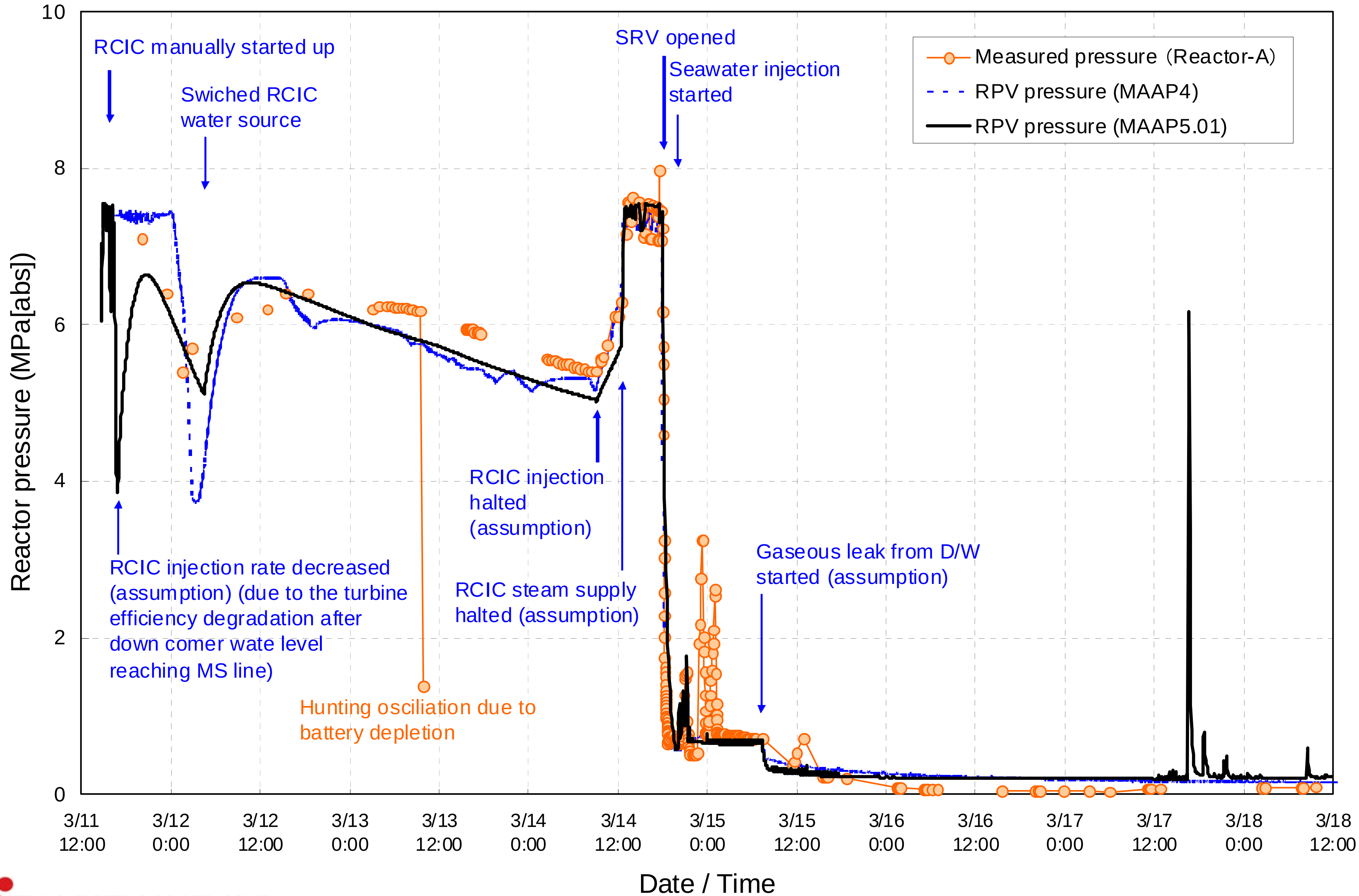
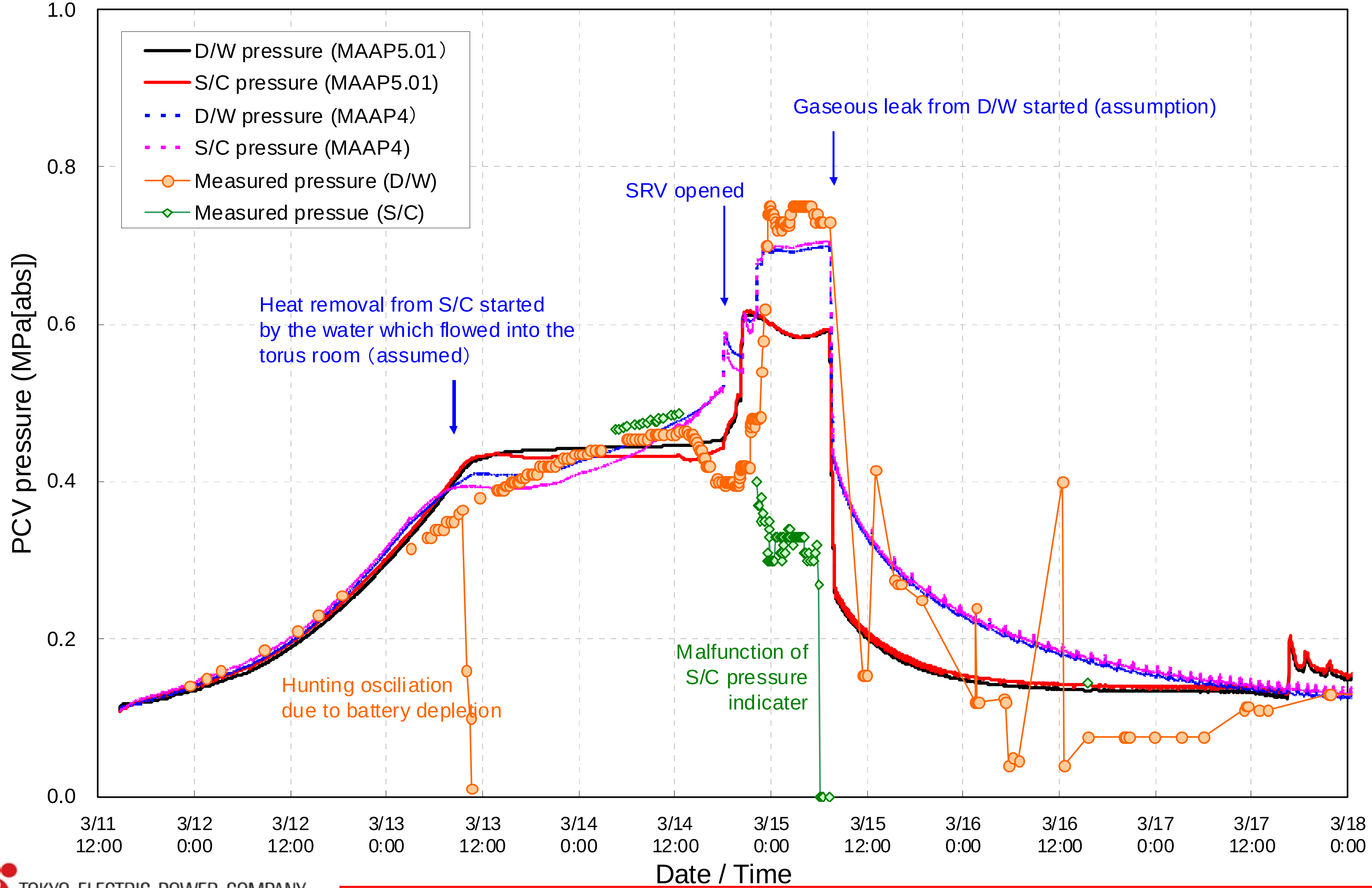
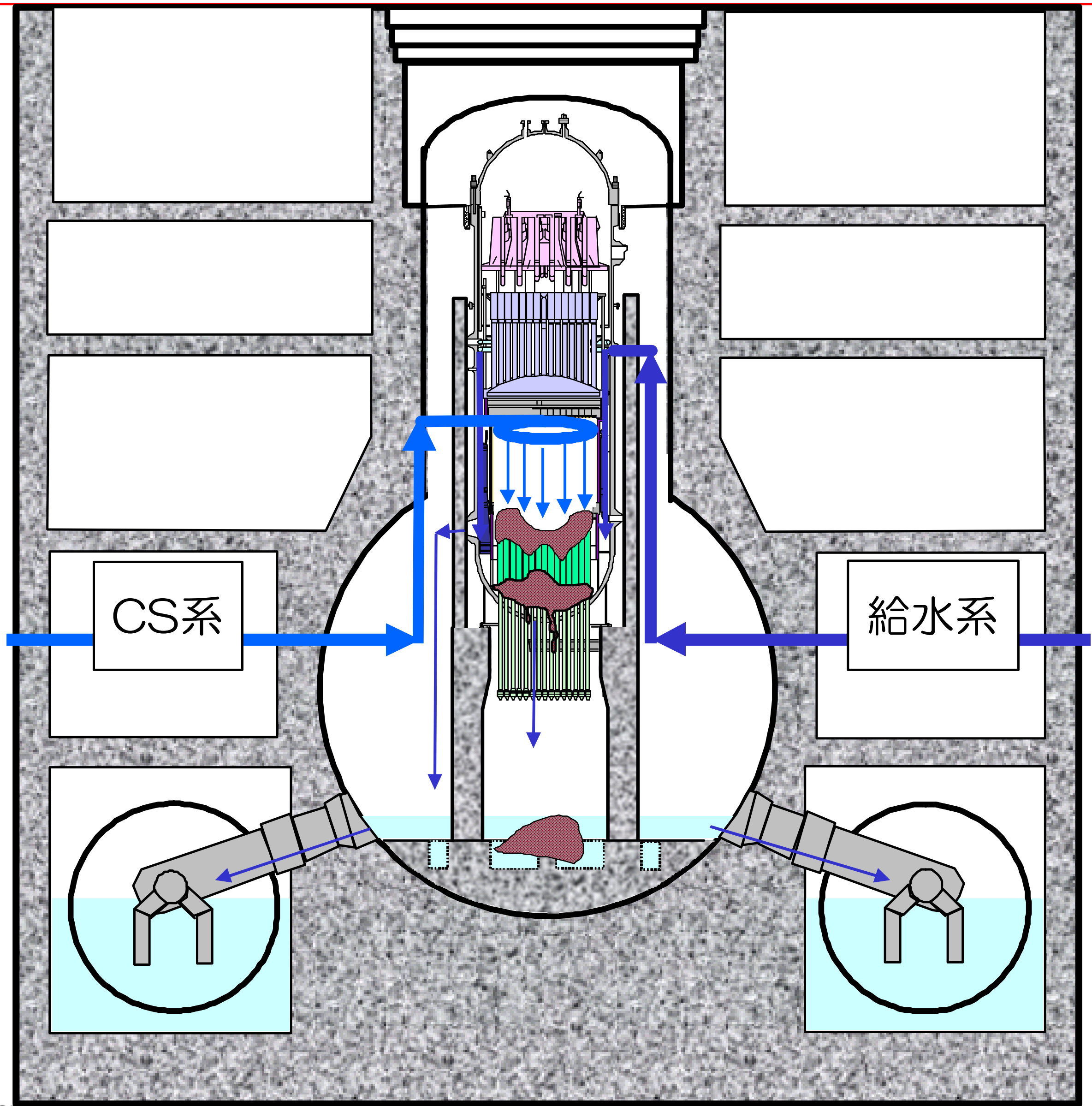
7. RPV pressure in unit 2



7. PCV pressure in unit 2

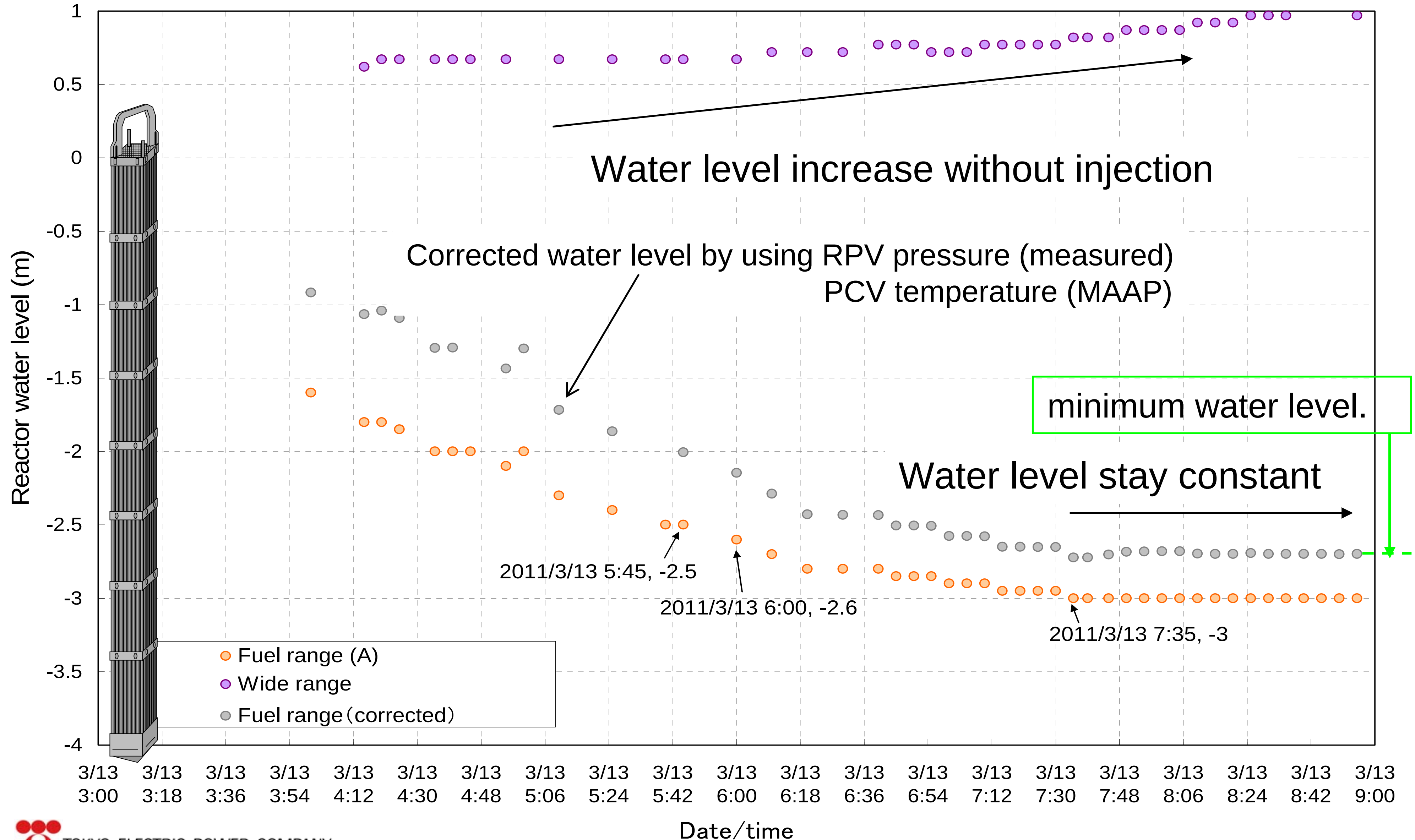


7. Estimation of the status of unit 2

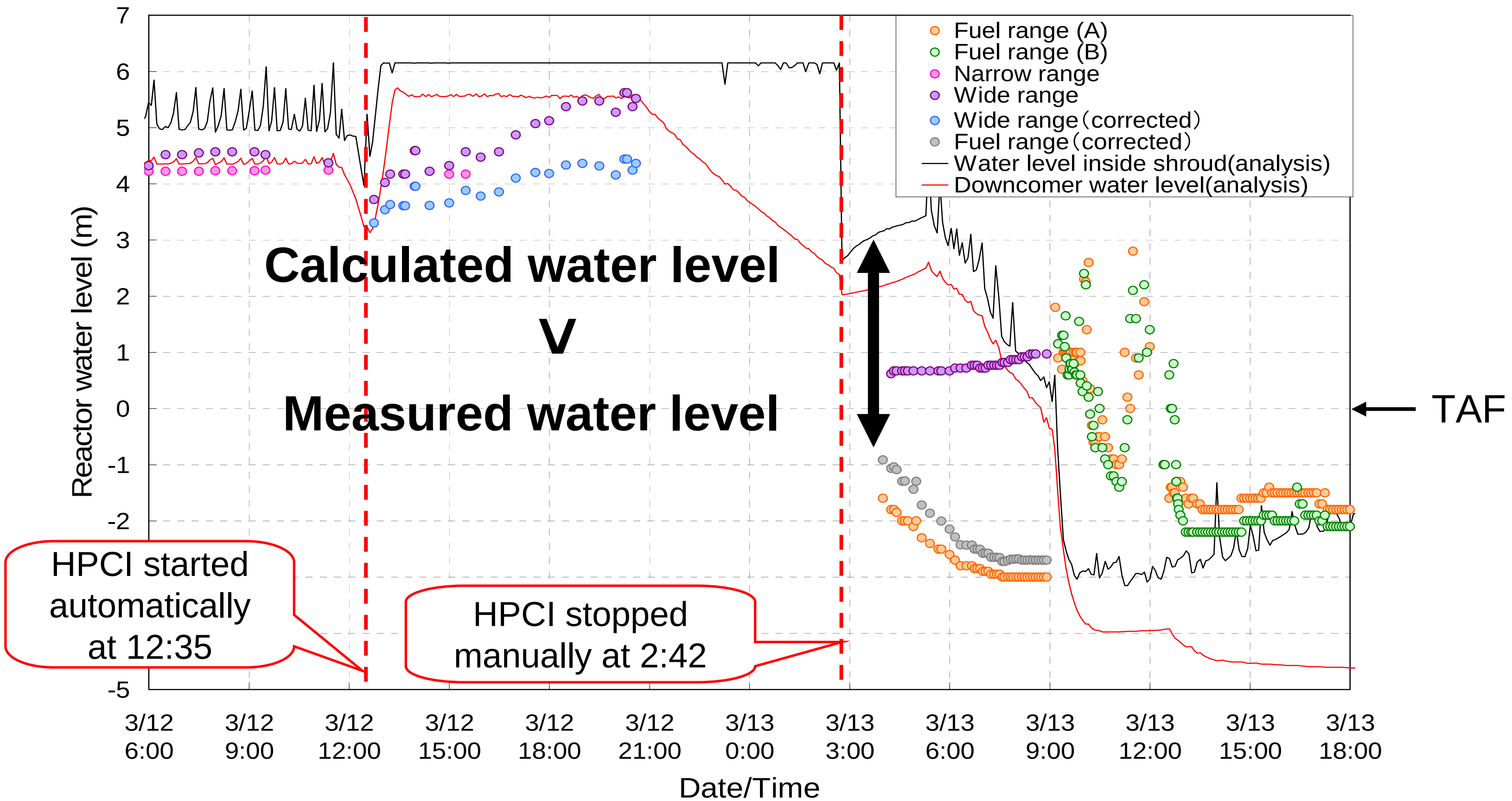


Unit 3 Accident progression

8. RPV water level behavior before depressurization

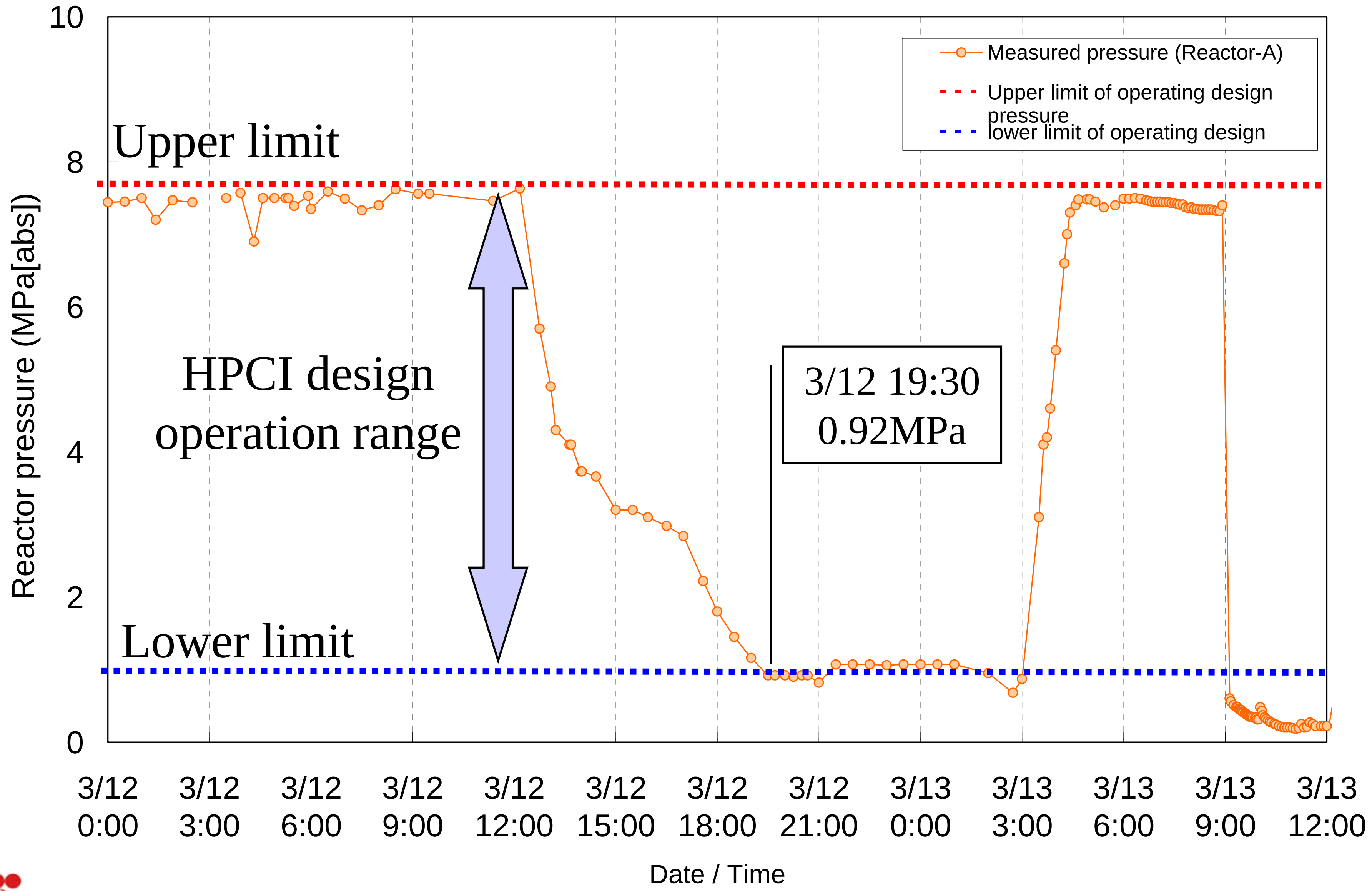


8. Discussion on RPV water level trend

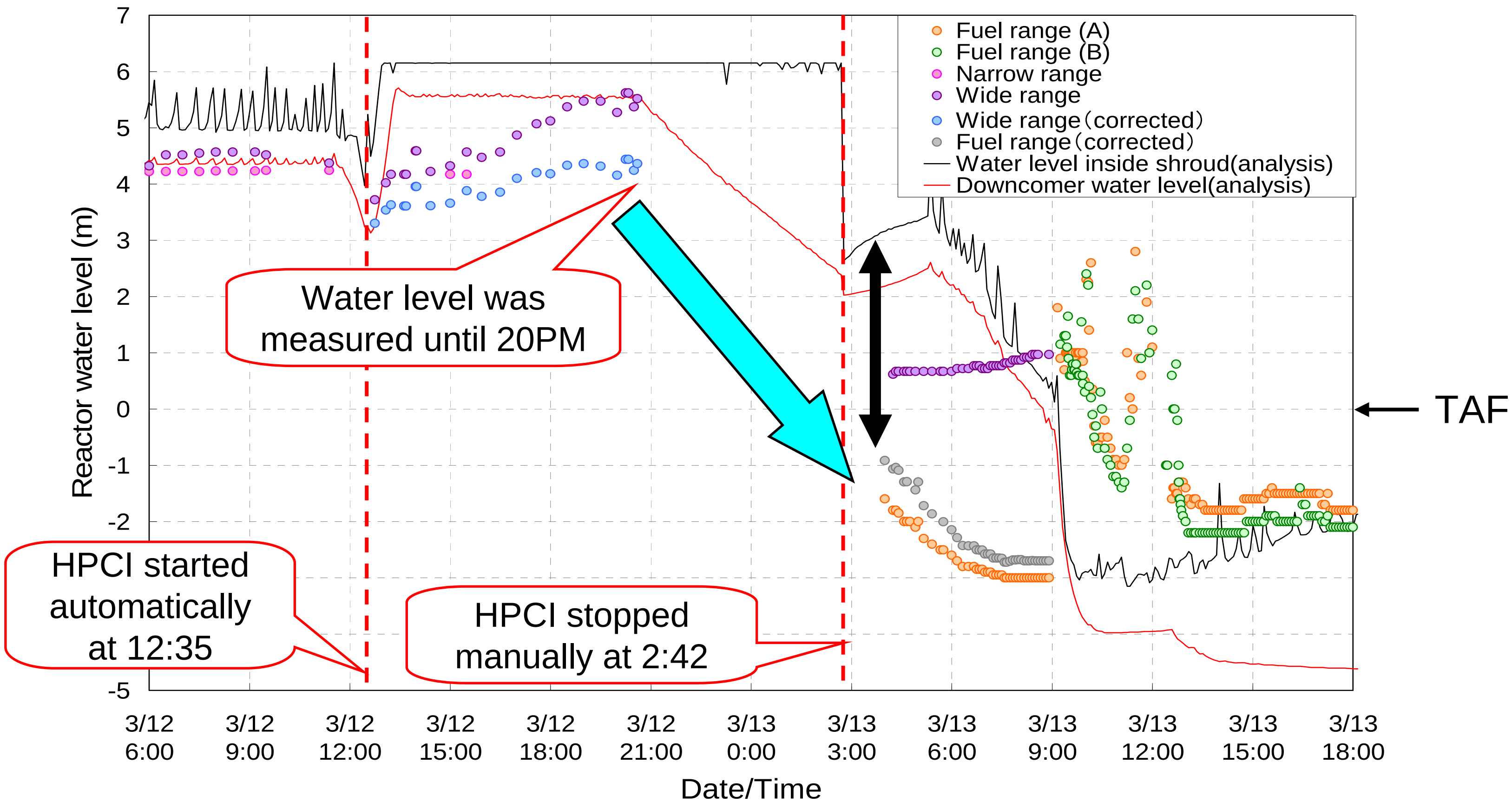


- RPV water level is too high compare to the measurement values.
- In this calculation, HPCI injection was continued until manual termination by operator.

8. RPV pressure trend during HPCI operation



8. Discussion on RPV water level trend



- It is highly possible that HPCI had lost the function to inject enough water to RPV before manual termination.
- It is highly possible that accident progression is faster than this former MAAP calculation.

8. Chronological accident description of unit 3 (1/2)

- 3/11 14:46
  - Earthquake : Reactor was automatically shutdown. Decay heat was continuously generated.
  - Loss of off-site power : However, DG was automatically started. Therefore, AC and DC power were available in this period.
- 14:50 – 15:37
  - RCIC injection : Reactor was cooled by RCIC, even though RCIC was tripped several times due to RPV water level too high.
- 15:37
  - Tsunami hit : AC power was lost but DC power was available. RCIC was kept in operation with operator's control.
- 3/12 11:36
  - RCIC operation was terminated due to trip signal "exhaust pressure high".
- 3/12 12:35
  - HPCI was automatically started due to RPV water level too low. RPV pressure decreased because HPCI consumed much steam.
- Around 20:00
  - HPCI could not inject enough water due to lack of RPV pressure to drive turbine.

8. Chronological accident description of unit 3 (2/2)

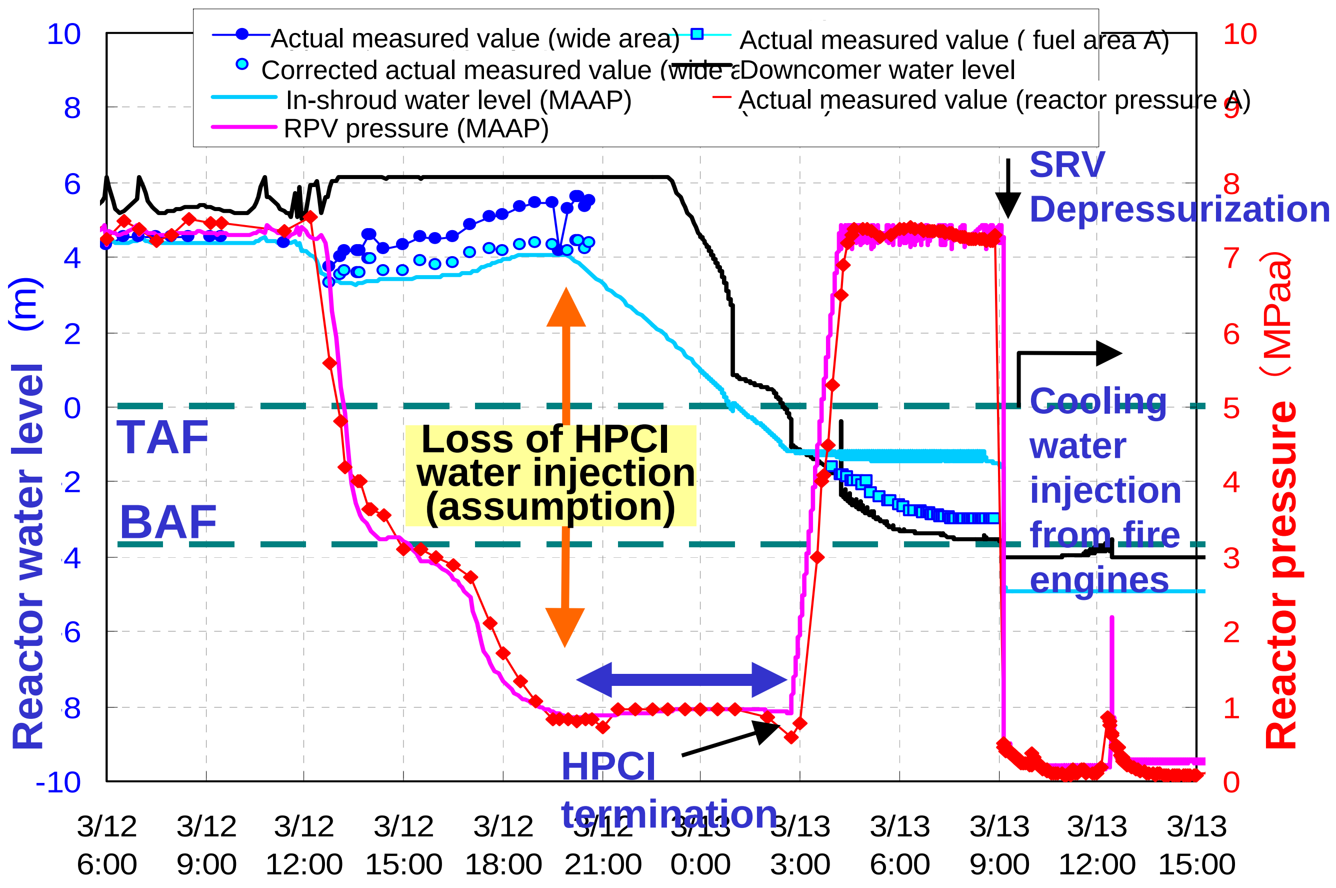
- After degradation of HPCI RPV injection
  - RPV water inventory decreased due to boiling.
- 3/13 02:42
  - HPCI was terminated manually by operator.
- Around 02:30 (from MAAP calculation*)
  - Core uncovery : Starting fuel heat up
- Around 5:10 (from MAAP calculation*)
  - Reactor core damage : Peak clad temperature became above 1200 degree-C
- After core damage (can NOT specify from MAAP calculation)
  - RPV bottom damage : Corium (melted fuel) slumping to PCV pedestal
  - Radioactive materials were released to environment

8. Calculation result reflecting the state of HPCI operating status

We conducted MAAP analysis, taking into account HPCI operational state.
We assumed that no cooling water was injected into the reactor after 20:00 on 3/12.

- analysis Conditions -

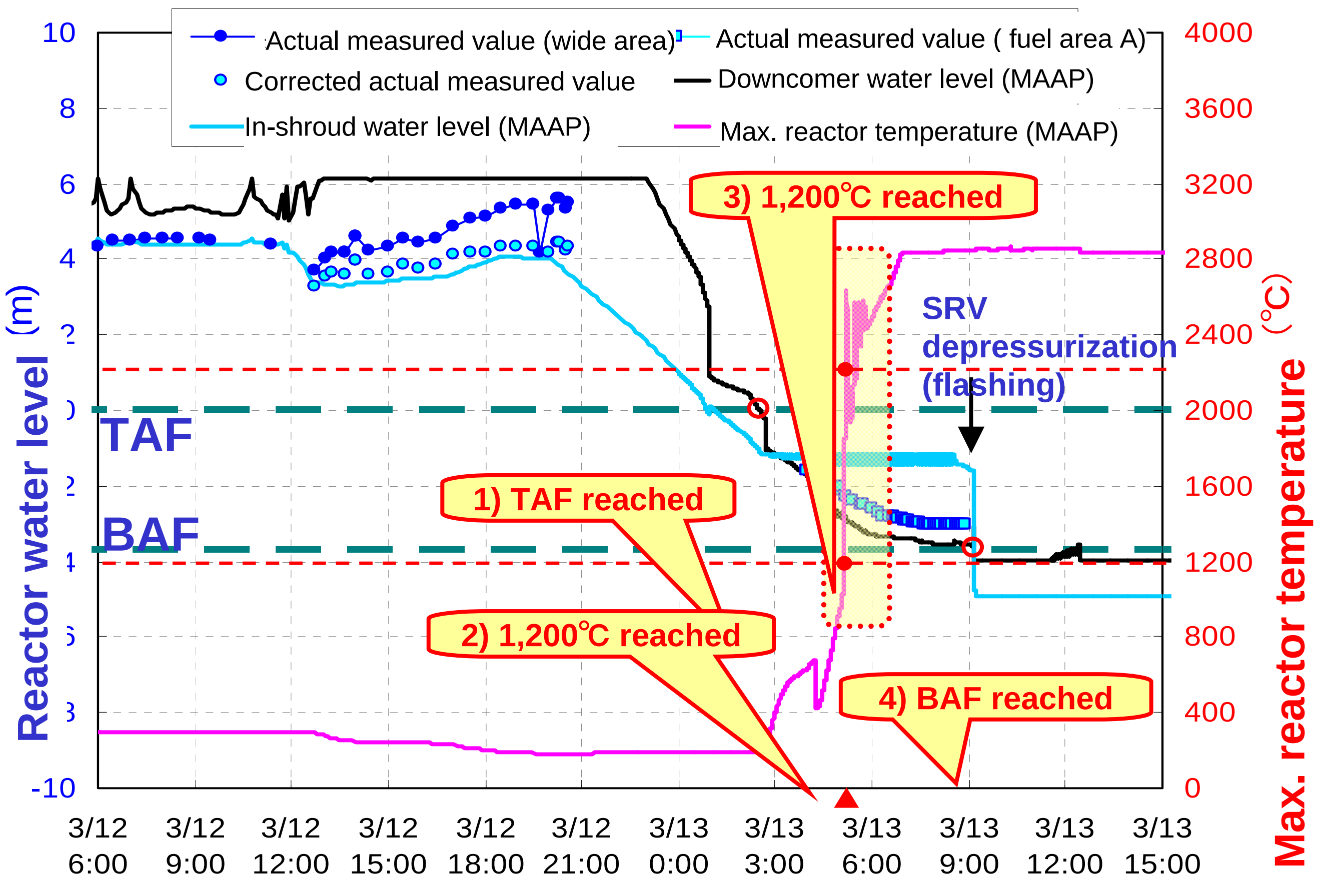
- ✓At 20:00 on March 12, reactor pressure fell below HPCI design condition 1MPag to about 0.8 Mpag. We assumed that no cooling water was injected into the reactor after that time.
- ✓In this HPCI operation condition, steam supply to the turbine continued and HPCI was working, but all of the discharge flow went back to CST.
- ✓After the HPCI's manual shutdown, reactor pressure began to increase.



8. Calculation result reflecting the state of HPCI operating status

- Result analysis -

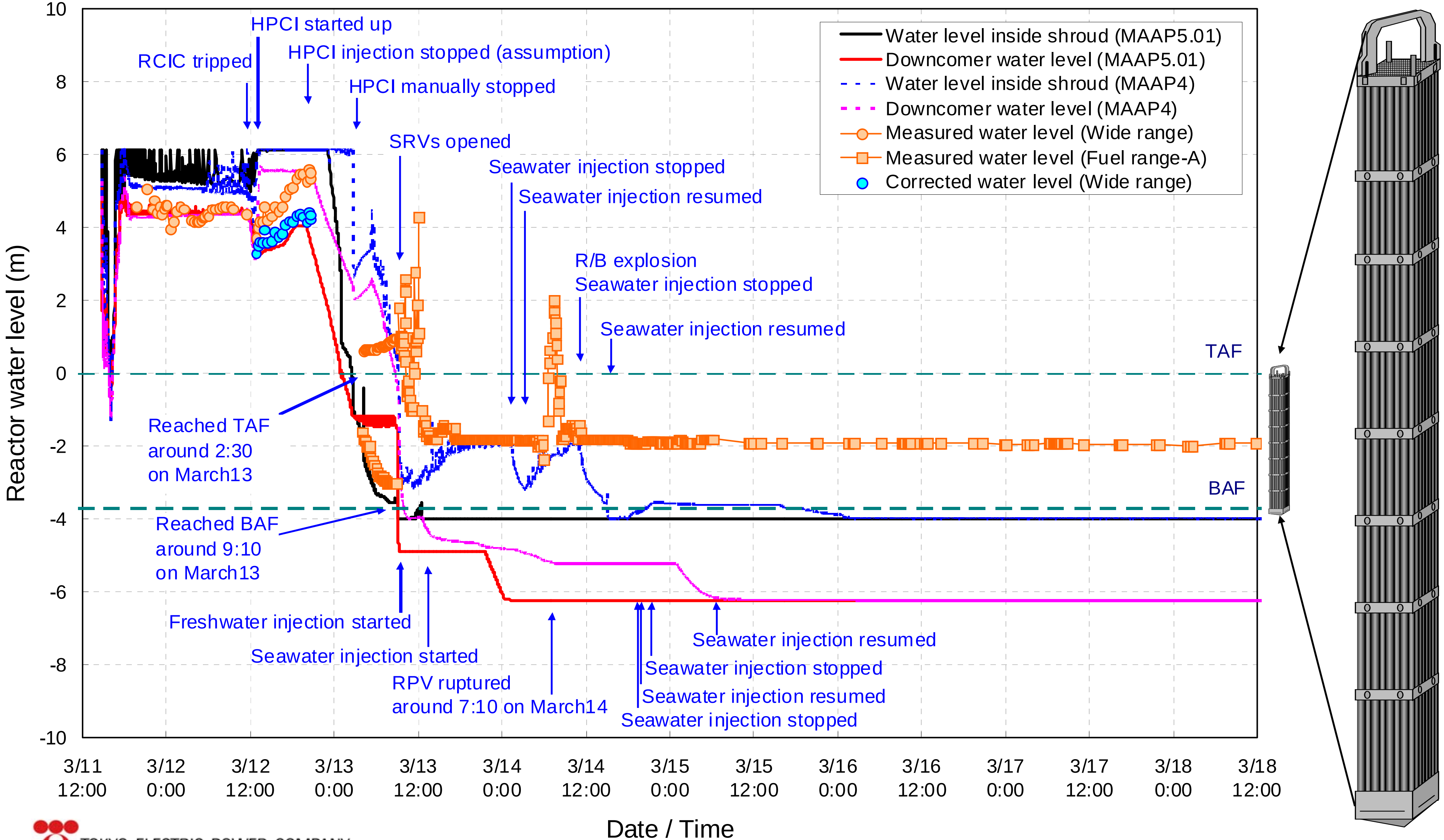
1) TAF reached	About 2:30 on 3/13
2) Maximum reactor temperature 1,200℃ reached	About 5:10 on 3/13
3) Maximum core temperature 2200℃ reached	(Fuel melting) About 5:30 on 3/13
4) RPV damaged	About 7:10 on 3/14



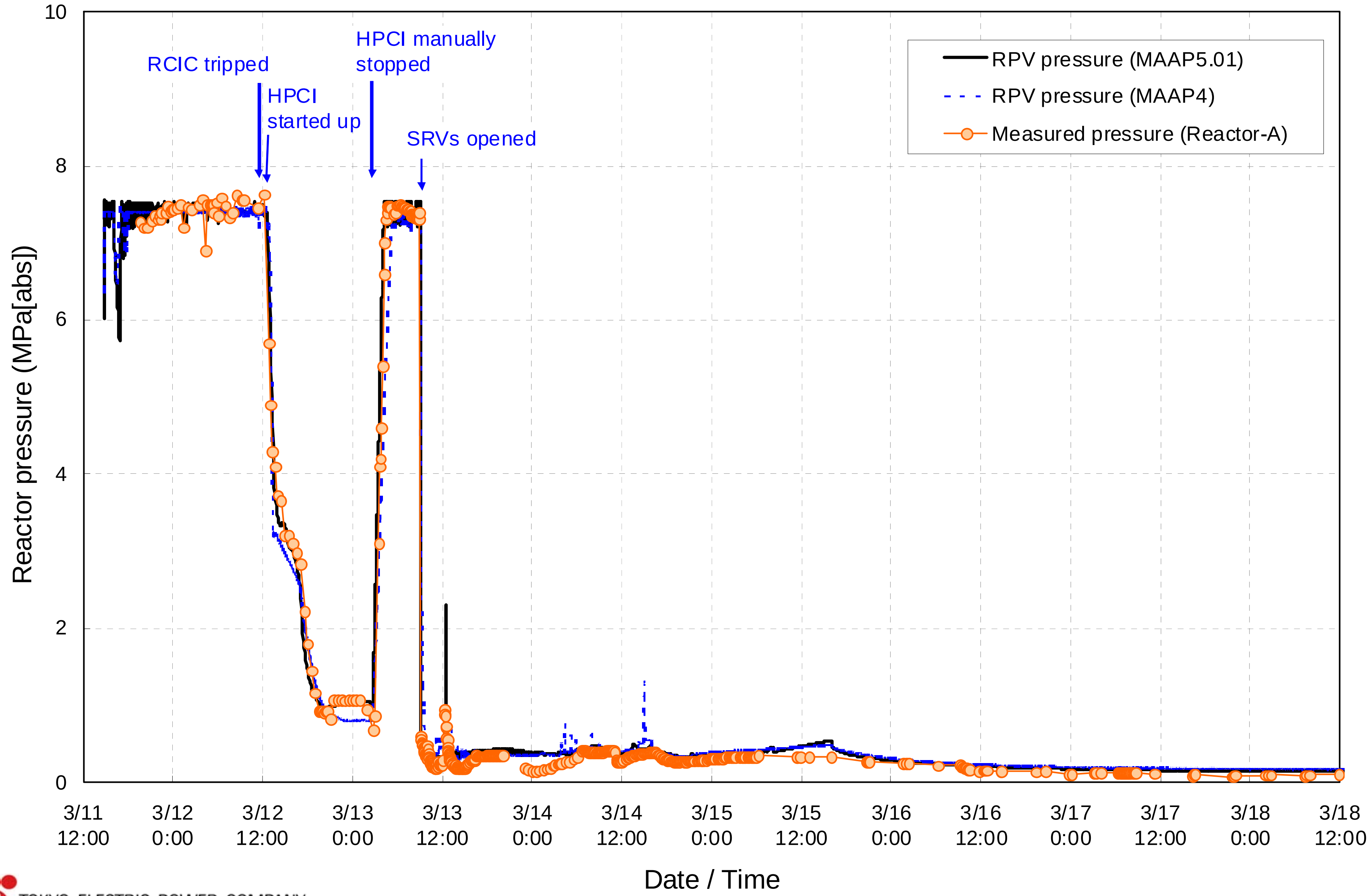
Core melt started before RPV water level reaching to BAF.

Steam generated by decay heat enhanced zirconium-water reaction and massive energy generated by zirconium-water reaction invoked the core melt.

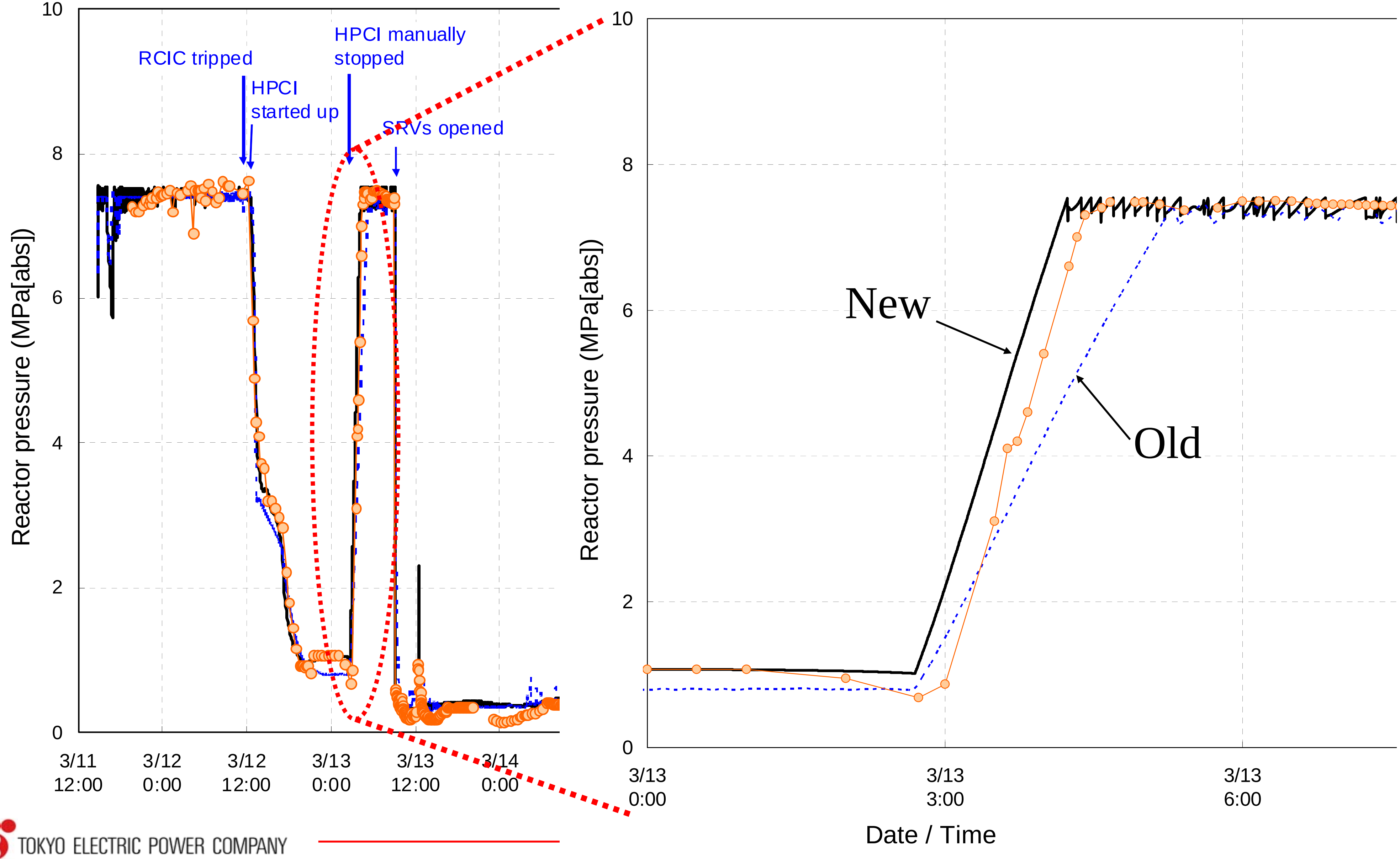
8. RPV water level in unit 3



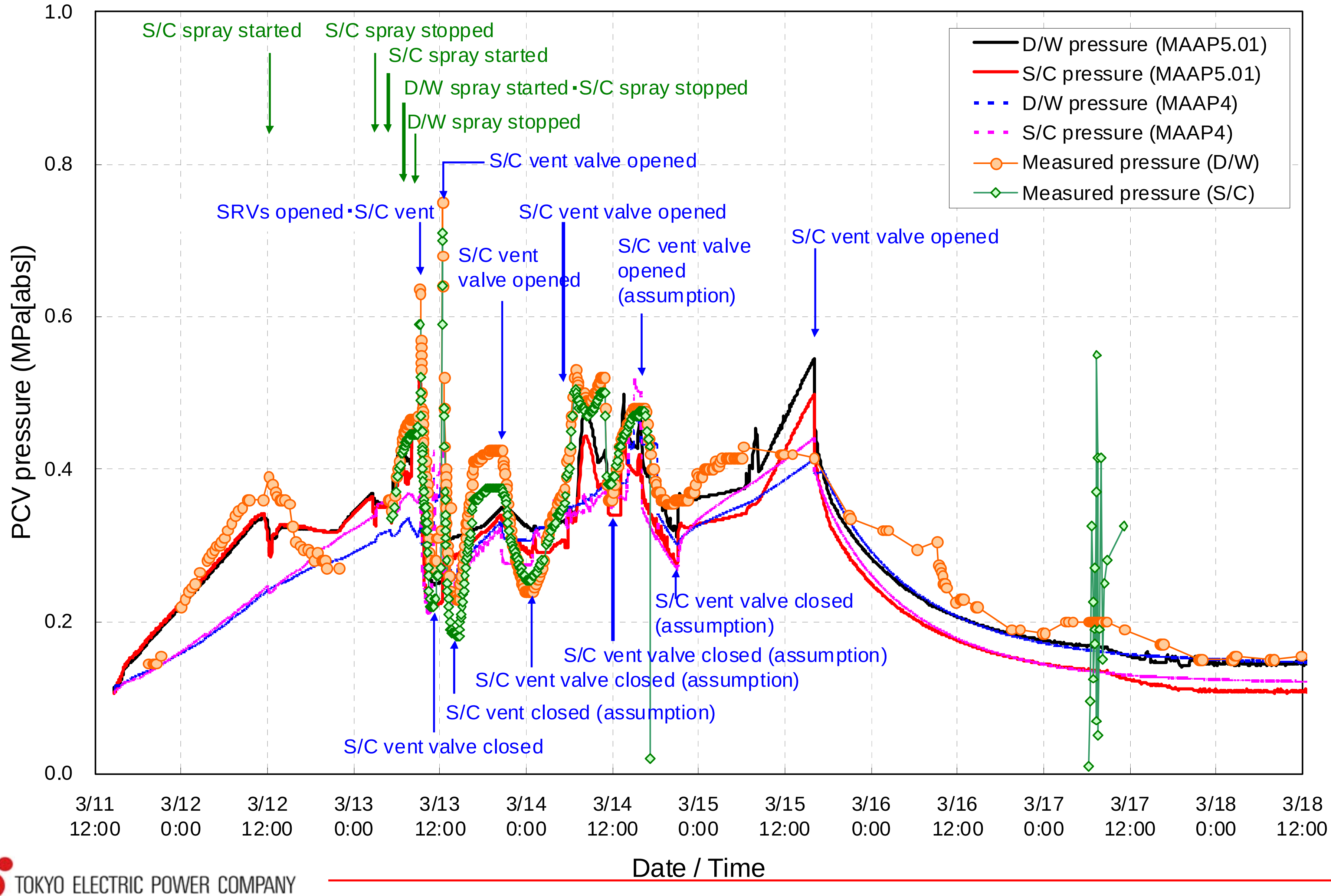
8. RPV pressure in unit 3



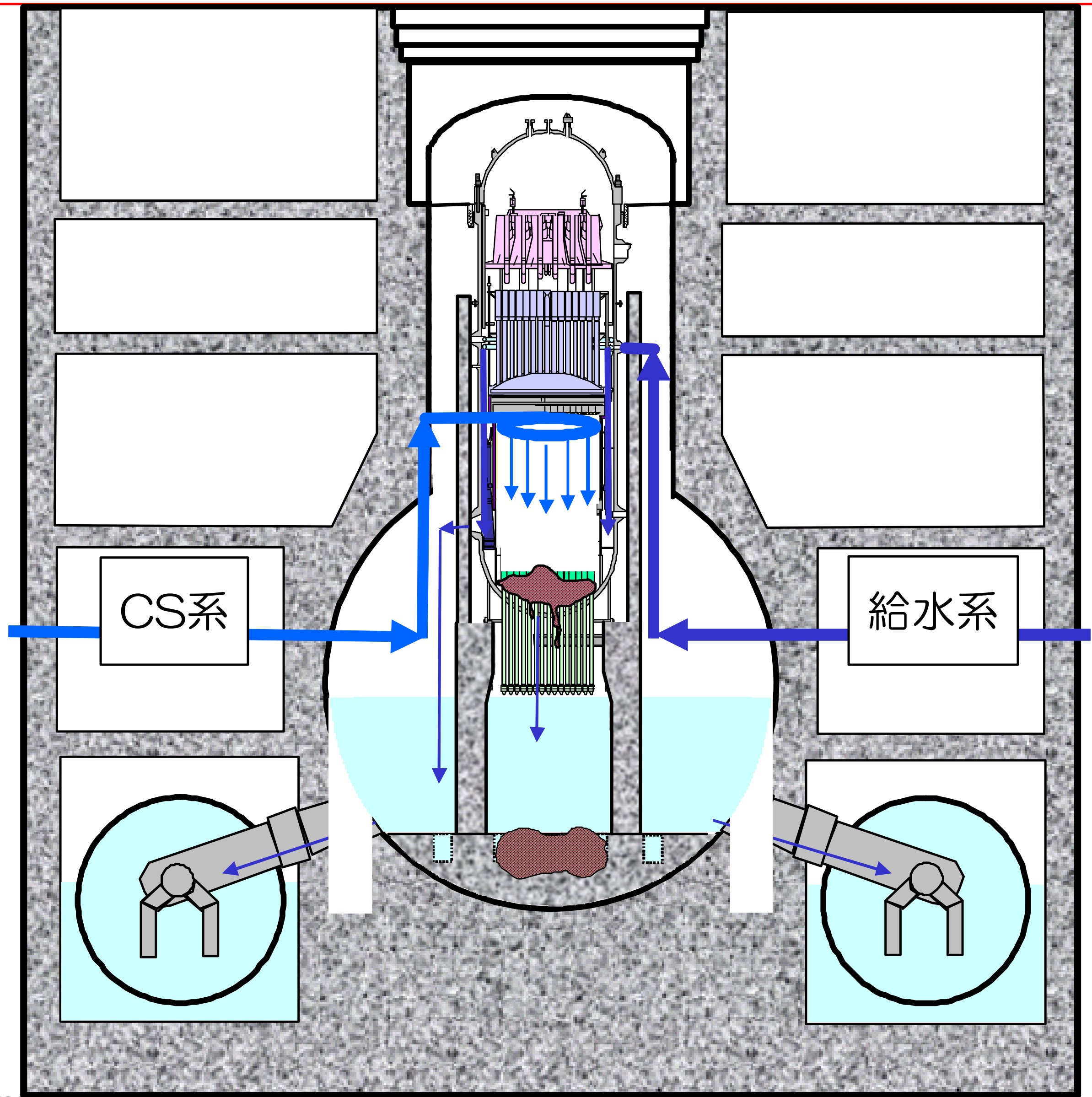
8. RPV pressure in unit 3



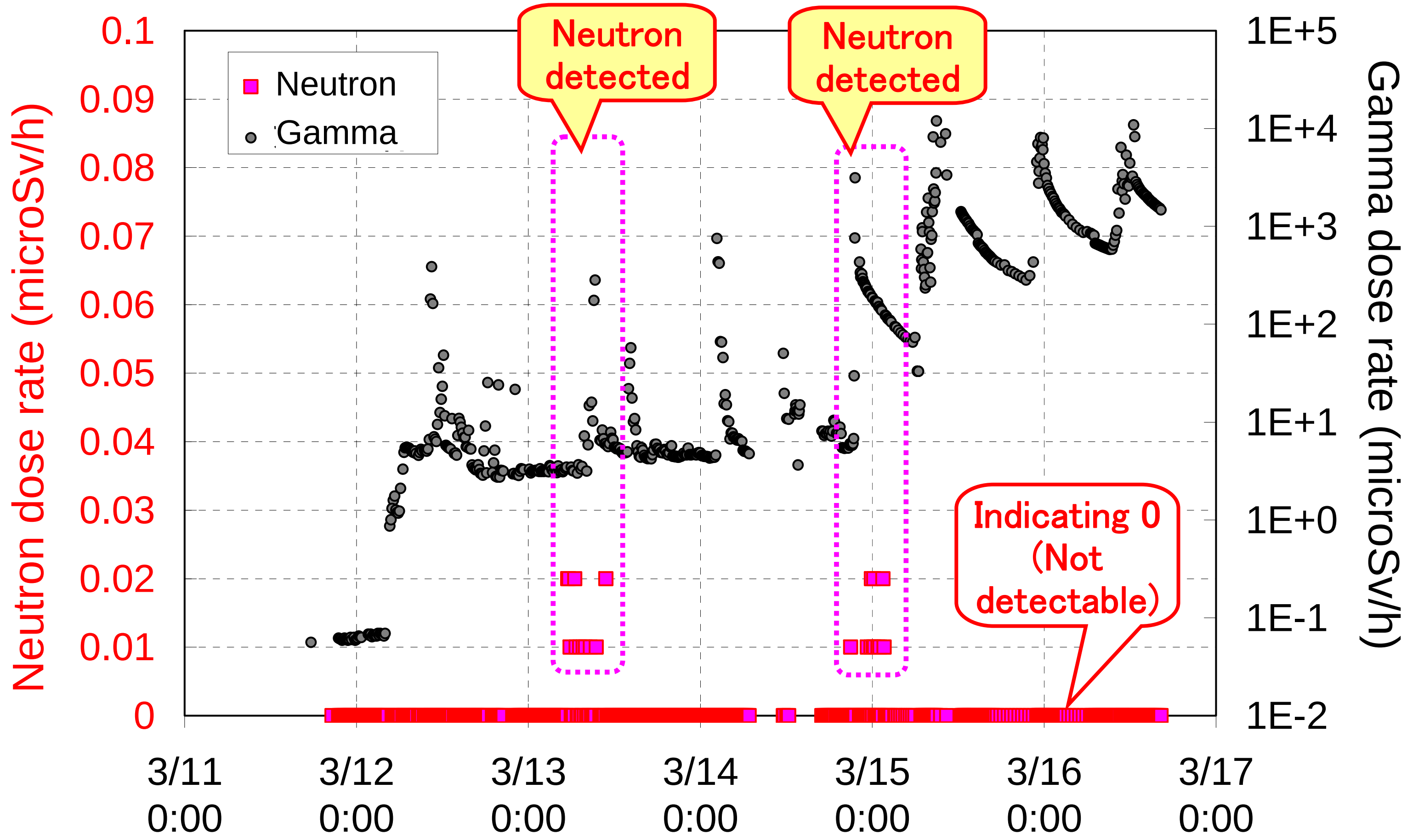
8. PCV pressure in unit 3



8. Estimation of the status of unit 3



9. Neutron monitoring result (near main gate)



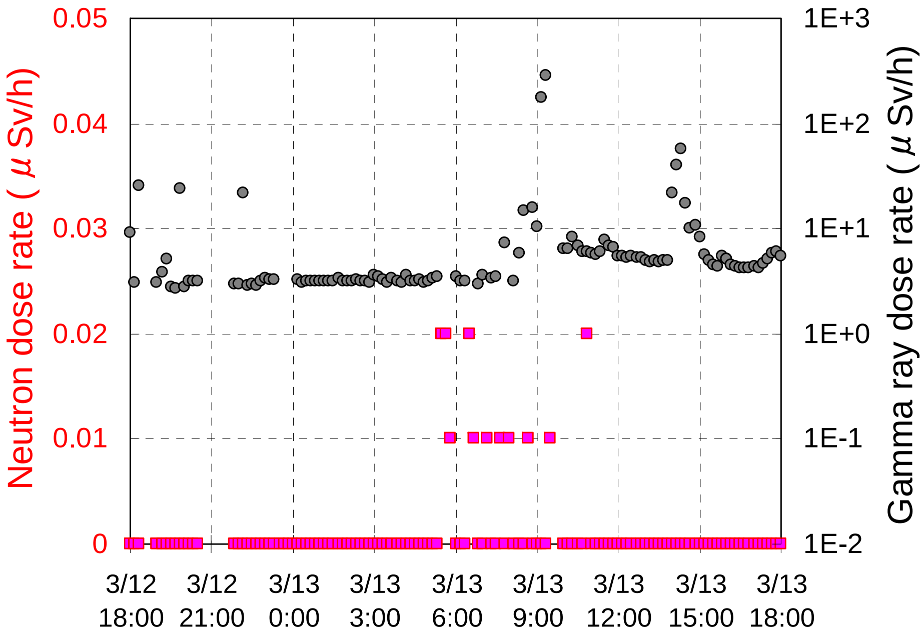
・Gamma dose:
Ion chamber installed in monitoring car

・Neutron dose:
Neutron survey meter (He-3 detector)
Measurement range 0.01～1E+4 microSv/h

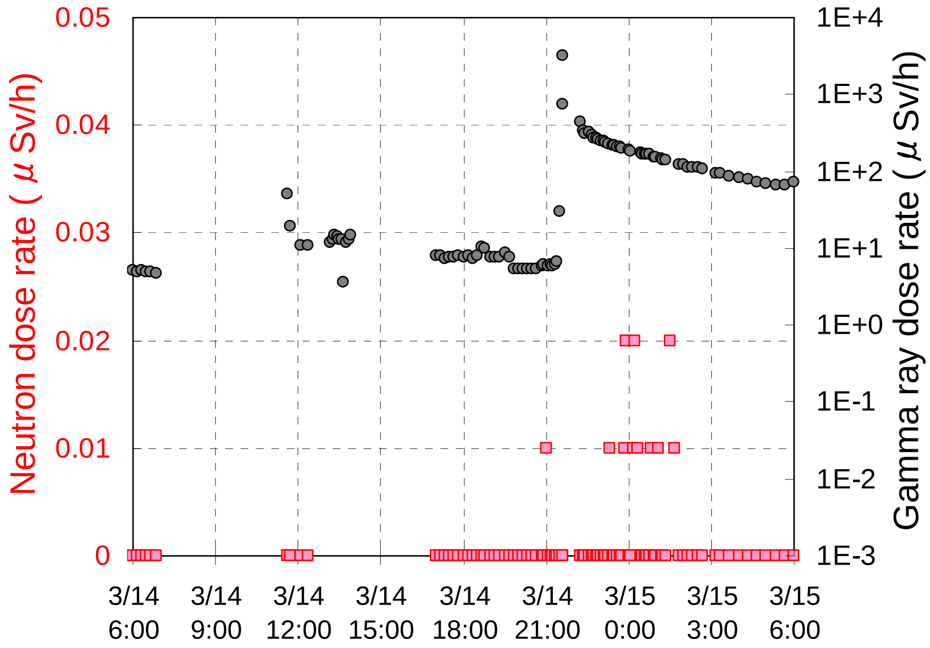
- We began the neutron monitoring from ca. 20:30 March 11. Neutrons were detected during the **two periods only**
- Measured value 0.02 μSv/h (corresponding about 2cpm) is judged to be **not noise but actual neutron signal** from the survey meter spec. such as the gamma ray sensitivity and background signal level

9. The timing to detect neutrons

First period to detect in the morning on March 13

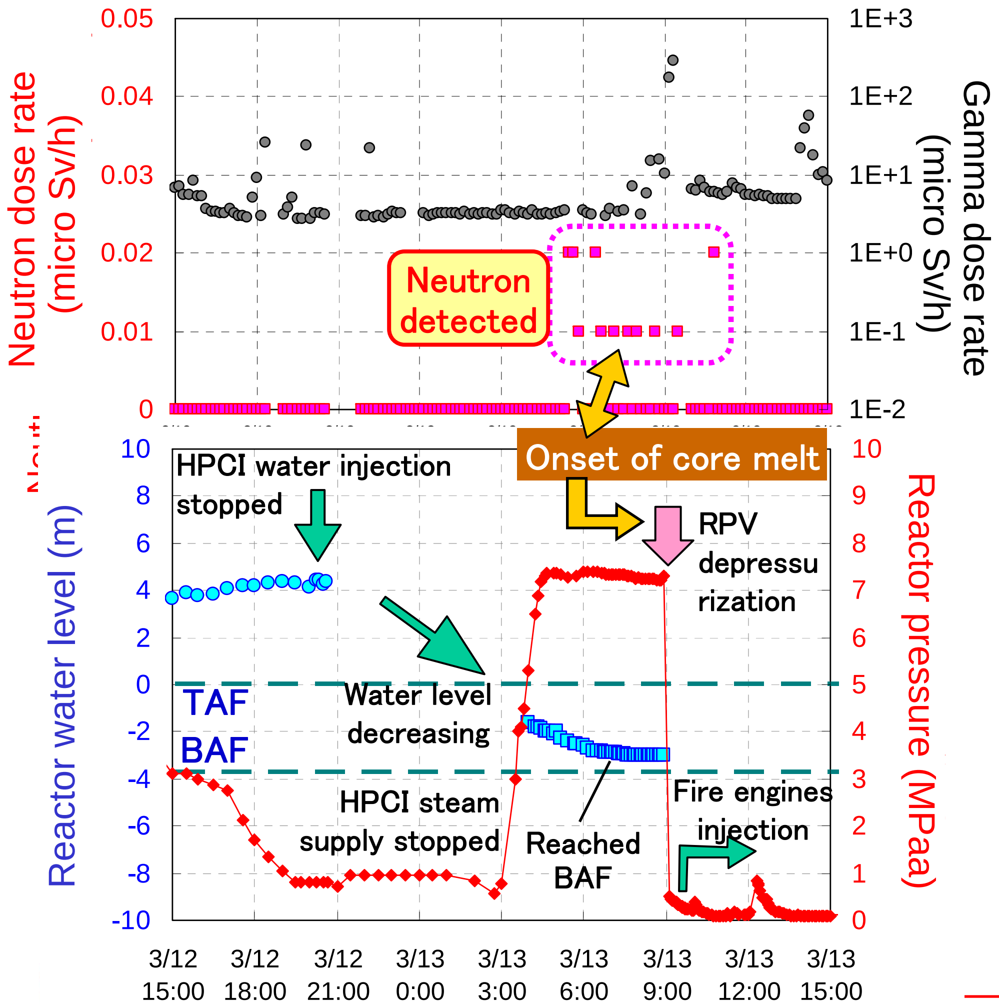


Second period to detect in the midnight on March 14

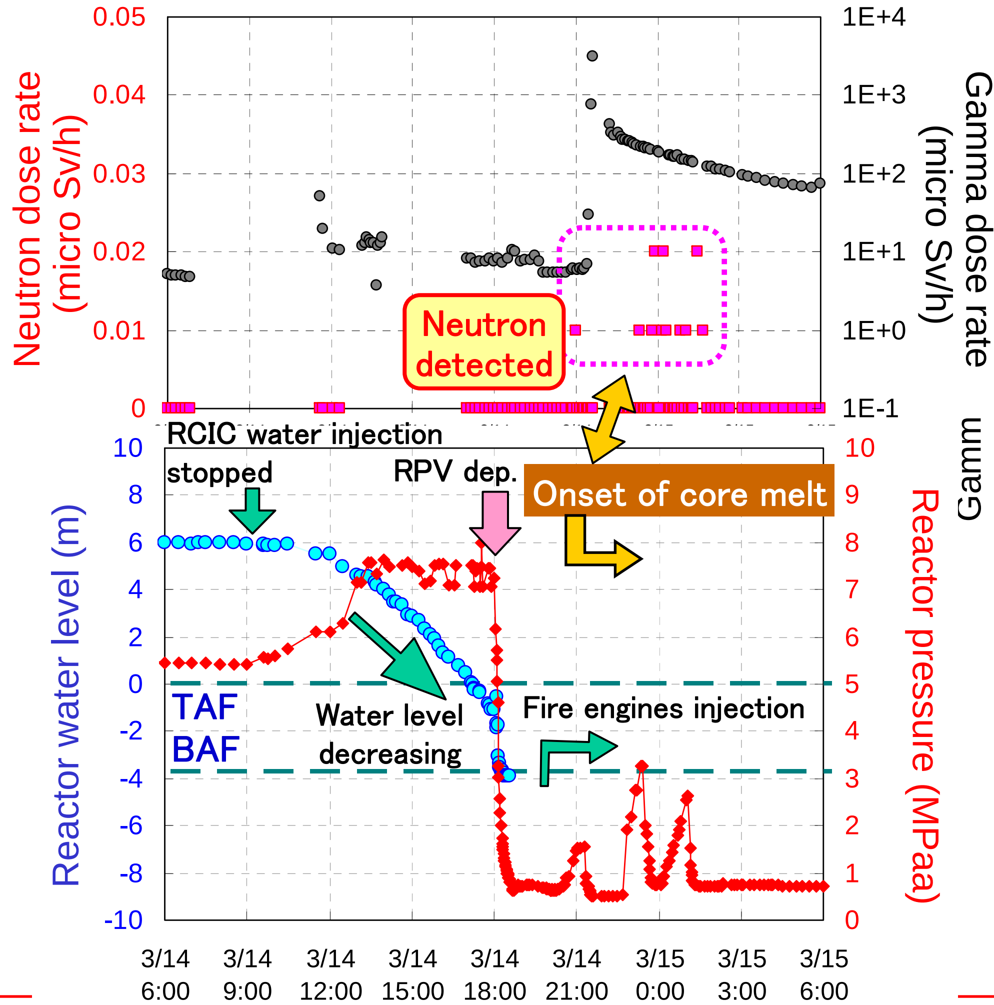


9. The timing to detect neutrons

First period to detect in the morning on March 13 coincides with the onset of core melt at Unit-3

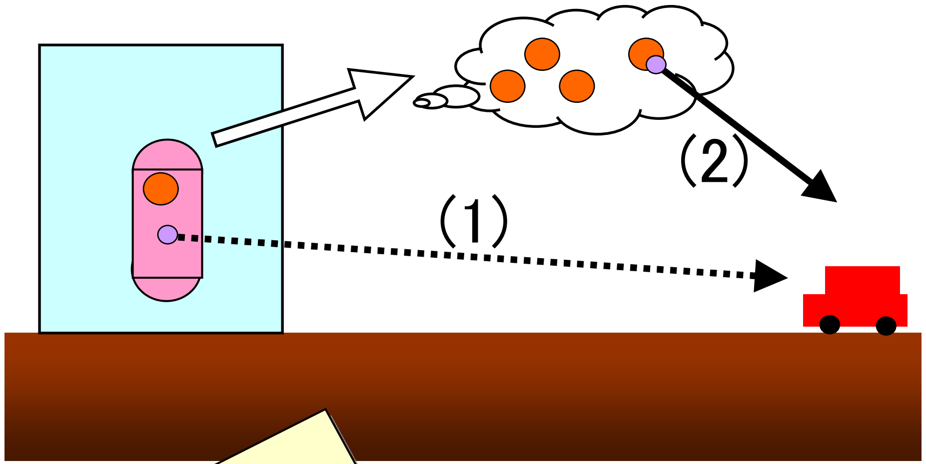


Second period to detect in the midnight on March 14 coincides with the onset of core melt at Unit-2



9. Origin of measured neutrons

The neutrons observed near the main gate were released in the course of fuel melting at Units 2 and 3, and may have been generated by the spontaneous nuclear fission of actinides.



The concentration in soil sampled in the power station's premises was similar to that preceding the accident. However, based on the detection of actinides with relatively short half-life, such as Cm-242 and Cm-244, we believe these may have been originated in the Fukushima Daiichi NPS accident.

Neutrons on route (1) inside the reactor were measured directly.

✕ Unlikely due to shielding

Delayed neutrons on route (2)-1 deriving from the collapse of discharged fission products (Br-87, etc.) were measured.

✕ Because of their short half-life, by this time delayed neutron precursors had become sufficiently decayed.

On route (2)-2, we measured neutrons deriving from the spontaneous nuclear fission of discharged actinides (Cm-242, etc.).

○
- The timing coincided with that of fuel melting.
- Possible given the detection of actinides in sampled soil thought to come from the Fukushima Daiichi NPS accident.

(we also estimate the Xe detected in gas within the PCV to have derived from spontaneous nuclear fission by Cm).

10. Summary

- Unit 1 was lost the cooling just after tsunami arrival. Therefore, accident progression was so fast.
- Unit 2 was lost the cooling due to loss of function of RCIC. However, unit 2 RCIC continued the cooling more than 70hr without AC and DC power.
- Unit 3 was lost the cooling, not by the HPCI manual termination by operator, but by lack of driving force of HPCI before manual termination due to RPV pressure decrease.

- You can see our activities in the latest investigation report.
http://www.tepco.co.jp/en/press/corp-com/release/2014/1240140_5892.html

FINE.