# The Evaluation Status of Reactor Core Damage at Fukushima Daiichi Nuclear Power Station Units 1 to 3

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Tokyo Electric Power Company

東京電力

TEPCO

# Summary

- Regarding the reactor core status at Units 1 to 3, we announced the following analysis results:
  - Ø Concerning the Unit 1, **the fuel pellets have melted, falling to the bottom of the reactor pressure vessel (RPV)** at a relatively early stage after the tsunami hit the station. (announced on May 15.)
  - Ø As for the Units 2 and 3, even though **the (fuel) cores were partially melted**, they remained within the fuel areas and **the RPVs were not damaged**. However, if we assume the actual water levels were lower, the analysis indicates that the RPVs were damaged. (announced on May 24)
- Following the announcements, proceeding with the reactor core status evaluation, a substantial amount of data have been collected such as changes in the reactor temperature behaviors and the temperature of RPV bottom at the time of injection method and flow amount modifications including core spray system injection. **Hence we have made a comprehensive review of the reactor core damage status at Units 1 to 3**.

## 1. Evaluation status of the RPVs

1-1 MAAP analysis【Units 1 to 3】
1-2 Heat balance evaluation per water injection records【Units 1 to 3】
1-3 Heat balance evaluation per temperature models【Units 2 and 3】
1-4 Evaluation per measured water levels【Units 1 and 2】

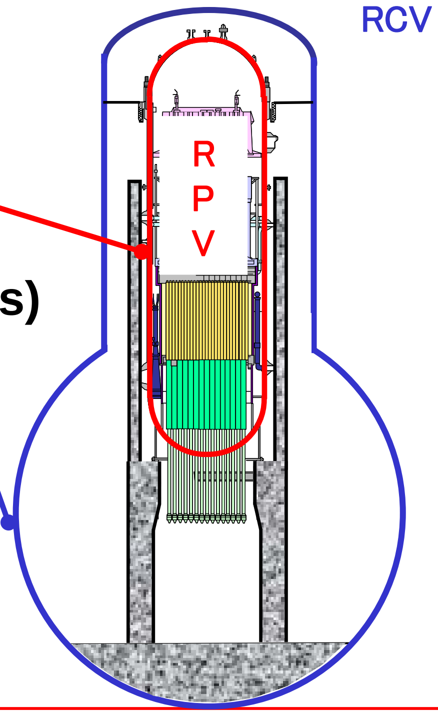
## 2. Evaluation status of the Reactor Containment Vessels (RCVs)

2-1 Gas concentration evaluation of the RCVs【Units 1 and 2】
2-2 Evaluation per Component Cooling Water System (CCWS)【Unit 1】

## 3. Evaluation status per measured temperature

3-1～3-4 Evaluation per measured temperatures【Units 1 to 3】

## 4. Summary



# 1. Evaluation status of the RPVs

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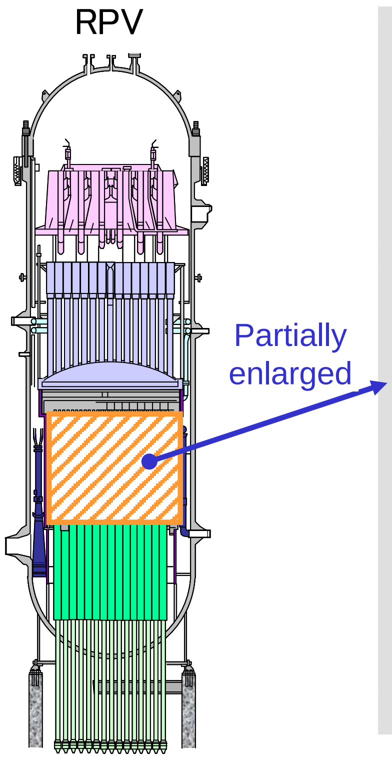
1-4 Evaluation per measured water levels【Units 1 and 2】

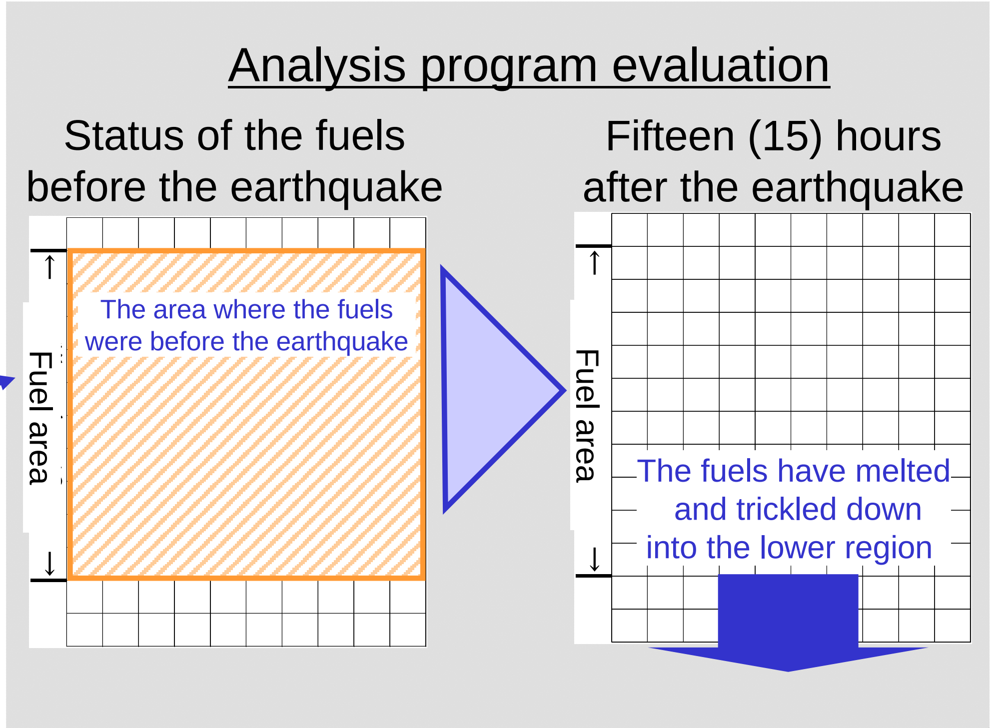
# 1-1. Evaluation status of the RPVs per analysis program (Unit 1)

Unit 1

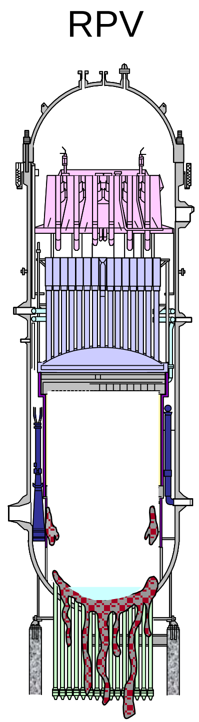
- **<u>As a result of the analysis, all the fuels have melted and trickled down into the lower region from the original position before the earthquake.</u>**
- **<u>Due to the fuel damage, it is highly possible that the RPV was also damaged.</u>**

Before the earthquake



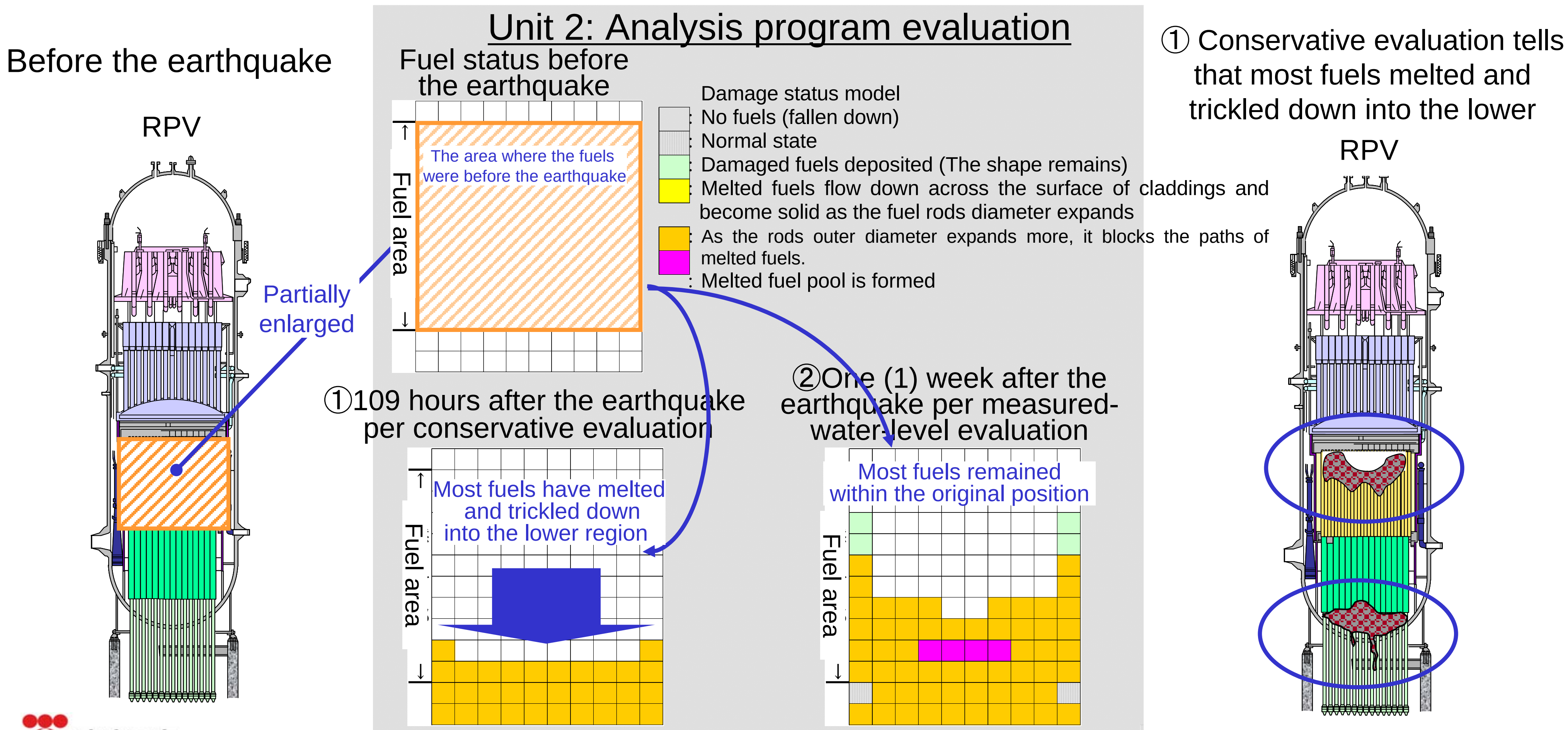

The fuels melted and trickled down into the lower region



# 1-1. Evaluation status of the RPVs per analysis program (Units 2 & 3)

Unit 2/3

- **<u>A conservative evaluation considering the uncertainty of water level gauge</u>** tells that **<u>most of the fuels have melted and trickled down into the lower region of the RPV.</u>**
- **<u>An evaluation per measured water levels</u>** shows that although the fuels were damaged, **<u>most of them remained within the original position at RPV</u>**.



# 【Reference】What is analysis program (MAAP) ?

- The Modular Accident Analysis Program (MAAP) is an program to analyze and evaluate the status of power plant at the time of a nuclear accident.
  ※ To cross check the results, JNES owns a different program called MELCOR.
- Utilizing the events of operations (loss of AC power, RCV venting, water injection, etc.) and the plant parameters（outputs, pressure and water levels before the earthquake, etc.）, it analyzes the changes in temperature and water levels after the nuclear accident, to evaluate mainly the status of the RPVs (fuel damage, etc.)

## The information used (Unit 1)

### Plant initial condition

| Items | Reactor condition |
|---|---|
| Output before the earthquake | 1380MW |
| Pressure before the earthquake | 7.03MPa |
| Water level | Normal |
| ・<br>・<br>・ | ・<br>・<br>・ |

### Event

| |
|---|
| 14:46 The earthquake occurred |
| 14:52 Emergency condenser automatically started |
| ・ |
| 15:37 Loss of all AC power |
| ・ |
| 5:46 Fresh water injection (fire pump) started |
| 14:30 RCV venting |
| ・ |
| 14:53 Fresh water injection finished |
| 20:20 Sea water injection started |

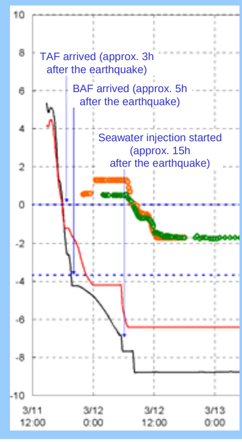
Analysis program evaluation

## Evaluation result (Unit 1)

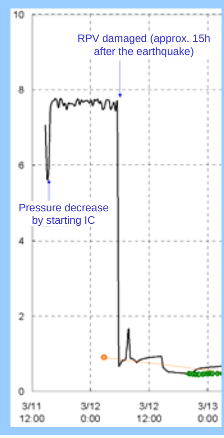
### Status of the reactor

| Items evaluated | Result |
|---|---|
| Fuel exposure started | 3 hours after the earthquake |
| Fuel damage started | 4 hours after the earthquake |
| RPV was damaged | 15 hours after the earthquake |

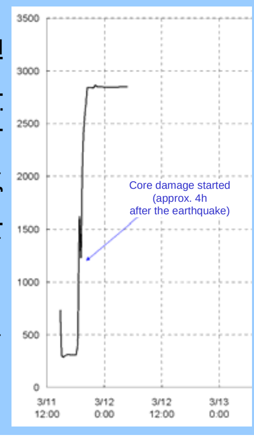
Water level




Pressure




The highest fuel temperature



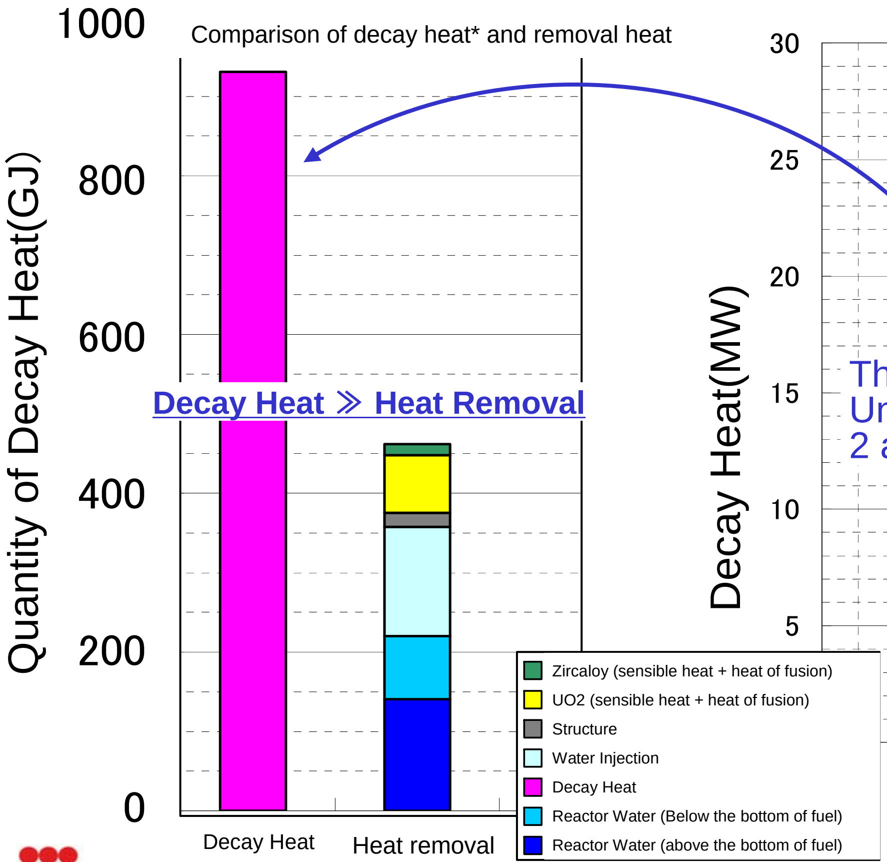
# 1-2. Reactor Situation Presumption from Heat Balance of Water Injection Work (Unit 1)

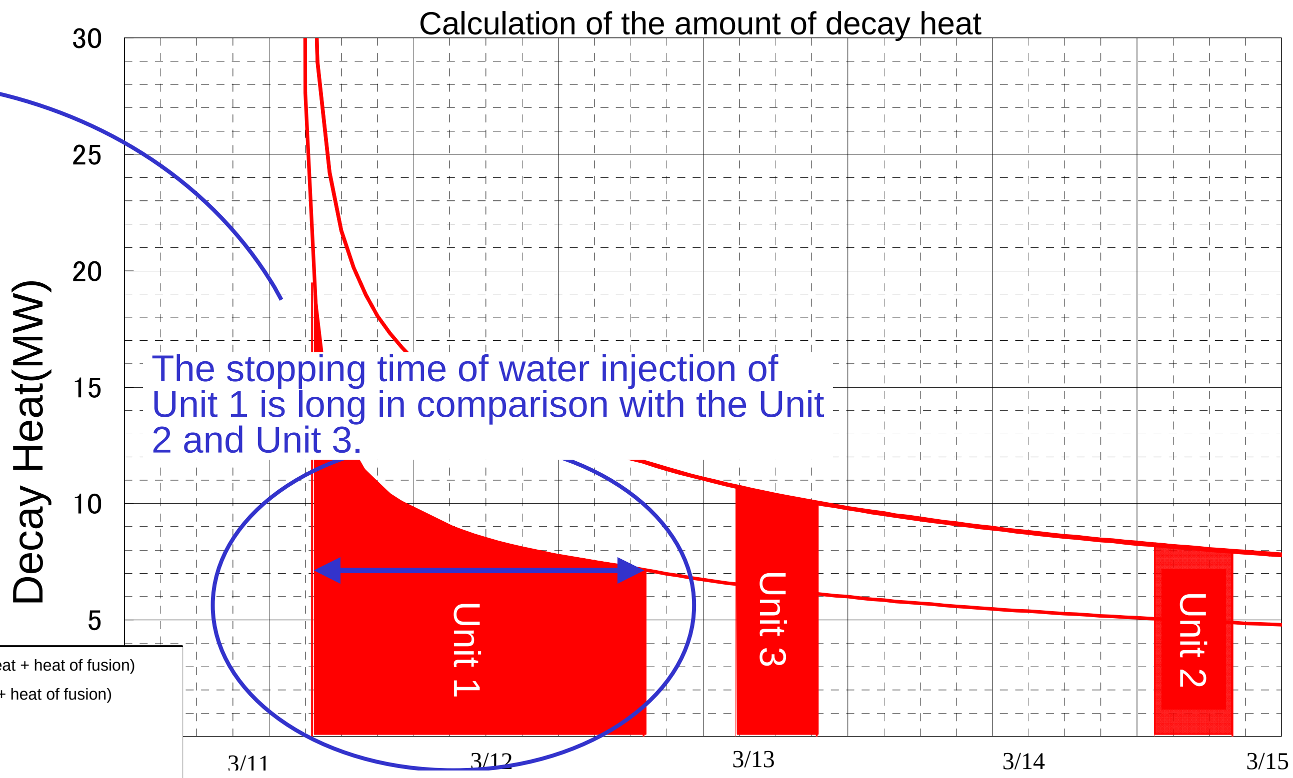
Unit 1

- In Unit 1 until the start of sea water injection, heat generated in the reactor (decay heat*), was much higher than the heat (heat removal) which absorbed by water and structures in the Reactor Pressure Vessel (RPV).

*Decay heat is the heat released as a result of radioactive decay which is the process by which radioactive material vary into the other material.

- As a result, **we presumed that the fuel melted at high temperature moved to the bottom of the RPV and the significant amount of the fuel fell out into the primary containment vessel (PCV) by destroying the RPV.**



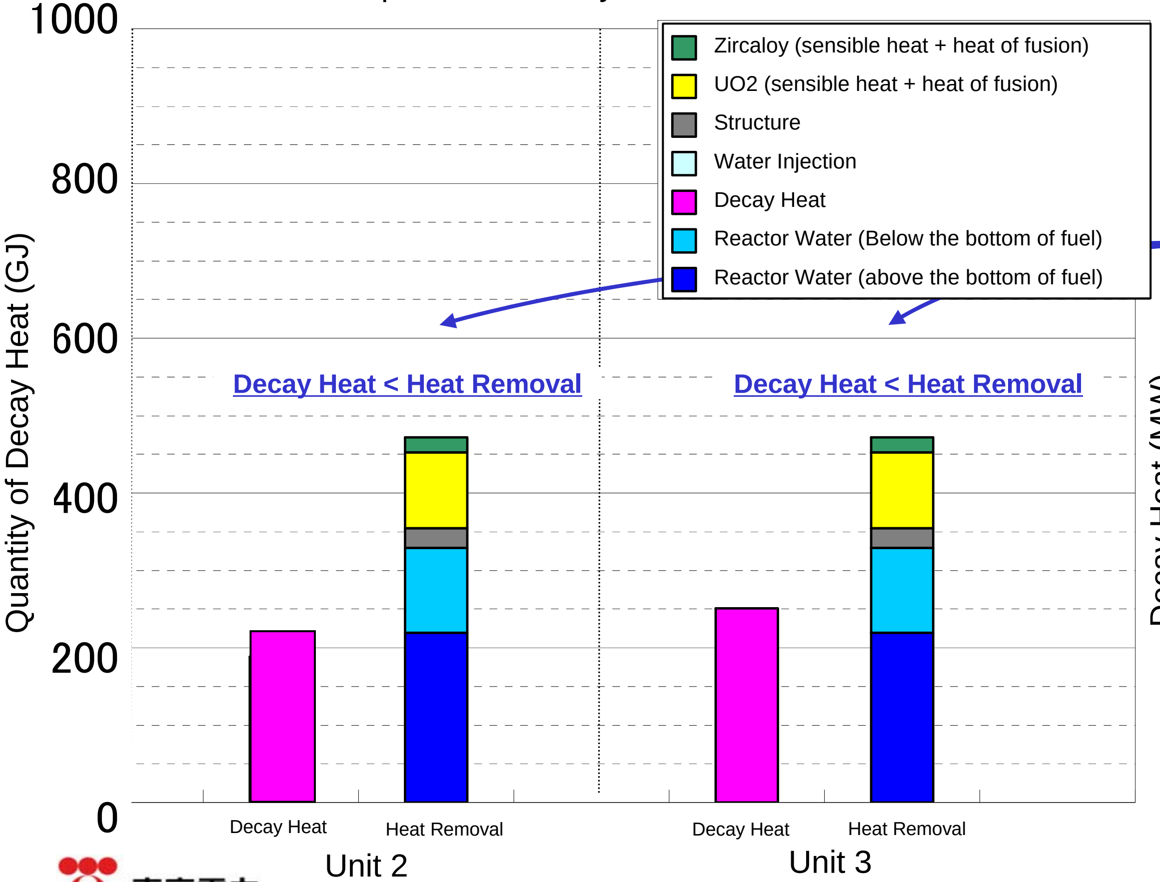

*The vertical axis is decay heat, and the horizontal axis is the time after the accident. Decay Heat x Time = Quantity of Decay Heat
In addition, the decay heat immediately after the accident is high (hot).

*Zircaloy: Fuel rod cladding (a type of metal), UO2: fuel pellets

# 1-2. Reactor Situation Presumption from Heat Balance of Water Injection Work (Units 2&3)

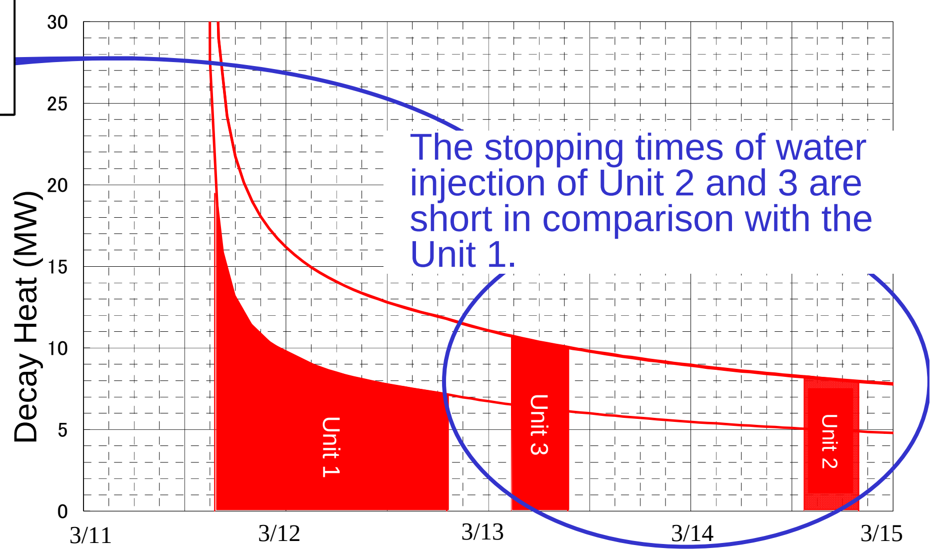
| Unit 2/3 | |
|---|---|
| Unit 2/3 | ● The decay heat during the water injection stop at Unit 2-3 was able to be absorbed by the evaporates of existing water.<br>● As a result, there was a possibility that a certain of fuel melted and moved to the bottom of the RPV, but **we presumed that the significant damage of RPV, such as large fuel fall into the bottom of the PCV, has not occurred.** |

Comparison of decay heat* and removal heat




*Zircaloy: Fuel rod cladding (a type of metal)
UO2: fuel pellets

Calculation of the amount of decay heat

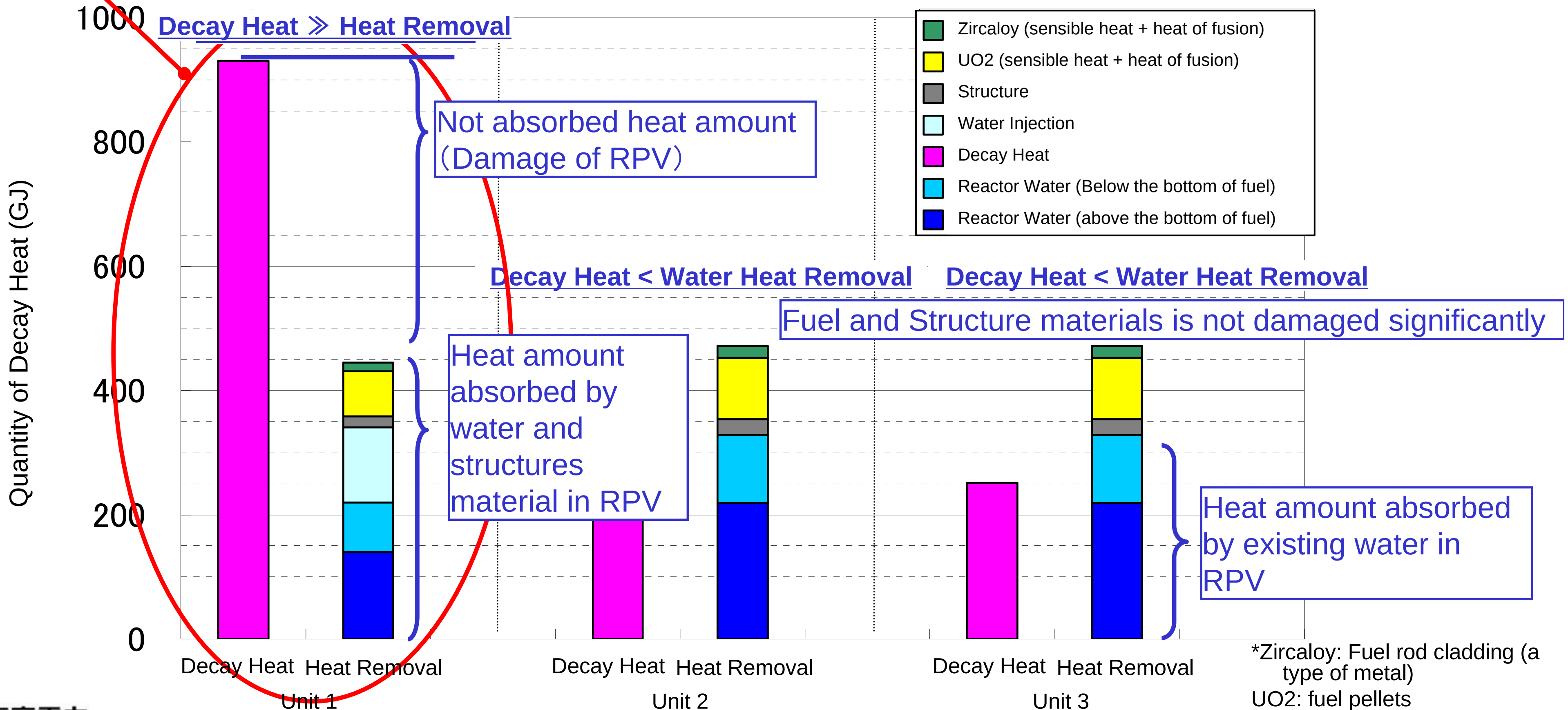



*The vertical axis is decay heat, and the horizontal axis is the time after the accident.
Quantity of Decay Heat x Time = Decay Heat
In addition, the decay heat immediately after the accident is very high (hot).

# 【Reference】Heat Balance

- We evaluated the heat balance of generated heat (decay heat) and the absorbed heat of absorption material such as water and structures.
- As of Unit 1, if decay heat was higher than heat removals (by water, vaporization, and heat absorption of structures), the structures would be melted and then the RPV would be damaged.

Comparison of decay heat and removal heat

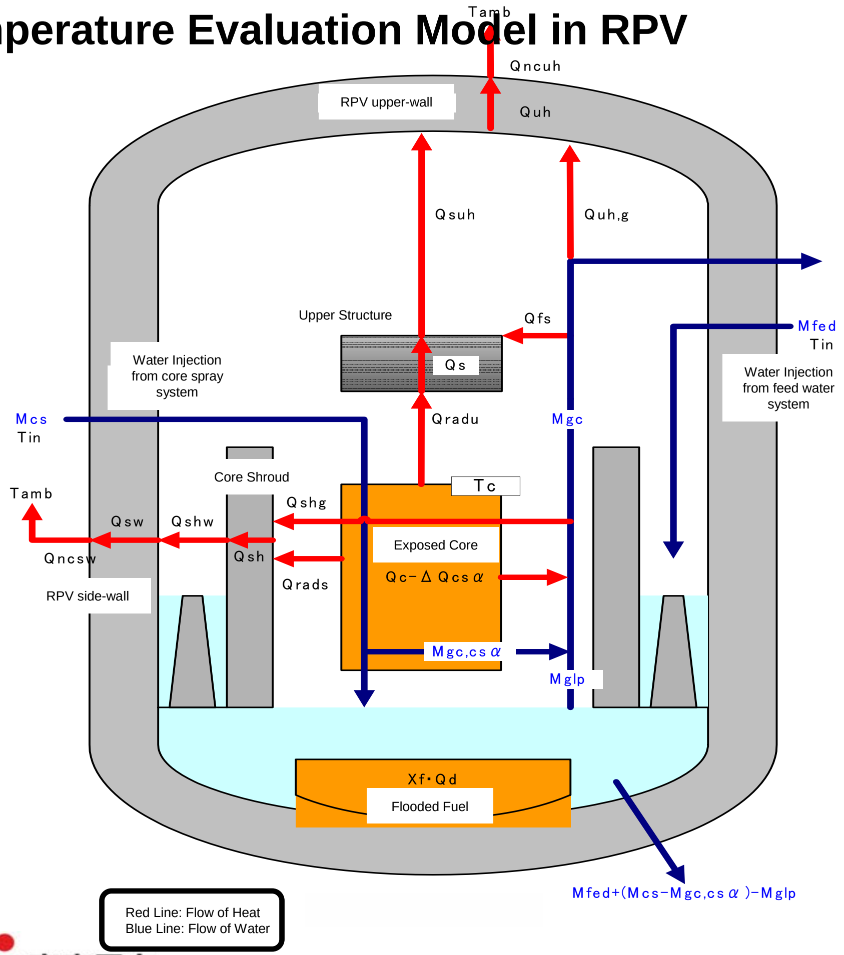



*Zircaloy: Fuel rod cladding (a type of metal)
UO2: fuel pellets

Unit 2/3

● From the result of the the fuel location presumption which reproduces the temperature distribution of RPV( as of October 10), the percentage of the exposed core is evaluated less than about 3% about Unit 2 and Unit 3. In addition, **the majority of fuel is estimated to have flooded at the bottom of RPV or in PCV.**

## Temperature Evaluation Model in RPV




### The Overview of Temperature Evaluation Model

- The water injected into the reactor is heated by **decay heat**, and flows out to the outside in the form of water or steam.
- To evaluate the consumption of the energy generated by the decay heat (heat balance)
- Forms of decay heat energy consumption are as follows
  - water temperature rise
  - water vaporization
  - steam temperature rise
  - fuel temperature rise
  - structural material temperature rise

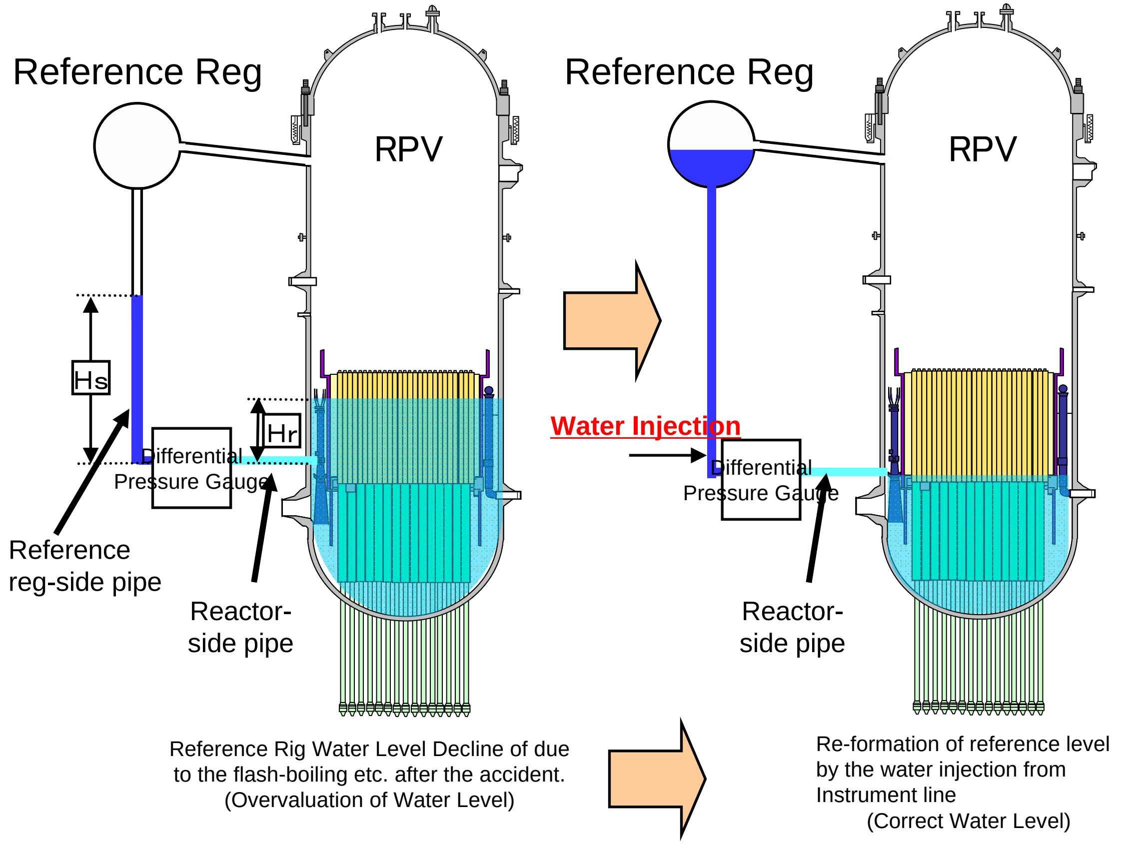
# 1-4. Situation Presumption inside RPV from Indicated values of water level gauges (Units 1&2)

**Unit 1/2**

- Because the both water level of Unit 1 and Unit 2 is not at the original fuel position as a result of calibration of reactor water level gauges, **there is not little possibility that fuel is at the original location and keeps original shapes.** Meanwhile, about unit 2, **we presumed that the fuel (heat source) is likely to exist near the reactor-side pipe**.

- Unit 1
  - On May 11, we conducted the RPV water gauge calibration by water injection to the reference leg.
  - RPV water gauge indicated less than -5m from the top of active fuel.
- Unit 2
  - On June 22 and October 21, we conducted water injection to the reference leg and On June 22 and October 21, we conducted water injection to the reference leg and filled the RPV water level gauge with water.
  - we presumed that the water level is less than -5m from the top of active fuel from temporary pressure gauge indication.
  - On June 22, The water of pipes at the both RPV-side and reference reg-side evaporated in a short time.
    In addition, On October 21, The water of pipes in RPV-side evaporated slowly.
- Unit 3
  - Because of the high dose of the location of the instrumentation, calibration of the RPV water level gauge is still not done.

* The water level in the reactor is measured by the pressure difference between the water head of RPV and reference rig. In addition, the water level is indicated higher than real water level if the water level of reference rig is low.




Calibration of RPV Water Level Gauge (Image)

# 2. Evaluation of state inside the Primary Containment Vessel

2-1 Estimation by the gas concentration in the Primary Containment Vessel 【Unit 1, 2】

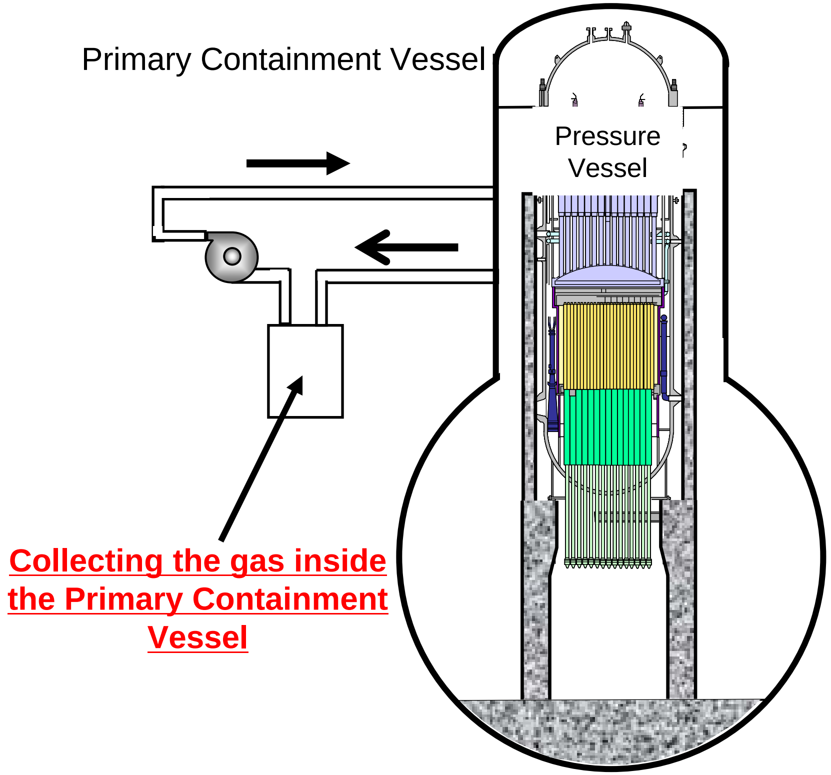
2-2 Estimation by Reactor Cooling Water system 【Unit 1】

# 2-1. Estimation from the gas radioactivity concentration inside the Primary Containment Vessel (Unit 1,2)

Unit 1/2

- After extracting gas inside the Primary Containment Vessel and measuring radioactivity concentration, we estimate that Cs-134,Cs-137 concentration is higher in Unit 1 which is estimated damaged than Unit2 ,and the amount of fuel which is dropped to the Primary Containment Vessel from the Pressure Vessel is much.

- Unit 1
  - At September 14, we extracted gas inside the Primary Containment Vessel and measured radioactivity concentration.
  - Cs-134 and Cs-137 is detected, but I-131 is below measurable limit.
- Unit 2
  - At September 9, we extracted gas inside the Primary Containment Vessel and measured radioactivity concentration.
  - Cs-134,Cs-137,Kr-85,Xe-131m is detected, but I-131 is below measurable limit.
- Unit ３
  - We have not measured radioactivity concentration because the suitable sampling line is not found.

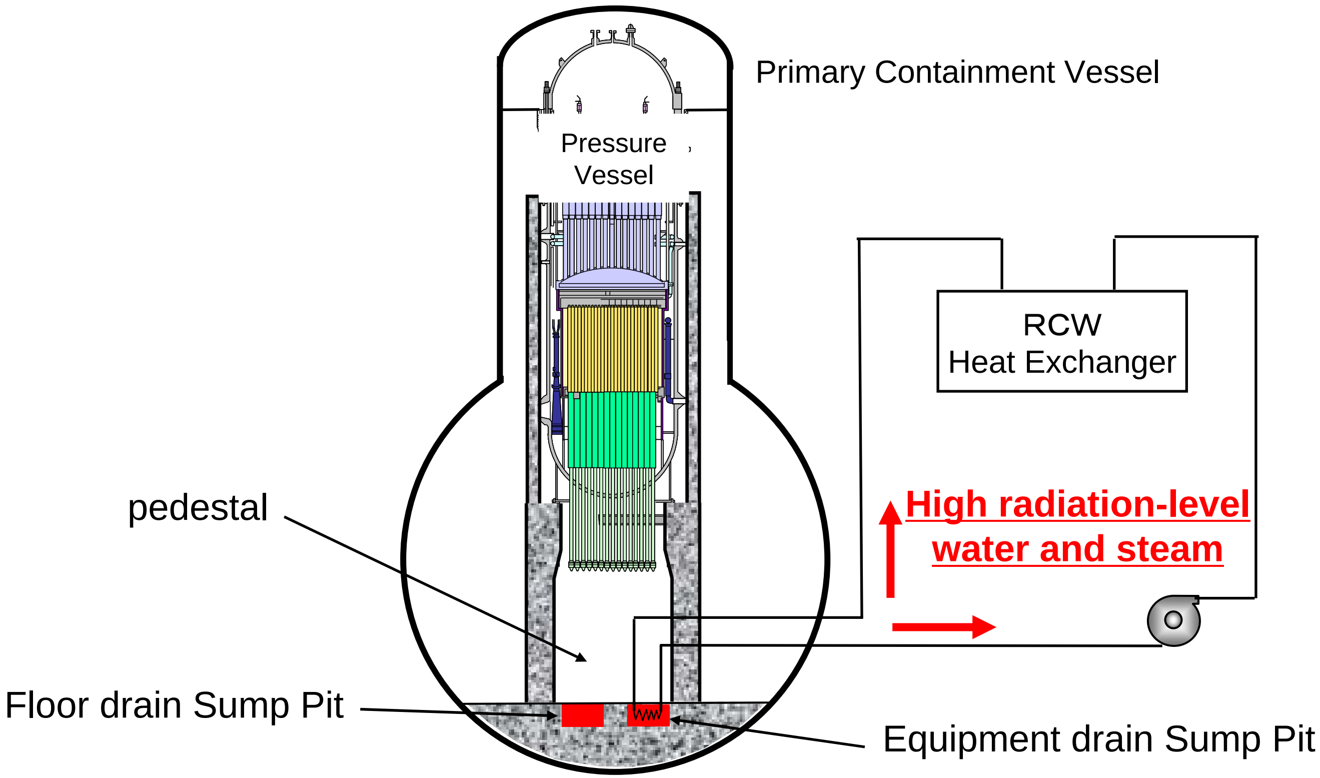



**Collecting the gas inside the PCV（image）**

## 2-2. Estimation the state inside the Primary Containment Vessel by the state of Reactor Cooling Water system (Unit 1)

Unit 1

- We have measured high exposure dose (220-260mSv/h) in May 5 at RCW lines located the north-east side of 1 floor in Reactor Building, and when the high temperature fuel which dropped from the pressure vessel falls into the Primary Containment Vessel, It is equal with the possibility that the high radiation–level water and steam including radioactive material will induct into the pipe due to damage the RCW-pipes for cooling that is laid into sampling pit of equipment drainage under the pedestal.
- On the other hand, there is the possibility that contributed to cooling of the molten fuel because water in the pipes induct into the Primary Containment Vessel by damage of RCW pipes.

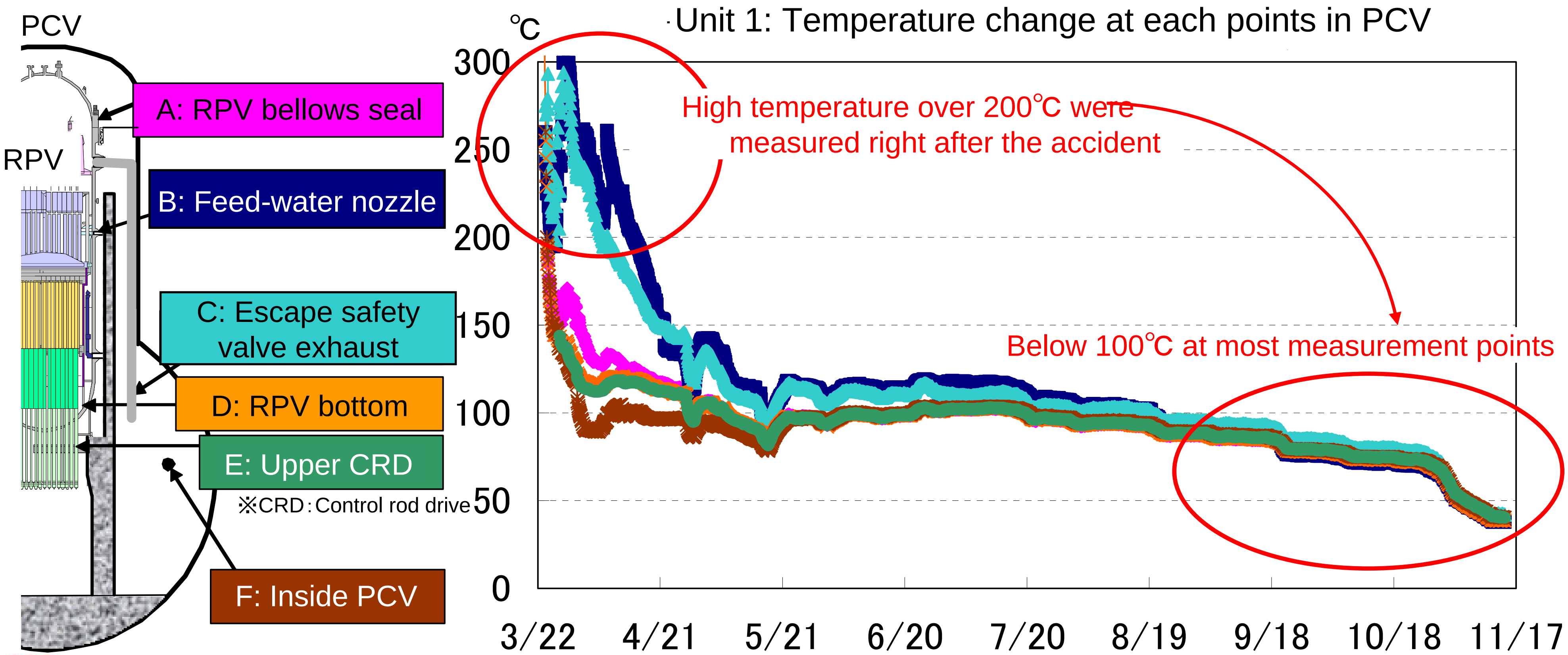


# 3. Current evaluation by Temperature indicator's data

3-1～3-4 Evaluation by temperature indicator's data
【Unit 1, 2, 3】

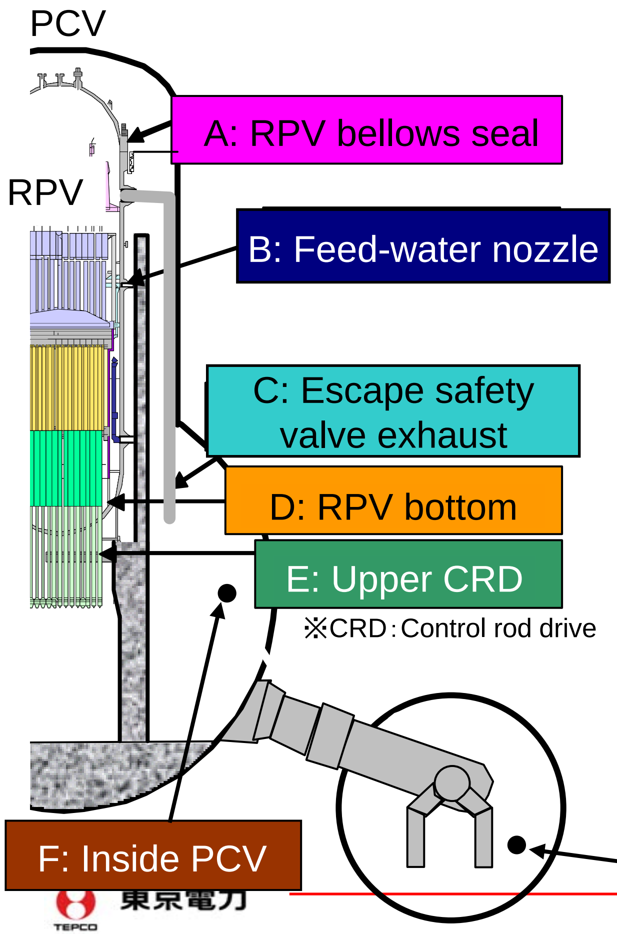
# 3-1. Confirmation of Estimation from Measured Temperature and Evaluation of Current Situation -1 (Unit 1)

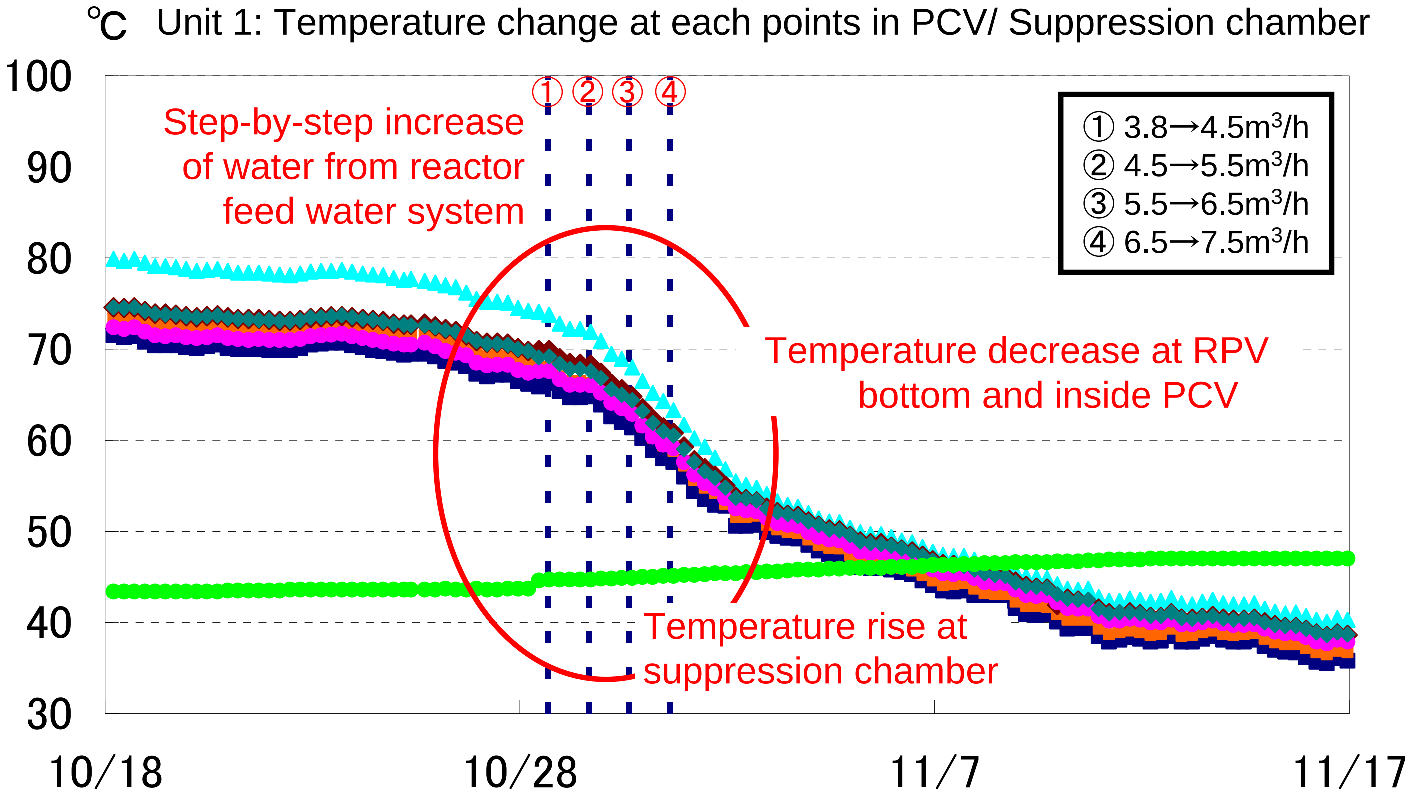
- High temperatures were measured right after the accident, but temperatures were decreased below 100 degrees at the most of the measurement points after August.
  - Currently, it is evaluated that **they are well cooled down, including the fuel dropped on the bottom of the reactor.**



# 3-2. Confirmation of Estimation from Measured Temperature and Evaluation of Current Situation -2 (Unit 1)

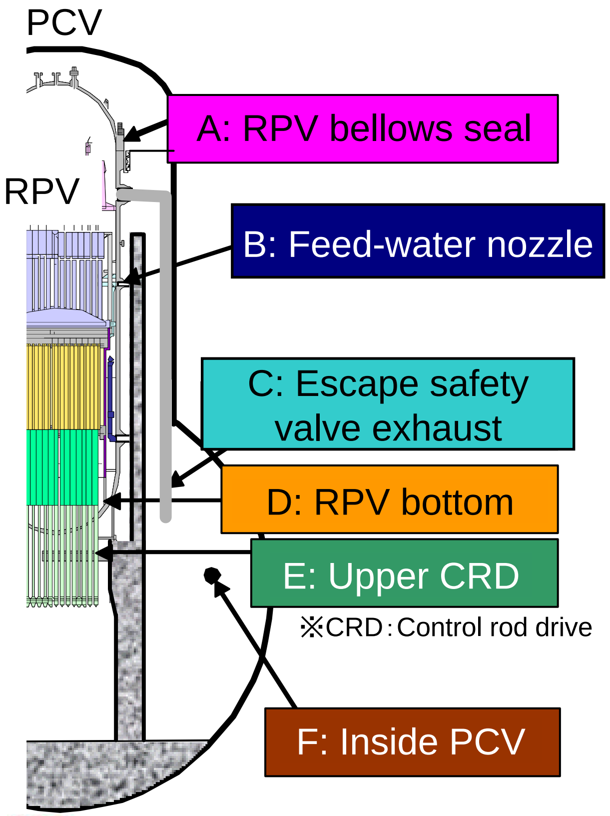
- Along with the increase of water injection from reactor feed water system on October 28, **temperature of suppression chamber rose**, with **temperature decrease at RPV bottom and inside PCV.**
  - Along with temperature decrease, since steam amount decreased, amount of hot water increase to cool fuel, and the temperature of suppression chamber rise due to the hot water flow-in
- From the trend of temperature change, it is estimated that **the injected water contributed to cool melted fuel.**

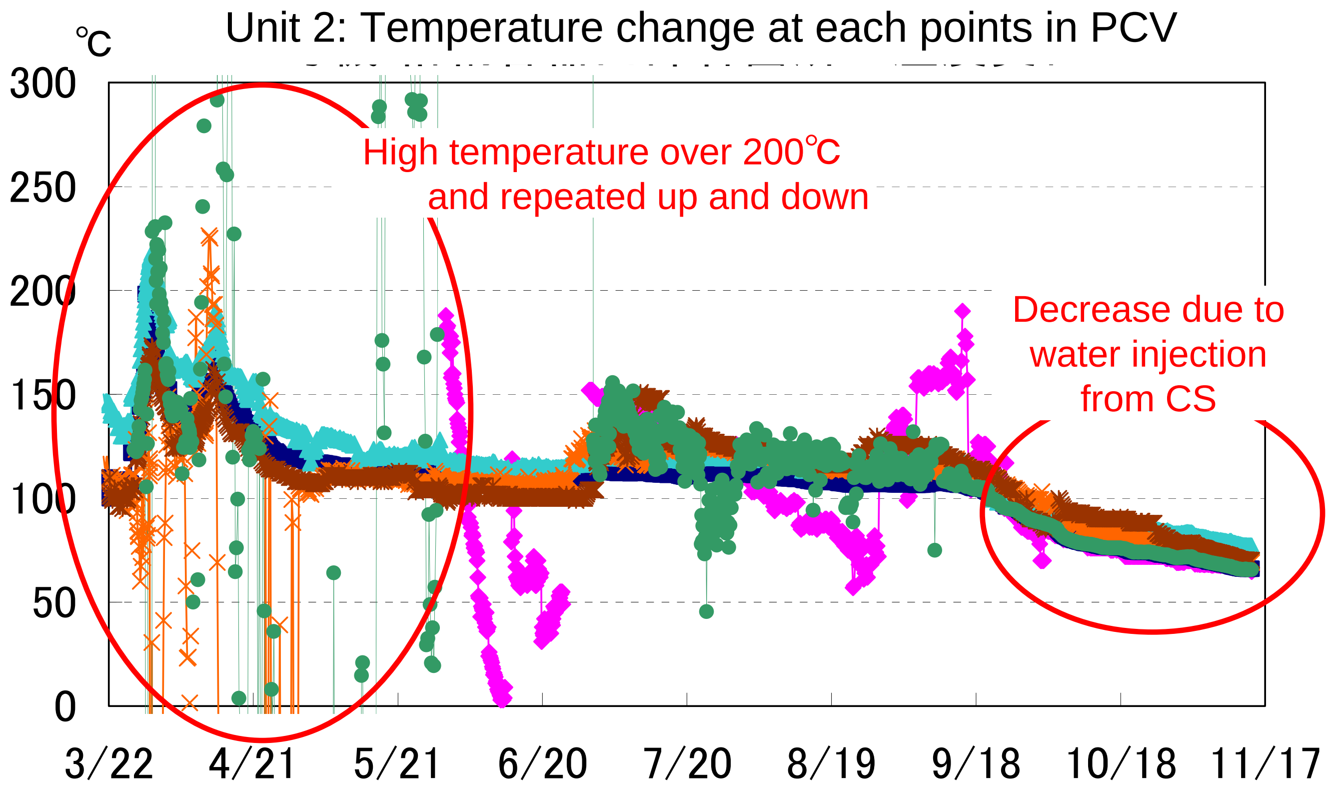


# 3-3. Confirmation of Estimation from Measured Temperature and Evaluation of Current Situation (Unit 2)

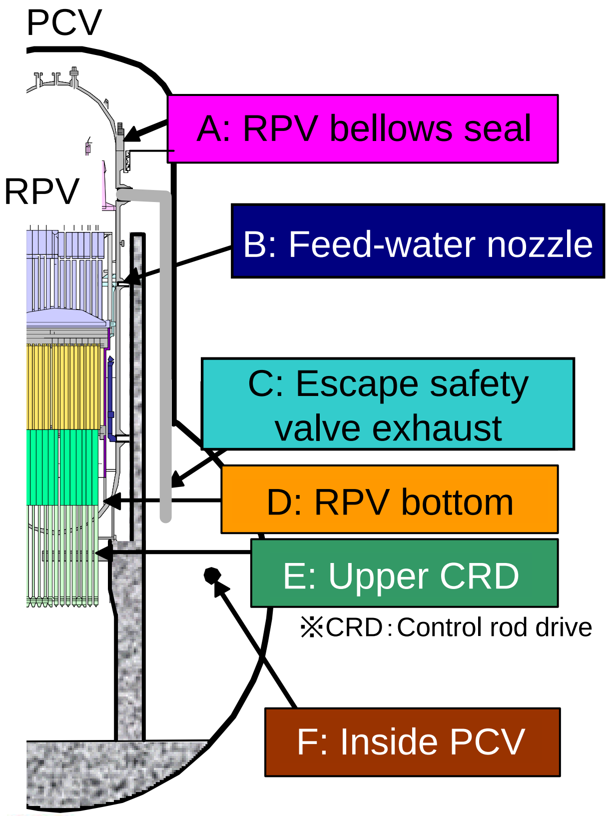
- High temperatures over 200 degrees with repeated up and down were measured at end of May, but **temperatures were decreased below 100 degrees at the most of the measurement points, after the water injection from core spray water system (CS) on September 14**, which can inject water directly from upward of the center of RPV, in addition to the reactor water feed system.
  - **Since most of the fuel is left in RPV** (little fuel is dropped on the bottom of PCV), it is evaluated that **the fuel is cooled sufficiently**.

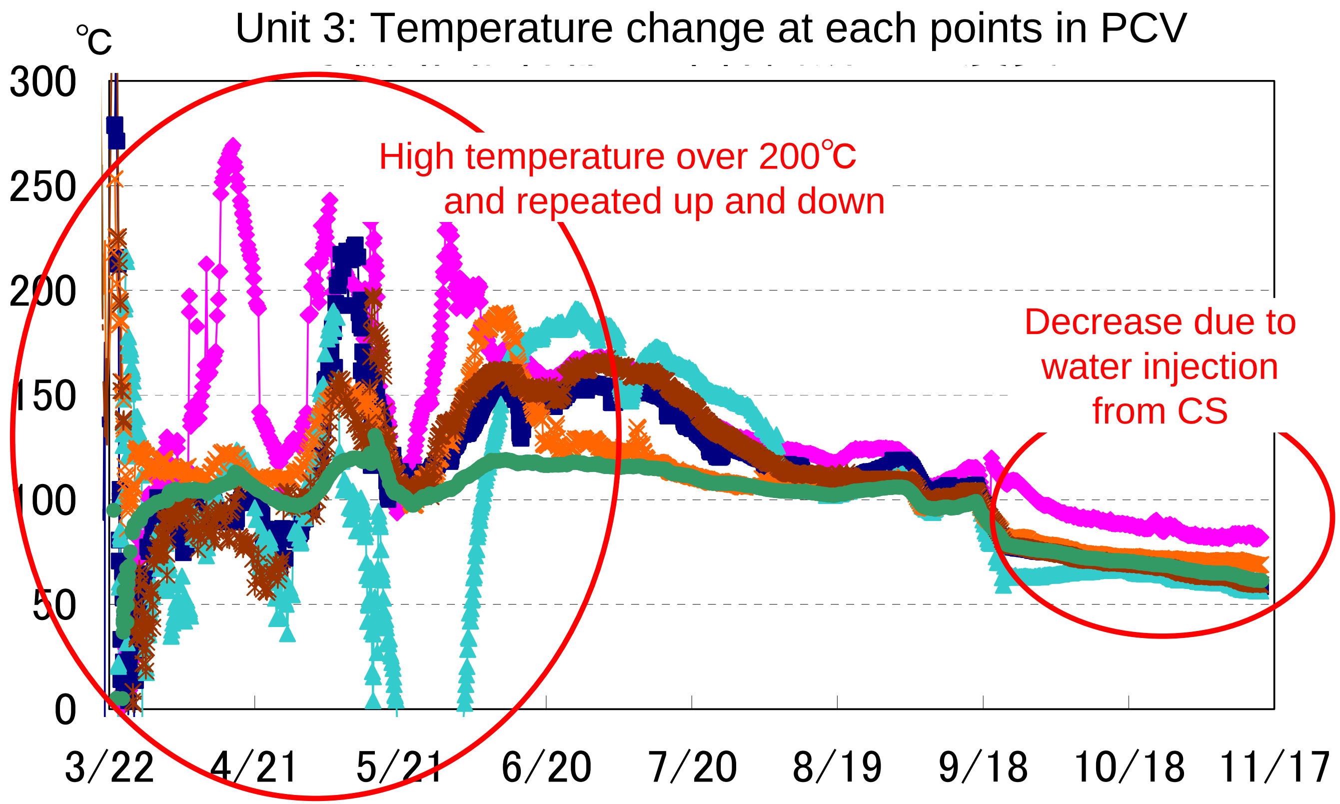


# 3-4. Confirmation of Estimation from Measured Temperature and Evaluation of Current Situation (Unit 3)

- High temperatures over 200 degrees with repeated up and down were measured at end of June, but temperatures were decreased below 100 degrees at the most of the measurement points, after the water injection from core spray water system (CS) on September 1, which can inject water directly from upward of the center of RPV, in addition to the reactor water feed system.
  - **Since most of the fuel is left in RPV** (little fuel is dropped on the bottom of PCV), it is evaluated that **the fuel is cooled sufficiently**.



# 4. Summary

# 4-1. Summary of the status of damaged fuel in Unit 1 ①

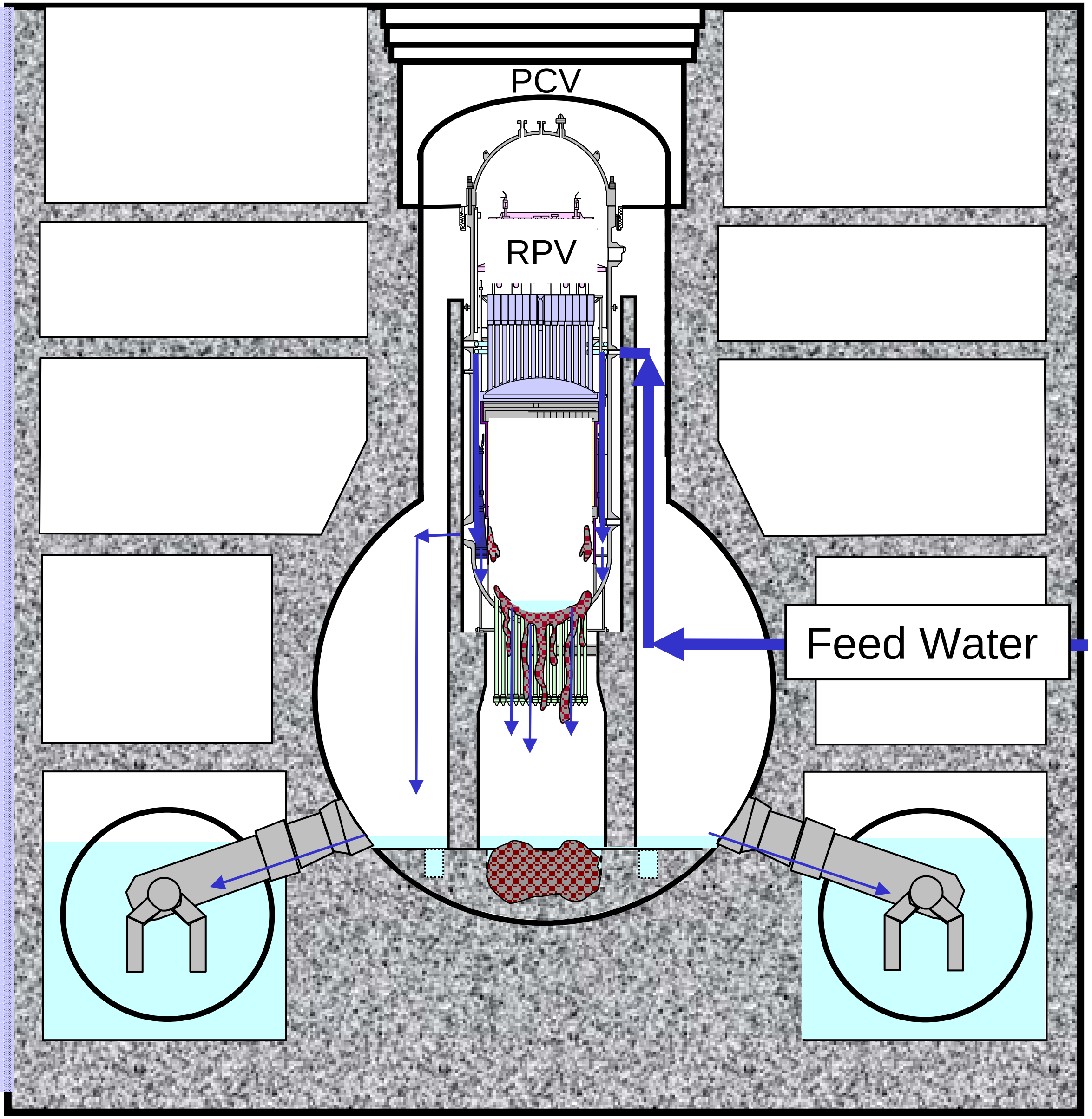
- **All fuel melted through PCV from original position.**

  [as per MAAP analysis]

- Further, **it is likely that the PRV was damaged so that considerable amount of fuel was assumed to be melted down to the bottom of PCV.**

  [Assumed from indicated level of water level gauge]
  [Assumed from heat balance based on the water injection record]
  [Assumed from gas concentration in PCV]
  [Assumed from Reactor Auxiliary Machine Cooling System]
  [Evaluation of indicated value of thermometer] etc.

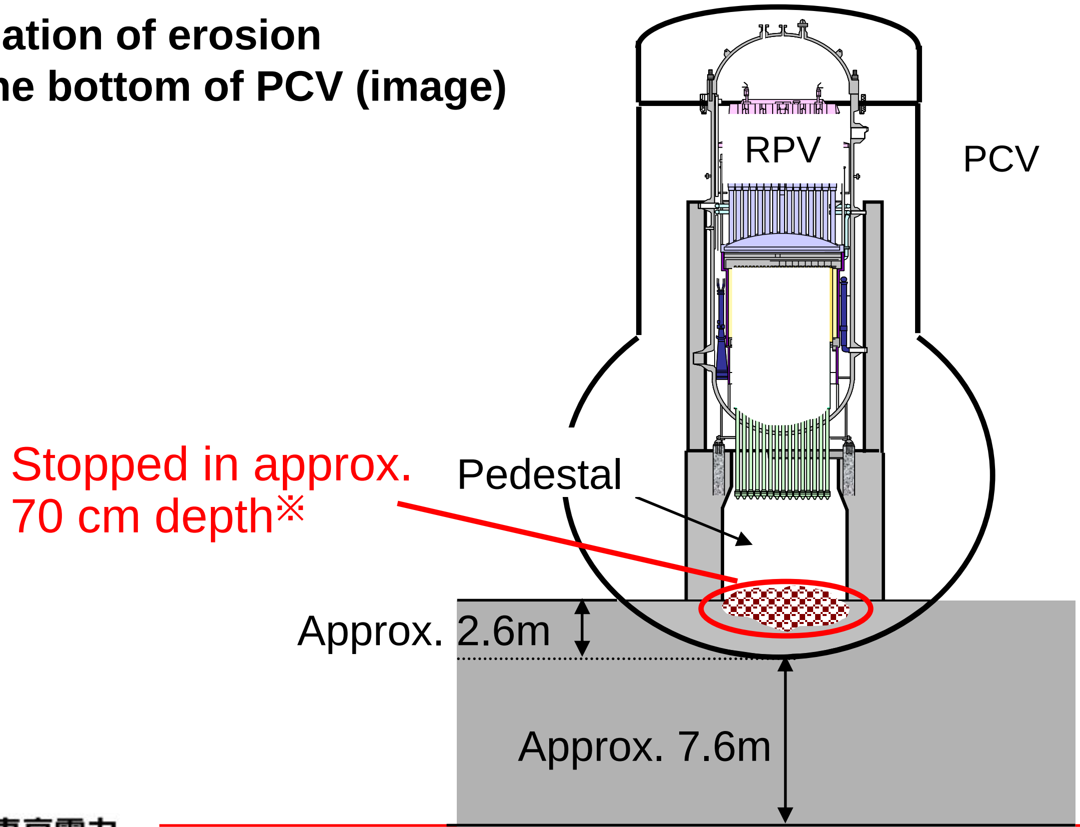
- Currently, water injection is continued through Feed Water Line so that the temperature at the bottom of RPV and inside of PCV is stabilized below 100 oC.
- Therefore, it is evaluated that **the fuel melted down to the PCV is substantially cooled down by injected water.**



# 4-2. Summary of the status of damaged fuel in Unit 1 ②

- It is likely that considerable amount of fuel melted through PRV to the bottom of PCV erodes concrete at the bottom of PCV. According to the evaluation for erosion of core concrete reaction in Unit 1 by analysis code (MAPP) under the practical conditions, it was resulted that **the erosion by melted fuel would be stopped in approx. 70cm depth.**
- In addition, **according to the gas sampling result in PCV, the gas caused by core concrete reaction is currently not detected. Therefore, it is estimated it is highly unlikely that the core concrete reaction still goes on.**

**Situation of erosion at the bottom of PCV (image)**



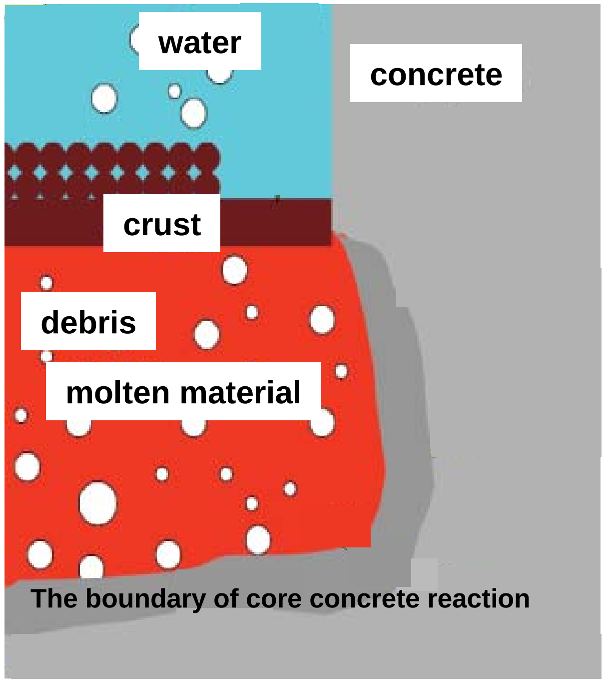

**Evaluation Condition**

- Heaping condition
  - Fuel debris melted down inside the pedestal would be spread over the dry-well floor (outside the pedestal) through slits (notches around cylindrical pedestal).
  - Certain amount of fuel debris would be heaped up on the equipment sump and floor sump at the pedestal.
- Decay heat
  - Volatile fission products are not be considered as the products would be already volatilized at the core concrete reaction.

# [Reference] Core concrete reaction

- It occurs when the damaged fuel (debris) with high temperature (more than a melting point of the concrete) fall to PCV and contact with the concrete of the PCV bottom (the phenomenon that debris dissolves the concrete)
- The decay heat of the heat source of debris decreases monotonously in times. In addition, the areas that concrete and debris come in contact increase (the amount of heat removal increase) as the reaction advances, the erosion of the concrete is restrictive.
- As of the following points, it is hard to estimate the concrete erosion depth correctly.
  - ➢ A shape of debris at the bottom of PCV (If it is flat, the effect of heat removal is big and the concrete reaction is easy to stop) is unidentified.
  - ➢ There are various opinions for the progress of the core concrete reaction※
    - ✓ Opinion that water does not arrive at the lower debris by making solidification (crust) that the upper part of debris is performed water cooling and a core concrete reaction progresses.
    - ✓ Opinion that the gas made by the core concrete reaction destroys the crust and flowing water into the debris layer cool them and stops a reaction.
    - ✓ Opinion that the gas made by the core concrete reaction which do not destroy crust, and is generated activates heat transfer in the debris, and a reaction progresses

The image of core concrete reaction




※Recognize one of the point of issue in WS

# 4-3. Summary of the status of PCV（Unit 2 and 3）

- **Even though the fuel was damaged and melted , a part of the fuel remains inside the core of RPV and the others dropped to the bottom of RPV plenum or the PCV pedestal.**

[Assumed from indicated level of water level gauge]

[Assumed from heat balance based on the water injection record]

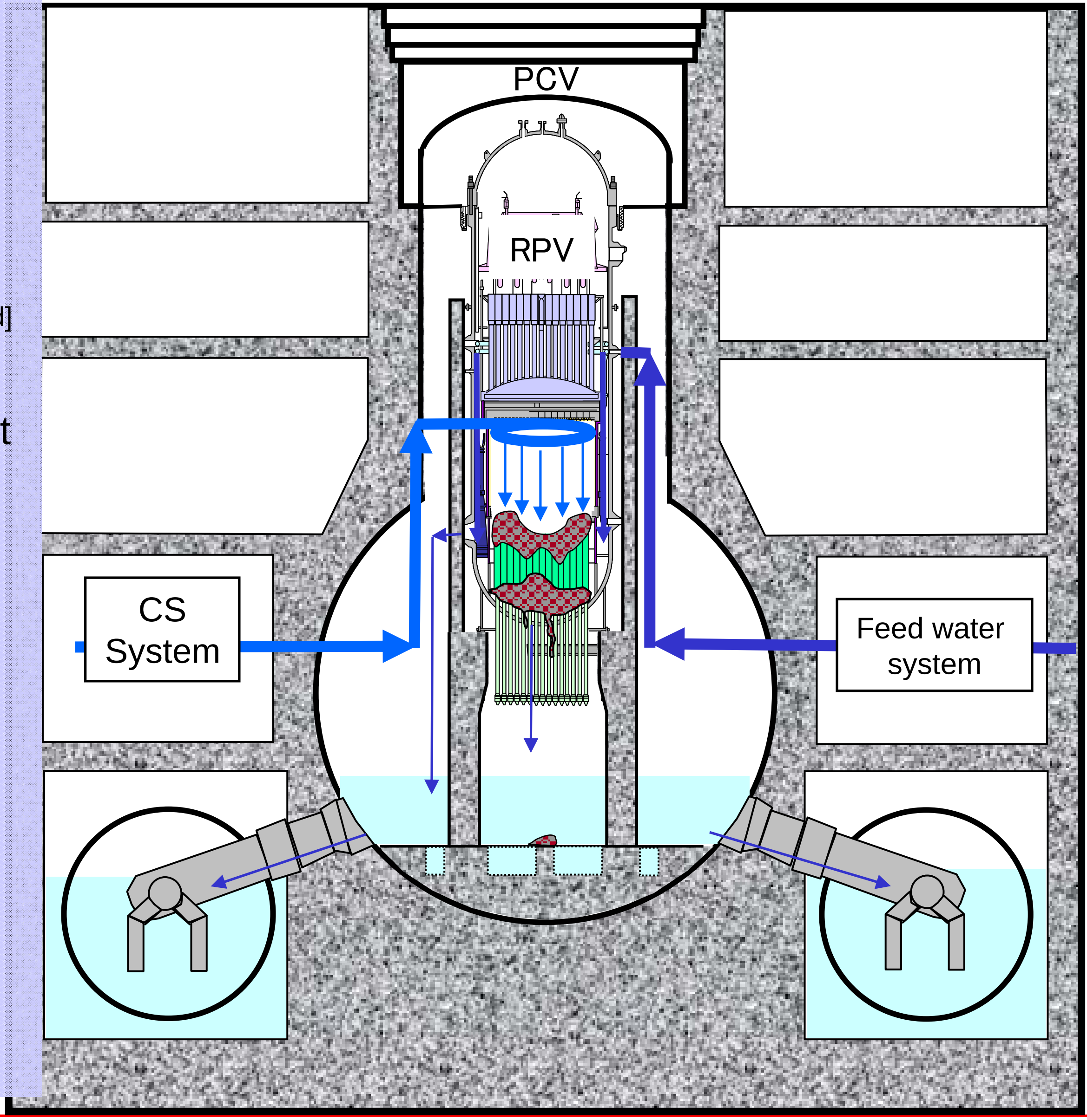
[Evaluation of indicated value of thermometer] etc.

- There is a range in the evaluation result from “damaged fuel dropped to part of the bottom of PCV” to “Almost all the fuel is left inside RPV”.

[Analysis by MAAP]

- Currently, water injection is conducted through the feed water system and CS system. The temperature in some points of PCV remain stable below 100℃.

- Therefore, it is evaluated that **all the moved fuel is expected to be cooled directly by water injection**.



# Reference

# [Reference] Confirmation of cooling condition from Unit 1 local situation

Comparison of the situation at the penetration part of 1st floor in Unit 1


Generated steam (photo taken on Jun. 3)


No generated steam (photo taken on Oct. 13)

Generated steam at the penetration part of 1st floor,
which had been observed on Jun. 3, was not observed on Oct. 13.

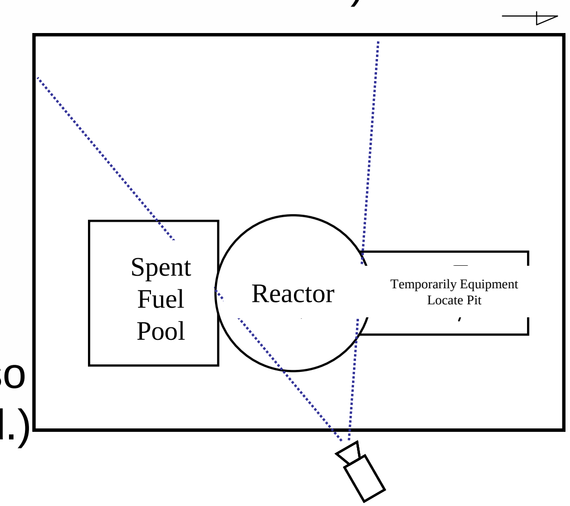
<u>Steam generation would be stopped, or a small quantity of steam would be generated but condensed (cooled) before leaking to the building.</u>

# [Reference] Confirmation of cooling condition from Unit 2 local situation

Condition of the directly above the reactor at 5th floor : Generated steam (photo taken on Sep. 17)

Condition of the directly above the reactor at 5th floor : **Non** Generated steam (photo taken on Oct. 20)

- **Generated steam** was not verified on Oct. 20 though it was verified on **Sep. 17**. Also, paint at overhead crane drastically came off on **Oct. 20** and it indicates the **dry environment** there (This event occurs when adhesibility of paint becomes weaken caused by high humidity and then atmosphere becomes dry)




Generated steam does not eject or does eject but very small amount and so it is condensed before it leaked to reactor building (Inside of PCV is cooled.)

## Thermal Monitor from Above

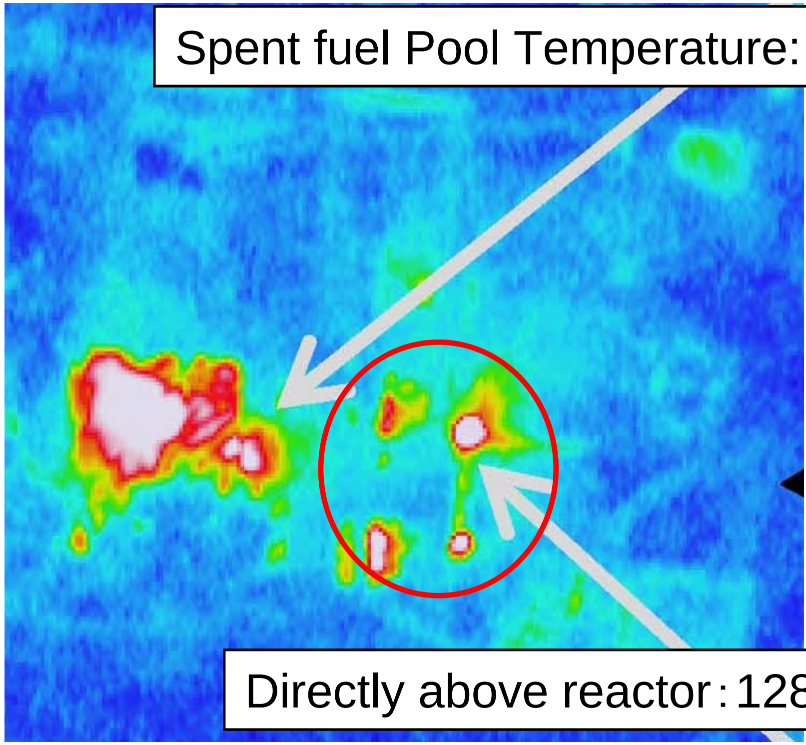



Photo taken on Mar. 20（Self Defense Force）

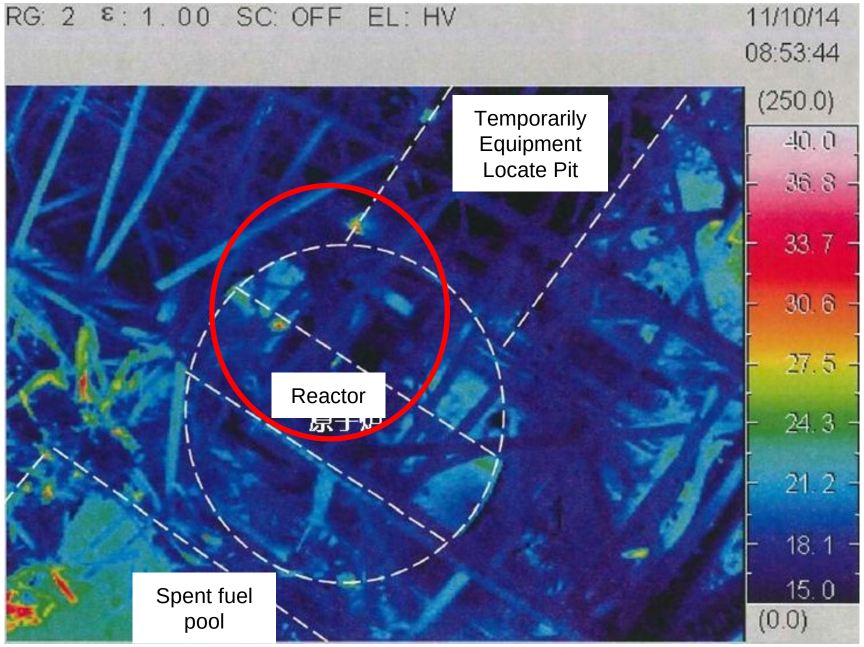



Photo taken on Oct. 14

The number of points where temperature rose became smaller and the range of influence shrank as of Oct. 14

The scale of generated steam ejection became smaller
(Inside of PCV is cooled)