

Estimation of current status inside RPV and PCV at Fukushima daiichi NPS

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IRID **IAE**

This document is based on the result of Subsidy Program "Project of Decommissioning and Contaminated Water Management (Upgrading Level of Grasping State inside Reactor)," which is a joint project by International Research Institute for Nuclear Decommissioning (IRID) and the Institute of Applied Energy (IEA).

0. Background

1. Unit 1 Estimation Diagram and its Basis

2. Unit 2 Estimation Diagram and its Basis

3. Unit 3 Estimation Diagram and its Basis

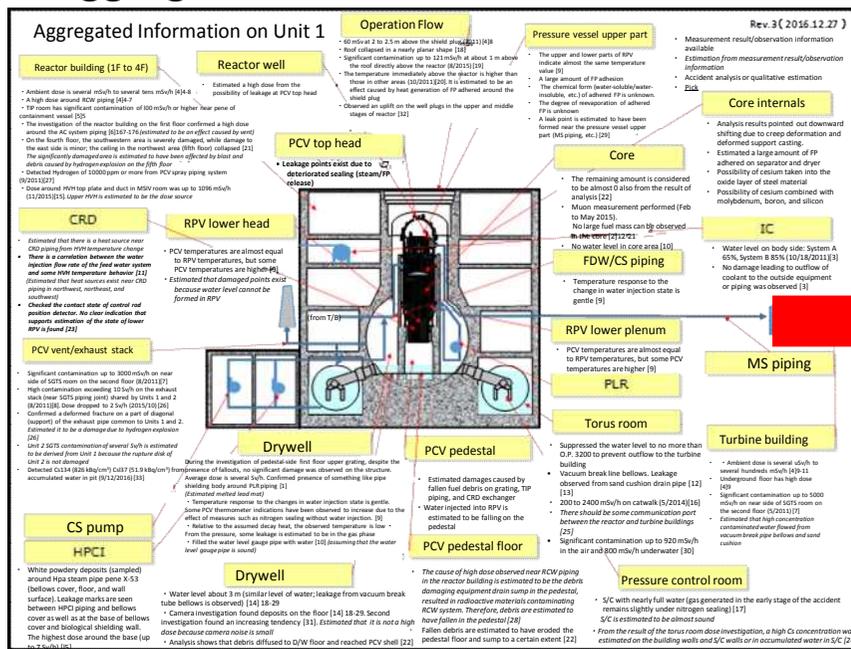
4. Summary and Future Plan

0-1 Background

- It is important to understand the status inside RPV and PCV for the fuel debris removal.
- TEPCO has been estimating it since the accident at the Fukushima Daiichi NPS.
- TEPCO is currently proceeding with the estimation in collaboration with IRID (International Research Institute for Nuclear Decommissioning) and IAE (Institute of Applied Energy). This presentation shows the distribution diagrams of fuel debris in Unit 1, 2, and 3 based on the various information and the latest knowledge obtained up to now.

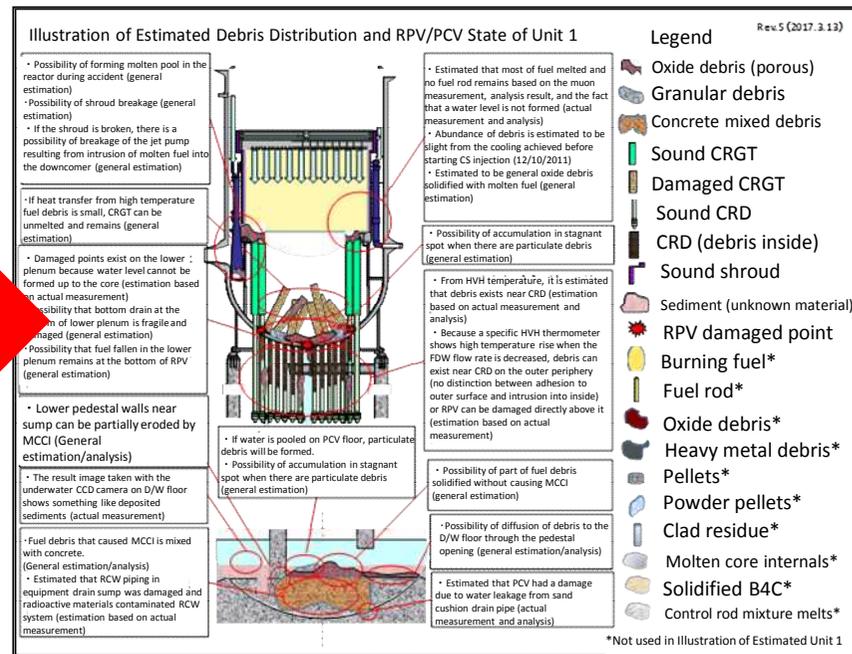
0-2. Background (Approach for Creating Illustrations of Estimation)

Aggregated Information on each Unit



Aggregated various information leading to estimation of fuel debris/FP distribution in each unit

Illustration of Estimated Fuel Debris Distribution

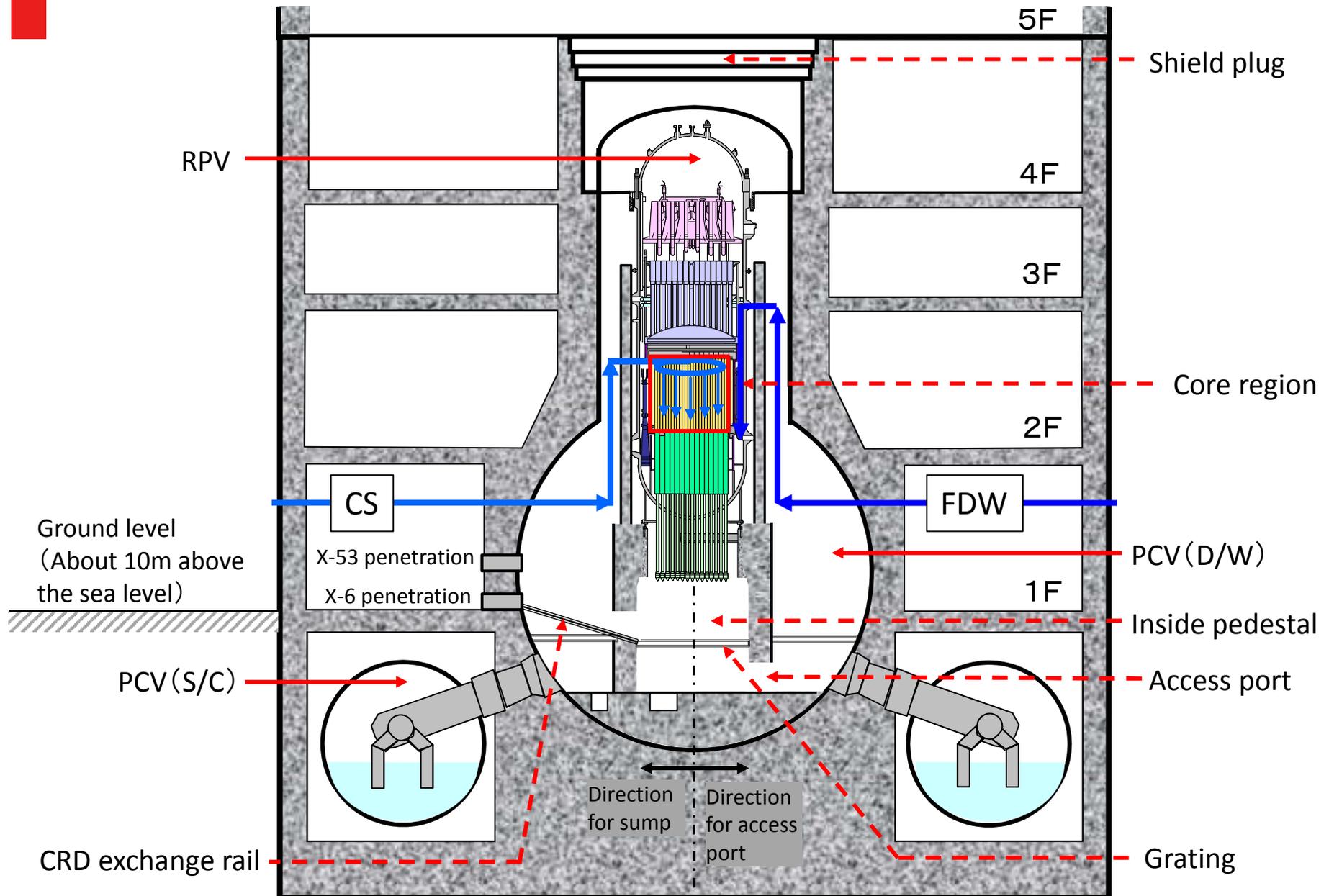


The analysis result has still uncertain/unknown points. Consider:

- Measured data during accident
- Information obtained from cooling of fuel debris after accident
- Information obtained from internal investigation for comprehensive estimation of fuel debris distribution

TEPCO has been discussing this fuel debris distribution with domestic and foreign experts from the meanings of information while transmitting observational information. TEPCO will continue to upgrade the distribution diagram based on new findings. ⇒ The following slides show the basis of representative estimation.

0-3. Background (Overview of RPV and PCV(Unit 2))



0-2. Background (Approach for Creating Illustrations of Estimation)

Aggregated Information on each Unit

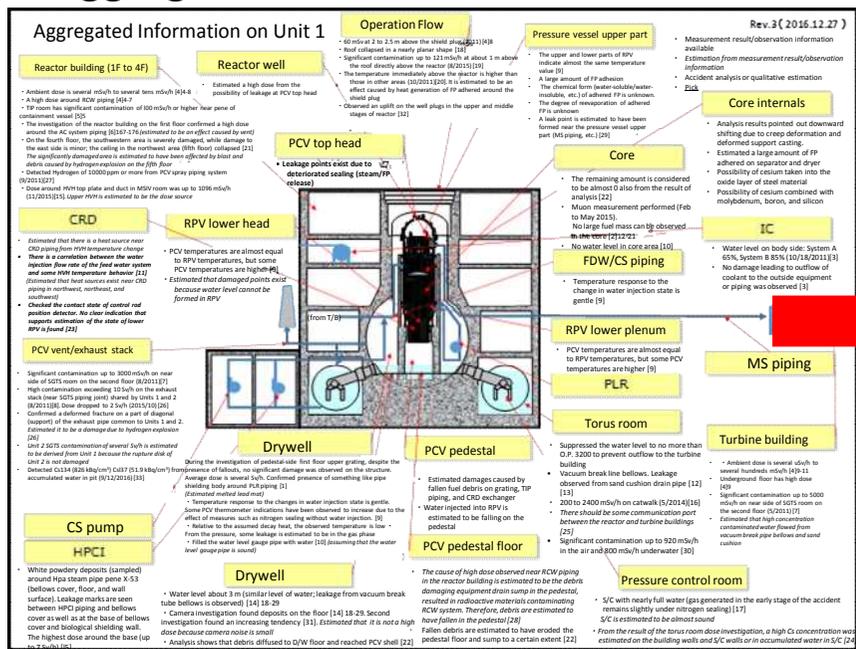
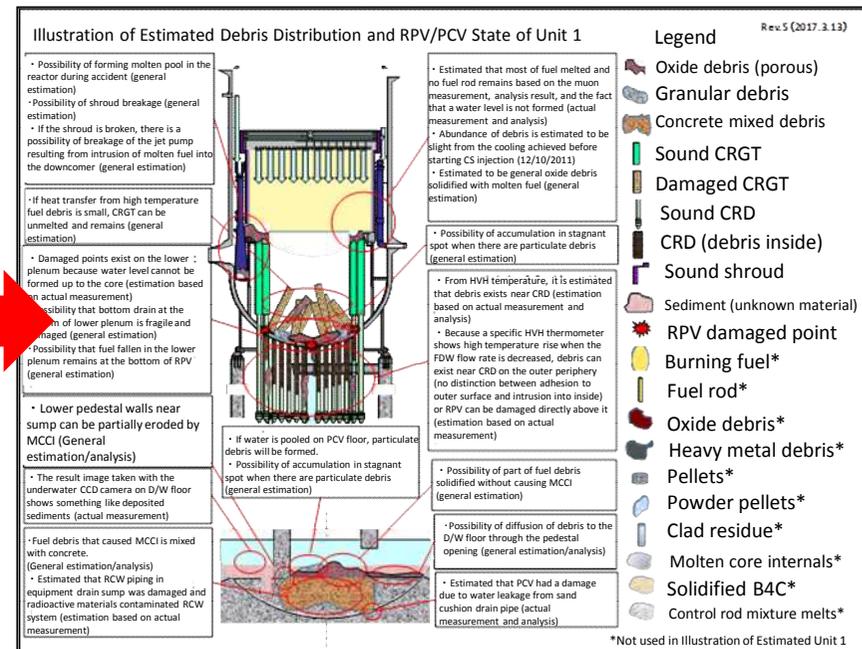


Illustration of Estimated Fuel Debris Distribution



Aggregated various information leading to estimation of fuel debris/FP distribution in each unit

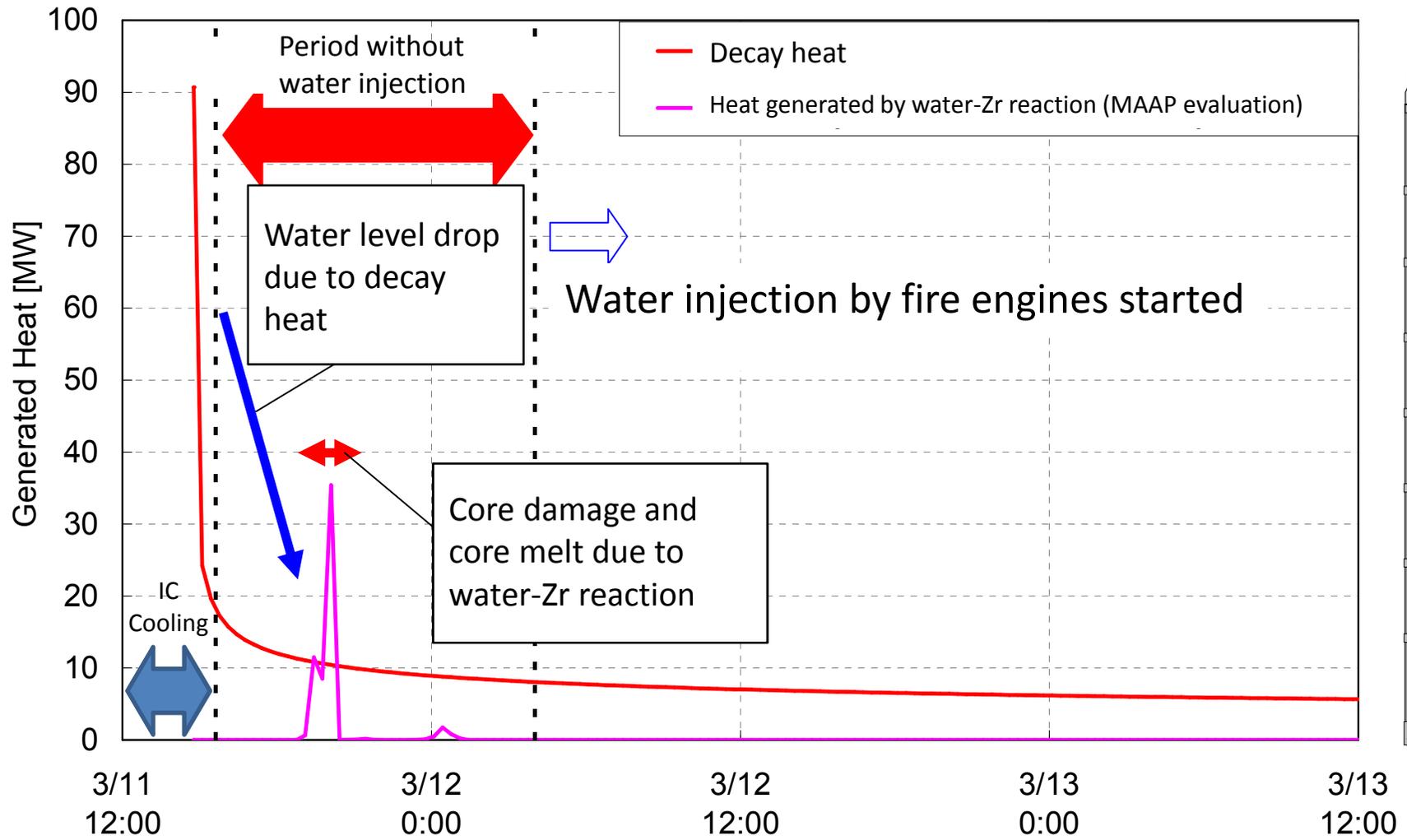
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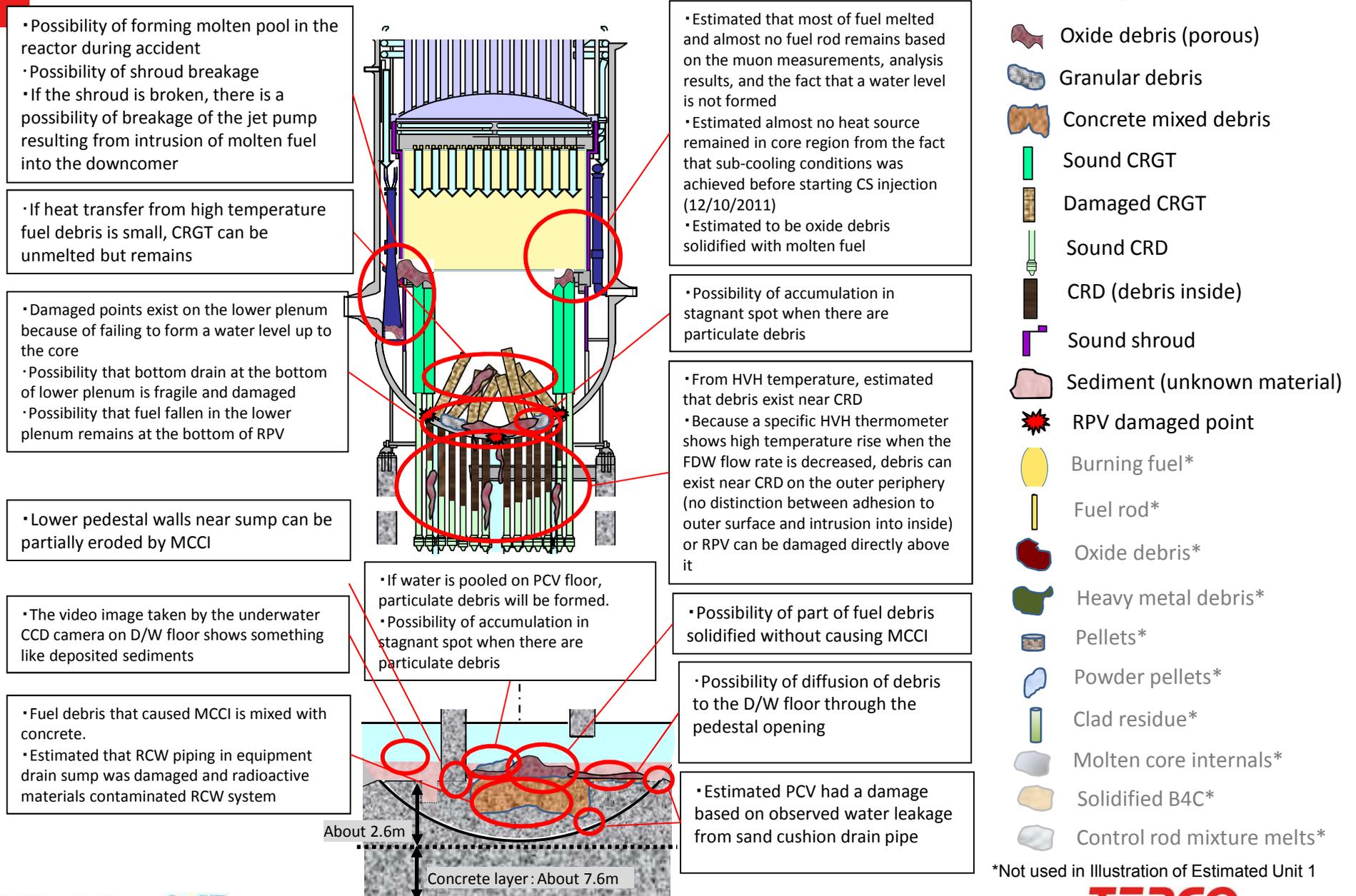
1. Unit 1 Estimation Diagram and its Basis

1-1 Decay Heat of Unit 1 and Heat Generated by Water-Zr Reaction



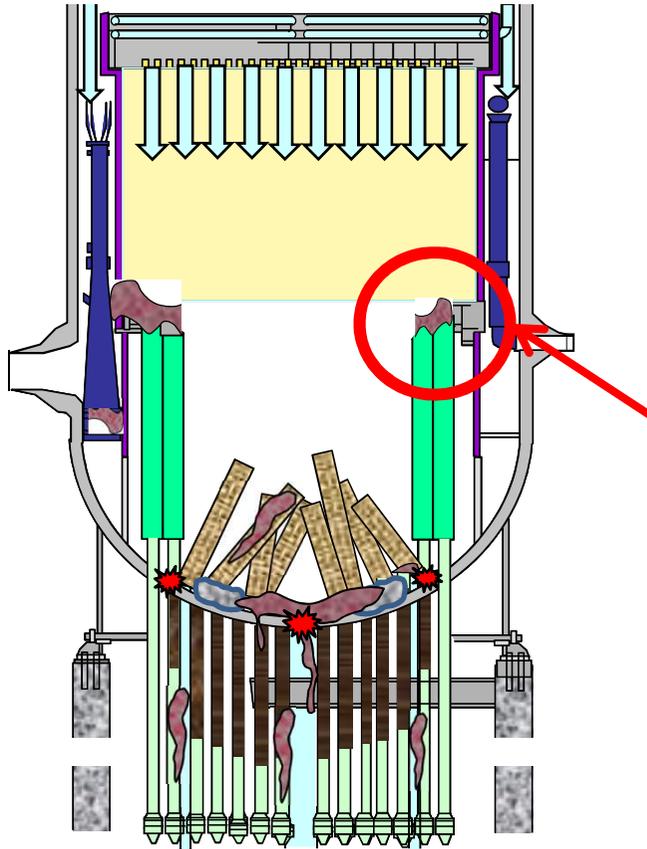
Unit 1 became uncoolable immediately after the tsunami arrival, which resulted in core damage/core melt in March 11 2011. Insufficient fire engine water injection made no contribution to water-Zr reactions

1-2 Unit 1 Estimation Diagram



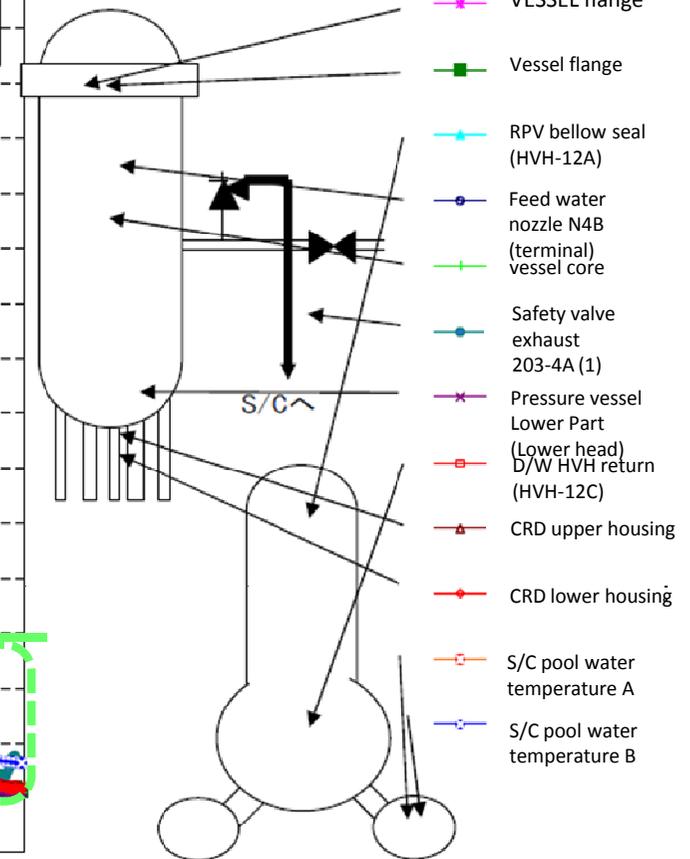
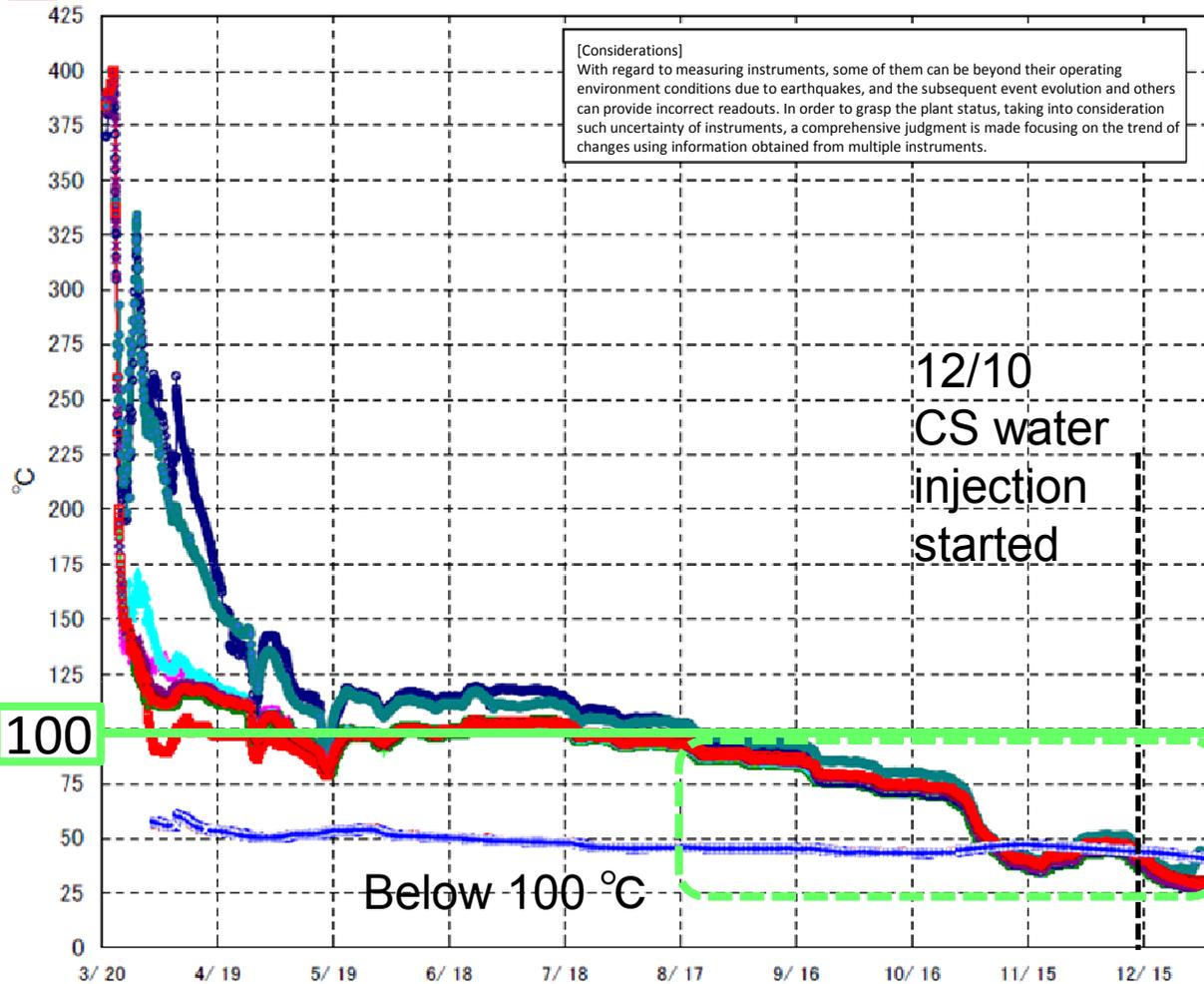
*Not used in Illustration of Estimated Unit 1

1-3 Estimated State of Core



- Estimated that most of fuel melted and almost no fuel rod remains based on the muon measurement, analysis result, and the fact that a water level is not formed
- Estimated almost no heat source remained in core region from the fact that sub-cooling conditions was achieved before starting CS injection (12/10/2011)

1-4 Temperature Behavior before Starting CS Water Injection



For Unit 1, water injection from CS system started on December 10, 2011. Before that, however, most of the observation points in the containment vessel fell below 100 °C. Therefore, estimated that almost no fuel remains in the core.

1-5 Result of Muon Measurements

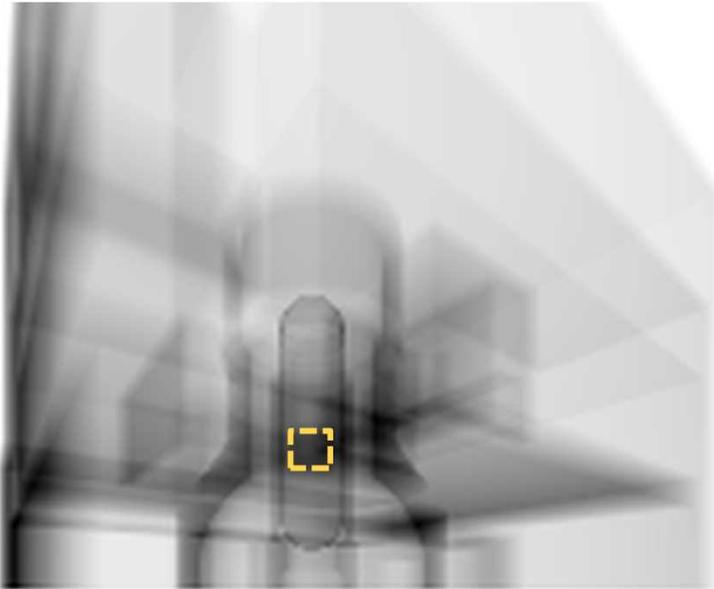


Image of estimated muon measurement result based on design drawing (Area enclosed by a broken line shows the core)

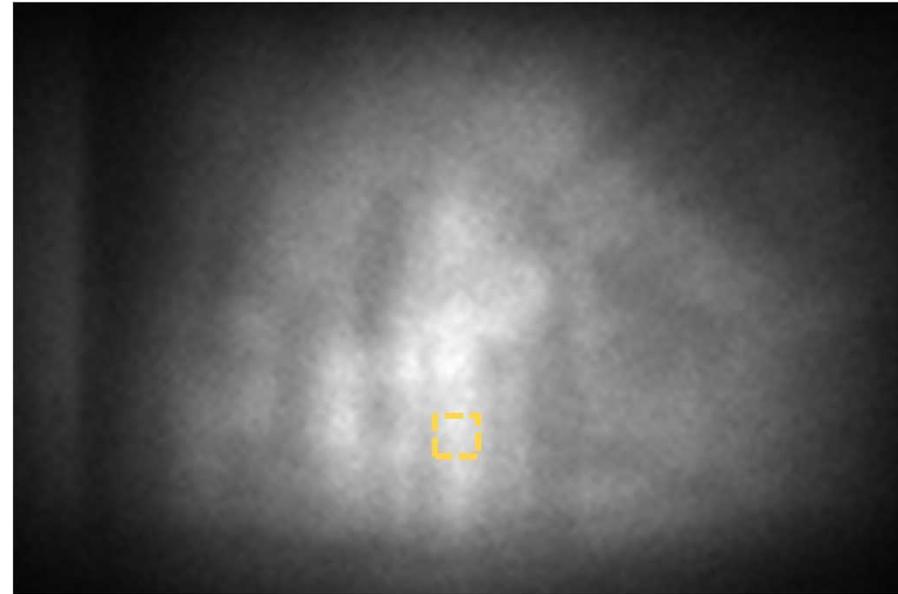
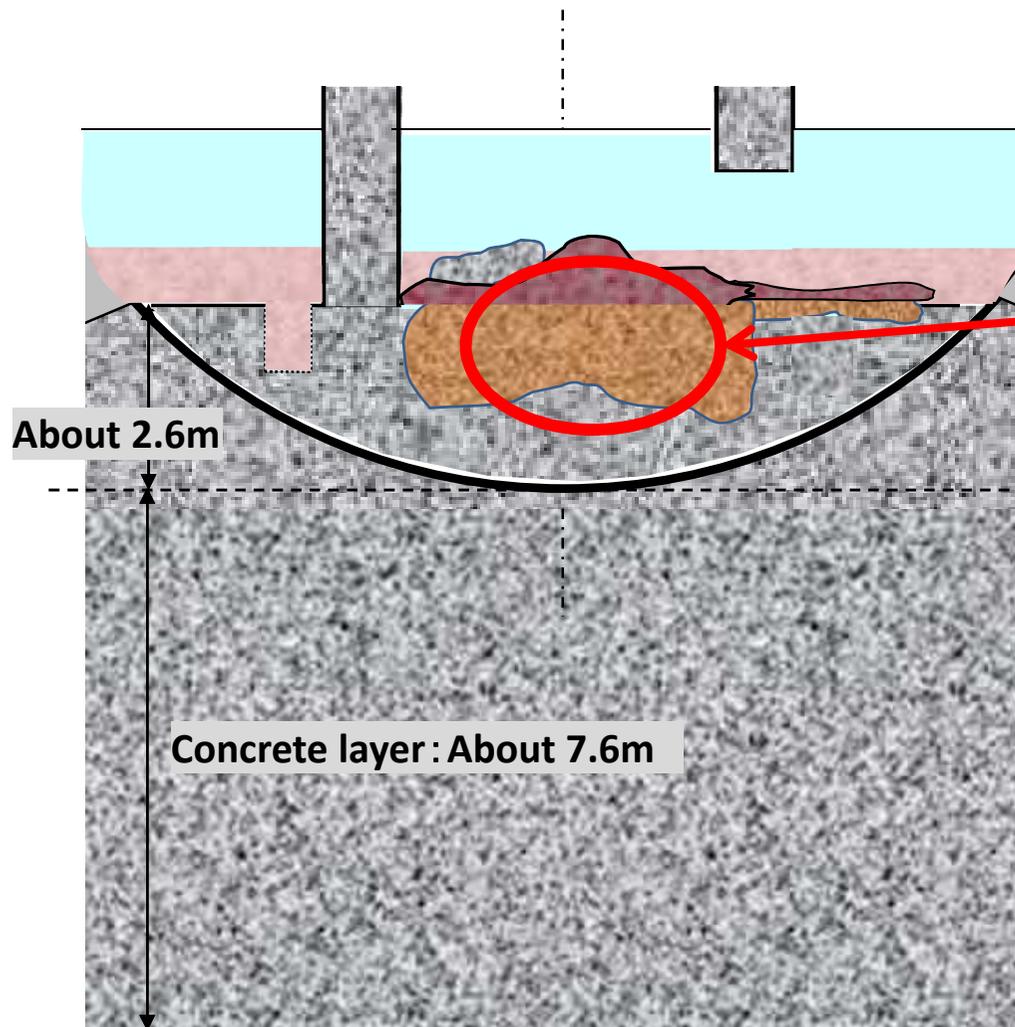


Image of muon measurement using 96 days' worth of data (Area enclosed by a broken line shows the core)

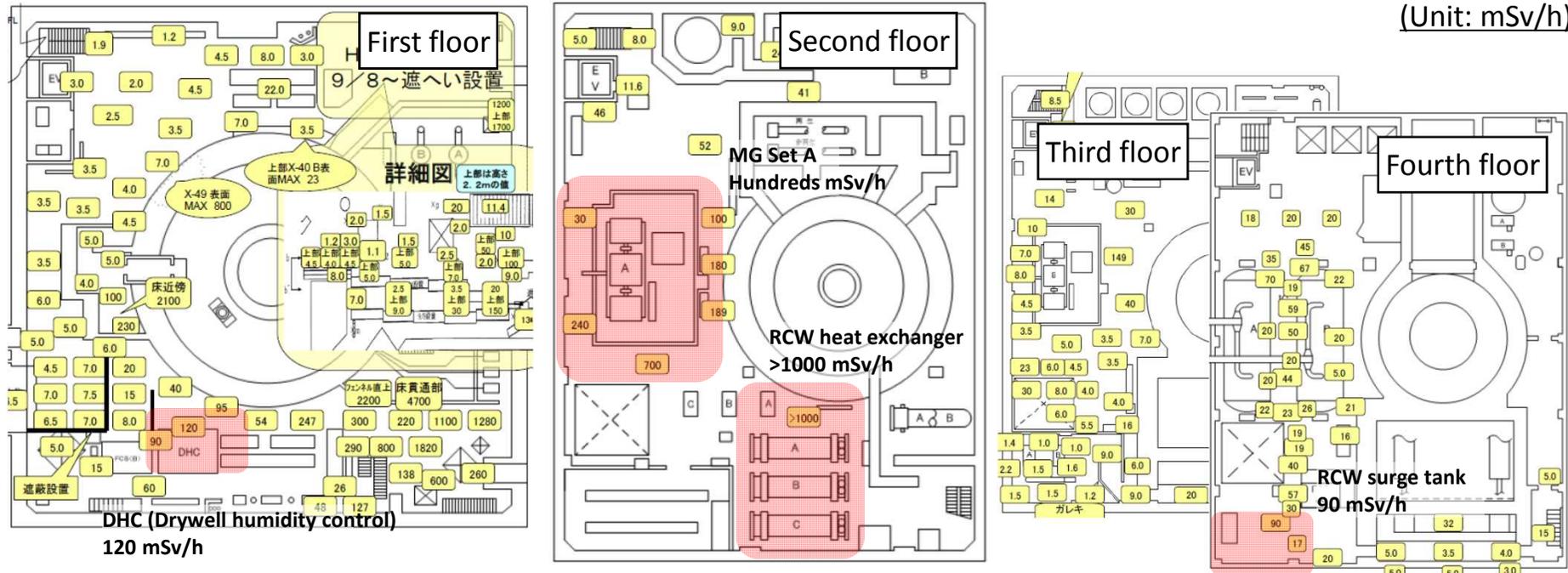
High-absorbent objects (except for fuel) such as pressure vessel walls, containment vessel walls, and reactor building walls can be confirmed by muon measurements. (Measurement period: February 9 to May 21, 2015)
Meanwhile, no large fuel mass exceeded 1 m in the core (resolution of the measurement).
⇒ **Estimated that almost no fuel remains in the core.**

1-6 Estimation of Pedestal Part



- Estimated that RCW piping in equipment drain sump was damaged and radioactive materials contaminated RCW system

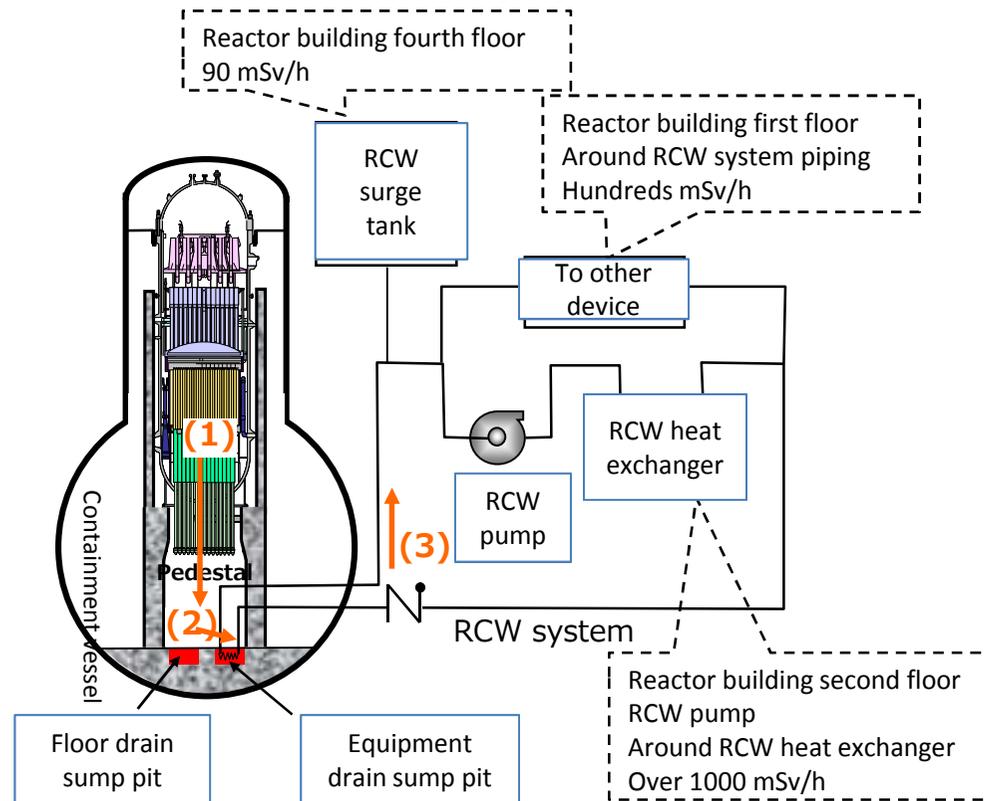
1-7 Contamination of RCW System



RCW system is a closed loop* and unlikely to experience high dose contamination in normal conditions. However, high dose was observed around equipment to be cooled by RCW over multiple floors in the reactor building.

*Closed loop: Piping network without opening in PCV

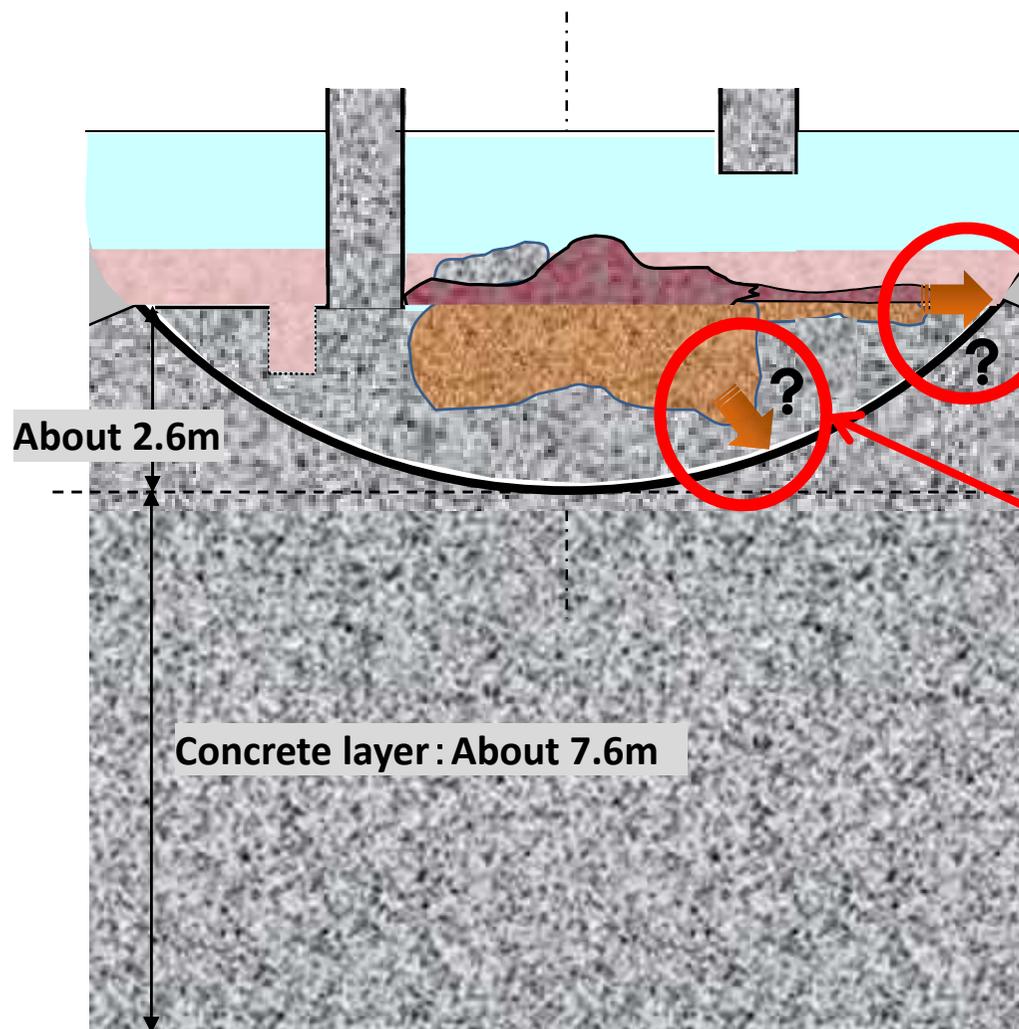
1-8 Contamination of RCW System



Because RCW system is cooling the equipment drain sump in the pedestal, the contaminants in RCW system are estimated to be:

- (1) Molten fuel fell into the equipment drain sump located in the containment vessel pedestal
- ⇒ (2) Molten fuel damaged RCW piping in equipment drain sump
- ⇒ (3) In Unit 1, with the containment pressure increased significantly during the accident progression, water and steam containing radioactive materials transferred to RCW piping

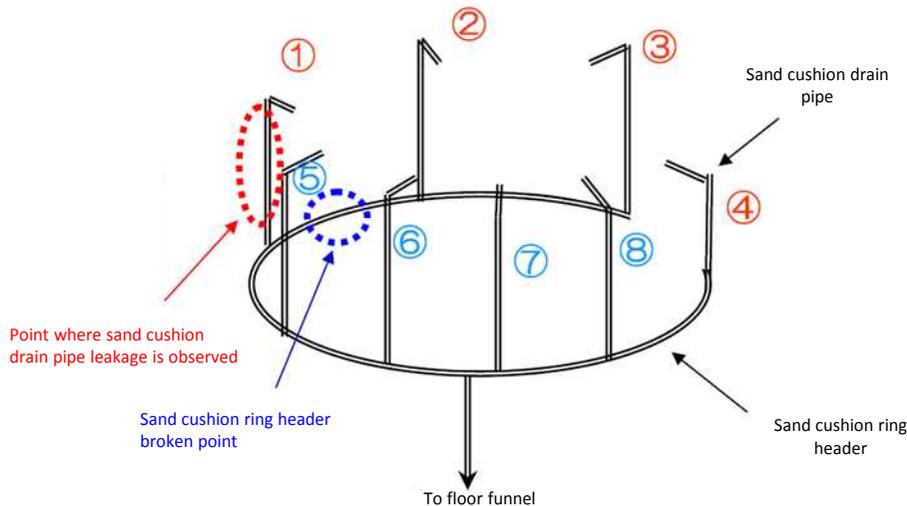
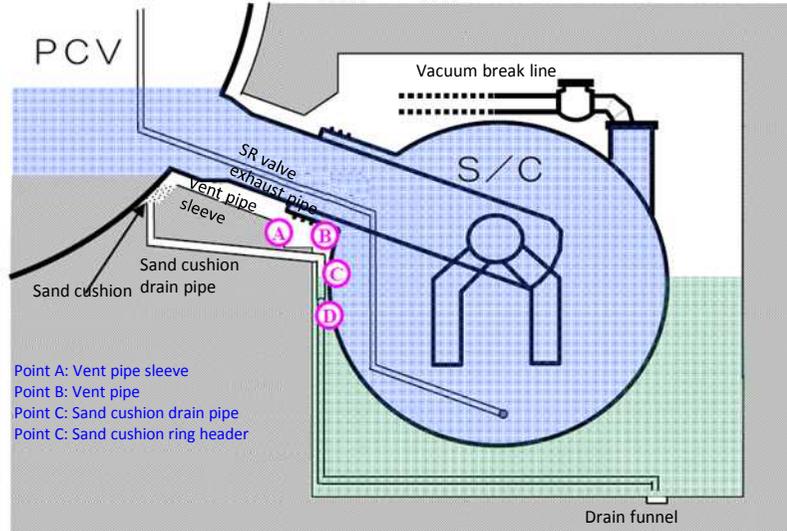
1-9 Estimation of Pedestal/Drywell Areas



- Estimated that PCV had a damage based on observed water leakage from sand cushion drain pipe

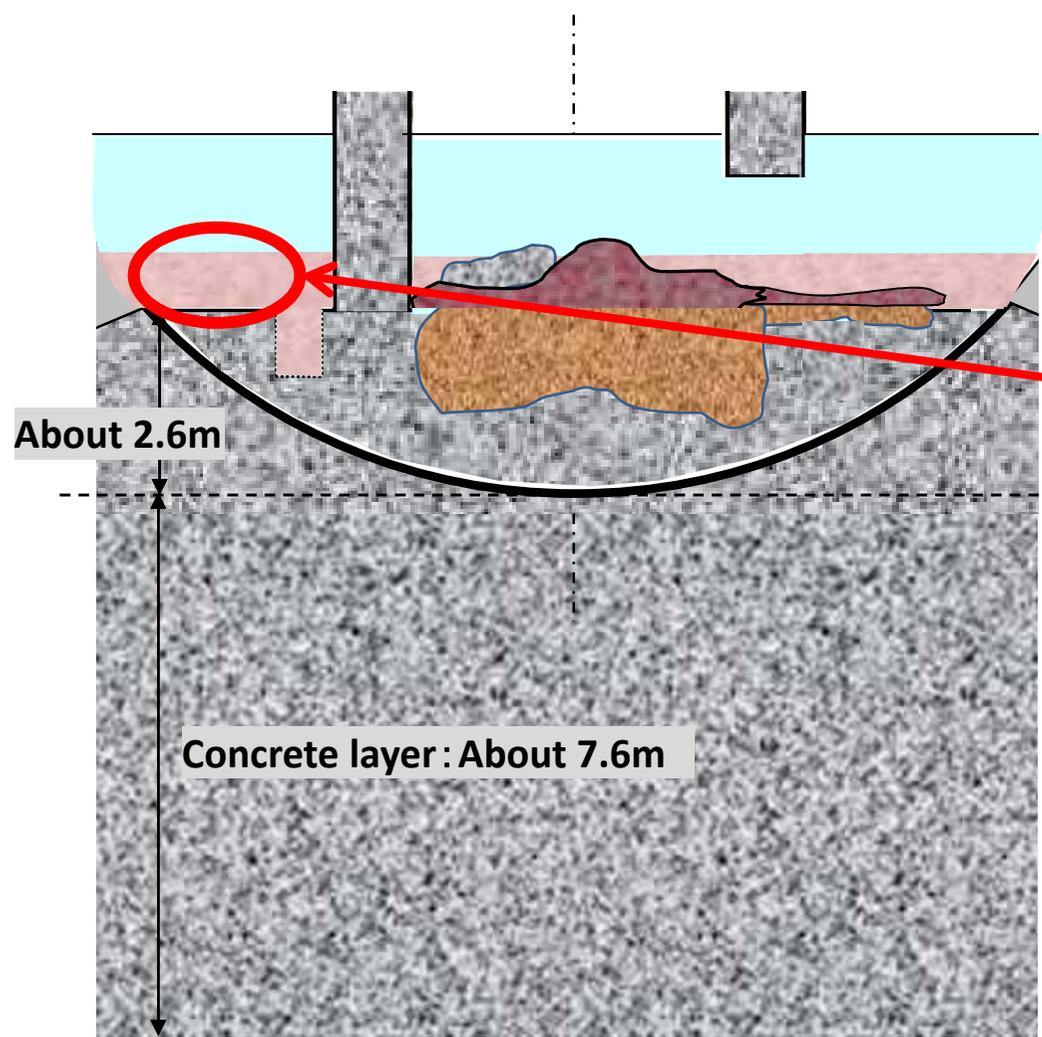
1-10 Leakage from Sand Cushion Drain Pipe

Using the video camera mounted on the remote boat, confirmed water leakage from the vent pipe and sand cushion drain pipe (November 13 and 14, 2013)



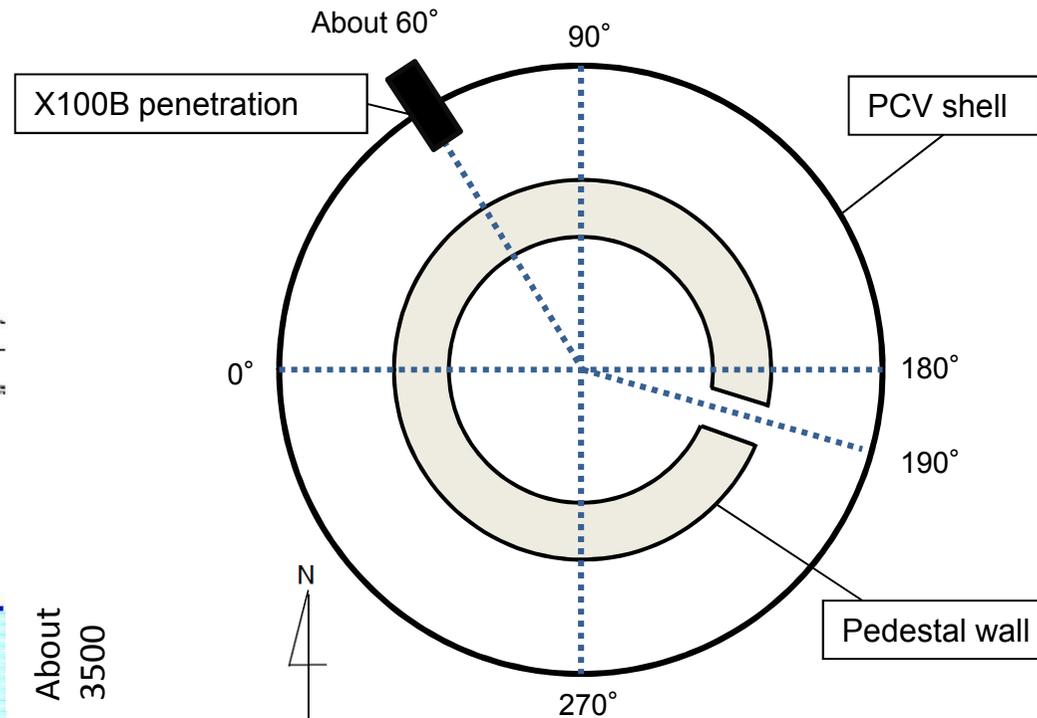
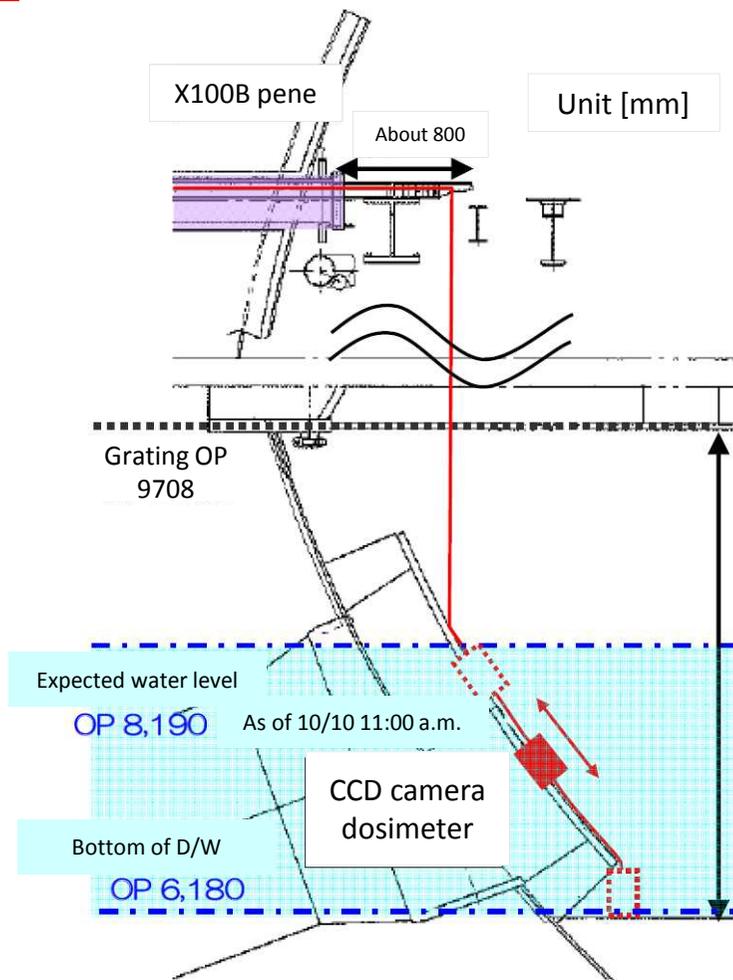
Leakage is observed from sand cushion drain pipe. Although the location cannot be identified, the iron shell below the water surface could possibly have a leakage point.

1-11 D/W Floor Condition



▪ The video image taken by the underwater CCD camera on D/W floor shows something like deposited sediments

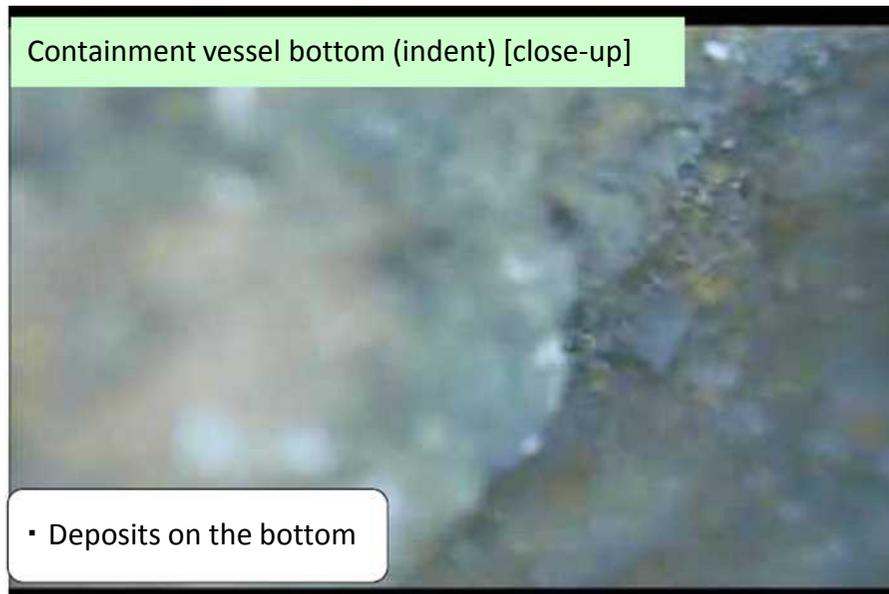
1-12 Result of PCV Internal Investigation



The dose in the air on the first floor in PCV is 4.7 to 9.8 Sv/h
 About 11.1 Sv/h at the end of pene when inserting the instrument
 Dose distribution tends to decrease as height decreases
 0.5 Sv/h underwater in accumulated water

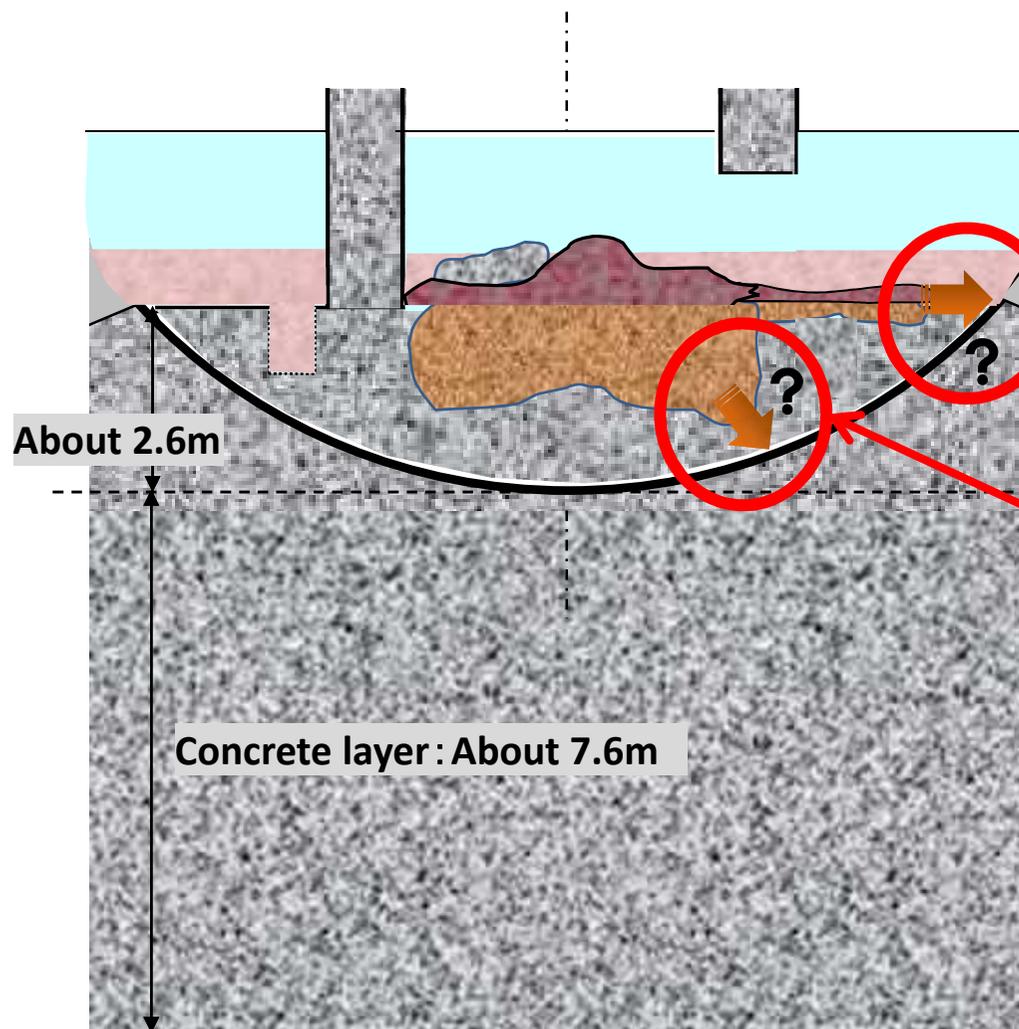
As a PCV internal investigation, CCD camera was inserted from X100B pene (October 11, 2012)

1-13 Result of PCV Internal Investigation



There are some deposits having a certain thickness at the bottom of containment vessel. Deposit seems not to be hard solids as it had a dent when the camera bumped it. Some deposits are bluish fragments. (Possibility of lead)

1-9 Estimation of Pedestal/Drywell Areas

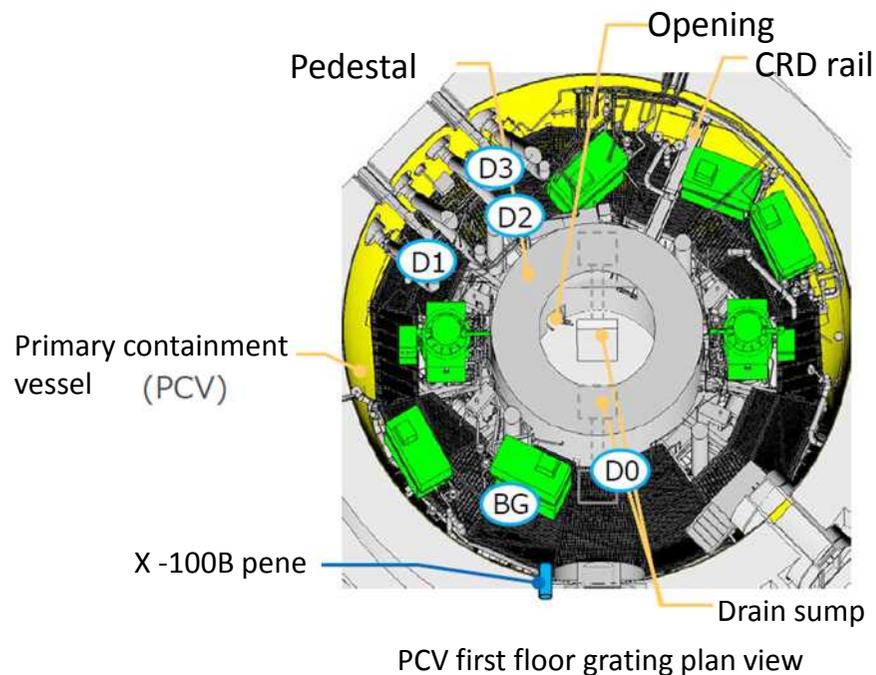


- Estimated that PCV had a damage based on observed water leakage from sand cushion drain pipe

1-14 Result of PCV Internal Investigation

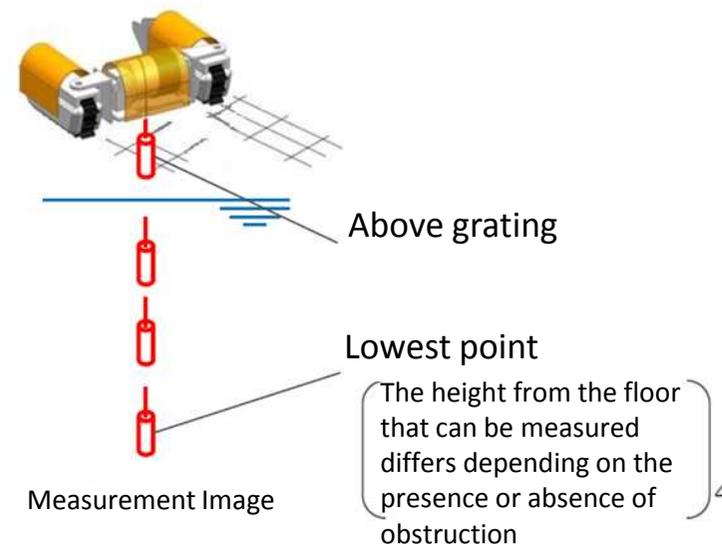
In March 2017, the PCV internal investigation was conducted to check the diffusion condition of fuel debris in the underground level out of pedestal and to check whether or not the fuel debris reached the PCV shell.

- Measurement points of the investigation are as follows:



Measurement point	Estimation
D0	Diffusion of fuel debris from the drain sump
BG	Background levels against D0-D3 measurements
D1, D2	Diffusion of fuel debris from the opening
D3	Possibility of fuel debris reaching to PCV shell

- Hang the measuring unit down to the bottom and then measure the dose while pulling it up at 5-cm intervals



1-15 Result of PCV Internal Investigation

Typical images taken are as follows:



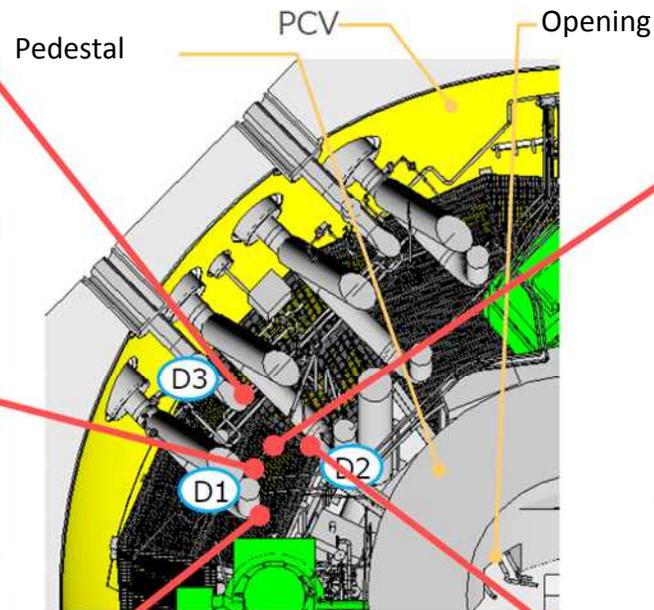
3/21 D3 Image near the lowest point



3/21 D1 (2) Image near the lowest point



3/21 D1 (1) Image near the lowest point



First floor PCV cross-section

• Detailed measuring points are currently under evaluation



3/22 D2 (3) Image near the lowest point



3/21 D2 (2) Image near the lowest point



3/20 D2 (1) Image near the lowest point

Deposits having a certain thickness are observed in each observation point in the same way as the investigation in 2012.

2. Unit 2 Estimation Diagram and its Basis

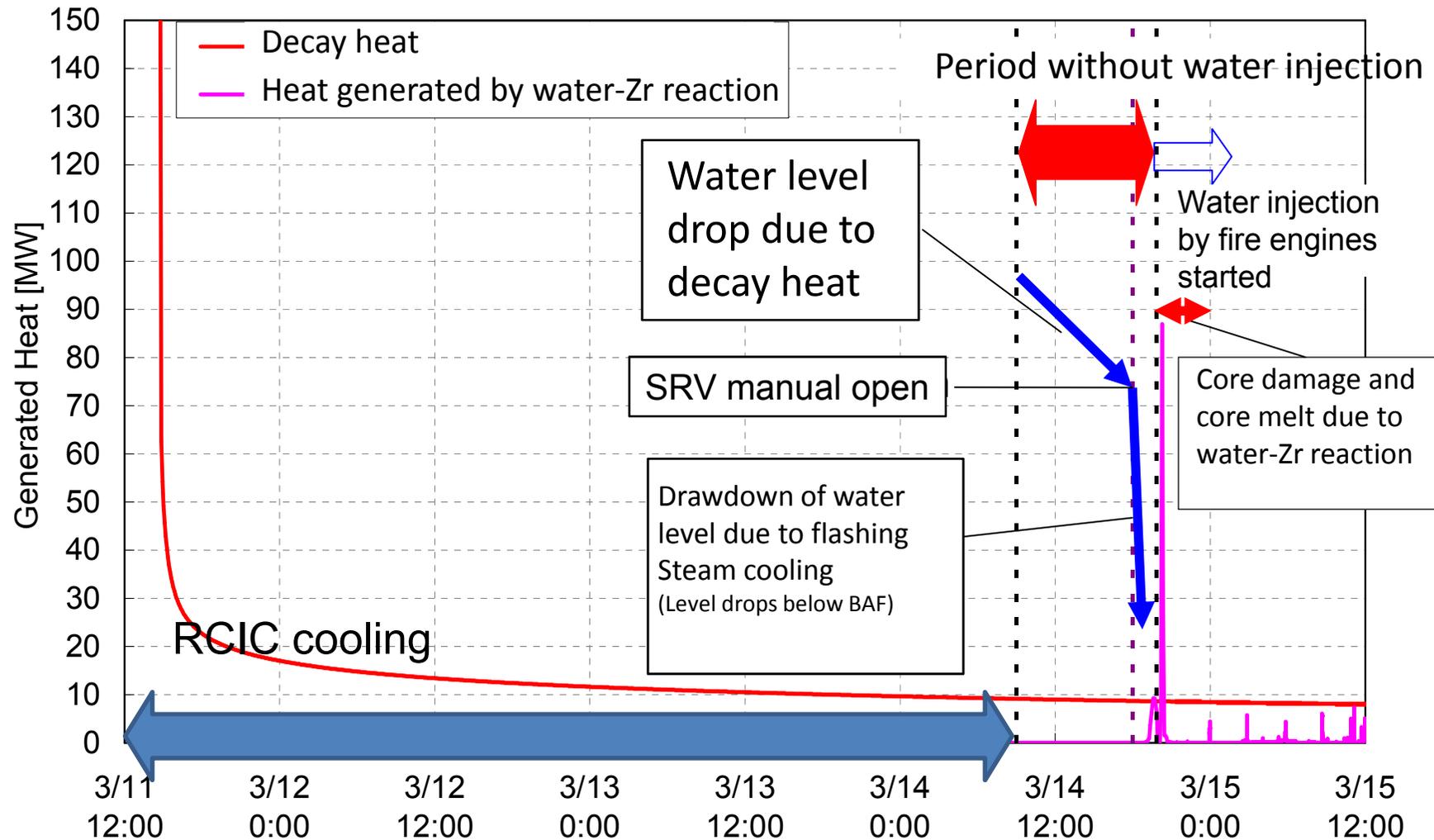
2-1 Decay Heat of Unit 2 and Heat Generated by Water-Zr Reaction

Unit 1

Unit 2

Unit 3

24



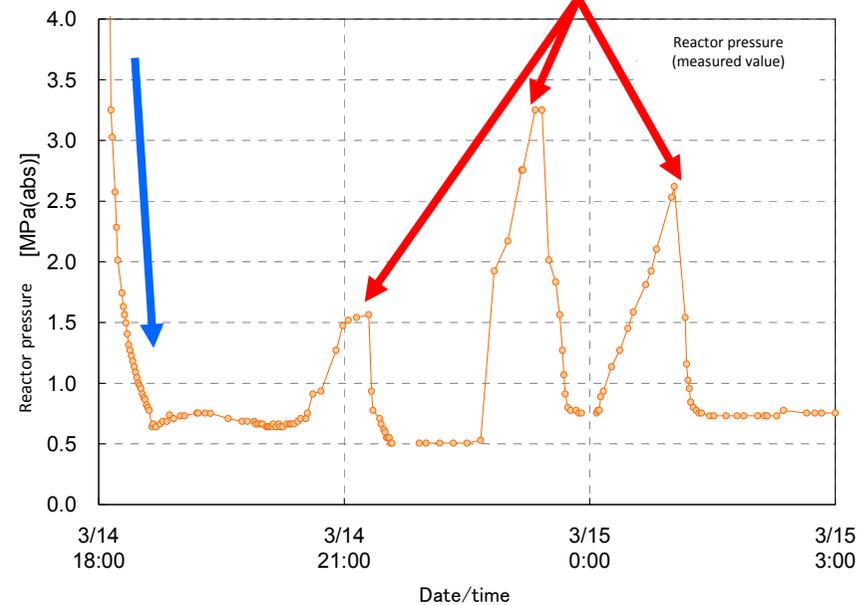
At Unit 2, fuel is fully exposed because water level dropped due to flashing. After that, the water-Zr reaction induced by fire engine water injection resulted in core damage and core melt.

2-2 Pressure Increase after Reactor depressurization

- At Fukushima Daiichi Unit 2, the reactor depressurization was successful upon forced SRV opening at 6:00 p.m. on March 14, but the reactor experienced a pressure rise three times during the period from that night to the next morning.
- This behavior was thought to be related to SRV opening operation (pressure increase = SRV closed, pressure decrease = SRV open). However, this does not directly show the open/close state of SRV.
- Along with this pressure increase, an increase in the containment vessel pressure associated with hydrogen has been confirmed, and this pressure increase is greatly related to the accident progression in Unit 2.

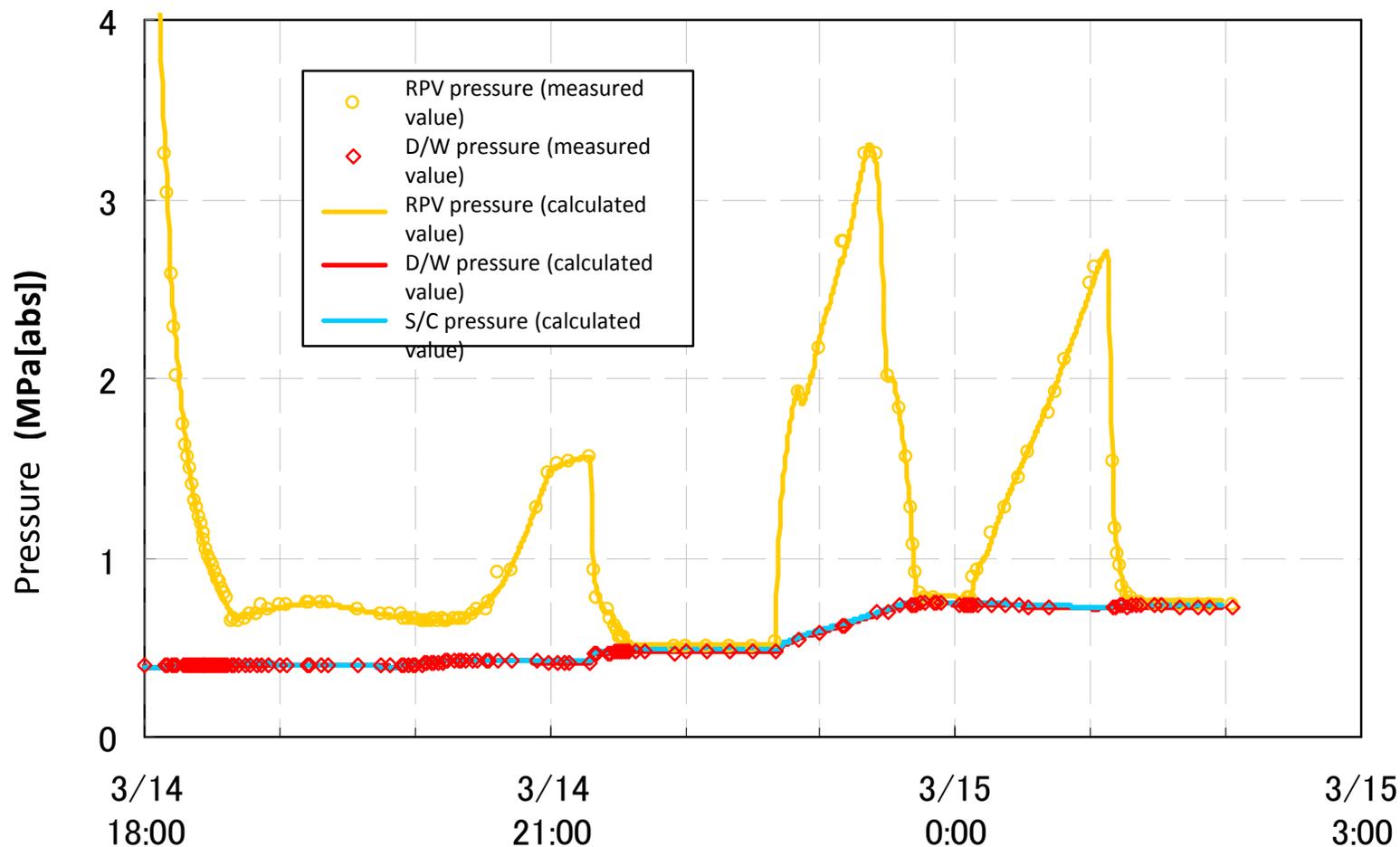
Reactor depressurization

Reactor pressure Rises



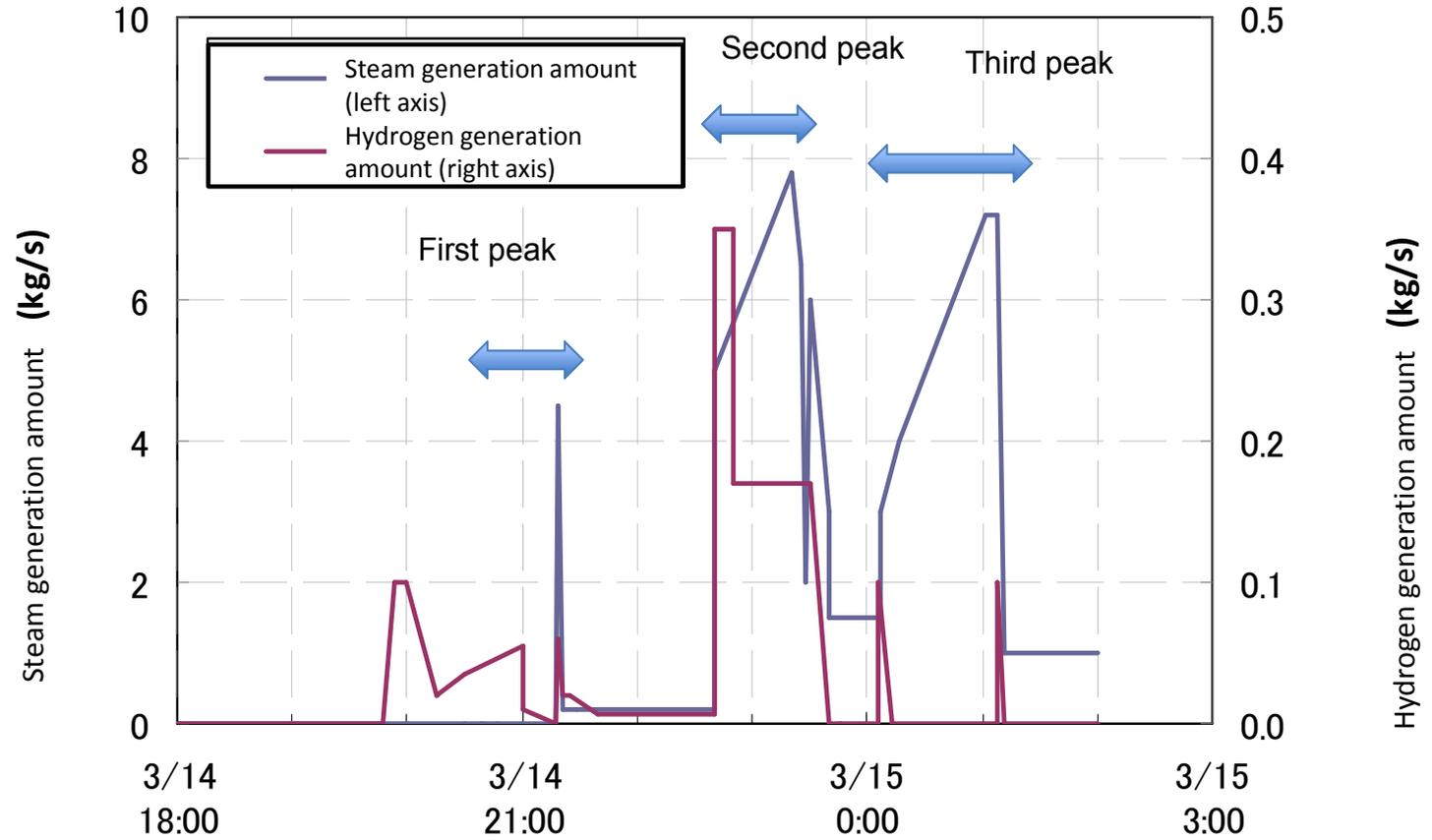
Understanding this behavior is extremely important in understanding the accident progression and core status of Unit 2

2-3 Pressure Increase after Reactor depressurization



- Adjusting the generation amount of steam and hydrogen by GOTHIC (Generation of Thermal Hydraulic Information in Containment) that is the general flow analysis code successfully reproduced the RPV pressure and PCV pressure.
- Assumed semi-opening (40%) of SRV to reproduce the RPV/PCV pressure behavior at the second peak.

2-4 Pressure Increase after Reactor depressurization



- The calculated result indicates that almost all of zirconium in the reactor reacted until the second peak.
- **Estimated that most of fuel melted during the second peak** from the relationship between hydrogen generation and energy generation due to water-zirconium reaction.

2-5 Unit 2 Estimation Diagram

Unit 1

Unit 2

Unit 3

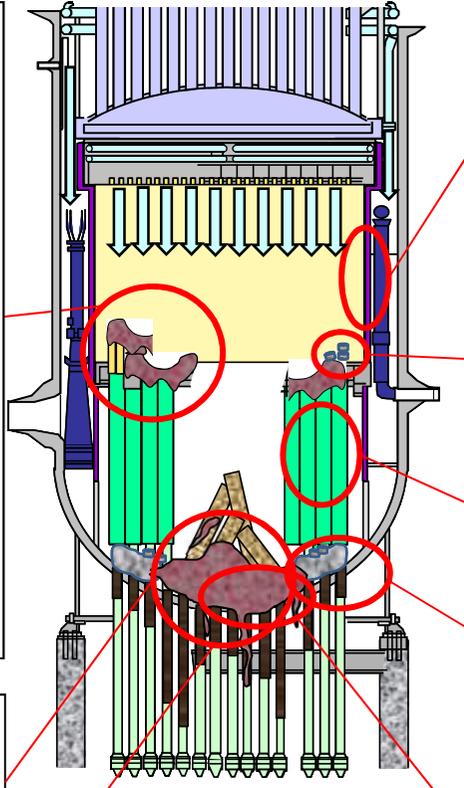
Legend 28

- Assuming the energy amount from PCV pressure increased due to hydrogen generation, most of fuels are estimated to have melted
- Because of the temperature drop confirmed during CS injection, the presence of fuel is estimated to be on the outer periphery of core where water is applied by CS injection at low flow rate (debris cannot be specifically located because the same behavior is shown even when molten fuel dropped and solidified in a fuel support casting or CRGT)
- The result of muon measurement shows the possibility that fuel exists on the outer periphery of core
- Fuel rods can exist only on the outer periphery if any
- Estimated to be general oxide debris solidified with molten fuel

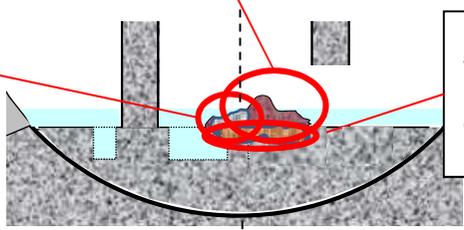
- A shadow of the high density material that is considered to be fuel debris has been confirmed at the bottom of pressure vessel by muon measurements. Possibility that fuel fallen in the lower plenum remains at the bottom of RPV

- Possibility that debris intrude in CRD accompanying breakage of CRGT

- If water is pooled on PCV floor, particulate debris will be formed.
- Possibility of accumulation in stagnant spot when there are particulate debris



- Possibility of part of fuel debris solidified without causing MCCI
- Steam rising is observed during PCV internal investigation.



- Possibility of water level formed outside the shroud because the PLR system pressure increased when the FDW flow rate increased
- Estimated that there is no large-scale damage of shroud from a temperature drop by CS injection and water level rise outside the shroud when injection rate increases

- Possibility of pellets remain on the outer periphery because the fuel temperature rise on the outer peripheral may not be so high

- If heat transfer from high temperature fuel debris is small, CRGT will be unmelted but remains

- Possibility of accumulation in stagnant spot when there are particulate debris and pellets

- CRD on the outer periphery was confirmed during PCV internal investigation, and the holes on grating panel and some melting material were observed which indicate RPV bottom failure (not large, center and off-center position)
- Some of debris that fell out of the hole are estimated to adhere on CRD

- Fuel debris that caused MCCI is mixed with concrete
- MCCI is estimated to be limited because of no symptom of PCV shell breakage (no leakage from sand cushion drain pipe)

- Fuel rod
- Oxide debris (porous)
- Granular debris
- Concrete mixed debris
- Sound CRGT
- Damaged CRGT
- Sound CRD
- CRD (debris inside)
- Sound shroud
- Pellets
- Burning fuel*
- Oxide debris*
- Heavy metal debris*
- Powder pellets*
- Clad residue*
- Molten core internals*
- Solidified B4C*
- Control rod mixture melts*

*Not used in Illustration of Estimated Unit 2

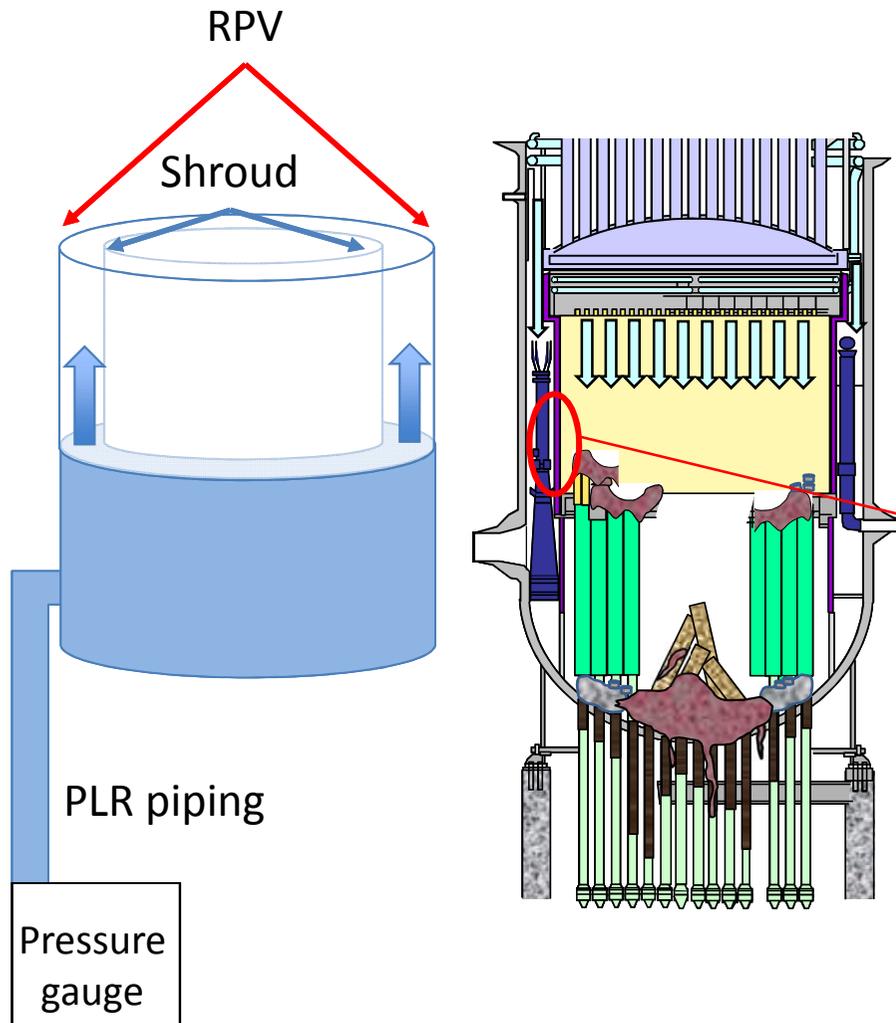
2-6 Estimated State of Core (Soundness of Shroud)

Unit 1

Unit 2

Unit 3

29



- Possibility of water level formed outside the shroud because the PLR system pressure increased when the FDW flow rate increased
- Estimated that there is no large-scale damage of shroud from a temperature drop by CS injection and water level rise outside the shroud when injection rate increases

2-7 Water Level in Annulus Expected from PLR Inlet Pressure when FDW Flow Rate Changes

Unit 1

Unit 2

Unit 3

30

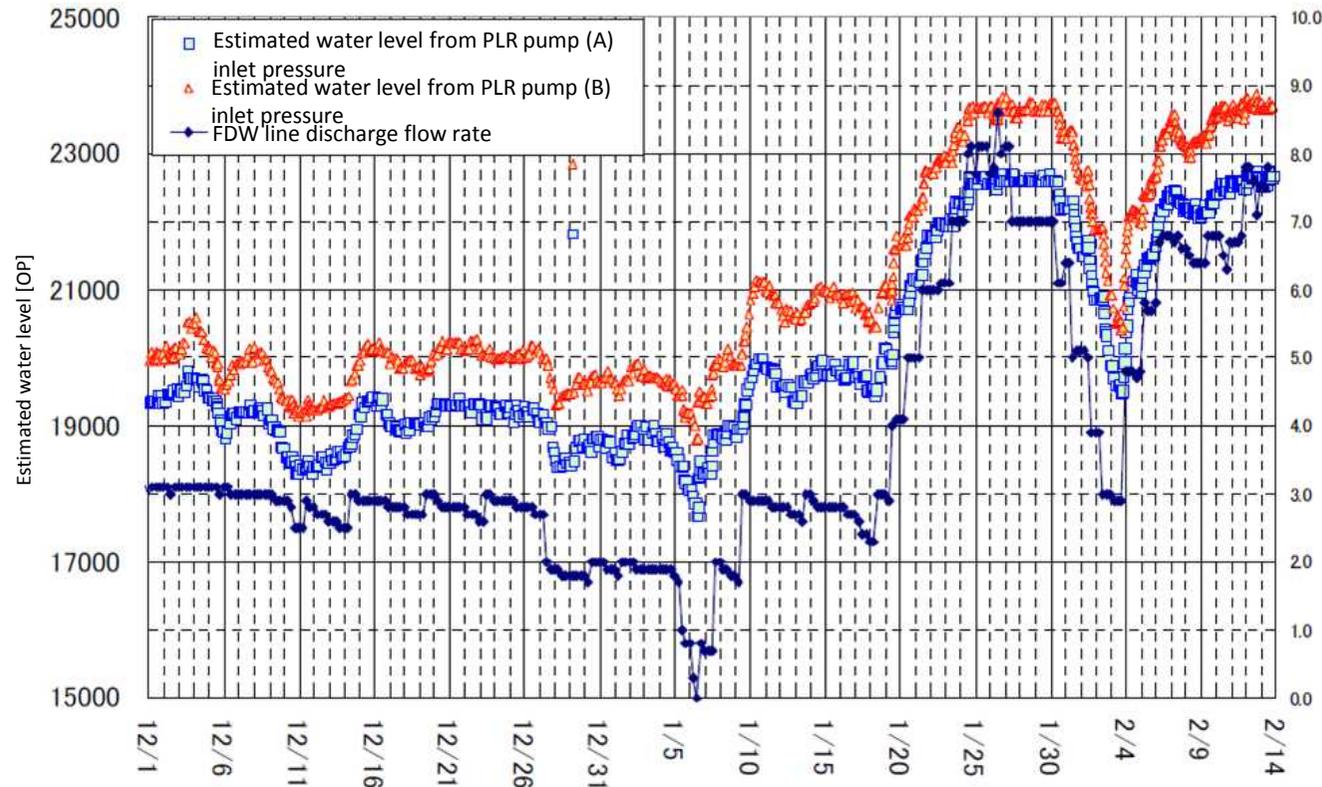


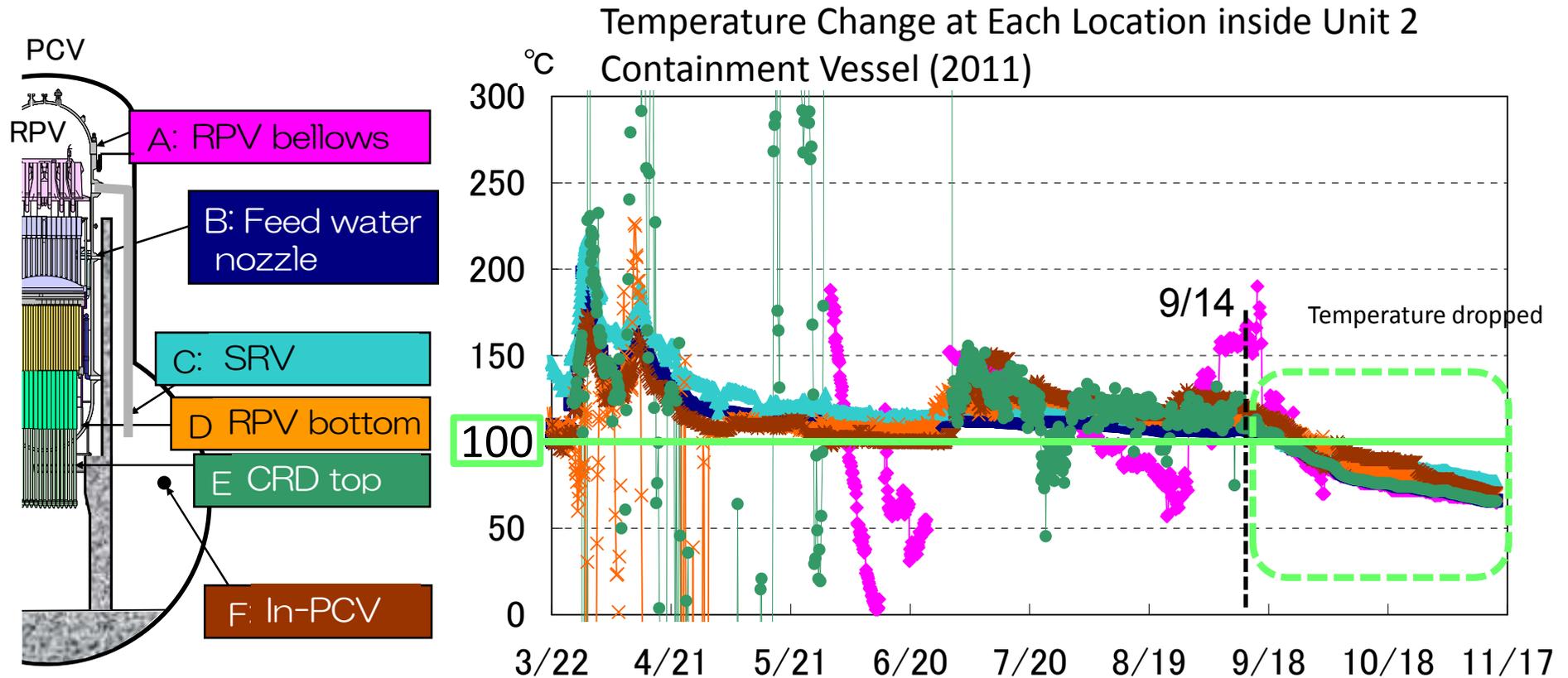
Figure Relationship between Water Injection Volume from FDW System and Water Level in Annulus (December 2011 to February 2012)

As the water injection rate increases, the water level in annulus rises.

⇒ (two possibilities)

- Possibility of water level formed outside the shroud with damage on shroud to small extent
- Because the total water injection rate is increasing, the water level in the reactor pressure vessel can be rising even though the shroud is damaged

2-8 Temperature Behavior when Starting CS Water Injection

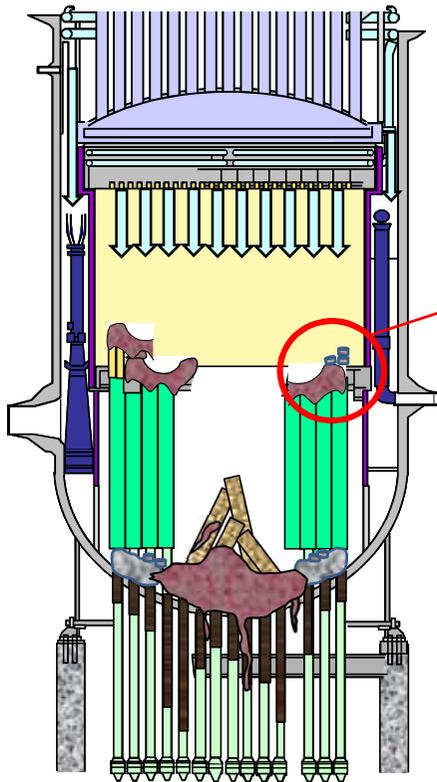


Along with water injection from CS system started on September 14, 2011, the temperatures of A to F decreased similarly

⇒

The heat source is considered to be located in the area that is cooled by water injection from CS system. This also supports that the shroud has only a minor damage.

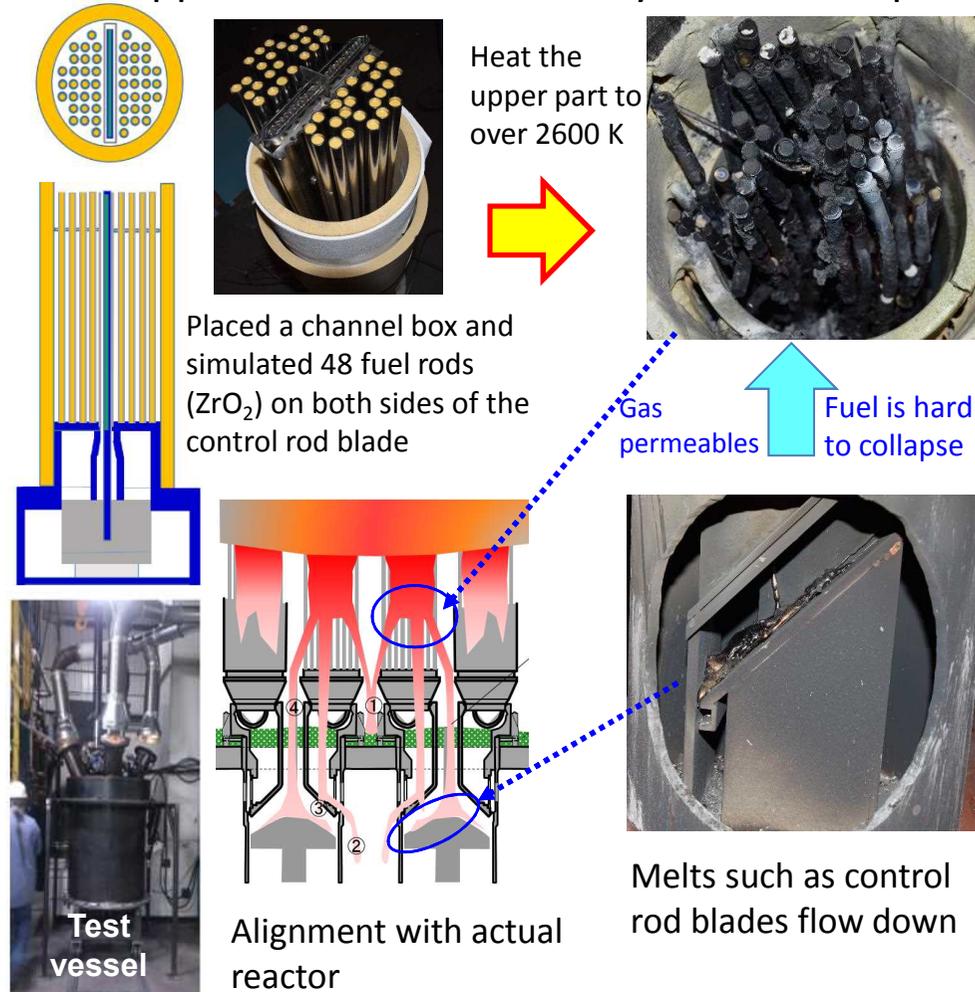
2-9 Estimated State of Core (Outer Periphery)



- Possibility of pellets remain on the outer periphery because the fuel temperature rise on the outer peripheral may not be so high

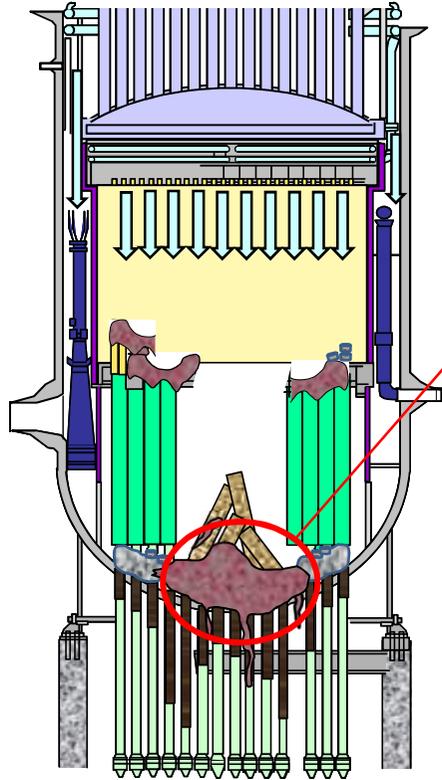
2-10 Result of Simulated Fuel Assembly Breakage Test

In order to know more about fuel behaviors such as melting and transfer in BWR system, a test was conducted by heating the test piece that simulates the core and lower support structure of BWR system with a plasma torch.



- The test result was, partly affected by radiation, that the fuel rods maintained their shape to a certain degree after heating.
- On the outer periphery of core where radiation in the shroud direction is large and the fuel temperature rise is not so high, pellets or the like could possibly remain.

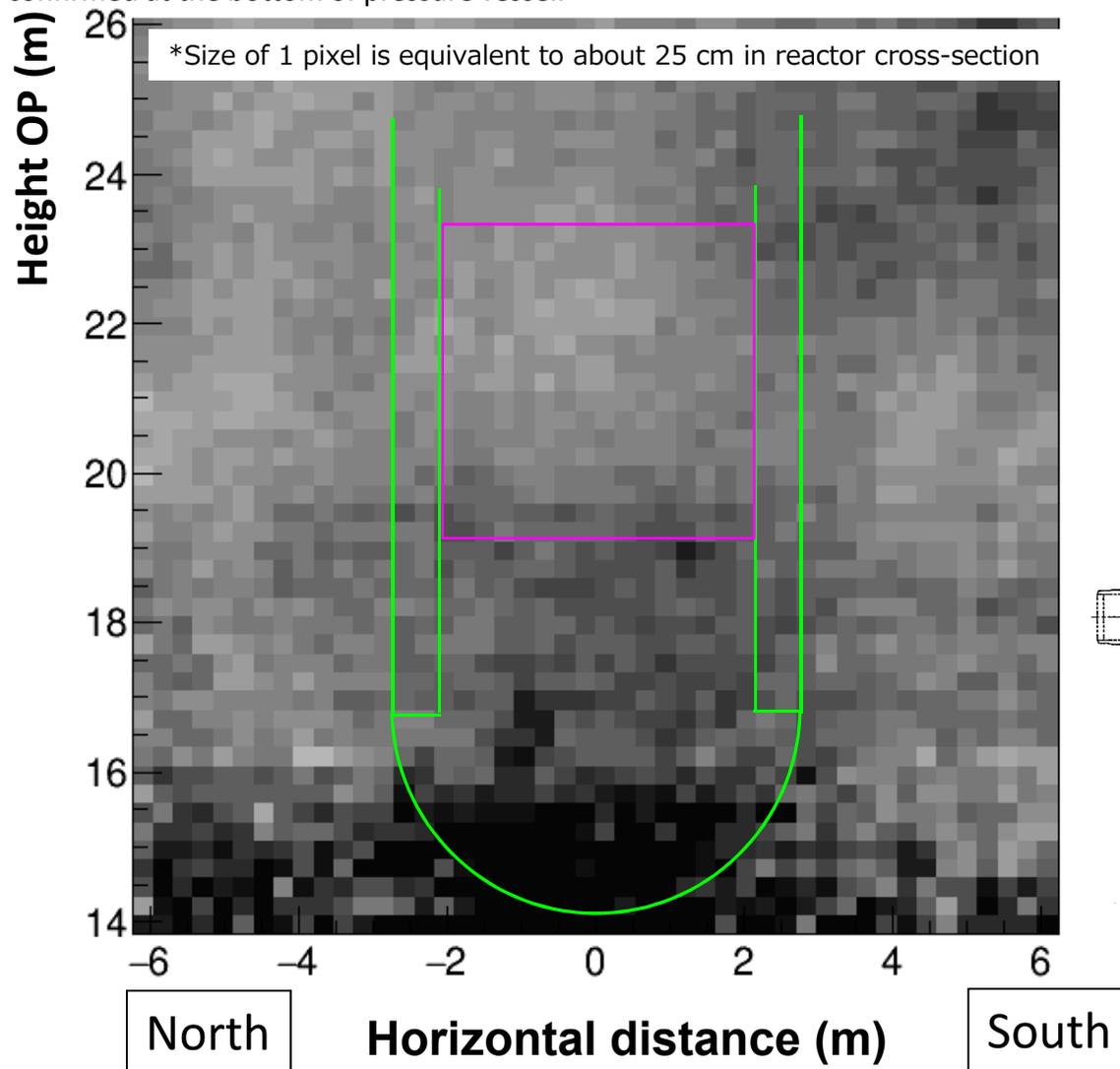
2-11 Estimation of Pressure Vessel Lower Part



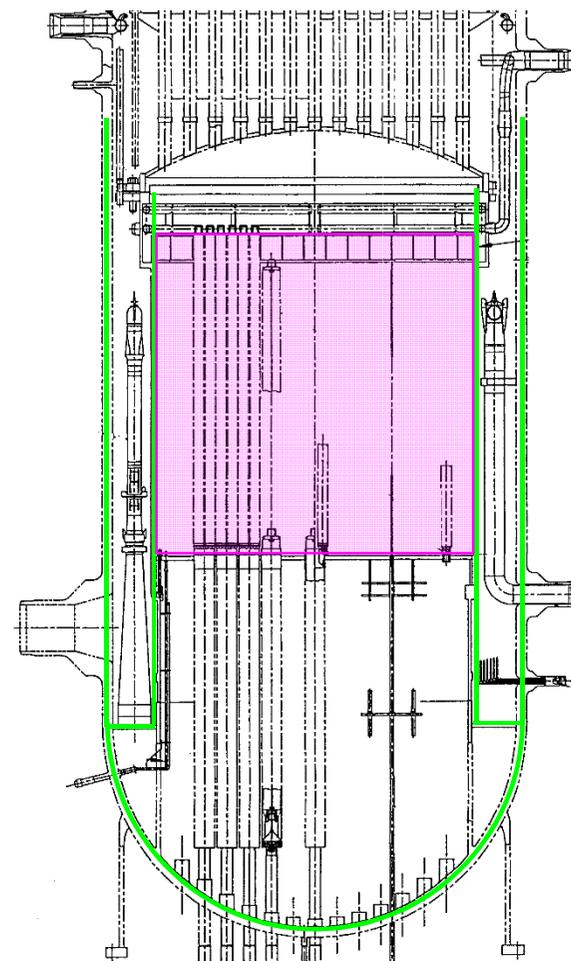
▪ A shadow of the high density material has been confirmed at the bottom of pressure vessel by muon measurements. Possibility that fuel fallen in the lower plenum remains at the bottom of RPV

2-12 Result of Muon Measurement

- A shadow of the high density material that is considered to be fuel debris has been confirmed at the bottom of pressure vessel.



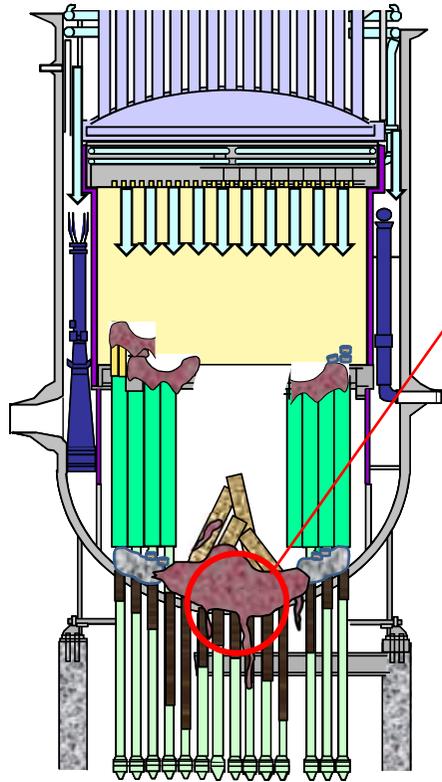
(Measurement result as of July 22, 2016)



Structure of pressure vessel Lower Part

Considered that fuel fallen in the lower plenum remains at the bottom of RPV.

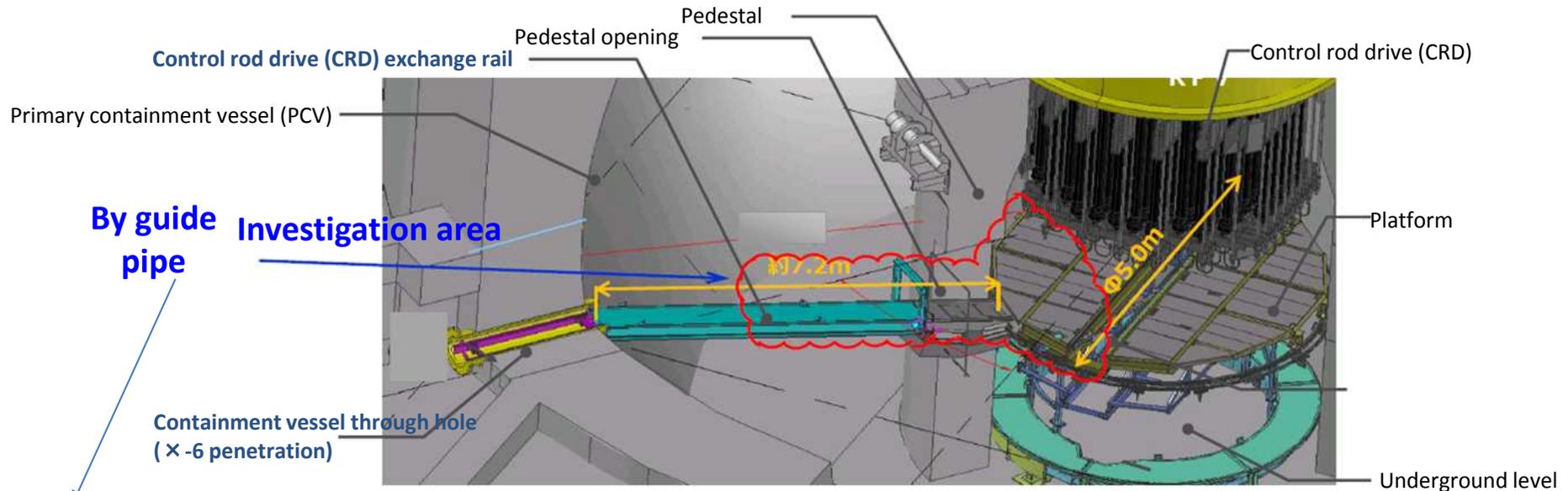
2-13 Estimation of Pressure Vessel Lower Part



- CRD on the outer periphery was confirmed during PCV internal investigation, and the holes on grating panel and some melting material were observed which indicate RPV bottom failure (not large, center and off-center position)

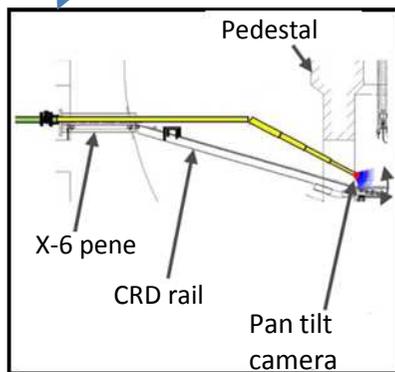
2-14 Result of Unit 2 Containment Internal Investigation

In January and February 2017, investigations were conducted on containment vessels to check the status of debris falling on the pedestal platform and to control rod drive (CRD) and the condition of pedestal structure.



Investigation area inside the pedestal

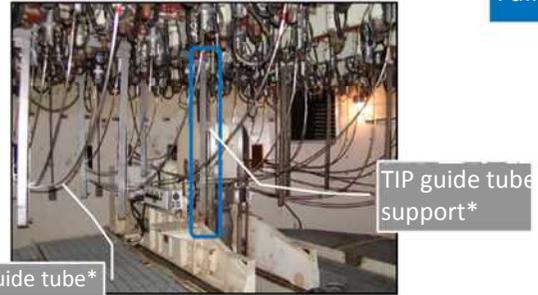
Collected much information on the situation in pedestal from the results of processing images taken during the investigation with the guide pipe as shown on the left.



2-15 Result of Unit 2 Containment Internal Investigation

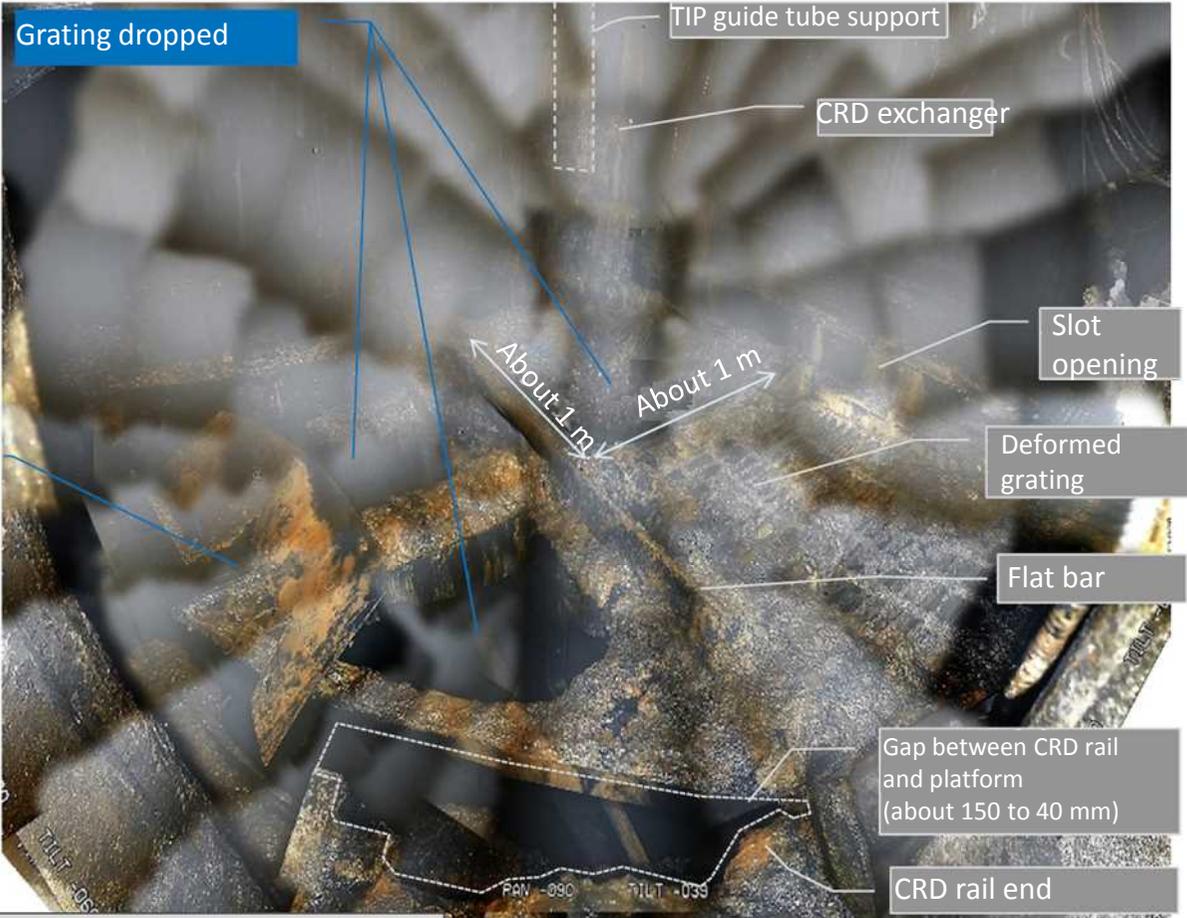


(Reference) Inside the pedestal for Unit 5



(Reference) Photo of regular inspection inside the pedestal for Unit 2
 *For inspection of Unit 5, its TIP guide tube, and TIP guide tube support have been removed

Fallout



Note: Joints remain since the individually sharpened images are patched (the same applies for the next and subsequent pages)

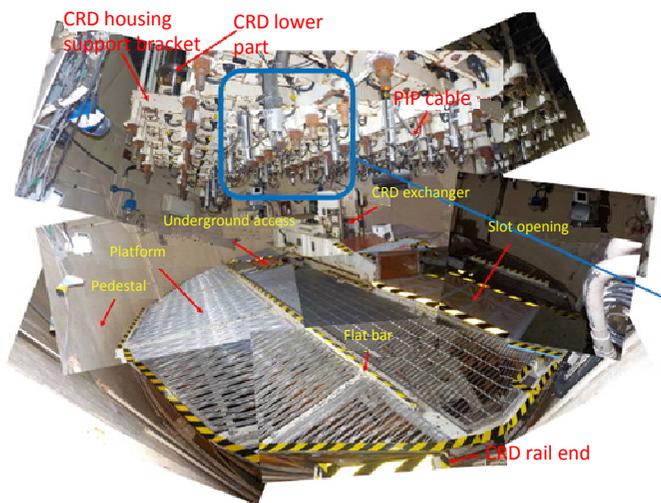
TIP (Traversing In-core Probe) : Used for LPRM calibration

Images provided by International Research Institute for Nuclear Decommissioning (IRID)
 Image processed by TEPCO Holdings, Inc.

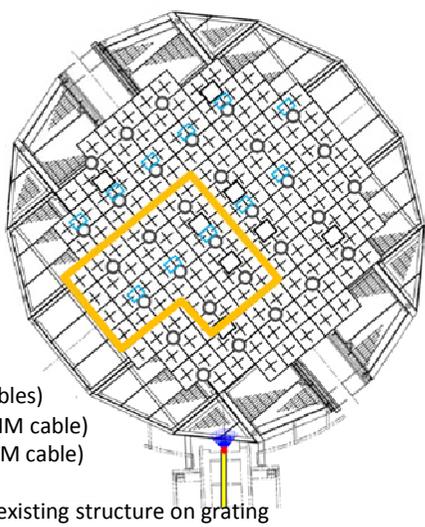
Image of inside the pedestal looked through from CRD rail
 Sharpening process allows us to view the position far away from camera

- Grating dropped on the left side of slot opening
- Steam rises from lower grating
- Grating not dropped out is observed to have adhered deposits and deformation

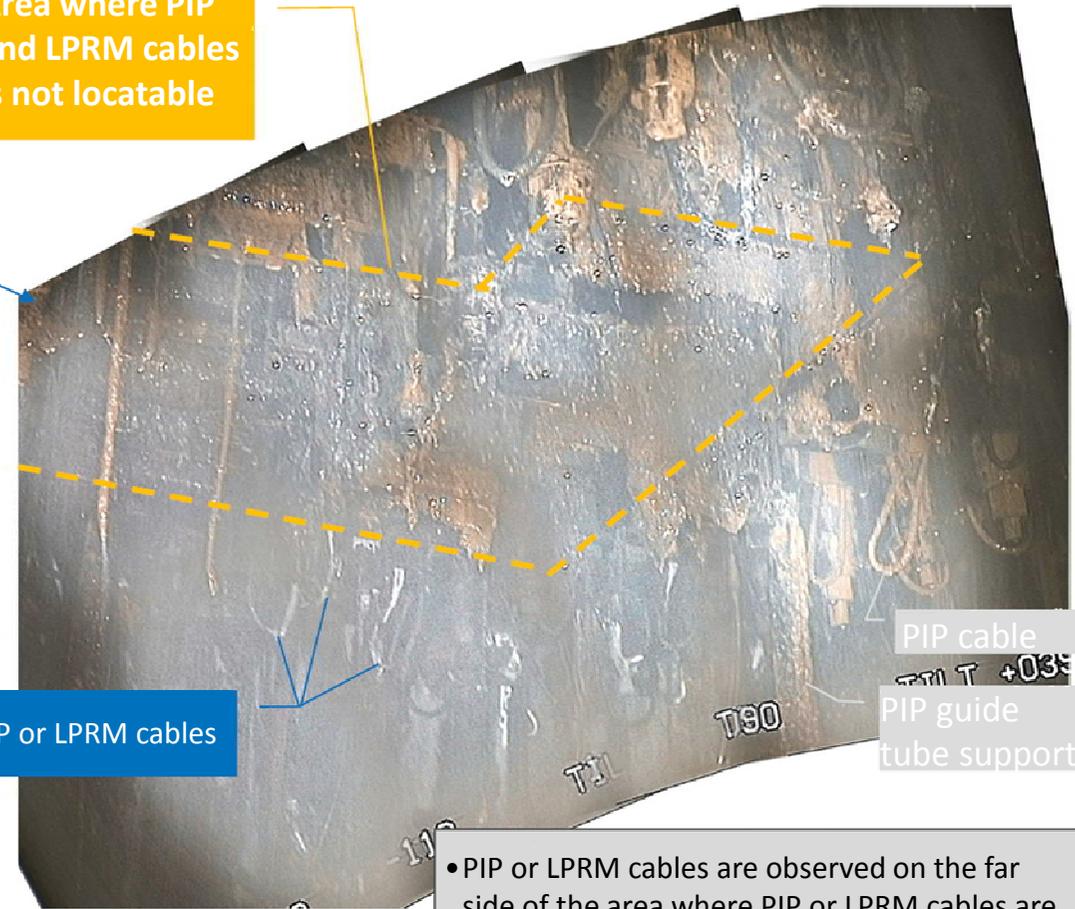
2-16 Result of Unit 2 Containment Internal Investigation



(Reference) Inside the pedestal for Unit 5

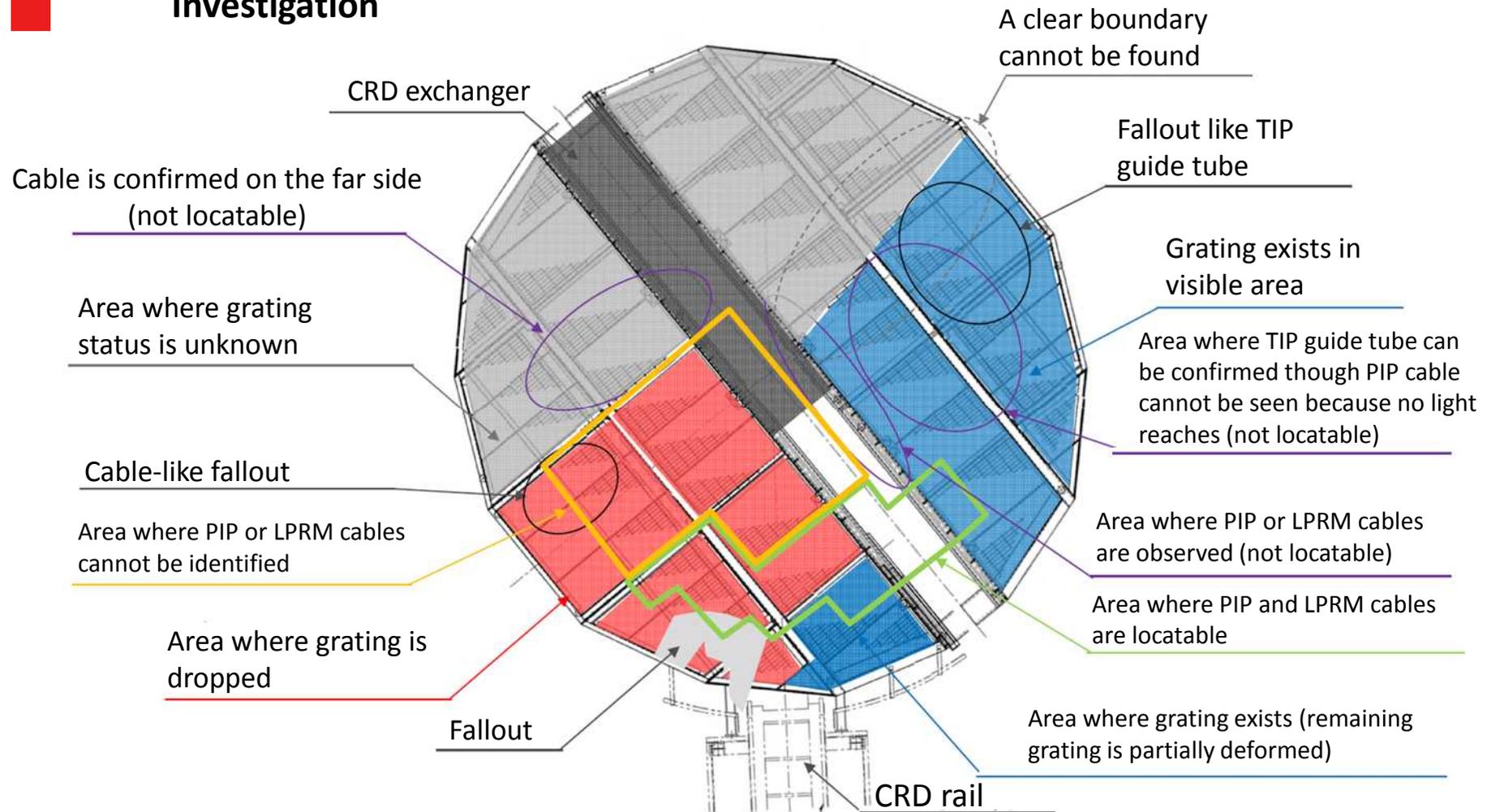


Area where PIP and LPRM cables is not locatable



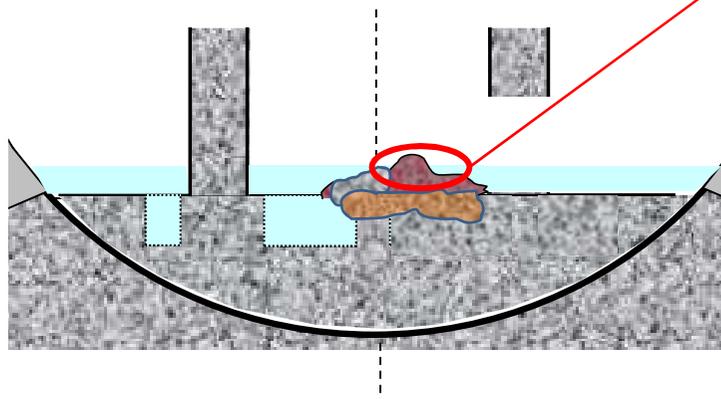
• PIP or LPRM cables are observed on the far side of the area where PIP or LPRM cables are not locatable

2-17 Result of Unit 2 Containment Internal Investigation



- The area where grating dropped and the area where cables under the pressure vessel are damaged generally match.
- Deformed grating could possibly be associated with fuel debris fallen and damaged points other than those in the center of pressure vessel.

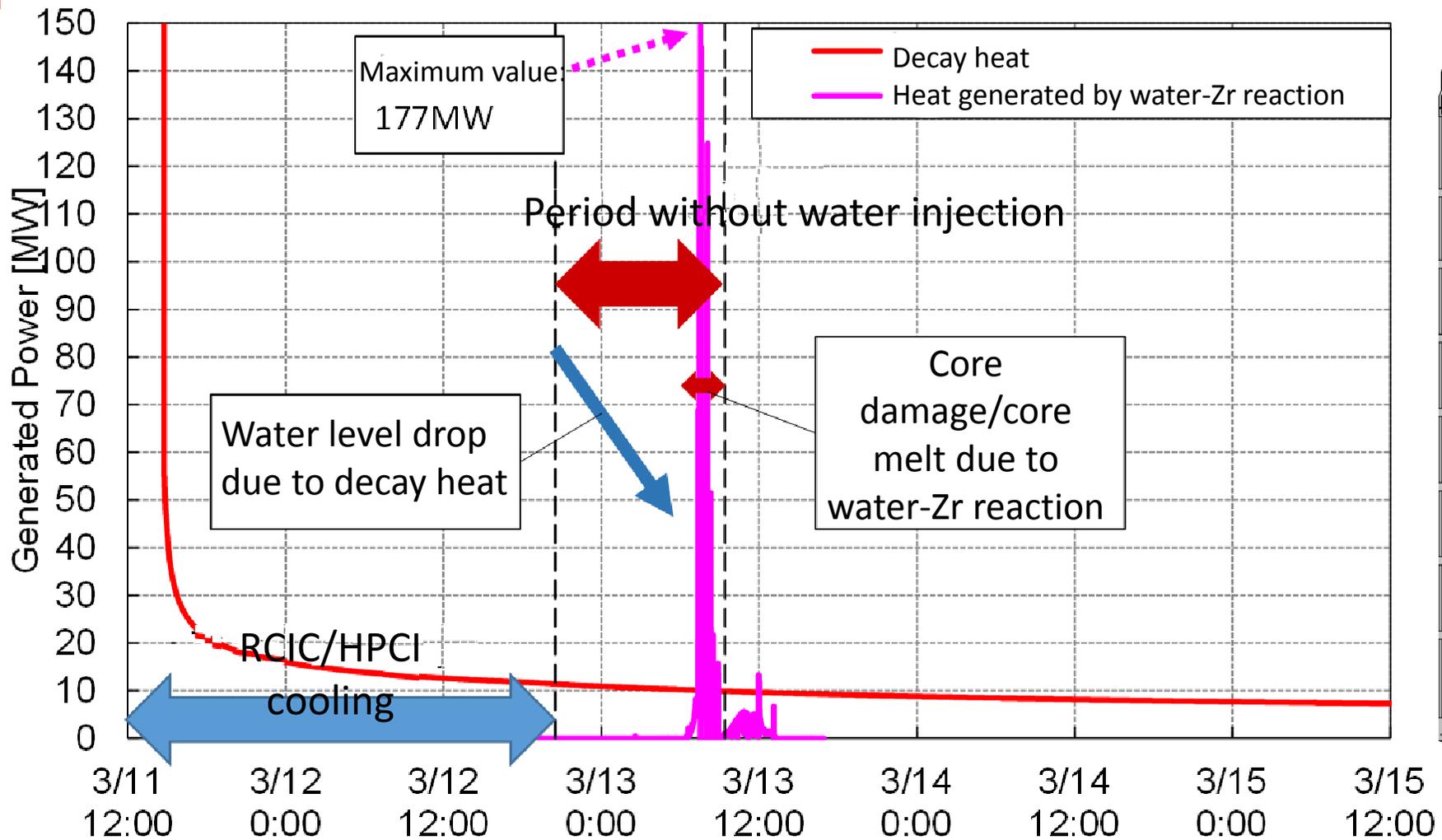
2-18 Estimation of Pedestal Part



- Observed steam rising during the PCV internal investigation.

3. Unit 3 Estimation Diagram and its Basis

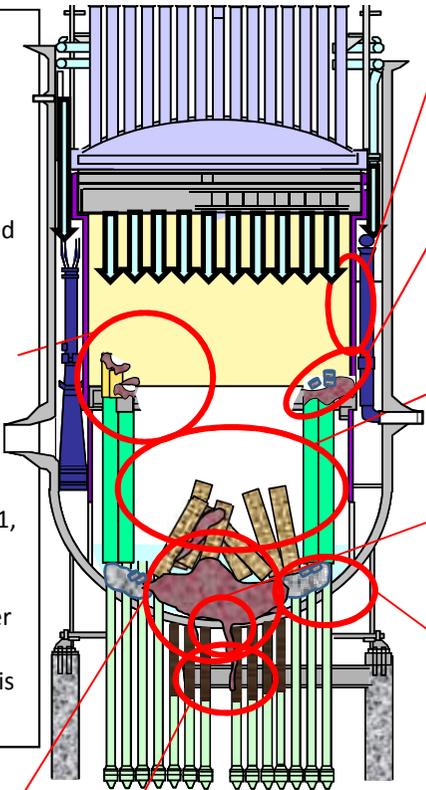
3-1 Decay Heat of Unit 3 and Heat Generated by Water-Zr Reaction



Unit 3 became uncoolable because its HPCI stopped, which resulted in core damage/meltdown during a no-injection period. Fire engine water injection made no contribution to water-Zr reactions

3-2 Unit 3 Estimation Diagram

- Assuming the energy amount from PCV pressure increased due to hydrogen generation, most of fuels are estimated to have melted
- Since no temperature increase was observed in each part of RPV when injection from CS system was stopped from 9 to 24 in December 2013 (keeping constant total flow by increasing flow from FDW), the amount of fuel debris in core is estimated to be small (smaller than that in Unit 2)
- Because temperature at RPV lower head dropped when water injection from CS system started (September 1, 2011), fuel debris is estimated to in lower plenum
- Fuel rods can exist only on the outer periphery if any
- Estimated to be general oxide debris solidified with molten fuel



- Currently, the shroud has two possibilities: sound or damaged.

- Possibility of pellets remaining on the outer periphery because the fuel temperature rise on the outer peripheral may not be so high

- If heat transfer from high temperature molten debris is small, CRGT will be unmelted but remains

- Lower part of pressure vessel can be damaged because MCCI is considered to occur

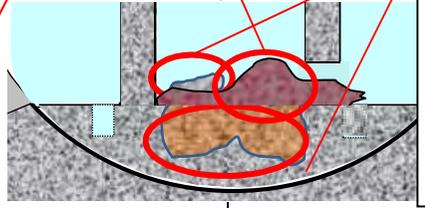
- Possibility of accumulation in stagnant spot when there are particulate debris and pellets

- In addition to Unit 4, Unit 3 also experienced an explosion to which hydrogen generated by MCCI could possibly have contributed.
- Meanwhile, DW spraying was performed for more than 1 h from 7:39 on March 13 in response to the accident. Diffusion of fuel debris could have been suppressed considering a water level on DW floor during pressure vessel breakage.
- Estimated that fuel debris diffuses outside the pedestal through the pedestal opening but has not reached shell attack
- If water is pooled on PCV floor, particulate debris can be formed.
- Possibility of accumulation in stagnant spot when there are particulate debris

- Fuel fallen in the lower plenum could remain at the bottom of RPV
- A time delay before temperature rise in response to reduction of water injection volume indicates a possibility of water retained in the pressure vessel

- Possibility of part of fuel debris solidified without causing MCCI

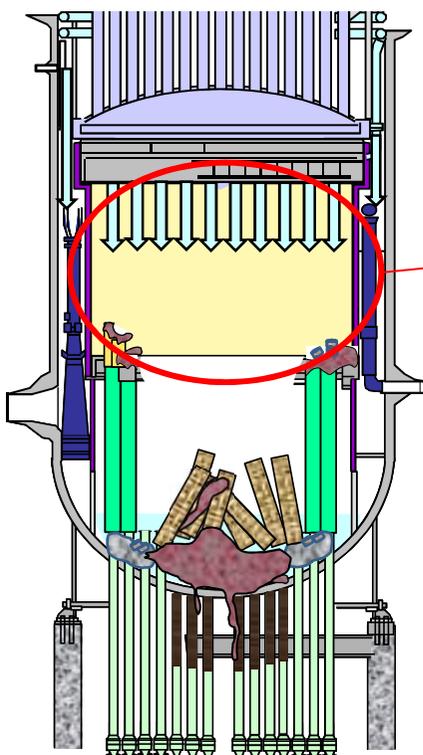
- Possibility that debris intrude in CRD accompanying breakage of CRGT



- Fuel rod
- Oxide debris (porous)
- Granular debris
- Concrete mixed debris
- Sound CRGT
- Damaged CRGT
- Sound CRD
- CRD (debris inside)
- Sound shroud
- Pellets
- Burning fuel*
- Oxide debris*
- Heavy metal debris*
- Powder pellets*
- Clad residue*
- Molten core internals*
- Solidified B4C*
- Control rod mixture melts*

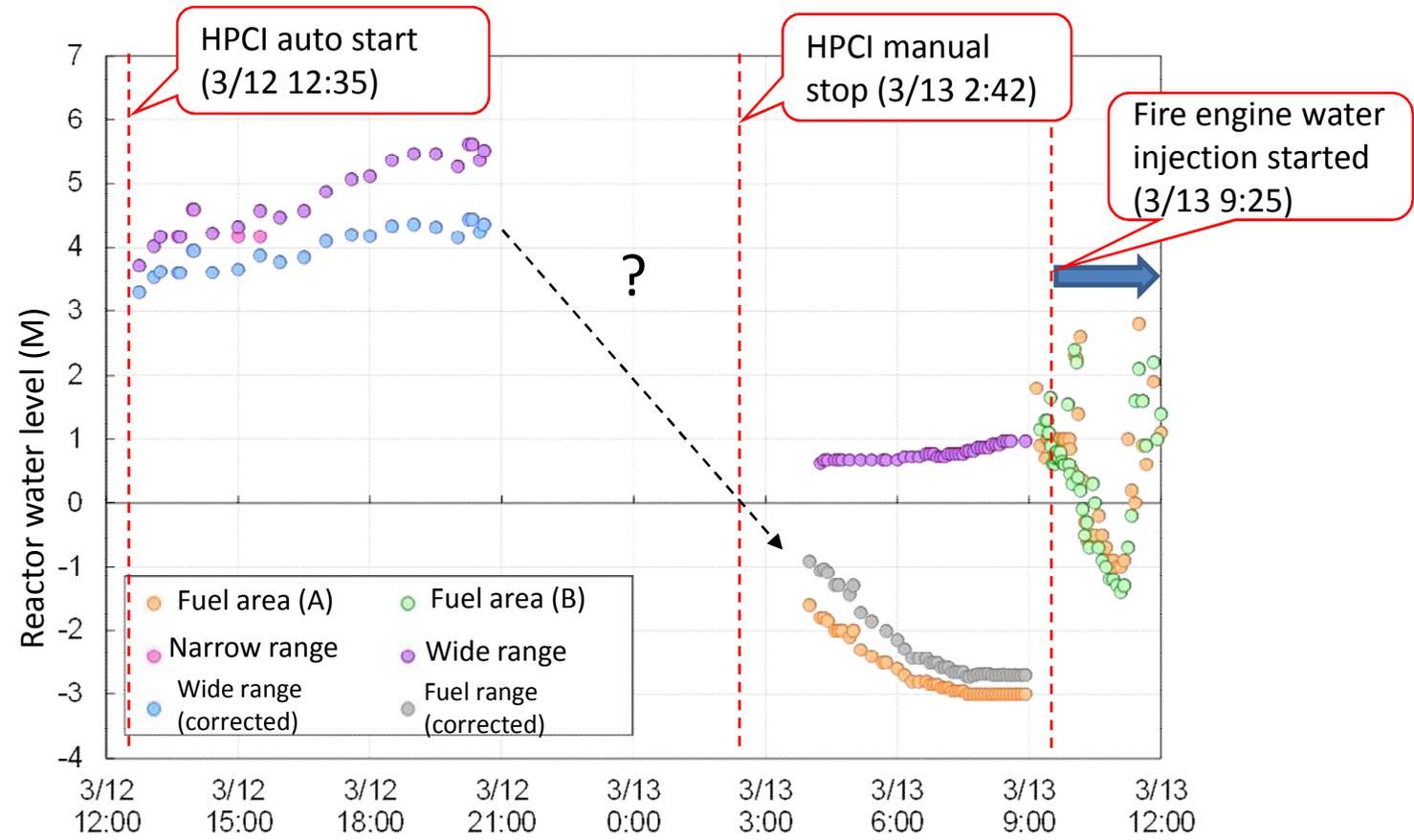
*Not used in Illustration of Estimated Unit 3

3-3 Estimated State of Core



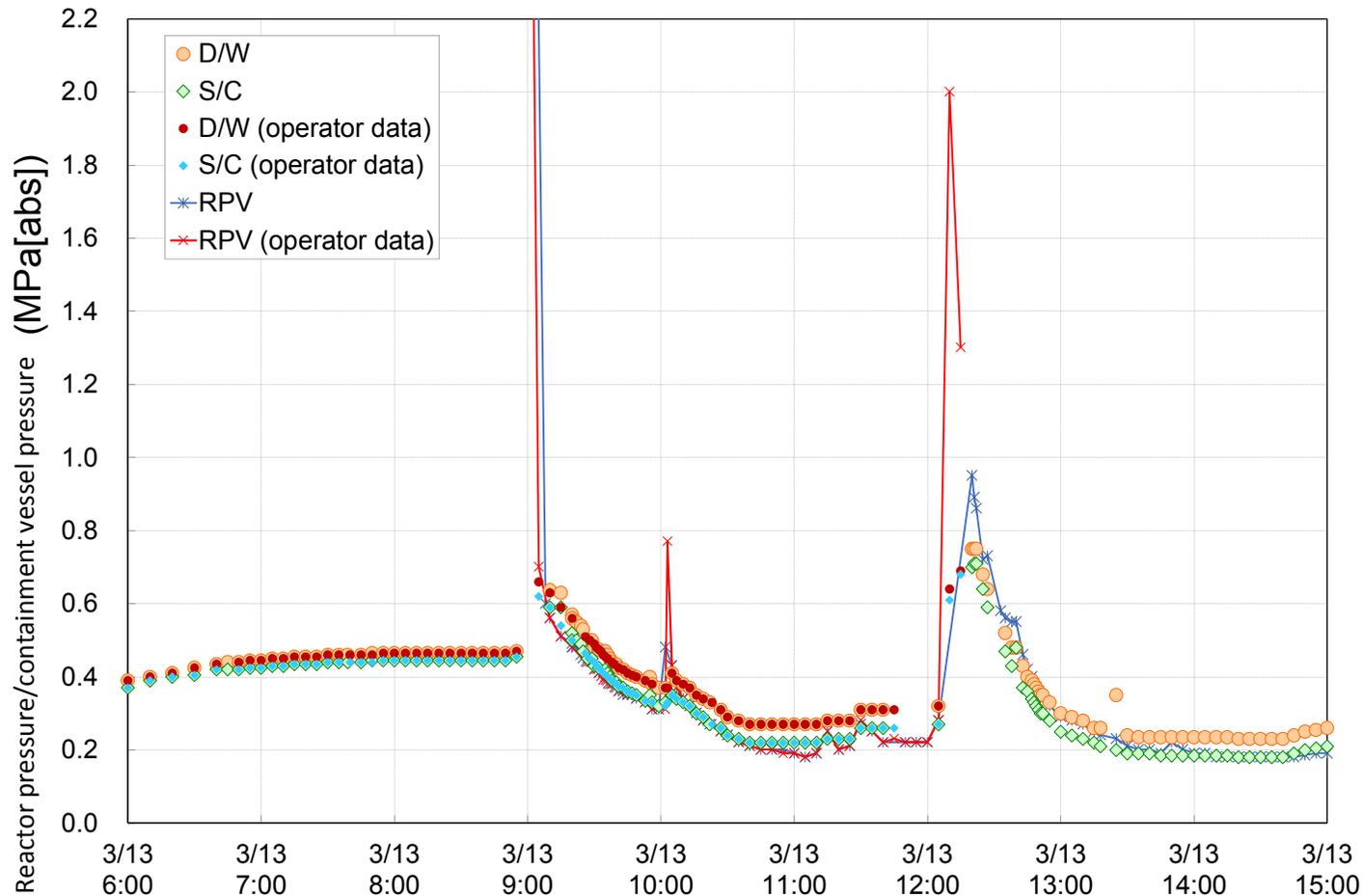
• Assuming the energy amount from the increased PCV pressure by hydrogen generation, it is estimated that most of fuels have melted

3-4 Change in Reactor Water Level



- Before HPCI was manually stopped, the reactor pressure was lower than the HPCI operable range and the HPCI discharge pressure was also low, which suggests a possibility that water injection into the nuclear reactor could be insufficient before stopping HPCI
- Fire engine water injection started at 9:25 on March 13, damage to fuel is considered to have progressed during the period when injection was not allowed.

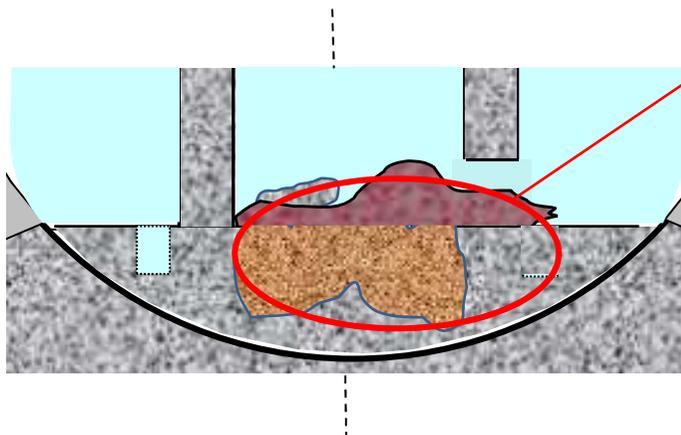
3-5 Behavior of Reactor Pressure/Containment Vessel Pressure



At around 9 o'clock and past 12 o'clock on March 13, 2011, the containment pressure has increased significantly.

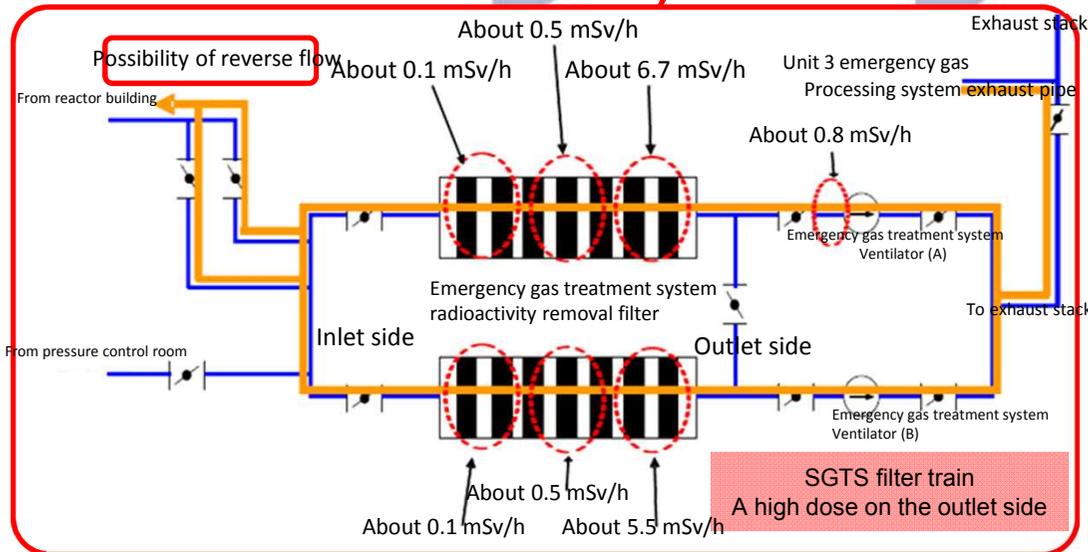
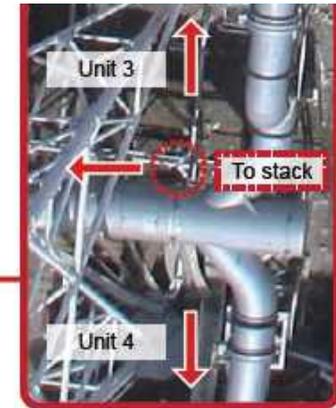
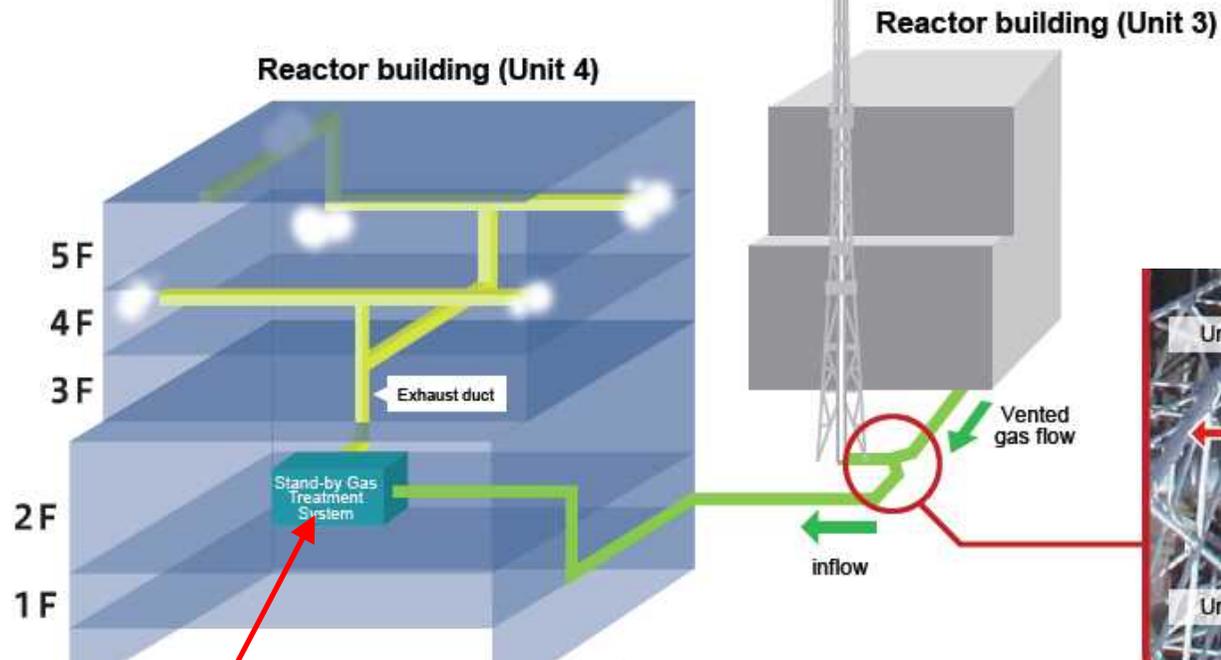
Like Unit 2, this could be caused by a large amount of hydrogen generated there and most of the fuel could have melted.

3-6 Estimation of Pedestal Part



- In addition to Unit 4, Unit 3 also experienced an explosion to which hydrogen generated by MCCI could possibly have contributed.
- Meanwhile, DW spraying was performed for more than 1 h from 7:39 on March 13 in response to the accident. Diffusion of fuel debris could have been suppressed considering a water level on DW floor during pressure vessel breakage.
- Estimated that fuel debris diffuses outside the pedestal through the pedestal opening but has not reached shell attack.

3-7 Flow into Unit 4 from Unit 3

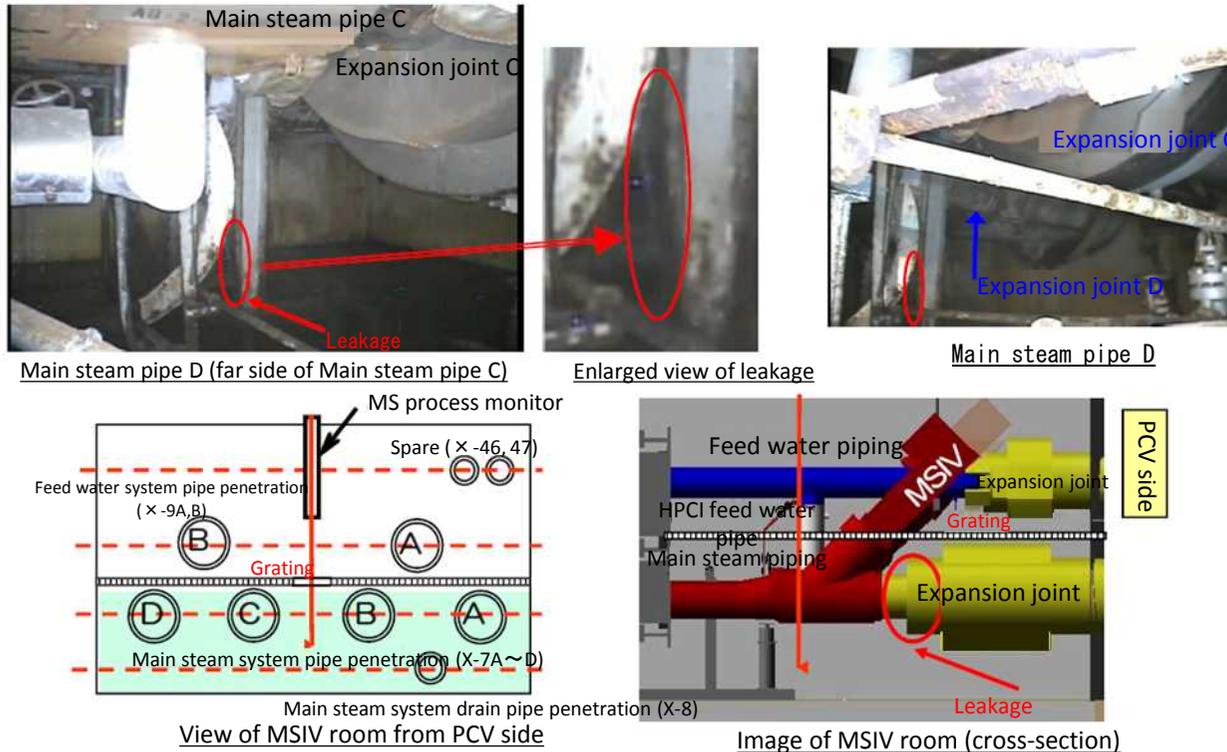


In Unit 4, hydrogen explosion occurred in the reactor building around 6:14 on March 15. The vent gas of Unit 3 is considered to be getting into the Unit 4 reactor building.

Units 3 and 4 exploded due to hydrogen generated in Unit 3. In addition to the hydrogen generated by water-Zr reaction, the hydrogen generated by MCCI could possibly have contributed to explosion.

3-8 Investigation Result of MSIV Room

- Leakage is observed from the periphery of the expansion joint of main steam pipe D.
- Leaked water is estimated to be the volume of 2 to 4 pencils.



- At Unit 3, water level in the containment vessel is relatively high (about 6 m) compared to Units 1 and 2. May 15, 2014, after the investigation of MSIV room, leakage of water is observed from the periphery of the expansion joint of main steam pipe D.
 → Because the containment vessel maintains a high water level, it is not considered to have reached shell attack.

4 Summary and Future Plan

[Summary]

- TEPCO has been making the best effort to estimate the fuel debris distribution in Unit 1 to 3 based on the various information and the latest knowledge (for example: the data obtained during the accident, the data obtained during the cooling of fuel debris after the accident, the results of on-site investigation, and the results of the accident progression analysis).

[Future Plan]

- TEPCO will continue to collect new information acquired in on-site investigation etc. and reflect it appropriately to the estimation.
- In some cases, it may be necessary to change the estimations in this presentation. But TEPCO will improve the understanding of the status inside RPV and PCV at Fukushima Daiichi NPS through these efforts and will use it to determine the policies and methods for the fuel debris removal.



Reference : Glossary

BWR : Boiling Water Reactor

CRD : Control Rod Drive

CRGT : Control Rod Guide Tube

CS : Core Spray

D/W : Drywell

FDW : Feed Water

GOTHIC : Generation of Thermal Hydraulic Information in Containments

HPCI : High Pressure Coolant Injection System

HVH : House Ventilation and Heating System

IC : Isolation Condenser

LPRM : Local Power Range Monitor

MAAP : Modular Accident Analysis Program

MCCI : Molten Core Concrete Interaction

MSIV : Main Steam Isolation Valve

PCV : Primary Containment Vessel

PIP : Position Indicator Probe

PLR : Primary Loop Recirculation System

RPV : Reactor Pressure Vessel

RCIC : Reactor Core Isolation Cooling System

RCW : Reactor Building Closed Cooling Water System

S/C : Suppression Chamber

SRV : Safety Relief Valve

TIP : Traversing Incore Probe System

Zr : Zirconium