Supporting information 2

Estimation of status inside reactor pressure vessels and containment vessels after the accident at the Fukushima Daiichi Nuclear Power Station

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1. Introduction

1.1. Overview

The March 11, 2011, Tohoku Chihou Taiheiyou Oki Earthquake and Tsunami (also known as the Off the Pacific Coast of Tohoku Earthquake and Tsunami of the Great East Japan Earthquake and Tsunami) caused a situation at the Fukushima Daiichi Nuclear Power Station (NPS) that greatly exceeded the design base event and also exceeded the degree of multiple failures assumed in the development of accident management measures. As a result, although the plant succeeded in "stopping" the reactors, it lost the functions related to "cooling", leading to the severe accident in Units 1 through 3.

TEPCO continues to estimate the conditions inside the reactor pressure vessels and containment vessels for the purpose of safe and efficient decommissioning work, including fuel debris retrieval, for Units 1 to 3, where the severe accident occurred. This estimate is based on the "Estimation of the state of the reactor core and containment vessel of Fukushima Daiichi NPS Units 1 to 3 and examination of unconfirmed and unsolved issues (hereinafter referred to as "Examination of Unsolved Issues")" conducted by TEPCO or the Ministry of Economy, Trade and Industry subsidy for decommissioning and contaminated water countermeasures implemented in 2016 and 2017 (referred to as a “Project to Improve Internal Status Understanding”).

This report summarizes the updated knowledge obtained in the course of the examination of the status estimation in the reactor pressure vessels and containment vessels of the Fukushima Daiichi Nuclear Power Station Units 1-3.

1.2. Abbreviations

The abbreviations used in this report for nuclear power systems are as follows.

AC: Atmospheric Control
CRD: Control Rod Drive
CRGT: Control Rod Guide Tube
CS: Core Spray System
D/W: Dry Well
FDW: Reactor Feed Water System
HPCI: High Pressure Core Injection System
IC: Isolation Condenser
IRM: Intermediate Range Monitor
LPRM: Local Power Range Monitor
MCCI: Molten Core Concrete Interaction

MSIV: Main Steam Isolation Valve
PCV: Primary Containment Vessel
PLR: Primary Loop Recirculation System
RCIC: Reactor Core Isolation Cooling System
RCW: Reactor Building Cooling Water System
RHR: Residual Heat Removal System
RPV: Reactor Pressure Vessel
SAMPSON: Severe Accident Analysis Code with Mechanistic, Parallelized Simulations Oriented towards Nuclear Fields
S/C: Suppression Chamber
SGTS: Stand-by Gas Treatment System
SHC: Shutdown Cooling System
SRM: Source Range Monitor
SRV: Safety Relief Valve
SV: Safety Valve

1.3. Treatment of O.P. in this report

In view of the ground subsidence caused by the earthquake at the Fukushima Daiichi NPS, the conventional O.P. (Onahama Port construction reference plane) is no longer used for the installation height of equipment and facilities, and the T.P. (Tokyo Bay means sea level) notation is used instead.

However, since this report is a summary of the status estimation efforts conducted so far in the RPV and PCV and is not intended for current plant construction or management, basically no problems will arise if the O.P. notation is used. Therefore, the O.P. notation based on pre-earthquake standards is used as-is.

In the case of applying the contents of this study to the actual operations of Fukushima Daiichi NPS in the future, it will be necessary to convert the pre-earthquake O.P. notation to T.P. notation using the following equation.

Turbine Building of Unit 1: "O.P. before earthquake" -1457mm
Turbine Building of Unit 2: "O.P. before earthquake" -1452mm
Turbine Building of Unit 3: "O.P. before earthquake" -1437mm
Turbine Building of Unit 4: "O.P. before earthquake" -1439mm
Reactor buildings of Units 1 to 4: "Pre-disaster O.P. notation" -1436mm＊
(＊The conversion for the reactor building is currently being replaced by the survey results of the on-site reference point.)

2. Time series related to the accident response to the Fukushima Daiichi NPS accident

In estimating the status in the RPV and PCV, it is important to understand the accident progression of Units 1-3.

The time series related to the accident response, which is important for understanding the accident progression, was compiled, and organized in the "Fukushima Nuclear Accident Investigation Report" (hereinafter referred to as the "Accident Investigation Report") on June 20, 2012.

Since the release of the Accident Investigation Report, TEPCO has continued to conduct investigations and examinations related to the progress of the accident, and has published them as examinations of unresolved issues.

Therefore, in this report, in addition to the results of the examination of unresolved issues, the descriptions are enhanced by reflecting the information published in the Accident Investigation Report, etc., such as information on reactor cooling, water injection, and PCV venting.

Details of the updated time series of events for Units 1-3 are shown in Appendices 1 to 3 of this document.

3. Outline of condition estimation in the reactor pressure vessels (RPVs) and containment vessels (PCVs)

Since the accident at the Fukushima Daiichi NPS, TEPCO has continued its efforts to estimate the conditions inside the RPVs and PCVs. When the first estimate was announced in November 2011 and after the cold shutdown state was achieved in December 2011, the company continued working on their estimation in order to contribute to the decommissioning of the reactors, including the removal of fuel debris, and using the knowledge obtained through the estimation for implementing safety measures for other existing reactors. In FY2016 and FY2017, the study was conducted in collaboration with the "Advancement of Comprehensive In-Reactor Status Understanding" project.

The estimation has proceeded through one or a combination of the following three approaches, which are complementary to each other (Figure 3-1).

- The approach to improve the reliability of the accident progression scenario analysis and the evaluation using the analysis code, and to advance the estimation.
- The approach to deepen the understanding of the phenomena through data analysis and inverse problem analysis to advance the estimation.
- The approach to provide information obtained from on-site investigations to advance the

estimation.

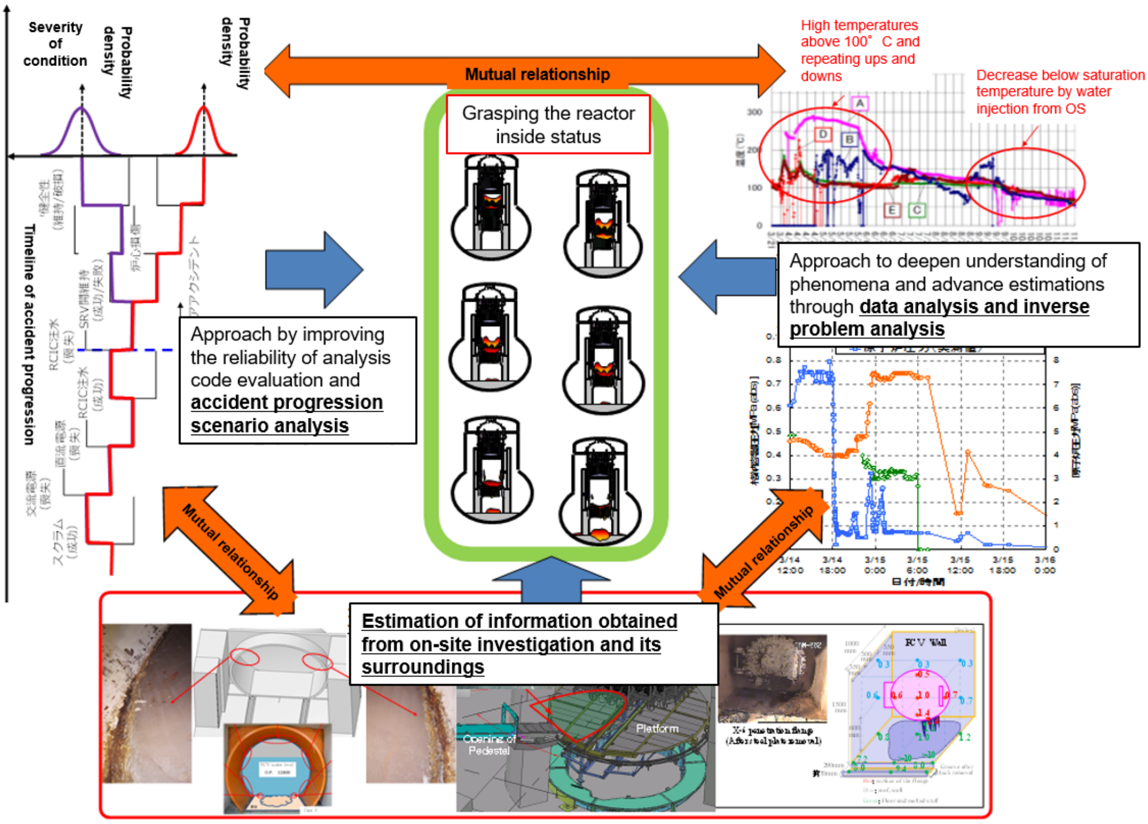


Figure 3-1　Three approaches to conducting an estimation

The estimation results have been updated at the following occasions. This report describes how updating was done on each of these occasions; and the changes of the estimates are described in Section 4.

- Core Condition of Fukushima Daiichi NPS Units 1-3
  (November 30, 2011)
- Estimation of the state of the core and containment vessel of Fukushima Daiichi NPS Units 1-3 and examination of unresolved issues, 1st Progress Report
  (December 13, 2013)
- Estimation of the state of the core and containment vessel of Fukushima Daiichi NPS Units 1-3 and examination of unresolved issues, 2nd Progress Report
  (August 6, 2014)
- Estimation of the state of the core and containment vessel of Fukushima Daiichi NPS Units 1-3 and examination of unresolved issues 3rd Progress Report
  (May 20, 2015)

・ Estimation of the state of the core and containment vessel of Fukushima Daiichi NPS Units 1-3 and examination of unresolved issues 4th Progress Report
(December 17, 2015)
・ Ministry of Economy, Trade and Industry, FY2014 supplementary budget: Subsidy for decommissioning and contaminated water countermeasures project, "Advancement of comprehensive in-vessel status understanding" (at the start of the project)
(July 2016)
・ Ministry of Economy, Trade and Industry, FY2014 supplementary budget: Subsidy for decommissioning and contaminated water remediation projects, "Advancement of comprehensive in-vessel status monitoring" (at the end of the first year of the project)
(March 2017)
・ Estimation of the state of the core and containment vessel of Fukushima Daiichi NPS Units 1-3 and examination of unresolved issues 5th Progress Report
(December 25, 2017)
・ Ministry of Economy, Trade and Industry, FY 2015 supplementary budget: Subsidy for decommissioning and contaminated water countermeasures project, "Advancement of comprehensive in-vessel status understanding" (at the end of the second year of the project)
(March 2018)
・ Autumn Conference of the Atomic Energy Society of Japan, 2018
(September 5-7, 2018)

4. Changes of the estimation of the conditions inside the reactor pressure vessels and containment vessels of Units 1-3

This section presents the resulting estimation figures, which summarize the estimation for the first time and for each of the nine updating occasions described in Section 3, as well as the characteristics of the estimation, the findings that helped in the estimation (for the first estimation only), what was updated from the previous estimation (after the second estimation onward), and the reasons for the update from the previous estimation (after the second estimation onward). In addition, even if the estimation was made in advance, if information supporting the estimation was obtained on some occasion, this information was described.

4.1. Initial estimation (November 30, 2011)

4.1.1. Unit 1

The estimation as of November 30, 2011 is shown in Figure 4.1.1-1.

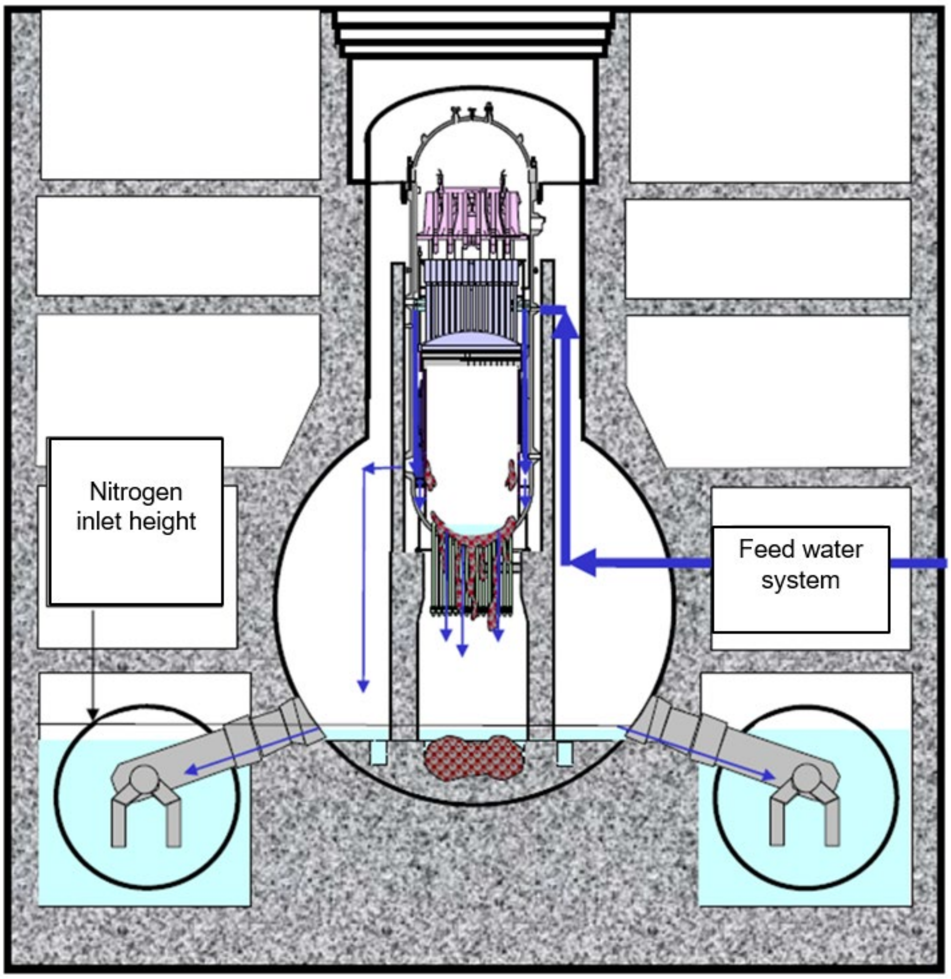


Figure 4.1.1-1 Unit 1 estimated as of November 30, 2011 [1-1]

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and it did not remain in the original core area. It is estimated that most of the fuel debris that fell into the lower plenum fell to the bottom of the PCV.

Regarding the water level in the D/W, it is estimated to be several tens of centimeters from the D/W floor.

○ Findings useful for estimation

The estimated diagram in Figure 4.1.1-1 was selected from the reactor damage patterns ① to ⑥ shown in Figure 4.1.1-2, and the condition of Unit 1 was estimated to be ⑥. The findings that were useful in selecting the pattern are described below.

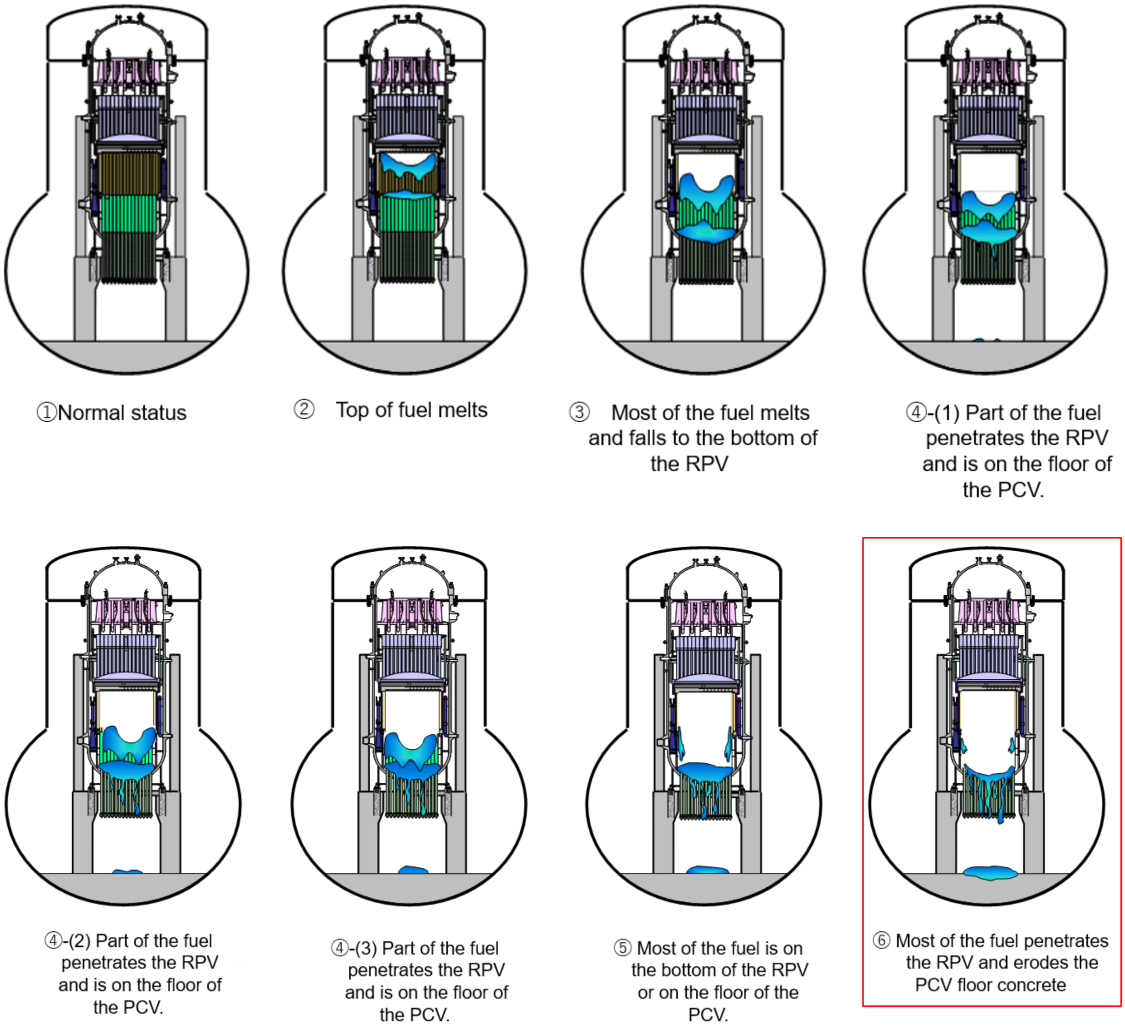


Figure 4.1.1-2 Patterns related to fuel debris distribution after the accident

・ Estimation from measured temperature and pressure

Figure 4.1.1-3 shows the temperature trends at representative points in Unit 1 10 days after the accident start. Despite the water injection method from the FDW nozzle, which does not directly pass through the core section, the measured temperature dropped below 100°C as of August, and it was estimated that the fuel had moved downward from the core section and was sufficiently cooled in the lower plenum of the RPV or the bottom of the PCV.

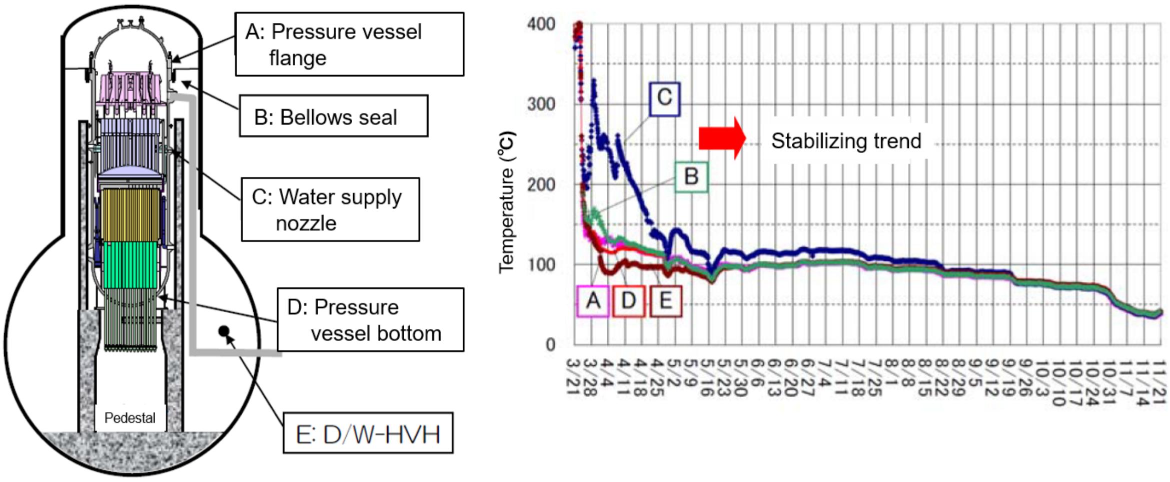


Figure 4.1.1-3　Temperature trend in Unit 1 [1-1]

・　Indicated value of reactor water level gauge

As shown in Figure 4.1.1-4, the reactor water level gauge is designed to maintain a constant water level by collecting water in a reference leg located outside the RPV and determining the water level by taking the difference (Hs-Hr) between the pressure generated by this water column and the pressure generated by the water level in the reactor. However, during an accident, the water in these instrumentation pipes may evaporate due to the high temperatures in the PCV, etc. If the water on the side of the reference leg evaporates, for example, the water level, which is the reference for comparison, will be lowered, resulting in a higher indication of the water level in the reactor (Figure 4.1.1-5).

In Unit 1, a temporary differential pressure gauge was installed on May 11, 2011, and water was injected into the reference leg and instrumentation piping to calibrate the reactor water level gauge. As a result, the reactor water level was found to be 5m below the top of active fuel (TAF). Therefore, it was estimated that the water level is not currently at the original fuel position, and it is unlikely that the fuel remains in its original position while maintaining its shape.

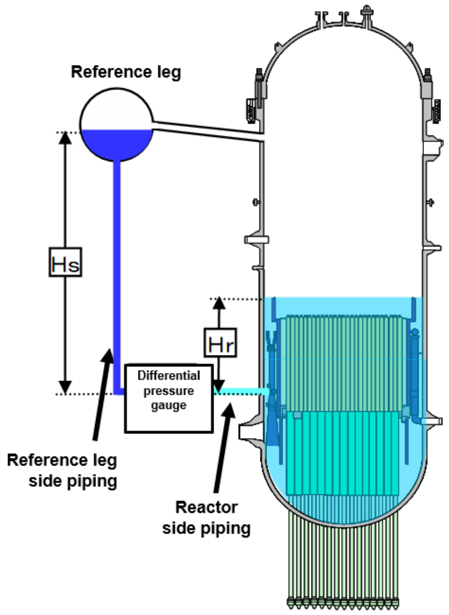


Figure 4.1.1-4　Schematic diagram of a reactor water level gauge [1-1]

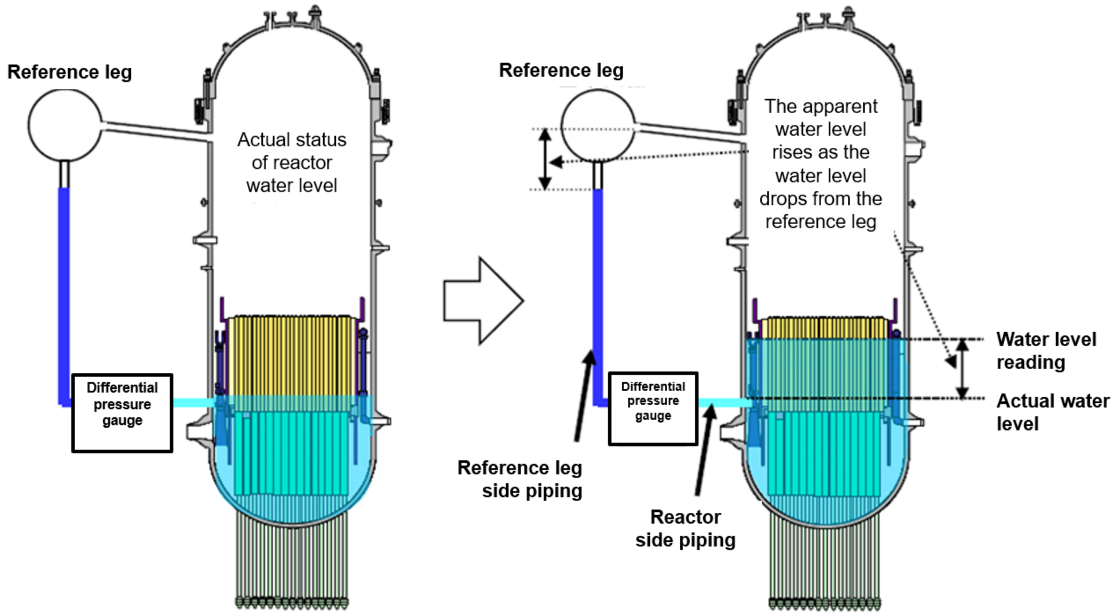


Fig. 4.1.1-5 Reactor water level gauge indication following a drop in water level in instrumentation piping [1-1]

・ RCW of Unit 1

In the reactor building of Unit 1, radiation dose was measured at various locations, and a high dose was measured in the RCW piping (Figure 4.1.1-6). The RCW is a closed-loop system mainly for cooling auxiliary equipment in the reactor building, and it is not designed with a release section inside the PCV. Therefore, contamination leading to dose rates as high as several hundred mSv/h is unlikely to occur under normal conditions. However, the RCW piping is laid over a wide area within the reactor building and it also plays a role in cooling the equipment in the PCV. Specifically, as shown in Figure 4.1.1-7, RCW piping is laid in the equipment drain pit at the bottom of the PCV for drain cooling. Therefore, the high level of contamination of the RCW piping in Unit 1 was most likely caused by fuel falling into the equipment drain pit and damaging the RCW piping. The damaged piping is considered to have caused steam or water to migrate into the RCW piping, with large amounts of radioactive materials occurring in the piping at the same time. However, if the RCW was damaged by fuel debris that fell into the PCV, water from the RCW piping may have entered the PCV and contributed to cooling the fuel debris.

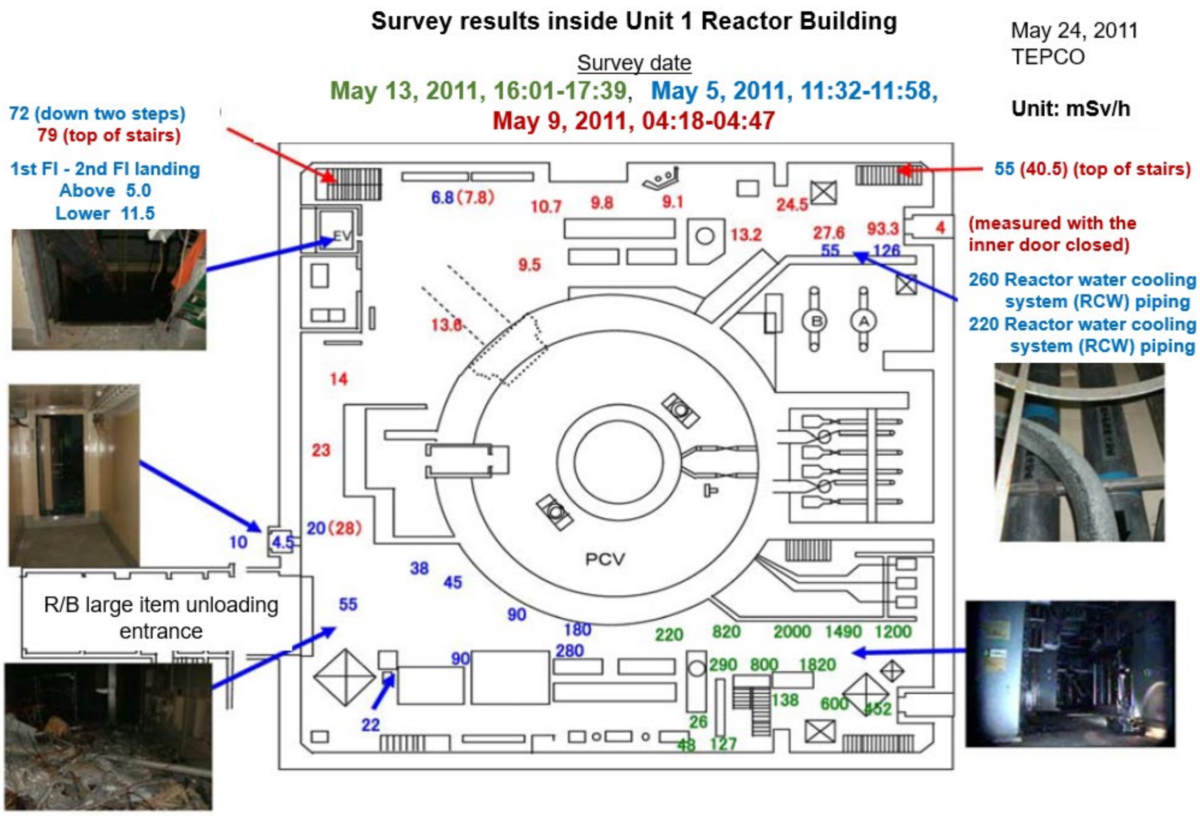


Figure 4.1.1-6 Results of reactor building dose survey for Unit 1 [1-1]

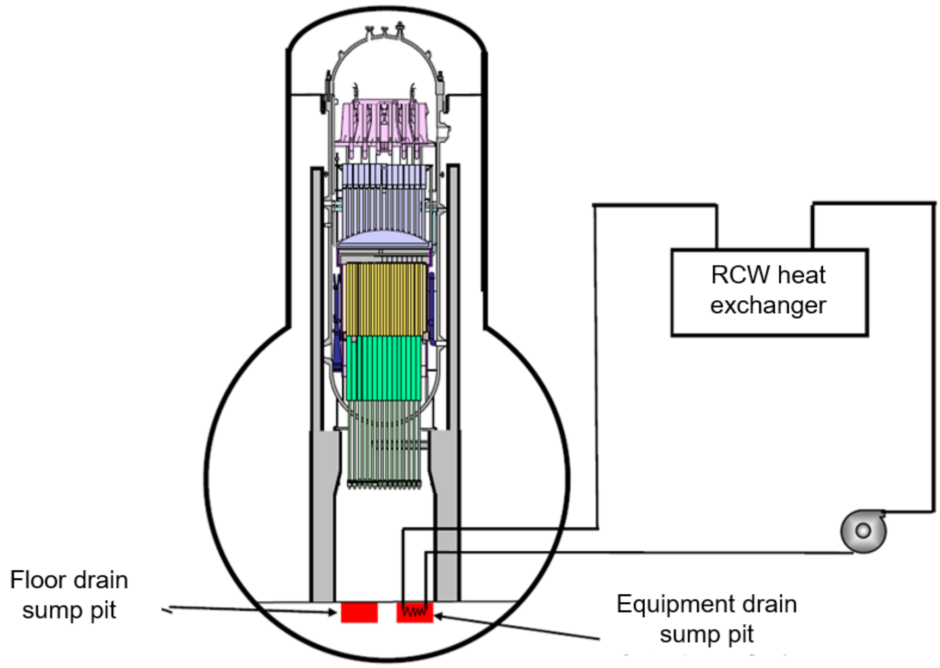


Figure 4.1.1-7 Schematic diagram of the RCW and equipment drain pit connections [1-1]

・ Water level of D/W

Figure 4.1.1-8 shows a graph of the D/W pressure and the nitrogen injection pressure that is measured to monitor the nitrogen injection status. If the nitrogen inlet is within the volume containing the gas phase, the nitrogen injection pressure shows the same behavior as the D/W pressure, but if the inlet is submerged, the pressure is higher than the D/W pressure because it requires a pressure that exceeds the water head pressure in addition to the D/W gas phase pressure. Figure 4.1.1-8 shows that after water injected into the Unit 1 reactor had increased on October 28, 2011, the nitrogen injection pressure exceeded the D/W pressure on about November 1, and the deviation became larger. Therefore, at that time, the D/W water level rose with the increase in water injection and exceeded the nitrogen inlet height, that is to say, the D/W water level was estimated to be in this vicinity.

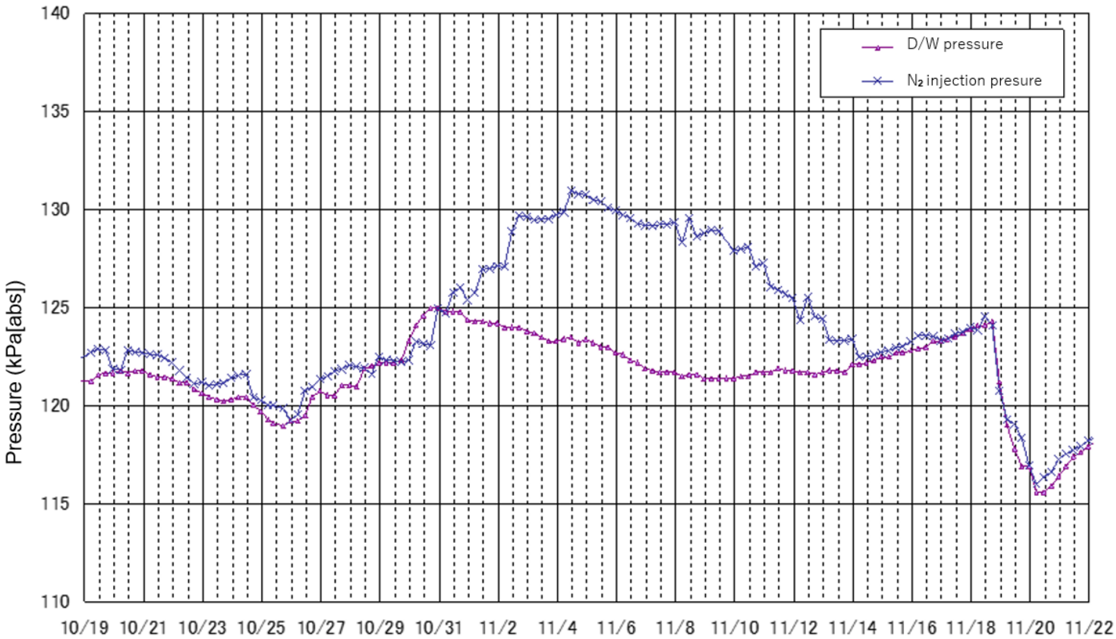


Figure 4.1.1-8 Change of D/W pressure and nitrogen injection pressure (2011) [1-1]

＊Regarding the D/W pressure data in the graph, the correct value is about 2kPa lower until 10/28 05:00, and then about 0.5kPa higher after 10/28 11:00. [1-2]

4.1.2. Unit 2

The estimation as of November 30, 2011 is shown in Figure 4.1.2-1.

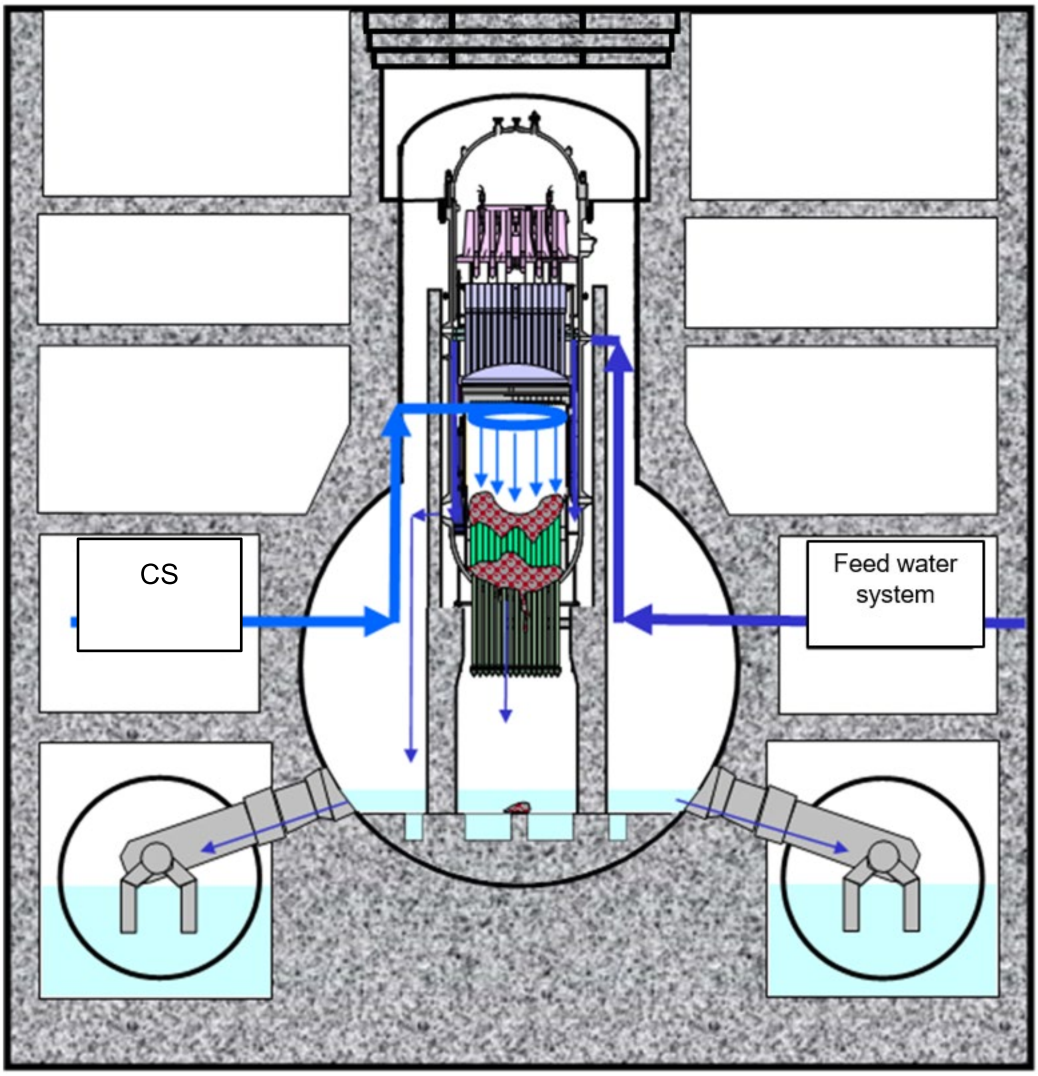


Figure 4.1.2-1 Unit 2 estimated as of November 30, 2011 [2-1]

For the estimation in Figure 4.1.2-1, the characteristics of the estimation and the findings that helped in the estimation are as follows.

○ Characteristics of estimation

Regarding the distribution of fuel debris, it is estimated that, after the accident, some part of the molten fuel remained in the core area and another part had fallen into the lower plenum of the RPV or to the bottom of the PCV.

Regarding the water level in the D/W, it is estimated that the fuel in the PCV is generally submerged.

○ Findings useful for estimation

The estimated figure in Figure 4.1.2-1 was selected from the reactor damage patterns of ① through ⑥ shown in Figure 4.1.2-2, and the condition of Unit 2 was estimated to be pattern ④-(1). The findings that were useful in selecting the pattern are described below.

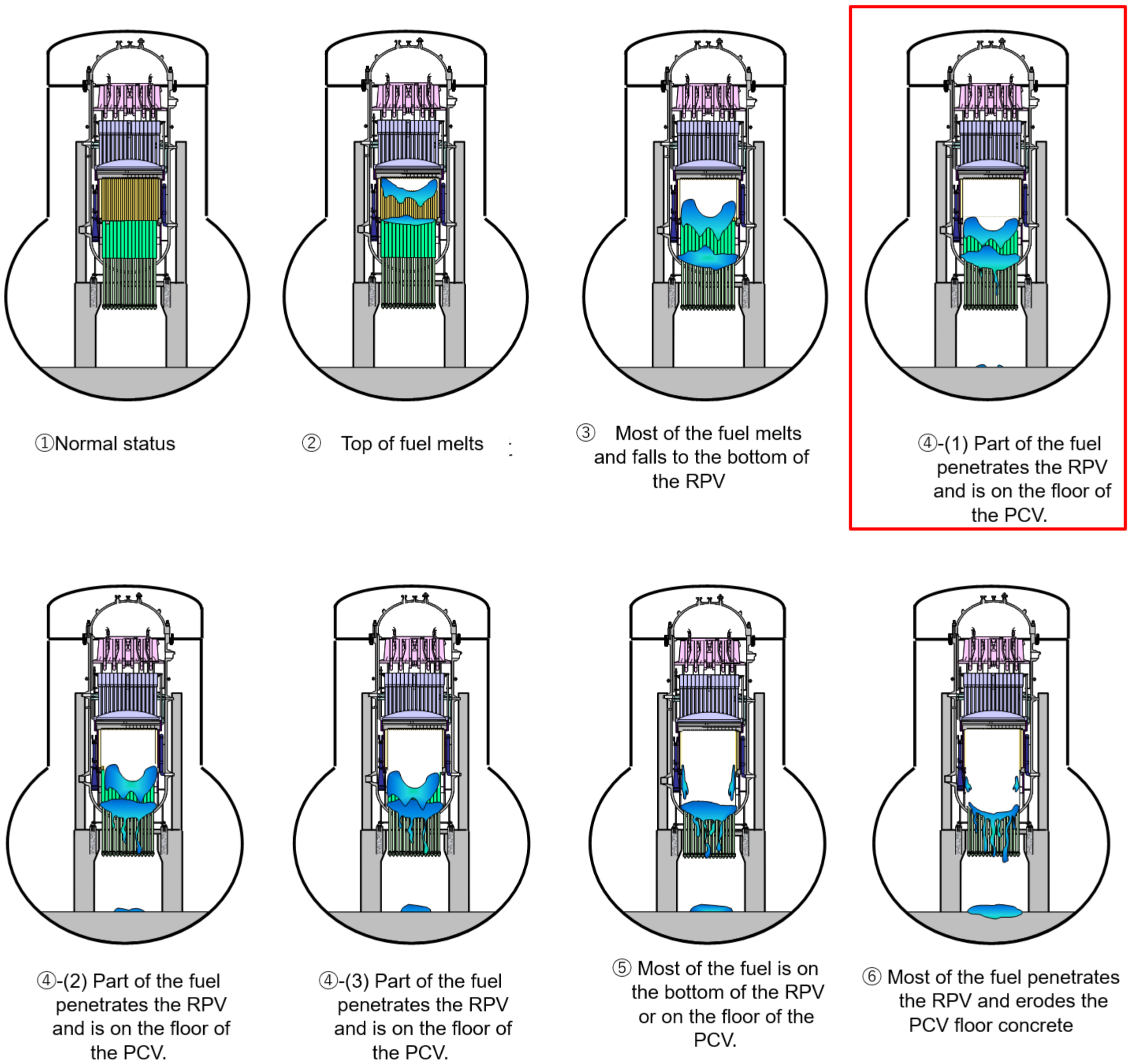
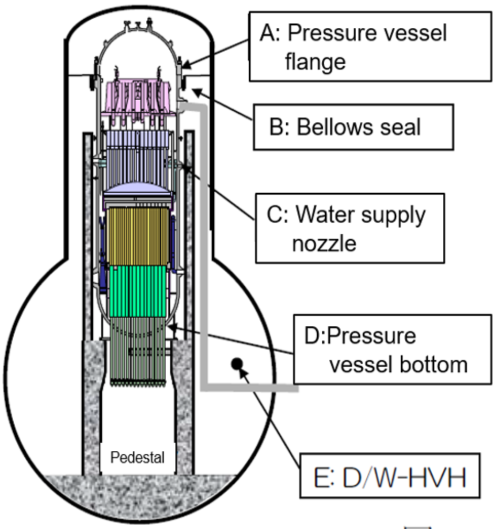


Figure 4.1.2-2 Patterns related to fuel debris distribution after the accident

・ Estimation from observed temperature and pressure

Figures 4.1.2-3, 4.1.2-4, and 4.1.2-5 show the temperature changes around the RPV and PCV from March to November 2011, when measurements were started with a thermometer.



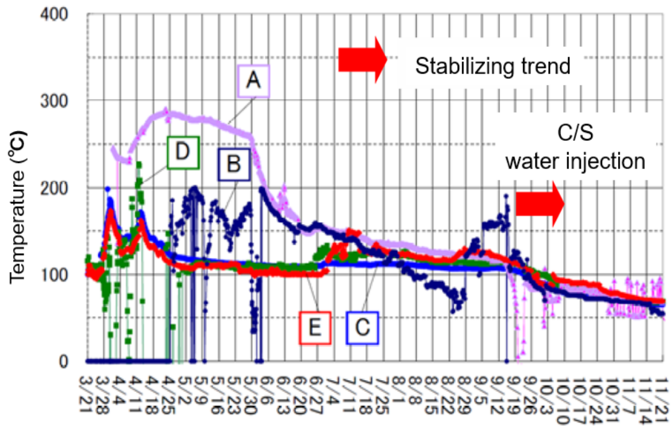


Figure 4.1.2-3 Temperature variation around RPV and PCV [2-1]

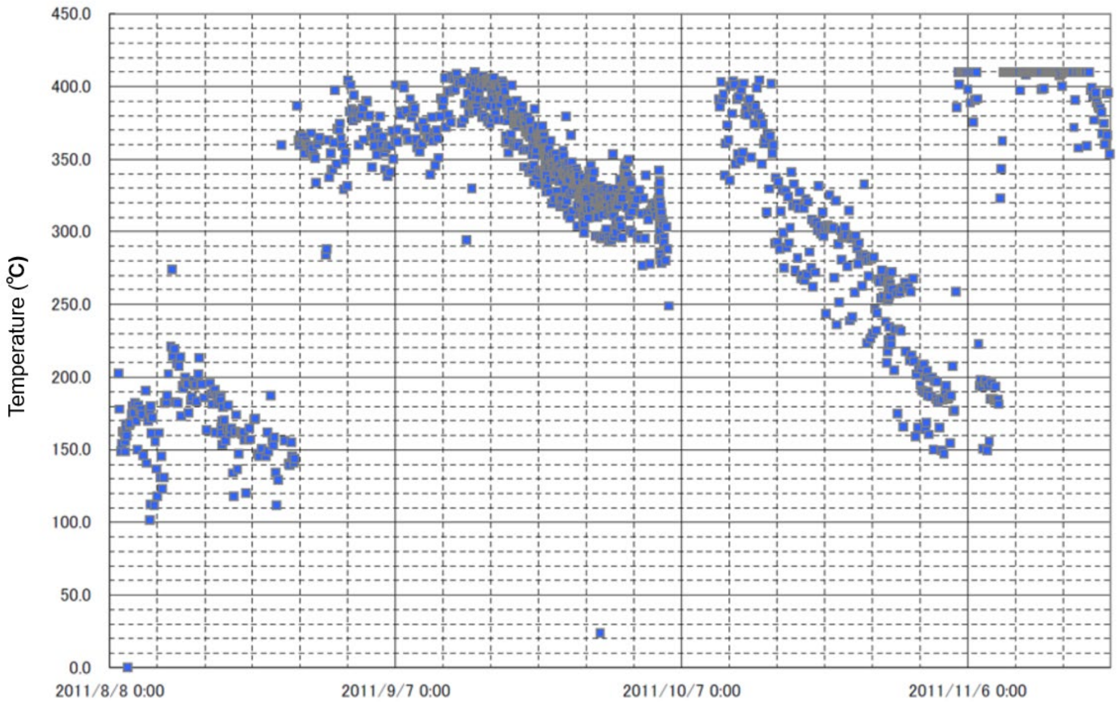


Figure 4.1.2-4 CRD housings temperature trend [2-1]

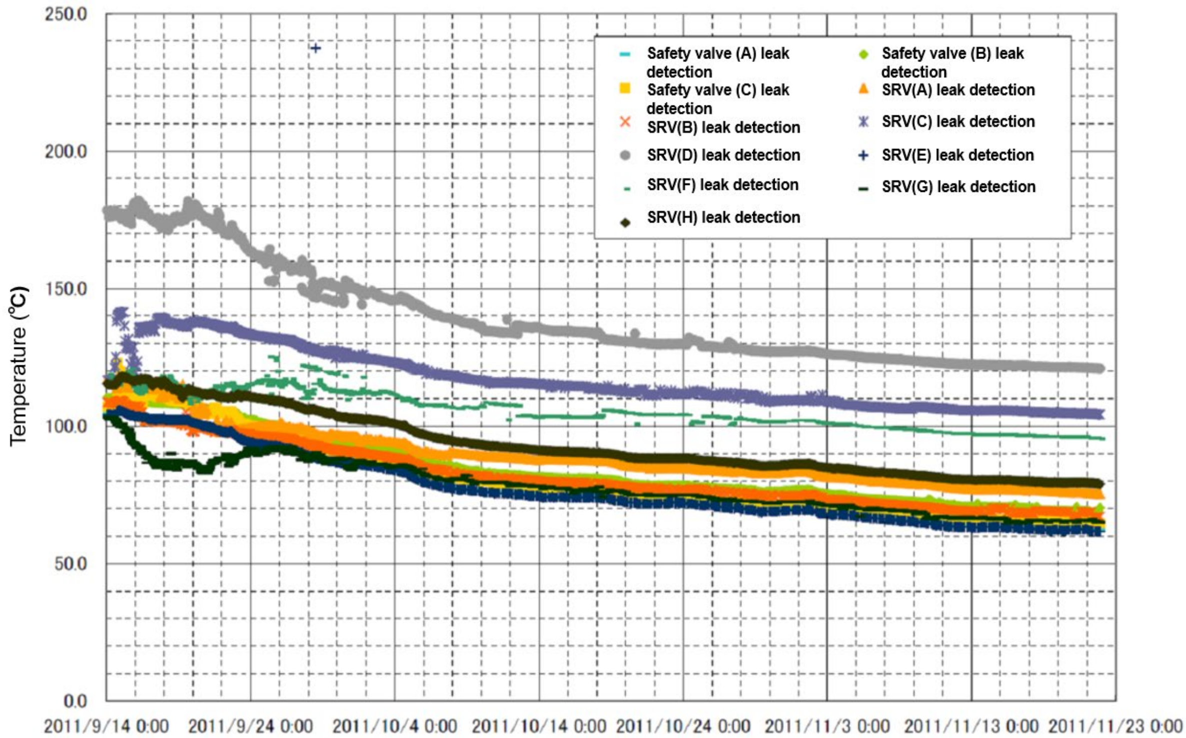


Figure 4.1.2-5 SV and SRV leakage detection temperature trends [2-1]

In Unit 2, water injection from the CS piping located directly above the reactor core was conducted from September 14, 2011. As a result, the following points were confirmed.

- The measured temperature at the top of the RPV fell due to water injection from the CS, which directly passed through the core, and fell below the saturation temperature by increasing the water injection.
- The ambient temperature of the PCV was almost below the saturation temperature, but there were some thermometers (CRD housings and SRVs) that showed high temperatures (above the saturation temperature) even as of November 2011.

Based on these observations, it is considered that a small amount of fuel exists in the core of the RPV, but most of the fuel is sufficiently cooled in the lower part of the RPV. In addition, there are also heating elements outside the RPV, which are sufficiently cooled, but there are some areas where the fuel is exposed (near the CRD housings) and some areas where moderate heat is generated (near the SRVs) due to the adhesion of volatile fission products and other materials.

- Indicated value of reactor water level gauge

As shown in Figure 4.1.2-6, the reactor water level gauge is designed to maintain a constant water level by collecting water in a reference leg located outside the RPV and determining the water level by taking the difference (Hs-Hr) between the pressure due to this water column and the pressure generated by the water level in the reactor. However, water in the instrumentation piping may evaporate during an accident. For example, if the water on the reference leg piping side evaporates, the water level, which is the reference for comparison, will be lowered, resulting in a higher indication of the water level in the reactor (Figure 4.1.2-7).

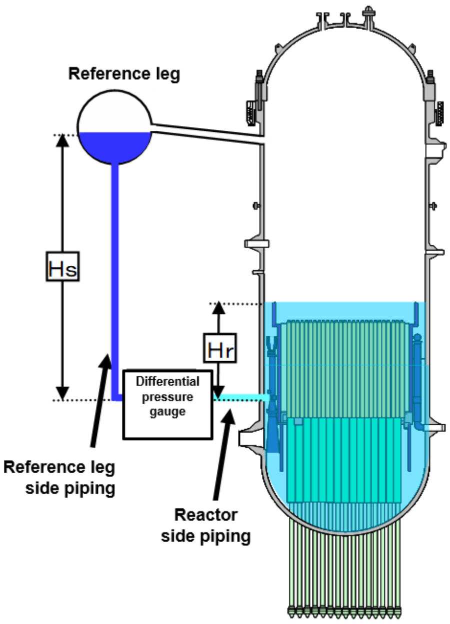


Figure 4.1.2-6 Schematic diagram of a reactor water level gauge [2-1]

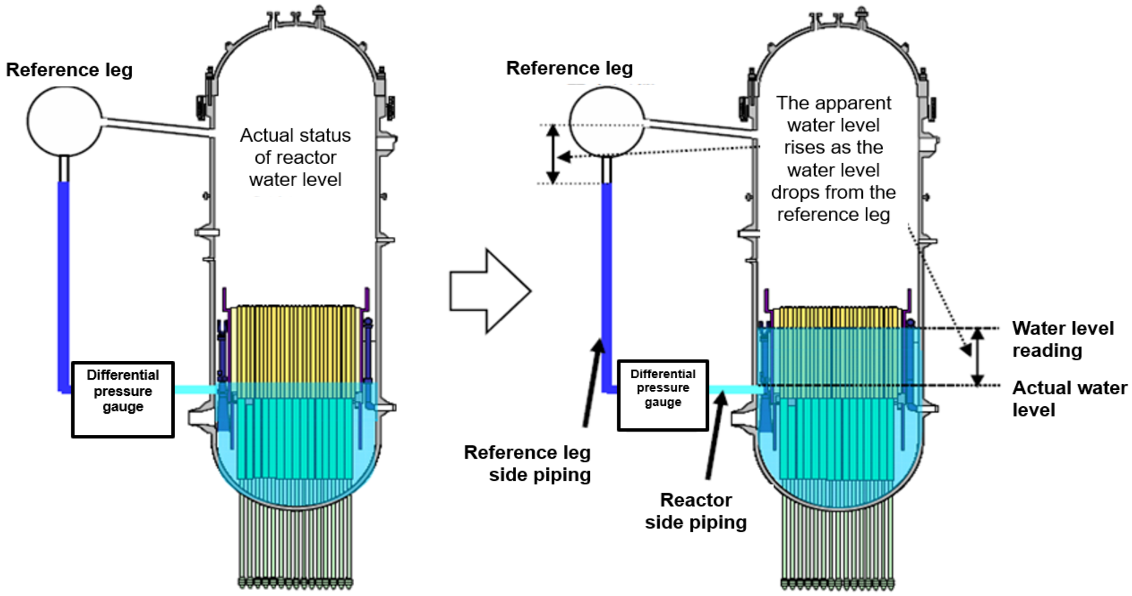


Figure 4.1.2-7 Reactor water level gauge indication following a drop in water level in instrumentation piping [2-1]

In Unit 2, although the calibration work of the reactor water level gauge was not conducted due to the high radiation dose, the reactor water level was estimated to be 5m below TAF based on the instantaneous value of the temporary differential pressure gauge installed after the accident. However, after adding water on June 22, 2011, a phenomenon was confirmed in which water on both the reactor side and the reference leg side piping evaporated in a short time, and after adding water on October 21, 2011, a phenomenon was confirmed in which water in the reactor side piping evaporated slowly.

Therefore, without a water level forming at the original fuel position, it is considered unlikely that the fuel has remained in its original position while maintaining its shape.

・ Water level in D/W

The fuel in Unit 2 was estimated to be generally submerged: because the amount of fallen fuel was estimated to be small, it was thought that a sufficient amount of water was being injected for cooling, and the measured temperature of the PCV atmosphere was not exceptionally high in any part.

4.1.3. Unit 3

The estimation as of November 30, 2011 is shown in Figure 4.1.3-1.

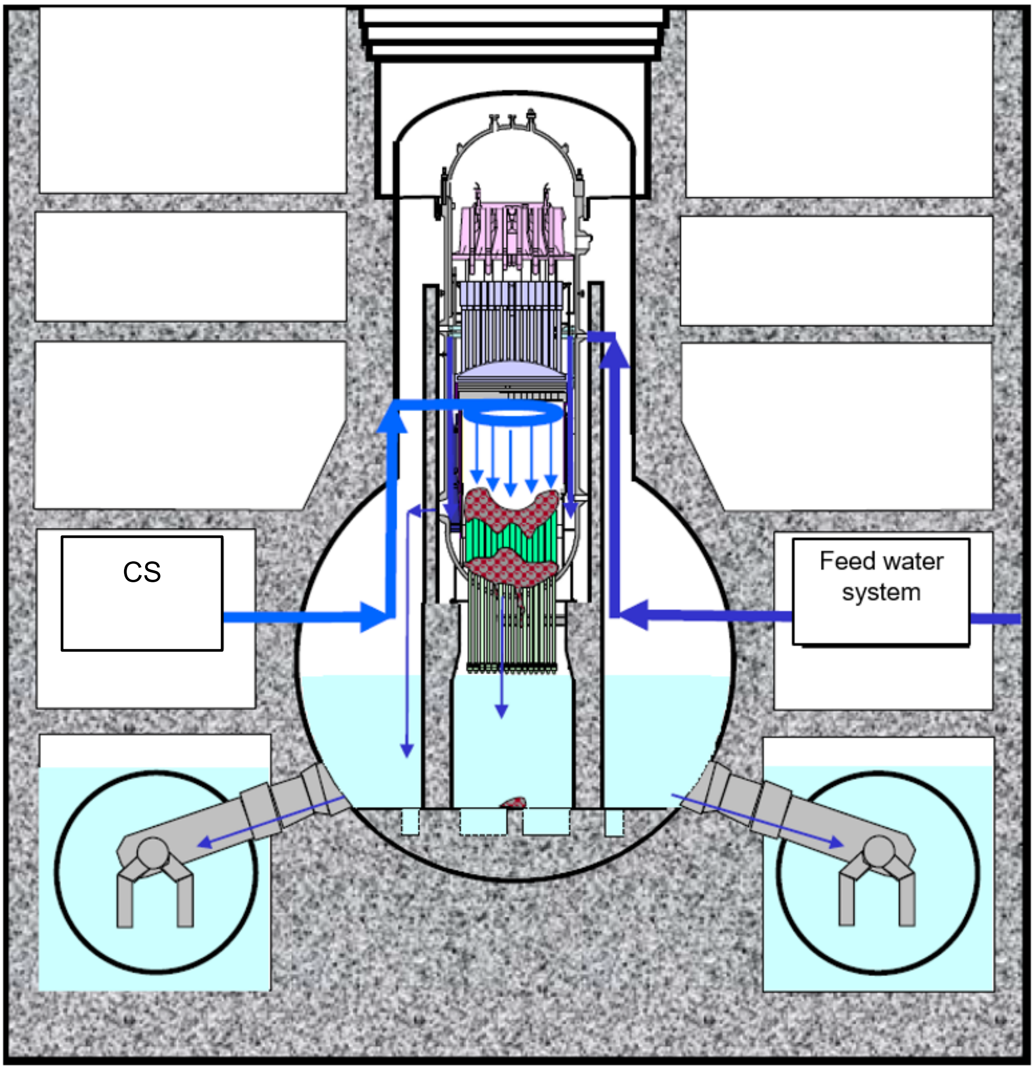


Figure 4.1.3-1 Unit 3 estimated as of November 30, 2011 [3-1]

For the estimation in Figure 4.1.3-1, the characteristics of the estimation and the findings that helped in the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, some part of the molten fuel fell into the lower plenum of the RPV or to the bottom of the PCV. Some of the fuel is estimated to remain in the original core section.

Regarding the water level in the D/W, it is estimated to be about 6.5 to 7.5m from the D/W floor.

○ Findings that were useful for estimation

The estimated diagram in Figure 4.1.3-1 was selected from the reactor damage patterns ① to ⑥ shown in Figure 4.1.3-2, and the condition of Unit 3 was estimated to be pattern ④-(1). The findings that were useful in selecting the pattern are described below.

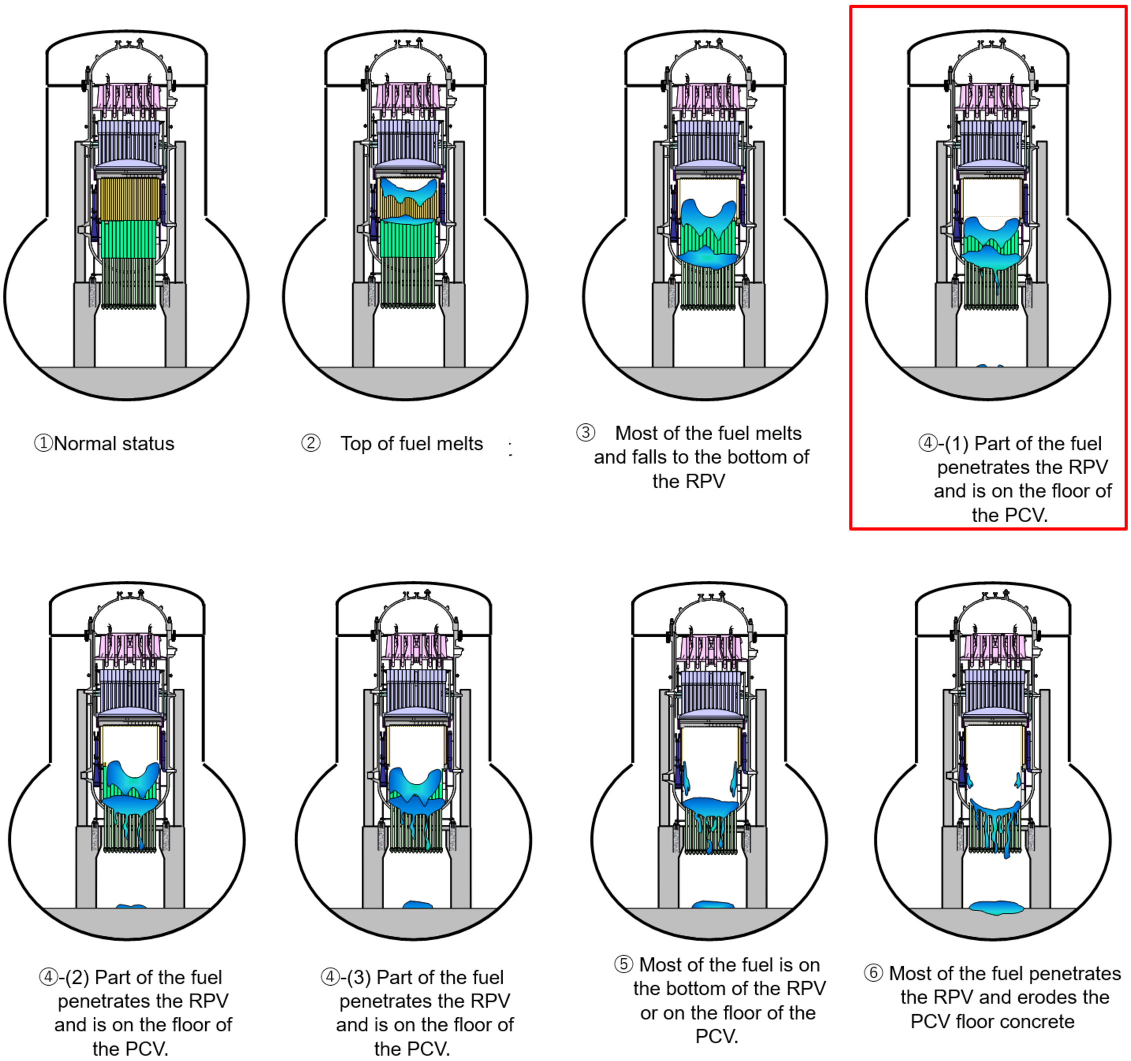


Figure 4.1.3-2 Patterns related to fuel debris distribution after the accident

・ Estimation from observed temperature and pressure

Figure 4.1.3-3 shows the temperature changes around the RPV and PCV from March to November 2011, when measurements were started with a thermometer.

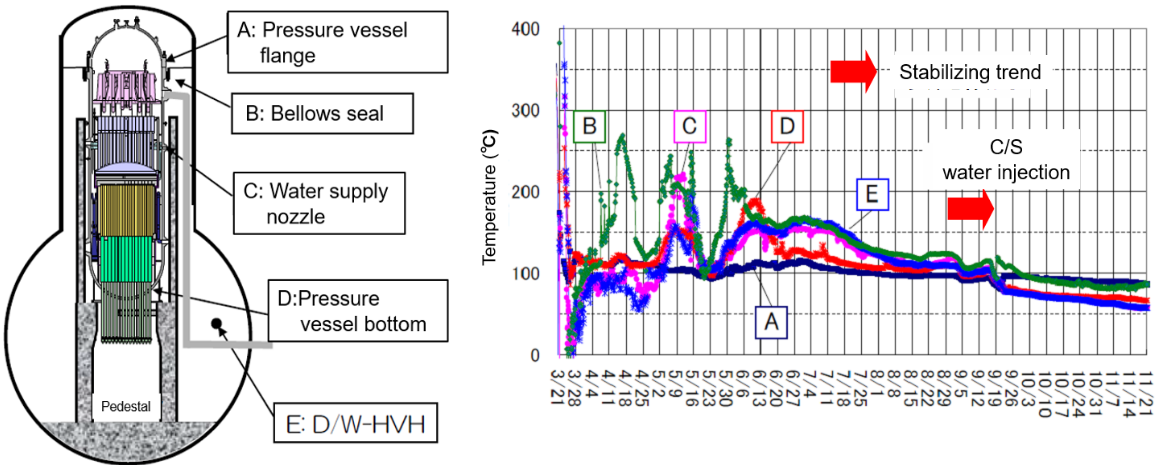


Figure 4.1.3-3 Temperature variation around RPV and PCV [3-1]

In Unit 3, a decrease in temperature around the RPV and PCV was observed due to water injection from the CS piping located directly above the reactor core, which was conducted from September 1, 2011. Since the temperature drop progressed due to the water injection from the system directly cooling the core section, it was estimated that fuel debris may have present in the core section at that time.

・ Water level in D/W

Figure 4.1.3-4 shows graphs of D/W pressure and S/C pressure from October to November 2011. Since the D/W and S/C are connected through the vacuum break valve, they basically show the same behavior. However, when the S/C water level rises and exceeds the vacuum break valve, this relationship is broken, and the S/C pressure becomes higher than the D/W pressure because, in addition to the D/W gas phase pressure, the water head pressure corresponding to the D/W water level is added to the S/C pressure. The trends of D/W pressure and S/C pressure in Figure 4.1.3-4 show that S/C pressure has always been higher than D/W pressure since October 1. Based on this differential pressure, the water level in the PCV (D/W) was estimated to be around 6.5m to 7.5m from the D/W floor. The amount of fuel falling into the PCV in Unit 3 was estimated to be small at that time, and the fuel in the PCV was estimated to be submerged, since water was being injected in sufficient quantities for sensible cooling, and the PCV atmosphere temperatures did not have any outstandingly high spots.

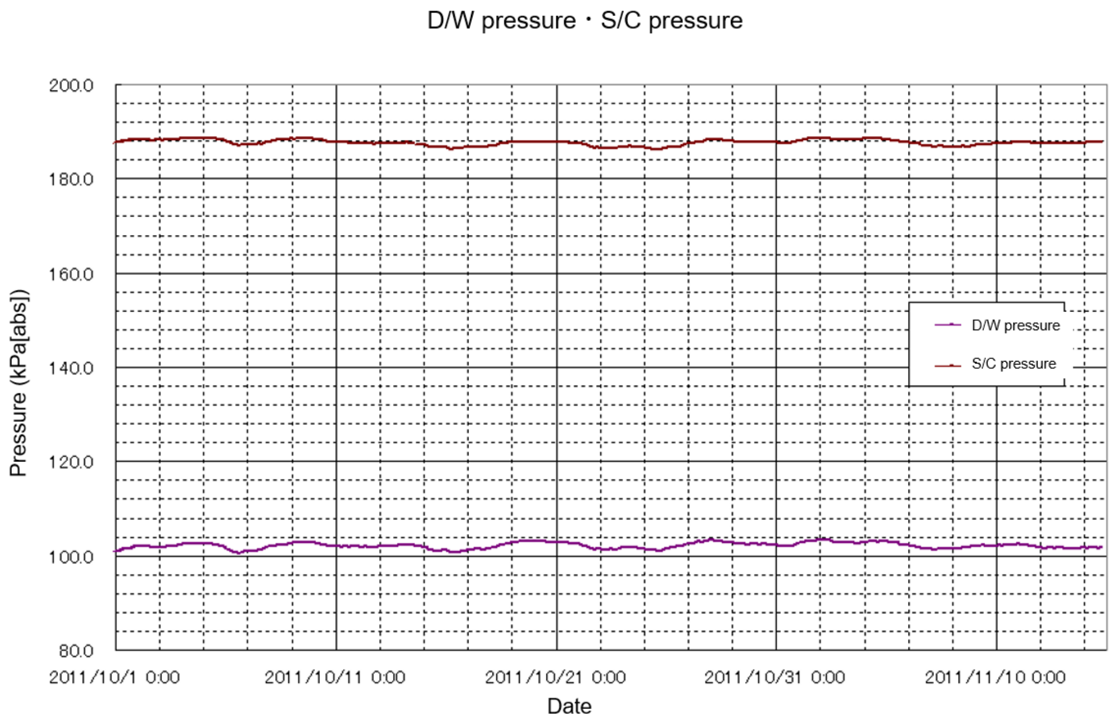


Figure 4.1.3-4　D/W pressure and S/C pressure [3-1]

4.2. Second estimation (December 13, 2013)

4.2.1. Unit 1

The estimation as of December 13, 2011 is shown in Figure 4.2.1-1.

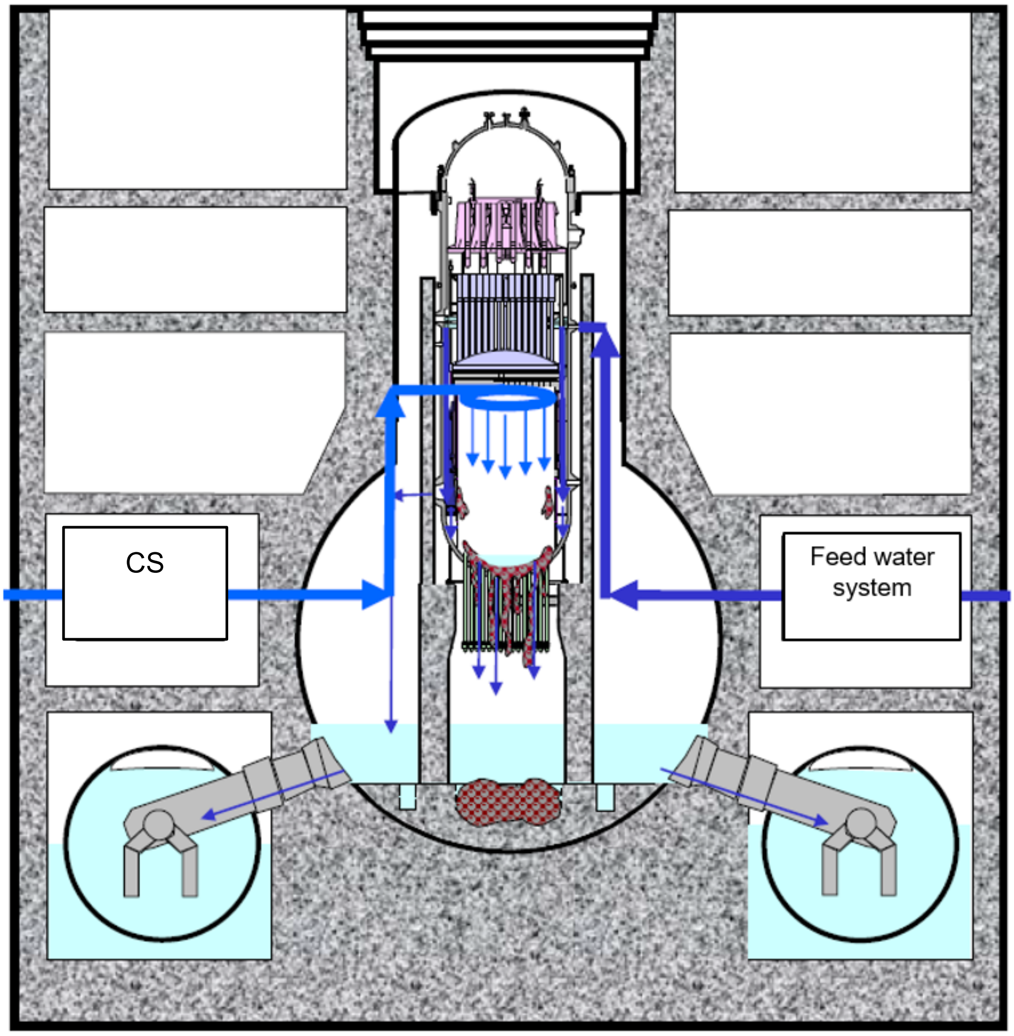


Figure 4.2.1-1 Unit 1 estimated as of December 13, 2013 [1-3]

For the estimation in Figure 4.2.1-1, the characteristics of the estimation, the updated contents from the initial estimation, and the findings that helped in the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and very little remained in the original core area. It is estimated that most of the fuel debris that fell into the lower plenum fell to the bottom of the PCV.

Regarding the water level in D/W, it was confirmed to be about 2.8m from the D/W floor.

○ Updated contents from the initial estimation

① The water level in the D/W was increased.

○ Reasons for updating from initial estimation.

① The water level in the D/W was increased.

In the Unit 1 PCV internal investigation conducted in October 2012, a hole was drilled in the PCV penetration (X-100B) on the first floor of the reactor building and an investigation device was inserted to take internal images with a camera, check the water level of accumulated stagnant water in the D/W, measure dose rate and temperature, collect and analyze the accumulated water, etc.

The water level in the D/W was measured by the cable feed length from the top of the grating to the point where the CCD camera came in contact with the water surface, and was confirmed to be approximately 2.8m from the D/W floor (Figure 4.2.1-2).

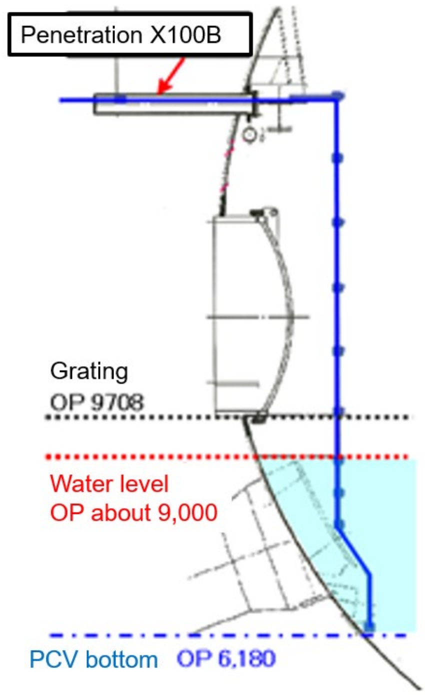


Figure 4.2.1-2 Residual water level measurement results in Unit 1 D/W [1-4]

○ Information that supports the estimation

The following information is considered to be reliable for the content of the estimation.

・ Results of nitrogen injection test to S/C

The nitrogen injection test to the S/C conducted in September 2012 demonstrated the estimated mechanism that Kr-85 and hydrogen remained in the upper part of the S/C in the early stage of the accident, and they were released into the D/W via the vacuum breaker tube when the water level in the S/C was pushed down. This confirmed that the water level in the S/C was almost full (near the lower end of the vacuum breaker tube) (Figure 4.2.1-3).

This test was conducted to verify the mechanism of intermittent increases in hydrogen and Kr-85 radioactivity concentrations measured at the Unit 1 PCV gas control facility since April 2012. These intermittent rises were assumed to be caused by the following: when the water level in the S/C drops, the gas remaining in the closed upper space of the S/C is discharged through the vacuum breaker tube to the D/W, and when the gas in the upper part of the S/C is discharged, the water level in the S/C rises again, the space becomes closed again, and the outflow is stopped. Kr-85 is a fission product with a long half-life, and its amount cannot be explained as a newly produced amount by spontaneous fission, etc. Therefore, it was considered to be derived from residual material in the early stage of the accident.

In a test conducted to verify the mechanism, the hydrogen concentration and Kr-85 radioactivity concentration measured by the PCV gas control equipment began to increase with a time delay after the S/C pressure (measured by the existing instrument) increased following the nitrogen injection test start, and each concentration began to drop when nitrogen injection was stopped. This is thought to reflect behavior of residual gas in the closed space of the upper S/C, which is pressurized by nitrogen injection into the S/C, pushing down the water level there and forming a gas flow from the vacuum breaker tube to the D/W. The residual gas in the closed space is then pushed to the D/W by the injected nitrogen.

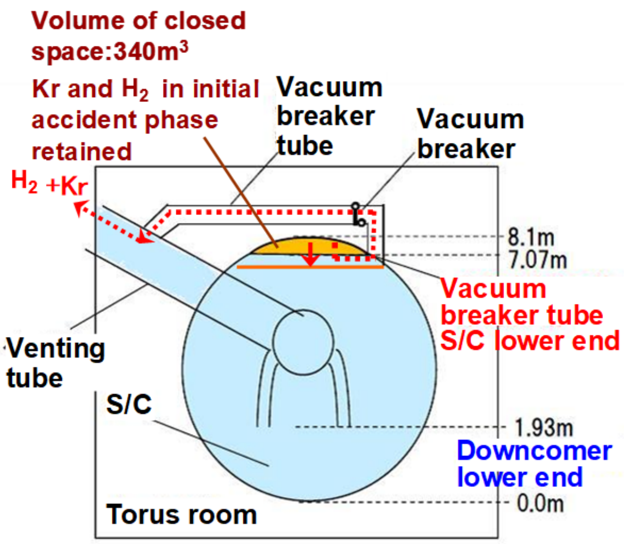


Figure 4.2.1-3 Situation of gas phase trapped in Unit 1 S/C [1-5]

4.2.2. Unit 2

The estimation as of December 13, 2011 is shown in Figure 4.2.2-1.

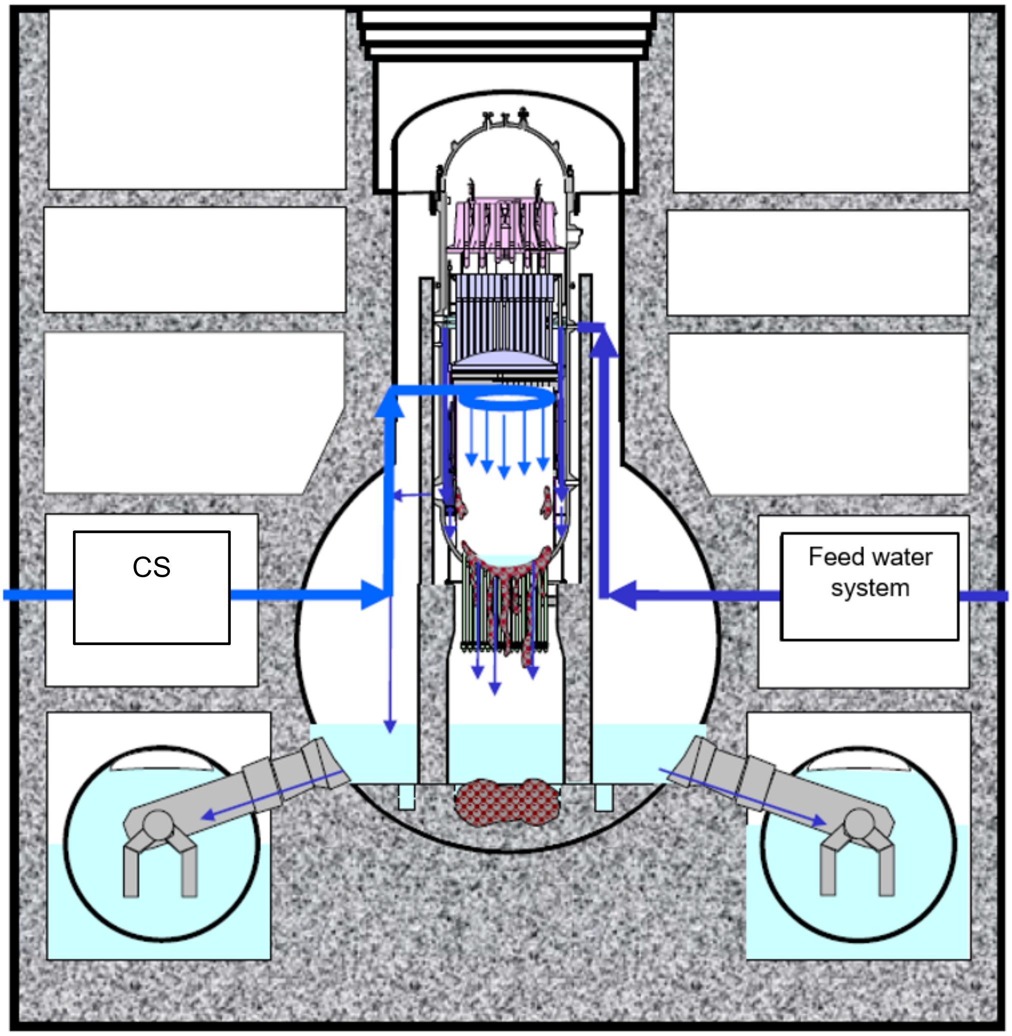


Figure 4.2.2-1 Unit 2 estimated as of December 13, 2013 [2-2]

For the estimation in Figure 4.2.2-1, the characteristics of the estimation, the contents updated from the initial estimation, the reasons for the update from the initial estimation, and the information supporting the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, some part of the molten fuel fell into the lower plenum of the RPV or to the bottom of the PCV after the accident. No observations indicating a behavioral tendency of D/W shell failure have been confirmed, and even if the fuel debris that fell to the bottom of PCV caused MCCI, it is estimated to be limited in its extent.

Regarding the water level in D/W, it was confirmed to be about 600mm from the D/W floor.

The water level in S/C was estimated to be about 6.3m from the bottom of the S/C.

○ Updated contents from the initial estimation

① Regarding fuel debris distribution, the amount of fuel debris that fell into the PCV was increased.

○ Reasons for updating from initial estimation

① Regarding fuel debris distribution, the amount of fuel debris that fell into the PCV was increased.

Because the initial estimation figure showed small-sized fuel debris falling into PCV, which could mislead the reader into thinking that RPV was not damaged, the figure was revised by making the fuel debris larger.

○ Information that supports the estimation

The following information is considered to be reliable for the content of the estimation.

・ Results of water level measurement inside D/W

During the Unit 2 PCV internal investigation conducted in March 2012, a hole was drilled through the PCV penetration (X-53 (1st floor of the reactor building)) and an investigation device was inserted to take internal images using a camera, confirm the water level of accumulated stagnant water in D/W, and measure the dose rate and temperature.

The water level was confirmed to be about 600mm (as of March 26, 2012) from the D/W floor using a video image scope (Figure 4.2.2-2).

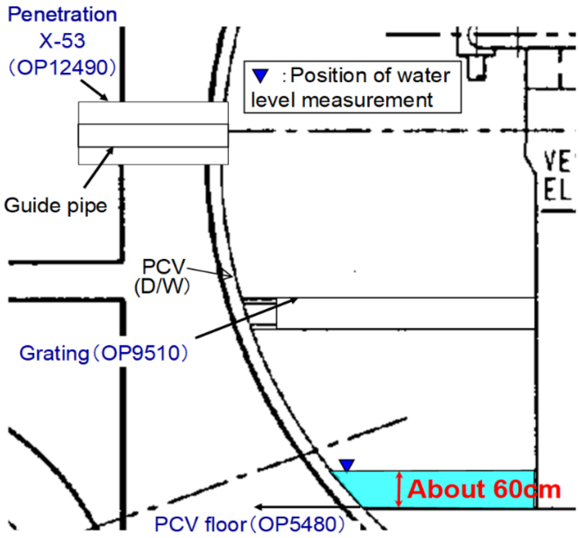


Figure 4.2.2-2　Residual water level measurement results in Unit 2 PCV [2-3]

・　Results of nitrogen injection test to S/C

A nitrogen injection test conducted in May 2013 confirmed that the S/C pressure was 3kPa(gage) (as of May 14, 2013), and although the exact value of the water level in the S/C is unknown since a nearly full water level in the S/C would result in a reasonable hydraulic head pressure, it was indicated to be around the nitrogen gas inlet (approximately 6.3m from the bottom of the S/C). Together with the low water level in the D/W, it is estimated that water injected into the reactor flows from the D/W into the S/C via the vent piping and leaks from the lower part of the S/C into the reactor building. In this case, the water level in the S/C is considered to be the same as the level of water in the torus room (Figure 4.2.2-3).

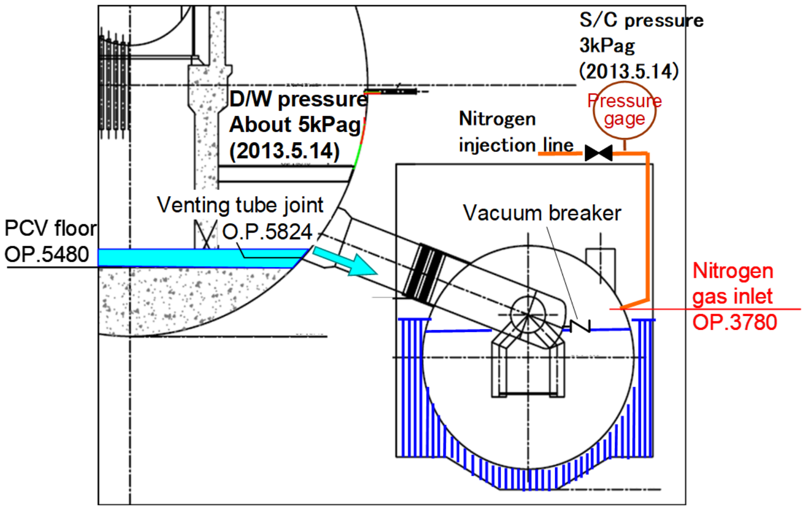


Figure 4.2.2-3　Situation of gas phase closed space in the Unit 2 S/C [2-2]

・ Results of the torus room venting tube lower area investigation

In the torus room survey of Unit 2 conducted in December 2012 and March 2013, a robot was used to investigate the area around the lower part of the venting tube. A small traveling vehicle attached to the end of the arm of a four-leg walking robot was seated on the S/C and moved to the vicinity of the venting tube to acquire images.

Although the location of the liquid phase leakage of the S/C was not identified, it was confirmed that there was no leakage from the lower end of the venting tube within the area that could be imaged (Figures 4.2.2-4 and 4.2.2-5).

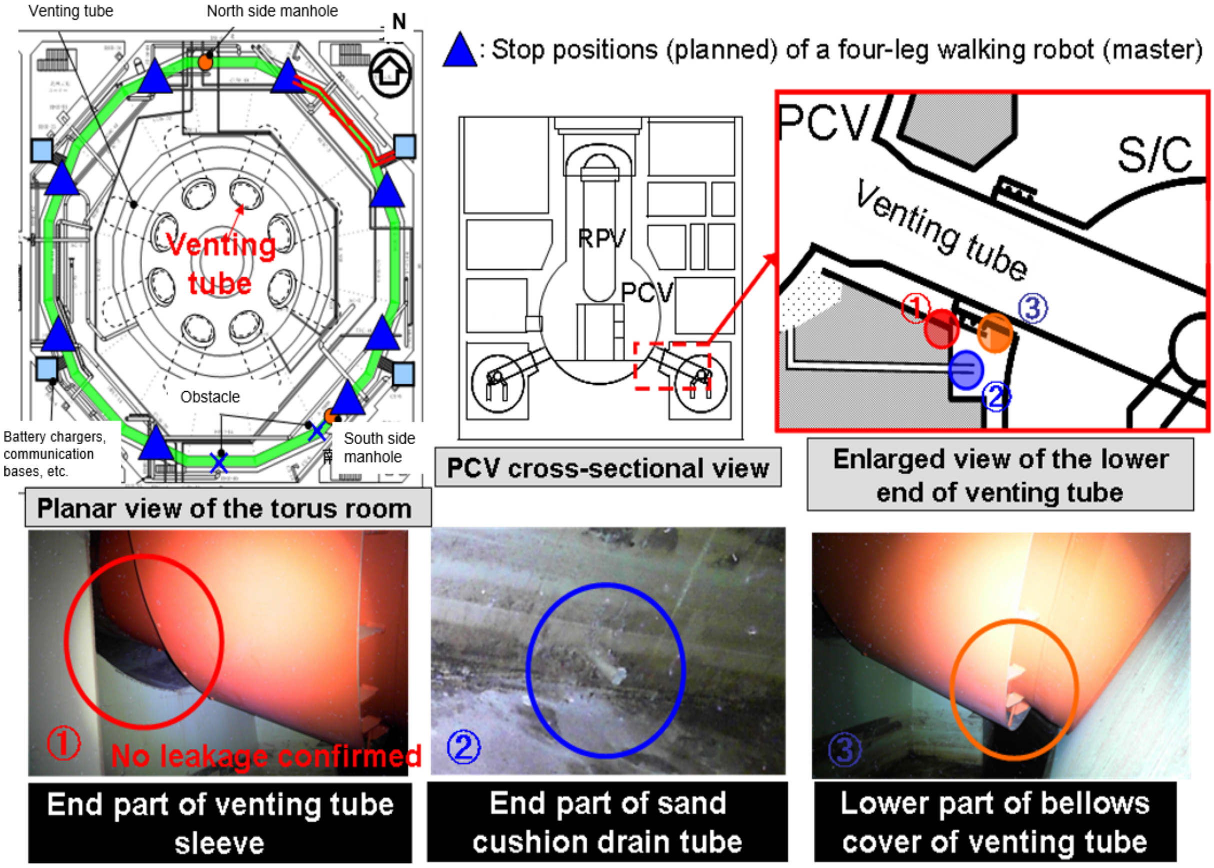


Figure 4.2.2-4 Camera images of the lower part of venting tube in Unit 2 torus room (excerpt) [2-4]

#	Date	Vent pipe sleeve end	Sand cushion drainpipe end	Vent pipe bellows cover lower part
①	Dec. 11, 2012	○	○	○
②※2	Mar. 5, 2013	○	○	○
③※2	Mar. 5, 2013	○※1		○
④※2	Mar. 5, 2013	○※1		○
⑤※2	Mar. 13, 2013	○※1		○
⑥※2	Mar. 13, 2013	○※1		○
⑦※2	Mar. 14, 2013	○	○	○
⑧※2	Mar. 15, 2013	○	○	○

※1
No water flow on the lower concrete stage, although not checked directly.

※2
Sound information was also obtained.
No sound like leakage was confirmed at this time.

Note: ○ no leakage

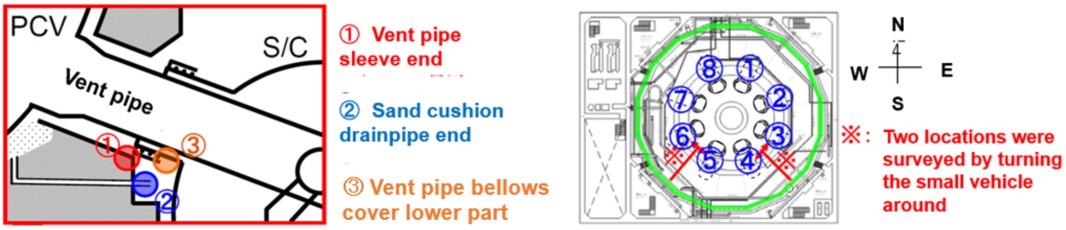


Figure 4.2.2-5 Investigation results around the lower part of the vent pipe in Unit 2 [2-4]

Based on the above, no observations indicating a behavioral tendency of D/W shell damage were confirmed, and even if the fuel debris that fell to the bottom of the PCV had reacted with the concrete, the extent of this reaction would have been limited.

4.2.3. Unit 3

The estimation as of December 13, 2011 is shown in Figure 4.2.3-1.

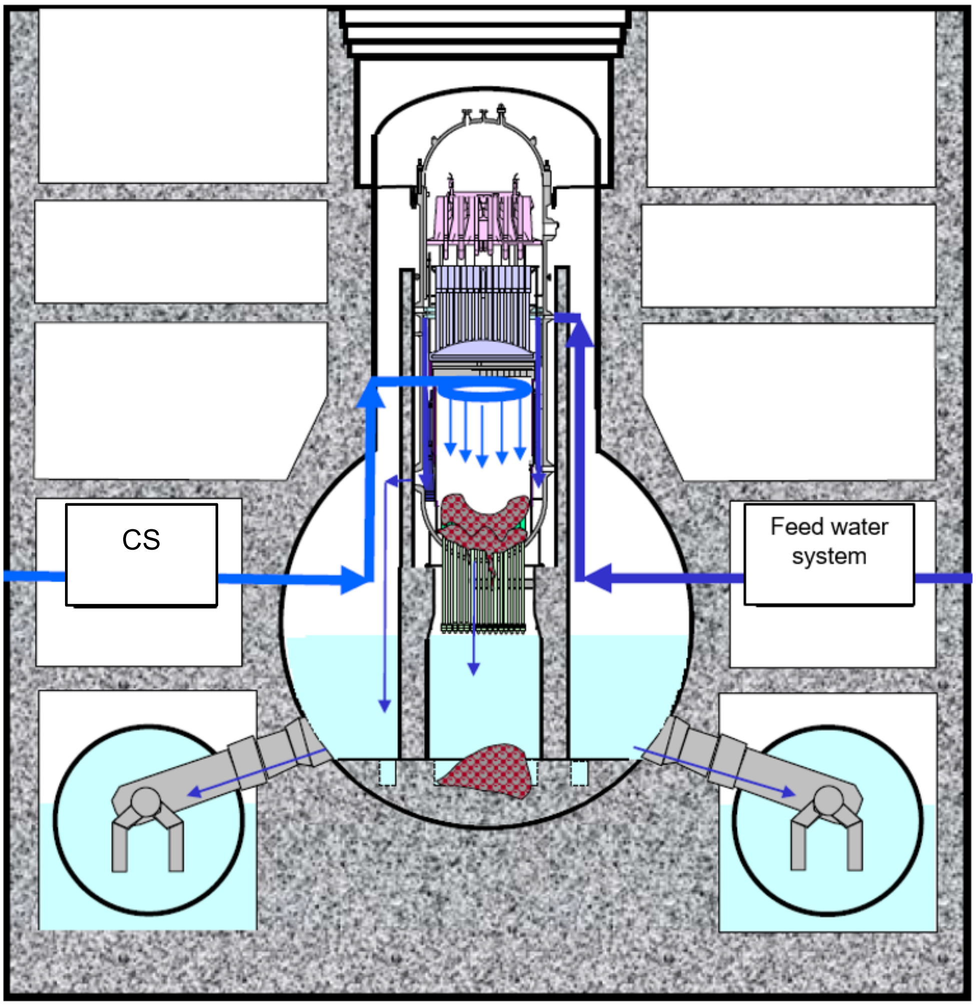


Figure 4.2.3-1 Unit 3 estimated as of December 13, 2011 [3-2]

For the estimation in Figure 4.2.3-1, the characteristics of the estimation, the contents updated from the initial estimation, and the reasons for the update from the initial estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that some part of the molten fuel fell into the lower plenum after the accident, and another part fell to the bottom of the PCV.

○ Contents updated from the initial estimation

① Regarding the distribution of fuel debris, the amount of fuel debris that fell downward in the RPV was increased, and the amount of fuel debris that fell into the PCV was also increased.

○ Reasons for updating from initial estimation

① Regarding the distribution of fuel debris, the amount of fuel debris that fell downward in the RPV was increased, and the amount of fuel debris that fell into PCV was also increased.

Since it was found that the reactor had been unable to be fully flooded even before the operator manually shut down the HPCI at 14:42 on March 13, 2011, it was assumed that the accident progressed more quickly than previously estimated, and more fuel was estimated to have fallen into the PCV. This is described in detail below.

Measured and analyzed values of the reactor water level during March 12-13, 2011 (results of the analysis published on March 12, 2012) are shown in Figure 4.2.3-2. The timings of ① to ⑤ shown in the figure are as following.

① 3/12 11:36 RCIC automatic shutdown

② 3/12 12:35 HPCI automatic startup

③ 3/12 20:36 Reactor water level measurement interrupted due to DC power supply depletion

④ 3/13 02:42 HPCI manual shutdown

⑤ 3/13 04:00 Battery connected to fuel range water level gauge; reactor water level measurement resumed

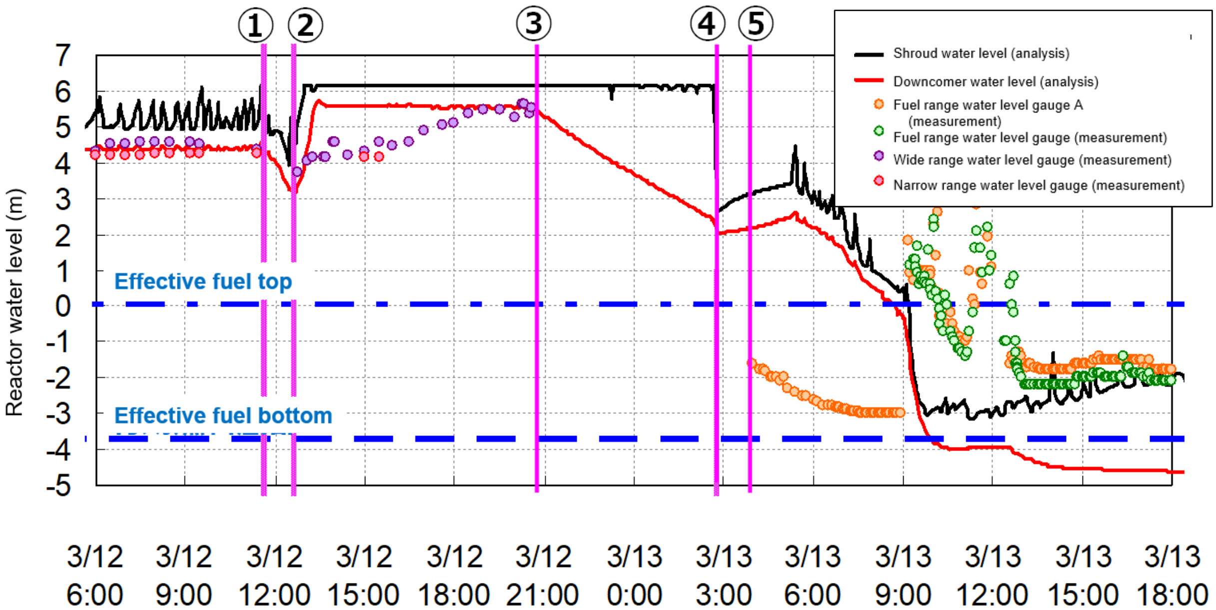


Figure 4.2.3-2 Measured and analyzed reactor water levels (2011) [3-3]

Regarding the water injection into the reactor, since the reactor water level was unknown after 20:36 on March 12, an analysis was conducted with a reduced amount of water injection by HPCI. However, a large discrepancy was found between the analyzed value and the measured value (fuel range water level gauge value) for the reactor water level after 04:00 on March 13 when the water level gauge measurement was restarted. It was considered that this meant that the water injection to the reactor was not sufficient even before the manual shutdown of the HPCI at 02:42 on March 13.

Thus, it was estimated that the accident progressed more quickly than previously estimated and that more fuel fell into the PCV than previously estimated.

○ Information supporting the estimation

None.

4.3. Third estimation (August 6, 2014)

4.3.1. Unit 1

The estimation as of August 6, 2014 is shown in Figure 4.3.1-1.

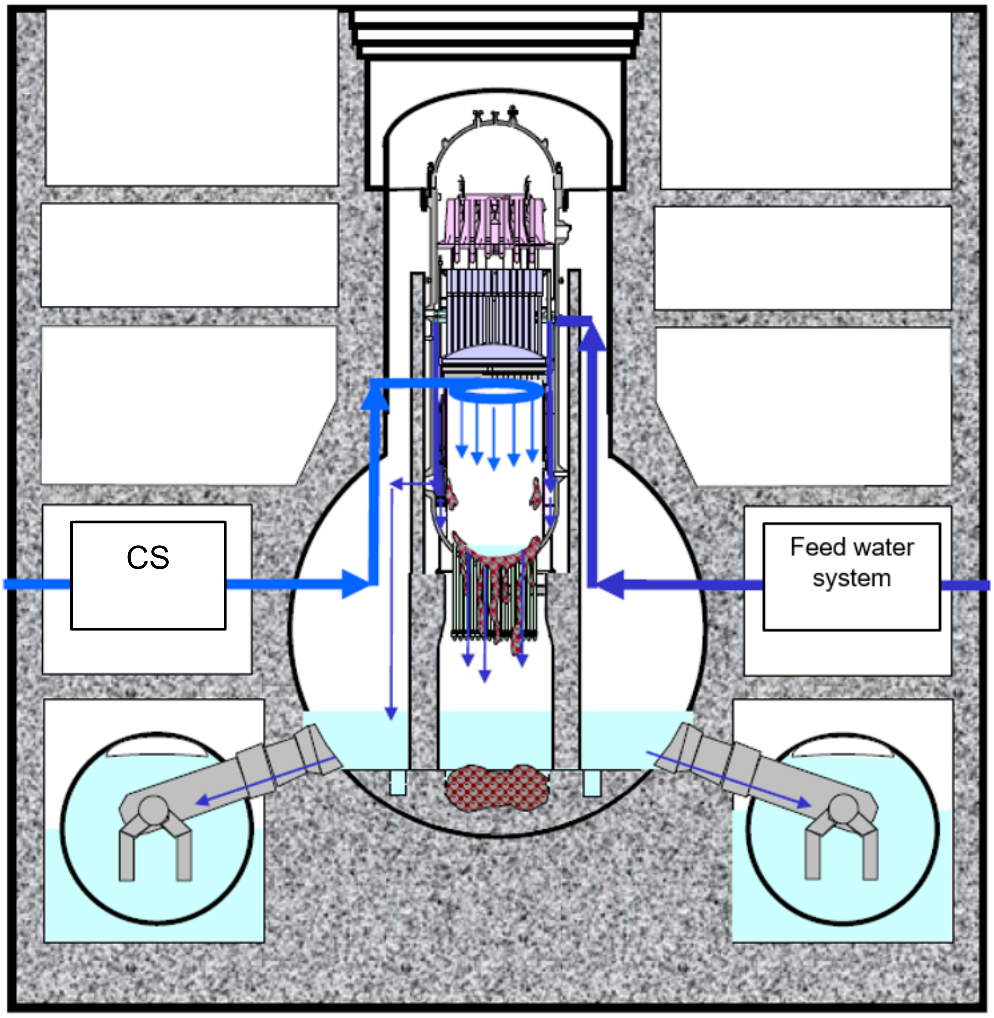


Figure 4.3.1-1 Unit 1 estimated as of August 6, 2014 [1-6]

For the estimation in Figure 4.3.1-1, the characteristics of the estimation and the findings that helped in the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and very little remained in the original core area. The fuel debris that fell into the lower plenum was estimated to have mostly fallen to the bottom of the PCV.

○ Updated contents from the second estimation

None.

○ Information that supports the estimation

The following information is considered to be reliable for the content of the estimation.

・ Torus room vent piping lower part survey results

In the Unit 1 torus room survey conducted in November 2013, a small boat equipped with a camera and dosimeter was dropped into the torus room through a 510mm diameter hole drilled in the northwest area of the first floor of the reactor building to check for water flow from the end of the vent piping sleeve at the connection point between the D/W and S/C, as well as the presence of water flow and dose measurements. The appearance of the sand cushion drainpipe was checked and dosimetry was conducted.

As result of the confirmation by camera images, water flow was confirmed from the following locations (Figure 4.3.1-2).

- X-5B vent piping (① in the figure): Water flows out from the disconnected sand cushion drainpipe＊.
- X-5E vent piping (④ in the figure): Water flows down from both sides of the vent piping through the surface of the S/C.

＊The sand cushion drainpipe connecting to ① in the figure was disconnected from the PVC piping (piping connecting the drainpipe to the drain funnel and connected by a plug-in joint), and water flow could be confirmed; however, ② through ⑧ drainpipes were not disconnected, so the presence of water flow could not be determined. In addition, it was observed to be wet all around the concrete joint under the sand cushion drainpipe.

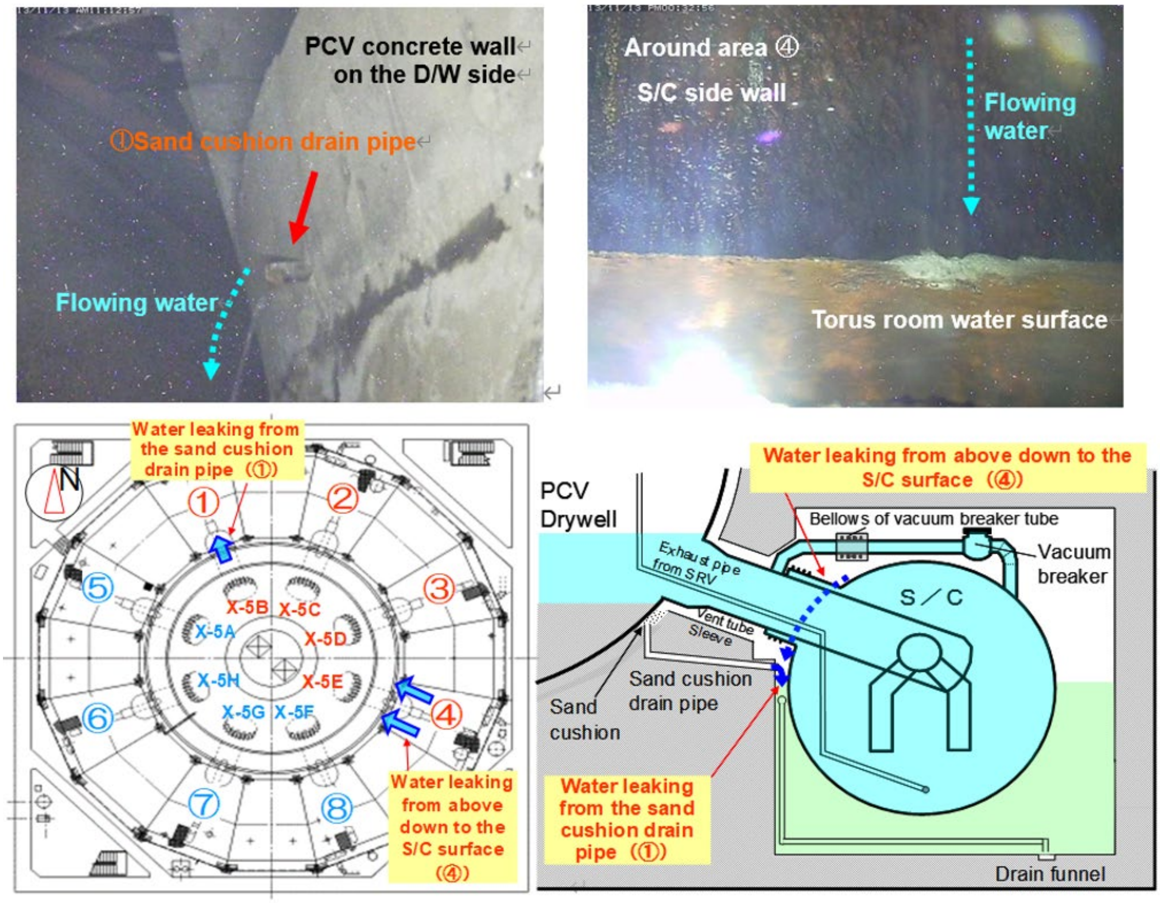


Figure 4.3.1-2 Camera images from the lower part of the torus room vent survey in Unit 1 (excerpt) [1-7]

Water intrusion into the sand cushion section occurs when there is a direct leakage from the D/W section, and the leakage point is considered to be at a low location below the water surface of the D/W (e.g., at the D/W shell or pipe penetration). This information is very important for estimating the state of the core and PCV.

In addition, water flowed from both sides of the X-5E vent piping through the surface of the S/C, suggesting that the leakage was coming from the vacuum breaker tube directly above the vent piping (e.g., the vacuum breaker tube bellows). The height of the bottom of the vacuum breaker tube is about 8.2m from the bottom of the S/C. This is the height at which the D/W water level stopped rising and leveled off when the amount of water injected into the reactor was increased to flood the D/W in May 2011, which was thought to be the height at which the leak port was located. The height of the leak (about 8.0m from the bottom of S/W) is almost the same as the height of the D/W (about 7500mm O.P. in Figure 4.3.1-3), where the leak was thought to occur.

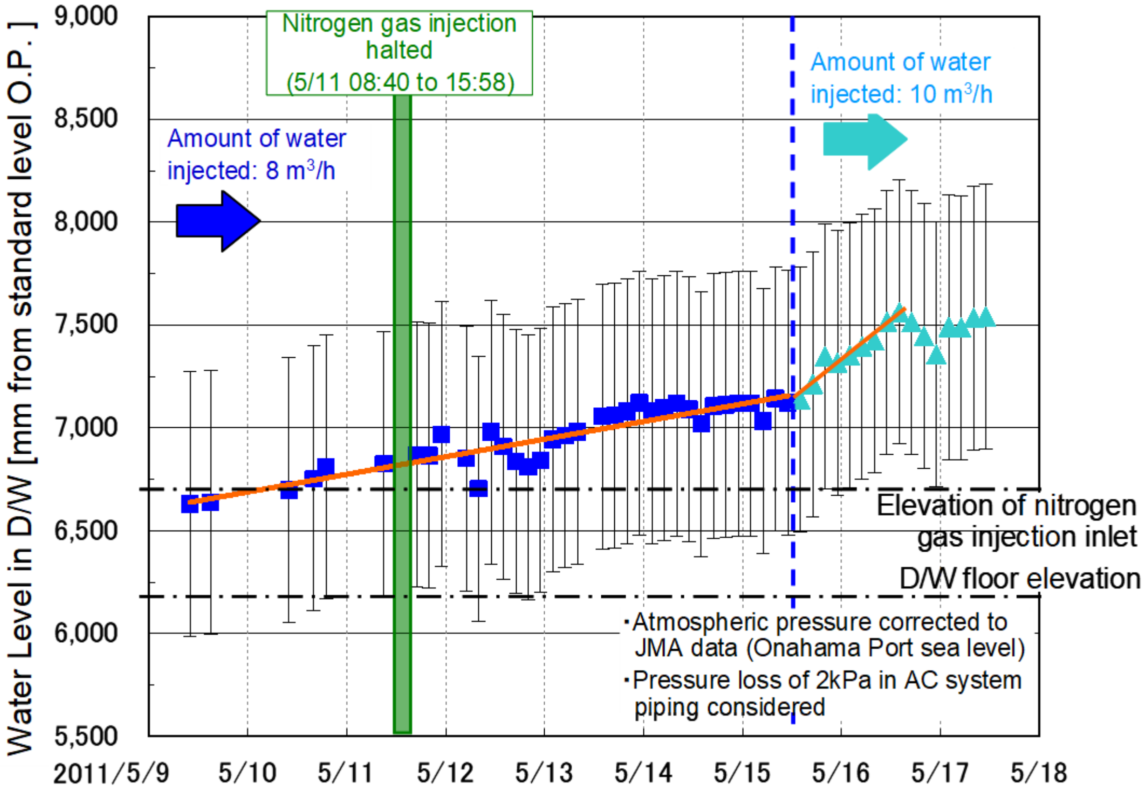


Figure 4.3.1-3 D/W water level (estimated) during Unit 1 D/W flooding operation [1-6]

Then, in May 2014, in order to identify the location of the leakage near the X-5E vent piping, where the water flow was confirmed, inspection equipment for the top of the S/C was deployed from a drilled point in the northwest area on the first floor of the Unit 1 reactor building, and a video survey of the area near the X-5E vent piping was conducted by moving on the outer catwalk. No leakage was confirmed to occur from the protective cover of the expansion joint of the vacuum break line. No leakage was observed in the vacuum breaker valve, torus hatch, SHC piping, or AC piping on the line (Figure 4.3.1-4).

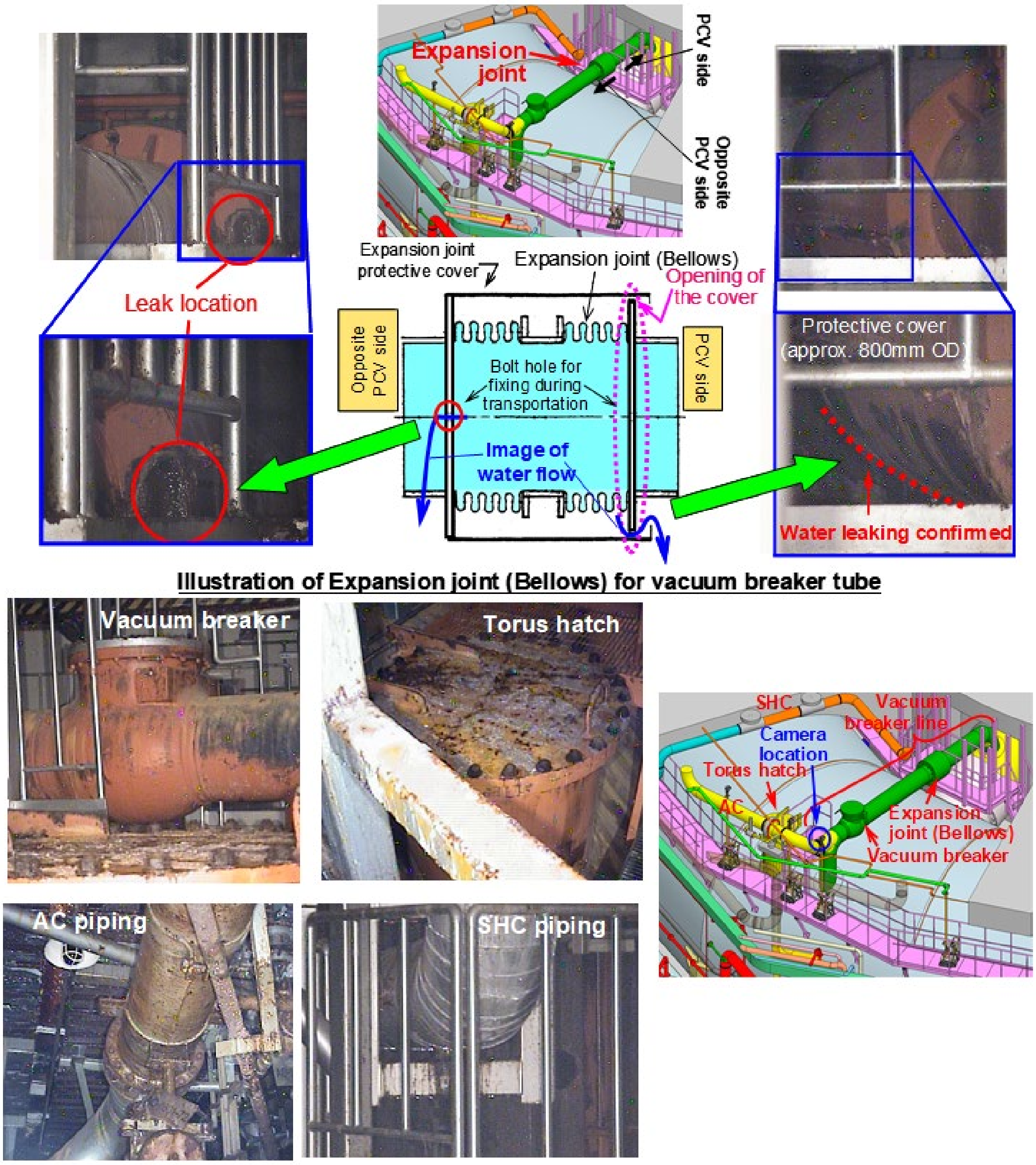


Figure 4.3.1-4 Camera image (excerpt) from the investigation at the top of Unit 1 S/C (around X-5E vent piping) [1-8]

4.3.2. Unit 2

The estimation as of August 6, 2014 is shown in Figure 4.3.2-1.

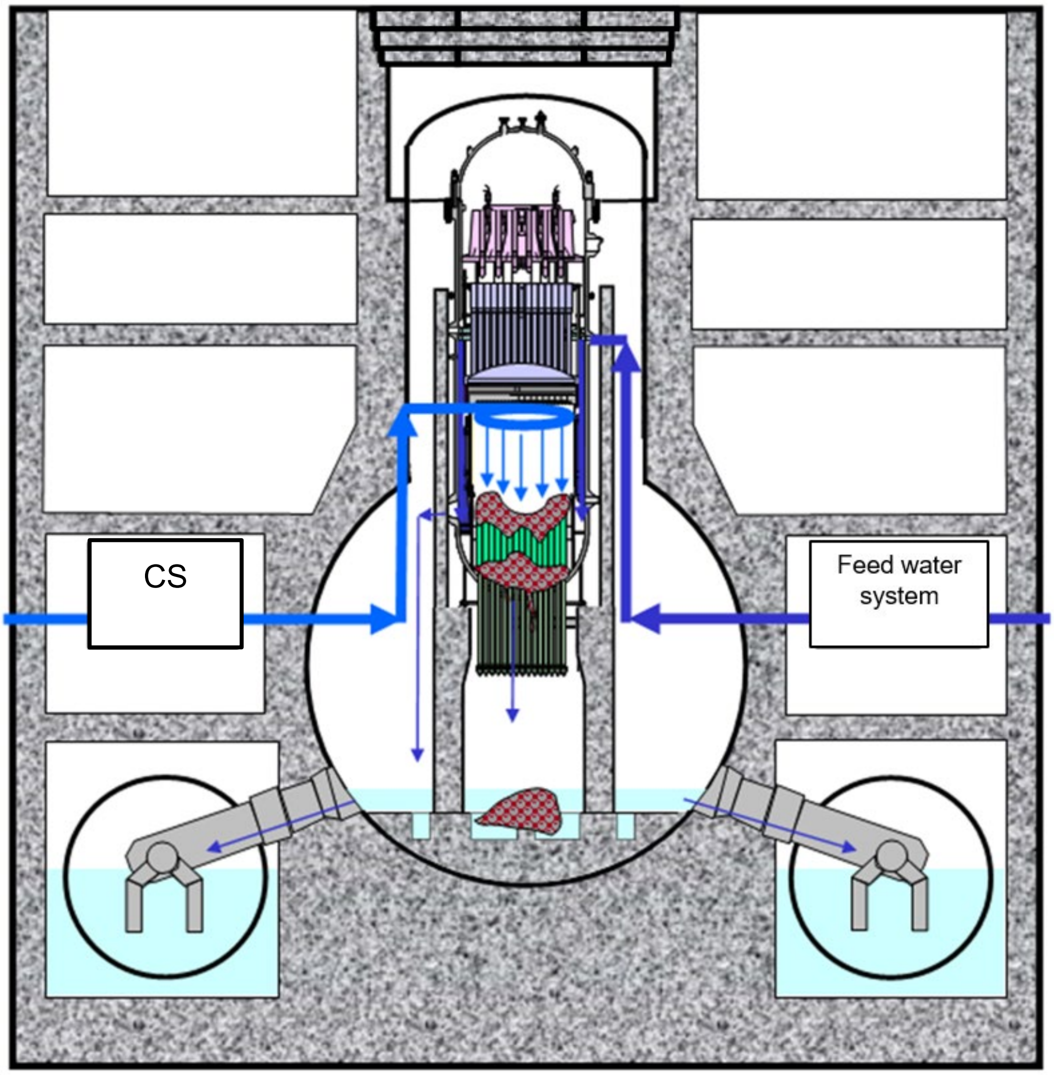


Figure 4.3.2-1 Unit 2 estimated as of August 6, 2014 [2-5]

For the estimation in Figure 4.3.2-1, the characteristics of the estimation and the information supporting the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that some of the molten fuel fell into the lower plenum of the RPV or to the bottom of the PCV after the accident, and some of the fuel remains in the core area. Even if the fuel debris that fell to the bottom of the PCV caused MCCI, the extent of MCCI is estimated to be limited.

The water level in the S/C is estimated to be about 5.7m from the bottom of the S/C.

○ Updated content from the second estimation

None.

○ Information supporting the estimation

The following information is considered to be reliable for the content of the estimation.

・ Results of nitrogen injection test to S/C

As described in Section 4.2.2, a nitrogen injection test into the S/C conducted in May 2013 indicated that the water level in the S/C was about 6.3m from the bottom of the S/C. An additional test was conducted in July 2013, in which nitrogen was injected into the D/W and it was confirmed that the D/W pressure increased, and the S/C pressure increased slightly following the increase in D/W pressure. The S/C pressure was confirmed to increase slightly in line with the increase in D/W pressure. In October 2013, nitrogen was again injected in the S/C, and after the S/C pressure rose and matched the D/W pressure, both pressures showed a tendency to rise in tandem. After nitrogen injection to the S/C was stopped, the S/C pressure decreased following the D/W pressure (Figures 4.3.2-2 and 4.3.2-3).

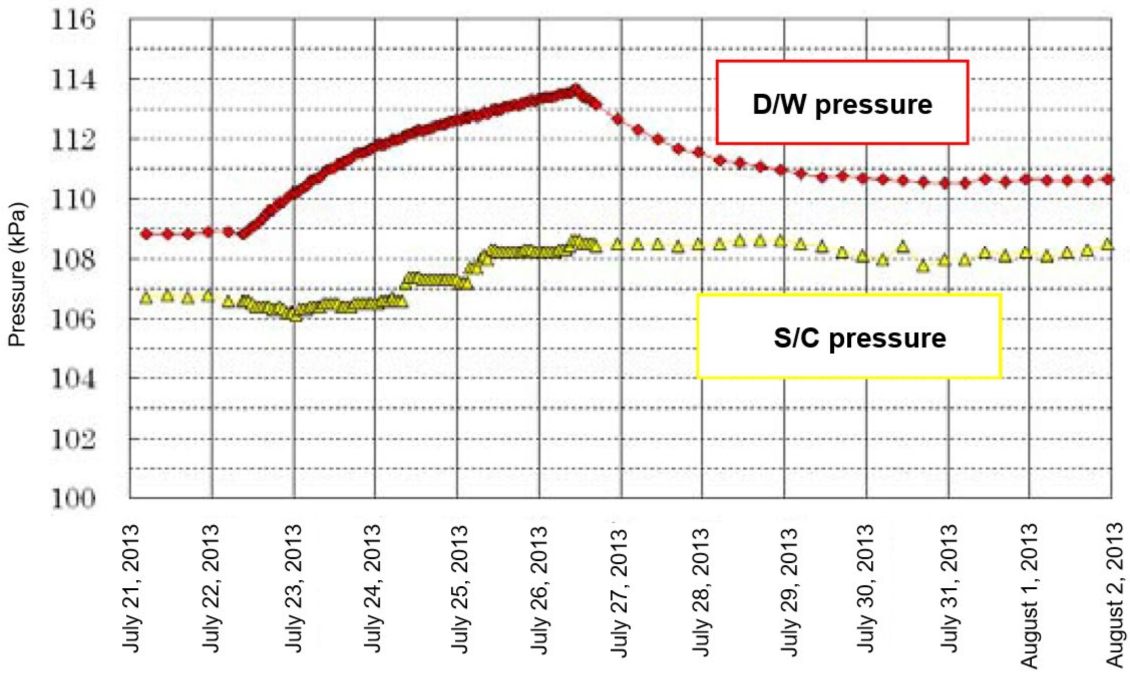


Figure 4.3.2-2 Results of nitrogen injection test in July 2013 [2-6]

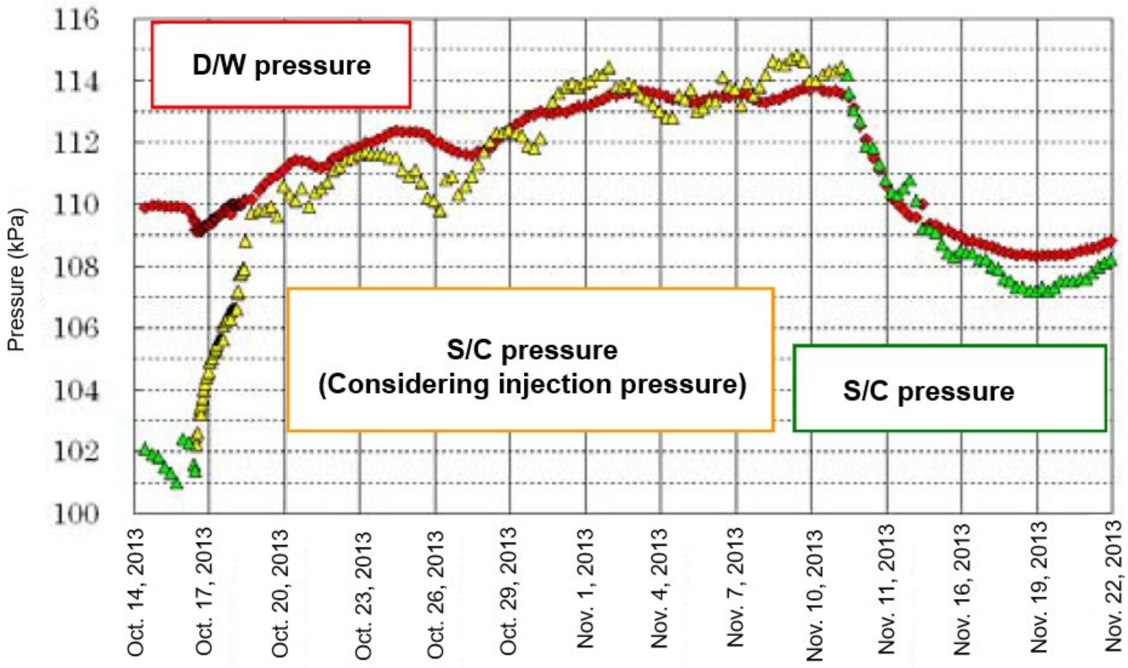


Figure 4.3.2-3 Results of nitrogen injection test in October 2013 [2-6]

From the above, it was confirmed that the nitrogen injected in the S/C was flowing to the D/W, while no response was observed in the hydrogen concentration measured by the PCV gas control equipment, and thus no hydrogen remained in the S/C. The water level in the basement of the reactor building during the test period was about 6.0m or less from the bottom of the S/C, and the water level in S/C is considered to be linked to the water level in the torus room (torus room water level - internal pressure pushing in). The vacuum breaker valve in the S/C (about 5.9m from the bottom of the S/C) was not submerged, and nitrogen was estimated to have flowed through the valve.

・ Results of water level measurement inside S/C

In January 2013, the water level in the S/C was measured by a method that uses a remote-controlled ultrasonic measurement technique to measure the water level in the S/C from the outside surface of the S/C by continuously measuring the reflected waves from the internal structure of S/C (including the opposite wall) and identifying the water level from the position of signal loss (Figure 4.3.2-4).

The water level in the S/C was linked to the accumulated water level in the torus room at almost the same level, as estimated by the nitrogen injection test in the S/C, and it was confirmed that liquid phase leakage was occurring from the lower part of the S/C (including the piping).

Measurement date	Jan. 14, 2014	Jan.15, 2014	Jan. 16, 2014
S/C water level	About OP 3210	About OP 3160	About OP 3150
Water level retained in the torus room (reference info.)	About OP 3230	About OP 3190	About OP 3160
Level difference	About 20mm	About 30mm	About 10mm
Method of measurement	Direct distance measurement between underwater structures		

(Note) S/C water level seems to be affected by water level retained in the torus room

Measurement scene

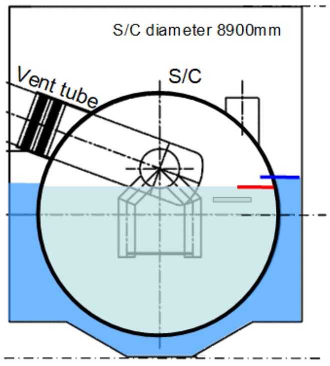


Figure 4.3.2-4 Results of water level measurement in the S/C of Unit 2 [2-7]

From the above, it was confirmed by ultrasonic measurement that the water level in the S/C is about O.P. 3150mm, or about 5.7m from the bottom of the S/C.

4.3.3. Unit 3

The estimation as of August 6, 2014 is shown in Figure 4.3.3-1.

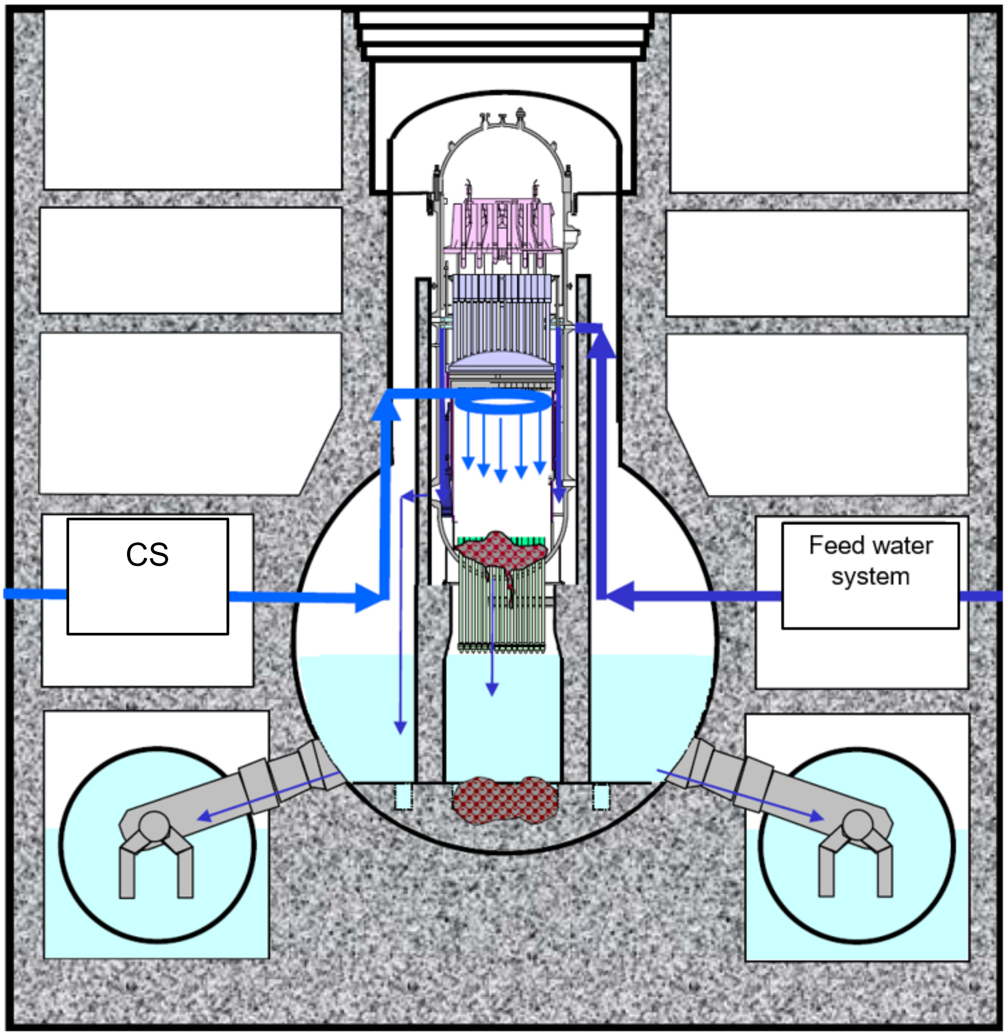


Figure 4.3.3-1 Unit 3 estimated as of August 6, 2014 [3-4]

For the estimation in Figure 4.3.3-1, the characteristics of the estimation, the contents updated from the second estimation, the reason for the update from the second estimation, and the information supporting the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that after the accident, molten fuel fell into the lower plenum of the RPV, and most of it fell further to the bottom of the PCV.

○ Contents updated from the second estimation

① Regarding the distribution of fuel debris, the amount of fuel debris that fell downward in the RPV was increased, and the amount of fuel debris that fell into the PCV was also increased.

○ Reasons for updating from the second estimation

① Regarding the distribution of fuel debris, the amount of fuel debris that fell downward in the RPV was increased, and the amount of fuel debris that fell into the PCV was also increased.

Based on the analysis, which considered the fact that it had not been possible to fully flood the reactor even before the operator manually shut down the HPCI at 14:42 on March 13, 2011, it was estimated that a large amount of fuel had fallen into the PCV. The following is a detailed description.

Figure 4.3.3-2 shows the changes in the reactor water level for the analysis conducted assuming that no water was injected into the reactor by the HPCI after about 20:00 on March 12, when the measurement of the reactor water level was interrupted due to depletion of the DC power supply. The deviation between the analyzed and measured water levels after 04:00 on March 13 decreased, as shown in Figure 4.2.3-2.

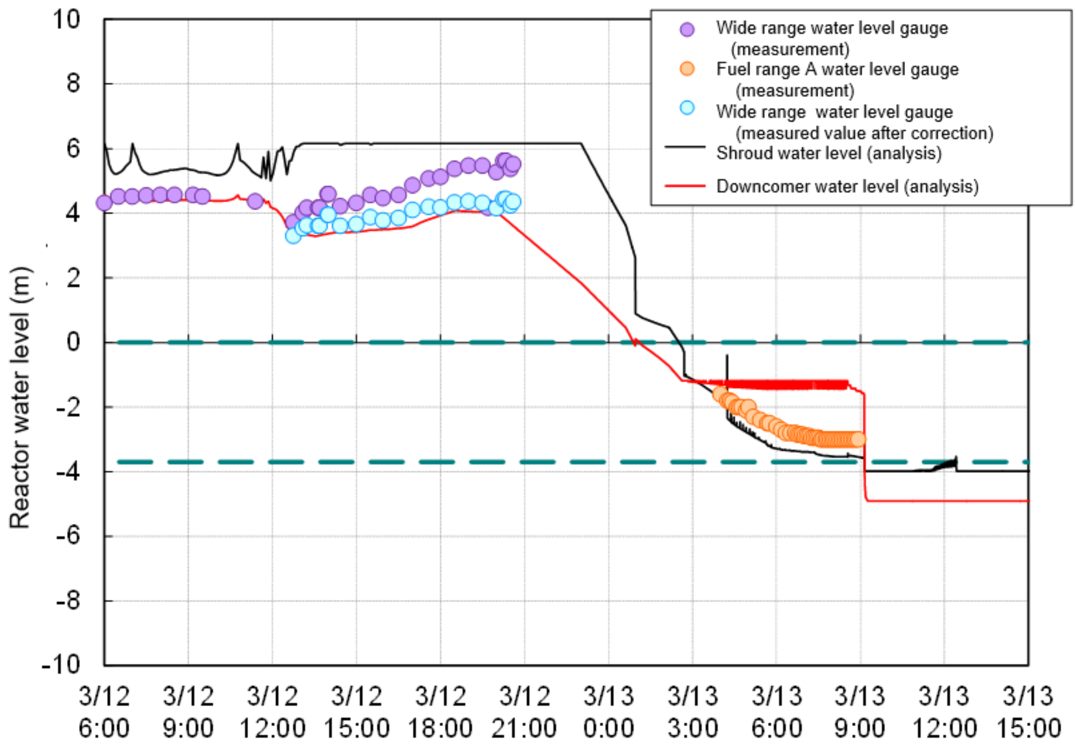


Figure 4.3.3-2 Measured and analyzed values of reactor water level [3-3]

This suggests that water injection by the HPCI was limited, after the measurement of the reactor water level was interrupted. Figure 4.3.3-3 shows the change in the distribution of fuel debris for the analysis shown in Figure 4.3.3-2. The analysis resulted in all of the molten fuel falling into the PCV.

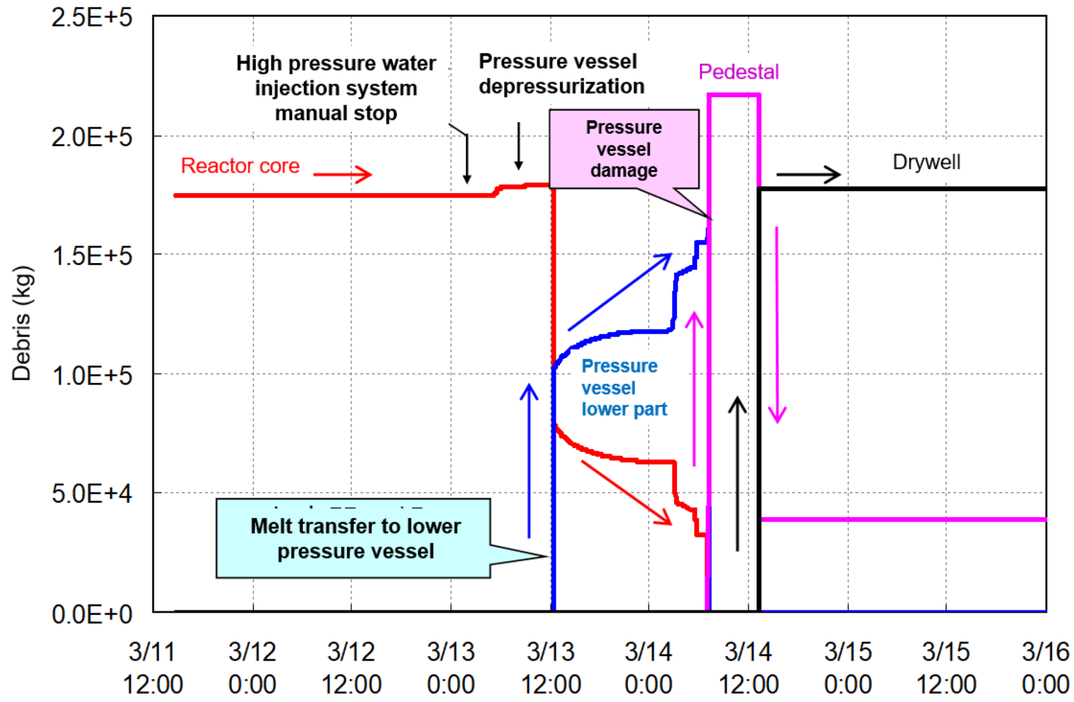


Figure 4.3.3-3 Change in fuel debris distribution [3-3]

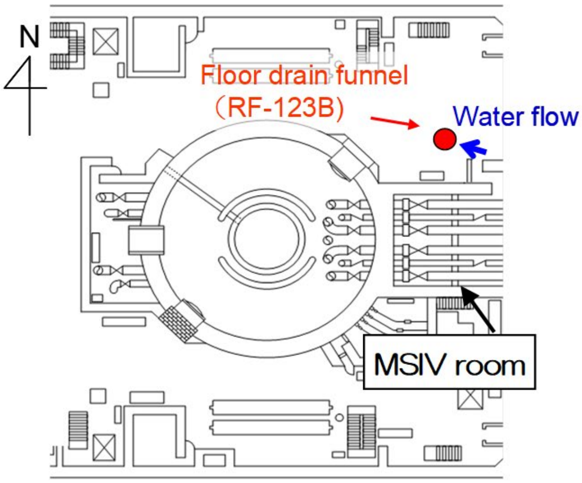
The analysis results do not represent the reality, because there are large uncertainties in the accident progression after the fuel meltdown, such as the migration behavior of molten fuel, and also in the analysis model that handles such uncertainties. However, based on these results, it is possible that a larger amount of fuel may have melted and fallen into the PCV than previously estimated.

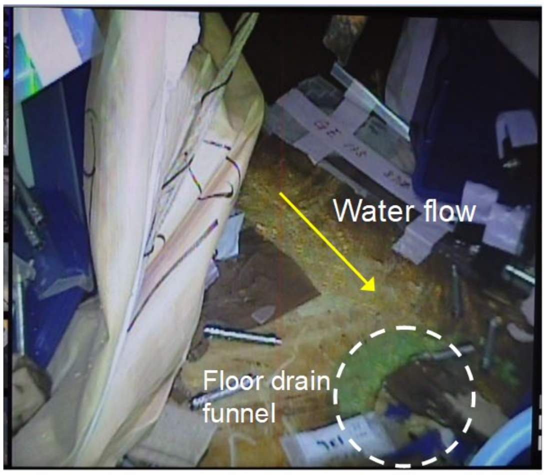
○ Information that supports the estimation

The following information is considered to be reliable for the content of the estimation.

・ Confirmation of leakage from PCV

In January 2014, while checking camera images from the Unit 3 reactor building debris removal robot, it was confirmed that water was flowing from near the door of the MSIV room in the northeast area of the first floor of the reactor building toward the floor drain funnel installed in the vicinity (Figure 4.3.3-4).





(Photo on Jan. 18, 2014)

Figure 4.3.3-4 Confirmation of water leakage from near the MSIV room door of Unit 3 [3-5]

The water level in the PCV (D/W) was about O.P. 12m (about 2m above the first floor of the reactor building), which is about the same height as the PCV penetration of the main steam piping, and it was estimated that the source of the water flow could be liquid phase leakage from the PCV penetration in the MSIV room. Therefore, in April and May 2014, to identify the source of the flowing water in the MSIV room, a device was inserted from the HVAC room on the second floor of the reactor building, and camera photography and dosimetry were conducted in the room. As a result, leakage was confirmed from around the expansion joint of the main steam piping D. No leakage was confirmed from main steam pipings A, B, C, or the main steam drain piping, and judging from the water flow on the floor, the leakage point was estimated to be only in main steam piping D (Figure 4.3.3-5).

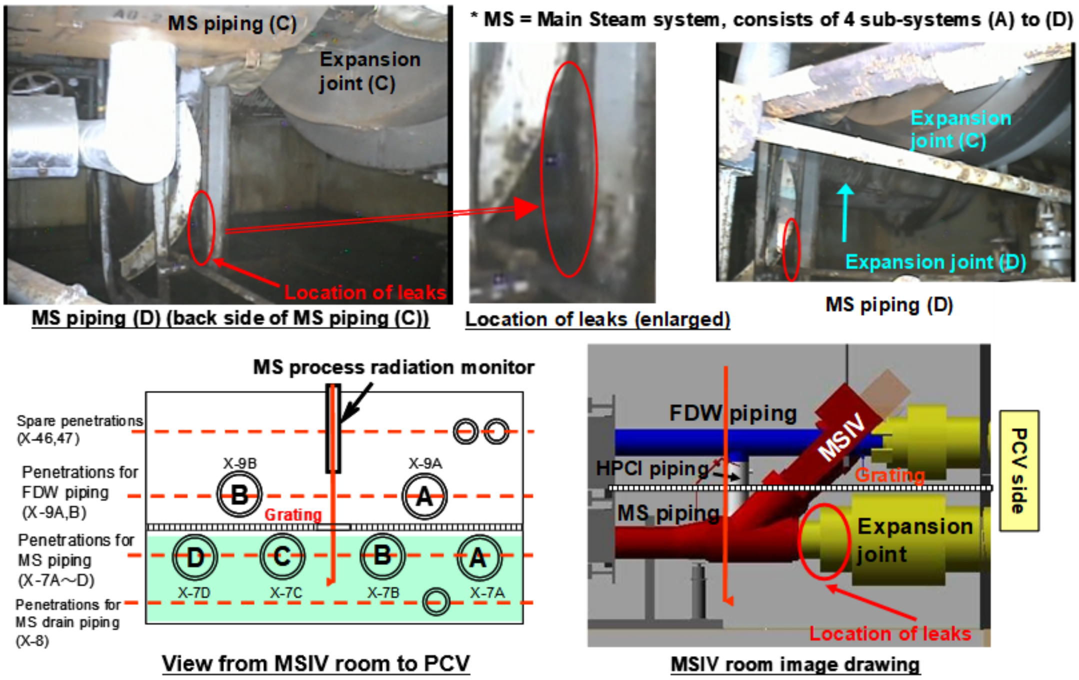


Figure 4.3.3-5 Confirmation of water leakage from main steam piping D in the MSIV room of Unit 3 [3-6]

The estimated height of the D/W water level in Unit 3 and the expansion joint height of the main steam piping D are about the same, and this height is considered to be the main leakage point of the water inside the D/W.

4.4. Fourth estimation (May 20, 2015)

4.4.1. Unit 1

The estimation as of May 20, 2015 is shown in Figure 4.4.1-1.

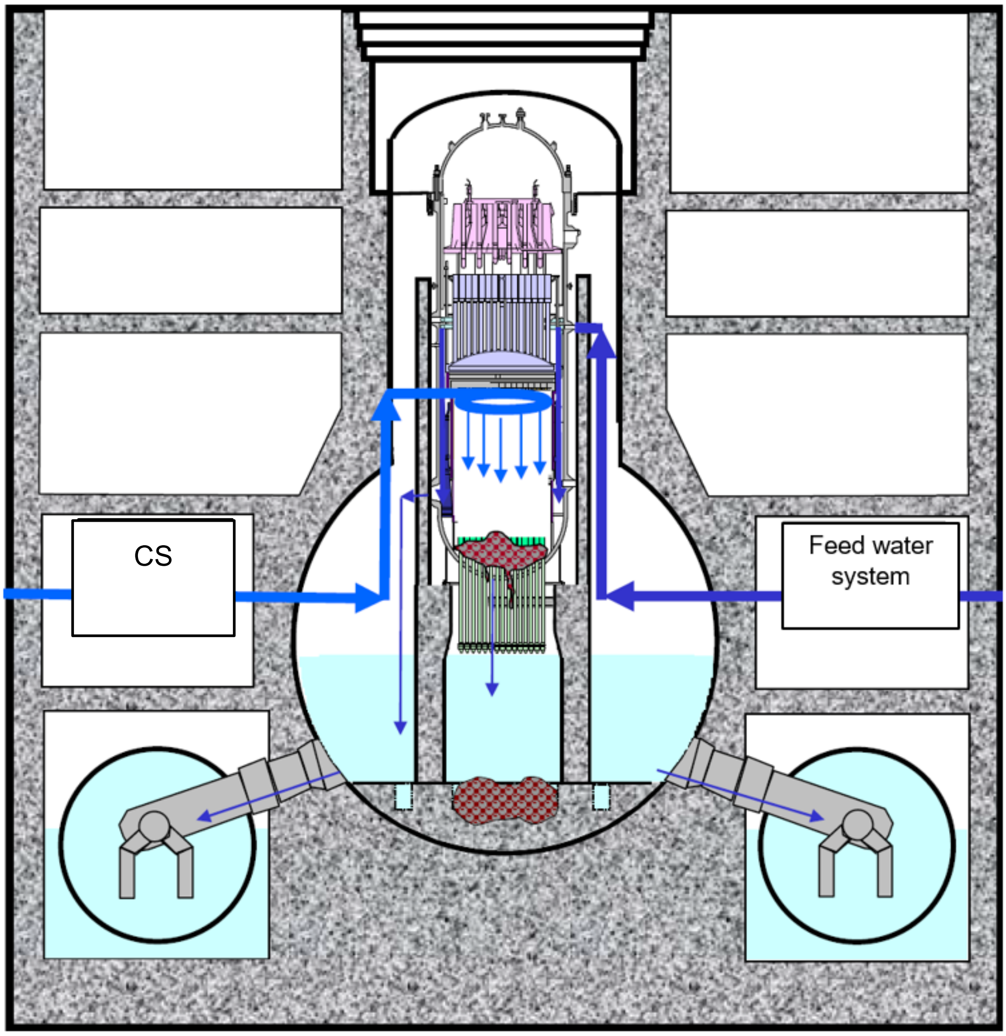


Figure 4.4.1-1 Unit 1 estimated as of May 20, 2015 [1-9]

For the estimation in Figure 4.4.1-1, the characteristics of the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and almost none remained in the original core section. It is estimated that most of the fuel debris that fell into the lower plenum fell to the bottom of the PCV.

○ Contents updated from the third estimate

None.

○ Information supporting the estimation

None.

4.4.2. Unit 2

The estimation as of May 20, 2015 is shown in Figure 4.4.2-1.

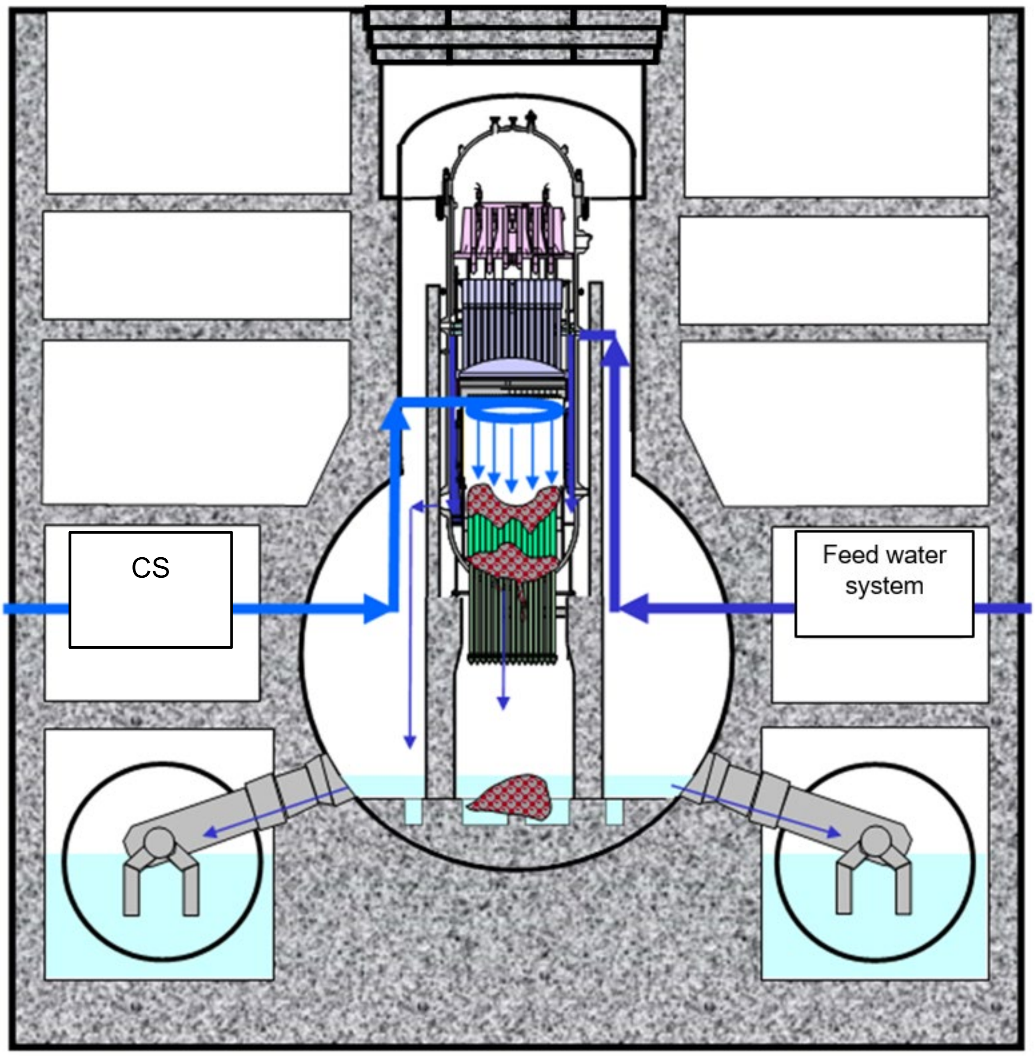


Figure 4.4.2-1 Unit 2 estimated as of May 20, 2015 [2-8]

For the estimation in Figure 4.4.2-1, the estimation characteristics are as follows

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that some of the molten fuel fell into the lower plenum of the RPV and some of it fell to the bottom of the PCV after the accident. No observation indicating a trend of D/W shell damage has been confirmed, and it is estimated that even if the fuel debris that fell to the bottom of the PCV caused MCCI, it would be limited in its extent.

○ Updated contents from the third estimation

None.

○ Information supporting the estimation

None.

4.4.3. Unit 3

The estimation as of May 20, 2015 is shown in Figure 4.4.3-1.

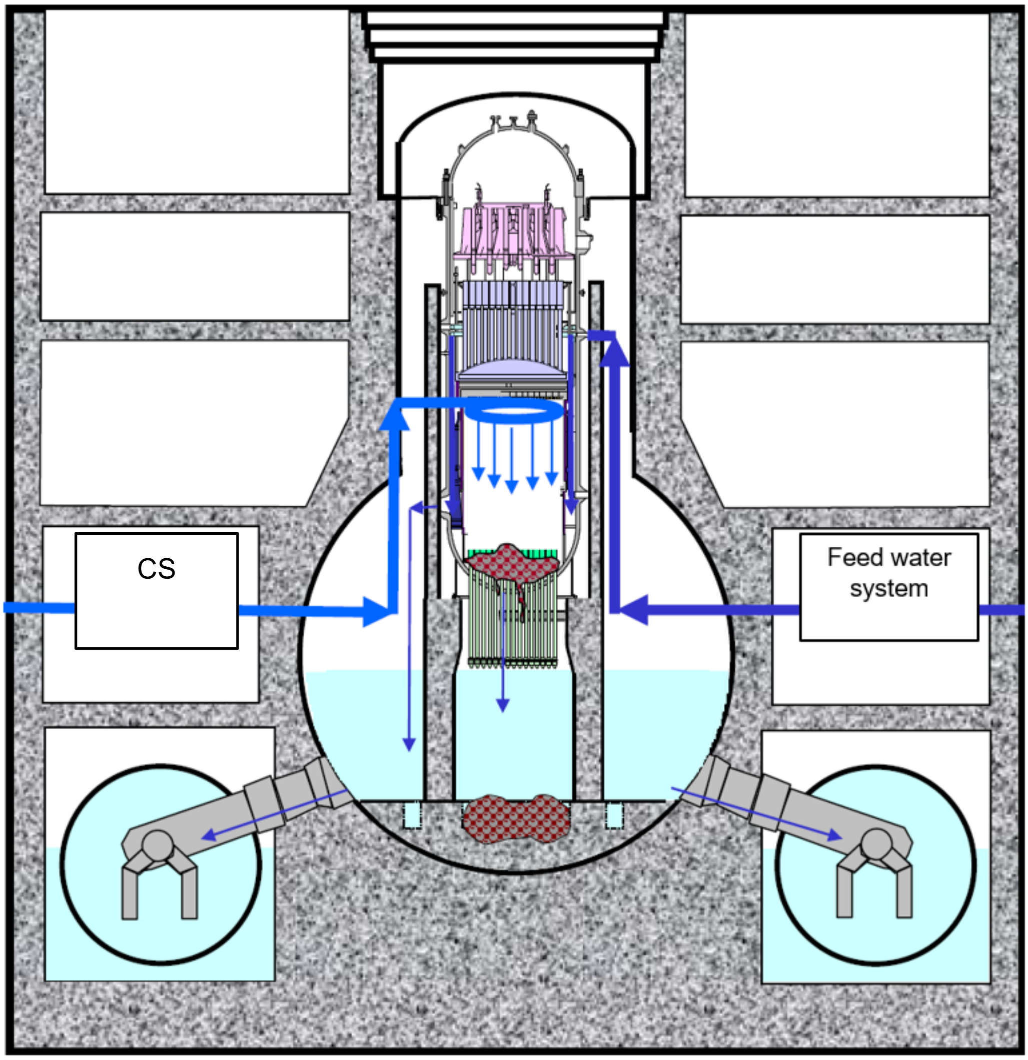


Figure 4.4.3-1 Unit 3 estimated as of May 20, 2015 [2-8]

For the estimation in Figure 4.4.3-1, the characteristics of the estimation are as follows

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that after the accident, molten fuel fell into the lower plenum of the RPV, and most of it fell further to the bottom of the PCV.

○ Updated contents from the third estimation

None.

○ Information supporting the estimation

None.

4.5. Fifth estimation (December 17, 2015)

4.5.1. Unit 1

The estimation as of December 17, 2015 is shown in Figure 4.5.1-1.

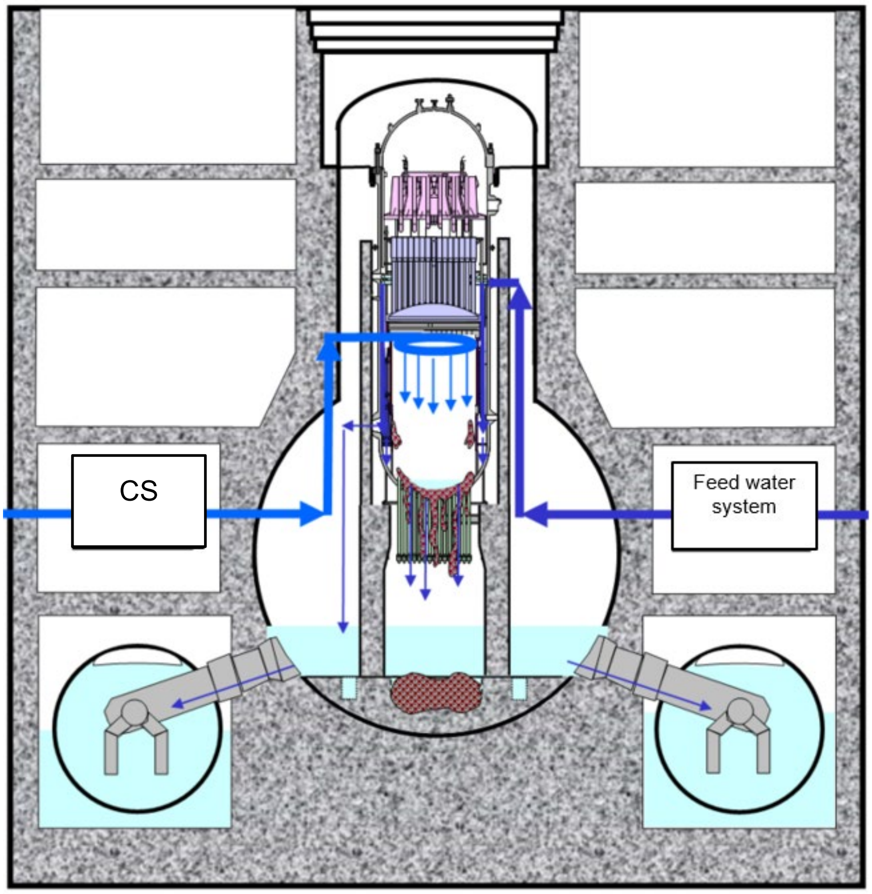


Figure 4.5.1-1 Unit 1 estimated as of December 17, 2015 [1-10]

For the estimation in Figure 4.5.1-1, the characteristics of the estimation and information that supports the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and almost none remained in the original core section. The fuel debris that fell into the lower plenum was estimated to have mostly fallen to the bottom of the PCV.

○ Updated contents from the fourth estimation

None.

○ Information that supports the estimation

The following information is considered to be reliable for the content of the estimation.

・ Investigation using the muon measurement device at Unit 1

As a subsidized project (development of in-reactor fuel debris detection technology) under the Agency for Natural Resources and Energy's "FY2013 Subsidy for Decommissioning and Contaminated Water Countermeasures Project," the IRID and High Energy Accelerator Research Organization have been developing reactor tomography technology (transmission method) using muons. From February 9 to May 21, 2015, data were collected over a period of 96 days to evaluate the status inside the reactor.

Figure 4.5.1-2 shows an estimation figure of the muon measurement results obtained with one instrument, based on the design drawing, and an actual muon measurement image using data of 96 days. The basic principle of the measurement by the muon transmission method is the same as that of an X-ray method, and since more muons are absorbed in the presence of dense material, the area in question is seen in black. In the estimated image assuming that the fuel is sound, black areas appear at the core location in the reactor. On the other hand, in the actual measured image, the high-density material, i.e., fuel, could not be seen at the original core location, although the presence of equipment expected to be visible, such as the fuel pool and the emergency condenser, could be confirmed.

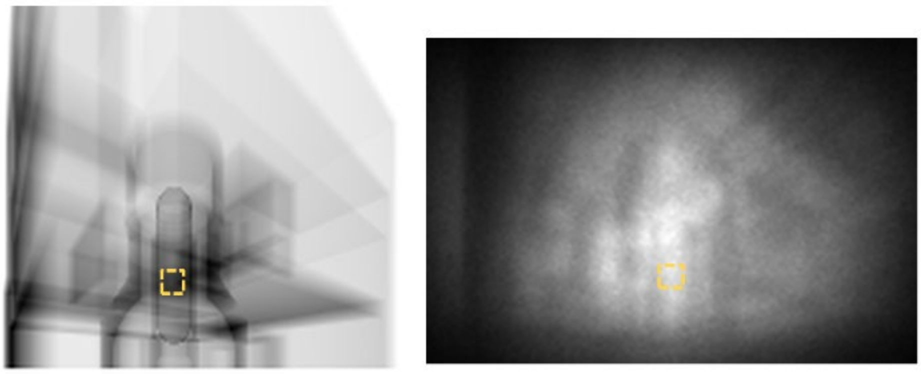


Figure 4.5.1-2 Estimation figure of muon measurement result based on design drawing (left) and muon measurement image based on 96 days of data (right)
(The dashed line indicates the core location.) [1-11]

When the measurement results from the two measurement devices are combined, three-dimensional reconstructed information is obtained. Figure 4.5.1-3 shows the distribution map of high density materials in each height section of the reactor building. In the distribution figure, the locations estimated to be high density for both units are shown in red. From the distribution diagram, the existence of high density materials can be confirmed at the fuel pool location, but not at the core location.

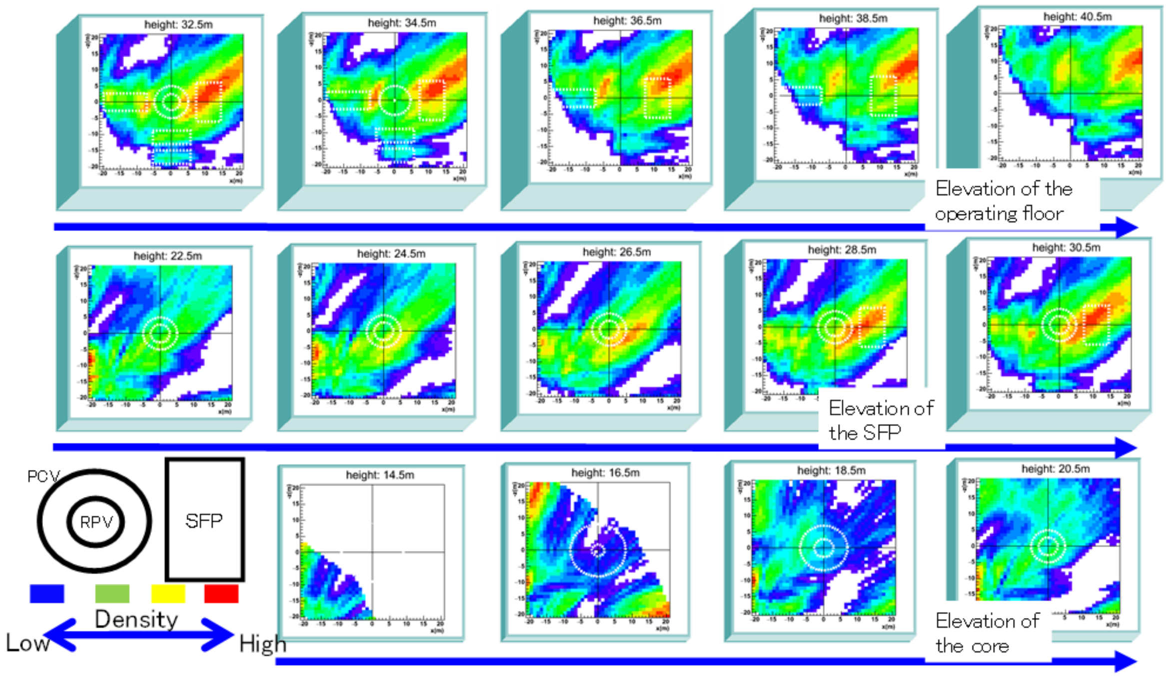


Figure 4.5.1-3 Distribution of high density material at each height section [1-11]

Based on these results, it is estimated that there is almost no fuel remaining in the core of Unit 1, which is basically consistent with the previous estimation.

4.5.2. Unit 2

The estimation as of December 17, 2015 is shown in Figure 4.5.2-1.

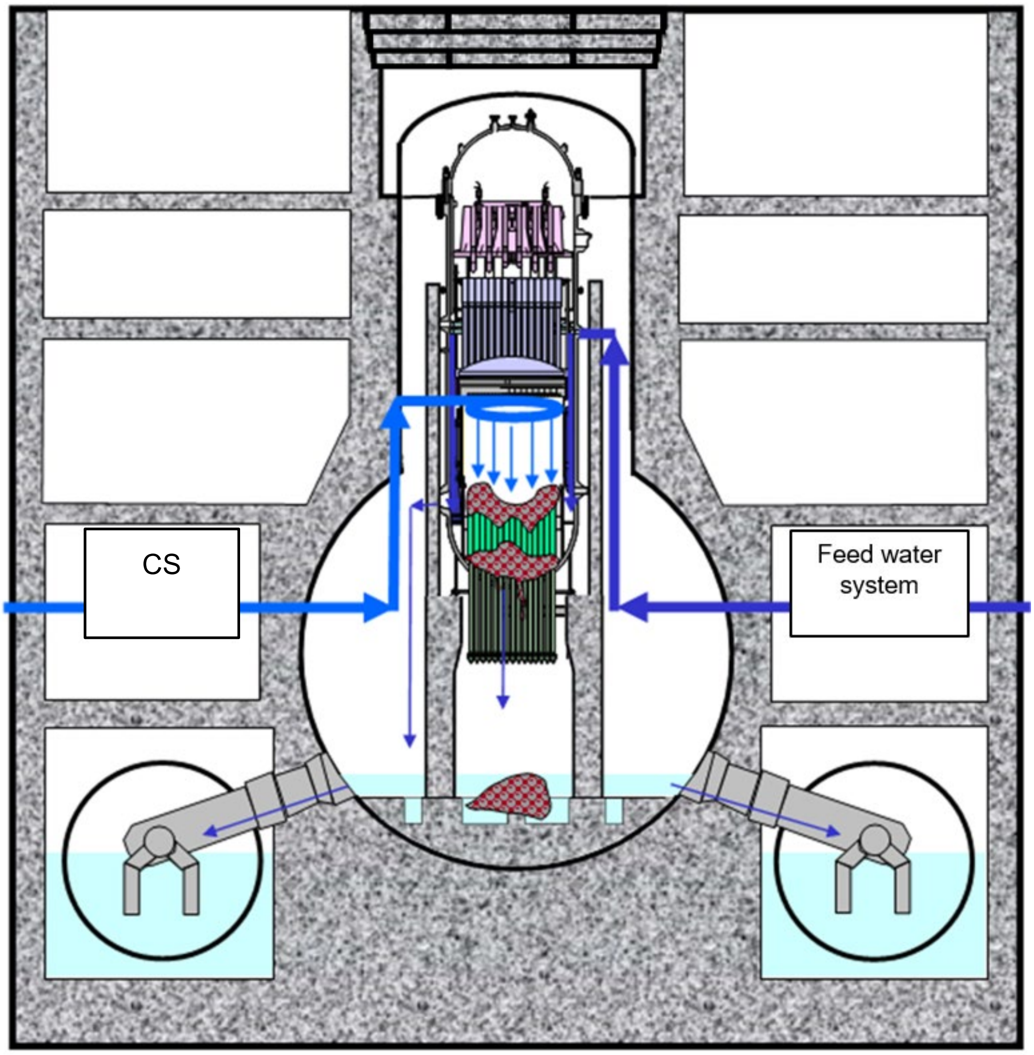


Figure 4.5.2-1 Unit 2 estimation as of December 17, 2015 [2-9]

For the estimation in Figure 4.5.2-1, the characteristics of the estimation and the information supporting the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that some of the molten fuel fell into the lower plenum of the RPV and some into the bottom of PCV after the accident and that there are no observations indicating a behavioral trend of D/W shell damage. The range of MCCI, if any, is estimated to be limited.

○ Updated contents from the fourth estimation

None.

○ Information supporting the estimation

The following information is considered to be reliable for the content of the estimation.

・ Location of the leak at the bottom of the S/C

As described in Section 4.3.2, the water level in the S/C is considered to be linked to the water level in the torus room, and the vacuum breaker valve in the S/C is not considered to be submerged.

The quantitative evaluation of the location and size of the leakage hole is summarized as follows.

- The leak hole was set at the bottom of the S/C and S/C water level fluctuation was calculated based on the measured data, which revealed that S/C water level fluctuated under the influence of D/W pressure, accumulated stagnant water level, and water injection volume.
- The leakage area that is consistent with the measured temperature data is about 9cm^2, and the leakage hole is located below O.P. 512mm (about 3m from the bottom of the S/C) (Figure 4.5.2-2). The piping penetrations below the location of the abovementioned leak hole are shown in Table 4.5.2-1.

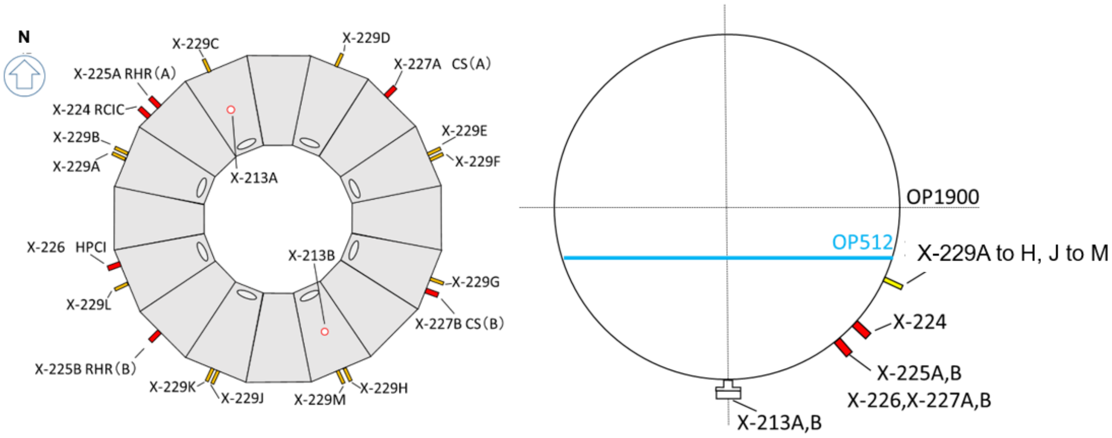


Figure 4.5.2-2 Unit 2 S/C structure [2-9]

Table 4.5.2-1 Unit 2 S/C piping penetrations below O.P. 512mm (about 3m from the bottom of the S/C) [2-9]

Penetration number	Quantity	Name	Height [mm]
X-213A, B	2	Closing plate for drain	O.P-2550
X-224	1	RCIC pump suction	O.P-960
X-225, B	8	RHR pump suction	O.P-1745
X-226	1	HPCI pump suction	O.P-1745
X-227A, B	2	CS pump suction	O.P-1745
X-229A to H, J to M	12	Pneumatic system for vacuum breaker valve drive	O.P 19

Based on the above, the S/C connection lines where the S/C leak hole may exist are the closing plate for the drain, the pump suction of RCIC, RHR, HPCI, and CS, and the pneumatic system line for the vacuum breaker valve drive.

The results of the nitrogen injection test and the measurement of the water level in the S/C until then also confirmed that the S/C water level was linked to the water level in the torus room at about the same level, and that a liquid phase leakage was occurring from the lower part of the S/C (including piping). This is supported by the estimated leakage being at less than about 3m below the bottom of the S/C, which is lower than the water level measured as of January 2014 (about 5.7m below the bottom of the S/C).

4.5.3. Unit 3

The estimation as of December 17, 2015 is shown in Figure 4.5.3-1.

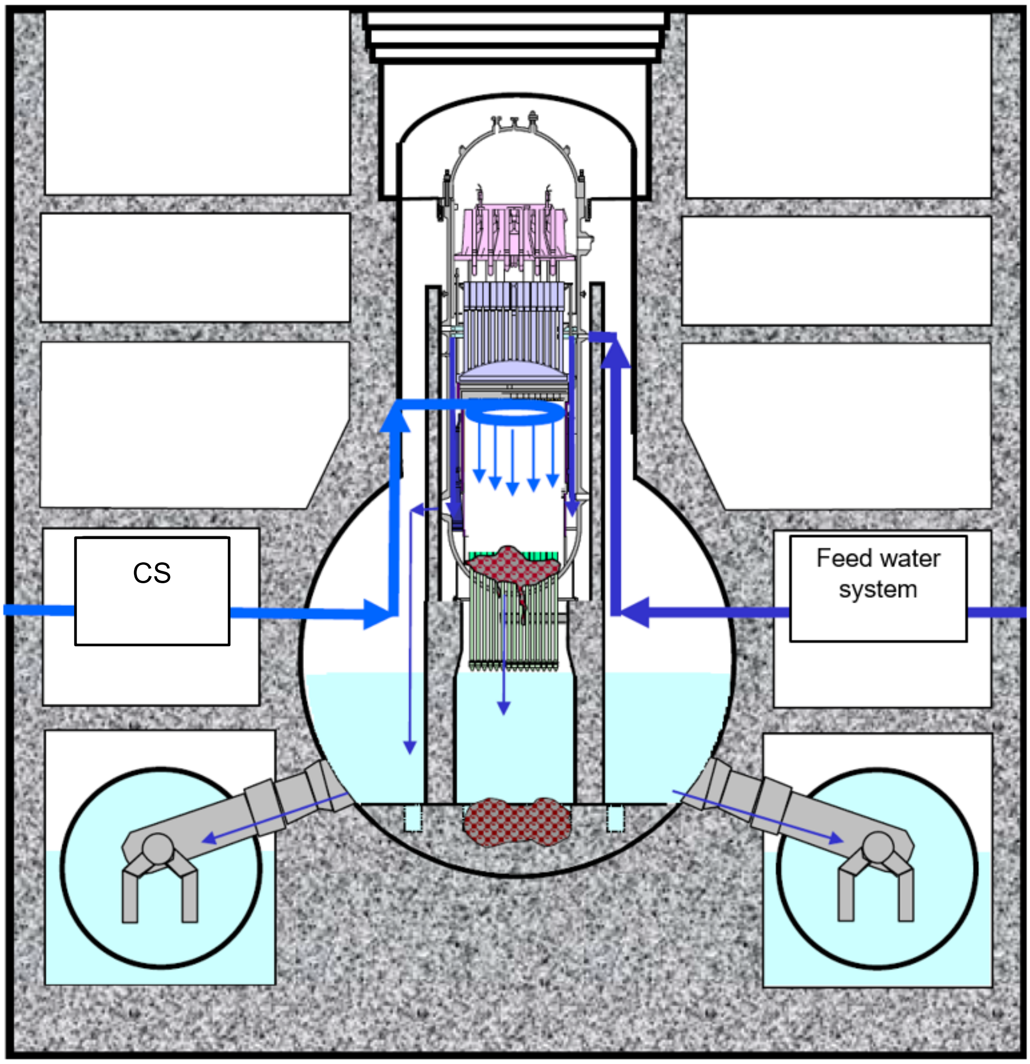


Figure 4.5.3-1 Unit 3 estimation as of December 17, 2015 [3-8]

For the estimation in Figure 4.5.3-1, the characteristics of the estimation and the information supporting the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it was estimated that after the accident, molten fuel fell into the lower plenum of the RPV, and most of it further fell into the bottom of the PCV. Regarding the water level in D/W, it was confirmed that it is about 6.3m from the D/W floor.

○ Updated content from the fourth estimation.

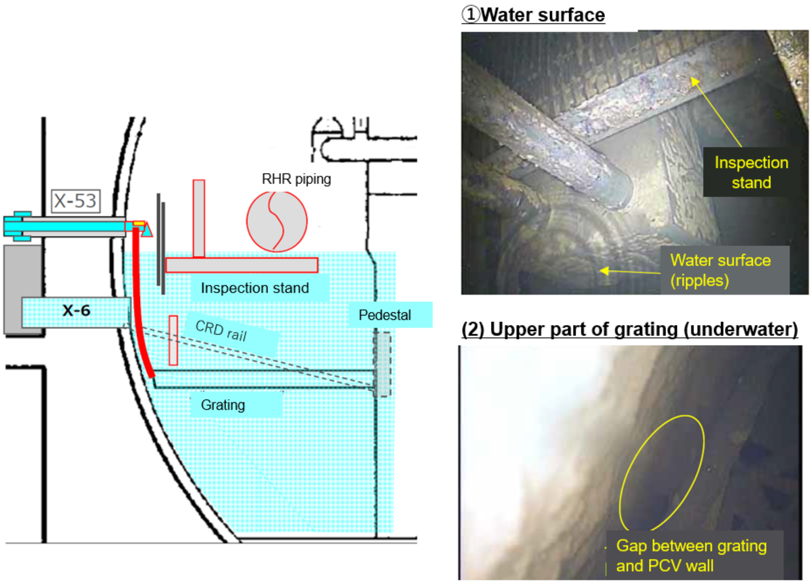
None.

○ Information supporting the estimation

The following information is considered to be reliable for the content of the estimation.

- Regarding the water level of D/W

During the PCV internal investigation conducted on October 20 and 22, 2015, the investigation device was inserted through the X-53 penetration to take internal photographs, check the water level, and confirm the temperature and radiation dose. The water level of the stagnant water in the D/W was about 70cm below the X-53 penetration and about 6.3m above the D/W floor and was generally consistent with the value estimated from the containment vessel pressure described in Section 4.1.3.



	PCV atmosphere
Temp.	About 26 - 27°C
Dose	About 1Sv/h
Water level	About 6.3m

Figure 4.5.3.3 Results of PCV internal investigation [3-9]

4.6. Sixth estimation (July 2016)

4.6.1. Unit 1

The estimation as of July 2016 is shown in Figure 4.6.1-1 and an enlarged version is shown in Figure 4.6.1-2.

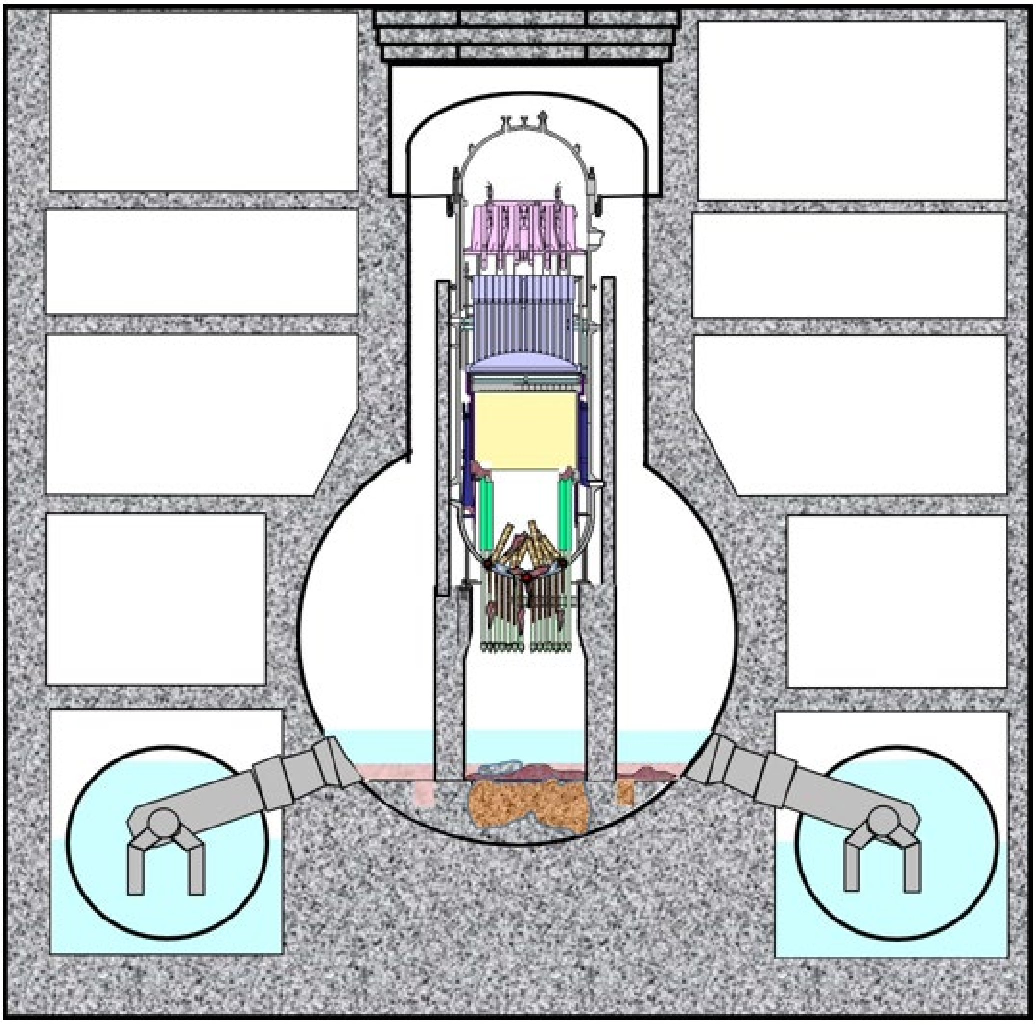


Figure 4.6.1-1 Unit 1 estimation as of July 2016 [1-12]

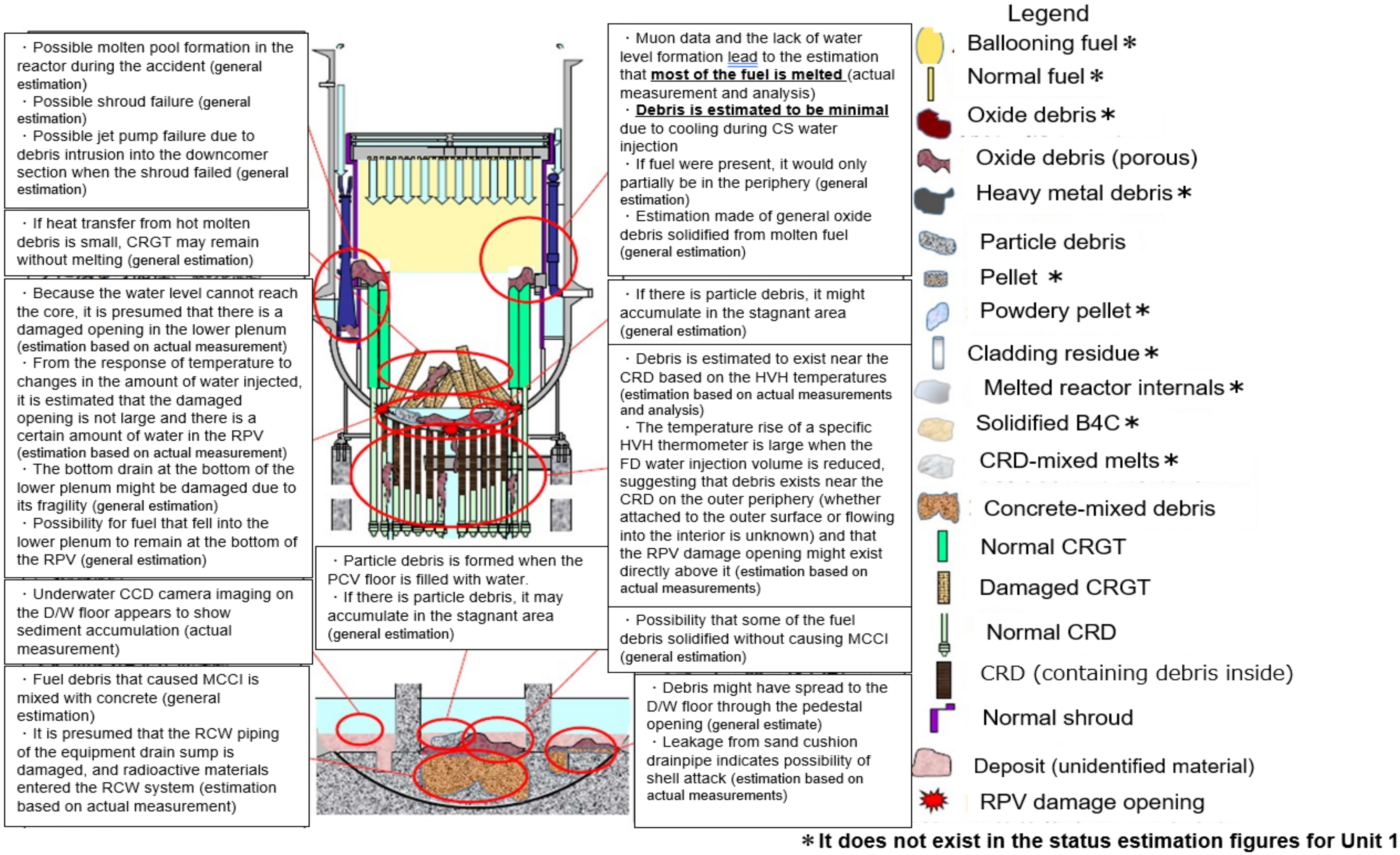


Figure 4.6.1-2 Unit 1 estimation figure as of July 2016 (enlarged) [1-13]

For the estimation in Figures 4.6.1-1 and 4.6.1-2, the characteristics of the estimation, the contents updated from the fifth estimation, and the findings that helped in the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and very little remained in the original core area. The fuel debris that fell into the lower plenum is estimated to have mostly fallen to the bottom of the PCV.

Regarding the status of the structures in the RPV and PCV, the CRGTs at the bottom of the RPV were damaged in the process of fuel melting and falling, and fuel debris is estimated to have penetrated into the CRD housings below the RPV.

It is estimated that unknown materials have accumulated at the bottom of the PCV.

○ Contents updated from the fifth estimation

Focusing on the RPV and the bottom of the PCV, the estimation was refined by estimating the status of the structure in addition to the distribution of fuel debris.

① The fuel debris is estimated to be in various states, including oxidized, particulate, and matter that fell into the PCV and reacted with concrete.
② Damaged CRGTs are estimated to exist at the bottom of the RPV.
③ Some CRGTs are estimated to remain in the periphery of the bottom of the RPV.
④ Damage openings are estimated to exist in the lower plenum of the RPV.
⑤ The center of the CRD housings under the RPV is estimated to be damaged and fuel debris is inside these CRD housings.
⑥ Unknown materials are estimated to have accumulated at the bottom of the PCV.

○ Reasons for the update from the fifth estimation

① The fuel debris is estimated to be in various states, including oxidized, particulate, and matter that fell into the PCV and reacted with concrete.

Based on previous findings, molten fuel during an accident is likely to be mixed with cladding and structures that have also melted. In addition, zirconium and iron, which are components of the cladding and structures, are likely to have been oxidized by the steam-metal reaction. Therefore, the main components of the debris are considered to be uranium oxide from the fuel, zirconium oxide from the cladding, and iron oxide from the structures.

Particle debris may have been generated in the process of molten materials migrating to the lower part of the RPV and contacting water, or in the process of disintegration of oxidized and embrittled structural materials, etc. Particle debris may be present in accumulated water areas (where water does not flow) in the RPV and PCV.

Furthermore, fuel debris that fell into PCV is considered to have reacted (MCCI) with the concrete on the PCV floor or pedestal wall.

② Damaged CRGTs are estimated to be located at the bottom of the RPV.

Based on previous findings, CRGTs located in the lower plenum of the RPV are considered to have been melted or damaged in the process of migration because it is on the migration path of fuel that had become hot and migrated downward from the core section. Therefore, there is a possibility that some damaged CRGTs remain at the bottom of the RPV.

③ Some CRGTs are estimated to remain in the periphery of the bottom of the RPV.

Based on previous findings, the CRGTs located in the lower plenum of the RPV are on the migration path of fuel that had become hot and migrated downward from the core, but if the heat transfer from the fuel debris is small, the CRGTs may remain without melting to some extent. The temperature of the core section is considered to rise from the center, from where the fuel melts and migrates downward, so it is possible that some CRGTs remain in the periphery.

④ Damage openings are estimated to exist in the lower plenum of the RPV.

Although water is injected into the RPV from the FDW and CS to cool the reactor, a water level is not formed in the core, as indicated by the calibrated reactor water level gauge, which indicates 5m below the TAF. Therefore, it is assumed that a damage opening exists in the lower plenum and water is flowing out from there.

⑤ The center of the CRD housings under the RPV is estimated to be damaged and fuel debris is inside these housings.

Based on previous findings, if the CRGTs and CRDs under the RPV are eroded by fuel debris, fuel debris may have penetrated inside the CRD housings. Fuel debris that has penetrated inside the CRD housings may have solidified and remained inside them.

⑥ Unknown materials are estimated to have accumulated at the bottom of the PCV.

In October 2012, a CCD camera was inserted from the X-100B penetration to obtain images of the inside of the PCV (Figure 4.6.1-3). It was confirmed that deposits had accumulated at the bottom, but the matter was not identified. In addition, a blue fragment-like object was observed in the deposits, which is thought to be melted lead.

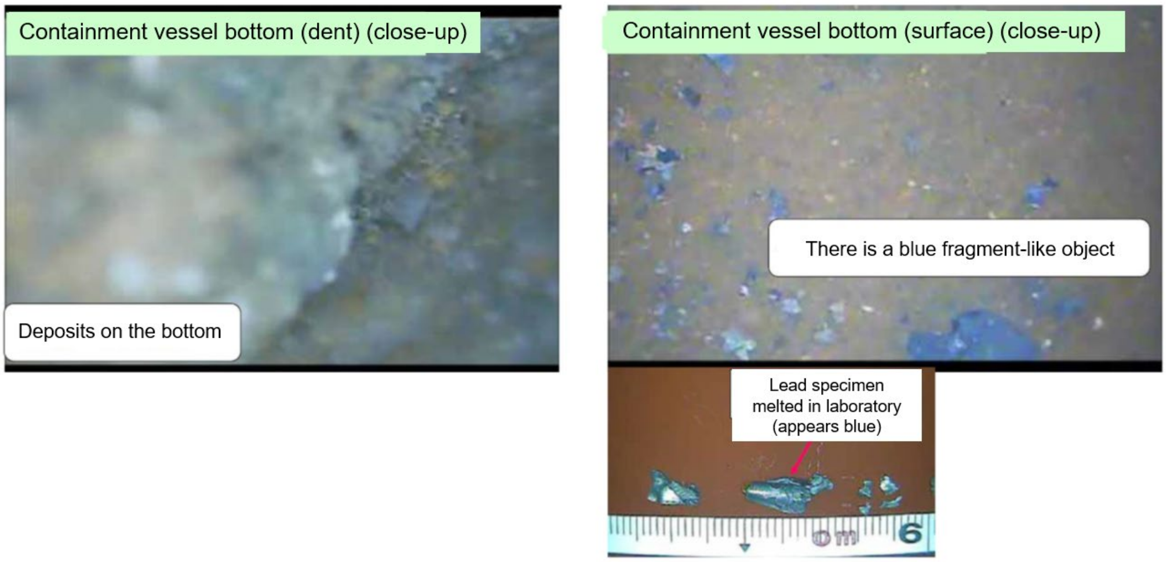


Figure 4.6.1-3 Images gotten on the PCV floor [1-14]

○ Information supporting the estimation

None.

4.6.2. Unit 2

The estimation as of July 2016 is shown in Figure 4.6.2-1 and an enlarged version is shown in Figure 4.6.2-2.

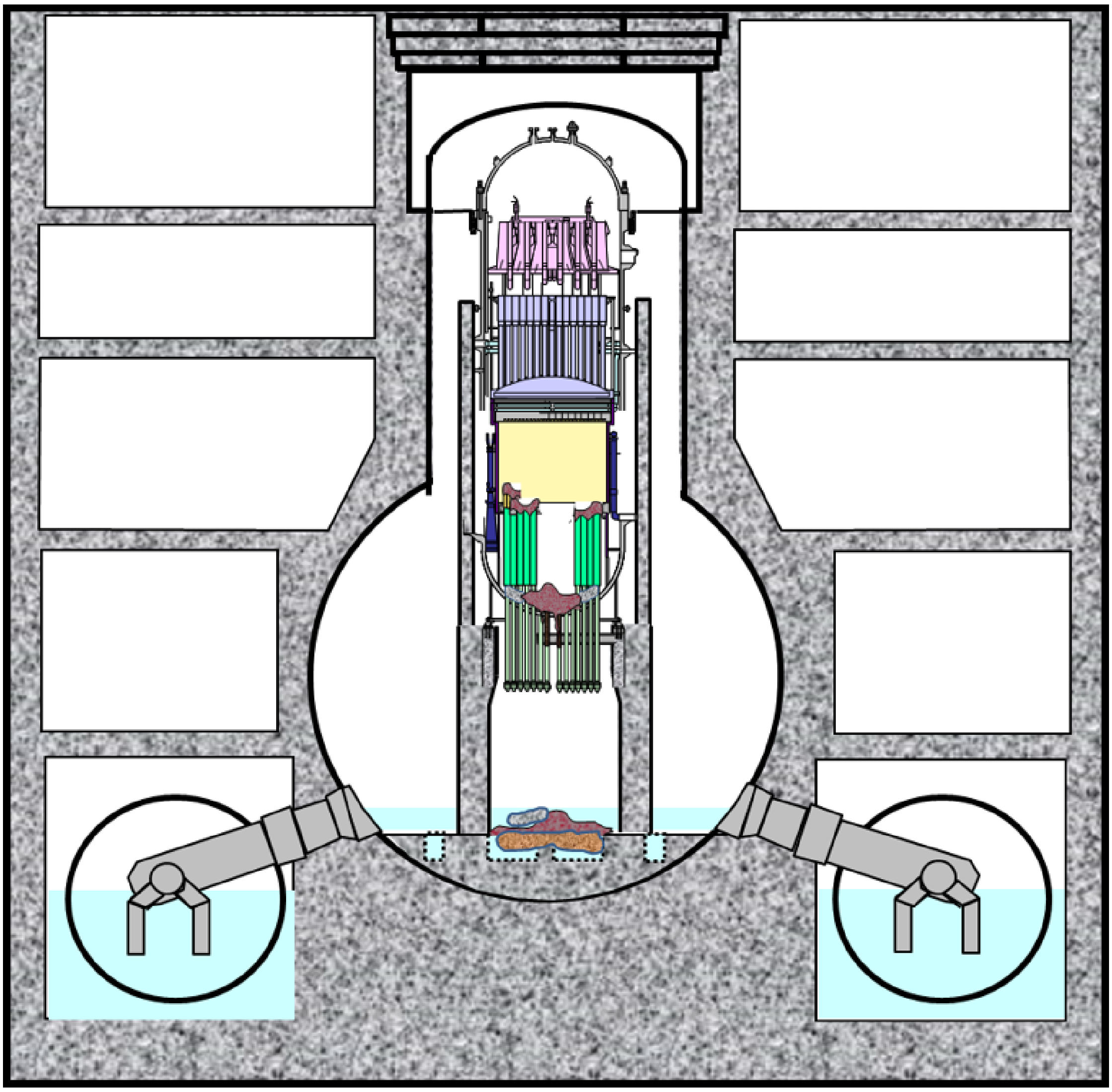


Figure 4.6.2-1 Unit 2 estimation as of July 2016 [2-10]

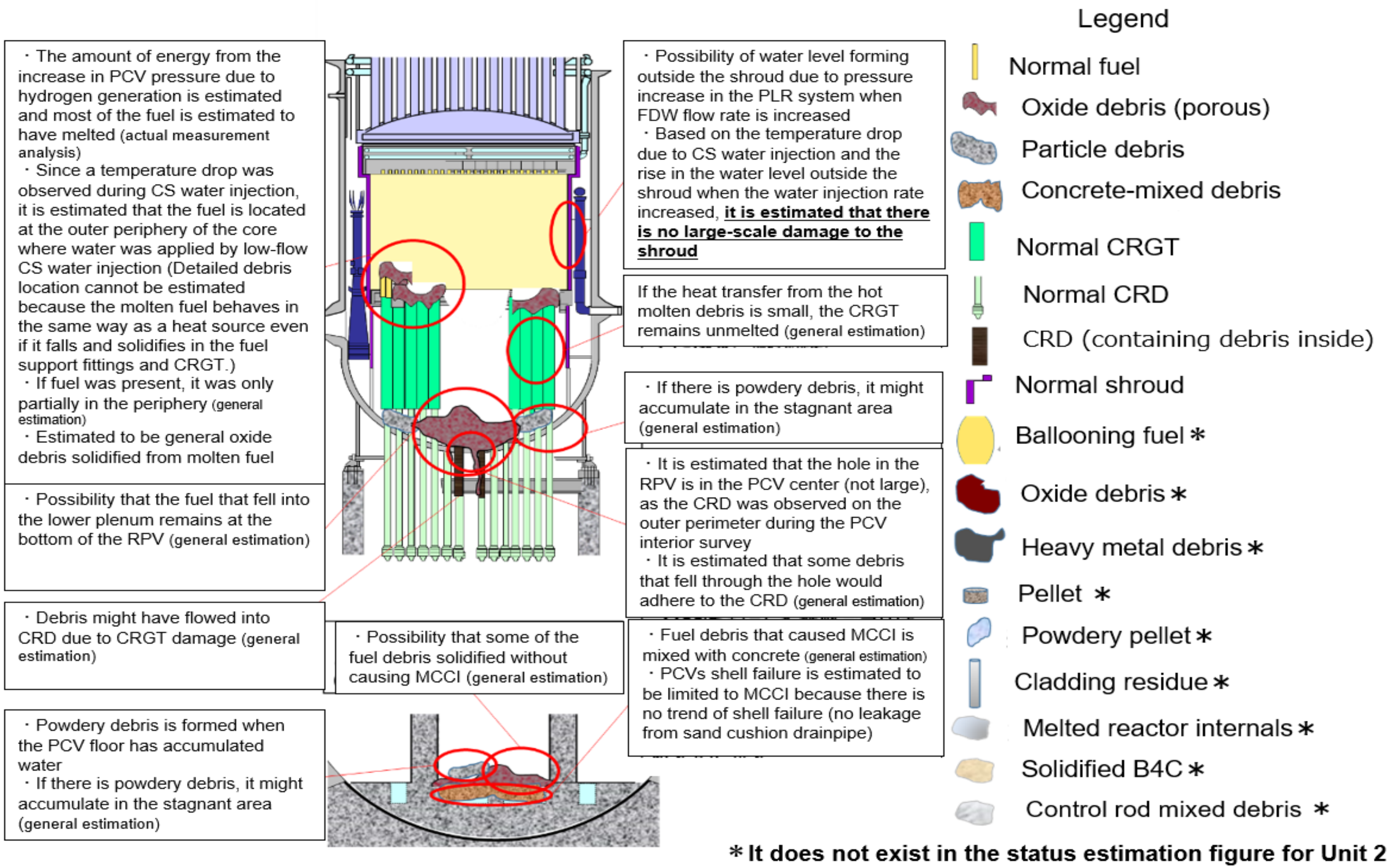


Figure 4.6.2-2 Unit 2 estimation figure as of July 2016 (enlarged) [2-10]

For the estimation in Figures 4.6.2-1 and 4.6.2-2, the characteristics of the estimation, the contents updated from the fifth estimation, the reasons for the update from the fifth estimation, and information supporting the estimation are as follows.

○ Characteristics of the estimation

Regarding the distribution of fuel debris, it is estimated that some of the molten fuel fell into the lower plenum of the RPV after the accident, and some more fell into the bottom of the PCV. The amount of fuel debris that has fallen into the PCV is estimated to be small and MCCI is estimated to be limited.

Regarding the status of the structures in the RPV and PCV, it is estimated that fuel debris has penetrated into the CRD housings below the RPV.

○ Contents updated from the fifth estimation

Focusing on the RPV and the PCV bottom, the estimation was refined by estimating the status of the structure in addition to the distribution of fuel debris.

① The fuel debris is estimated to be in various states, including oxidized, particulate, and matter that fell into the PCV and reacted with concrete.

② Partially melted fuel is estimated to remain in the outer periphery of core.

③ The CRGTs are estimated to remain in the periphery of the bottom of the RPV.

④ The center of the housings under the RPV is estimated to be damaged and fuel debris is inside the CRD housings.

○ Reasons for the update from the fifth estimate

① The fuel debris is estimated to be in various states, including oxidized, particulate, and matter that fell into PCV and reacted with concrete.

Based on previous findings, during the accident molten fuel was likely to have been mixed with cladding and structures that had also melted. In addition, zirconium and iron, which are components of the cladding and structures, were likely to have been oxidized by the steam-metal reaction. Therefore, the main components of the debris are considered to be uranium oxide from the fuel, zirconium oxide from the cladding, and iron oxide from the structures.

Particle debris is also considered to have been formed in the process of molten materials migrating to the lower part of the structure and contacting water, or in the process of disintegration of oxidized and embrittled structural materials, etc. Particle debris may exist in accumulated water areas (where water does not flow) in RPV and

PCV.

Furthermore, fuel debris that fell into PCV is considered to have reacted with the concrete (MCCI) on the PCV floor or pedestal wall.

② Partially melted fuel is estimated to remain in the outer periphery of core.

As shown in Figure 4.6.2-3, temperatures in the RPV and PCV decreased since the start of water injection from the CS on September 14, 2011. However, during the period shown in Figure 4.6.2-3 after the start of water injection by the CS, the maximum water injection rate was 7.2m^3/h, which is considerably less than the design flow rate of 1141m^3/h for the CS. At low flow rates, the water spray is not expected to spread as much, which means that there is a possibility that there is fuel in the area where water is applied even with low flow rate water injection from the CS, e.g., at the outer periphery of the core. However, although this information suggests the possibility of a heat source at the periphery, it does not distinguish whether fuel debris remains at the periphery of the core or whether the heat source is fuel debris that has solidified due to molten fuel falling into the fuel support fittings or CRGTs, and the detailed fuel debris distribution in the vertical direction cannot be determined.

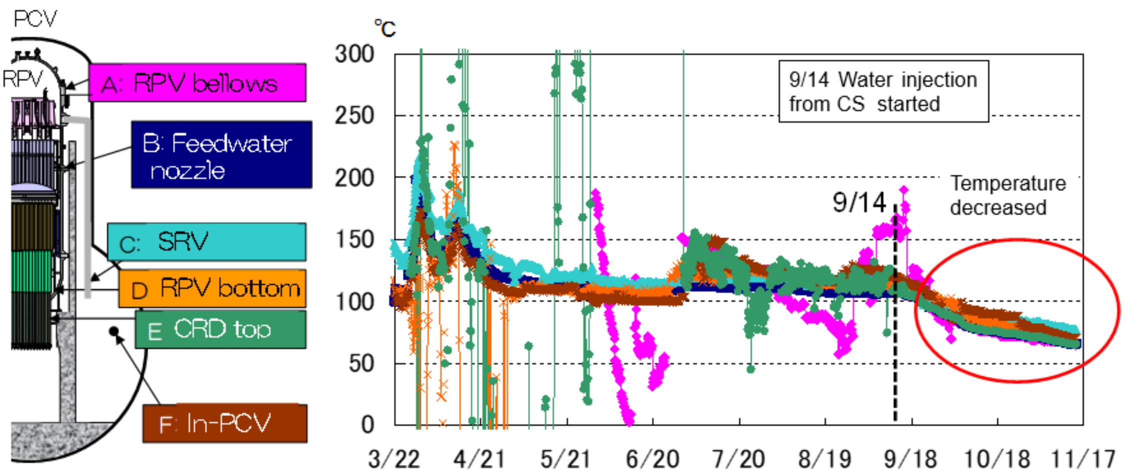


Figure 4.6.2-3 Temperatures of various parts of Unit 2 PCV (2011) [2-11]

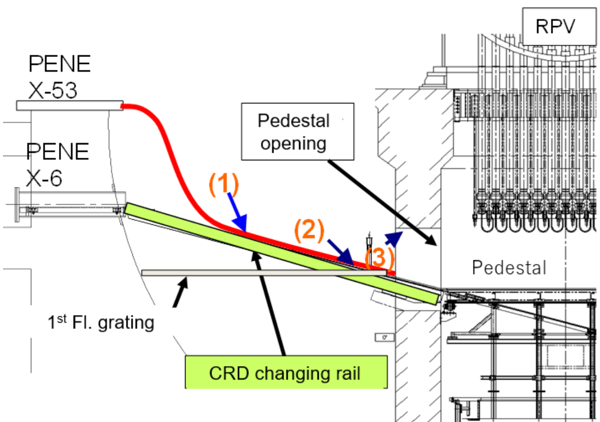
Based on previous findings, it is assumed that the temperature of the core section rises from the center and fuel melting proceeds from there. Although it is not possible to determine the detailed location of fuel debris in the vertical direction around the inner and outer perimeters of the RPV, it is estimated that partially melted fuel remains in some parts of the outer perimeter of the core.

③ The CRGTs are estimated to remain in the periphery of the bottom of the RPV.

Based on previous findings, the CRGTs located in the lower plenum of the RPV are on the migration path of fuel that had become hot and migrated downward from the core section, but if heat transfer from the fuel debris is small, the CRGTs may remain without melting to some extent. The temperature of the core section is considered to rise from the center, from where the fuel melts and migrates downward, so there is a possibility that some CRGTs remain in the outer periphery of the core section.

④ The center of the CRD housings under the RPV is estimated to be damaged and fuel debris is inside these CRD housings.

As shown in Figure 4.6.2-4, survey equipment was deployed from the X-53 penetration in August 2013 to investigate the CRD replacement rail and the area near the RPV pedestal opening. U-shaped cables can be observed in the photograph taken from point (3) in Figure 4.6.2-4 looking into the pedestal. Next, Figure 4.6.2-5 shows the inside of the pedestal of Unit 5. The photo on the left was taken from the same angle as the photo in Figure 4.6.2-4, and the U-shaped cable can be observed as in Unit 2. Therefore, since the CRD housings do not appear to be damaged at the confirmed outer perimeter, it is estimated that the center of the housings was damaged.



	Dose	Temperature
(1)	about 24 Sv/h	about 41 ℃
(2)	about 30 Sv/h	about 45 ℃
(3)	about 36 Sv/h	about 45 ℃

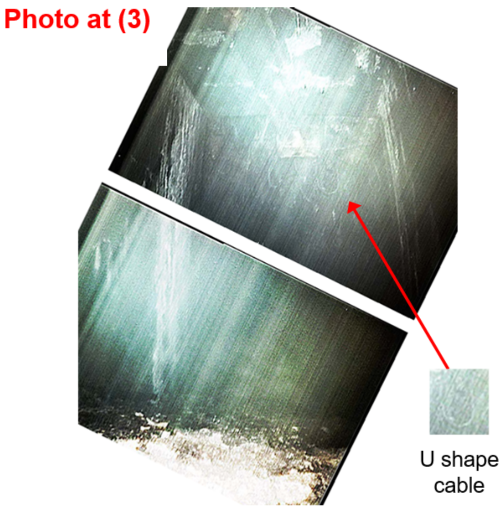
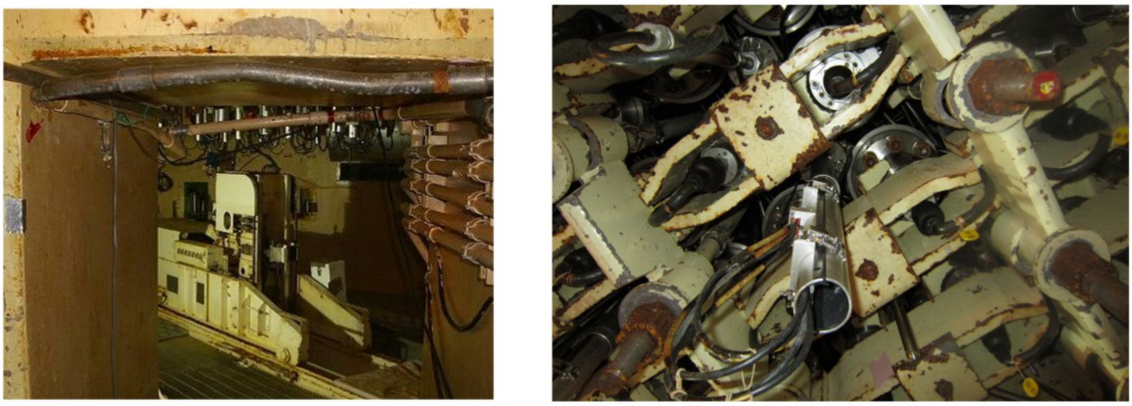


Figure 4.6.2-4 Images of the inside of Unit 2 pedestal [2-9][2-12]



Looking inside through the pedestal opening　　Looking up at the bottom of the RPV

Figure 4.6.2-5　Images of the inside of Unit 5 pedestal [2-12]

Based on the previous findings, if the CRGTs and CRD housings below the RPV were eroded by fuel debris, there is a possibility that fuel debris may have penetrated into the CRD housings. The fuel debris that has entered the CRD housings may have solidified and remained inside them.

○ Information that supports the estimation

The following information is considered to be reliable for the content of the estimation.

- PCV pressure increase due to hydrogen formation

In Unit 2, the reactor was successfully depressurized at 18:00 on March 14, 2011, following the forced opening of the SRVs, but three increases in reactor pressure occurred during the following night and early morning (Figure 4.6.2-6). The records indicate that this behavior was caused by the SRV opening operation (pressure increase = SRV closed, pressure decrease = SRV open). However, the SRV open/close status was not directly confirmed.

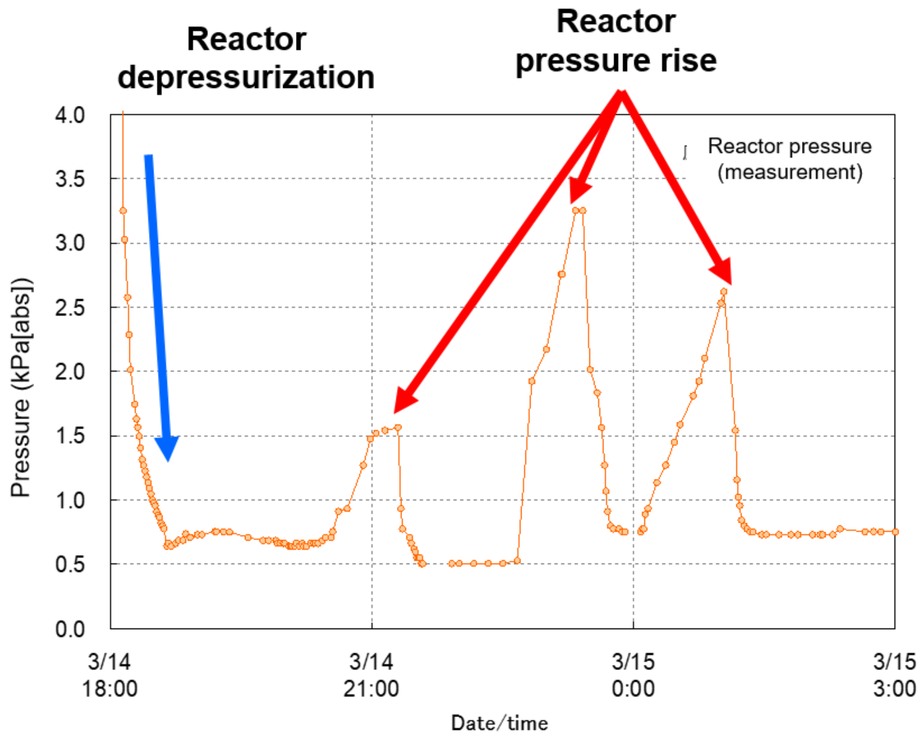


Figure 4.6.2-6 RPV pressure increase after RPV depressurization [2-13]

In conjunction with this pressure increase, a rise in PCV pressure was observed, which is thought to be associated with the formation of a large amount of hydrogen, and this pressure increase is thought to be significantly related to the development of the accident at Unit 2. This is because hydrogen formation associated with the water-zirconium reaction is an exothermic reaction, and a large amount of hydrogen formation means a large amount of energy generation, which is thought to have led to the melting of the fuel.

In this examination of unresolved issues regarding the behavior of reactor pressure, the general thermal-hydraulic analysis code GOTHIC (Generation of Thermal-Hydraulic Information for Containments) was used to adjust the amount of steam and hydrogen formation to try to reproduce the actual measured values of reactor pressure and D/W pressure (Fig. 4.6.2-7).

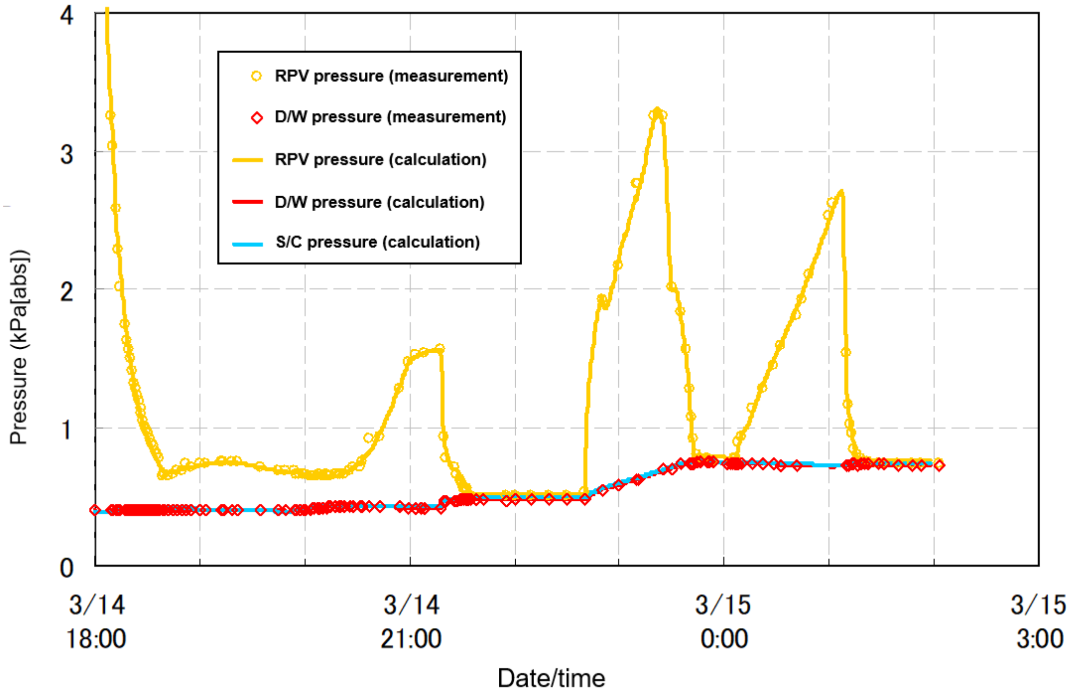


Fig. 4.6.2-7 Comparison of measured reactor pressure and PCV pressure with GOTHIC analysis results [2-13]

In order to reproduce the actual pressure measurements and have a realistic amount of steam and hydrogen formation, it is necessary to assume the amount of formation shown in Figure 4.6.2-8. The results show that most of the zirconium in the reactor reacted by the timing of the second peak, and the hydrogen formation was particularly significant then.

Therefore, the relationship between hydrogen formed and energy production associated with the water-zirconium reaction suggests that most of the fuel melted at the timing of the second peak. This confirms the previous estimation that most of the core has migrated to the lower part of the RPV.

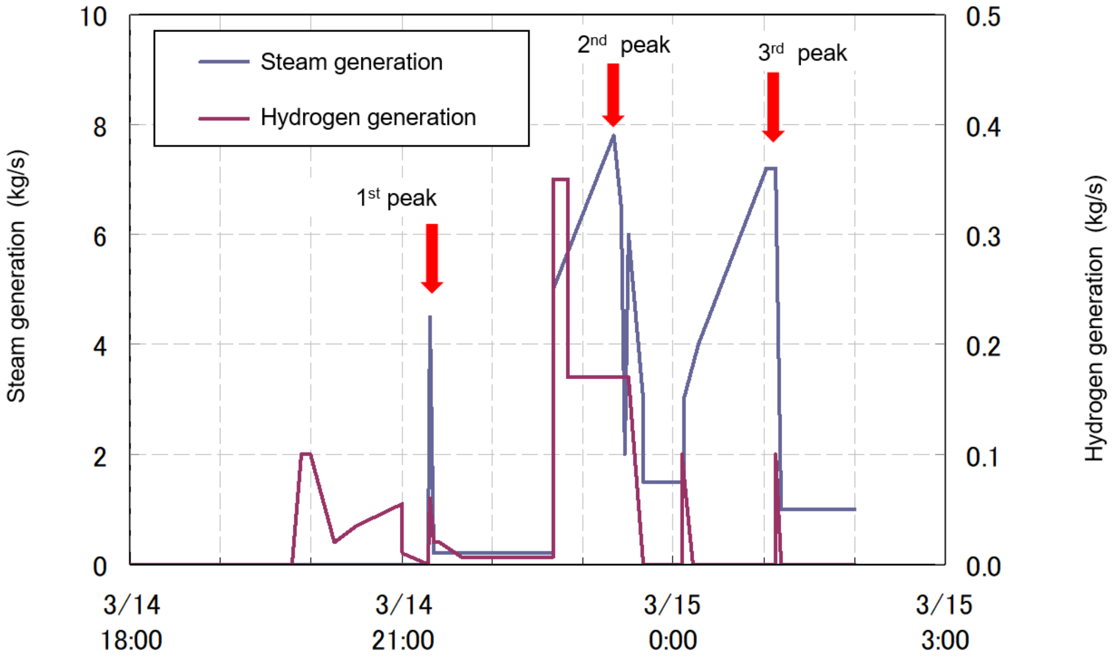


Figure 4.6.2-8 Steam and hydrogen generation setting for GOTHIC analysis [2-13]

・ About the shroud section

Figure 4.6.2-9 shows the relationship between the amount of water injected from the FDW and the water level in the annulus section estimated from the PLR inlet pressure from December 2011 to February 2012. The water level outside the shroud rises as the amount of water injected from the FDW changes.

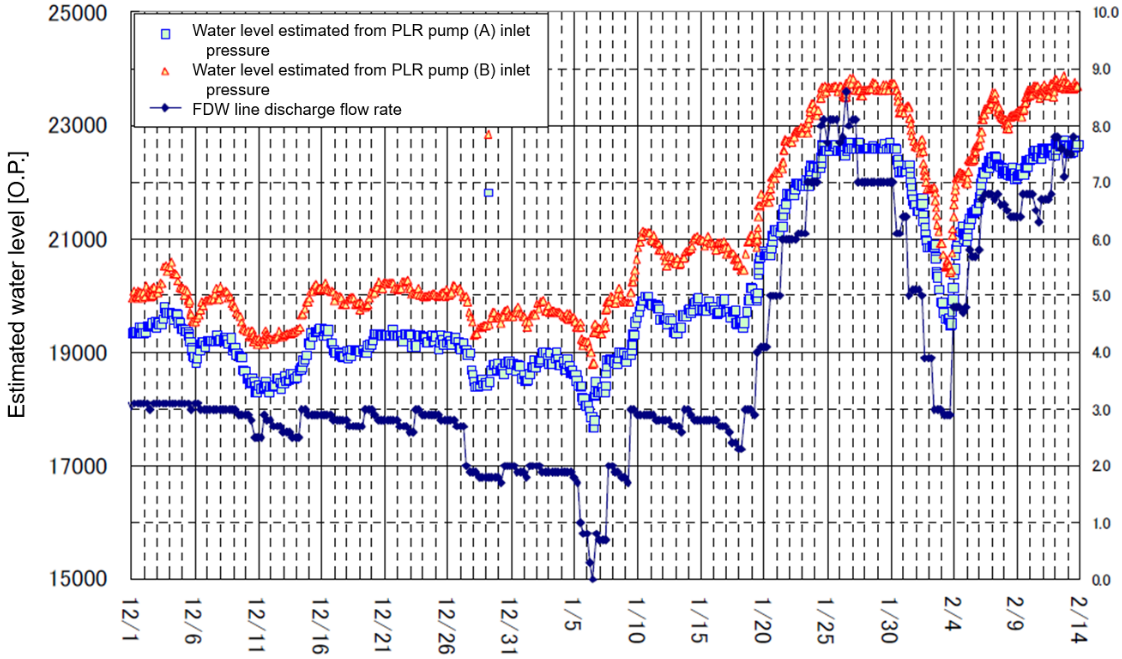
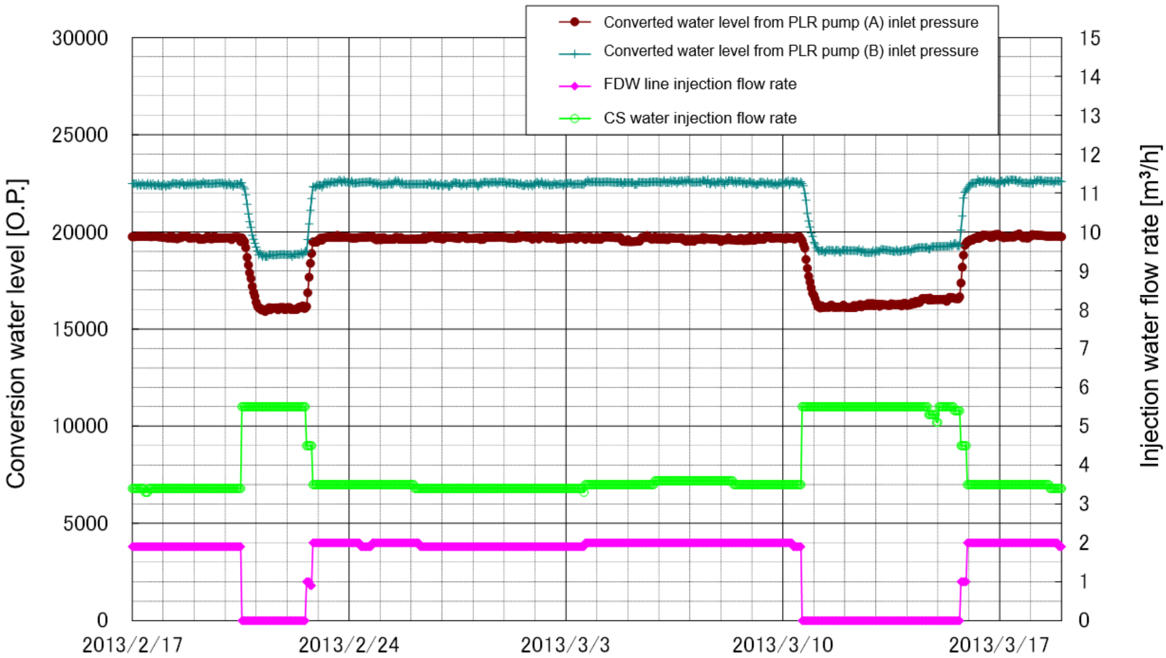


Figure 4.6.2-9 Relationship between the amount of water injected from the FDW and the water level in the annulus estimated from PLR inlet pressure (December 2011 - February 2012) [2-13]

This suggests the following two possibilities. The first is that the degree of damage to the shroud is small and some level of water may have formed outside the shroud. The second is that the amount of water injected from the FDW has increased, and the water level in the RPV is rising, although the shroud is damaged.

Figure 4.6.2-10 similarly shows the relationship between the amount of water injected from the FDW and the water level in the annulus estimated from the PLR inlet pressure from February 2013 to March 2013. During the time shown in the graph, there are two periods when the amount of water injected from FDW was set to zero, while the total amount of water injected from the FDW and CS remained unchanged. Just at this timing, the water level in the annulus, estimated from the PLR inlet pressure, is decreasing. This behavior can be attributed to the fact that some level of water has formed to some extent outside the shroud, and the first of the two possibilities described above is likely to be true. Therefore, the possibility of significant damage to the shroud is considered small.



4.6.2-10 Relationship between water injected from the FDW and CS and water level in annulus section estimated from PLR inlet pressure (February 2013 - March 2013) [2-10]

As shown in Figure 4.6.2-3, the temperature of each part of the PCV uniformly decreased with water injection from the CS that started on September 14, 2011. The amount of water injected from the FDW at this time was about the same before and after the CS started.

This suggests that the heat source is located at the point cooled by the water injection from the CS, and the possibility that the shroud is damaged, and the heat source is transferred outside the shroud is small; in other words, the possibility that the shroud is severely damaged is small.

4.6.3. Unit 3

The estimation as of July 2016 is shown in Figure 4.6.3-1 and an enlarged version is shown in Figure 4.6.3-2.

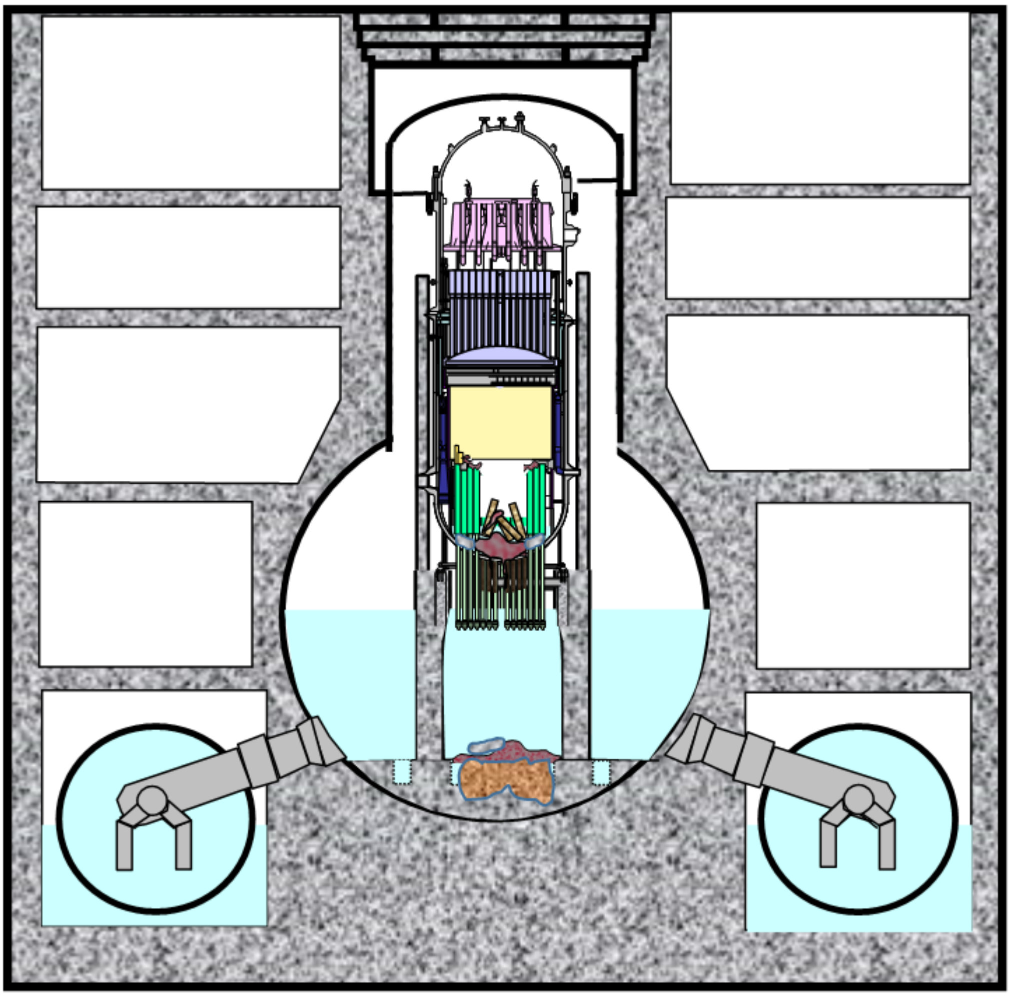


Figure 4.6.3-1 Unit 3 estimation as of July 2016 [3-10]

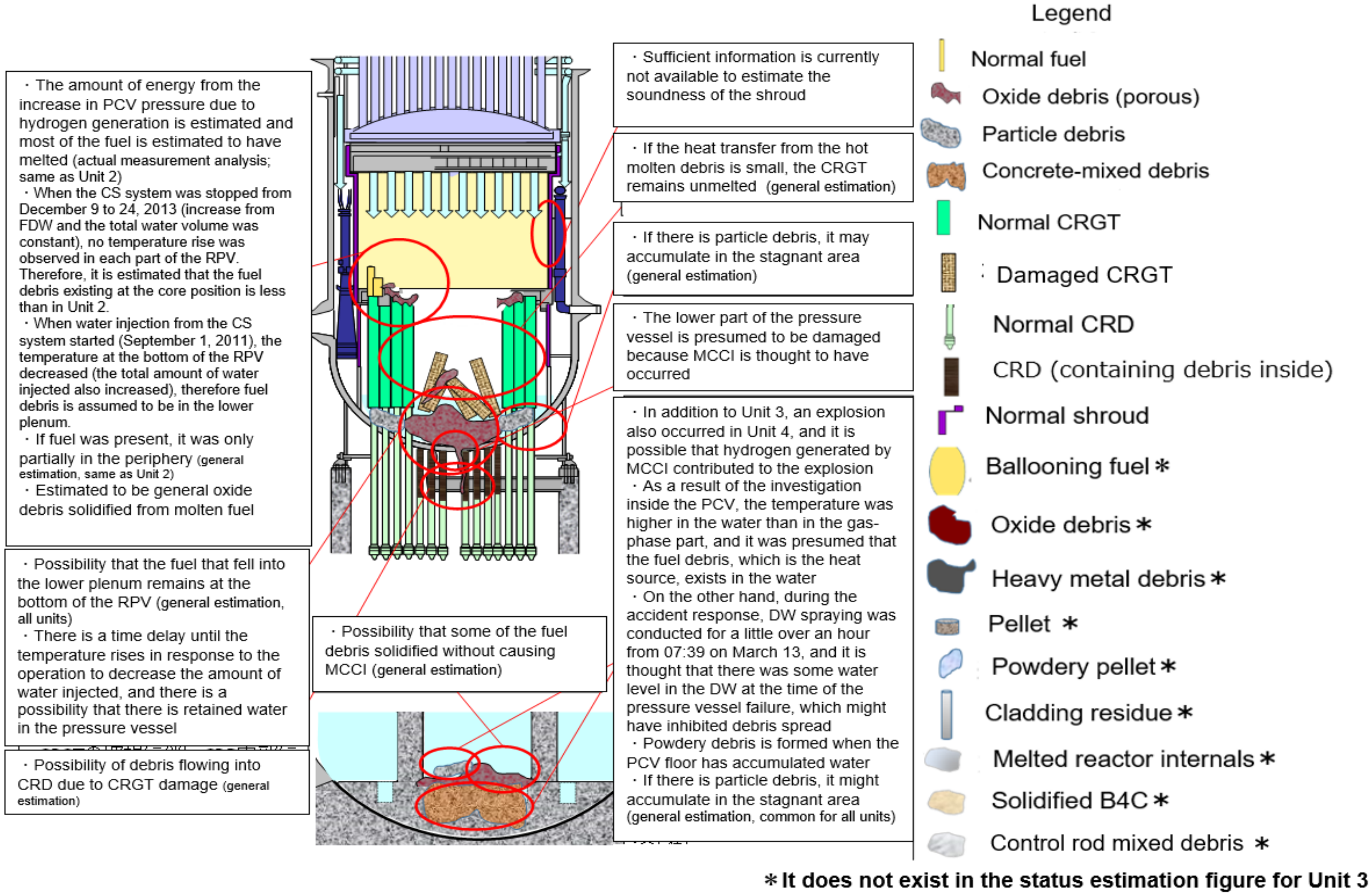


Figure 4.6.3-2 Unit 3 estimation figure as of July 2016 (enlarged) [3-10]

For the estimation in Figures 4.6.3-1 and 4.6.3-2, the characteristics of the estimation, the content updated from the fifth estimation, the reasons for the update from the fifth estimation, and information supporting the estimation are as follows.

○ Characteristics of estimation

The distribution of fuel debris is estimated to be as follows. Molten fuel fell into the lower plenum of the RPV after the accident, and most of it fell further into the PCV. Fuel debris remaining in the core of the RPV is estimated to be small, and some fuel debris exists at the bottom of the RPV. Although there is a lot of fuel debris that fell into the PCV, it is estimated not to have spread all over the floor.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the fuel melting and falling down, and that fuel debris has penetrated into the CRD housings under the RPV.

○Contents updated from the fifth estimation

The estimation was refined by focusing on the bottom of the PCV, inside the RPV, and by estimating the status of the structure in addition to the distribution of fuel debris.

① Estimation of the status of fuel debris in various states, including oxidized, particle, and matter that has fallen into the PCV and reacted with concrete.

② Partially melted fuel is estimated to remain in the periphery of the core.

③ Damaged CRGTs are estimated to be present at the bottom of the RPV.

④ Some CRGTs are estimated to remain in the outer periphery of the RPV bottom.

⑤ Water is estimated to accumulate at the bottom of the RPV.

⑥ The center of the housings under the RPV is estimated to be damaged and fuel debris is inside these CRD housings.

○ Reason for updating from the fifth estimation

① Estimation of the status of fuel debris in various states, including oxidized, particle, and matter that has fallen into the PCV and reacted with concrete.

Based on previous findings, during the accident molten fuel was likely to be mixed with cladding and structural materials that also melted. In addition, zirconium and iron, which are components of the cladding and structures, were likely to have been oxidized by the steam-metal reaction. Therefore, the main components of the debris are considered to be uranium oxide from the fuel, zirconium oxide from the cladding, and iron oxide from the structures.

Particle debris may have been formed during the process of molten material migrating to the bottom and contacting water, or during the collapse of oxidized and embrittled structural materials. Particle debris may exist in accumulated water areas (areas where water does not flow) in the RPV and PCV.

Furthermore, fuel debris that fell into the PCV is considered to have reacted with concrete on the PCV floor or pedestal wall (MCCI).

② Partially melted fuel is estimated to remain in the periphery of the core.

Based on previous findings, it was estimated that the temperature in the core section rose from the center, from where the fuel melting proceeded, and at that time, the partially melted fuel was estimated to remain in some parts of the periphery of the core.

③ Damaged CRGTs are estimated to be present at the bottom of the RPV.

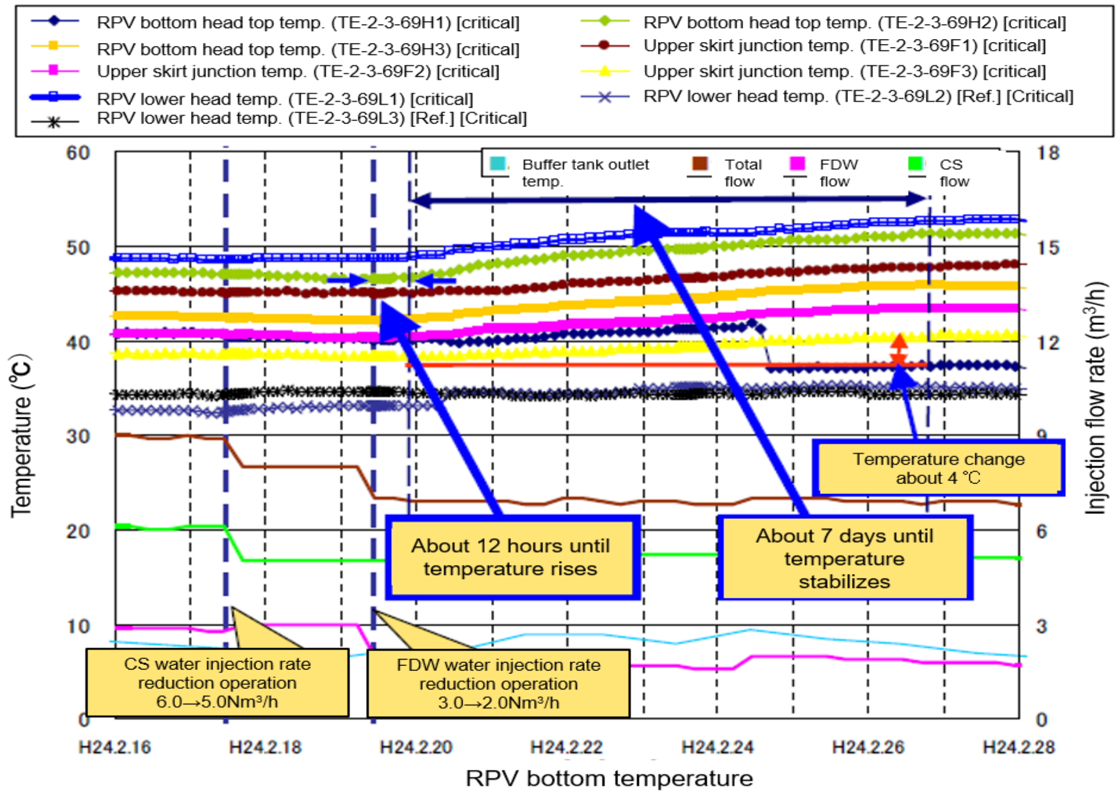
Based on previous findings, the CRGTs located in the lower plenum of the RPV are considered to have melted or been damaged during the migration process because it is on the migration path of fuel that has become hot and migrated downward from the core section. Therefore, there is a possibility that some damaged CRGTs remain at the bottom of the RPV.

④ Some CRGTs are estimated to remain in the outer periphery of the RPV bottom.

Based on previous findings, the CRGTs located in the lower plenum of the RPV are on the migration path of fuel that had become hot and migrated downward from the core, but if the heat transfer from the fuel debris is small, there is a possibility that some of the CRGTs remained without melting. In addition, the temperature in the core is considered to rise from the center of the core, where the fuel melts and migrates downward, so it is possible that the CRGTs in the outer periphery remain.

⑤ Water is estimated to accumulate at the bottom of the RPV.

When the amount of water injected from the CS and FDW was reduced in February 2012, a gradual temperature change was observed with a time delay (Figure 4.6.3-3). It took about 12 hours for a clear temperature increase to be observed, followed by about 7 days for the temperature to stabilize. Therefore, at that time, the reason for this time delay was estimated to be the possibility that there was some amount of water at the bottom of the RPV.



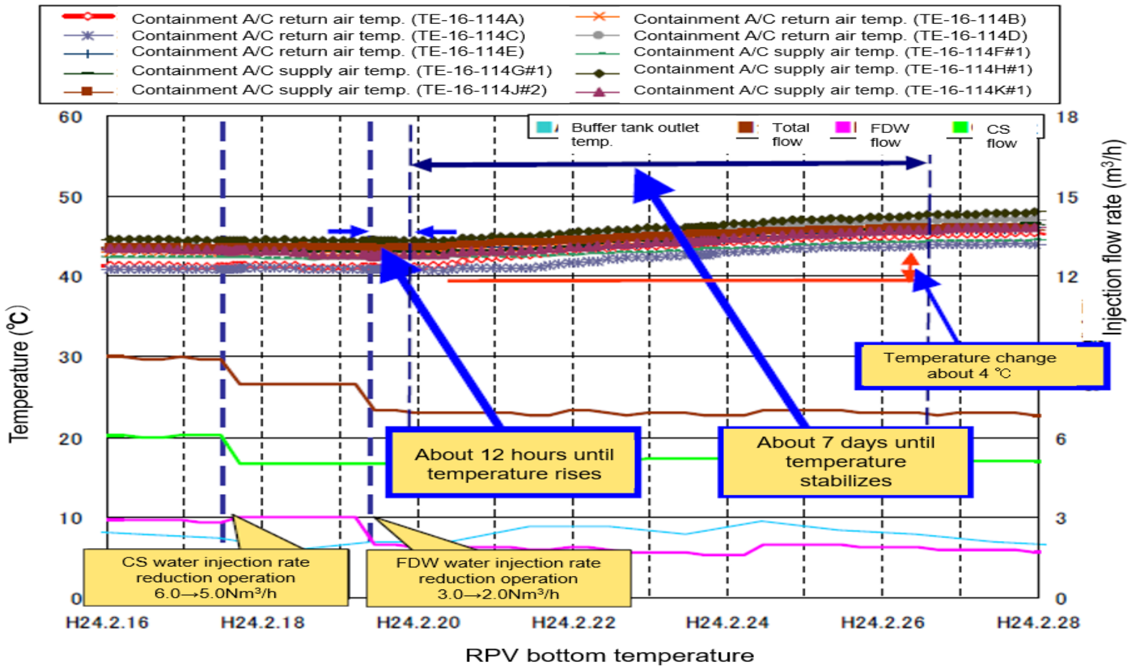


Figure 4.6.3-3 Temperature behavior of each part when water injection rate decreases [3-11]

⑥ The center of the CRD housings under the RPV is estimated to be damaged and fuel debris is inside these CRD housings.

Based on the previous findings, if the CRGTs and the CRD housings are eroded by fuel debris in the lower part of the RPV, fuel debris may have penetrated into the CRD housings. The fuel debris that has entered the CRD housings may have solidified and remained inside.

○ Information supporting the estimation

The following information is considered to be reliable for the content of the estimation.

・Increase in PCV pressure due to hydrogen formation

The PCV pressure increased significantly at about 09:00 and after 12:00 on March 13, 2011 (Figure 4.6.3-4). This pressure increase was thought to be caused by a large amount of hydrogen being formed, which melted most of the fuel. Based on the results of the accumulated investigations, including the analyses conducted up to this time, it is considered that there is almost no fuel remaining in the core.

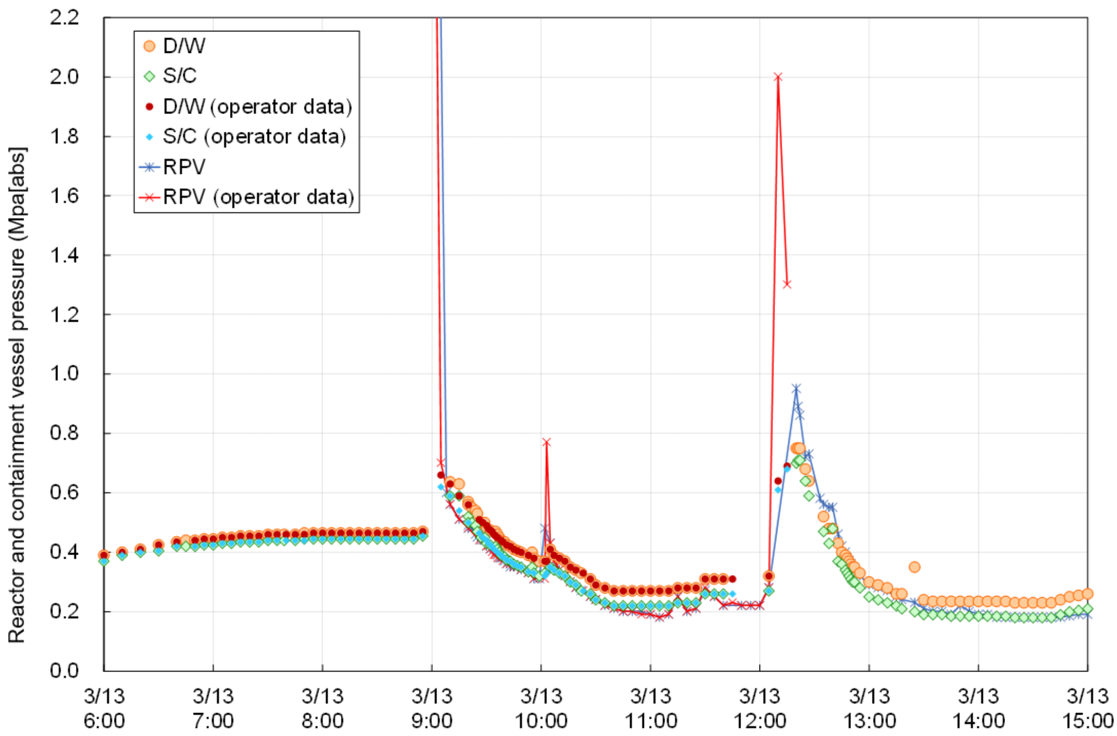
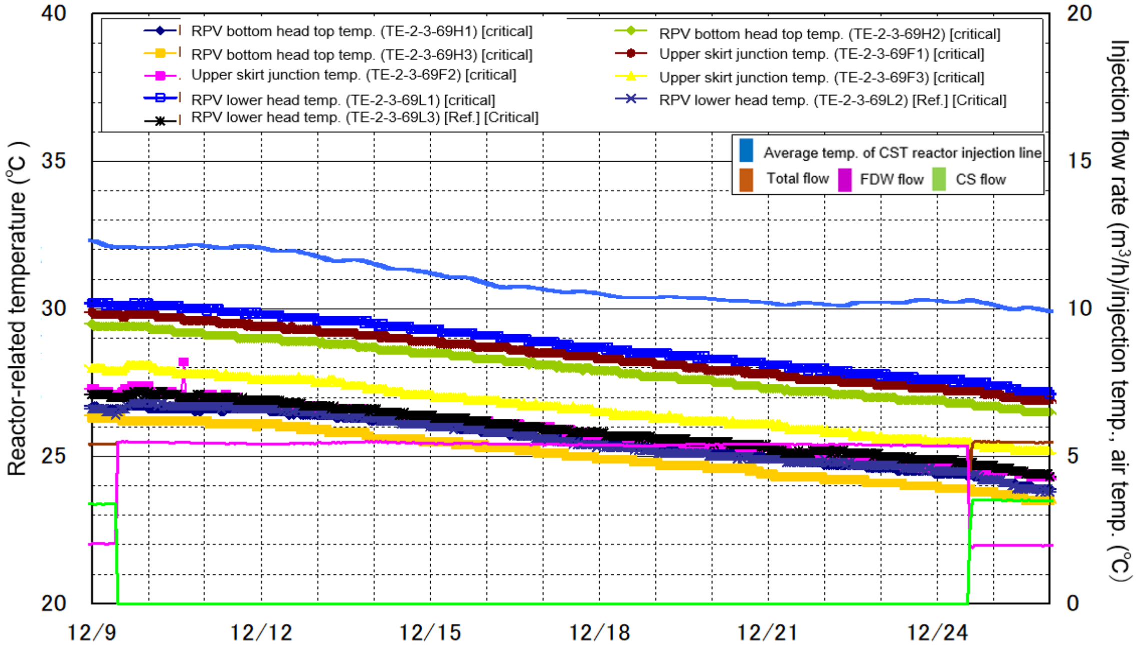
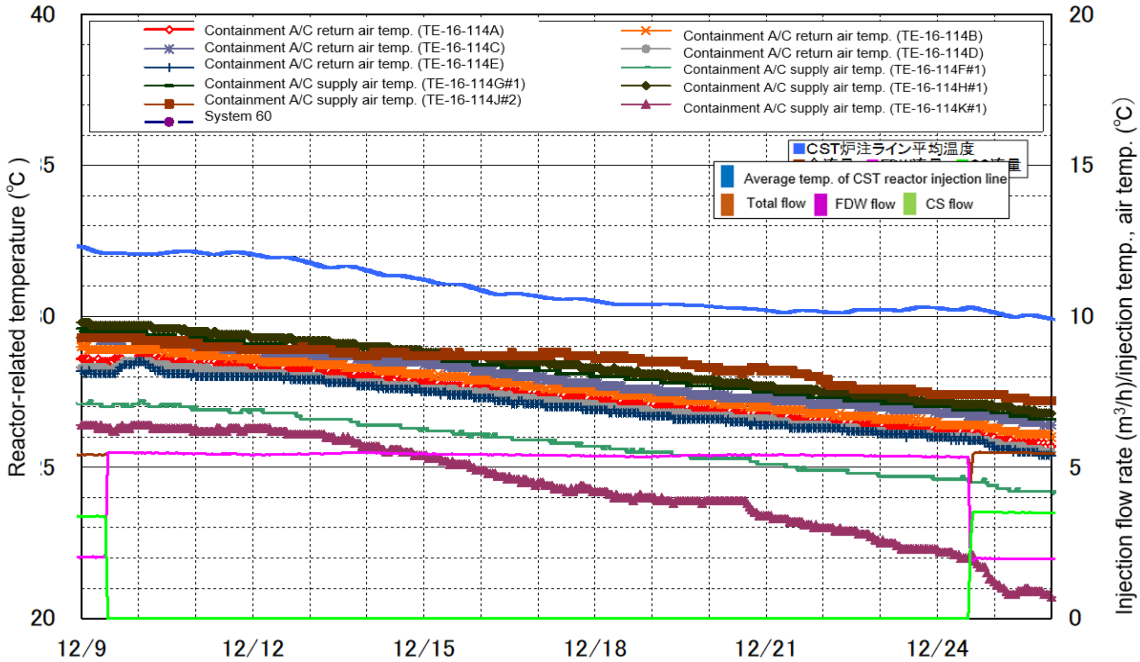


Figure 4.6.3-4 Change in PCV pressure (2011) [3-10]

・ Water injection from the CS and FDW

Water injection from the CS was stopped for 15 days from December 9 to 24, 2013, and water injection was conducted only from the FDW (no change in total water injection volume). As shown in Figure 4.6.3-5, no temperature increase was observed due to the suspension of water injection from the CS, and no noticeable effect on the reactor cooling status was observed. Thus, it is considered that there is little fuel debris in the core area because the cooling status of each part did not change even after the water injection from the CS was stopped.





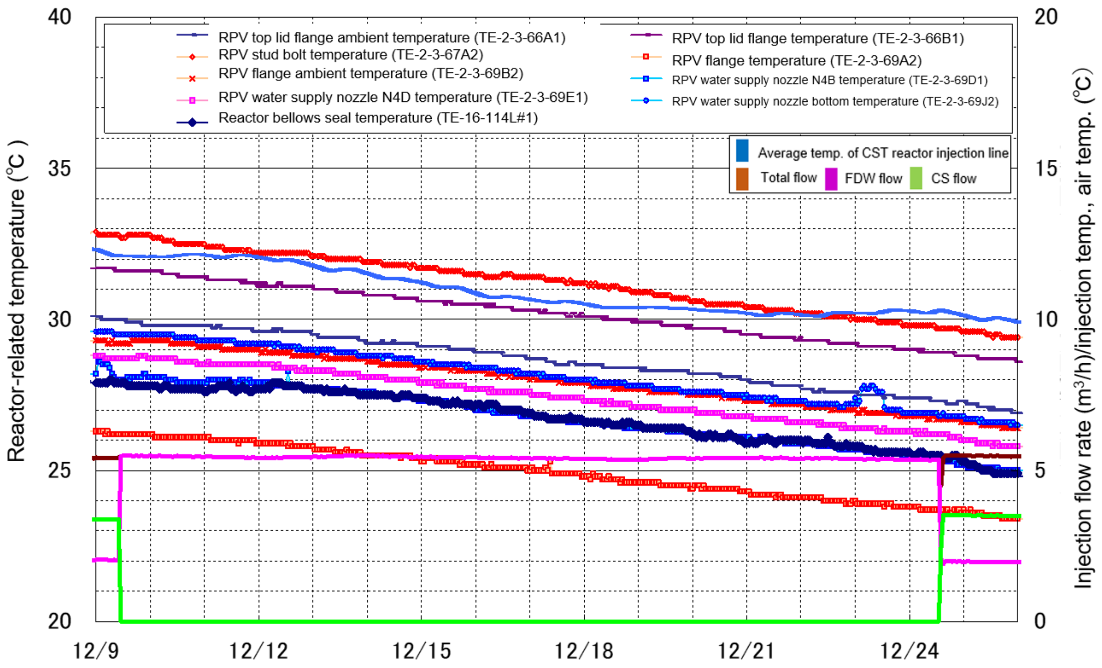


Figure 4.6.3-5 Temperature change during stopping period of water injection in the CS (2013) [3-10]

When water injection from the CS began (September 1, 2011), the temperature at the bottom of the RPV decreased (Figure 4.6.3-6). At this time, the total volume of water injection also increased. As mentioned previously, considering the small amount of fuel debris existing in the core area, it is estimated that the main reason for this temperature decrease was not that the fuel debris in the core, which had not been sufficiently cooled down before, was cooled down now with the start of CS water injection (Section 4.1.3), but that the increase in the total amount of water injection resulted in the cooling of the fuel debris existing in the lower part of the RPV. Therefore, fuel debris is considered to exist in the lower plenum to some extent.

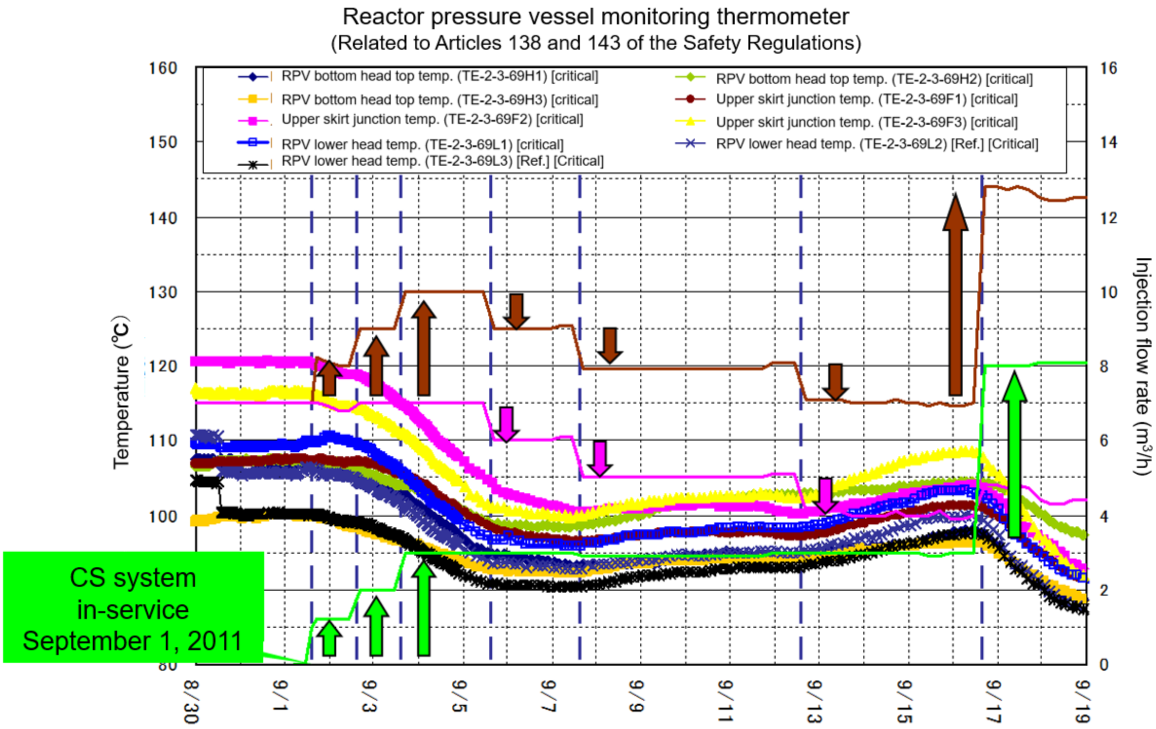


Figure 4.6.3-6 Temperature change after water injection by the CS stopped (2011) [3-10]

・Status of PCV at the time of the accident

In Unit 3, a D/W spray was conducted for a little over an hour from 07:39 on March 13, 2011, to remove heat from the PCV. Therefore, it is assumed that water had accumulated on the D/W floor at the stage when the RPV was subsequently damaged, and this water may have limited the spread of the fuel debris when it fell into the PCV.

・The cause of the hydrogen explosion in Unit 4

The Unit 3 PCV venting was conducted multiple times, and the first two times (after 09:00 on March 13, 2011 and after 12:00 on March 13, 2011) are considered to have been successful based on the PCV pressure and information from photographs taken at the site. As for the cause of the explosion of the Unit 4 reactor building at about 06:14 on March 15, it is believed that this Unit 3 vent gas flowed back through the SGTS piping, causing hydrogen to migrate inside the Unit 4 reactor building.

Dose rate measurement of the SGTS filter train in Unit 4 showed a higher dose rate on the outlet side (exhaust stack side), which is considered to be evidence of backflow (Figure 4.6.3-7). In addition, the hydrogen formed in the water-zirconium reaction in the Unit 3 reactor contributed to the explosion in Unit 4, based on consideration of the progression of the accident in Unit 3. Therefore, considering that most of the hydrogen formed up to that point due to the venting was exhausted from the PCV, it is estimated that the hydrogen formed due to MCCI may have contributed to the explosion in Unit 3. In other words, it is estimated that MCCI may have occurred in Unit 3.

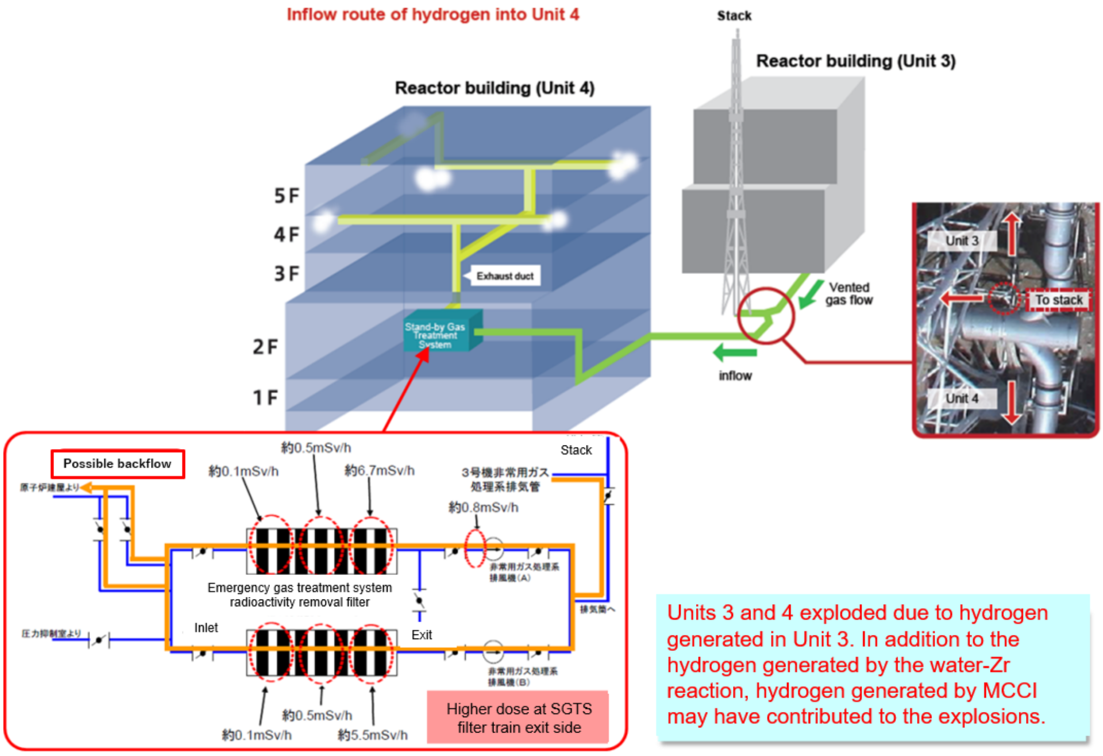


Figure 4.6.3-7　Unit 4 SGTS filter train dose measurement results [3-10]

・Results of the Unit 3 PCV internal investigation (conducted in October 2015)

In Unit 3, survey equipment (camera, thermometer, and dosimeter) was inserted through the PCV penetration (X-53) in October 2015 to conduct a survey mainly to confirm the cooling status inside the PCV. The information obtained during this investigation showed that the temperature in the liquid phase was higher than that in the gas phase (Figure 4.6.3-8). Therefore, it was estimated that fuel debris, which is the heat source, is present in the water.

- The water level in the PCV was OP 1800, which was roughly consistent with the estimated value＊.
  ＊ Estimated value: pressure conversion OP: 11970 mm (October 20, 5:00)
- The temperature inside the PCV was about 26-27℃ in the gas phase and about 33-35℃ in the water.

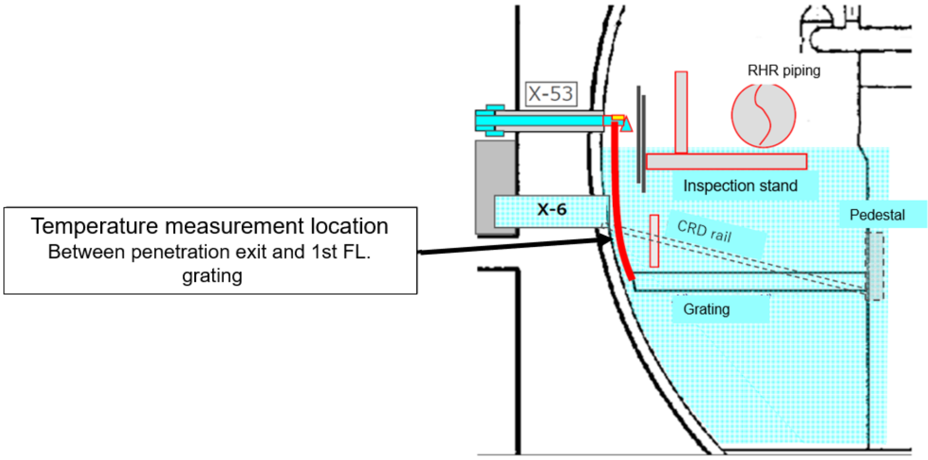


Figure 4.6.3-8 PCV internal investigation results (conducted in October 2015) [3-12]

4.7. Seventh estimation (March 2017)

4.7.1. Unit 1

The estimation as of March 2017 is shown in Figure 4.7.1-1 and an enlarged version is shown in Figure 4.7.1-2.

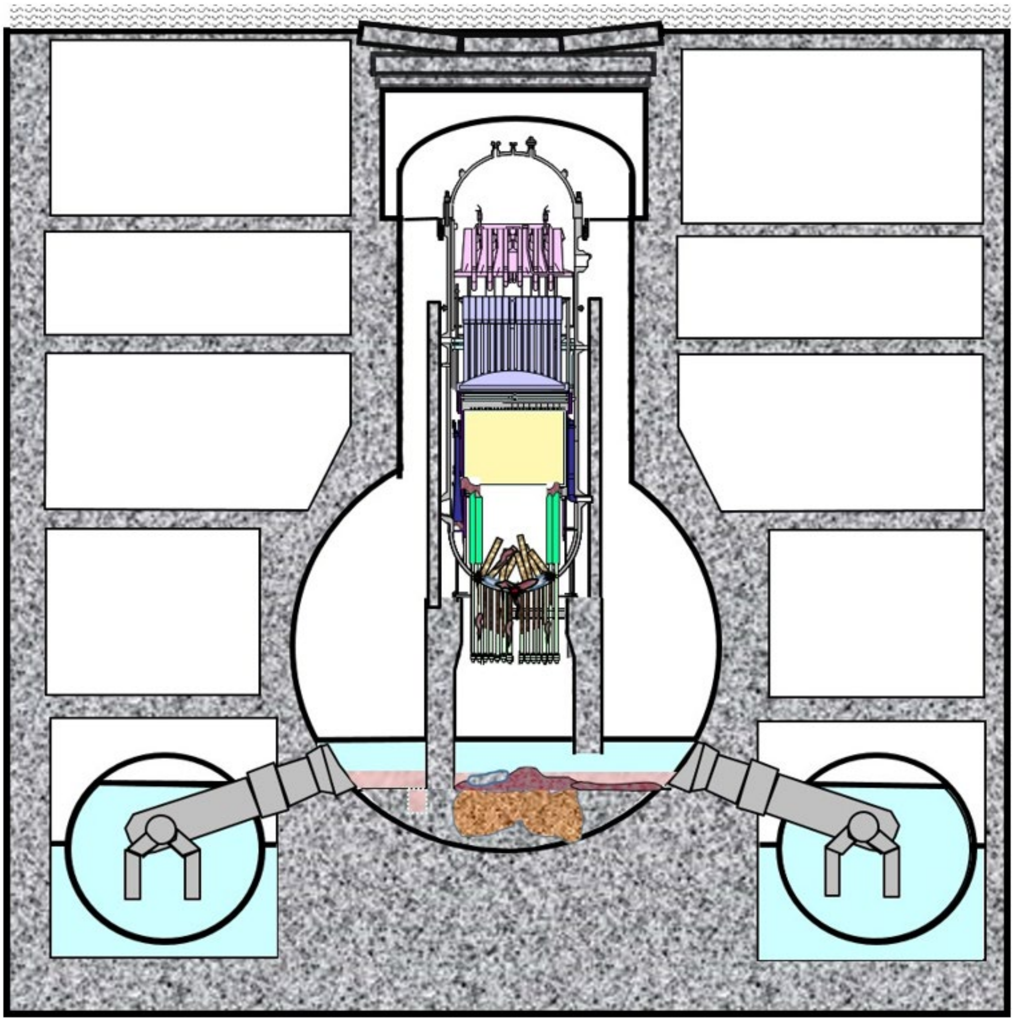


Figure 4.7.1-1 Unit 1 estimation as of March 2017 [1-13]

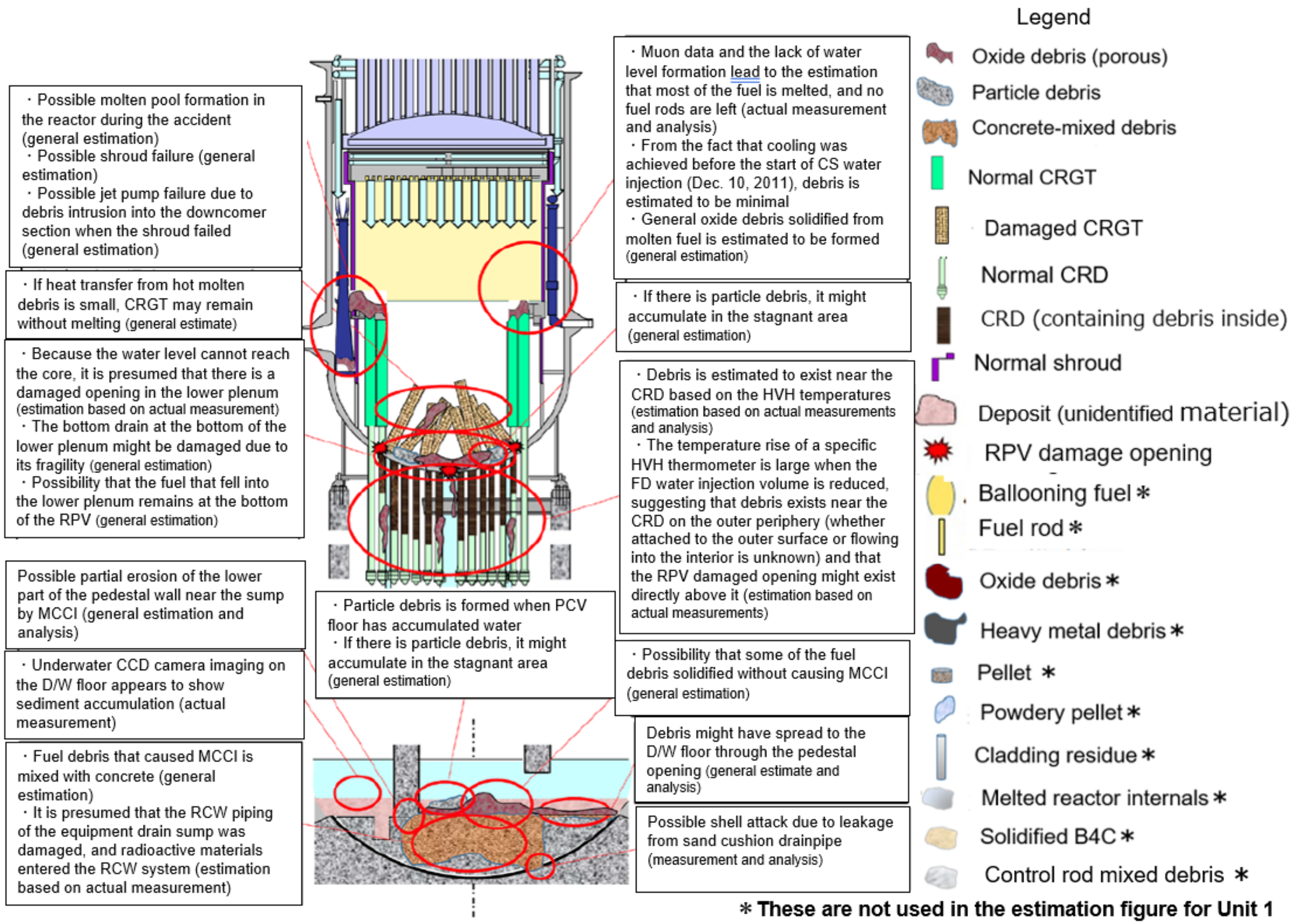


Figure 4.7.1-2　Unit 1 estimation figure as of March 2017 (enlarged) [1-13]

For the estimation in Figures 4.7.1-1 and 4.7.1-2, the characteristics of the estimation, the contents updated from the sixth estimation, and the findings that helped in the estimation are as follows.

○ Characteristics of estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and almost none remained in the original core area. It is estimated that most of the fuel debris that fell into the lower plenum fell into the bottom of PCV.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the process of fuel melting and falling, and fuel debris has penetrated into the CRD housings below the RPV.

It is estimated that unknown materials have accumulated at the bottom of the PCV.

○ Contents updated from the sixth estimation

① Clear indication of the displacement and lifting of the rubble and well-plugs on the operating floor.

② To show the spread of fuel debris on the PCV floor, the opening of the RPV pedestal is depicted.

○ Reasons for updating from the sixth estimation

① Clear indication of the displacement and lifting of the rubble and well-plugs on the operating floor.

Photographs taken in 2014 for the purpose of installing the building cover of the operating floor confirmed that the collapsed roof had fallen in an almost flat shape and became rubble (Figure 4.7.1-3). In addition, the reactor well-plugs were found to have been shifted and lifted up, and these confirmations were reflected in the estimation figure (Figure 4.7.1-4).

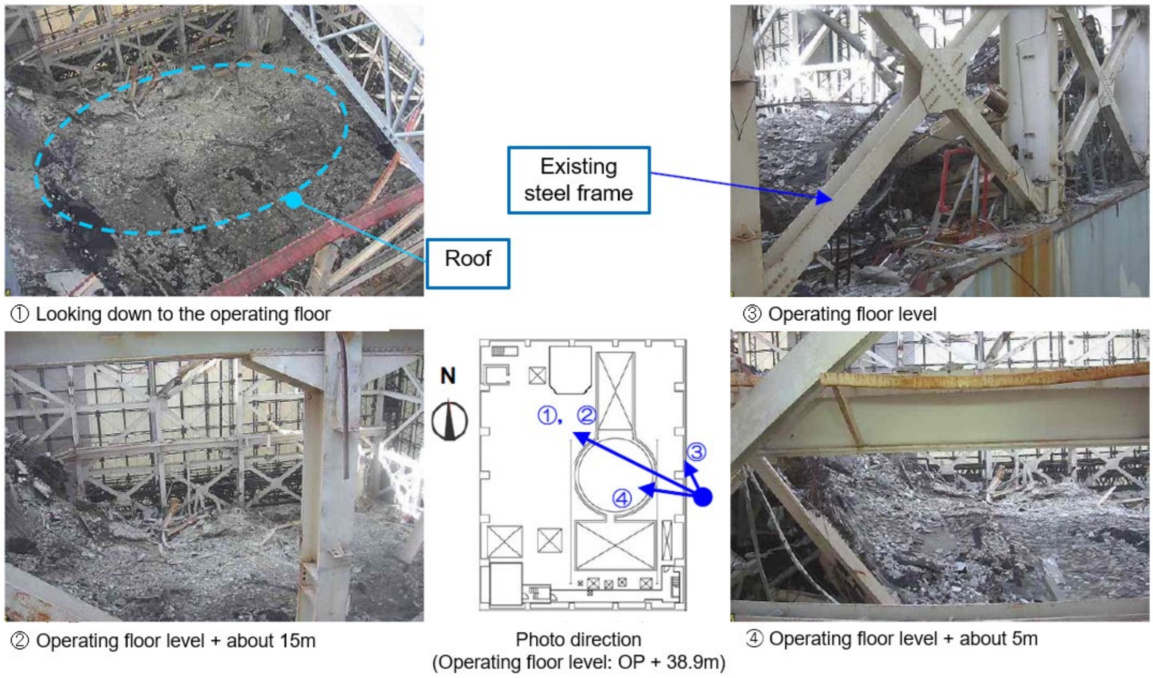


Figure 4.7.1-3 Operating floor confirmation image [1-15]

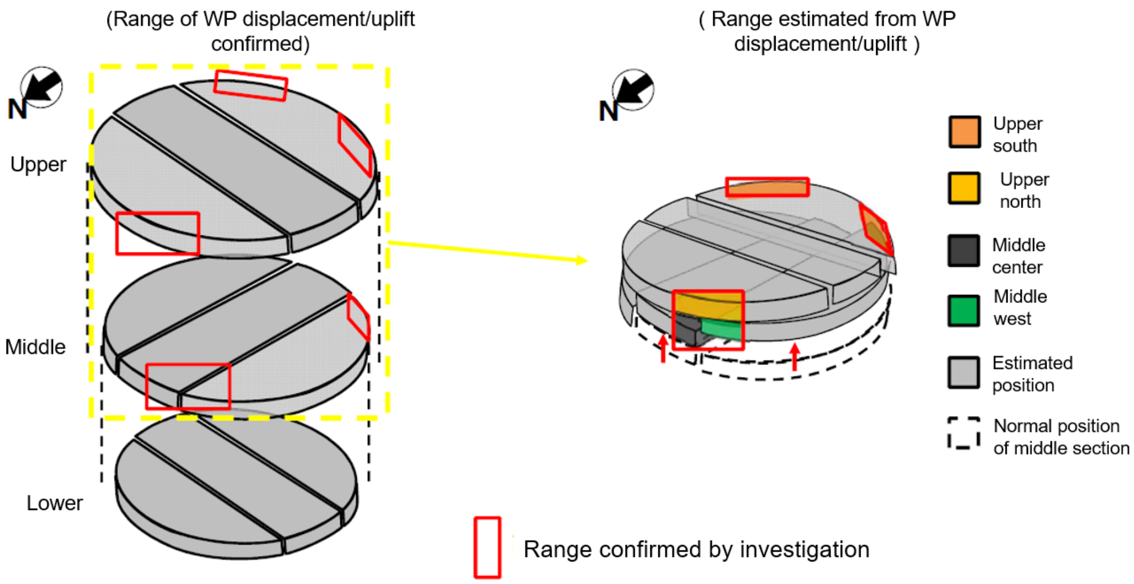


Figure 4.7.1-4 Displacement and lifting up of the well-plug [1-16]

② To show the spread of fuel debris on the PCV floor, the opening of the RPV pedestal is depicted.

At the bottom of the PCV, the pedestal supporting the RPV has a cylindrical shape, and it has an opening for worker access. Therefore, it is estimated that the fuel debris that fell into the PCV spread laterally and depiction of the opening in the estimation figure is made accordingly.

○ Information to support the estimation

None.

4.7.2. Unit 2

The estimation as of March 2017 is shown in Figure 4.7.2-1 and an enlarged version is shown in Figure 4.7.2-2.

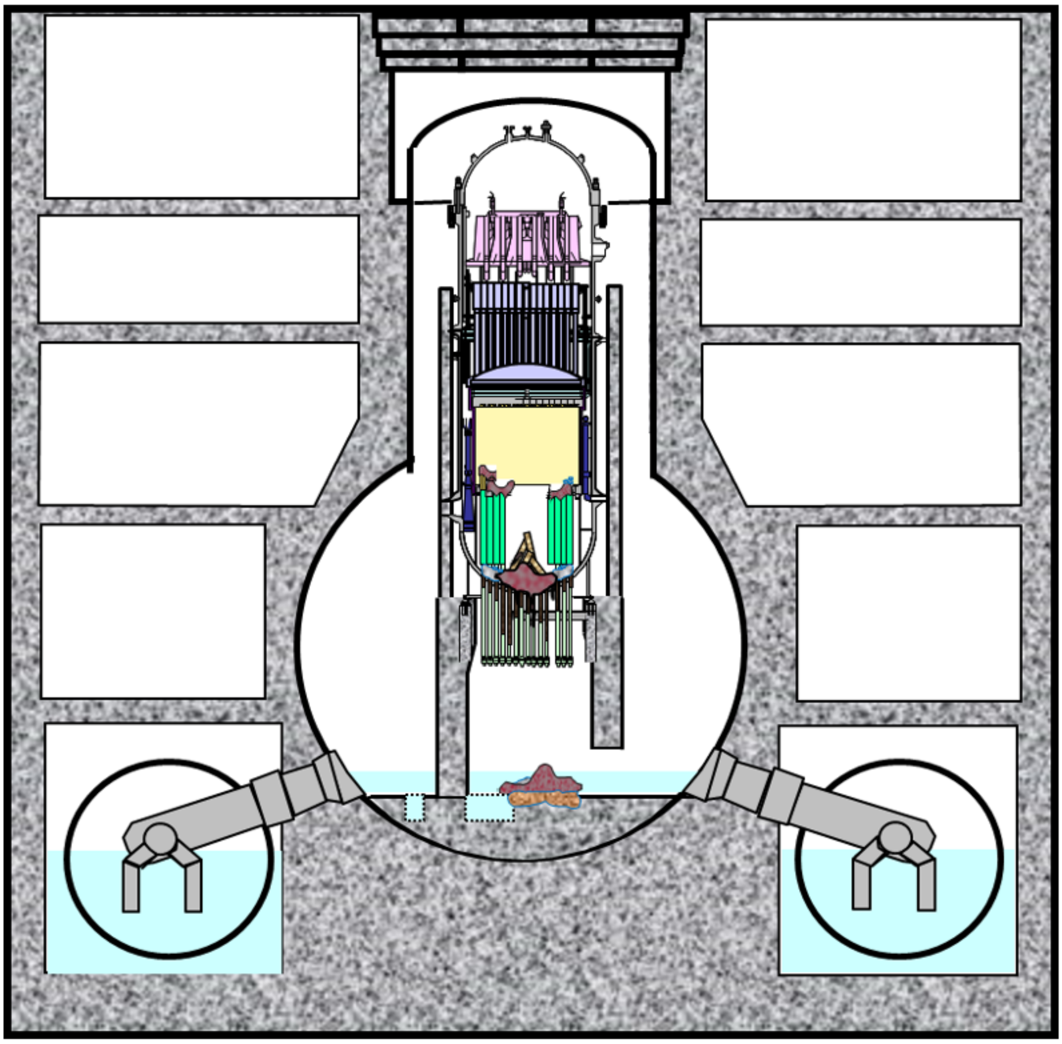


Figure 4.7.2-1 Unit 2 estimation as of March 2017 [2-10]

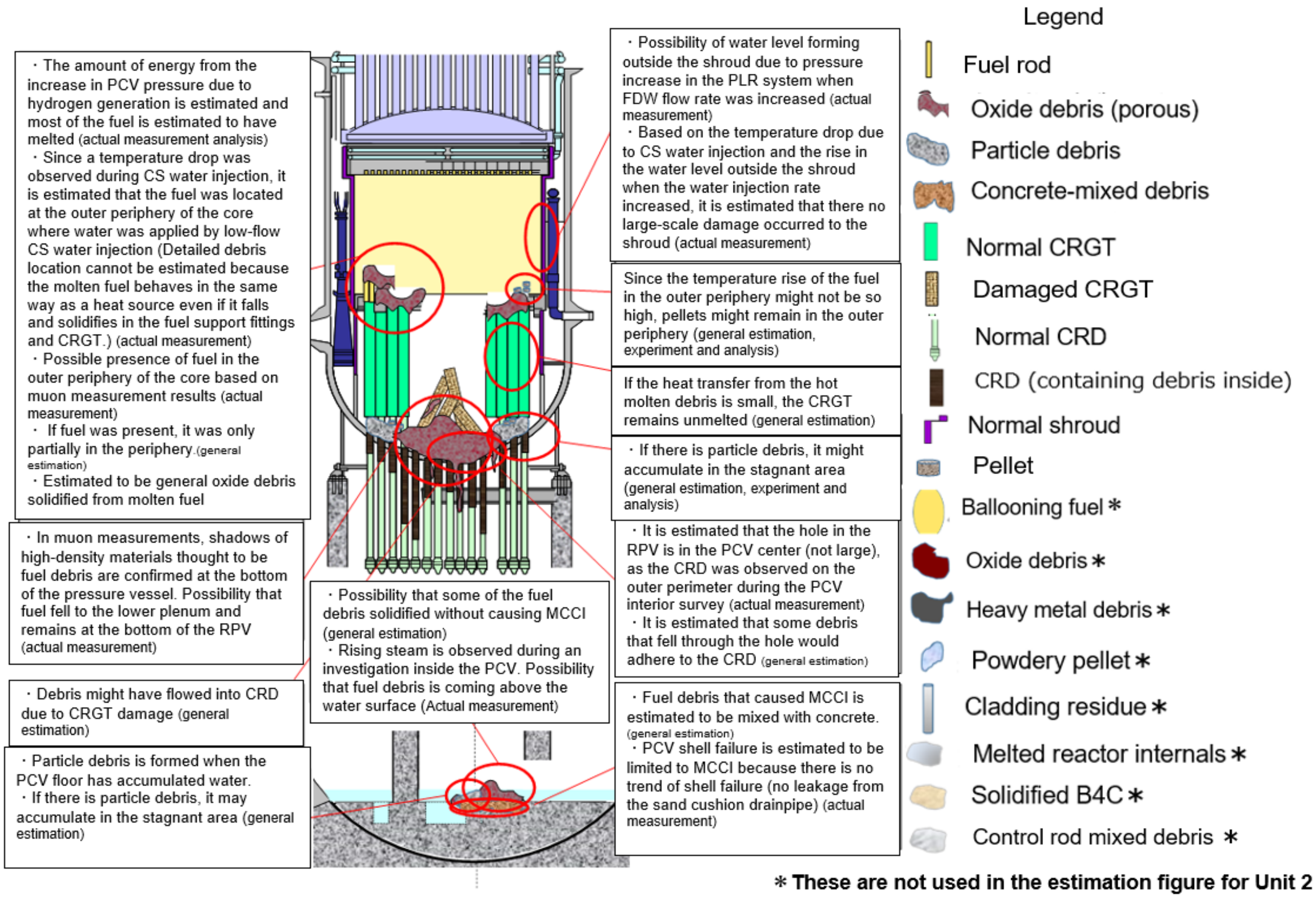


Figure 4.7.2-2 Unit 2 estimation figure as of March 2017 (enlarged) [2-10]

For the estimation in Figures 4.7.2-1 and 4.7.2-2, the characteristics of the estimation, the contents updated from the sixth estimation, and the reasons for the update from the sixth estimation are as follows.

○Characteristics of estimation

The estimation of the distribution of fuel debris is as follows: a part of the molten fuel fell into the lower plenum of the RPV after the accident, and another part fell into the PCV; in the RPV, a part of the fuel remains in the core, and most of the fuel debris is estimated to be at the bottom of the RPV. The amount of fuel debris that fell into the PCV is small, so it is estimated that MCCI occurred only to a limited extent.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the process of falling molten fuel, and fuel debris has penetrated into the CRD housings under the RPV.

○Updated contents from the sixth estimation

① Estimation that pellet-shaped fuel remains in the RPV at the periphery.
② Estimation that there are damaged CRGTs at the bottom of the RPV.
③ Estimation that the amount of fuel debris inside the CRD housings is larger.
④ Damaged parts of CRDs are estimated to be at the center and its periphery.
⑤ The estimated amount of fuel debris at the bottom of the PCV is less and some of it is exposed above the water surface.
⑥ The opening of the RPV pedestal is depicted to show the spread of fuel debris on the PCV floor.

○ Reasons for updating from the sixth estimation

① Estimation that pellet-shaped fuel remains in the RPV at the periphery.

In the "Advancement of comprehensive internal reactor status assessment" project, a test was made in which a channel box and simulated fuel (ZrO_2) were placed on both sides of a control rod blade that was heated by a plasma torch (Figure 4.7.2-3); the purpose was to obtain information on the behavior of fuel melting and migration to the lower part of the fuel. As shown in Figure 4.7.2-3, the fuel rods maintained their shape to some extent even after heating, partly due to the effect of the heat easily escaping outside the test system. It is possible that fuel pellets may have fallen or remained in the shape of the fuel rods in areas with high radiation heat transfer, such as the outer periphery of the core, because the fuel rods did not melt sufficiently since the high temperature was not maintained.

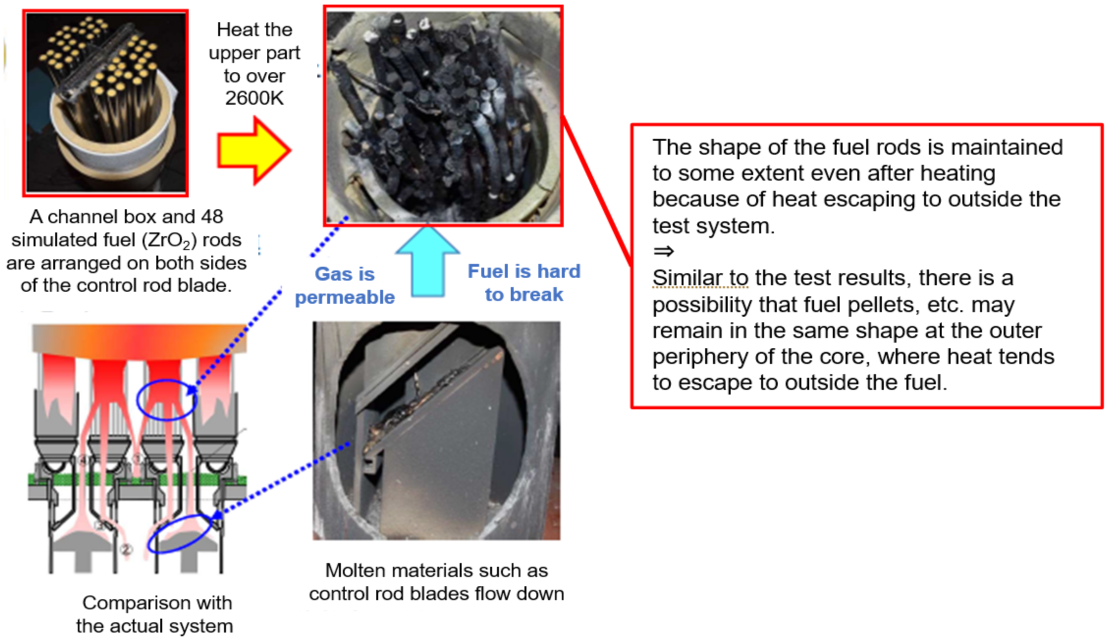


Figure 4.7.2-3 Simulated fuel assembly failure test [2-14]

In addition, measurements using the muon transmission method were conducted from March to July 2016 to analyze and evaluate the location of fuel debris in the RPV (Figures 4.7.2-4 and 4.7.2-5). Figure 4.7.2-6 shows the evaluation results on the distribution of the amount of material in the RPV by comparing the number of muons measured with the results of simulations at ① the upper core, ② the lower core, ③ the lower part of the RPV, and ④ the bottom of the RPV. When focusing on the lower part of the core ②, comparison of the measured results and the simulation results assuming "no fuel" and assuming "with fuel" at the outer periphery of the core shows that the simulation results assuming “with fuel” are close to the measured results. Therefore, it is possible that fuel remains in the outer periphery of the core.

Muon measurement equipment (Small device, about 1m x 1m x height 1.3m)

Figure 4.7.2-4 Muon measurement device [2-15]

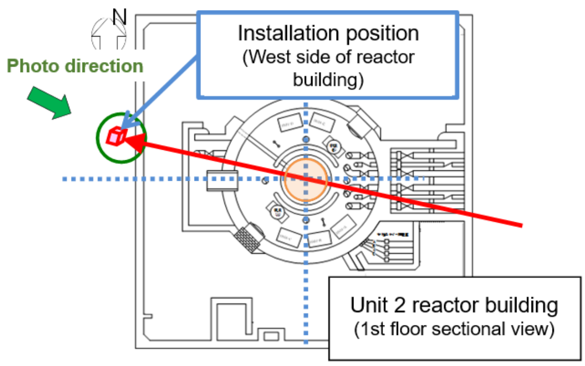


Figure 4.7.2-5 Location of device [2-15]

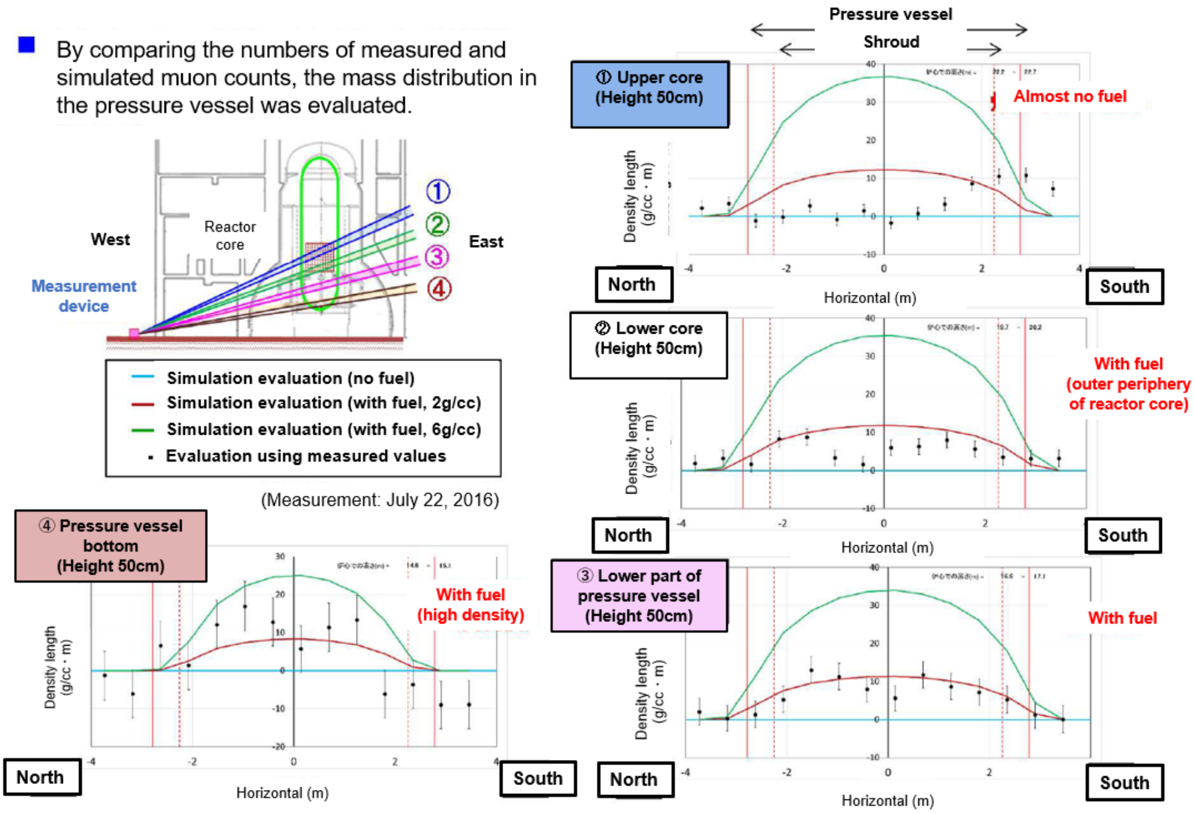


Figure 4.7.2-6 Comparison of muon measurement results with simulation results [2-15]

②Estimation that there are damaged CRGTs at the bottom of the RPV.

Based on previous findings, the CRGTs located in the lower plenum of the RPV are considered to have melted or been damaged during the migration process, since they are on the migration path of fuel that had become hot and migrated downward from the core section. Therefore, there is a possibility that damaged CRGTs remain at the bottom of the RPV.

③ Estimation that the amount of fuel debris inside the CRD housings is larger.

In the "Advancement of comprehensive internal reactor status assessment" project, the "penetration tube melting test" done at KAERI (Korea Atomic Energy Research Institute) was examined to obtain information on fuel debris penetration into the interior of the CRD.

In the KAERI "penetration tube melting test," the melting of the penetration tube by the corium formed in the RPV and the behavior of the corium falling from the penetration tube were investigated through experiments using IRM/SRM and a penetration tube simulating the actual CRD. Although this specimen was shorter than the actual specimen, particulate corium was released from the lower end of the piping in the IRM/SRM test, and corium reached the lower end of the specimen in the CRD test. Considering the piping length of the actual instruments, the corium will penetrate to the piping section projecting outside the RPV. Sensitivity analysis using the SAMPSON model, which assumes that the corium falls while filling the piping, showed that the higher the corium temperature at the time of through-pipe failure, the greater the corium penetration length inside the piping. And if the temperature was high enough for the corium to melt completely, the evaluation showed that the corium would penetrate to the piping section projecting outside the RPV.

In Unit 2, it is estimated that the lower head of the RPV was damaged, and debris migrated to the PCV; the location of the RPV damage opening has not yet been determined, but it is estimated that the temperature of the corium near the damage opening rose to the point of complete melting, and fuel debris is also estimated to be present inside the CRD housings near that area.

Since the accident progression in Unit 2 was slow and at least some part of the alternative water injection is believed to have reached inside the reactor, the penetration of fuel debris inside the CRD housings may have been relatively restrained. However, since the LPRMs and other parts closest to the opening were not found in the guide pipe PCV internal investigation conducted in January 2017 (Figures 4.7.2-8 and 4.7.2-9), it is estimated that the instrument tubes and welded parts were damaged at the periphery. In the KAERI "through-pipe melt test," welded parts were not damaged, and corium was considered to have penetrated inside the piping even though the piping did not fall off. The locations of the LPRMs and other equipment could not be confirmed in Unit 2, and the estimation was made that fuel debris was present inside the CRD housings.

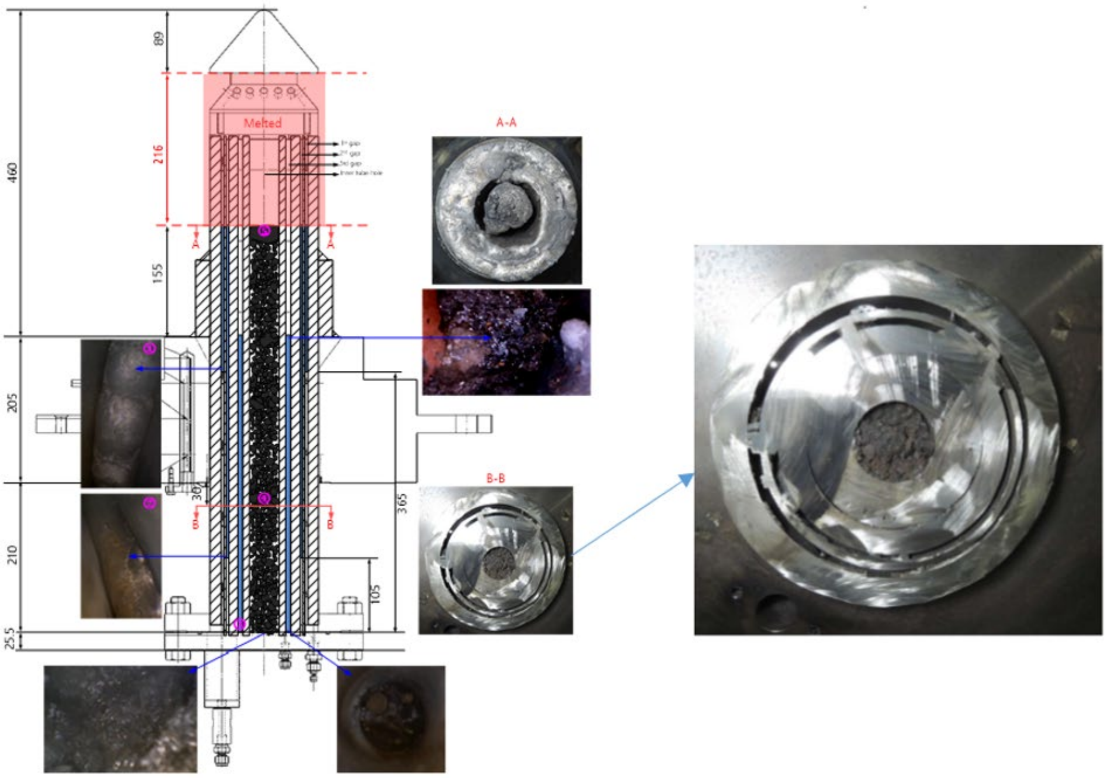


Figure 4.7.2-7 Results of cutting inspection of KAERI "through-pipe melt test" body [2-10]

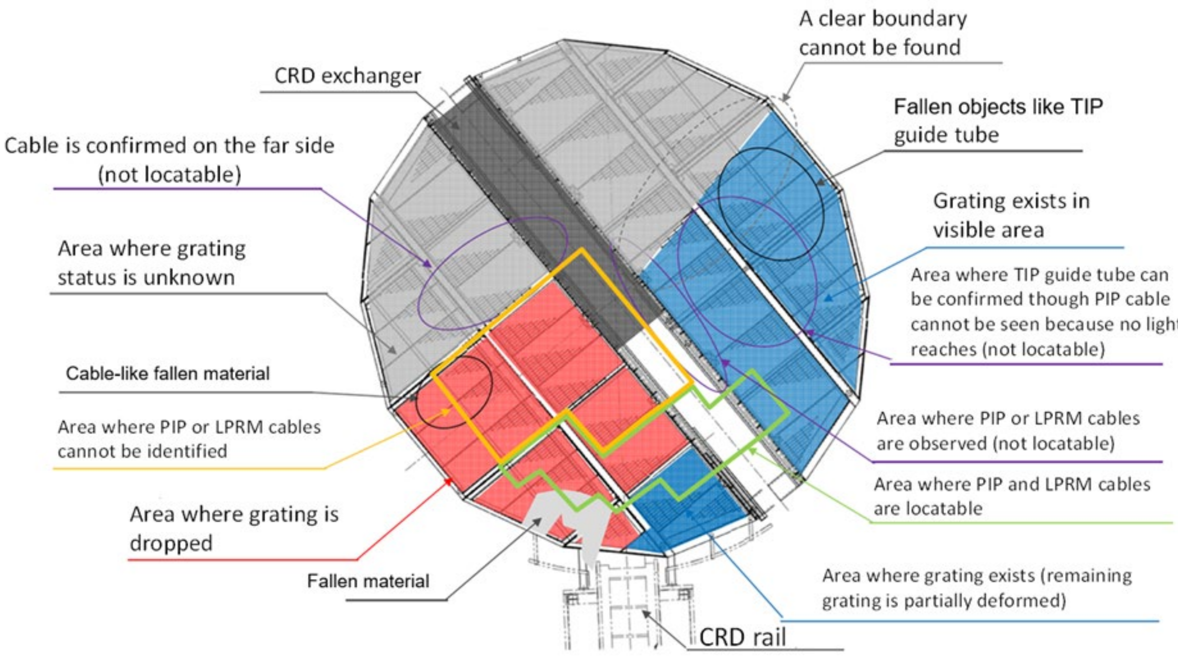


Figure 4.7.2-8 Results of the internal investigation of the pedestal (upper part) [2-16]

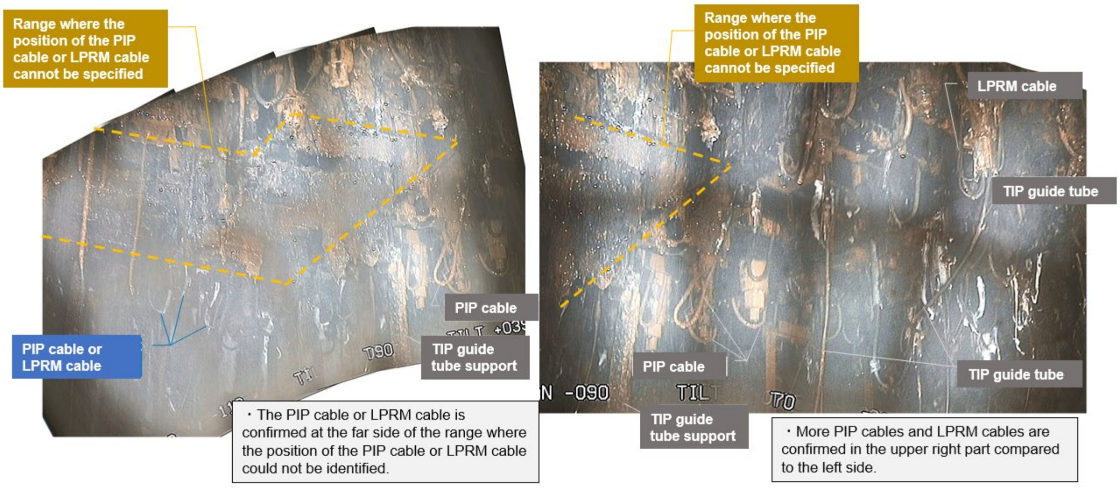


Figure 4.7.2-9 Results of the internal investigation of the pedestal (summary) [2-16]

From the above, it was estimated that the amount of fuel debris penetrating into the CRD housings was larger than in the sixth estimation.

① Damaged parts of CRDs are estimated to be at the center and its periphery.

Images obtained during the guide pipe PCV internal investigation conducted in January 2017 (Figures 4.7.2-8, 4.7.2-10, and 4.7.2-11) and the summary results of the investigation (Figure 4.7.2-9) show that the grating is slightly displaced inside the pedestal from the periphery (it is not in the center) and it is about to fall down along with the deposits. In addition, when the viewpoint is shifted upward, the cable sheaths retain their shape, suggesting the possibility that relatively low-temperature fuel debris may have fallen in that location. Based on this information, it is estimated that there may be holes in the RPV center and its periphery, and that they are not large based on the images taken during the internal investigation.

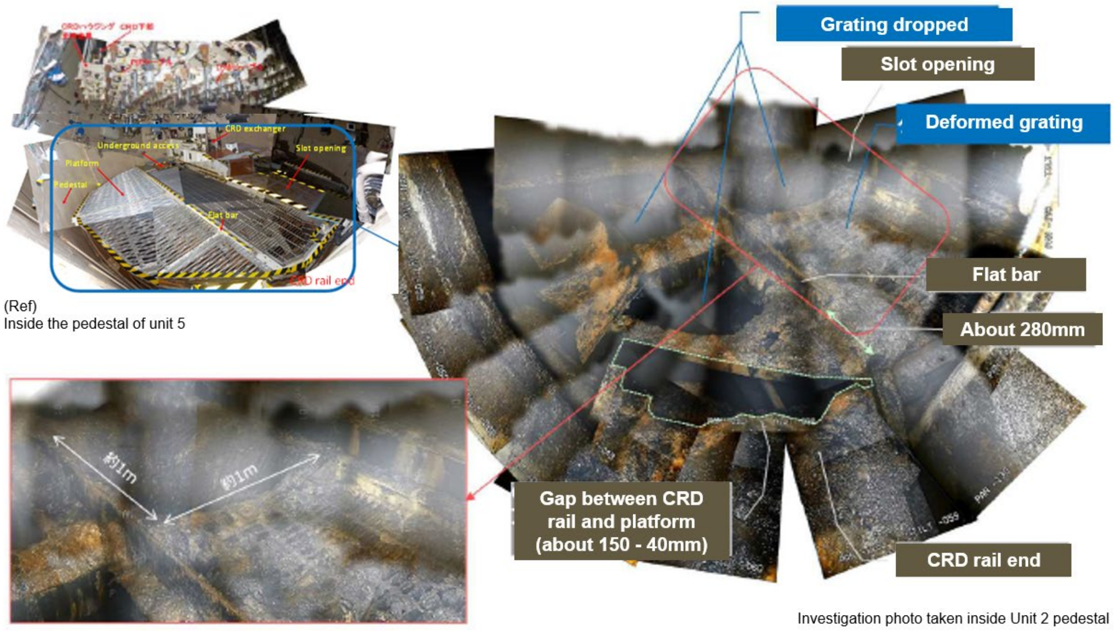


Figure 4.7.2-10 Images showing the inside of the Unit 2 pedestal (1/2) [2-17]

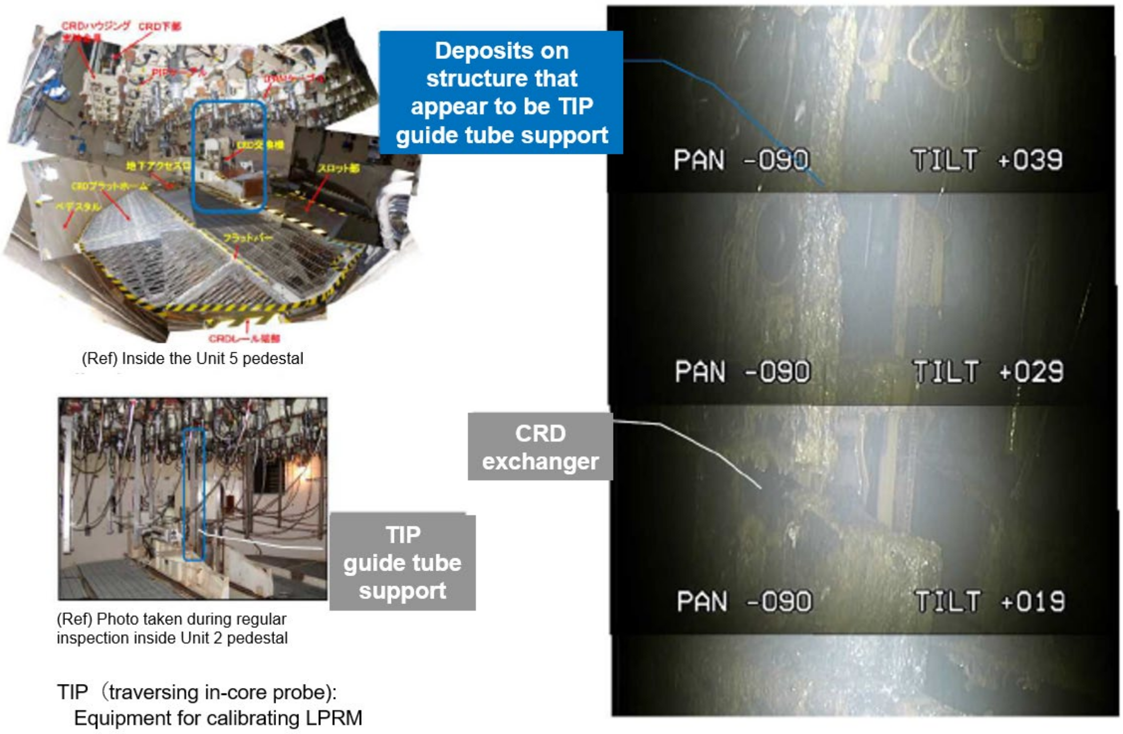


Figure 4.7.2-11 Images showing the inside of the Unit 2 pedestal (2/2) [2-17]

⑤ Estimated amount of fuel debris at the bottom of the PCV is less and some of it is exposed above the water surface.

In the images from the January 2017 PCV internal investigation, the rising steam was unevenly distributed by location; in Section 4.1.2, it was estimated that the fuel in the PCV was generally in a submerged state, but if the fuel debris flooded the pedestal, the steam would rise uniformly in the pedestal. Therefore, it is possible that the fuel debris is not fully submerged, but some of it may be exposed above the water surface.

As shown in Figures 4.7.2-12 and 4.7.2-13, muon measurements conducted from March to July 2016 showed shadows of high density material that appeared to be fuel debris at the bottom of the RPV.

Therefore, it is estimated that the fuel debris that fell into the lower plenum remained at the bottom of the RPV and that the amount of debris at the bottom of the PCV was less than previously assumed.

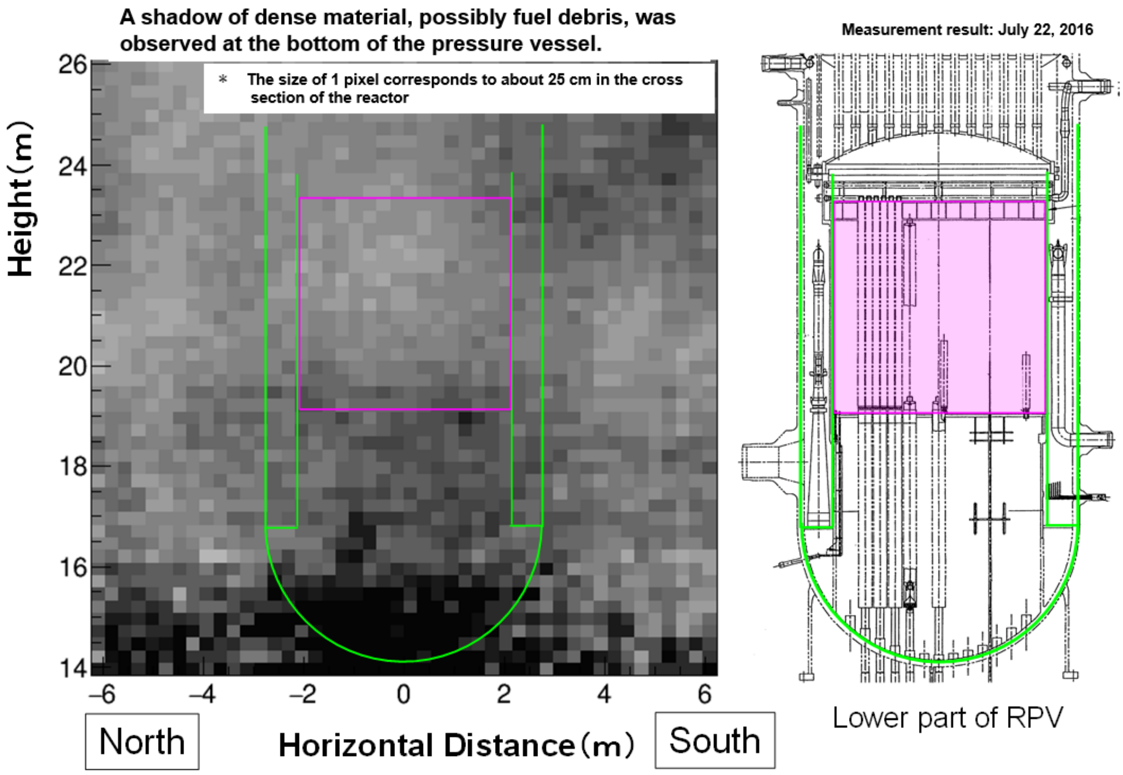
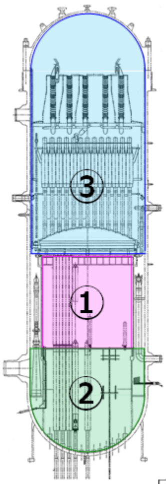


Fig. 4.7.2-12　Muon measurement results for Unit 2 [2-15]



<Quantitative Evaluation Results>

Measurement result: July 22, 2016

	Evaluation results [ton]		(Reference) quantities before the accident※ [ton]
① Core region (Inside shroud)	Approx. 20 - 50	Uncertainties in evaluation results: About several tens of tons	Approx. 160 (Fuel assemblies) Approx. 15 (Control rods)
② Bottom of RPV	Approx. 160		Approx. 35 (Structures) Effect of water is not considered
①+②	Approx. 180 - 210		Approx. 210
(Reference) ③ Upper part of RPV	Approx. 70 - 100		Approx. 80 (Structures)

*Weights in design. They do not necessarily agree with the muon results because part of the structures was ignored for simplicity and the muon measurements were performed looking upward and in the tilt direction.

Figure 4.7.2-13 Quantitative evaluation results on amount of materials in RPV [2-15]

⑥ The opening of the RPV pedestal is depicted to show the spread of fuel debris on the PCV floor.

The pedestal supports the RPV at its bottom, and there is an opening for workers to access the pedestal. Since it is possible the fuel debris that fell into the PCV may have spread to the D/W floor through the worker access opening, it is estimated that this fuel debris spread laterally in the PCV and the access opening is depicted accordingly in the estimation figure.

○ Information to support the estimation

None.

4.7.3. Unit 3

The estimation as of March 2017 is shown in Figure 4.7.3-1 and an enlarged version is shown in Figure 4.7.3-2.

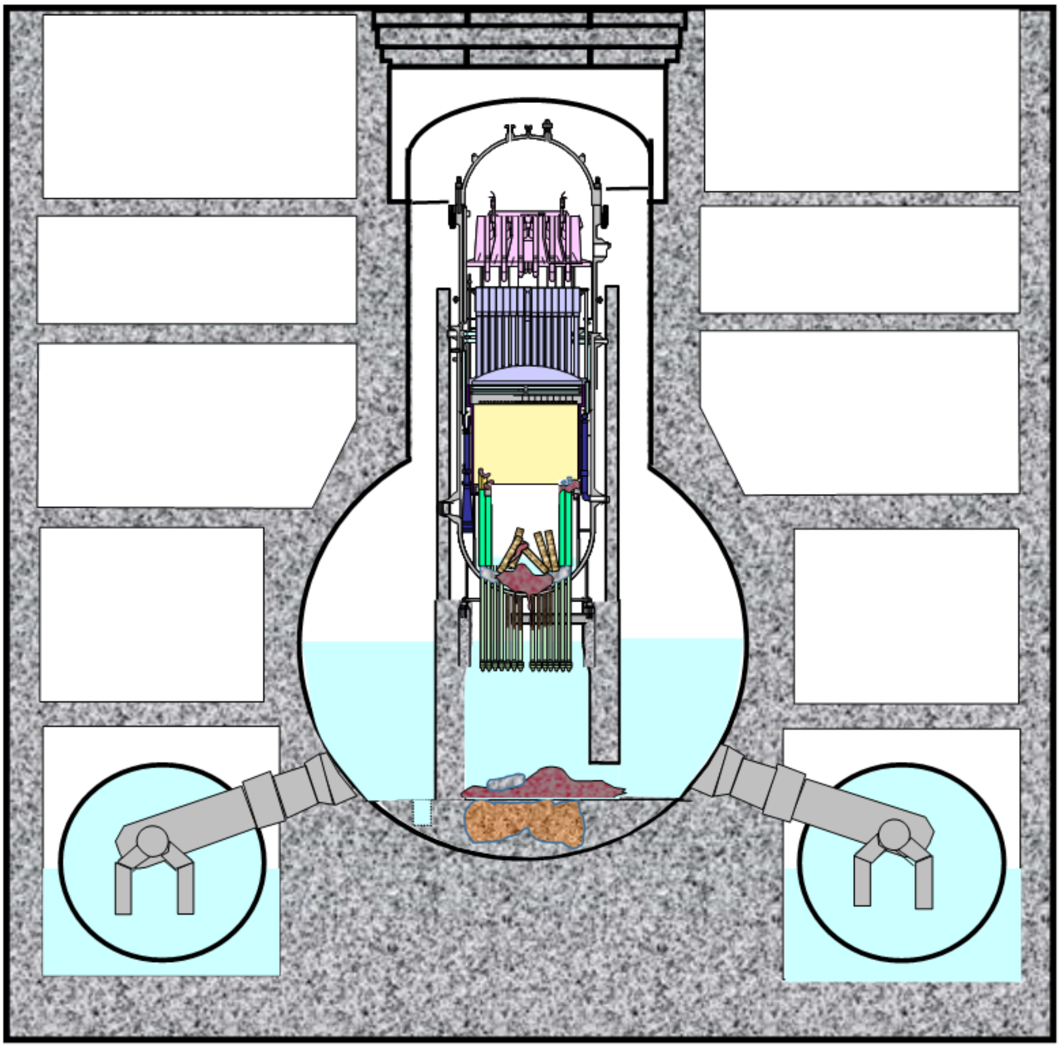


Figure 4.7.3-1 Unit 3 estimation as of March 2017 [3-10]

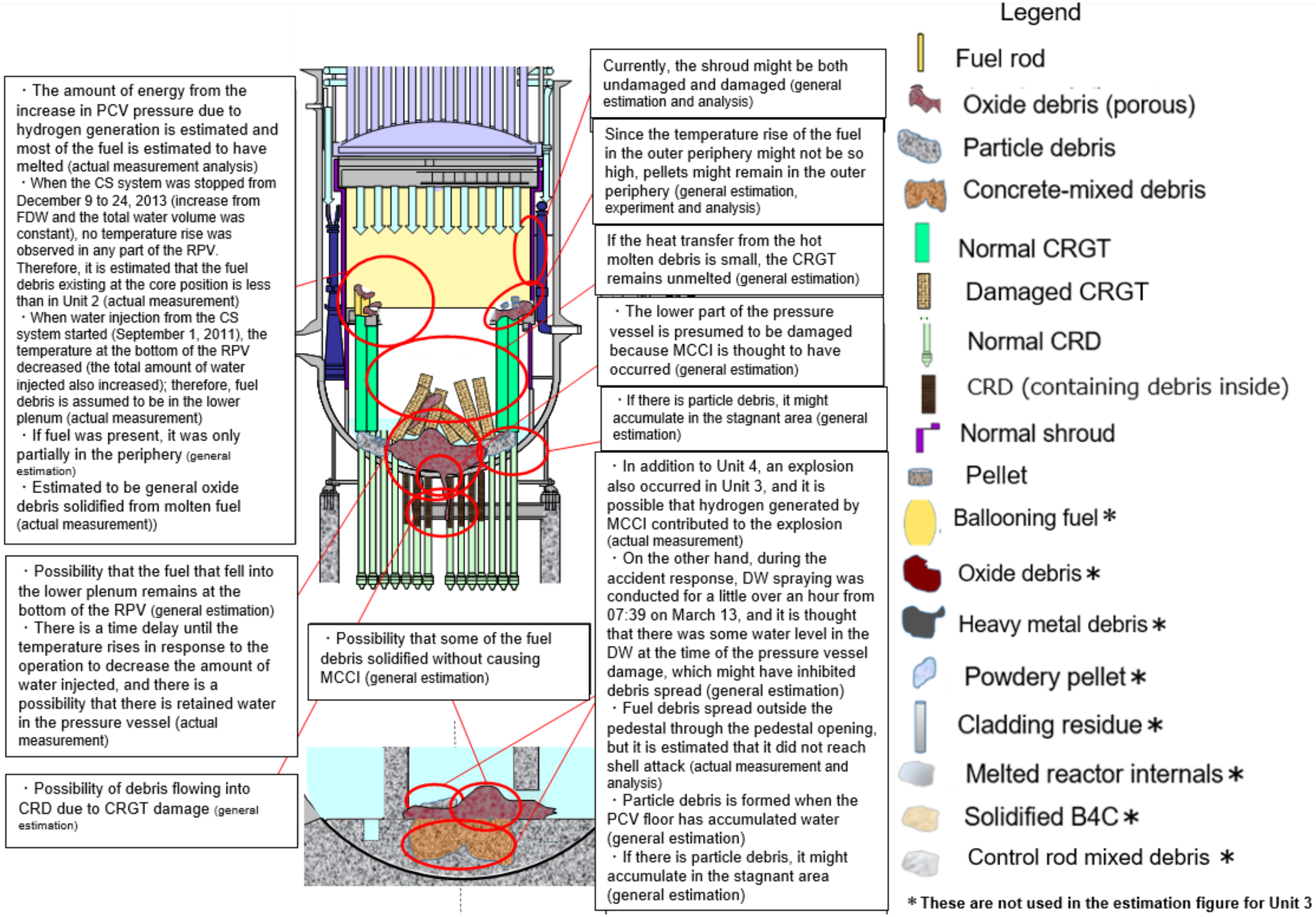


Figure 4.7.3-2 Unit 3 estimation figure as of March 2017 (enlarged) [3-10]

For the estimation in Figures 4.7.3-1 and 4.7.3-2, the characteristics of the estimation, the contents updated from the sixth estimation, and the reasons for the update from the sixth estimation are as follows.

〇Characteristics of estimation

The distribution of fuel debris is estimated to be as follows. Molten fuel fell into the lower plenum of RPV after the accident, and most of it fell further into the PCV. In the RPV, the amount of fuel debris remaining in the core area is small, and it is estimated that some fuel debris exists at the bottom of the RPV. Although there is a lot of fuel debris that fell into the PCV, it is not spread all over the floor.

Regarding the status of the structures in the RPV and PCV, it is estimated that CRGTs at the bottom of the RPV were damaged by the process of fuel melting and falling, and that fuel debris has entered the CRD housings under the RPV.

〇Contents updated from the sixth estimation

① Estimation of the possibility of fuel pellets remaining in the periphery of the core and a stagnant area at the bottom of the RPV.

② The number of CRGTs in the outer periphery of the bottom of RPV is reduced.

③ The opening of the RPV pedestal is depicted to represent the spread of fuel debris on the PCV floor.

④ Estimation that fuel debris spread to outside the pedestal through the pedestal opening but did not reach the stage of shell attack.

〇 Reason for updating from the sixth estimation.

① Estimation of the possibility of fuel pellets remaining in the periphery of the core and a stagnant area at the bottom of RPV.

In the "Advancement of comprehensive assessment of internal reactor status" project funded by the subsidy for decommissioning and contaminated water measures, a test specimen with channel boxes and simulated fuel (ZrO_2) on both sides of a control rod blade was heated by a plasma torch (Figure 4.7.3-3); the purpose was to obtain information on the behavior of fuel melting and migration to the bottom. As shown in Figure 4.7.3-3, the fuel rods maintained their shape to some extent even after heating. In Unit 3, there is no information (see Section 4.6.2) on the shape of the shroud being maintained as in Unit 2, but it is possible that the fuel was not fully melted in the area where the radiation heat transfer is large, such as the outer periphery of the core, because the high temperature is not maintained, and the fuel may fall or remain in the shape of pellets.

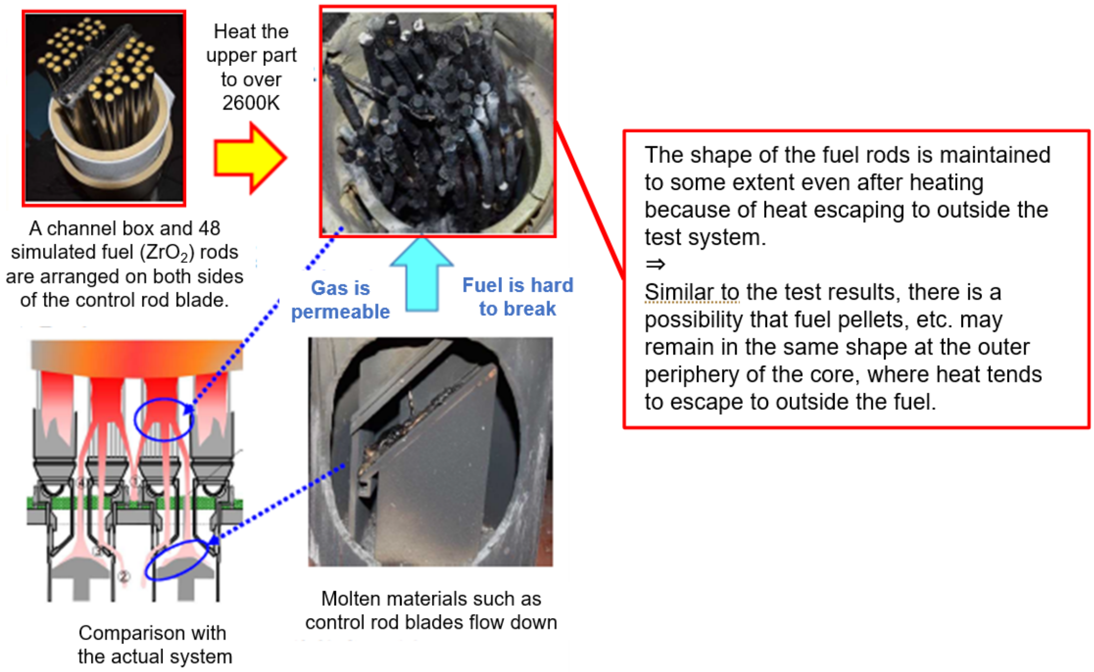


Figure 4.7.3-3 Simulated fuel assembly failure test [3-3]

② The number of CRGTs in the outer periphery of the bottom of the RPV is reduced.

For Units 1 through 3, although they all share the same point of fuel meltdown leading to the severe accident, observation data and on-site investigations have revealed different statuses in RPVs and PCVs. The differences in status are thought to be due to differences in accident progression. The differences in accident progression can be seen in the differences in the cooling status of the fuel since the accident. The timing at which the fuel could no longer be cooled by the existing cooling system in each unit is shown in Figure 4.7.3-4. In each unit, after depressurizing the reactor, the fire trucks shifted to low-pressure water injection. However, the actual amount of water that reached the reactor was considered to be less than the discharge flow rate of the fire trucks, partly due to the bypass to a route other than the reactor.

- Unit 1: IC cooling stopped due to the tsunami that hit at about 15:36 on March 11.
- Unit 2: Water injection function of the RCIC was lost about 09:00 on March 14.
- Unit 3: Water injection function of the HPCI was lost at some point after reactor water level measurement stopped at about 20:36 on March 12 and before the manual shutdown of the HPCI at 02:42 on March 13.

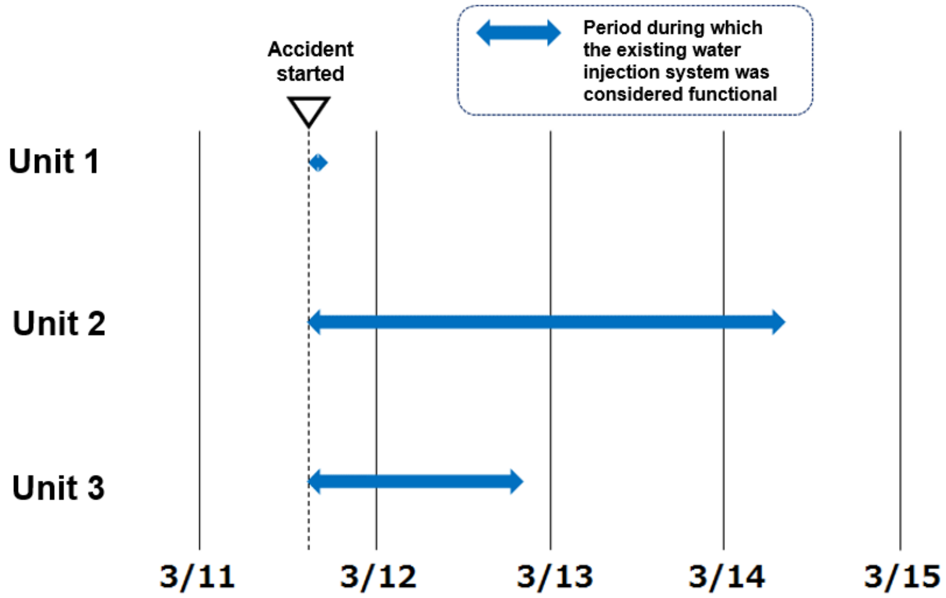
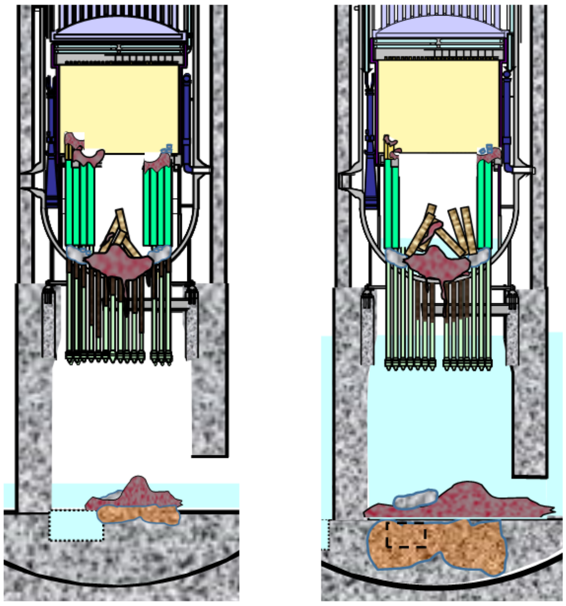


Figure 4.7.3-4 Cooling period of fuel by each unit's existing cooling system [3-3]

As mentioned above, Unit 1 had the shortest cooling period in the initial phase of the accident, followed by Unit 3 and Unit 2, and therefore, Unit 1 is considered to have the largest degree of damage, followed by Unit 3 and Unit 2, in that order.

Based on the above, the number of structures remaining in the RPV in Unit 3 is considered to be smaller than in Unit 2, and the number of CRGTs in the outer periphery of the bottom of RPV is assumed to be smaller than in Unit 2 (Figure 4.7.3-5).



Unit 2 Unit 3

Figure 4.7.3-5 Comparison of the status of remaining structures in RPV (Units 2 and 3)

③ The opening of the RPV pedestal is depicted to represent the spread of fuel debris on the PCV floor.

The pedestal supports the RPV at its bottom, and there is an opening for workers to access the pedestal. Since it is possible the fuel debris that fell into the PCV may have spread to the D/W floor through the worker access opening, it is estimated that this fuel debris spread laterally in the PCV and the access opening is depicted accordingly in the estimation figure.

④ Estimation that fuel debris spread outside the pedestal through the pedestal opening but did not reach the state of shell attack.

As described in Section 4.6.3, the spread of fuel debris in the Unit 3 PCV is considered to have been suppressed by the effect of water accumulated from the D/W spray operation. On the other hand, as also described in Section 4.6.3, the cooling of the fuel debris by the accumulated water was not sufficient, and the reaction with the concrete is considered to have progressed to some extent, and some of the fuel is considered to have been in a molten state and may have spread outside the pedestal through the worker access opening. However, since the PCV water level is high in Unit 3 and water leakage has been confirmed from the MSIV room as described in Section 4.3.3, it is considered that there are no large-scale liquid phase leakage points in the lower parts of the PCV. In other words, shell attack by fuel debris is not considered to have occurred.

○ Information supporting the estimation

None.

4.8. Eighth estimation (December 25, 2017)

4.8.1. Unit 1

The estimation as of December 25, 2017 is shown in Figure 4.8.1-1 and an enlarged version is shown in Figure 4.8.1-2.

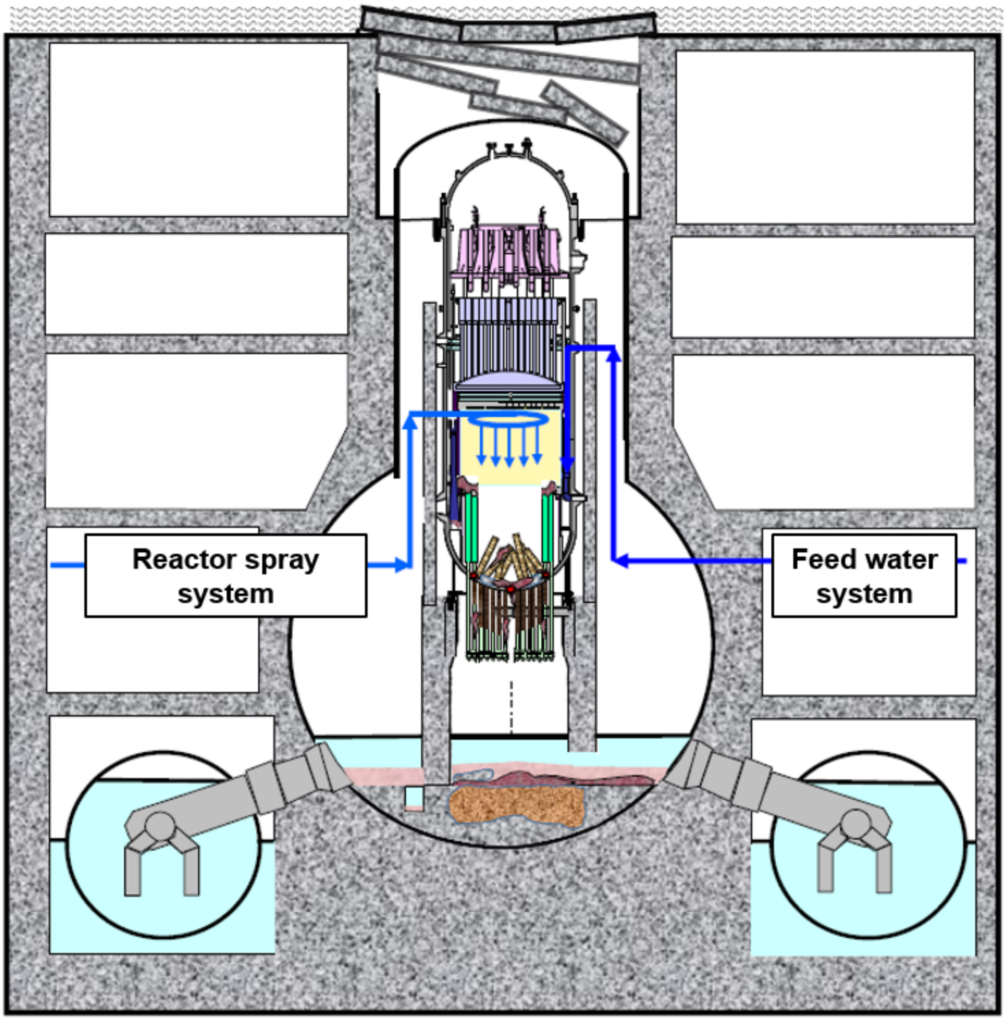


Figure 4.8.1-1 Unit 1 estimation as of December 25, 2017 [1-17]

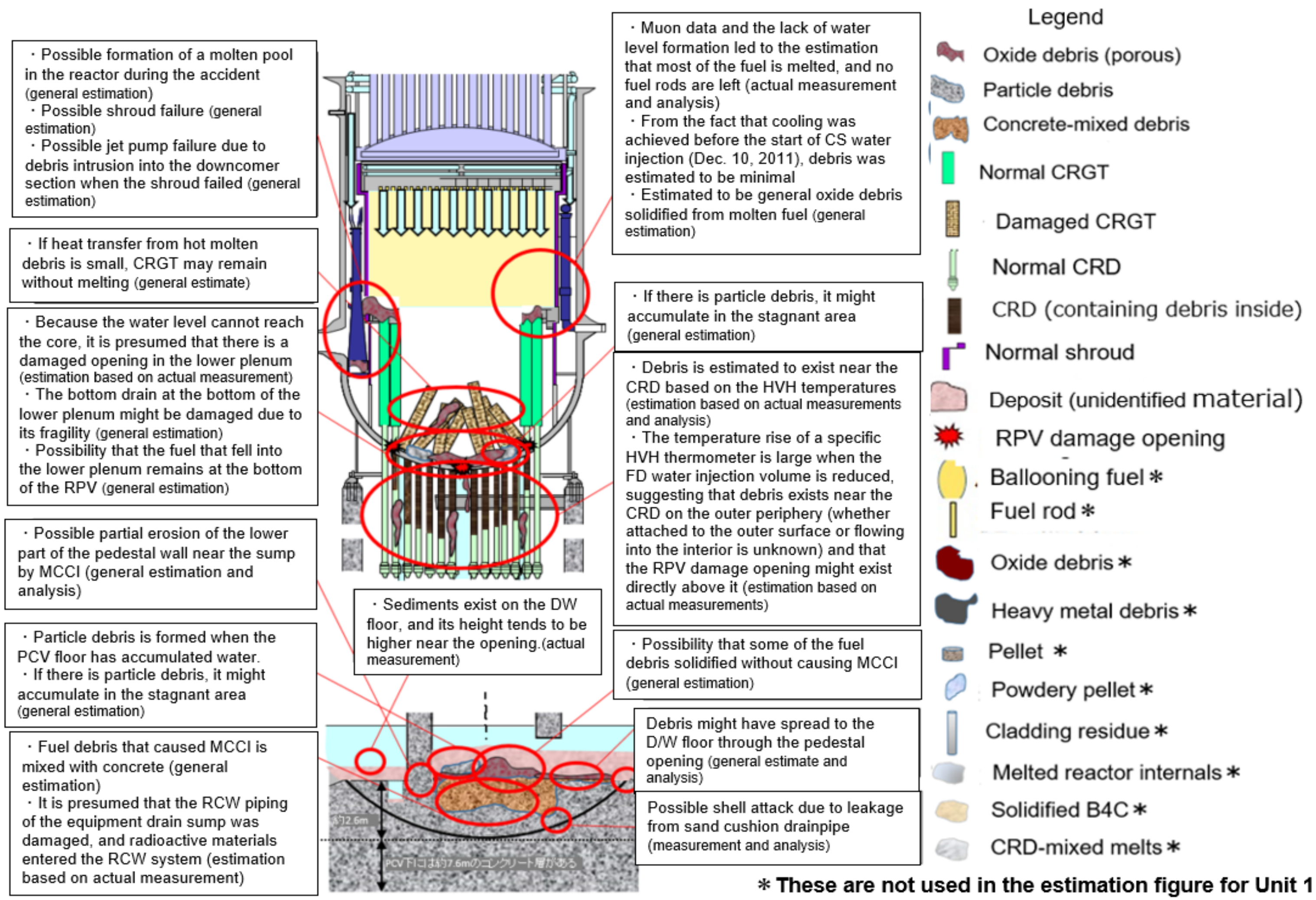


Figure 4.8.1-2 Unit 1 estimation figure as of December 25, 2017 (enlarged) [1-18]

For the estimation in Figures 4.8.1-1 and 4.8.1-2, the characteristics of the estimation, the contents updated from the seventh estimation, and the findings that helped in the estimation are as follows.

○ Characteristics of estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and almost none remained in the original core area. It is estimated that most of the fuel debris that fell into the lower plenum fell into the bottom of the PCV.

Regarding the status of the structures in the RPV and PCV, it is estimated that CRGTs at the bottom of the RPV were damaged by the process of fuel melting and falling, and fuel debris has penetrated into the CRD housings under the RPV.

It is estimated that unknown materials have accumulated at the bottom of the PCV.

○Contents updated from the seventh estimation.

① Clear indication of the fall of the middle and lower layer pieces of the well-plug.

○ Reasons for updating from the seventh estimation.

① Clear indication of the fall of the middle and lower layer pieces of the well-plug.

The reactor well-plug was investigated during the investigation on the north side of the operating floor that started in November 2016. The well-plug has three layers (upper, middle, and lower), and each layer consists of three concrete pieces.

Figure 4.8.1-3 shows results confirming the status of the well-plug damage on the operating floor. Based on the analysis of the images acquired during the investigation, pieces of the well-plug were estimated to have been displaced as shown in Figure 4.8.1-4. As shown in Figure 4.8.1-5, the north side upper layer piece was observed to have moved 720mm to the west. It was also confirmed that the center piece of the upper layer moved a maximum of 155mm and the north side upper layer piece moved a maximum of 84mm downward.

In the estimation figure, the status of the confirmed well-plug pieces is expressed.

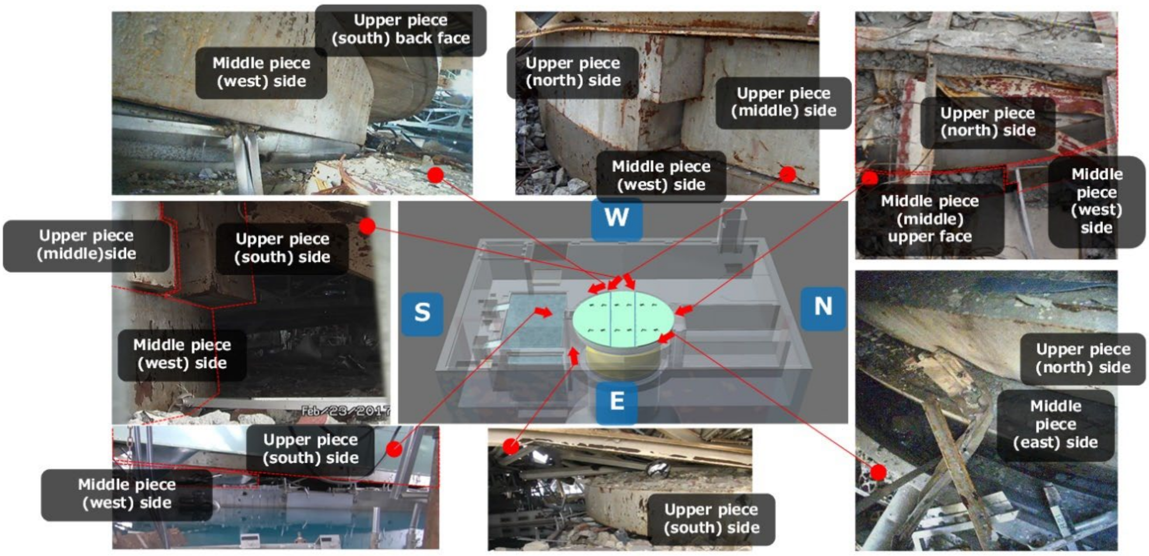


Figure 4.8.1-3 Results of confirming well-plug status on the operating floor [1-19]

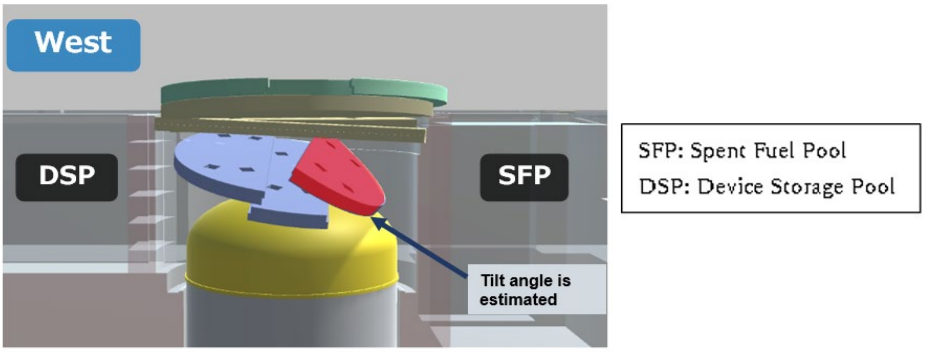


Figure 4.8.1-4 Image created based on the investigation results [1-20]

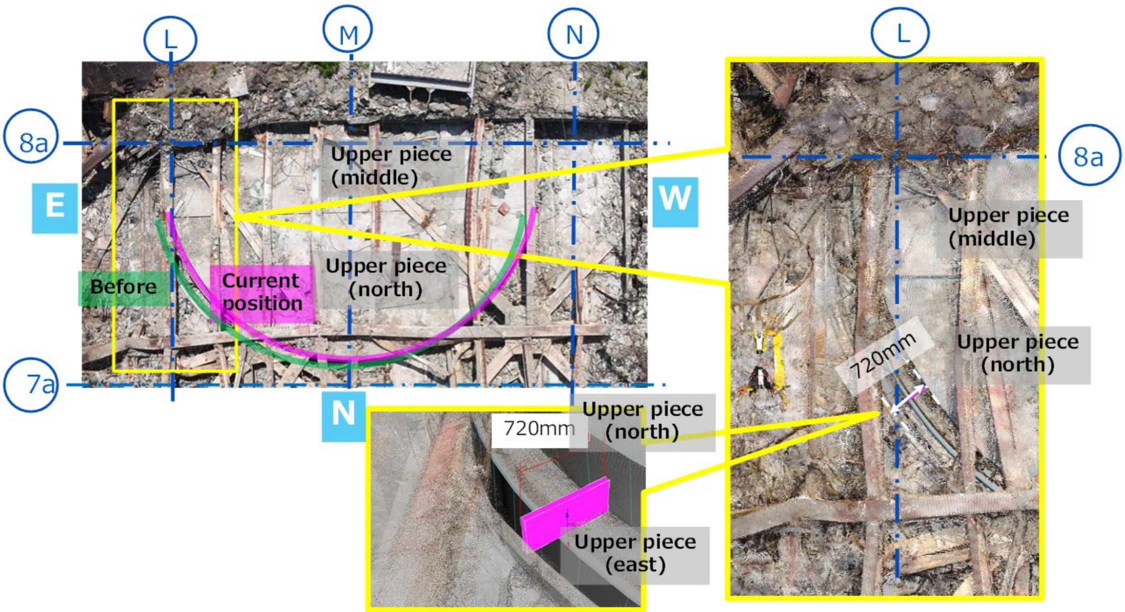


Figure 4.8.1-5 Status of well-plug displacement [1-20]

○ Information supporting the estimation

None.

4.8.2. Unit 2

The estimation as of December 25, 2017 is shown in Figure 4.8.2-1 and an enlarged version is shown in Figure 4.8.2-2.

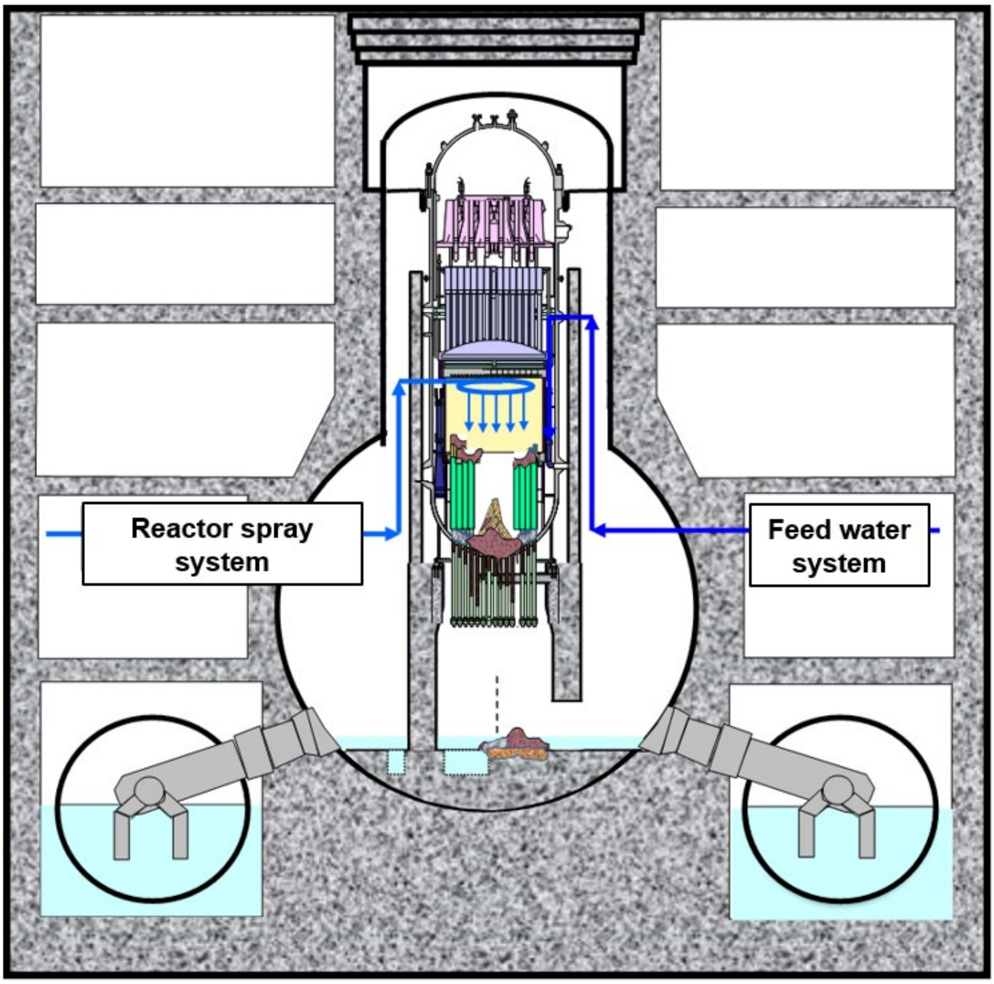


Figure 4.8.2-1 Unit 2 estimation as of December 25, 2017 [2-18]

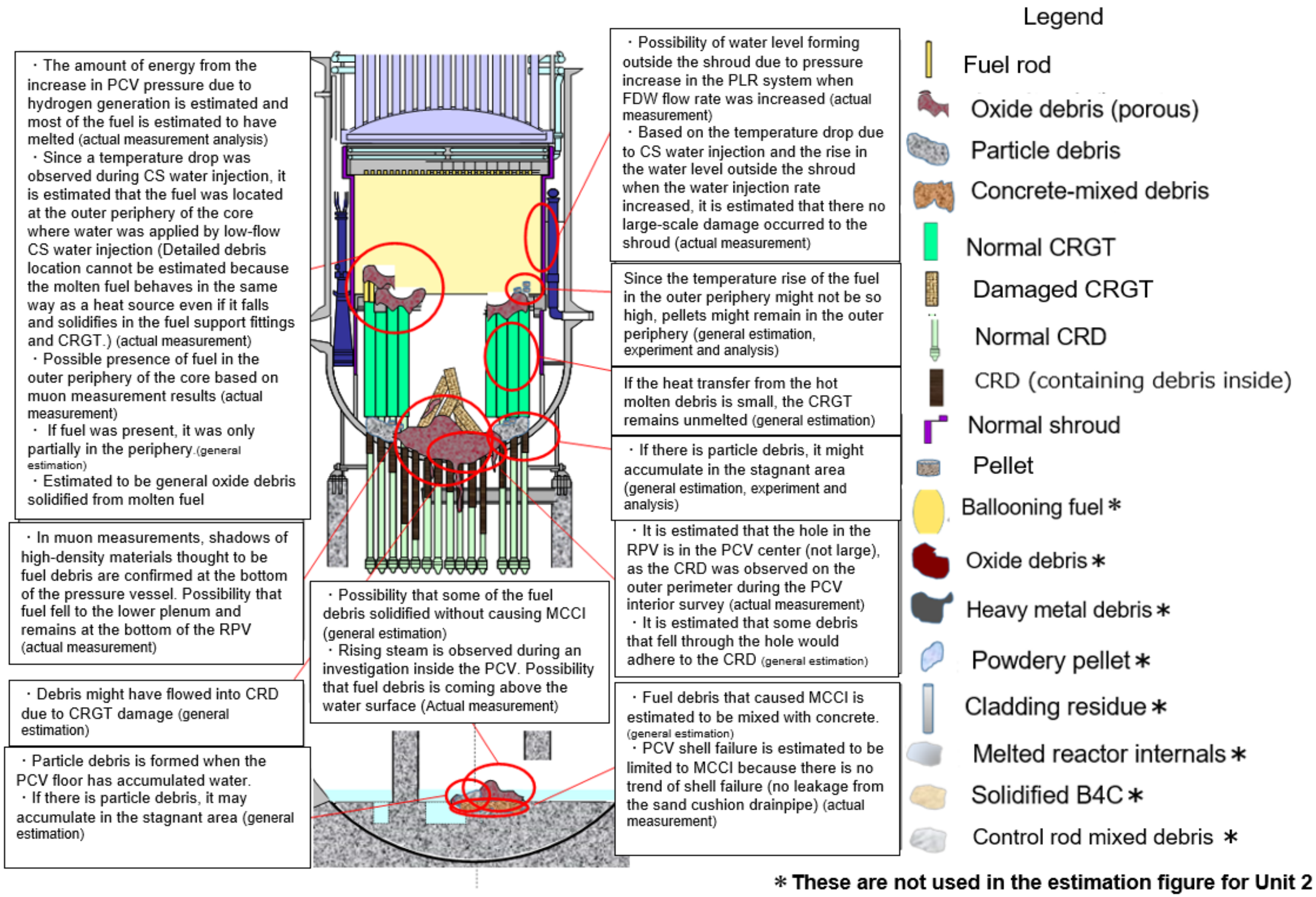


Figure 4.8.2-2 Unit 2 estimation figure as of December 25, 2017 (enlarged) [2-19]

For the estimation in Figures 4.8.2-1 and 4.8.2-2, the characteristics of the estimation, the contents updated from the seventh estimation, and the reasons for the update from the seventh estimation are as follows.

○ Characteristics of estimation

The estimation of the distribution of fuel debris is as follows: some part of the molten fuel fell into the lower plenum of the RPV after the accident, and another part fell into the PCV; in the RPV, some of the fuel remains in the core, and most of it is estimated to be at the bottom of the RPV. The amount of fuel debris that fell into the PCV is considered small, and the extent of MCCI is limited.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the process of falling molten fuel, and fuel debris has penetrated into the CRD housings below the RPV.

Regarding the water level in the D/W, it was confirmed to be about 300mm from the D/W floor.

○Updated contents from the seventh estimation

① PCV water level is lowered.

○Reasons for updating from the seventh estimation

① PCV water level is lowered.

The water level was about 600mm above the D/W floor according to the video scope confirmation of the water level during the PCV internal investigation conducted in March 2012. Since the main purpose of this was to determine the rough location of the water surface, the level of the accumulated water was again confirmed during the installation of the monitoring instrument inside the PCV conducted in June 2014. The action of landing the instrument tip on the water and the position of the bottom of the tip were confirmed by a camera and the water level was measured from the difference in length of cable insertion, resulting in the confirmation that the water level was about 300mm above the D/W floor (Figures 4.8.2-3 and 4.8.2-4).

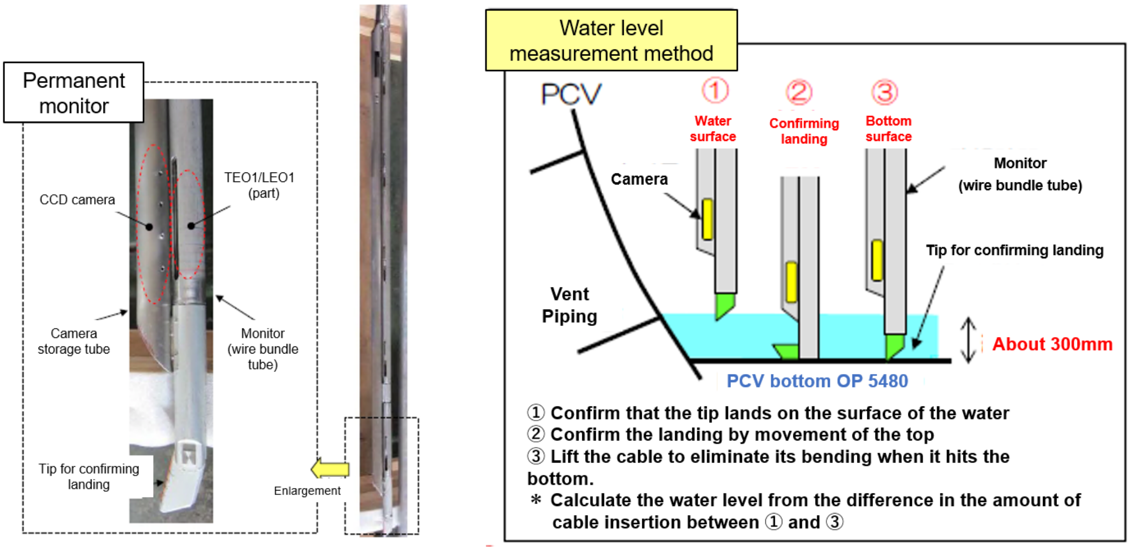


Figure 4.8.2-3 Results of PCV water level measurement during reinstallation of the monitoring instrument in Unit 2 PCV [2-20]

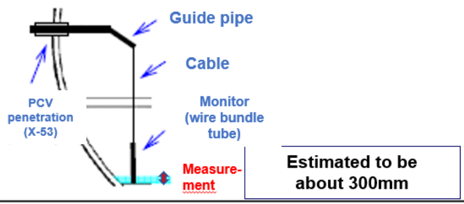
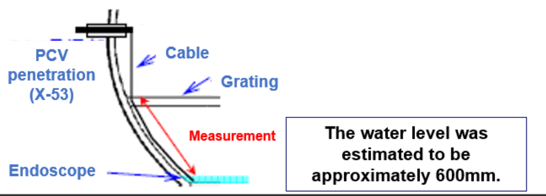
Date	June 6, 2014 (this time)	March 26, 2012 (last time)
Outline		
Procedure	● A monitor (with camera) was inserted vertically. ● The water level was calculated from the difference in the length of insertion, which was confirmed by the camera at the water surface position and the bottom landing position of the tip. ⇒ A range of about 300mm (water surface - bottom) was measured. ● The amount of insertion was measured with a tape measure outside the PCV penetration.	● The endoscope was inserted along the PCV wall. ● The water level was calculated from the difference in the insertion length of after confirming the position of the endoscope passing through the grating and the position where the tip landed on the water. ⇒ A range of about 3700mm (grating – water surface) was measured. ● The amount of insertion was measured using a 500mm pitch cable marked as a guideline.
Cable bending	● After landing on the bottom surface, the cable was pulled up again in order to eliminate the bending.	● No consideration for cable deflection.
Note		● If the cable bending was greater when it passed through the grating than when it landed on the water surface, the water level might be overestimated. ● The PCV wall curvature was corrected when calculating water surface.

Figure 4.8.2-4 Comparison of PCV water level measurements in March 2012 and June 2014 [2-20]

○ Information supporting estimation

None.

4.8.3. Unit 3

The estimation as of December 15, 2017 is shown in Figure 4.8.3-1 and an enlarged version is shown in Figure 4.8.3-2.

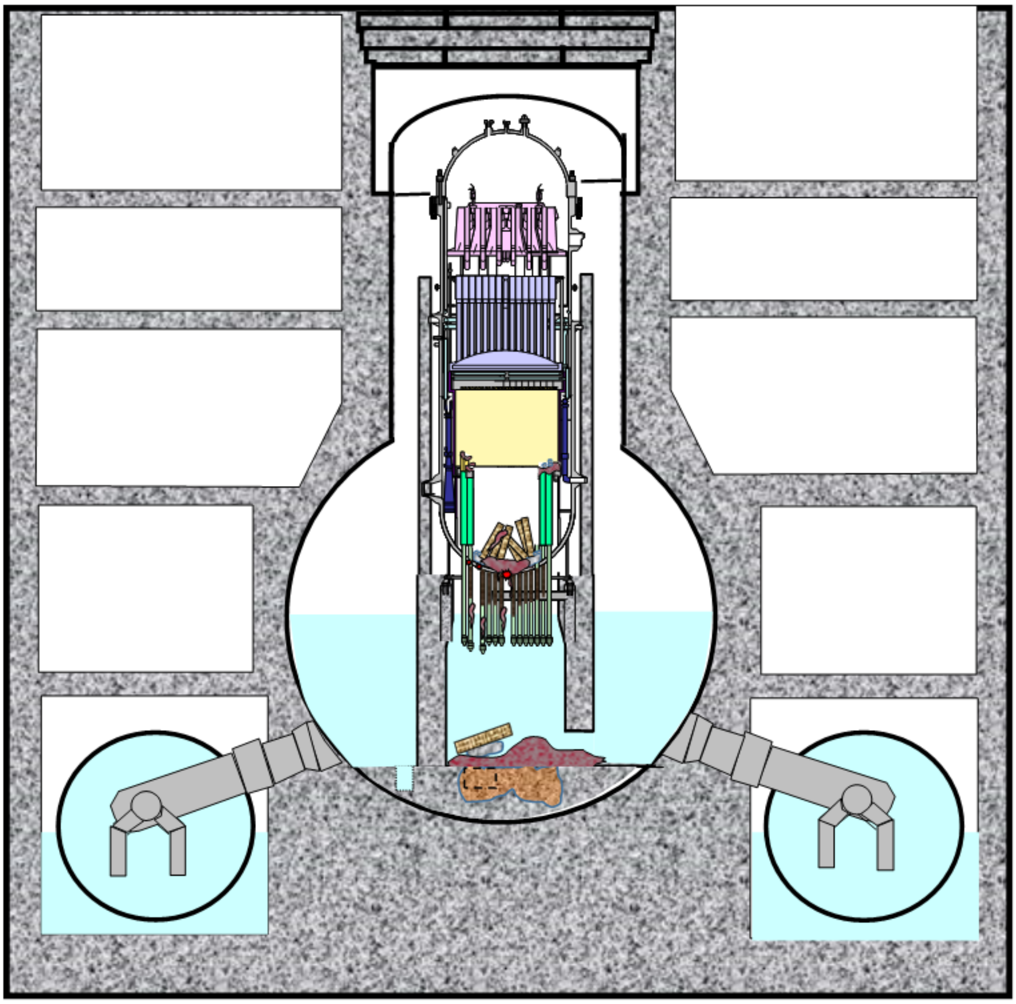


Figure 4.8.3-1 Unit 3 estimation as of December 25, 2017 [3-13]

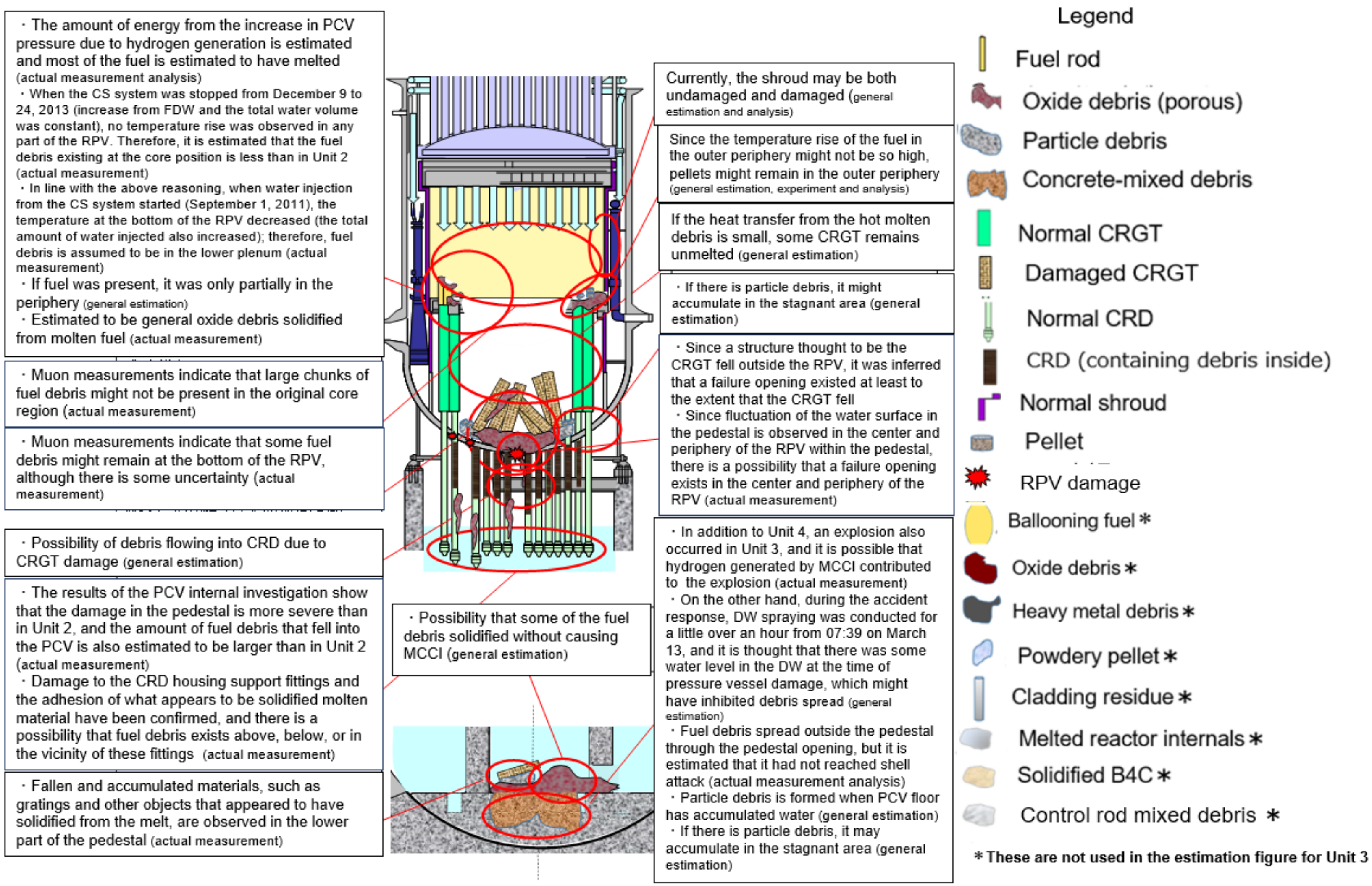


Figure 4.8.3-2 Unit 3 estimation figure as of December 25, 2017 (enlarged) [3-14]

For the estimation in Figures 4.8.3-1 and 4.8.3-2, the characteristics of the estimation, the contents updated from the seventh estimation, the reasons for the update from the seventh estimation, and information supporting the estimation are as follows.

○ Characteristics of estimation

The estimation of the distribution of fuel debris is as follows. Molten fuel fell into the lower plenum of the RPV after the accident, and most of it fell further into the PCV. In the RPV, the amount of fuel debris remaining in the core is small, and it is estimated that some fuel debris exists at the bottom of the RPV. Although there is a lot of fuel debris that fell into the PCV, it is not spread all over the floor. The amount of fuel debris in the RPV is estimated to be small.

Regarding the status of the structures in the RPV and PCV, CRGTs at the bottom of the RPV are estimated to have been damaged by the fuel melting and falling, and the fuel debris has penetrated into the CRD housings under the RPV. In addition, objects thought to be damaged CRGTs have fallen into the PCV.

○Contents updated from the seventh estimation

① Damage openings of the RPV are clearly indicated on the estimation figure.

② Deletion of water holding in RPV.

③ The degree of damage to the CRD housings is updated to depict fuel debris attached to these housings.

④ Damaged CRGTs are depicted at the bottom of the PCV.

○Reasons for updating from the seventh estimation

① Damage openings of the RPV are clearly indicated on the estimation figure.

Previously, it was estimated that a hole was formed in the bottom of the RPV during the accident progression and fuel debris fell into the bottom of the PCV; information obtained from the PCV internal investigation conducted in July 2017 led to estimation of the location and size of the holes, which are depicted as damage openings in the bottom of the RPV.

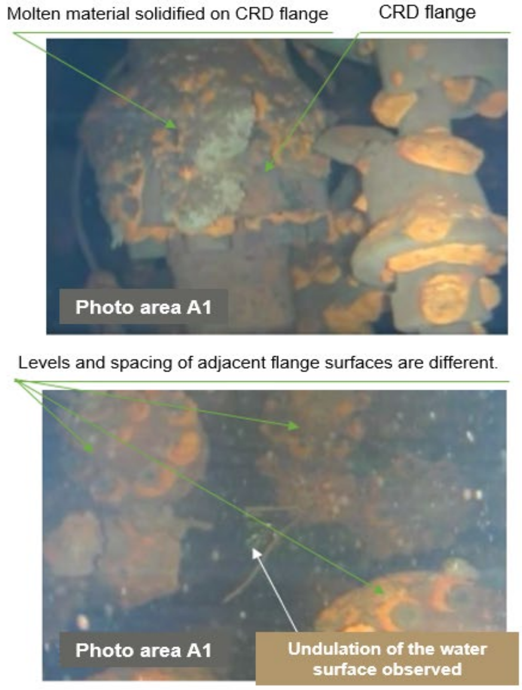
Specific findings obtained from the PCV internal investigation are described below.

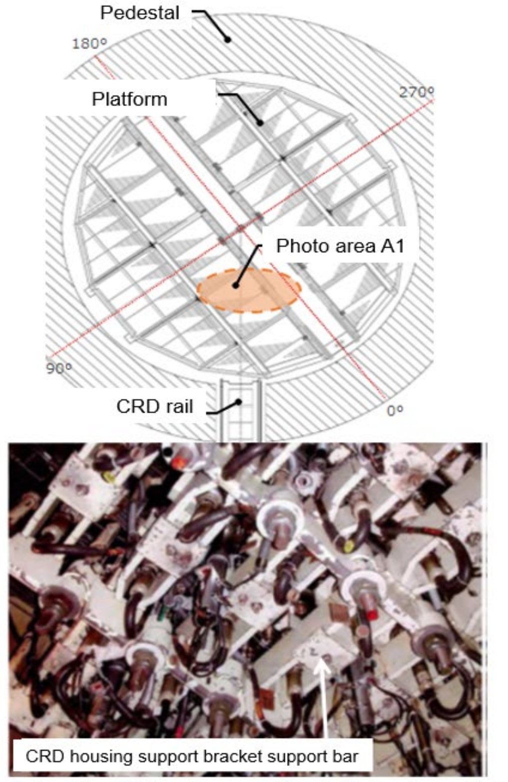
In Unit 3, due to the high water level in the PCV, the investigation inside the PCV was conducted using an underwater swimming robot. When looking up through the water toward the bottom of the RPV, the CRD housings and their supporting structure are normally in a uniform line as shown in the bottom right photo in Figure 4.8.3-3. However, as shown in the two photos on the left taken during the investigation, the CRD flanges were covered with solidified molten material, and the height levels and spacing of the flange surfaces, which should have been identical, were different. At this time, the water surface seen through the gap between the CRD housings was observed to be undulating, which may indicate that water injected into the RPV was dripping onto the surface of the water. In other words, there is a possibility that the damage opening of the RPV exists at the top where water is dripping from the surface. Although the underwater robot did not investigate the entire surface of the water in the pedestal, as shown in Figure 4.8.3-4, observations were made at the edge of the pedestal as well as near the center of the pedestal, where the water surface was undulating. This suggests that there may be more than one damage opening at the bottom of the RPV.

As shown in Figure 4.8.3-5, in the image looking up at the bottom of RPV near the center, a cylindrical structure is observed, with a bar-shaped structure inside. Notches that appear to be at regular intervals can be seen on the bar-shaped structure. At the time of the accident, the CR was fully inserted, and the CRD index tube was in a state of containment within the CRGT. Based on these facts, the cylindrical structure is considered to be the CRGT, and the bar-shaped structure is considered to be the CRD index tube. Regarding the size, the outer diameter of the cylindrical structure was estimated from the image based on the fact that the notch interval of the CRD index tube is about 15cm, and the estimated value was about 28cm, which is roughly consistent with the design value of the CRGT outer diameter of about 28cm. Figure 4.8.3-6 shows a comparison of the cylindrical structure and the CRGT structure.

The CRGTs are originally located at the bottom of the RPV, and the fact that they have fallen into the PCV suggests that a hole large enough for the CRGTs, which have a diameter of about 28cm, to fall through opened up at the bottom of the RPV during the accident progression.

Based on the above information, the damage openings at the bottom of the RPV are clearly indicated in the estimation figure.





Status of the CRD housing support bracket before the accident (Unit 3)

- **Support brackets of CRD housing are damaged/dropped off in several places**
- **Levels and spacing of adjacent flange surfaces are different.**
- **Undulation observed in the water surface is seen through the gap in the CRD housing (suggesting the possibility of water dripping from the top)**

Figure 4.8.3-3 Bottom of RPV [3-15]

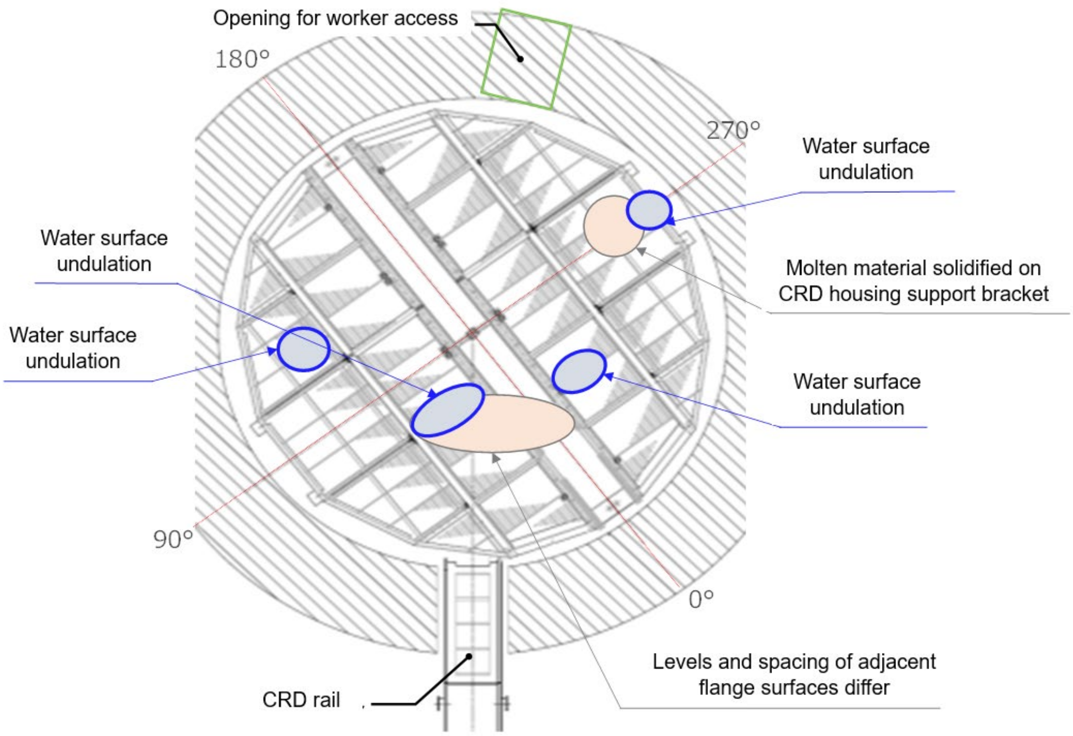


Figure 4.8.3-4 Areas where undulating water surface was observed [3-15]

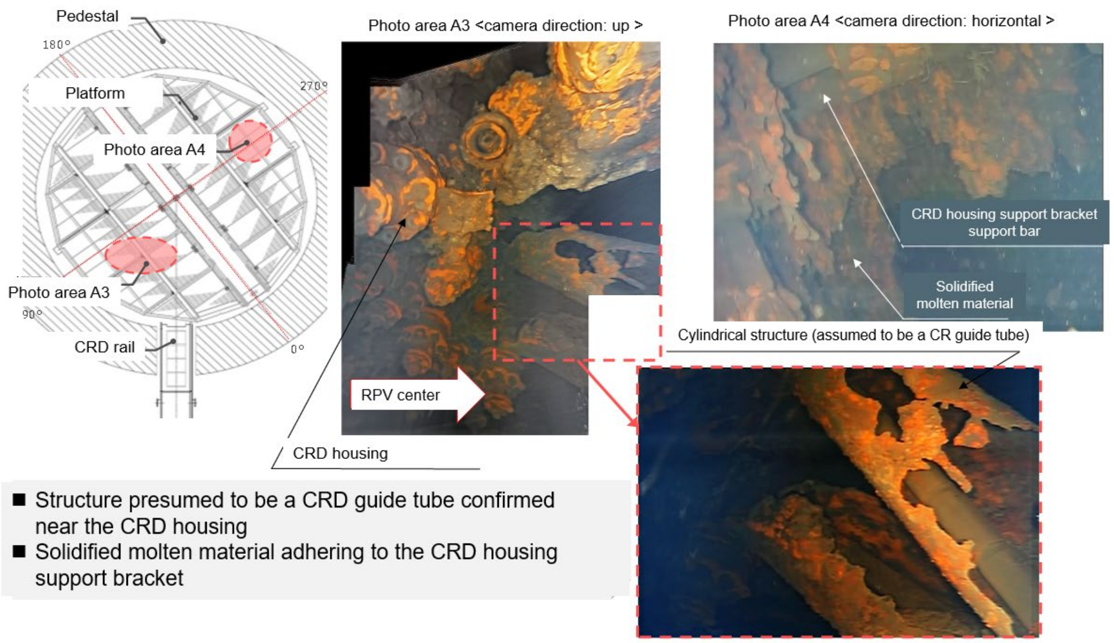
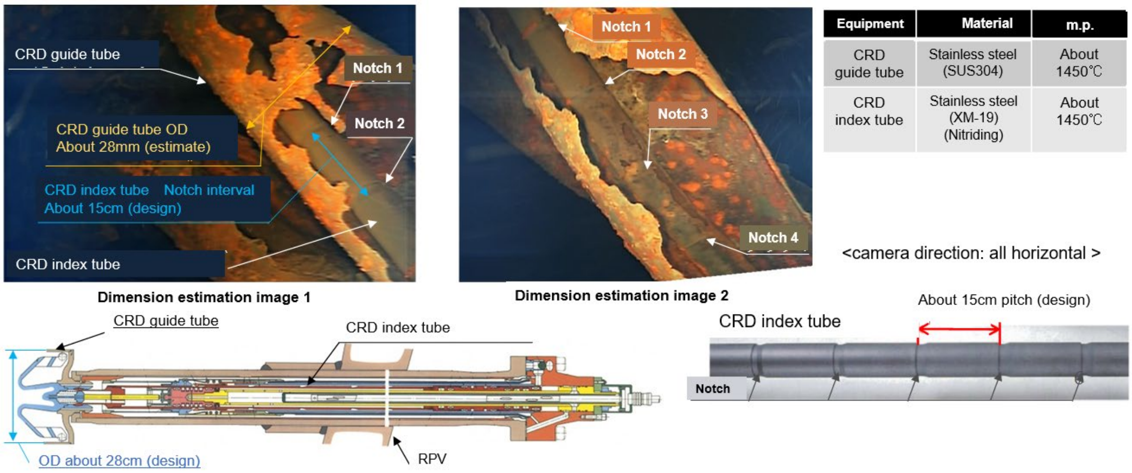


Figure 4.8.3-5　Structure believed to be a CRGT identified near the center [3-15]



Equipment	Material	m.p.
CRD guide tube	Stainless steel (SUS304)	About 1450℃
CRD index tube	Stainless steel (XM-19) (Nitriding)	About 1450℃

Figure 4.8.3-6　Comparison of the structure near the CRD housings and the CRGT structure [3-15]

② Deletion of water holding in the RPV.

As described in ①, the hole in the bottom of RPV is considered large enough to allow an object thought to be a CRGT, which is about 28cm in diameter, to fall through, and also multiple damage openings are considered to be present. The amount of water injection into the reactor was about 1.5m^3/h from the FDW and 1.5m^3/h from the CS, totaling about 3m^3/h as of July 2017, and considering the size of the hole that is thought to be near the center and the possibility of multiple damage openings, it is thought that water is not being held in the bottom of RPV. Therefore, the estimation that water may be present at the bottom of the RPV described in Section 4.6.3 was updated.

③ The degree of damage to the CRD housings is updated to depict fuel debris attached to these housings.

The estimation figure reflects the damage to the CRD housings that could be seen when looking up at the bottom of the RPV shown in Figures 4.8.3-3 and 4.8.3-5, as described in ①.

As shown in the upper right image in Figure 4.8.3-5, icicle-like coagulates were observed in the vicinity of the CRD housings. Although it is difficult to identify the substance of these solidified materials from the image, it is considered that fuel debris may exist around the CRD housings because the bottom of the RPV was heated by the fuel debris, which caused damage to that bottom, and the fuel debris fell through the damage opening.

④ The damaged CRGT is depicted at the bottom of the PCV.

As shown in Figure 4.8.3-5, the structure believed to be a CRGT has fallen onto the PCV, which is reflected in the estimation figure.

○Information supporting the estimation

The following information is considered to be reliable for the content of the estimation.

・Investigation of fuel debris distribution in RPV by muon measurement

In Unit 3, an investigation of the distribution of fuel debris in the RPV was conducted from May to September 2017 using the muon transmission method. The investigation results are shown in Figure 4.8.3-7 for the core and Figure 4.8.3-8 for the bottom of the RPV. In both figures, the contour plot on the left side shows the amount of material inside the RPV, expressed in colors, compared to the situation where there is no material inside it.

In Figure 4.8.3-7, the right graph shows the distribution of the amount of material present in the upper and lower sections of the core, respectively. If the fuel were not damaged, the evaluated value would be plotted on the yellow line in the upper graph, but the evaluated value is lower than that, indicating that the amount of material in the core has decreased significantly. This confirms the previous estimation that most of the fuel has melted and moved downward.

In Figure 4.8.3-8, the graph on the right side shows the distribution of material at the top and bottom of the RPV, and in each cross section. Under normal conditions, the bottom of the RPV is covered with many CRGTs with a density of about 0.3g/cm^3. In the graph below, the measured density of CRGTs in some areas exceeded the yellow-green line representing the average CRGT density of a sound (undamaged) core. This confirms the previous estimation that fuel debris remains at the bottom of the RPV.

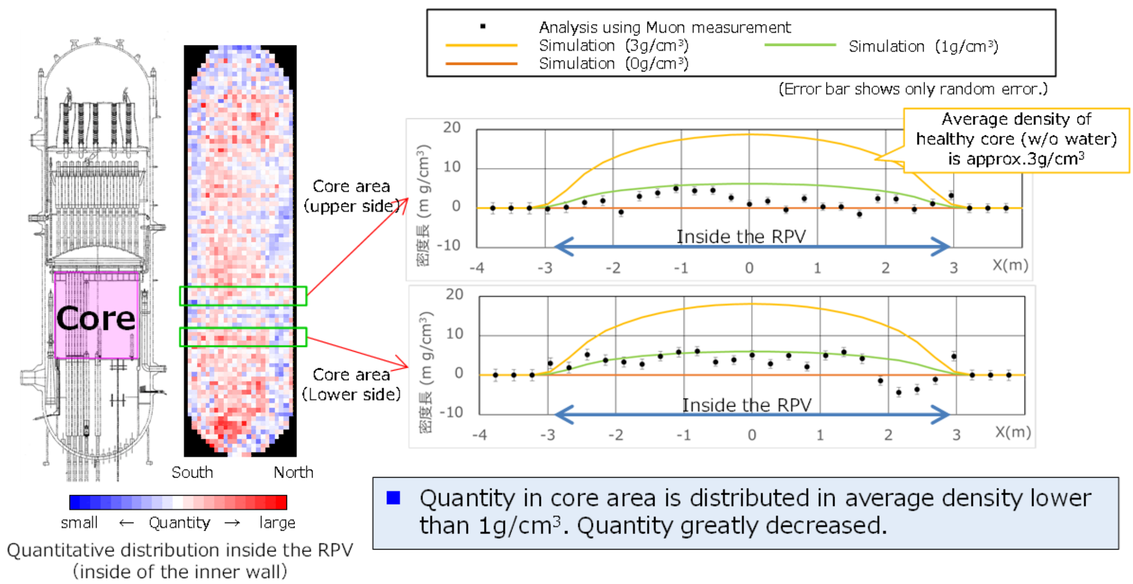


Fig. 4.8.3-7 Muon measurement results (core section) [3-16]

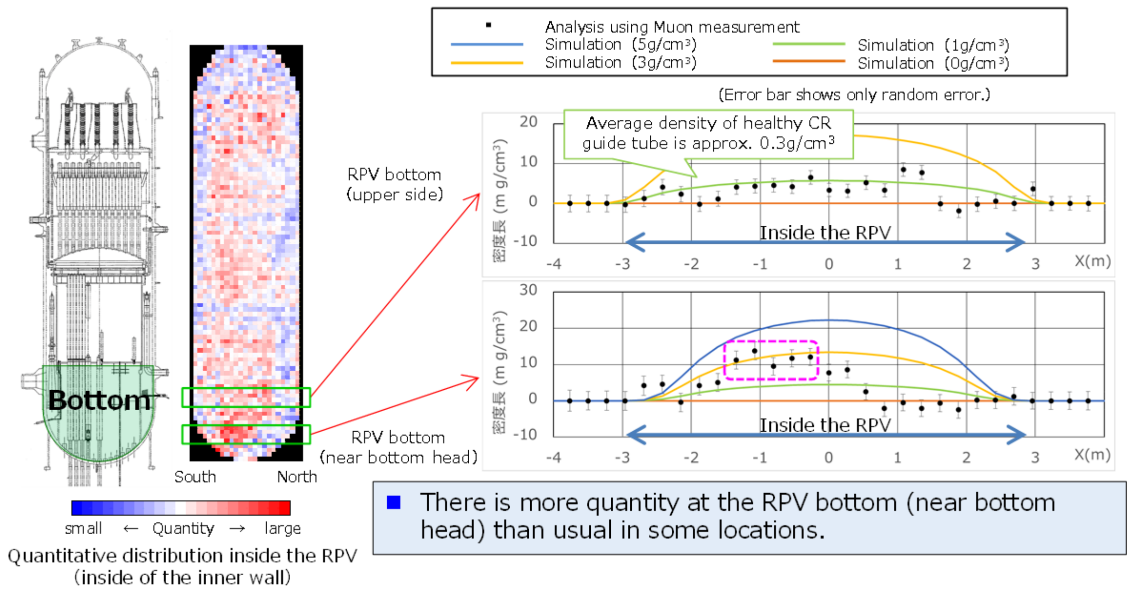
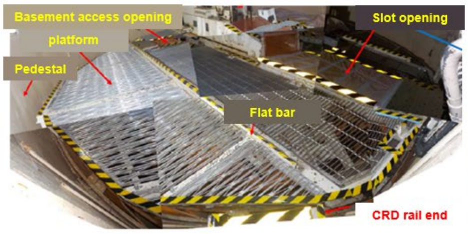


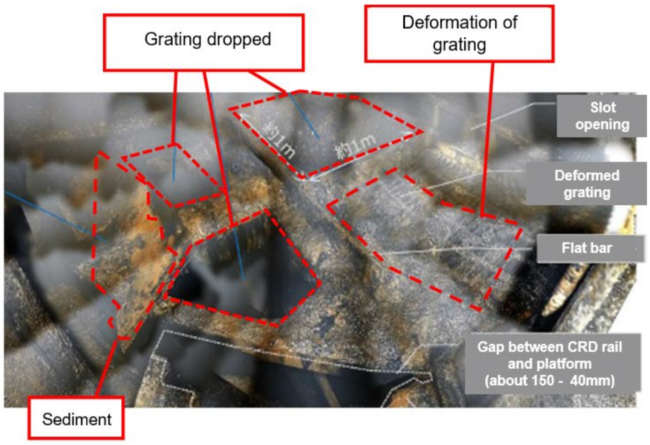
Fig. 4.8.3-8 Muon measurement results (bottom of RPV) [3-16]

・Comparison of PCV internal investigation results for Units 2 and 3

Figure 4.8.3-9 shows images obtained from the Unit 2 PCV internal investigation conducted in January and February 2017, looking into the inside of the pedestal from the pedestal opening leading from the CRD rail, where the workspace called the platform is laid out. Although some of the grating was deformed or fell down, some of the grating near the CRD rail had not collapsed and was still in its original position. Figure 4.8.3-10 shows a photograph of the area near the platform in Unit 3; the grating in a similar location in Unit 3 has collapsed and part of the platform has also collapsed. Around the CRD flanges in Unit 3 more damage was seen than in Unit 2. This damaged status suggests that more fuel debris fell into the Unit 3 PCV than into the Unit 2 PCV, and the information confirms the previous estimation.



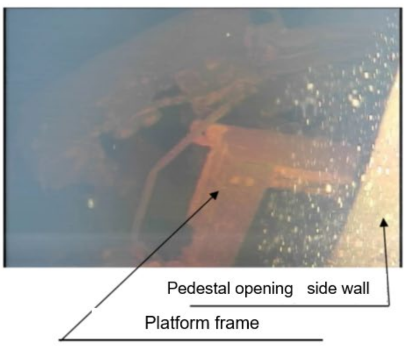
(Ref) Inside Unit 5
Superimposed image of multiple photos

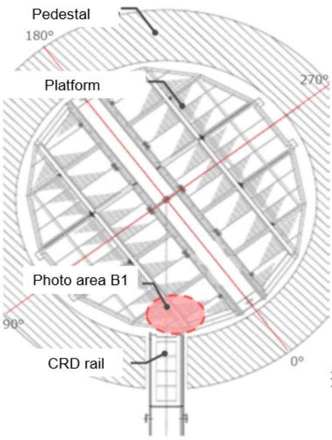


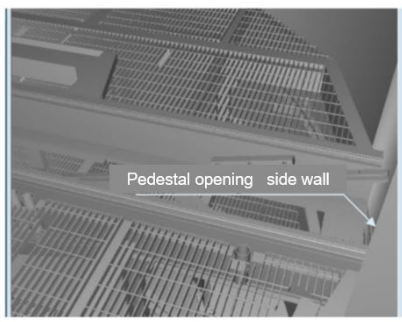
Superimposed image of multiple photos

Figure 4.8.3-9 Photos taken near the platform during Unit 2 PCV internal investigation [3-17]

Photo area B1 <camera direction: down>







CAD drawing with the same angle of view as the captured image (left)

Figure 4.8.3-10 Photos taken near the platform during Unit 3 PCV internal investigation [3-15]

・Status of the bottom of the PCV confirmed during the PCV internal investigation

Figure 4.8.3-11 shows photos of the bottom of the PCV taken during the PCV internal investigation. Sand-like, pebble-like, sediment, and lumpy deposits (massive sediment) were observed at the bottom. The worker access opening was not visible, but sediment was observed in the vicinity (photo area C5). In addition, grating and other structures that may have fallen from the platform and possibly a control rod speed limiter were observed (photo area C2). These situations suggest that fuel debris has fallen into the Unit 3 PCV.

The photo area C4 shows the central area of the bottom of the PCV. The central area is where the structure thought to be a CRGT has fallen down, and the lumpy deposits seen in the photo may contain a large amount of fuel components.

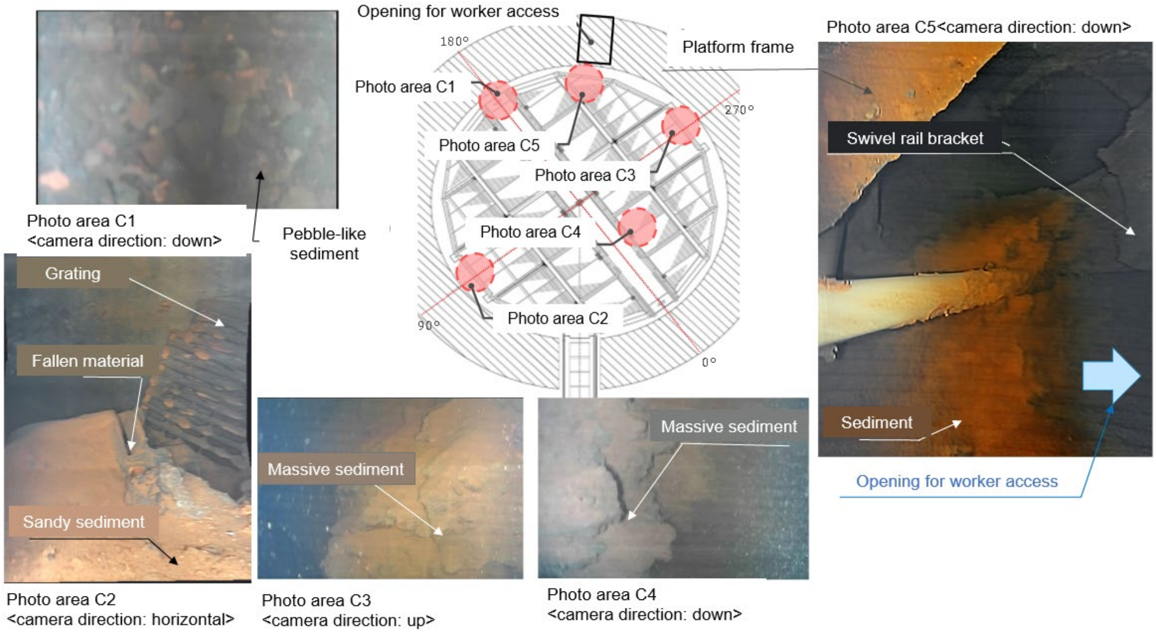


Figure 4.8.3-11 Photos for the bottom of the pedestal captured during the PCV internal investigation [3-15]

4.9. Ninth estimation (March 2018)

4.9.1. Unit 1

The estimation as of March 2018 is shown in Figure 4.9.1-1 and an enlarged version is shown in Figure 4.9.1-2.

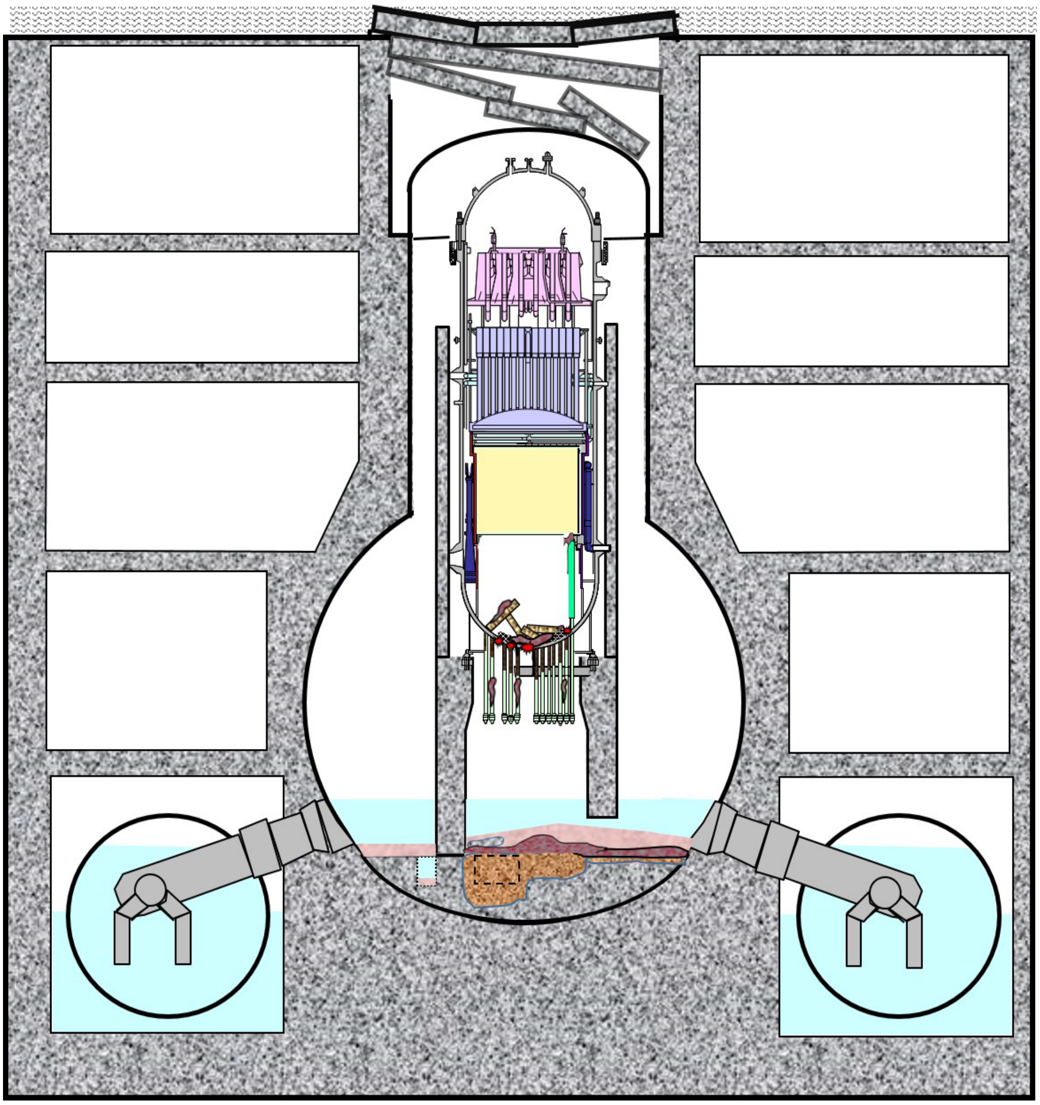


Figure 4.9.1-1 Unit 1 estimation figure as of March 2018 [1-18]

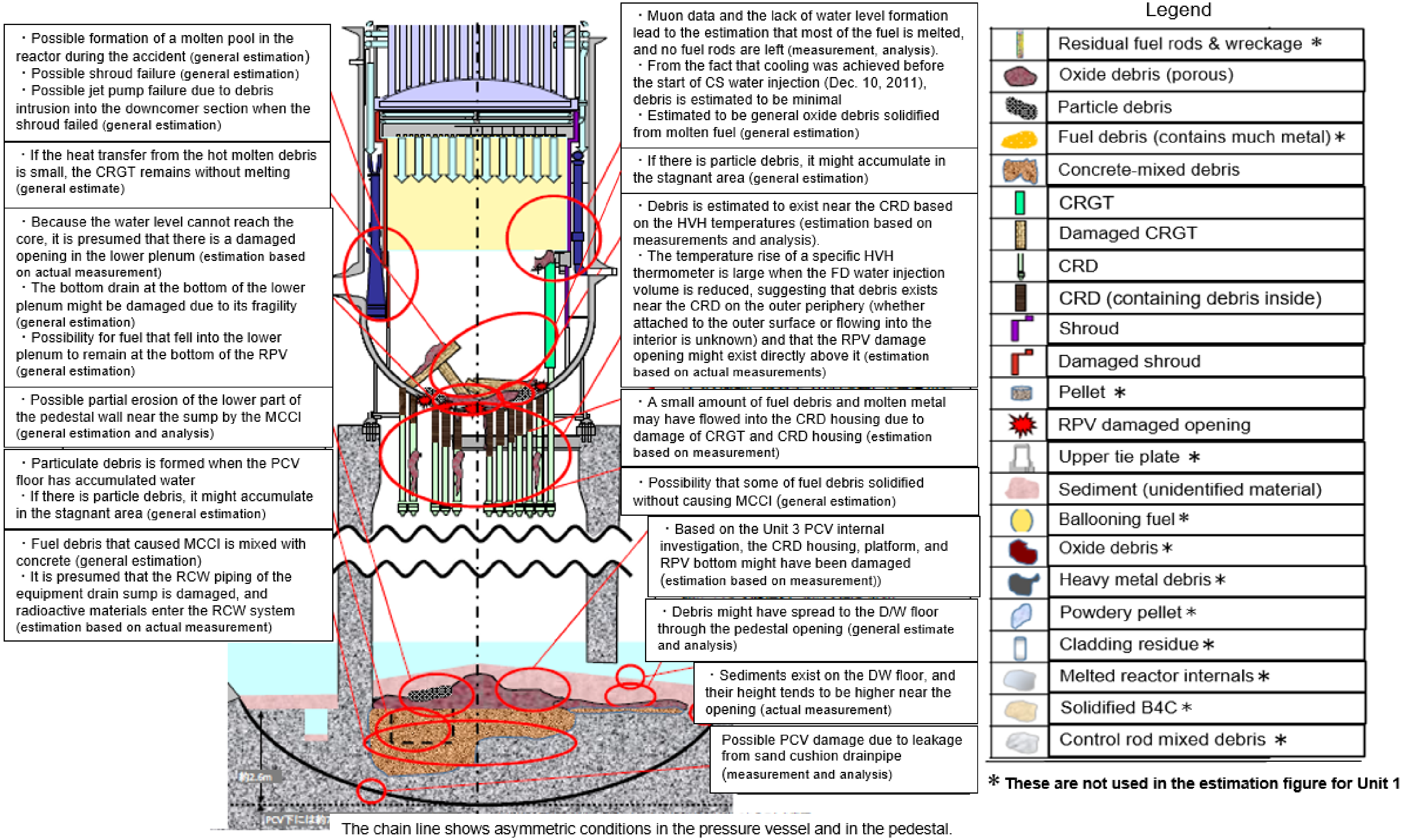


Figure 4.9.1-2 Unit 1 estimation figure as of March 2018 (enlarged)[1-18]

For the estimation in Figures 4.9.1-1 and 4.9.1-2, the characteristics of the estimation, the contents updated from the eighth estimation, and the reasons used in the estimation are as follows.

○ Characteristics of estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and almost none remained in the original core area. It is estimated that most of the fuel debris that fell into the lower plenum fell into the bottom of the PCV.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the process of fuel melting and falling, and fuel debris has penetrated into the CRD housings under the RPV.

It is estimated that unknown matter sediments are deposited at the bottom of the PCV.

○Contents updated from the eighth estimation

① Updated description based on the asymmetry of the status in the RPV and PCV (decreased number of CRGTs remaining in the RPV, updated description of the concrete mixed debris).

② Clear indication of the possibility of shroud damage.

③ Decreased amount of fuel debris entering the CRD housings.

④ Changed height of sediment deposits.

○ Reasons for updating from the eighth estimation

① Updated description based on the asymmetry of the status in the RPV and PCV (decreased number of CRGTs remaining in RPV, updated description of the concrete mixed debris).

As shown by the results of the PCV internal investigation and muon measurements of multiple units including Unit 1, the status inside the RPV and PCV is asymmetric. In order to reflect this situation in the estimation figure, the estimation figure was updated by assuming that there are places in the RPV where the CRGTs remain in the outer periphery and places where they do not. The description of concrete erosion by fuel debris at the bottom of the PCV was also updated to reflect the estimation that erosion around the sump at the bottom of the PCV is expected to be particularly progressed.

② Clear indication of the possibility of shroud damage.

Figure 4.9.1-3 shows the temperature change in the shroud evaluated with the SAMPSON code. The water level outside the shroud quickly decreased due to decay heat and heat from the water-zirconium reaction. The shroud reached its melting temperatures due to radiation heat from the fuel debris.

In Unit 1, water injection by fire trucks could not be performed at the time of fuel damage and melting, so the shroud was not cooled by water outside it, and the shroud was thought to become hotter due to the effect of heat transfer from the fuel that had risen in temperature or from the molten fuel. Since the strength of steel decreases with increasing temperature, it was estimated that the shroud may have been deformed, broken, or buckled due to the temperature increase.

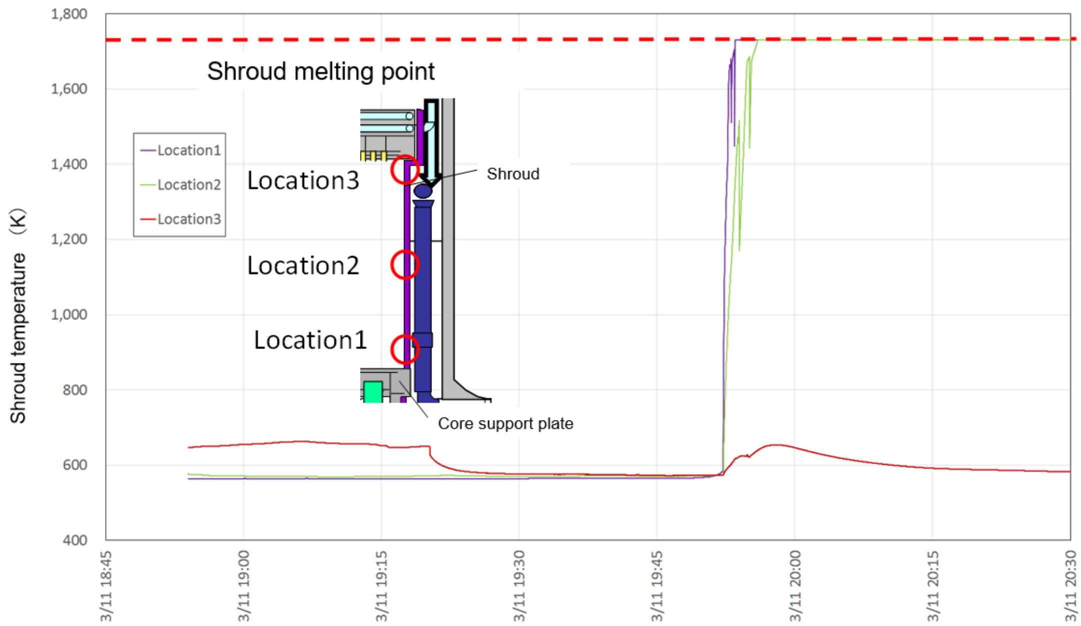


Figure 4.9.1-3 Temperature change of the shroud according to the SAMPSON code [1-18]

③ Decreased amount of fuel debris entering the CRD housings.

If the CRGTs and CRD housings are eroded by fuel debris in the lower part of the RPV, it is possible that fuel debris has penetrated inside the CRD piping. According to the results of the KAERI test described in Section 4.7.2, the molten CRD housings themselves penetrated into the CRD piping before the fuel debris penetrated into the piping. In addition, the CRD housings have a shape for which it is difficult to dissipate heat due to the low vertical heat conduction, so they are considered to be easily eroded when they come into contact with hot molten fuel.

The higher the temperature of the molten fuel debris, the easier it is to maintain fluidity and the longer it is expected to penetrate into the CRD piping. If the decay heat of the fuel debris that has penetrated into the CRD piping is high, the fuel debris may penetrate deeper into the CRD piping while melting. On the other hand, if water remains inside the CRD piping, contacting water with the fuel debris is considered to cool the fuel and reduce its fluidity, making the penetration into the interior less likely to proceed.

If the decay heat per volume of fuel debris is small due to factors such as the presence of metallic components or the release of volatile FPs, the volume inside the CRD piping is small, so the amount of heat generated is also limited, and the fuel debris may solidify and remain inside the piping due to the balance with the amount of heat released from the CRD housing.

Based on the above contents, the amount of fuel debris entering the CRD housings was reduced in Unit 1 in conjunction with the reduction of the amount of fuel debris entering the CRD housings in Unit 2, as described in Section 4.9.2.

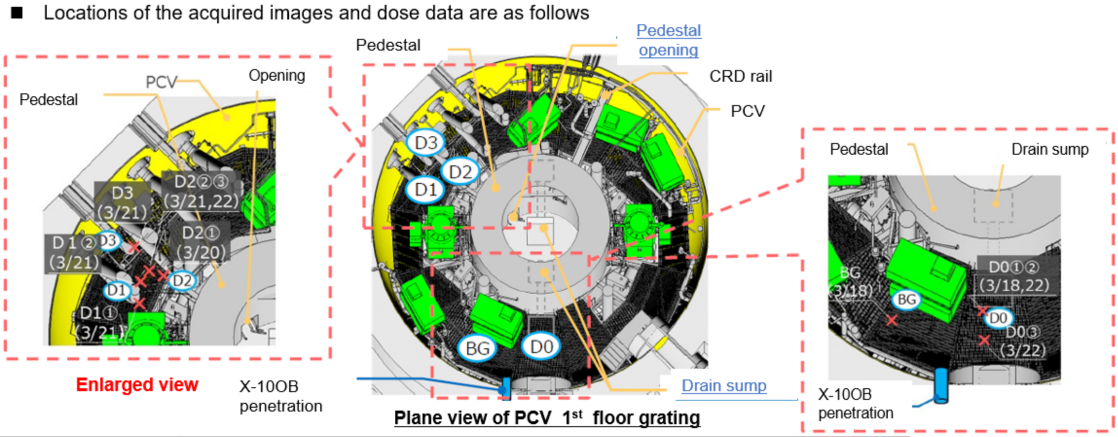
In Unit 1, the fuel debris in the lower plenum contained more energy than in other units because the accident progressed more quickly than in other units and the fuel debris migrated to the lower plenum during a high decay heat condition, and cooling by water injection from fire trucks could not be performed between the core meltdown and the RPV failure period. Therefore, it is estimated that the fuel debris in the lower plenum contained more energy than in other units, and it is considered that the fuel debris penetrated into the CRD piping more easily than in other units.

Therefore, the amount of penetration was depicted to be the highest among Units 1-3.

④ Changed height of sediment deposits.

The investigation robot was deployed from the X-100B penetration to investigate the D/W floor from March 18 to March 22, 2017. Figure 4.9.1-4 shows the measurement points and Figure 4.9.1-5 shows the image taken at the lowest point at each investigation point. The deposits identified during the October 11, 2015 investigation when the CCD camera was inserted from the X-100B penetration were again identified near the floor drain sump, located on the opposite side to the pedestal opening. Similar matter was also observed near the pedestal opening. Figure 4.9.1-6 shows the estimation for the sediment deposit surface height at each investigation point. The surface height was about 0.3m on the opposite side of the pedestal opening, but the maximum surface height of about 1.0m was observed near the PLR piping near the pedestal opening.

■ Images acquired during the PCV internal investigation in March 2017 were clarified to see if any new findings could be obtained, and the presence or absence of debris spread through the pedestal opening was estimated from the acquired dose data
■ Locations of the acquired images and dose data are as follows



Measuring point	Purpose of setting measurement points
D0 ① - ③	Estimating the presence or absence of fuel debris spreading from the drain sump
BG	Understanding the background level for DO-D3 measurements
D1 ① ②, D1 ① - ③	Estimating the presence or absence of fuel debris dispersion from the pedestal opening
D3	Estimation of the possibility of fuel debris reaching the PCV shell

Note:
Measuring date
(MM/DD)

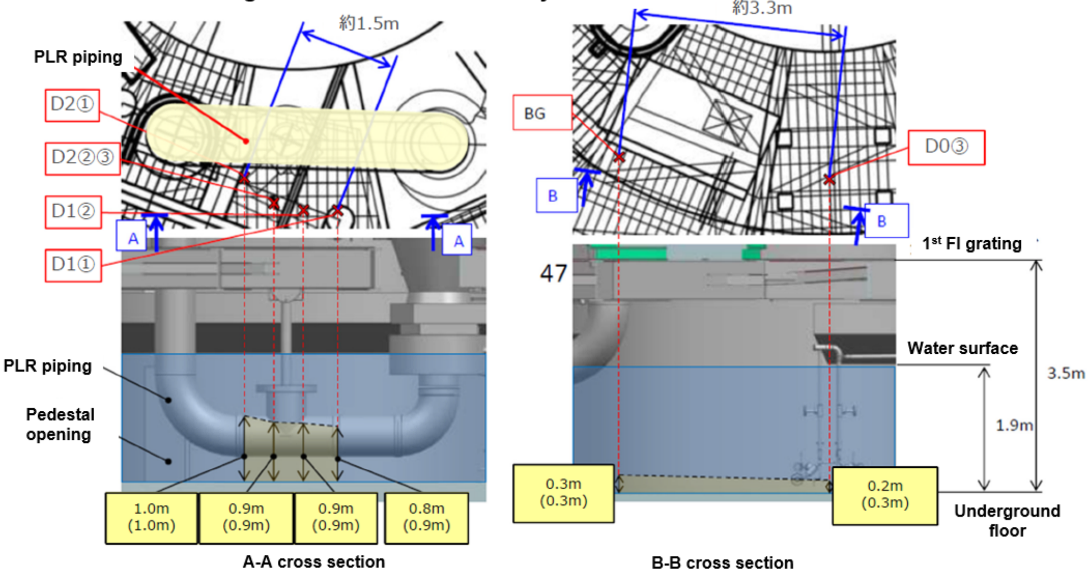
Figure 4.9.1-4 PCV internal investigation points [1-21]

■ Data other than D0② points were also clarified.
■ A new fallen material was confirmed at the D2③ point, but no new information was obtained at the D0 and D1 points.

	D0③ point	D1② point	D2③ point
Original image			
After clarification			

Figure 4.9.1-5 Images taken at the lowest point for each investigation point [1-21]

■ **Evaluation result of the height of the sediment surface by video ＊1**



＊1: The distance between the sensor and the sediment surface was calculated by SFM (Structure from Motion), and the height of the sediment surface was evaluated by combining the amount of sensor descent.

- The numbers in the yellow frame are the estimated heights of the sediment surface calculated by image analysis.
- The number in ( ) is the height of the lowest hanging point of the sensor.
- The thickness of the sediment below the surface of the sediment was not confirmed.

Figure 4.9.1-6 Estimated sediment deposit surface height for each investigation point [1-21]

○ Information supporting the estimation

None.

4.9.2. Unit 2

The estimation as of March 2018 is shown in Figure 4.9.2-1 and an enlarged version is shown in Figure 4.9.2-2.

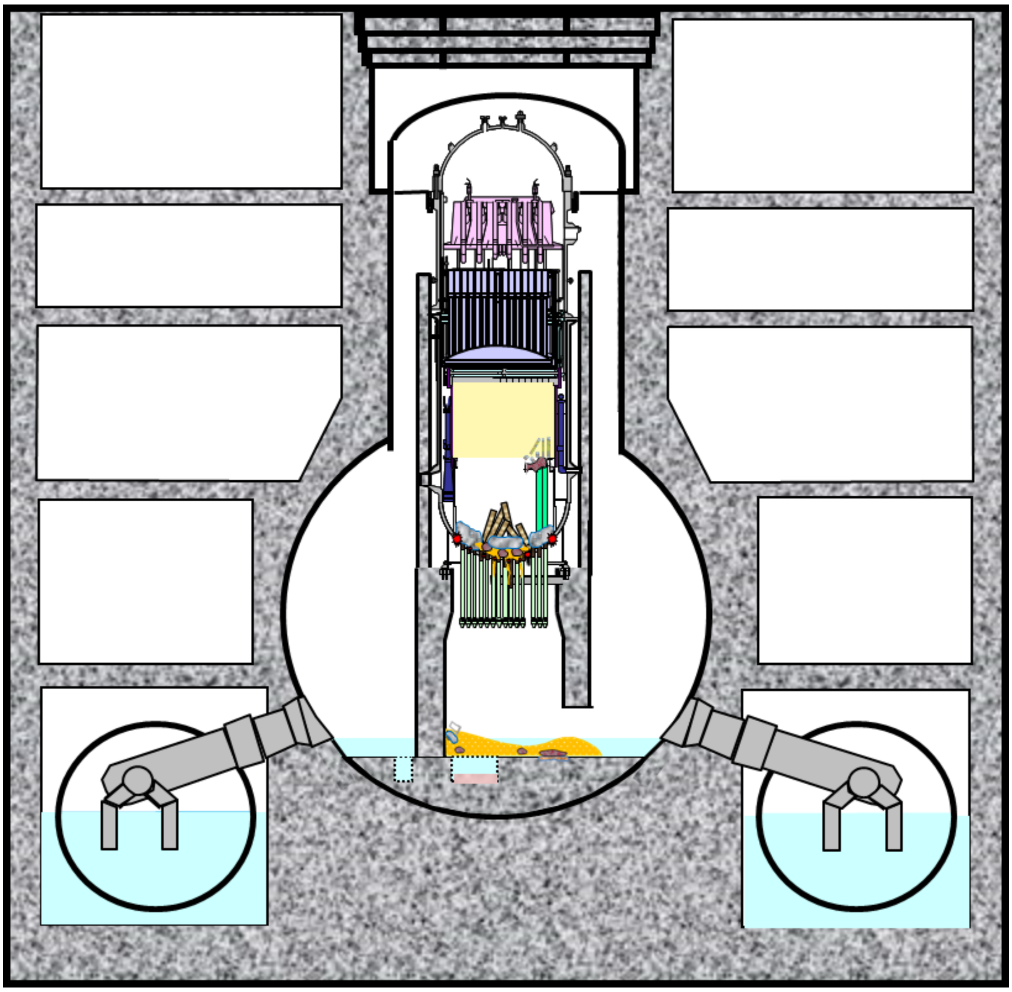
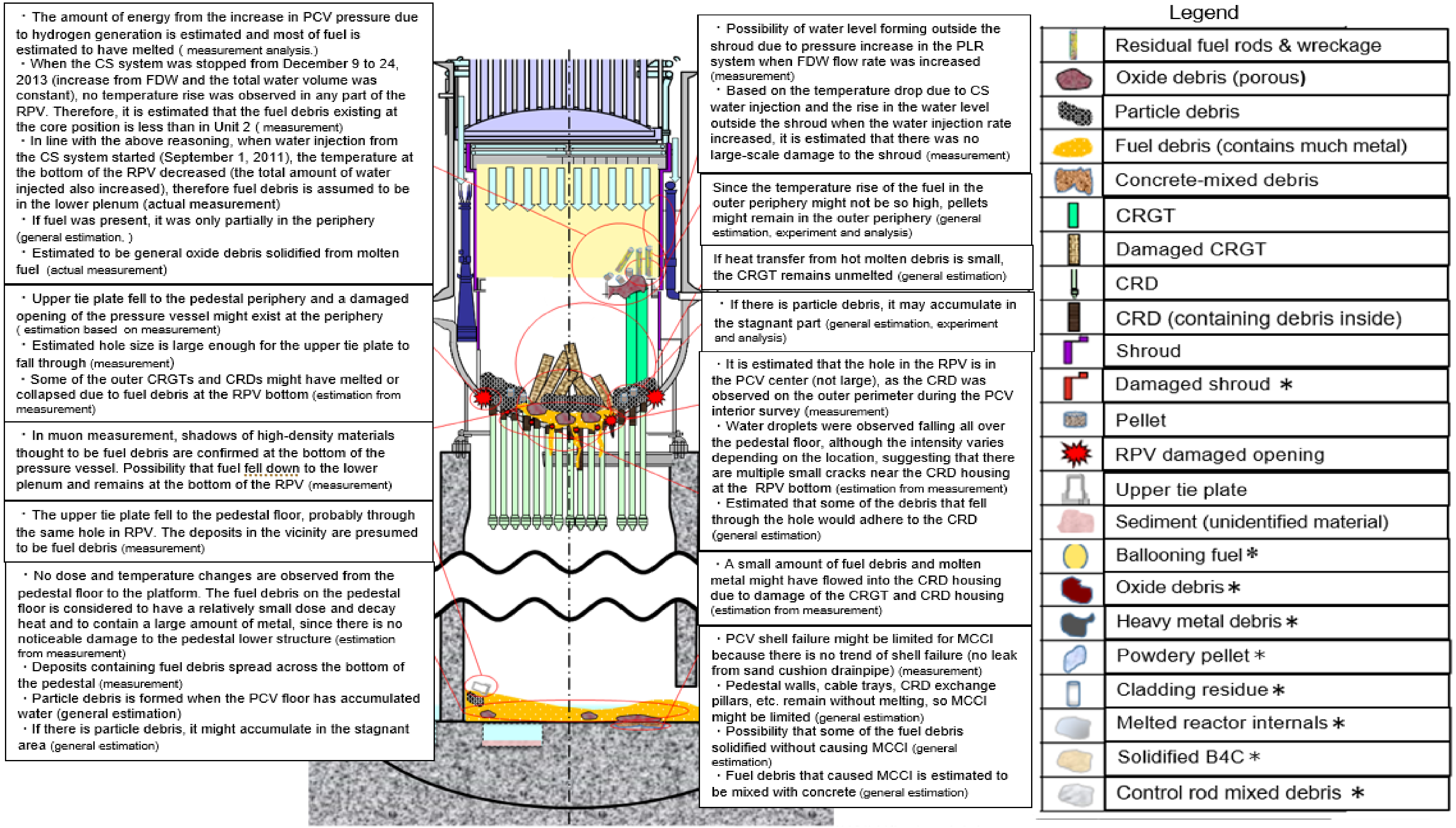


Figure 4.9.2-1 Unit 2 estimation as of March 2018 [2-19]



The chain line shows asymmetric conditions in the pressure vessel and in the pedestal.

＊These are not used in the estimation figure for Unit 2

Figure 4.9.2-2 Unit 2 estimation figure as of March 2018 (enlarged) [2-19]

For the estimation in Figures 4.9.2-1 and 4.9.2-2, the characteristics of the estimation, the contents updated from the eighth estimation, and the reasons for the update from the eighth estimation are as follows.

○Characteristics of estimation

The estimation of the distribution of fuel debris is as follows. Some of the molten fuel fell into the lower plenum of the RPV and some fell into PCV after the accident. In the RPV, some of the fuel remains in the core and most of it is in the bottom of the RPV. The amount of fuel debris that fell into the PCV is considered small, and the extent of MCCI is limited.

Estimation of the fuel debris that fell to the bottom of the PCV includes the metal structures in the RPV and PCV that have melted and solidified.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the process of falling molten fuel, and that fuel debris has penetrated into the CRD housings under the RPV.

○ Contents updated from the eighth estimation

① Updated the description based on the asymmetry of the status in the RPV and PCV (number of CRGTs remaining in the RPV is reduced).

② Changed the depiction of the fuel remaining in the core section.

③ Added damage openings near the CRD housings at the bottom of the RPV and at the outer periphery.

④ Some of the CRGTs in the outer periphery and CRDs may have melted or collapsed due to debris accumulated in the bottom of the RPV.

⑤ Fuel debris containing a lot of metal was added in the RPV and the bottom of the PCV.

⑥ Decreased the amount of fuel debris entering the CRD housings.

⑦ Fuel debris distribution at the bottom of the PCV was updated and reactor internal structure was added.

⑧ Reduced the extent of erosion of concrete by MCCI, since it is considered that fuel debris may have solidified without causing much MCCI.

○ The reasons for the update from the eighth estimation

① Updated the description based on the asymmetry of the status in RPV and PCV (number of CRGTs remaining in the RPV is reduced).

As can be understood from the PCV internal investigation results and muon measurements described in Section 4.7.2, the status inside the RPV and PCV is asymmetric. In order to reflect this situation in the estimation figure, it was updated by assuming that there are places inside the RPV where the CRGTs remain in the outer periphery and places where they do not remain.

② Changed the depiction of the fuel remaining in the core section.

As shown in Figure 4.6.2-2, the description stated that there was a possibility that some fuel remained in the outer periphery of the core in a completely undamaged state, although it was not in a completely sound state. However, it is considered unlikely that the fuel remaining in the outer periphery of the core is in the original state due to thermal effects, etc., as shown in the results of the simulated fuel assembly failure test described in Section 4.7.2, and the wording in the legend used was changed to "residual fuel rods and their broken remains" to describe them.

③ Added damage openings near the CRD housings at the bottom of the RPV and at the outer periphery.

Images obtained during the PCV internal investigation in January 2018 (Figure 4.9.2-3) show water droplets falling all over the floor inside the pedestal. In addition, based on the results of the muon measurements described in Section 4.7.2, most of the fuel debris is thought to have fallen and remained in the lower plenum, and it is quite possible that the bottom of the RPV has been damaged by the heat from the fuel debris.

Based on this information, it is possible that there are several small damage openings near the CRDs at the bottom of the RPV.

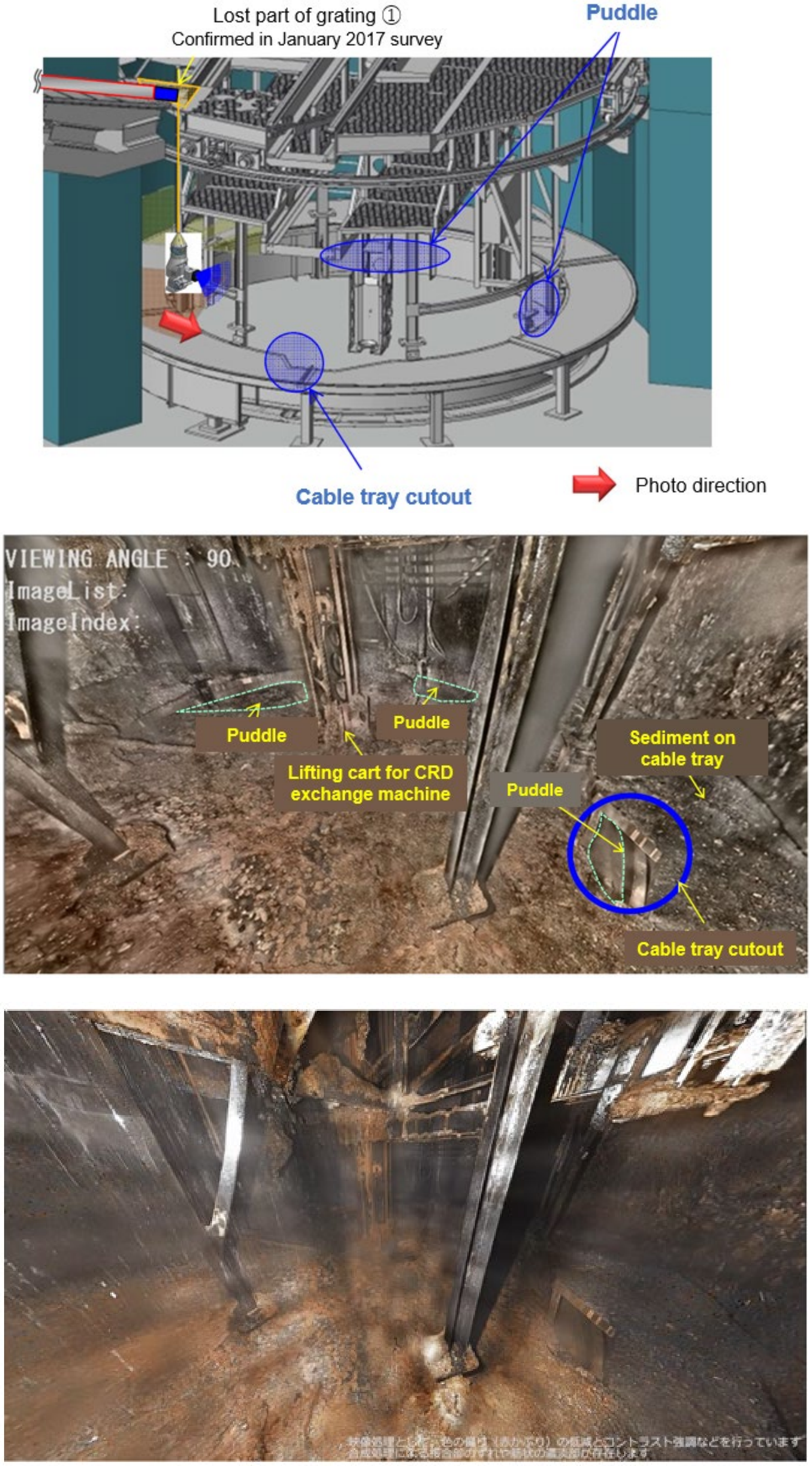


Figure 4.9.2-3 Images of the inside of the pedestal of Unit 2 (1/3) [2-21][2-22]

Images obtained during the PCV internal investigation conducted in January 2018 using a guide pipe and telescopic survey equipment (Figures 4.9.2-4 and 4.9.2-5) show that the upper tie plate of the fuel assembly has fallen to the floor inside the pedestal. Therefore, it is considered that at least a hole large enough for the upper tie plate to fall through was formed in the RPV. In addition, since the location of the fallen object was near the inner wall of the pedestal and the result of confirming the upper pedestal as shown in Section 4.7.2 indicates that the CRDs remained in the outer periphery, it is possible that the upper tie plate fell through the damage opening formed outside the area where the CRDs are located at the bottom of the RPV.

Based on the above, damage openings were added near the CRD housings at the bottom of the RPV and at the outer perimeter.

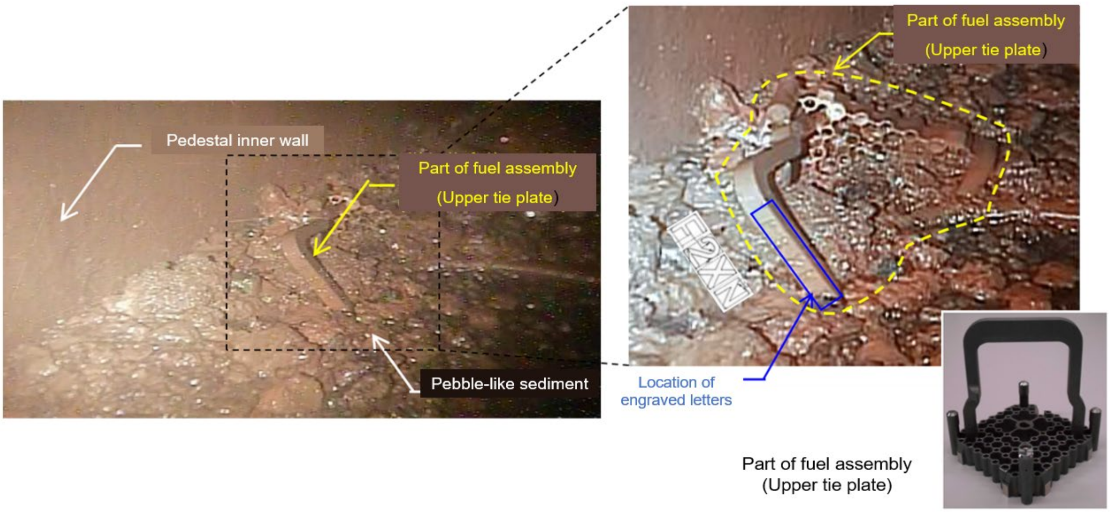


Figure 4.9.2-4　Images of the inside of the pedestal of Unit 2 (2/3) [2-21]

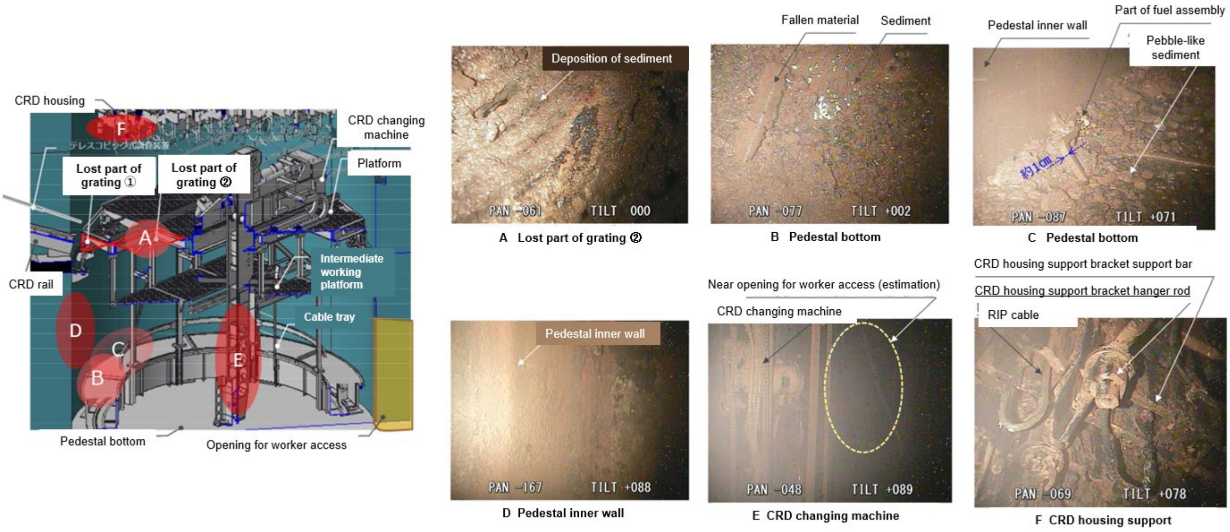


Figure 4.9.2-5　Images of the inside of the pedestal of Unit 2 (3/3) [2-23]

④ Some of the CRGTs in the outer periphery and CRDs may have melted or collapsed due to debris accumulated in the bottom of the RPV.

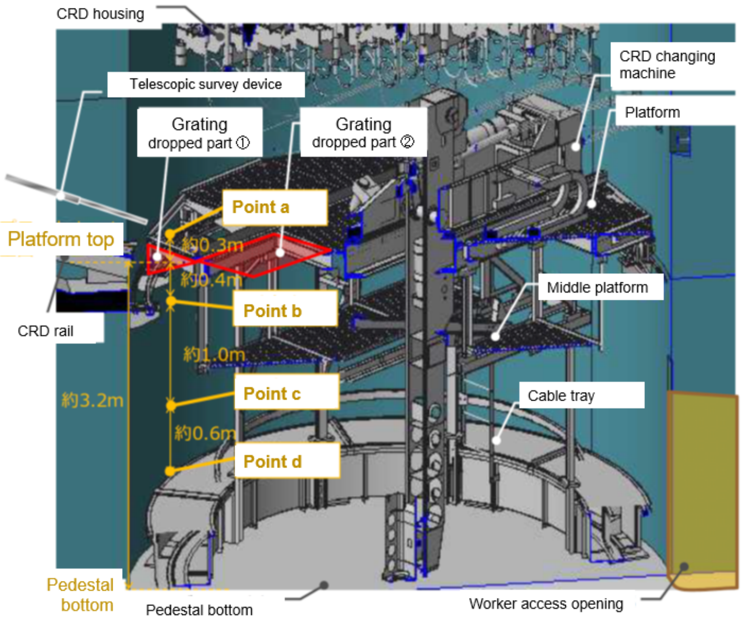
Findings obtained during the PCV internal investigation conducted in January 2018 confirmed that debris was spread over the entire inside floor of the pedestal and that there was a distribution in the debris deposition height. In particular, it is possible that a relatively large amount of debris fell at a high deposition height and then spread over the inner pedestal floor. Looking at the distribution of the debris accumulation height, it is estimated that a damage opening of a size that allows at least the upper tie plate to pass through was formed around the periphery of the bottom of the RPV, above the fuel assembly tie plate, because the accumulation was unevenly distributed around the pedestal interior and the upper tie plate was confirmed to be inside the pedestal.

It is also possible that the path for the upper tie plate to reach the damage opening was formed by the melting and collapse of a CRGT in the outer periphery and the CRD.

Based on the above, the CRGTs in the outer periphery (left side of the figure) and CRDs were removed.

⑤ Fuel debris containing a lot of metal was added in the RPV and the bottom of the PCV.

Images obtained during the PCV internal investigation conducted in January 2018 using a guide pipe and telescopic survey equipment (Figures 4.9.2-4 and 4.9.2-5) showed that the upper tie plate of the fuel assembly had fallen to the floor inside the pedestal. If the fuel debris also fell through the hole through which the upper tie plate fell, the material near the upper tie plate that fell to the floor in the pedestal is considered to be fuel debris. Dose rate and temperature measurements were also taken during the same investigation in January 2018. The measurement results are shown in Figure 4.9.2-6. The results showed that there was almost no change in the dose rate and temperature status from the inner pedestal floor to the platform, and that the values were relatively small (dose, 7 to 8Gy/h; temperature, 21.0°C). In other words, the contribution of the dose from the fuel debris dropped on the floor in the pedestal or as a heat source is considered to be small. There was no noticeable damage to the cable tray or other structures in the pedestal, and the deposits were spread over the entire floor of the pedestal, although some local extremities were observed in the deposit heights. This suggests that the fuel debris fell while at a low temperature and a certain degree of fluidity. In addition, most of the fuel debris in the pedestal is exposed but cooled, suggesting that the decay heat may be relatively low. The fuel debris deposited on the floor of the pedestal may contain a large amount of metal and have a low melting point.



Measuring point	Dose rate *1,2 [Gy/h]	Temp.*2 [℃]
a	7	21.0
b	8	21.0
c	8	21.0
d	8	21.0

Ref: Outside the pedestal*3

Dose rate : Max. 42 [Gy/h]

Temp. : Max 21.1 [℃]

＊1: Calibrated by Cs-137 source

＊2: Errors: dosimeter ±7%; thermometer ±0.5℃

＊3: Reference values as measurements were taken with the instrument housed in the survey equipment.

Figure 4.9.2-6 Results of dose rate and temperature measurements inside the pedestal of Unit 2 [2-21]

⑥ Decreased the amount of fuel debris entering the CRD housings.

In the KAERI test described in Section 4.7.2, the molten CRD housing itself penetrated into the piping before the fuel debris penetrated into the interior. In addition, the CRD housing has a shape for which it is difficult to discharge heat due to its low vertical heat conduction, so the CRD housing is considered to be easily eroded when it comes into contact with hot molten fuel.

The higher the temperature of the molten fuel debris, the more likely it is to remain fluid, and the longer it will penetrate into the CRD piping. If the decay heat of the penetrated fuel debris is high, it may penetrate deeper into the CRD piping while melting the CRD piping.

On the other hand, if water remains inside the CRD piping, water contacting with the fuel debris is considered to cool the fuel and reduce its fluidity, making the penetration into the interior less likely to proceed.

If the decay heat per volume of fuel debris is small due to factors such as the presence of metallic components or the release of volatile FPs, the amount of heat generated is also limited due to the small inside volume of CRD piping and the fuel debris may solidify and remain inside the piping due to the balance with the amount of heat released from the CRD housings.

In Unit 2, the fuel was cooled for about three days by the operation of the RCIC. Therefore, when the fuel debris migrated to the lower plenum, the amount of fuel debris entering the CRD housings was reduced because the decay heat was smaller compared to other units and because alternative water injection was also implemented, so it was considered more difficult for fuel debris to enter the CRD piping than was the case for the other units.

⑦ Fuel debris distribution at the bottom of PCV was updated and reactor internal structure was added.

Images obtained during the PCV internal investigation conducted in January 2018 using a guide pipe and telescopic survey equipment (Figure 4.9.2-3) show sediment deposits spread over the entire pedestal floor. These deposits are considered to contain fuel debris. From Figures 4.9.2.4 and 4.9.2-5, it can be seen that the upper tie plate of the fuel assembly has fallen to the floor in the pedestal. Assuming that the fuel debris also fell through the hole through which the upper tie plate fell, the deposits near the upper tie plate that fell to the floor of the pedestal are considered to be fuel debris. Based on the above, the distribution of fuel debris at the bottom of the PCV was updated and internal reactor structures were added.

⑧ Reduced the extent of erosion of concrete by MCCI, since it is considered that fuel debris may have solidified without causing much MCCI.

Images obtained during the PCV internal investigation conducted in January 2018 using guide pipe and telescopic survey equipment (Figure 4.9.2-3) confirm the presence of the pedestal wall, the cable tray near the wall, and the CRD exchange machine pillar without melting.

In particular, the fact that the cable tray, which is made of stainless steel and is only 4mm thick, remained without melting suggests that the fuel debris had a low temperature and low heat generation density at the time it fell. This may be due to the fact that the accident progressed more slowly in Unit 2 than in Units 1 and 3, and the decay heat of the fuel debris had decreased by the time it fell to the PCV floor, or, as described in ⑤, the fallen fuel debris may have been mainly composed of metal. In order for the fuel debris that fell to the PCV floor to undergo MCCI, the concrete must be heated above its melting point, but the circumstances described above suggest that the fuel debris may have solidified with almost no MCCI. Therefore, the degree of erosion of concrete by MCCI was reduced.

○ Information supporting estimation

None.

4.9.3. Unit 3

The estimation as of March 2018 is shown in Figure 4.9.3-1 and an enlarged version is shown in Figure 4.9.3-2.

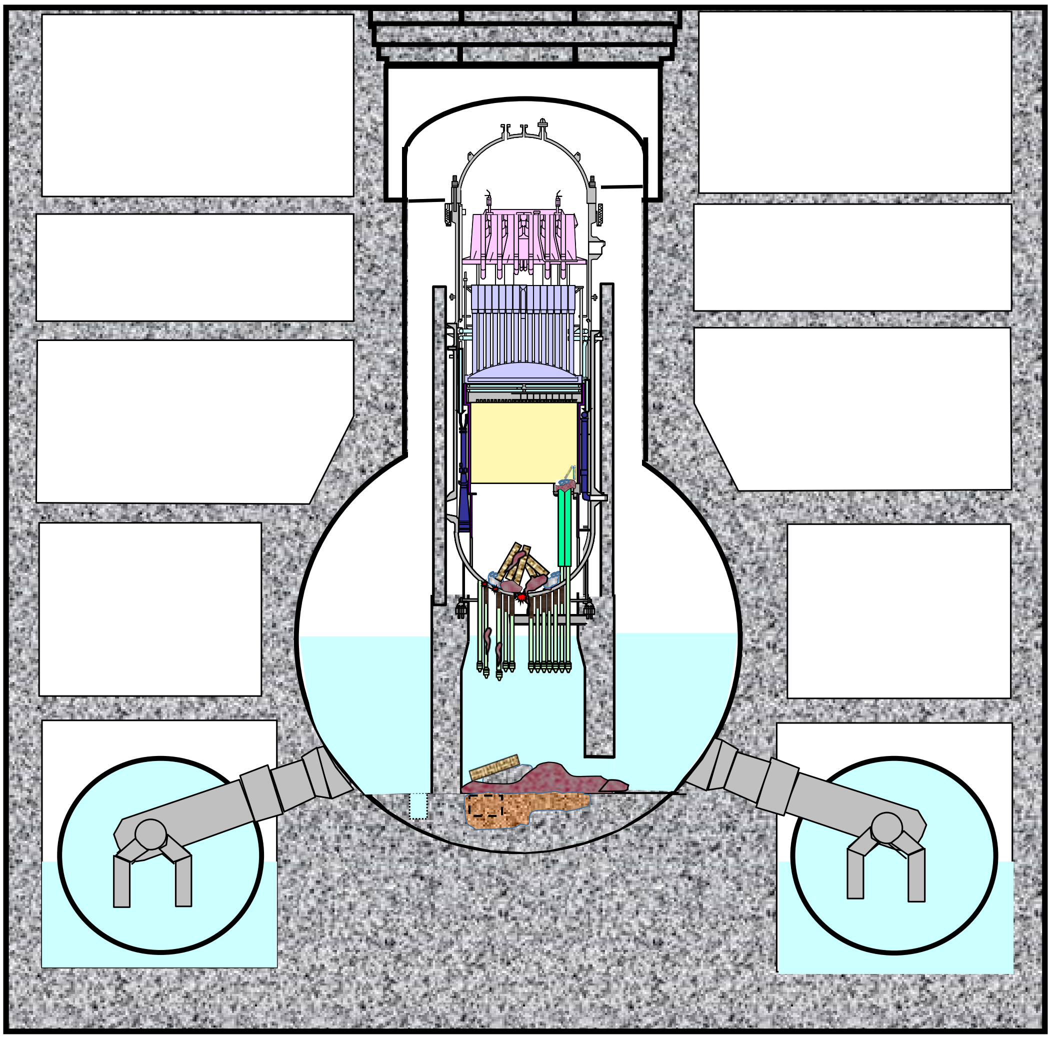


Figure 4.9.3-1 Unit 3 estimation figure as of March 2018 [3-14]

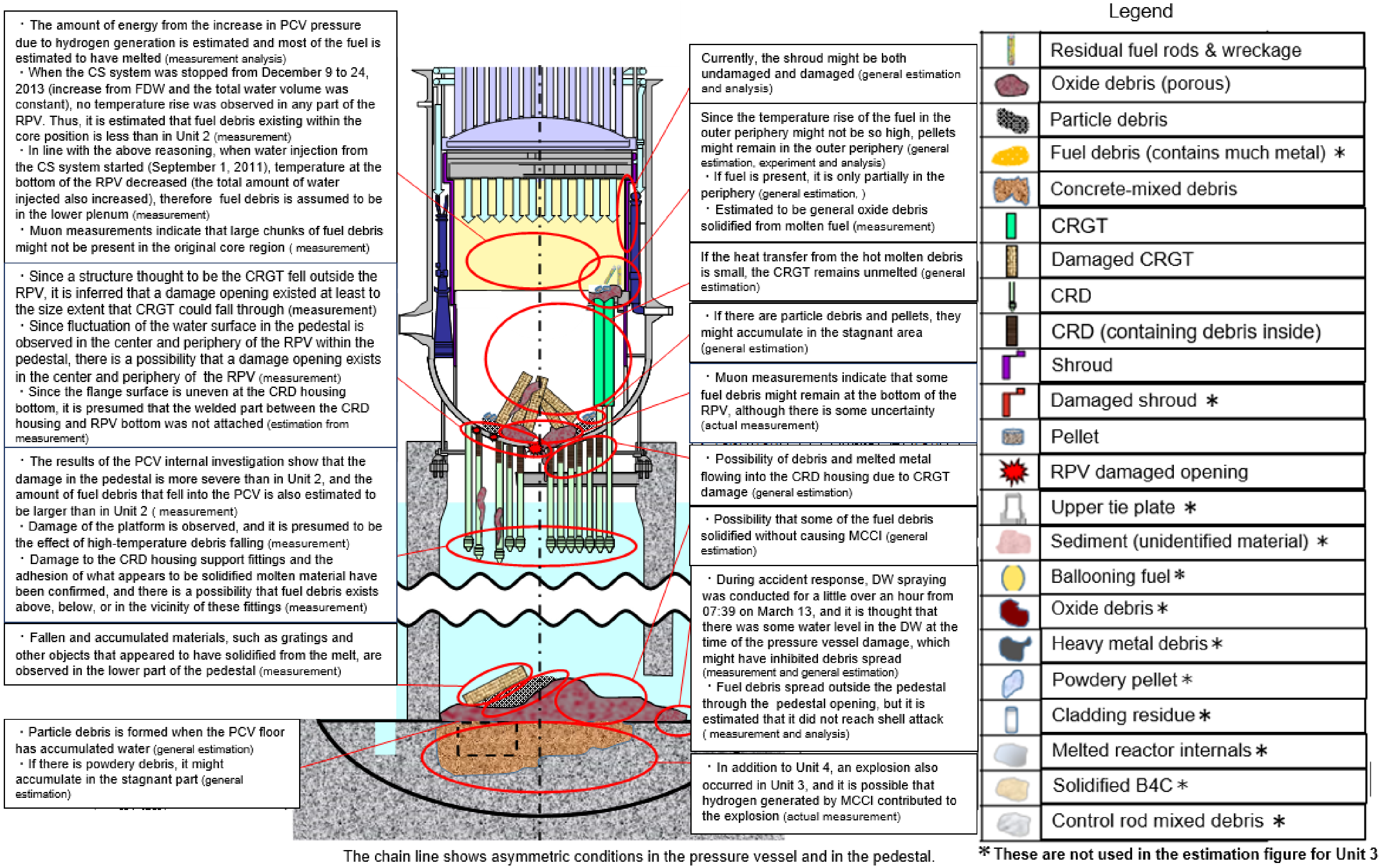


Figure 4.9.3-2 Unit 3 estimation figure as of March 2018 (enlarged) [3-14]

For the estimation in Figures 4.9.3-1 and 4.9.3-2, the characteristics of the estimation, the contents updated from the eighth estimation, and the reasons for the update from the eighth estimation are as follows.

○Characteristics of estimation

The distribution of fuel debris is estimated to be as follows. Molten fuel fell into the lower plenum of the RPV after the accident, and most of it fell further into the PCV. In the RPV, the amount of fuel debris remaining in the core is small, and it is estimated that some fuel debris exists at the bottom of RPV. Although there is a lot of fuel debris that fell into the PCV, it is not spread all over the floor.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of RPV were damaged by the fuel melting and falling down, and that fuel debris has penetrated into the CRD housings under the RPV.

○ Contents updated from the eighth estimation

① Updated depiction based on the asymmetry of the status in the RPV and PCV (decreased number of CRGTs remaining in the RPV, updated depiction of concrete mixed debris).

② Changed the depiction of the fuel remaining in the core section.

③ Decreased the amount of fuel debris entering the CRD housings.

○ The reasons for the update from the eighth estimation

① Updated depiction based on the asymmetry of the status in the RPV and PCV (decreased number of CRGTs remaining in the RPV, updated depiction of concrete mixed debris).

As can be understood from the PCV internal investigation results and muon measurement results described in Section 4.8.3, the status of the RPV and PCV is asymmetric. In order to reflect this situation in the estimation figure, the estimation figure was updated by assuming that there are places inside the RPV where the CRGTs remain in the outer periphery and places where they do not remain. The depiction of concrete erosion by fuel debris at the bottom of the PCV was also updated to reflect the estimation that erosion around the sump at the bottom of the PCV is expected to be particularly severe.

② Changed the depiction of the fuel remaining in the core section.

As shown in Figure 4.6.3-2, the description stated that there was a possibility that some fuel remained in the outer periphery of the core in a completely undamaged state, although it was not in a completely sound state. However, it is considered unlikely that the fuel remaining in the outer periphery of the core is in the original state due to thermal effects, etc., as shown in the results of the simulated fuel assembly failure test described in Section 4.7.3, and the wording in the legend used was changed to "residual fuel rods and their broken remains" to describe them.

③ Decreased the amount of fuel debris entering the CRD housings.

If the CRGTs and CRD housings are eroded by fuel debris in the lower part of the RPV, it is possible that fuel debris has penetrated inside the CRD piping. According to the results of the KAERI test described in Section 4.7.2, the molten CRD housings themselves penetrated into the CRD piping before the fuel debris penetrated into the piping. In addition, the CRD housings have a shape for which it is difficult to discharge heat due to its low vertical heat conduction, so housings are considered to be easily eroded when hot molten fuel comes into contact.

The higher the temperature of the molten fuel debris, the easier it is to maintain fluidity and the longer it is expected to penetrate into the CRD piping. If the decay heat of the fuel debris that has penetrated into the CRD piping is high, the fuel debris may penetrate deeper into the CRD piping while melting. On the other hand, if water remains inside the CRD piping, water contacting with the fuel debris is considered to cool the fuel and reduce its fluidity, making the penetration into the interior less likely to proceed.

If the decay heat per volume of fuel debris is small due to factors such as the presence of metallic components or the release of volatile FPs, the volume inside the CRD piping is small, so the amount of heat generated is also limited, and the fuel debris may solidify and remain inside the piping due to the balance between the amount of heat released from the CRD housing.

Based on the above contents, the amount of fuel debris entering the CRD housings was reduced in Unit 3 in conjunction with the reduction of the amount of fuel debris entering the CRD housings in Unit 2 as described in Section 4.9.2.

In Unit 3, the fuel was cooled for about 1.5 days due to the operation of the RCIC and HPCI. The timing of the migration of fuel debris into the lower plenum is considered to have been intermediate between Units 1 and 2. Therefore, it is estimated that the energy contained by the fuel debris in the lower plenum was larger than in Unit 2 and smaller than in Unit 1, and the ease of penetration of the fuel debris into the CRD piping was also between the two units.

Therefore, the amount of penetration was depicted to be in the middle between Units 1 and 2.

○ Information supporting the estimation

None.

4.10. Tenth estimation (September 2018)

4.10.1. Unit 1

The estimation as of September 2018 is shown in Figure 4.10.1-1 and enlarged in Figure 4.10.1-2.

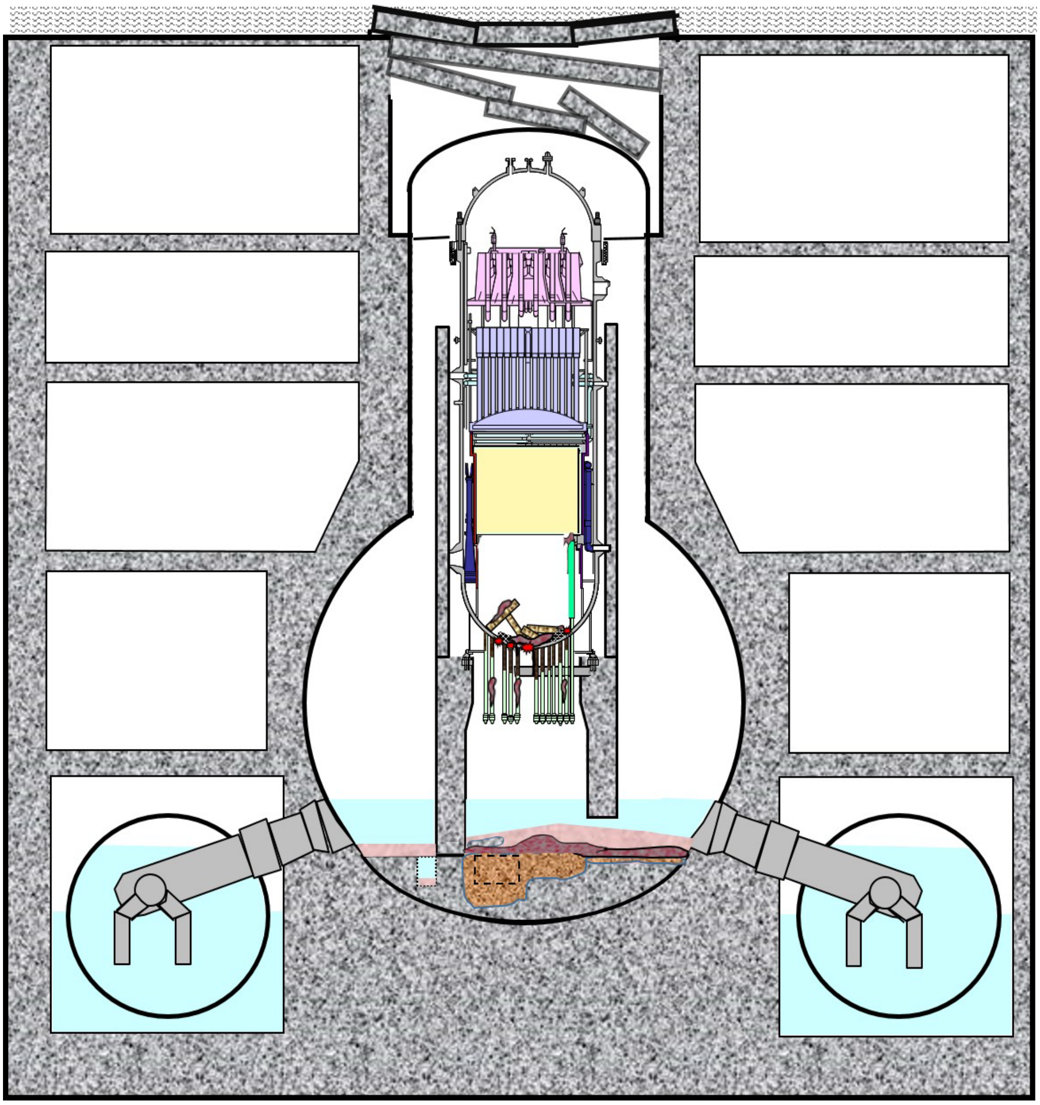


Figure 4.10.1-1 Unit 1 estimation as of September 2018 [1-22]

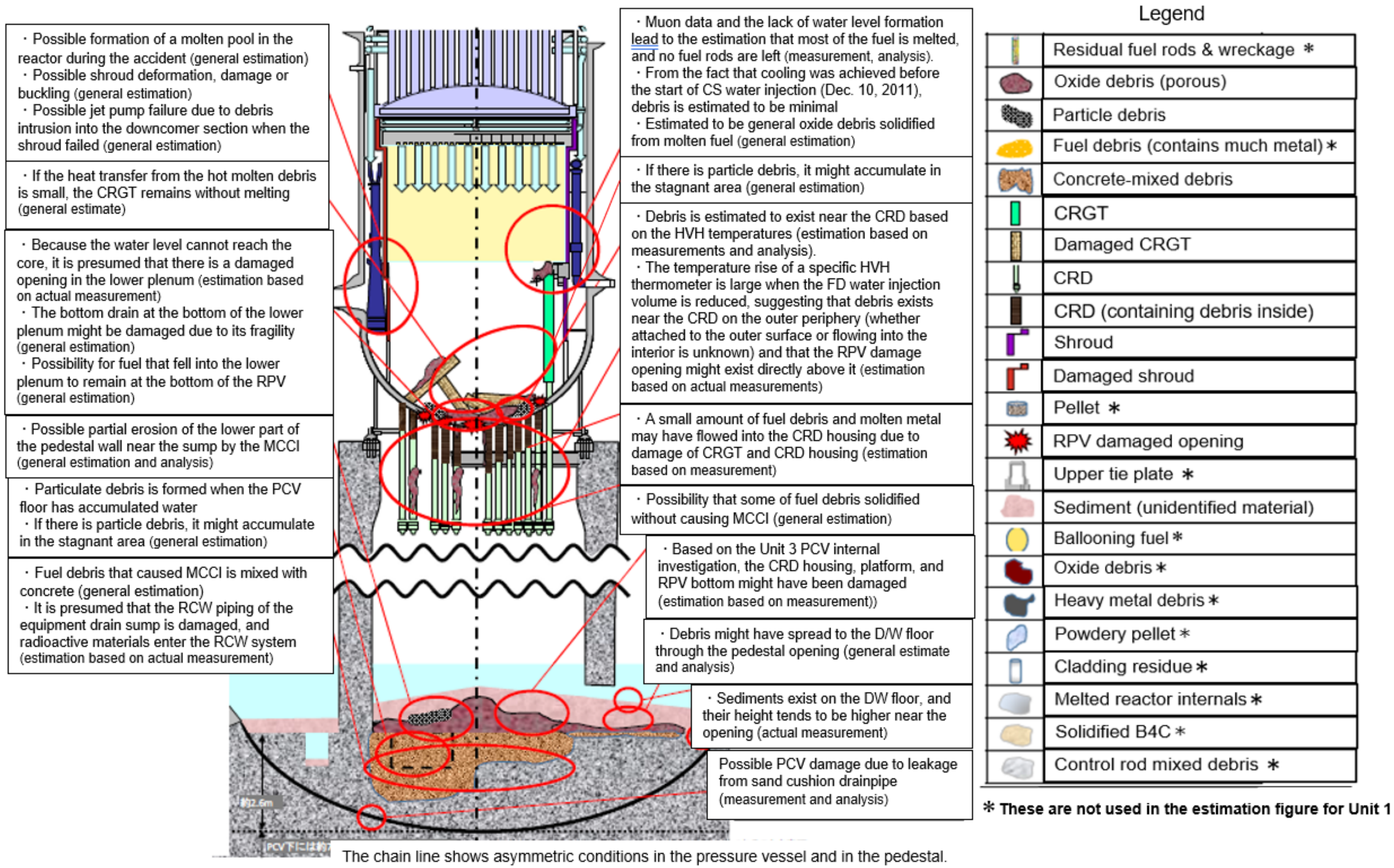


Figure 4.10.1-2　Unit 1 estimation figure as of September 2018 (enlarged) [1-22]

For the estimation in Figures 4.10.1-1 and 4.10.1-2, the characteristics of the estimation are as follows.

○ Characteristics of estimation

Regarding the distribution of fuel debris, after the accident, almost all of the molten fuel fell into the lower plenum of the RPV, and almost none remained in the original core area. It is estimated that most of the fuel debris that fell into the lower plenum fell into the bottom of the PCV.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of RPV were damaged by the process of fuel melting and falling, and fuel debris has penetrated into the CRD housings under the RPV.

It is estimated that unknown materials have accumulated at the bottom of the PCV.

○ Updated contents from the ninth estimation

None.

○ Information supporting the estimation

None.

4.10.2. Unit 2

The estimation as of September 2018 is shown in Figure 4.10.2-1 and an enlarged figure in Figure 4.10.2-2.

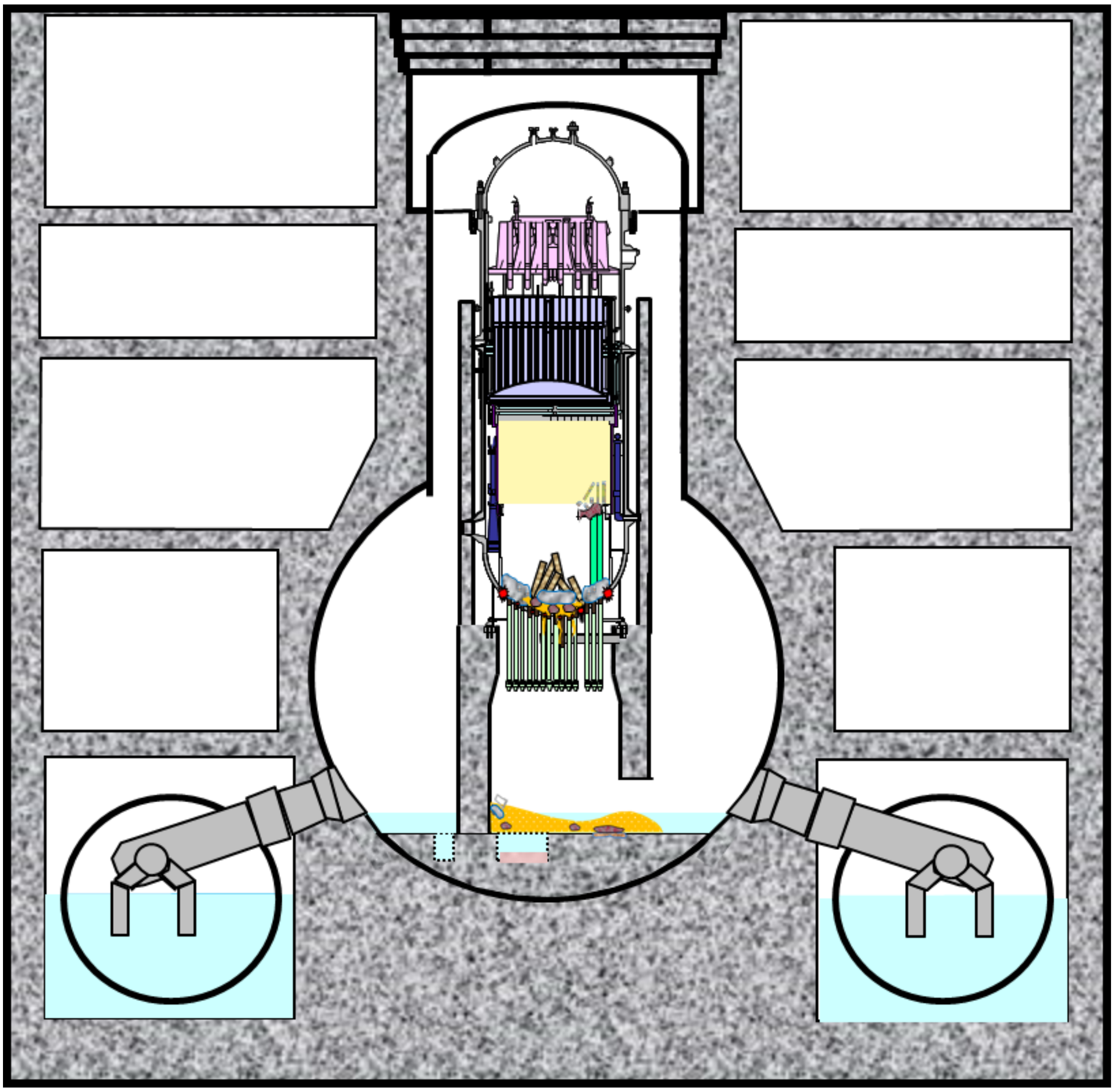


Figure 4.10.2-1 Unit 2 estimation as of September 2018 [2-24]

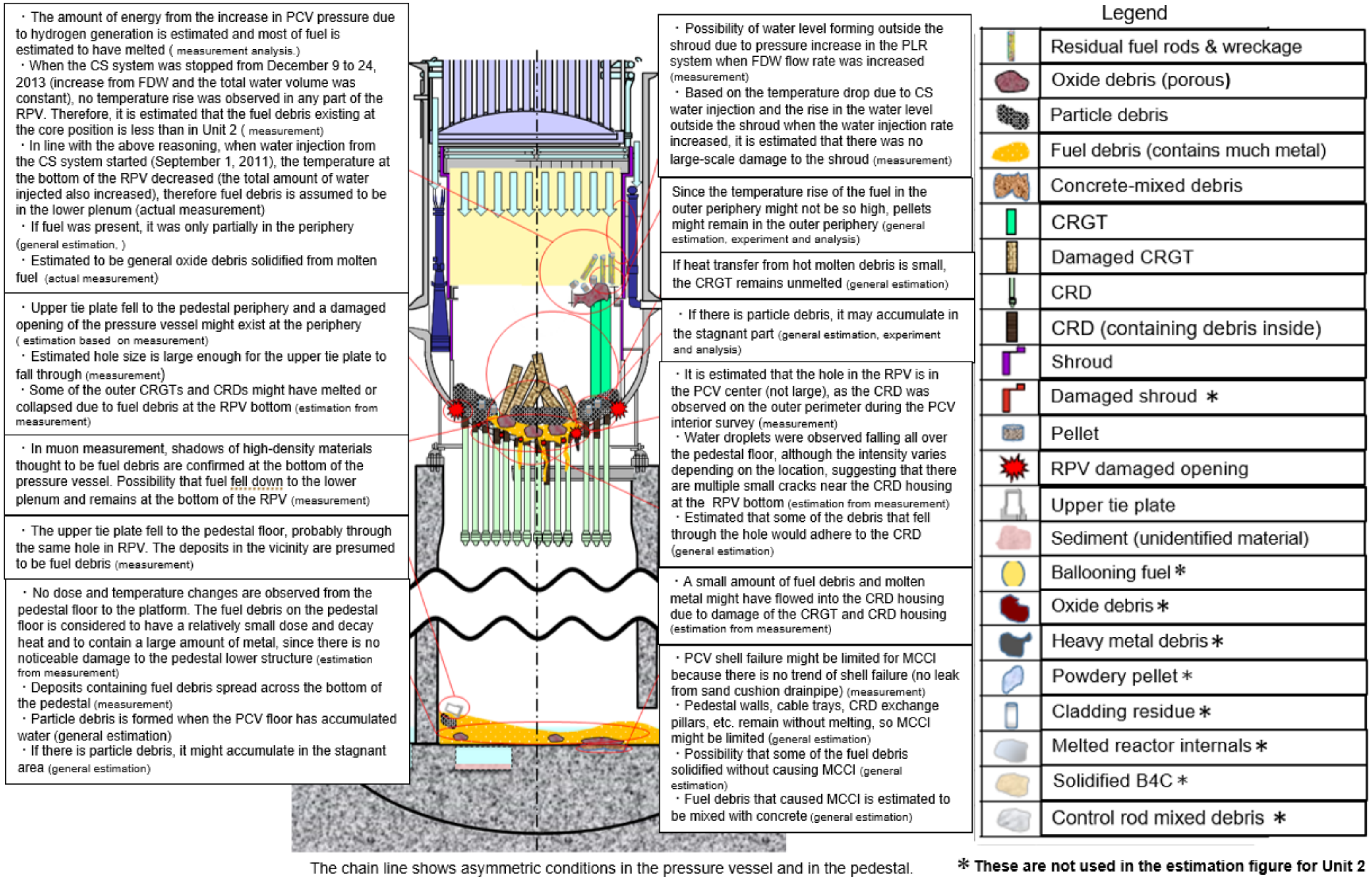


Figure 4.10.2-2 Unit 2 estimation figure as of September 2018 (enlarged) [2-24]

For the estimation in Figures 4.10.2-1 and 4.10.2-2, the characteristics of estimation are as follows.

○ Characteristics of estimation

The estimation of the distribution of fuel debris is as follows. Some of the molten fuel fell into the lower plenum of RPV and some fell into PCV after the accident. In the RPV, some of the fuel remains in the core and most of it is in the bottom of RPV. The amount of fuel debris that fell into the PCV is considered small, and the extent of MCCI is limited.

Estimation of the fuel debris that fell to the bottom of PCV includes the metal structures in the RPV and PCV that have melted and solidified.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the process of falling molten fuel, and that fuel debris has penetrated into the CRD housings under the RPV.

○ Updated contents from the ninth estimation.

None.

○ Information supporting the estimation

None.

4.10.3. Unit 3

The estimation as of September 2018 is shown in Figure 4.10.3-1 and an enlarged version is shown in Figure 4.10.3-2.

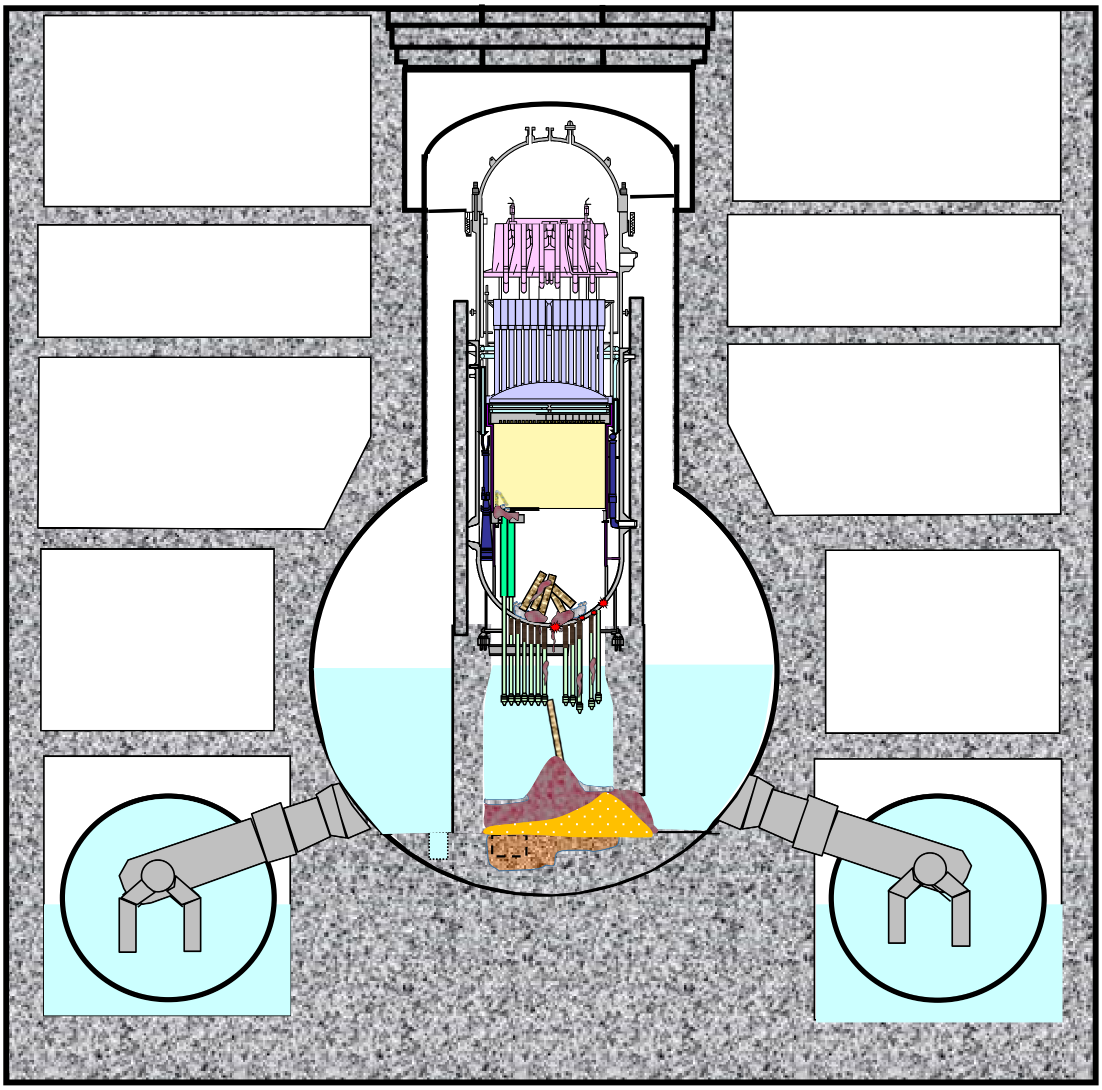


Figure 4.10.3-1 Unit 3 estimation as of September 2018 [3-18]

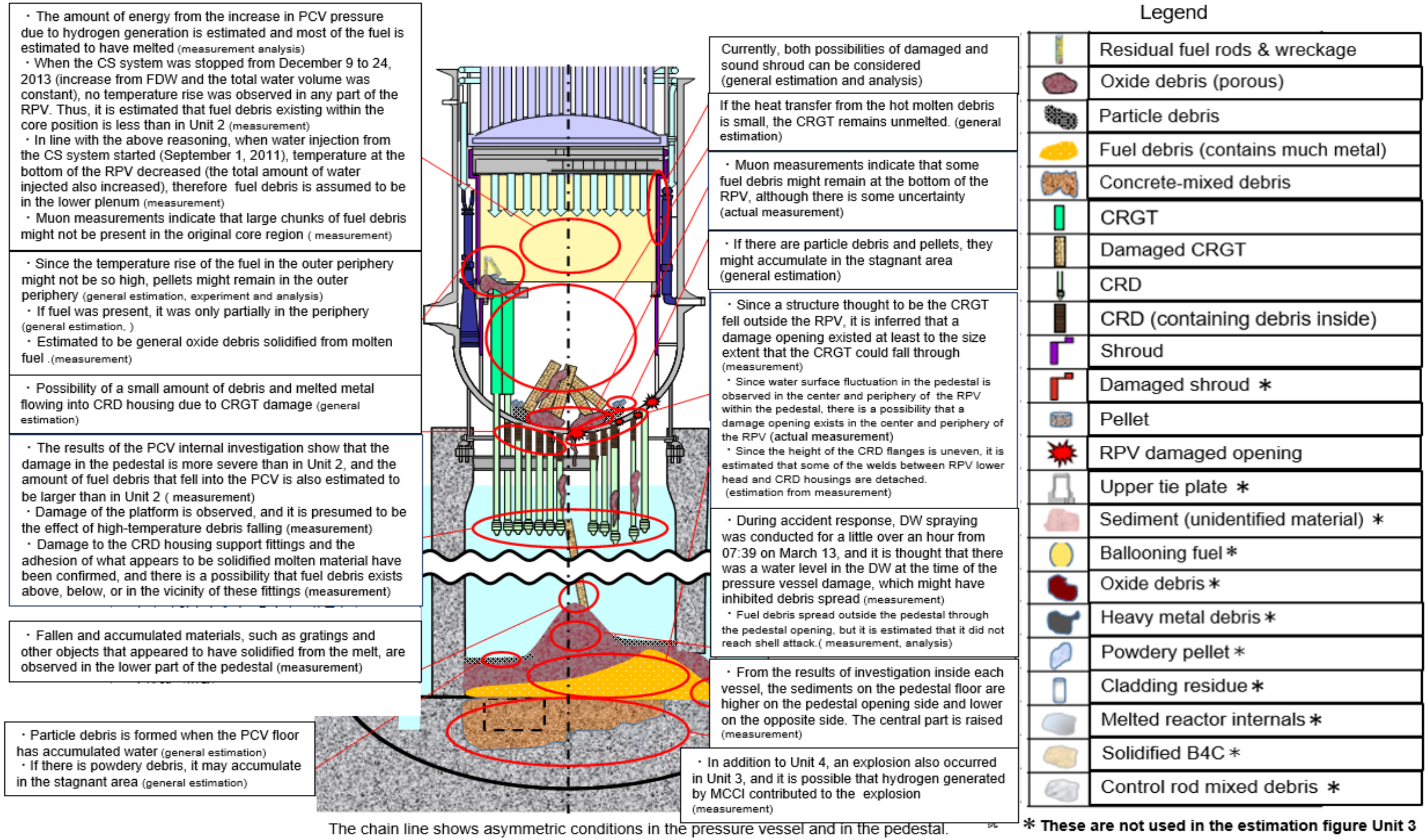


Figure 4.10.3-2 Unit 3 estimation figure as of September 2018 (enlarged) [3-18]

For the estimation in Figures 4.10.3-1 and 4.10.3-2, the characteristics of the estimation, the contents updated from the ninth estimation, and the reasons for the update from the ninth estimation are as follows.

○ Characteristics of estimation

The distribution of fuel debris is estimated to be as follows. Molten fuel fell into the lower plenum of the RPV after the accident, and most of it fell further into the PCV. In the RPV, the amount of fuel debris remaining in the core is small, and it is estimated that some fuel debris exists at the bottom of RPV. Although there is a lot of fuel debris that fell into PCV, it is not spread all over the floor.

Estimation of the fuel debris that fell to the bottom of PCV includes the debris formed by melting and solidification of the metallic structures in the RPV and PCV.

Regarding the status of the structures in the RPV and PCV, it is estimated that the CRGTs at the bottom of the RPV were damaged by the fuel melting and falling down, and that fuel debris has penetrated into the CRD housings under the RPV.

○ Updated contents from the ninth estimation

① Updated status of damaged CRGTs that fell into the PCV.

② Updated distribution of fuel debris deposited at the bottom of the PCV.

③ Updated location of CRGTs remaining in the RPV, and the location where the damage to the CRD housings is described.

○ Reasons for updating from the ninth estimation

① Updated status of damaged CRGTs that fell into the PCV.

Figure 4.10.3-3 shows a 3D reconstructed image of the video obtained from the PCV internal investigation conducted in July 2017. In the left figure, the light blue areas are the structures actually identified, and the right figure depicts each structure in a different color. In the right figure, the yellow-green structure standing near the center indicates an object that is thought to be a CRGT, which fell from the center of the RPV and is leaning against CRD housings. This status is represented in the estimation figure.

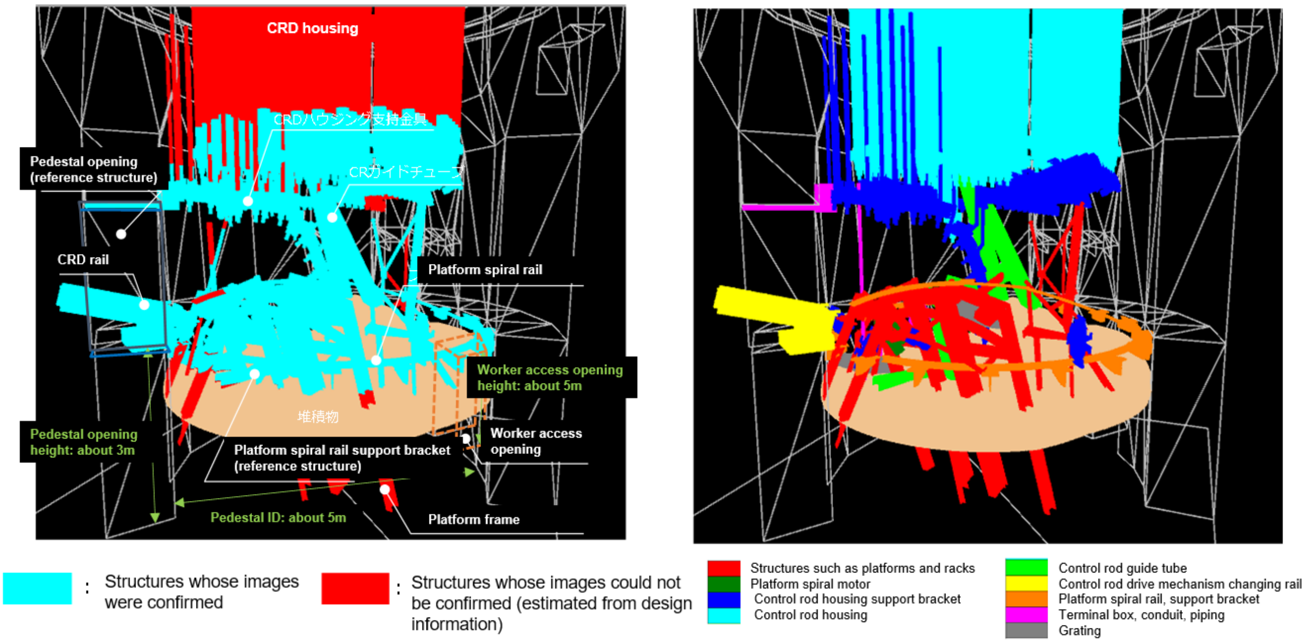


Figure 4.10.3-3 3D reconstructed image of the inside of PCV [3-19]

② Updated distribution of fuel debris deposited at the bottom of the PCV.

The processed 3D reconstruction of the height distribution of sediments at the bottom of the PCV is shown in Figure 4.10.3-4. The greatest height was near the center, and was about 3m from the floor of the PCV. Regarding the height on the inner wall side of the pedestal, it was found that the sediment deposit height tended to be higher in the direction where the worker access opening was located than on the opposite side. This height is considered to be related to the location where the fuel debris fell from the RPV, i.e., the location of the hole at the bottom of the RPV. Therefore, it is assumed that there are damage openings in the RPV near the center and above the worker access opening.

Figure 4.10.3-5 also shows the results of the Unit 2 PCV internal investigation conducted in January and February 2018. As described in Section 4.9.2, although deposits were found to be spread over the entire floor of the PCV, there was no noticeable damage to the cable tray at the bottom of PCV or structures such as pillars, and the deposits are considered to contain little high-temperature fuel components and a large amount of metals.

The deposits that accumulated at the bottom of PCV in Unit 3 exceeds the volume of the total fuel, and it is possible that, in addition to fuel components, the deposits may contain melted and solidified metal structures of the RPV and PCV, as in Unit 2. Therefore, fuel debris containing a large amount of metal was depicted.

The height of sediment deposits near the worker access opening is higher than that on the opposite side of the pedestal inner wall, so the area was depicted as possibly containing more metal-rich fuel debris than on the other side of the pedestal.

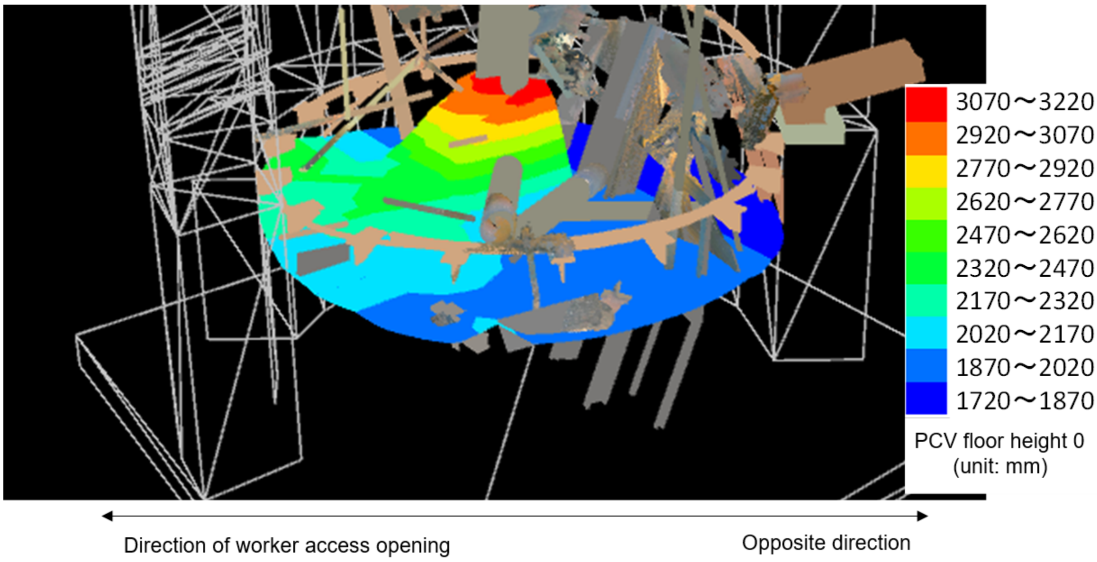


Figure 4.10.3-4　Sediment deposits at the bottom of the PCV [3-3]

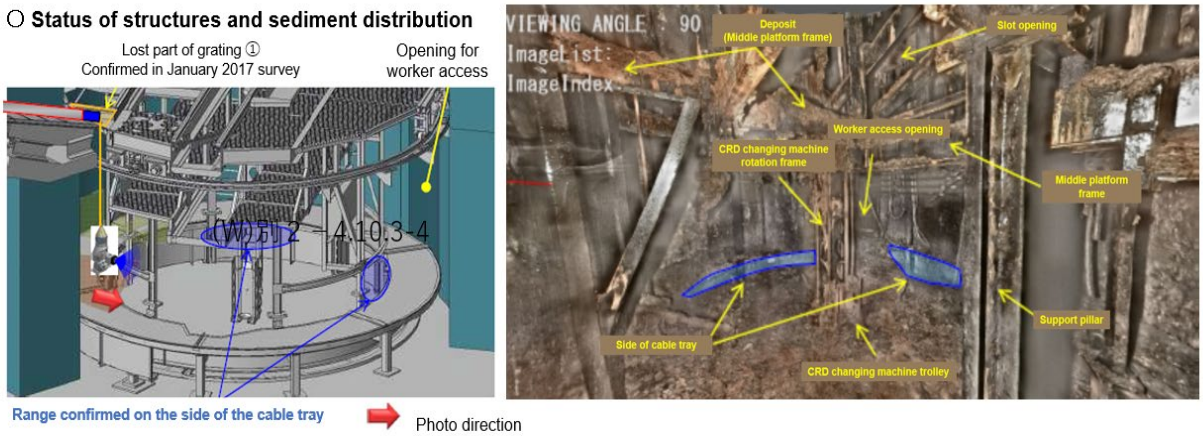


Figure 4.10.3-5　Results of the PCV internal investigation at Unit 2 [3-20]

③ Updated location of CRGTs remaining in the RPV, and the location where damage to the CRD housings is described.

As described in ②, there is a possibility that the damage opening of the RPV is located above the worker access opening, and the estimation figure was updated to depict the remaining CRGTs in the outer periphery as possibly being damaged by fuel debris. Based on the same idea for the damaged (fallen down) area of the CRD housings, the estimation figure was updated to depict the upper part of the worker access opening as possibly damaged.

○ Information supporting the estimation

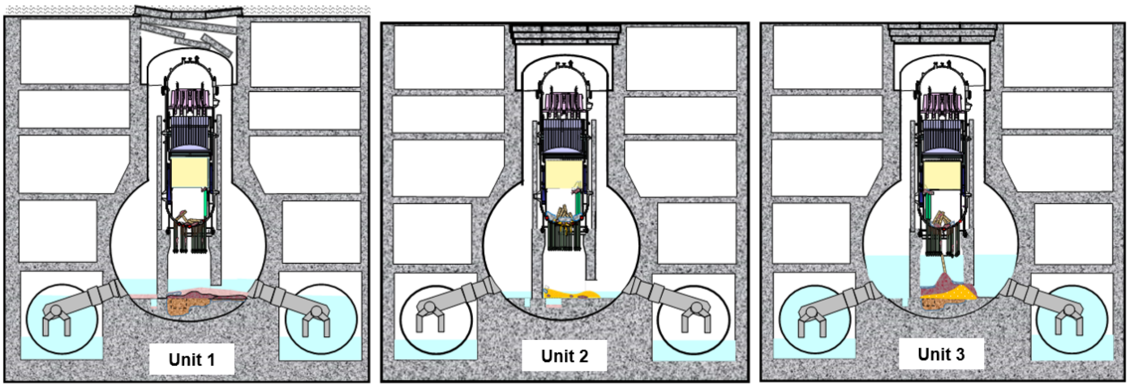
None.

5. Summary

TEPCO has continuously conducted estimations of the status inside the RPVs and PCVs for Units 1-3 that have experienced severe accidents, with the aim of safely and efficiently proceeding with decommissioning work, including fuel debris removal.

Regarding the estimation figures described in Section 4, the estimation figures for Units 1-3 as of June 2021 are shown in Figure 5.1.

	Distribution of fuel debris			Water level in containment vessel	
	Core	Pressure vessel bottom	Containment vessel	D/W water level＊	SC water level
Unit 1	Almost none	Almost none	Almost all	About 2m	Almost full
Unit 2	Little	A lot	Little	About 0.3m	Middle
Unit 3	Less than U 2	Less than U 2	More than U 2	About 5m	Full



＊Water level as of January 2021 (Due to an earthquake on February 13, 2021, the water level in containment vessels (dry wells) of Units 1 and 3 changed.)

Figure 5.1 Summary of estimation for Units 1-3 [3-3]

Direct information obtained from the site is important for estimating the conditions inside the RPV and PCV, but at present, there are areas that have not been fully investigated, not only inside the RPV but also inside the PCV. The information obtained as the decommissioning work progresses to remove the fuel debris will be actively utilized, and on-site investigations for accident analysis will also be promoted.

TEPCO will continue these efforts and contribute to improving the safety of nuclear power plants around the world by reflecting the findings in safety measures at the Kashiwazaki-Kariwa NPS as well as disseminating them widely.

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Appendix 1

Major time series of events and actions from the earthquake occurrence to Tuesday, March 15 at Fukushima Daiichi Nuclear Power Station Unit 1

The contents of the accident investigation report and the estimation results from the examination of unresolved issues were included in the time series of events to enhance the description of information that assists in understanding the progress of the accident, such as information on reactor cooling, water injection, and containment vessel venting (the information related to the examination of unresolved issues is described in italics).

March 11, 2011 (Friday)

14:46 The Off the Pacific Coast of Tohoku Earthquake and Tsunami (Great East Japan Earthquake) occurred. Reactor automatically shut down. The third emergency state was automatically issued.

14:47 The main turbine automatically shut down and the emergency diesel generator automatically started up due to the loss of external power.

14:52 The emergency condensers ("IC") (A), (B) automatically started up.

15:02 Reactor subcriticality was confirmed.

15:03 The return piping isolation valves (MO-3A, 3B) of the IC were temporarily "fully closed" (IC (A), (B) stopped) in order to comply with the reactor coolant temperature drop rate of 55°C/h. The IC (A), (B) were then shut down. Then, reactor pressure control by IC(A) was initiated.

15:05 Containment vessel cooling system ("CCS") B started cooling the suppression chamber ("S/C").

15:06 The Emergency Disaster Control Headquarters was set up at the Head Office (to assess the damage caused by the earthquake, restore power, etc.).

15:10 CCS A system began cooling the S/C.

15:17 IC(A) started.

15:19 IC(A) stopped.

15:24 IC(A) started.

15:26 IC(A) stopped.

15:27 The first tsunami arrived at the wave gauge located about 1.3km offshore from the power plant.

15:32 IC(A) started.

15:34 IC(A) stopped.

15:35 The second tsunami arrived at the wave gauge.

About 15:36 It was estimated that the tsunami arrived at the power station site.

*(Examination of unresolved issues*1)*

*It was estimated that the tsunami caused the loss of the emergency seawater system necessary for cooling the equipment. (Examination of unresolved issues*2)*

15:37 Loss of all AC power (loss of emergency bus bar A and B voltages) and DC power occurred due to building flooding.

15:37 Cooling of the S/C by CCS A, B stopped due to the loss of all AC power.

15:42 It was determined that a specified event (loss of all AC power) had occurred under the provisions of Article 10, Paragraph 1 of the Act on Special Measures Concerning Nuclear Emergency Preparedness ("Nuclear Emergency Preparedness Act"), and the authorities were notified.

15:42 The first emergency state was issued. The Emergency Response Headquarters was set up (it became a joint headquarters with the Emergency Disaster Response Headquarters).

About 16:00 Checking the status of roads on the site started.

About 16:00 Checking the integrity of the power supply facilities (external power supply) started.

16:10 Instruction was issued by the Power Distribution Department of the Head Office to all branch offices to secure high- and low-voltage power supply vehicles and confirm transportation routes.

16:36 The reactor water level could not be confirmed, the indicator light of the high-pressure water injection system was off and could not be started. The status of water injection was unknown. It was judged that a specified event (emergency core cooling system water injection failure) had occurred in accordance with the provisions of Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law, and the authorities were notified at 16:45.

16:36 The second emergency state was issued.

16:45 The reactor water level was confirmed, and it was determined that the occurrence of a specific event (emergency core cooling system water injection failure) was canceled in accordance with Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law. The authorities were notified at 16:55.

About 16:50 All high- and low-voltage power supply vehicles departed sequentially for Fukushima.

16:55 Checks of diesel-driven fire pumps (DDFP) were started.

17:07 Since the reactor water level could not be confirmed again, it was determined that a specified event (emergency core cooling system water injection failure) occurred in accordance with Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law, and the authorities were notified at 17:12.

17:12 **Plant Superintendent ordered the start of a review of the fire extinguishing line installed as an accident management measure and the method of water injection into the reactor using a fire truck.**

17:19 The operators left for the reactor building to check the site. They arrived in front of the double doors of the reactor building, opened the handle of the outer door of the double doors, and took one step in, but gave up checking the site because they confirmed that the indicator of the GM counter (a radiation measuring instrument) they were carrying went out of range and the situation was unusual. At 17:50, they turned back to report the situation.

17:30 The DDFP was automatically started up by the fault recovery operation, but it stopped because the reactor alternative water injection line was not yet configured (and it was then held in a stopped status to prevent it from starting).

About 18:00 Checking the integrity of the power supply equipment (power supply in the plant) began.

18:18 The indicator lights of the isolation valves for the IC return piping (MO-3A) and supply piping (MO-2A) were lit, and when the lighting status was checked, they were closed. Expecting that the isolation valves inside the containment vessel (MO-1A, 4A) were open, the valves were opened, and steam generation was confirmed.

18:25 Steam generation stopped a short time later, and the return piping isolation valve (MO-3A) was closed due to concern that the water on the shell side, which is cooling water for the IC, might have run out.

18:35 The reactor alternative water injection line configuration was started.

About 19:00 The gate between Units 2 and 3 was opened to allow vehicles to pass through to Units 1 to 4.

19:24 The results of confirming integrity of the roads on the site were reported to the power station response headquarters.

20:47 Temporary lighting in the central control room was turned on.

20:50 As the reactor alternative water injection line was completed, the stopped status was released and the DDFP automatically started up (water injection was possible after reactor depressurization) by the fault recovery operation.

20:50 Fukushima Prefecture government ordered residents within a 2km radius of Fukushima Daiichi NPS to evacuate.

20:56 The results of confirming the integrity of the power supply facilities (external and internal power supplies) were reported to the power station response headquarters.

21:19 The reactor water level was confirmed to be +200mm above top of active fuel (TAF). *It is estimated that the water level gauge readings do not indicate the correct water level at this stage due to evaporation of water in the water level gauge piping (the same applies below). (Examination of unresolved issues[*3, *4])*

21:23 Prime Minister ordered evacuation within a 3km radius of Fukushima Daiichi NPS and to shelter indoors for residents within a 3 to 10km radius.

21:30 The DDFP was activated and the water supply to the shell side of the IC was ready, and the return piping isolation valve (MO-3A) was opened. The steam generation was confirmed.

21:51 An operator, who had entered the reactor building, reported to the central control room that the APD (pocket dosimeter with alarm) read 0.8 mSv in a very short period and that he had given up checking the site. Since the radiation level in the reactor building increased, entry into the building was prohibited.

About 22:00 It was confirmed that the first team of Tohoku Electric Power Company had arrived with high-voltage power supply truck.

22:10 The government offices were informed that the reactor water level was in the vicinity of TAF+450mm.

23:00 As a result of the survey, the elevated radiation dose rates in the turbine building were reported to the authorities at 23:40. (They were 1.2mSv/h in front of the double doors on the north side of the turbine building 1st floor and 0.5mSv/h in front of the double doors on the south side of the turbine building 1st floor.)

March 12, 2011 (Saturday)

00:06 The drywell pressure might exceed 600kPa[abs], and the plant general manager was ordered to proceed with preparations for containment vessel venting ("venting").

00:30 The completion of evacuation measures for evacuated residents was confirmed by the government (confirmation of the completion of evacuation measures within 3km of the site in Futaba Town and Okuma Town, confirmed again at 01:45).

00:49 Since the D/W pressure might have exceeded 600kPa[abs], it was determined that a specified event (an abnormal increase in containment vessel pressure) has occurred in accordance with Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law, and this was notified to the authorities at 00:55.

About 01:20 Arrival of a high-voltage power supply vehicle from TEPCO was confirmed.

About 01:30 Prime Minister, Minister of METI, and NISA gave their approval for the request on venting of Units 1 and 2.

01:48 DDFP stopped due to fuel shortage.

02:03 Consideration began to connecting fire truck hose to the water supply outlet of the fire extinguishing line.

02:47 Authorities were notified that the D/W pressure had reached 840 kPa[abs] at 02:30.

02:56 DDFP refueling completed. Startup operation was performed, but startup failed.

03:06 A press conference was held regarding the venting.

About 04:00 Fire truck injection of fresh water into the reactor was begun from the fire extinguishing line; 1,300 liters injected.

04:01 The exposure assessment results in case of venting were reported to the authorities.

04:55 It was confirmed that radiation dose rates inside the power plant site had increased (0.069μSv/h (04:00) → 0.59μSv/h (04:23) near the main gate), and the authorities were notified.

05:14 Radiation levels inside the power plant site were increasing and D/W pressure was decreasing, therefore it was determined that "radioactive materials leakage to the outside" occurred, and authorities were notified.

05:44 Prime Minister ordered residents within a 10km radius of Fukushima Daiichi NPS to evacuate.

05:46 Water injection, which was temporarily suspended due to increased radiation levels, **was resumed by fire trucks through the fire extinguishing line into the reactor (at 04:22,** water injection was suspended and workers evacuated to the seismic isolation building).

05:52 Fire truck injection completed for 1,000 liters of fresh water through the fire extinguishing line into the inside reactor.

About 06:00 *It was estimated that the lower head of the reactor pressure vessel was damaged. (Examination of unresolved issues*[*4, 5]*)*

06:30 Fire truck injection of 1,000 liters of fresh water through the fire extinguishing line inside the reactor.

06:33 It was confirmed that the evacuation of the area from Okuma to Miyakoji was under consideration.

06:50 Minister of METI ordered venting based on laws and regulations (manual venting).

07:11 Prime Minister arrived at Fukushima Daiichi NPS.

07:55 Fire truck injection of 1,000 liters of fresh water through the fire extinguishing line to inside the reactor.

08:03 Plant general manager ordered venting to be performed at target time of 09:00.

08:04 Prime Minister left Fukushima Daiichi NPS.

08:15 Fire truck injection of 1,000 liters of fresh water through the firefighting line to inside the reactor.

08:27 It was confirmed that parts of Okuma Town had not been evacuated.

08:30 Fire truck injection of 1,000 liters of fresh water through the fire extinguishing line to inside the reactor.

08:37 Message was sent to Fukushima Prefecture government informing that preparation was being made to begin venting about 09:00. Coordination was made to vent after checking the evacuation status.

09:02 It was confirmed that the evacuation of Okuma Town (part of the Kuma district) was complete.

09:04 The operator departed to perform venting operations.

09:05 A press release on the venting operation was issued.

09:15 Fire truck injection completed for 1,000 liters of fresh water through the fire extinguishing line into the inside reactor.

09:15 The containment vent valve (MO valve) was manually opened.

09:32 Attempt was made to operate the small S/C vent valve (AO valve) but was abandoned due to high radiation level.

09:40 Fire truck injection of 15,000 liters of fresh water through the fire extinguishing line to inside the reactor.

09:53 The exposure assessment in case of venting was carried out again and the results were reported to the authorities.

About 10:15 TEPCO confirmed that 72 power supply vehicles dispatched by TEPCO and Tohoku Electric Power Company had arrived at Fukushima (high-voltage power supply vehicles: 12 at Fukushima Daiichi and 42 at Fukushima Daini; low-voltage power supply vehicles: 7 at Fukushima Daiichi and 11 at Fukushima Daini).

10:17 The opening operation of the small valve of the S/C vent valve (AO valve) conducted three times at the central control room at 10:17, 10:23, and 10:24 (excepting residual pressure in the compressed air system for instrumentation).

10:40 Radiation levels at the main gate and near monitoring post No. 8 were observed to be rising, and it was determined that radioactive materials were likely to have been released due to the venting.

11:15 It was confirmed that the venting might not have been fully effective because the radiation level was decreasing.

11:39 The radiation exposure of one TEPCO employee who entered the reactor building to operate the vent exceeded 100mSv (106.30mSv).

12:53 DDFP battery replacement work was completed. Operator performed start-up operation, but the cell motor was unusable due to a ground fault.

14:30 Temporary air compressor was installed at about 14:00 to operate the large S/C vent valve (AO valve), and it was confirmed that the D/W pressure was decreasing. It was determined radioactive material were released due to venting, and the authorities were notified at 15:18.

14:53 Freshwater injection into the reactor by fire truck was completed, with about 80,000 liters (cumulative total) injected.

14:54 Plant Superintendent ordered injection of seawater into the reactor. (Freshwater in the fire tank on the Unit 1 side was running out, so freshwater was quickly transferred from other fire tanks, etc., while the operation was switched to seawater injection.)

15:18 The boric acid water injection system was being restored, and as soon as it was ready, the boric acid water injection system pumps were to be started up and inject inside the reactor. Also, as soon as the fire extinguishing system was ready, seawater was to be injected into the reactor. This was reported to authorities.

About 15:30 The route for supplying power from the high-voltage power supply vehicle to the Unit 1 small-capacity low-voltage motor control center (MCC) via the Unit 2 low-voltage power center (P/C) was configured. Power transmission was started to the front of the boric acid water injection system pump, and adjustment of the high-voltage power supply vehicle was completed.

15:36 An explosion occurred in the reactor building. (The explosion damaged the hoses for seawater injection and the power cables of the boric acid water injection system. Evacuation from the site and safety confirmation were performed. Recovery and preparation work were suspended until the situation at the site was confirmed.)

16:27 Radiation dose rate exceeding 500μSv/h (1,015μSv/h) was measured near monitoring post No.4. It was judged that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law occurred, and the authorities were notified.

About 17:20 Fire trucks departed for an investigation of the condition of the building, etc.

18:05 The order from Minister of METI (for water injection) was shared between the Head Office and the power plant.

18:25 Prime Minister ordered evacuation of residents within a 20km radius of the Fukushima Daiichi NPS.

18:36 Investigation of the fire trucks, buildings, etc., confirmed that the site was in a state of disarray and **that the hoses for seawater injection that had been prepared were damaged and unusable.**

19:04 **Fire truck injection of seawater through the fire extinguishing line to inside the reactor began.**

20:45 Injection of boric acid mixed with seawater to inside the reactor began.

＊1 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment Earthquake and Tsunami - 1) Arrival times of tsunami at the Fukushima Daiichi Nuclear Power Station site

＊2 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment Earthquake and Tsunami – 2) Additional examination of emergency AC power equipment losses due to tsunami

＊3 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression Progress Report No. 5
(Attachment 1-2) Evaluation of plant status by the fuel range water level indicators of Unit-1

＊4 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 1-6) Estimation of Unit-1 accident progression based on the measured data and results of analysis to data

＊5 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 1-11) Estimation of accident progression at Unit-1 based on the air dose rate monitoring data.

Appendix 2

Major time series of events and actions from the earthquake occurrence to Tuesday, March 15 at Fukushima Daiichi Nuclear Power Station Unit 2

The contents of the accident investigation report and the estimation results from the examination of unresolved issues were included in the time series of events to enhance the description of information that assists in understanding the progress of the accident, such as information on reactor cooling, water injection, and containment vessel venting (the information related to the examination of unresolved issues is described in italics).

March 11, 2011 (Friday)

14:46 The Off the Pacific Coast of Tohoku Earthquake and Tsunami (Great East Japan Earthquake and Tsunami) occurred. The third emergency state was automatically issued.

14:47 Reactor automatically shut down, and the main turbine automatically shut down. The emergency diesel generator automatically started up due to the loss of external power.

14:50 The reactor core isolation cooling system (RCIC) was manually started.

14:51 RCIC automatically stopped (reactor water level high).

15:01 Reactor subcriticality was confirmed.

15:02 RCIC was manually started.

15:06 The Emergency Disaster Control Headquarters was set up at the Head Office (to assess the damage caused by the earthquake, restore power, etc.).

15:07 Cooling of the suppression chamber (S/C) by system A of the residual heat removal system (RHR) began.

15:25 S/C cooling by RHR A system was switched from cooling mode to spray mode.

15:27 The first tsunami arrived at the wave gauge located about 1.3km offshore from the power plant.

15:28 RCIC automatically stopped (reactor water level high).

15:35 The second tsunami arrived at the wave gauge.

About 15:36 It was estimated that the tsunami arrived at the power station site. *(Examination of unresolved issues*[*1]*)*
It is estimated that the tsunami caused the loss of the emergency seawater system necessary for cooling the equipment. (Examination of unresolved issues[*2]*)*

15:37 S/C cooling stopped by RHR A system.

15:39 RCIC was manually started.

15:41 Loss of all AC power due to flooding of the building (loss of emergency bus bar A and B voltages at 15:37 and 15:40, respectively).

15:42 It was determined that a specified event (loss of all AC power) had occurred under the provisions of Article 10, Paragraph 1 of the Act on Special Measures Concerning Nuclear Emergency Preparedness ("Nuclear Emergency Preparedness Act"), and the authorities were notified.

15:42 The first emergency state was issued. The Emergency Response Headquarters was set up (it became a joint headquarters with the Emergency Disaster Response Headquarters).

15:50 It was confirmed that reactor water level was unknown. In addition to all AC power, DC power was lost due to flooding in the building.

About 16:00 Checking the status of roads on site started.

About 16:00 Checking the integrity of the power supply facilities (external power supply) started.

16:10 Instruction was issued by the Power Distribution Department of the Head Office to all branch offices to secure high- and low-voltage power supply vehicles and confirm transportation routes.

16:36 The reactor water level was unknown, the operational status of the RCIC could not be confirmed, and all the indicator lights on the control panel of the high-pressure water injection system were off making it impossible to start the system. It was judged that specific event (emergency core cooling system water injection failure) in accordance with the provisions of Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 16:45.

16:36 The second emergency state was issued.

About 16:50 All high- and low-voltage power supply vehicles departed sequentially for Fukushima.

17:12 Plant Superintendent ordered the start of a review of the fire extinguishing line installed as an accident management measure and the method of water injection into the reactor using a fire truck.

About 18:00 Checking of the integrity of the power supply equipment (power supply in the plant) began.

About 19:00 The gate between Units 2 and 3 was opened to allow vehicles to pass through to Units 1 to 4.

19:24 The results of confirming integrity of the roads on the site were reported to the power station response headquarters.

20:47 Temporary lighting in the central control room was turned on.

20:50 Fukushima Prefecture government ordered residents within a 2km radius of Fukushima Daiichi NPS to evacuate.

20:56 The results of confirming the integrity of the power supply facilities (external and internal power supplies) were reported to the power station response headquarters.

21:02 The reactor water level was unknown, and the status of water injection into the reactor by the RCIC could not be confirmed. The authorities were notified to the possibility that the reactor water level might reach top of active fuel (TAF).

21:13 TAF was estimated to be reached at 21:40, and the authorities were notified.

21:23 Prime Minister ordered evacuation for residents within a 3km radius of Fukushima Daiichi NPS and to shelter indoors within a 3 to 10km radius.

21:50 The reactor water level was found and confirmed to be at TAF+3400mm, and it was assessed that it would take some time to reach TAF. The authorities were notified at 22:10.

About 22:00 It was confirmed that one high-voltage power supply truck of Tohoku Electric Power Company arrived.

March 12, 2011 (Saturday)

00:30 The completion of evacuation measures for evacuated residents was confirmed by the government (confirmation of the completion of evacuation measures within 3 km of the site in Futaba Town and Okuma Town, confirmed again at 01:45).

01:20 It was confirmed that the diesel-driven fire pump was stopped

About 01:20 Arrival of high-voltage power supply vehicle from TEPCO was confirmed.

About 01:30 Prime Minister, Minister of METI, and NISA gave their approval for the request on venting of Units 1 and 2.

02:55 Power station response headquarters confirmed the RCIC was operating.

03:06 Press conference held regarding the venting.

03:33 The exposure assessment results in case of venting were reported to the authorities.

04:20 RCIC began switching the water source from the condensate storage tank to the S/C.

04:55 Radiation levels inside the power plant site were increasing and D/W pressure was decreasing, therefore it was determined that "radioactive materials leakage to the outside" occurred, and authorities were notified.

05:00 Changing water source for RCIC was completed.

05:44 Prime Minister ordered residents within a 10 km radius of Fukushima Daiichi NPS to evacuate.

06:50 Minister of METI ordered venting based on laws and regulations (manual venting).

07:11 Prime Minister arrived at Fukushima Daiichi NPS.

08:04 Prime Minister left Fukushima Daiichi NPS.

About 10:15 TEPCO confirmed that 72 power supply vehicles dispatched by TEPCO and Tohoku Electric Power Company arrived at Fukushima (high-voltage power supply vehicles: 12 at Fukushima Daiichi and 42 at Fukushima Daini; low-voltage power supply vehicles: 7 at Fukushima Daiichi and 11 at Fukushima Daini).

About 15:30 The route for supplying power from the high-voltage power supply vehicle to the Unit 1 small-capacity low-voltage power supply panel (MCC) via the Unit 2 low-voltage power supply panel (P/C) was configured. Power transmission was started to the front of the boric acid water injection system pump, and adjustment of the high-voltage power supply vehicle was completed.

15:36 An explosion occurred in the reactor building of Unit 1. (The explosion damaged the cables that had been laid and stopped the P/C from receiving power.)

16:27 Radiation dose rate exceeding 500μSv/h (1,015μSv/h) was measured near monitoring post No.4. It was judged that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law occurred, and the authorities were notified.

17:30 Plant Superintendent ordered start of preparation for venting.

18:25 Prime Minister ordered evacuation of residents within a 20km radius of the Fukushima Daiichi NPS.

March 13, 2011 (Sunday)

08:10 The containment vent valve (MO valve) was opened.

08:30 The high-voltage power supply vehicle was started and attempted to re-transmit power to the Unit 2 P/C. However, the overcurrent relay was activated, and power could not be transmitted.

08:56 Radiation dose rate exceeding 500μSv/h (882μSv/h) was measured near monitoring post No. 4, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law occurred and the authorities were notified at 09:01.

10:15 Plant Superintendent ordered performance of venting.

11:00 Vent line configuration was completed, except for the rupture disk.

11:20 A press release on the venting operation was issued.

12:05 Plant Superintendent ordered preparations to use seawater to proceed.

13:10 The battery was connected to the safety relief valve (SRV) control panel and configured to open with an operating switch.

14:15 Radiation dose rate exceeding 500μSv/h (905μSv/h) was measured near monitoring post No. 4, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 14:23.

15:18 The exposure assessment results in case of venting were reported to the authorities.

March 14, 2011 (Monday)

02:20 Radiation dose rate exceeding 500μSv/h (751μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 04:24.

02:40 Radiation dose rate exceeding 500μSv/h (650μSv/h) was measured near monitoring post No. 2, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 05:37.

04:00 Radiation dose rate exceeding 500μSv/h (820μSv/h) was measured near monitoring post No. 2, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) had occurred under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law. Authorities were notified at 08:00.

About 09:00 *It was estimated that RCIC's ability to inject water into the reactor had decreased. (Examination of unresolved issues*3)*

09:12 Radiation dose rate exceeding 500μSv/h (518.7μSv/h) was measured near monitoring post No. 3, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 09:34.

11:01 An explosion occurred in the reactor building of Unit 3. (The explosion damaged fire truck and hoses of the seawater injection line, which had already been prepared, and made them unusable.)

12:50 The circuit for electromagnetic valve excitation of the large valve of the S/C vent valve (AO valve) was disconnected due to the Unit 3 explosion and confirmed closed.

13:05 The water injection line, for which preparations had been completed, was unusable due to damage to fire truck and hoses. The seawater injection line configuration, including fire trucks, was resumed

13:18 Since the reactor water level was on a downtrend, the authorities were notified to immediately proceed with preparatory work for seawater injection operations into the reactor.

13:25 The reactor water level was decreasing and the RCIC might have lost its function. The specific event (loss of reactor cooling function) was determined to have occurred in accordance with the provisions of Article 15, Paragraph 1 of the Nuclear Disaster Prevention Act, and the authorities were notified at 13:38.

15:28 Analysis estimated water level was to reach TAF at 16:30, and the authorities were notified.

About 15:30 Fire truck started to inject seawater into the reactor.

16:34 Depressurization of the reactor started and seawater injection was started from fire extinguishing line, and the authorities were notified.

16:34 SRV (A) opening operation was attempted but the valve did not open, and SRVs (B), (C), and (G) opening operations were also attempted but the SRVs did not open. *It is estimated that the reason why SRVs did not operate was that the battery supply range to excite the solenoid valves for the opening operation of the SRV control circuit was not only for the solenoid valves, but for the entire circuit. (Examination of unresolved issues*[4])*

17:17 Reactor water level reached TAF. The authorities were notified at 17:25.

18:02 SRV (E) started depressurizing the reactor by directly connecting the battery to the solenoid valve for opening the SRV control circuit. Since the reactor pressure was not decreasing, two valves, SRV (F) and (D), were placed in the open status. The reactor pressure decreased and depressurization resumed (6.998MPa[gage] (16:34) → 6.075MPa[gage] (18:03) → 0.63MPa[gage] (19:03)).

18:22 Reactor water level reached TAF-3,700mm, and it was judged that the entire fuel was exposed. The authorities were notified at 19:32.

19:20 It was confirmed that the fire truck used to inject seawater into the reactor had stopped due to running out of fuel.

19:54 Seawater injection into the reactor from the fire extinguishing line started by fire trucks (one began at 19:54 and the other at 19:57).

A**bout 21:00 Operation to open the small valve of the S/C vent valve (AO valve) was performed. Vent line configuration was completed except for the rupture disk.**

21:20 Two valves of SRV(A),(B) were opened, and it was confirmed that the reactor water level had recovered. The authorities were notified at 21:34. (As of 21:30, reactor water level was TAF-3,000mm).

It is estimated that the water level gauge readings did not indicate the correct water level at this stage due to evaporation of water in the water level gauge piping. (Examination of unresolved issues[*5], [*6]*)*

21:35 Radiation dose rate exceeding 500μSv/h (760μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 22:35.

22:50 The drywell (D/W) pressure exceeded the maximum working pressure of 427kPa[gage], and it was judged that a specified event (abnormal increase in containment vessel pressure) in accordance with the provisions of Article 15-1 of the Nuclear Disaster Prevention Law occurred and the authorities were notified at 23:39.

23:00 It was confirmed that the reactor pressure increased, and after the SRV opening operation was continued, the reactor pressure decreased.

23:35 Since the pressure on the S/C side was lower than the rupture disk operating pressure and the pressure on the D/W side was rising, the decision was made to vent the reactor by opening the small D/W vent valve.

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00:01 D/W vent valve (AO valve) operation was performed to open the small valve, but it was confirmed that the valve closed after a few minutes.

00:10 Reactor pressure rose again. In this order, SRV(C),(G),(E),(A),(B),(E),(G),(H),(C), solenoid valves for opening operation were excited and reactor pressure dropped at about 01:10.

It is estimated that the cause of the failure of multiple SRVs may be due to leakage of the nitrogen gas required to drive the SRVs, or due to the relationship between the nitrogen gas supply pressure, reactor pressure, and containment vessel pressure. (Examination of unresolved issues[*4]*)*

03:00 Since D/W pressure exceeded the maximum design pressure, depressurization and water injection into the reactor were being attempted. The authorities were notified.

05:35 The Integrated Headquarters for Fukushima Nuclear Power Station Accident Response was established.

About 06:14 Loud impact sound and vibration occurred, and the indicated value of S/C pressure became downscaled. This was reported to the power station response headquarters as 0kPa[abs]. (The S/C pressure gauge might have failed, since D/W pressure (which remained above 700kPa[abs] from about 06:00 to past 07:00) and the S/C pressure were almost the same value. Regarding the impact noise, it was estimated that it was caused by an explosion in the Unit 4 reactor building, based on an analysis of data from a temporary seismic observation recorder installed inside the power plant site*[7]).

06:50 Radiation dose rate exceeding 500μSv/h (583.7μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 07:00.

07:00 The authorities were notified of a temporary evacuation of personnel to Fukushima Daini, except for personnel necessary for monitoring and operations.

08:11 Radiation dose rate exceeding 500μSv/h (80 μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 08:36.

08:25 White smoke (steam-like) was observed coming from the wall near the 5th floor of the reactor building. The authorities were notified at 09:18.

10:30 Orders came from Minister of METI based on laws and regulations. (Water injection into the reactor must be carried out as soon as possible. Vent the drywell as necessary.)

11:00 Prime Minister ordered residents within a radius of 20 to 30 km from Fukushima Daiichi NPS to shelter indoors.

16:00 Radiation dose rate exceeding 500μSv/h (531.6μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 08:36.

23:05 Radiation dose rate exceeding 500μSv/h (4,548μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 23:20.

＊1 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment Earthquake and Tsunami - 1) Arrival times of tsunami at the Fukushima Daiichi Nuclear Power Station site

＊2 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment Earthquake and Tsunami – 2) Additional examination of emergency AC power equipment losses due to tsunami

＊3 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 2-1) Reactor pressure behaviors at Unit 2

＊4 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 2-12) SRV operation states after the core damage at Unit 2

＊5 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 1-2) Evaluation of plant status by the fuel range water level indicators of Unit 1

＊6 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in

the accident progression, Progress Report No. 5
(Attachment 2-14) Estimation of reactor water levels at the time when core damage and core melt progressed at Unit 2

＊7 Fukushima Nuclear Accident Examination Report (June 20, 2012)

Appendix 3

Major time series of events and actions from the earthquake occurrence to Tuesday, March 15 at Fukushima Daiichi Nuclear Power Station Unit 3

The contents of the accident investigation report and the estimation results from the examination of unresolved issues were included in the time series of events to enhance the description of information that assists in understanding the progress of the accident, such as information on reactor cooling, water injection, and containment vessel venting (the information related to the examination of unresolved issues is described in italics).

March 11, 2011 (Friday)

14:46 **The Off the Pacific Coast of Tohoku Earthquake and Tsunami (Great East Japan Earthquake and Tsunami) occurred.** The third emergency state was automatically issued.

14:47 **Reactor automatically shut down,** and the main turbine automatically shut down.

14:48 The emergency diesel generator automatically started up due to the loss of external power.

14:54 Reactor subcriticality was confirmed.

15:05 The reactor core Isolation cooling system (RCIC) was manually started.

15:06 The Emergency Disaster Control Headquarters was set up at the Head Office (to assess the damage caused by the earthquake, restore power, etc.).

15:25 RCIC automatically stopped (reactor water level high).

15:27 The first tsunami arrived at the wave gauge located about 1.3km offshore from the power plant.

15:35 The second tsunami arrives at the wave gauge.

About 15:36 **It was estimated that the tsunami arrived at the power station site.**
(Examination of unresolved issues[*1]*)*
It is estimated that the tsunami caused the loss of the emergency seawater system necessary for cooling the equipment. (Examination of unresolved issues[*2]*)*

15:38 Loss of all AC power due to flooding of the building (loss of emergency bus bar A and B voltages at 15:38 and 15:39, respectively).

15:42 **It was determined that a specified event (loss of all AC power) had occurred under the provisions of Article 10, Paragraph 1 of the Act on Special Measures Concerning Nuclear Emergency Preparedness ("Nuclear Emergency**

Preparedness Act") and the authorities were notified.

15:42 The first emergency state was issued. The Emergency Response Headquarters was set up (it became a joint headquarters with the Emergency Disaster Response Headquarters).

About 16:00 Checking the status of roads on the site started.

About 16:00 Checking the integrity of the power supply facilities (external power supply) started.

16:03 RCIC was manually started (no water injection to the reactor yet).

16:10 Instruction was issued by the Power Distribution Department of the Head Office to all branch offices to secure high- and low-voltage power supply vehicles and confirm transportation routes.

16:16 RCIC started reactor water injection.

16:36 The second emergency state was issued.

About 16:50 All high- and low-voltage power supply vehicles departed sequentially for Fukushima.

About 18:00 Checking of the integrity of the power supply equipment (power supply in the plant) began.

About 19:00 The gate between Units 2 and 3 was opened to allow vehicles to pass through to Units 1 to 4.

19:24 The results of confirming integrity of roads on the site were reported to the power station response headquarters.

20:50 Fukushima Prefecture government ordered residents within a 2km radius of Fukushima Daiichi NPS to evacuate.

20:56 The results of confirming the integrity of the power supply facilities (external and internal power supplies) were reported to the power station response headquarters.

21:23 Prime Minister ordered evacuation within a 3km radius of Fukushima Daiichi NPS and to shelter indoors for residents within a 3 to 10km radius.

21:27 Temporary lighting in the central control room was turned on.

About 22:00 It was confirmed that one high-voltage power supply truck of Tohoku Electric Power Company had arrived.

March 12, 2011 (Saturday)

00:30 The completion of evacuation measures for evacuated residents was confirmed by the government (confirmation of the completion of evacuation measures within 3km of the site in Futaba Town and Okuma Town, confirmed again at 01:45).

About 01:20 Arrival of high-voltage power supply vehicle from TEPCO was confirmed.

03:27 The diesel-driven fire pump (DDFP) did not start.

04:55 The radiation level inside the power plant site was confirmed to have increased (0.069μSv/h (04:00) → 0.59μSv/h (04:23) near the main gate), and the authorities were notified.

05:44 Prime Minister ordered residents within a 10km radius of Fukushima Daiichi NPS to evacuate.

07:11 Prime Minister arrived at Fukushima Daiichi NPS.

08:04 Prime Minister left Fukushima Daiichi NPS.

About 10:15 TEPCO confirmed that 72 power supply vehicles dispatched by TEPCO and Tohoku Electric Power Company arrived at Fukushima (high-voltage power supply vehicles: 12 at Fukushima Daiichi and 42 at Fukushima Daini; low-voltage power supply vehicles: 7 at Fukushima Daiichi and 11 at Fukushima Daini).

11:13 The fire control panel confirmed automatic startup of the DDFP by pressing the failure recovery button.

11:36 The DDFP was stopped by the control panel of the fire extinguishing system after the startup was confirmed.

11:36 RCIC automatically stopped. (The status of the stop was confirmed on site, and start-up operation was performed in the central control room, but the steam stop valve closed immediately after startup and stopped.)
*It is estimated that the automatic stop logic of "high turbine exhaust pressure" was activated. (Examination of unresolved issues*3)*

12:06 DDFP started, and alternative S/C spraying by DDFP began.

12:35 High pressure water injection system (HPCI) automatically started (reactor water level low).

16:27 Radiation dose rate exceeding 500μSv/h (1,015μSv/h) was measured near monitoring post No.4. It was judged that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law occurred and the authorities were notified.

17:30 Plant Superintendent ordered preparation for venting to start.

18:25 Prime Minister ordered evacuation of residents within a 20km radius of the Fukushima Daiichi NPS.

20:36 The reactor water level was unknown due to loss of power to the reactor water level gauge.

March 13, 2011 (Sunday)

02:42 **HPCI was stopped manually to switch to alternative reactor water injection by the DDFP.**
*It is estimated that the HPCI had likely lost its water injection capability before the manual shutdown. (Examination of unresolved issues*4)*

02:45 The safety relief valve (SRV) (A) was opened but did not work. Attempts were made to open all 8 valves in sequence, but they did not open.
*It is estimated that the failure to open the SRVs was due to insufficient voltage in the DC power supply. (Examination of unresolved issues*5)*

03:05 The central control room was notified that the configuration of the alternate reactor water injection line (switching from alternate S/C spray to alternate reactor water injection) was completed.

03:35 An attempt to start the HPCI was made, but the flow controller display was off, and startup was not possible.

03:37 The vacuum pumps were operated at the RCIC control panel to prepare for RCIC startup, but they did not start.

03:38 The status indicator light of the SRV was on, so attempts were made to open the operation switches of all 8 SRV valves again, but they did not work.
*It is estimated that the failure to open the SRVs was due to insufficient voltage in the DC power supply. (Examination of unresolved issues*5)*

03:39 The HPCI auxiliary oil pump was stopped to prolong the life of the DC power supply as much as possible. At 04:06 the HPCI condensate pump was also stopped.

03:51 Reactor water level gauge restored.

04:52 Opening of the large valve of the pressure suppression chamber (S/C) vent valve (AO valve) was tried using power from a small generator, but the filling pressure of the air cylinder was zero, and closure was confirmed.

05:08 Alternative S/C spraying by DDFP started (stopped at 07:43).

05:10 Since reactor water injection by RCIC was not possible, it was judged to be a specific event (loss of reactor cooling function) based on the provisions of Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law occurred and the authorities were notified at 05:58.

05:15 **Plant Superintendent ordered completion of the vent line, except for the rupture disk.**

05:23 Replacing of air cylinders was started to open the large valve of the S/C vent valve (AO valve).

05:50 A press release on the venting operation was issued.

06:19 Top of active fuel (TAF) was judged to have been reached at 04:15 and the authorities were notified.

07:35 The exposure assessment results in the case of venting were reported to the authorities.

07:39 Spraying of the alternative drywell (D/W) was started, and the authorities were notified at 07:56.

08:35 Containment vessel vent valve (MO valve) was opened.

08:40 Switchover operation from alternative D/W spray to alternative reactor water injection was started (switchover at 09:10).

08:41 By opening the large S/C vent valve (AO valve), the vent line configuration except for the rupture disk was completed. The authorities were notified at 08:46.

08:56 Radiation dose rate exceeding 500μSv/h (882μSv/h) was measured near monitoring post No. 4, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 09:01.

About 09:08 While connecting batteries in series to drive the SRVs, the operator observed a decrease in reactor pressure. SRVs rapidly depressurized the reactor. At 09:20, the authorities were notified that water injection into the reactor by the fire extinguishing line would be started.

It is estimated that the rapid depressurization was caused by the opening of multiple SRVs (at least 6 among the SRVs (A), (B), (C), (E), (G), and (H)), and it is highly likely that the automatic depressurization device function of the SRVs was activated. (Examination of unresolved issues[*4])*

09:25 Fresh water injection (with boric acid) through the fire extinguishing line was started to the reactor by a fire truck.

09:36: The authorities were notified that the D/W pressure had decreased since about 09:20 due to venting operations, and that water injection into the inside reactor through the fire extinguishing line had started.

10:30 Plant Superintendent instructed planning of seawater injection should be included.

11:17 Closure of the large valve of the S/C vent valve (AO valve) was confirmed (due to low air cylinder pressure).

12:20 Fresh water injection was terminated because fresh water in the fire prevention tank was running low.

12:30 The large valve of the S/C vent valve (AO valve) was opened (replacing the air cylinder).

13:12 Seawater injection by fire trucks through the fire extinguishing line was started.

14:15 Radiation dose rate exceeding 500μSv/h (905μSv/h) was measured near monitoring post No. 4, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 14:23.

14:20 Power transmission from the high-voltage power truck to the low-voltage power panel (P/C) of Unit 4 began.

14:31 Measurements were reported to be over 300mSv/h on the north side of the reactor building double doors and 100mSv/h on the south side.

14:45 Radiation dose rates increased (about 300mSv/h) near the double doors of the reactor building. As in Unit 1, hydrogen might have accumulated inside the reactor building, and the danger of an explosion increased, so evacuation of the site started (work resumed about 17:00).

21:10 It was determined that the S/C vent valve (AO valve) was to be opened due to a decrease in D/W pressure (a temporary air compressor was installed).

*Only the first and second vent opening operations at around 09:00 and 12:00, respectively, on March 13 were clearly successful, and it is estimated that no further vent opening operations were successful. (Examination of unresolved issues*6)*

March 14, 2011 (Monday)

01:10 The fire truck operation was stopped to supply seawater inside the backwash valve pit because the seawater supplied to the reactor was running low.

02:20 Radiation dose rate exceeding 500μSv/h (751μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 04:24.

02:40 Radiation dose rate exceeding 500μSv/h (650μSv/h) was measured near monitoring post No. 2, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 05:37.

03:20 Seawater injection by fire trucks was resumed.

04:00 Radiation dose rate exceeding 500μSv/h (820μSv/h) was measured near monitoring post No. 2, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 08:00.

04:08 Power was supplied via the Unit 4 P/C, and some functions of the containment vessel atmosphere monitor were recovered.

05:20 Opening operation of the small valve of the S/C vent valve (AO valve) began.

06:10 The opening of the small valve of the S/C vent valve (AO valve) was confirmed.

About 06:30 D/W pressure increased, and there was concern about the possibility of an explosion, so evacuation began (work resumed at about 07:35).

09:05 Seawater supply from the unloading area to the backwash valve pit was started.

09:12 Radiation dose rate exceeding 500μSv/h (518.7μSv/h) was measured near monitoring post No. 3, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 09:34.

About 10:00 Restoration work of the condensate transfer pump was started. While the power supply to the pump was being restored via the P/C of Unit 4, an explosion occurred in the reactor building.

11:01 An explosion occurred in the reactor building of Unit 3.

13:05 Since the water injection line was unusable due to damage to the fire truck and hoses, the line configuration for seawater injection including the fire truck was restarted.

15:30 Seawater injection was stopped due to damage to the fire truck and hoses caused by the explosion. A new line was constructed to inject seawater into the reactor from the unloading area by replacing the fire truck and hoses, and seawater injection was resumed.

19:20 Seawater injection stopped due to fire truck running out of fuel.

19:54 Seawater injection was resumed by fire trucks (one started at 19:54 and the other at 19:57).

21:35 Radiation dose rate exceeding 500μSv/h (760μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 22:35.

21:14 Seawater injection into Unit 3 by the fire trucks was stopped to ensure seawater was injected into Unit 2.

March 15, 2011 (Tuesday)

02:30 Seawater injection by fire trucks was resumed.

05:35 The Integrated Headquarters for Fukushima Nuclear Power Station Accident Response was established.

About 06:14 Loud impact sound occurred. In the central control room, the ceiling on the Unit 4 side was shaking. (Regarding the impact noise, it was estimated that it was caused by an explosion in the Unit 4 reactor building, based on an analysis of data from a temporary seismic observation recorder installed inside the power plant site*[7]).

06:50 Radiation dose rate exceeding 500μSv/h (583.7μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and the authorities were notified at 07:00.

07:00 The authorities were notified of a temporary evacuation of personnel to Fukushima Daini, except for personnel necessary for monitoring and operations.

07:55 It was confirmed that steam was floating above the reactor building. The authorities were notified.

08:11 Radiation dose rate exceeding 500μSv/h (807μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law occurred, and the authorities were notified at 08:36.

11:00 Prime Minister ordered residents within a radius of 20 to 30km from Fukushima Daiichi Nuclear Power Station to shelter indoors.

16:00 Radiation dose rate exceeding 500μSv/h (531.6μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) had occurred under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law. Authorities were notified at 08:36.

16:00 Confirmation of closing of the large and small valves of the S/C vent valve (AO valve) (due to failure of the small generator).

16:05 The large valve of the S/C vent valve (AO valve) was opened (the small generator was replaced). Operation to open large and small valves of the S/C vent valve (AO valve) was carried out several times after that.

23:05 Radiation dose rate exceeding 500μSv/h (4,548μSv/h) was measured near the main gate, and it was determined that a specified event (abnormal increase in radiation dose rate at the site boundary) under Article 15, Paragraph 1 of the Nuclear Disaster Prevention Law had occurred and authorities were notified at 23:20.

＊1 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment Earthquake and Tsunami - 1) Arrival times of tsunami at the Fukushima Daiichi Nuclear Power Station site

＊2 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment Earthquake and Tsunami – 2) Additional examination of emergency AC power equipment losses due to tsunami

＊3 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 3-5) The cause of RCIC shutdown in Unit 3

＊4 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 3-3) Reactor pressure decreasing behavior at about 09:00 on March 13tin Unit 3

＊5 Evaluation of the situation of cores and containment vessels of Fukushima Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 3-4) Reactor pressure changes from about 02:00 to about 12:00 on March 13 in Unit-3

＊6 Evaluation of the situation of cores and containment vessels of Fukushima

Daiichi Nuclear Power Station Units 1 to 3 and examination into unsolved issues in the accident progression, Progress Report No. 5
(Attachment 3-8) Leaks from the Unit-3 PCV and steam release in a large amount

＊7 Fukushima Nuclear Accident Examination Report (June 20, 2012