OECD/NEA International Conference on Regulator's Views and Priorities on Nuclear Safety and Radiation Protection 10 Years After TEPCO Fukushima Daiichi NPS Accident
Poster Exhibition, November 28th – 29th, 2022, Grand Nikko Tokyo Daiba

NRA JAPAN Nuclear Regulation Authority

Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (1/9)

NRA investigation and analysis of TEPCO's Fukushima Daiichi NPS accidents

Background to investigation and analysis of TEPCO's Fukushima Daiichi NPS accidents

After TEPCO's Fukushima Daiichi Nuclear Power Station (NPS) accidents in March 2011, various investigations were conducted not only by the Nuclear Regulation Authority (NRA), but overseas organizations such as the International Atomic Energy Agency (IAEA), Institute of Nuclear Power Operations (INPO), World Association of Nuclear Operators (WANO), U.S. Nuclear Regulatory Commission (NRC), and Institute for Radiological Protection and Nuclear Safety (IRSN).
Recently, progress in the decommissioning of TEPCO's Fukushima Daiichi NPS and improved accessibility to the inside of the reactor building have made it possible to conduct further investigations, such as checking facility conditions and collecting samples. Based on this situation, NRA started additional investigations and analyses in 2019.

Background of accidents

As described in the final report of the Accident Investigation and Verification Commission of the Japanese government and other documents, the accidents at TEPCO's Fukushima Daiichi NPS on March 11, 2011 progressed as follows:

March 11, 2011 14:46	Earthquake occurred
March 11, 2011 15:37	Tsunami hit
March 12, 2011 In the afternoon	Unit 1 Vent
March 12, 2011 Around 15:36	Hydrogen explosion in Unit 1 reactor building
March 13, 2011 In the morning	Unit 3 vent
March 14, 2011 Around 11:01 AM	Hydrogen explosion in Unit 3 reactor building
March 15, 2011 Around 6:12 AM	Hydrogen explosion in Unit 4 reactor building

Damages at Unit 1-4 Reactor Buildings

March 20, 2011 9:30 AM. Photo by Japan Air Self-Defense Force

- Units 1, 3, and 4: Hydrogen explosion damaged the reactor building and the top floor collapsed
- Units 1, 2, and 3 suffered damage to the reactor core and reactor pressure vessel, resulting in leakage from the primary containment vessel (PCV).

Accident analysis by area of investigation

Findings from on-site investigations conducted by NRA's investigation team are described for each of the following topics

Section A: Contamination by Cs-137	Investigation and analysis of highly contaminated by Cs-137 such as shielding plugs and PCV vent lines were conducted to determine leakage and contamination pathways of radioactive materials from PCVs.
Section B: Hydrogen explosion in reactor building	Hydrogen behavior such as building damage due to deflagration and generation of flammable organic gases in the PCV were examined based on images of hydrogen explosions and damage to buildings, etc.
Section C: Damage to Unit 1 PCV pedestal	Progression of events after core meltdown was investigated based on damage to piping and concrete around the PCV pedestal and deposits of fuel debris and other materials.

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Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (2/9)

Section A: Contamination by Cs-137

Outline of investigation

The team conducted field investigations and analyses, such as dose rate measurements of shielding plug*1 and SGTS*2 pipe, to assess the Cs-137 contamination situation and estimate the migration behavior during the accident.

*1 Three layers of concrete plates installed on top of the primary containment vessel (PCV) for shielding.

*2 Stands for Standby Gas Treatment System, an air conditioning system for treating the air in the reactor building to which the PCV vent line is connected.

As a result, the following findings were obtained:

A-1: Contamination in gaps in the shielding plug
A-2: Cs-137 leakage route
A-3: Migration model of Cs-137

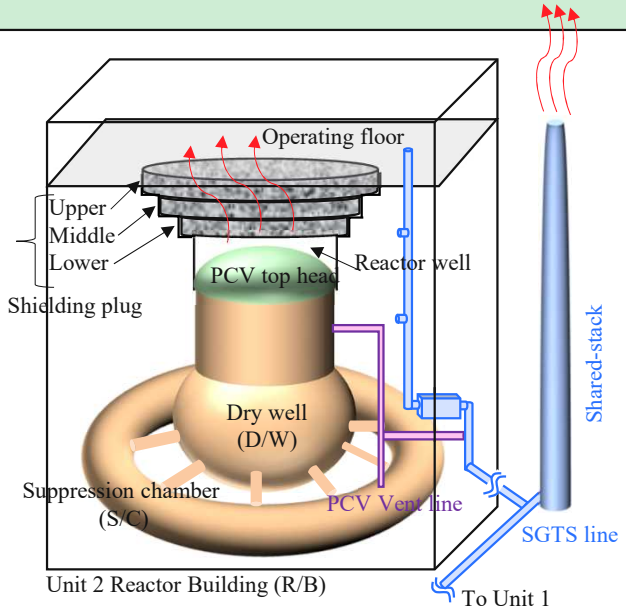

Figure. Names of sites related to the Cs-137 leakage routes

Obtained findings

A-1: Contamination in gaps in the shielding plug

The results of dose rate measurements on the operating floor and reactor well indicated that a radiation source existed in the gap between the shielding plugs. Based on the TEPCO's measurement results, the investigation team concluded that there were tens of PBq of Cs-137 in Unit 2 and about 30 PBq of Cs-137 in Unit 3 between the upper shielding plug and middle shielding plug.

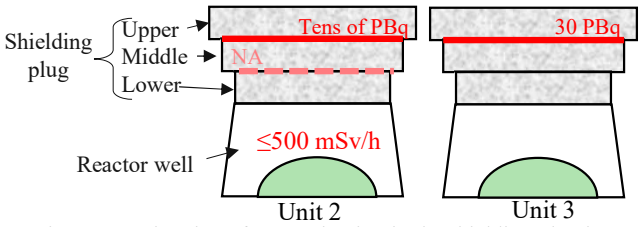

Figure 1. Estimation of contamination in the shielding plug in Unit 2 and Unit 3

A-2: Cs-137 leakage route

The results of the dose rate measurement on the top surface of the Unit 2 shielding plug confirmed that high doses at the joints of the shielding plug, which is divided into three parts, and at the intersection of the joints, suggesting that the joints of the shielding plug (rather than the outer edge of the shielding plug as previously thought) are likely to be the main leakage routes of Cs-137.

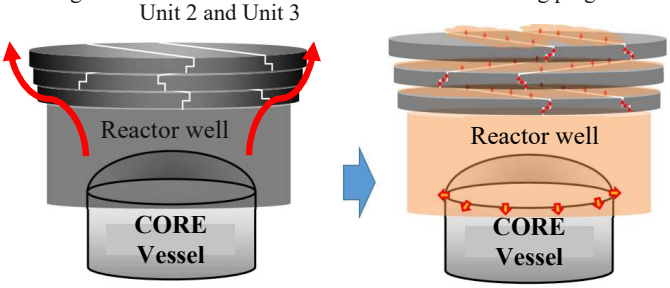

Figure 2: Cs-137 leakage routes

A-3: Cs-137 migration model

The results of the SGTS pipeline dose rate measurements revealed the following situation:

- High levels of contamination at the bottom of the shared-stack.
- Unit 2 is more contaminated than Unit 1 SGTS pipeline, which was successfully vented.

The analysis of vapor flow reproduction using the RELAP code also suggested that Cs-137 migrates with vapor flow and that contamination accumulates when the vapor condenses.

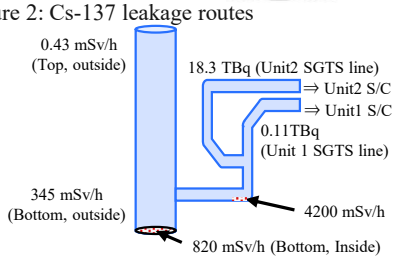

Figure 3. Contamination situation of No. 1, No. 2 shared-stacks and SGTS

Discussion and future research directions

The contamination of the shielding plug and SGTS pipeline suggests that Cs-137 migrated with the steam and accumulated due to condensation. To investigate the dose increase at the off-site side after the release of radioactive materials from the power plant, data from monitoring posts and other sources located off-site are being analyzed. Data around March 12, when background doses were low, and data from the peak period after that will be used to analyze the release behavior of radionuclides.

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Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (3/9)

Section A: Contamination by Cs-137 (A-1: Contamination in gaps in the shielding plugs)

Investigation of contamination of Unit 2 shielding plug

<Structure of shielding plug>

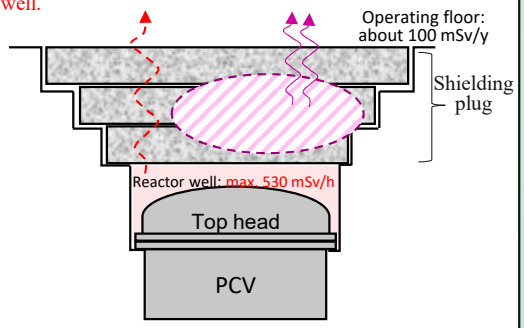
- Consists of three layers of 60-cm-thick reinforced concrete (upper, middle, and lower layers).
- Each layer has a diameter of 11.3–11.8 m and is divided into three sections.

Identification of sources contributing to the air dose rate on the shielding plug

- Even after the decontamination of the operating floor, the air dose rate above the shielding plug did not decrease and remained higher than that on the surrounding floor (about 100 mSv/h).
- The maximum air dose rate in the reactor well was 530 mSv/h.
- The surface contamination density on the shielding plug was similar to that on the surrounding floor.

Therefore, it is presumed that there is a very strong dose at one of the locations inside the shielding plug.

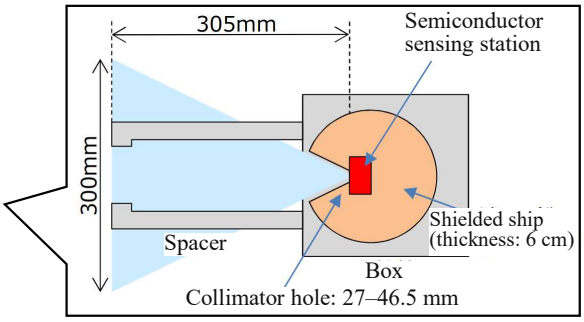
Given the shielding by the shielding plug, it is unlikely that this is due to radiation from the reactor well. ⇨ Presumed to be from shielding plug



Estimation of contamination level in gaps in the shielding plug

- In November 2018, TEPCO measured the air dose rate at a height of 1.5 m from the floor (*2) and found it to be 79-148 mSv/h on the shielding plug. Based on the values, an evaluation was conducted using the gamma-ray calculation code (*3), and it was estimated that approximately 70 PBq of Cs-137 was present in the gap between the upper shielding plug and the middle shielding plug.
- Additionally, it was estimated to be more than 20-40 PBq based on the results of measurement by TEPCO using a detector with lead shielding at a height of 30.5 cm from the floor (right figure).

Based on the above, it is considered that tens of PBq of Cs-137 exists in the gap between the upper shielding plug and middle shielding plug.

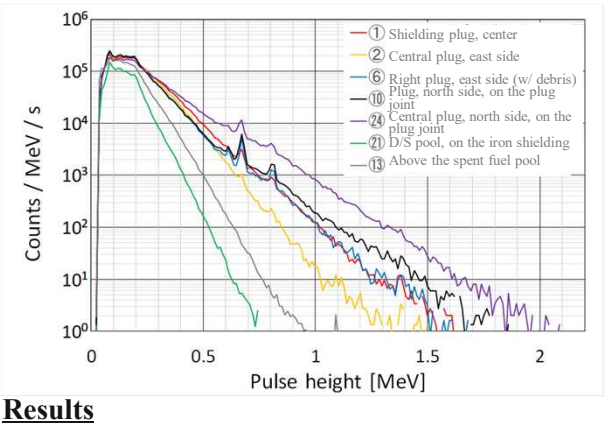


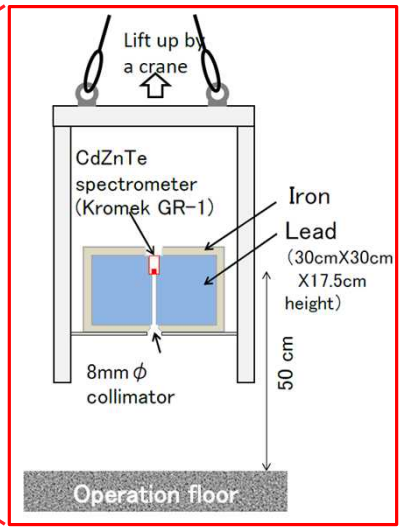
*1 TEPCO, " Situation of response to high concentration of contamination in Unit 2shielding plug," July 8, 2021
*2 TEPCO, "Results of the investigation after moving and cleaning up the remaining objects in the Unit 2 reactor building opefro," February 28, 2019
*3 Electromagnetic cascade Monte Carlo code egs5

Investigation of contamination of Unit 2 shielding plug

Measurement method

Measured on Unit 3 shielding plug by spectrometer with lead collimator hung by crane





Results

The surface of the shielding plug of Unit 3 was eliminated by about 5 mm thick, and hence surface contamination is unlikely. Consequently, it seems that the total absorption peaks observed in this measurement with a sufficient collimator represent transmission lines from the lower part of the shielding plug. Based on this assumption, the contamination density of Cs-137 on the underside of the shielding plug was estimated to be 2.7×10^{10} Bq/cm^2 on average (equivalent to 31 PBq assuming a simple uniform distribution over the entire surface).

Source: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 31st meeting Document 3-1, https://www.nra.go.jp/data/000315708.pdf

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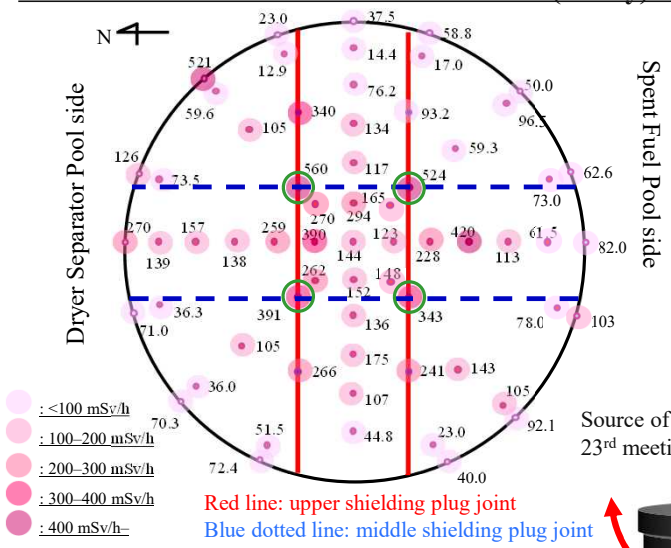
Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (4/9)

Section A: Contamination by Cs-137 (A-2: Cs-137 leakage pathways)

Investigation of contamination of Unit 2 shielding plug

In October 2021, TEPCO and the NRA measured the dose rate on the Unit 2 shielding plug and obtained the following results.

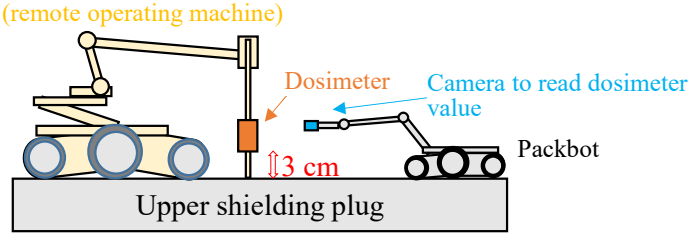
Measurement results of ambient dose rate (mSv/y) at 64 points



Red line: upper shielding plug joint
Blue dotted line: middle shielding plug joint

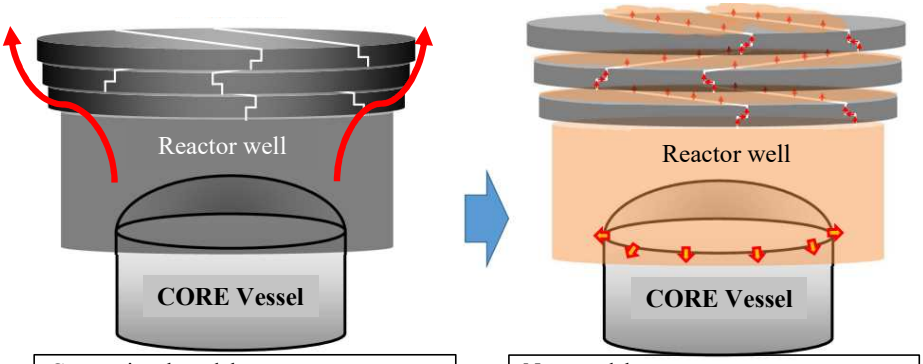
Measurement Methods

Using remote operation machine, values of dosimeter are read by camera at 3cm high



Source of left figure: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 23rd meeting Document 5-1, https://www.nra.go.jp/data/000367850.pdf

- The dose rates on the dividing line of the shielding plug (red line) and at the intersection of the dividing lines (green circle) are higher than those at the circumference, suggesting that the leakage routes of Cs-137 are not at the outer circumference of the shielding plug as previously assumed, but at the shielding plug joints.

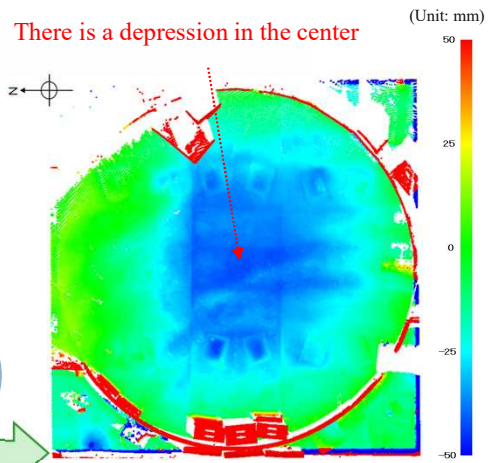


Investigations on Unit 2 shielding plug shape

In December 2021, the NRA measured the shielding plug geometry using a 3D laser scanner in order to investigate the leakage routes and it turned out that the center of the shielding plug was dropped by 6cm in the most.

Unit 2 shielding plug

There is a depression in the center



- This deformation indicates that the dividing line of the shielding plug may be a Cs leakage route.

Source: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 28rd meeting Document 2-1-3, https://www.nra.go.jp/data/000382268.pdf

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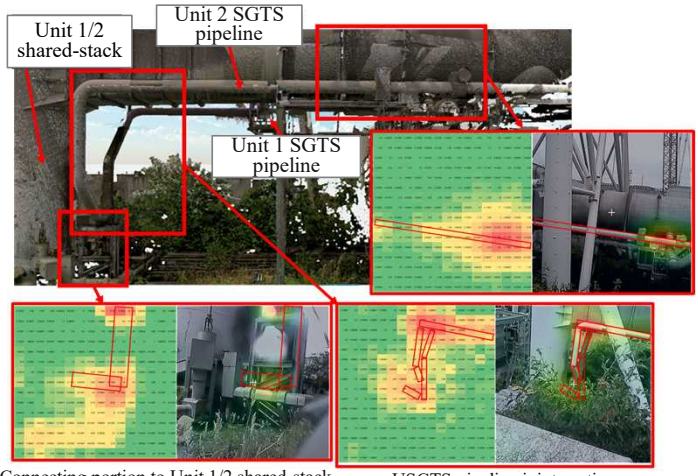
Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (5/9)

Section A: Contamination by Cs-137 (A-3: Cs-137 migration model)

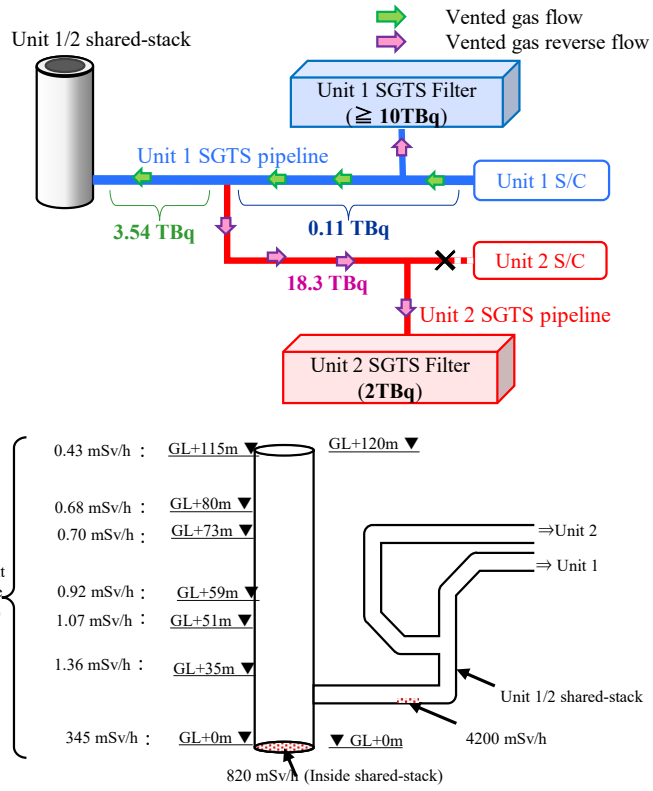
Investigation of Unit 1 & 2 SGTS pipeline contamination

The investigation team performed dose rate measurements and gamma camera measurements in the SGTS pipelines of Units 1-4, which were used for PCV venting, and summarized the contamination situation.

① The Unit 2 SGTS pipeline without successful PCV venting is more contaminated than the Unit 1 SGTS pipeline with successful PCV venting.
② The Unit 1 SGTS filter train is more contaminated than the Unit 2 SGTS filter train.
③ The contamination of the Unit 1/2 shared-stack is more severe at the bottom of the exhaust stacks.



Data collected from the Secretariat of the Nuclear Regulation Authority on July 9, 2020



Source of left picture: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 13th meeting Document 3, https://www.nra.go.jp/data/000325407.pdf

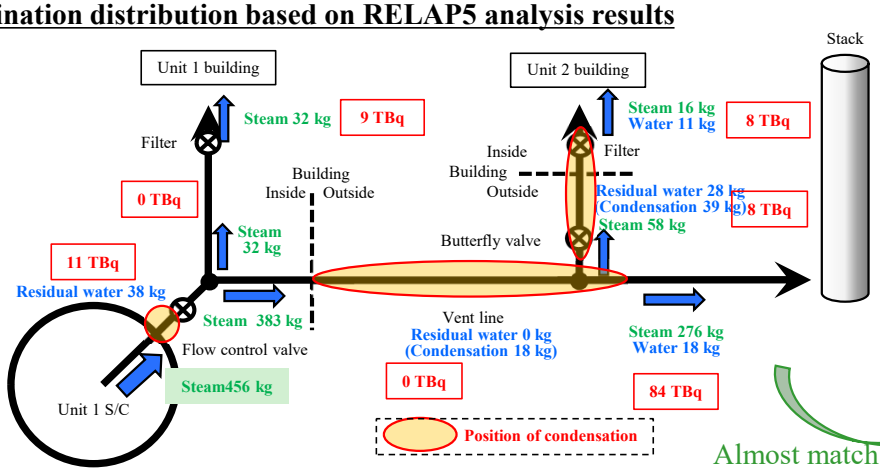
Analysis of contamination inside Unit 1 & 2 SGTS pipeline

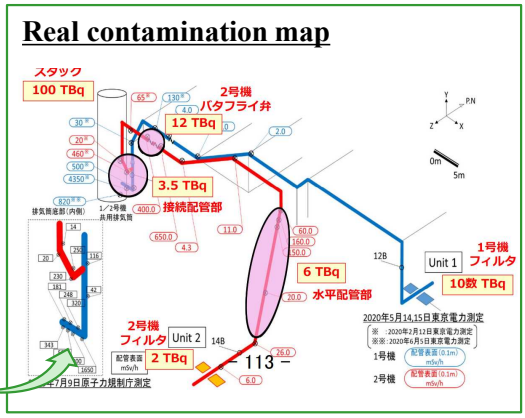
The causes for the increased contamination in Unit 2 without PCV venting compared to Unit 1 with PCV venting were analyzed by replication using the thermal hydraulic system analysis code RELAP5 to analyze the SGTS pipeline contamination.

Evaluation assumptions

- Assume 130 TBq for a total mass of 456 kg of steam flowing out of the S/C
- Assume that the portion reaching the outlet boundary of Unit 1 & 2 buildings remains in the filter

Contamination distribution based on RELAP5 analysis results





Almost match

- Backflow occurred at the gravity damper in the Unit 1 & 2 SGTS pipeline system, and Unit 1 PCV vent gas flowed back into each reactor building.
- Vapor condensation in the pipelines was suggested to be the primary cause of the contamination.
  - The residual location of the condensate coincided with the highly contaminated area (identified in the on-site investigation).

Source: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 32nd meeting Document 3, https://www.nra.go.jp/data/000408673.pdf

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Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (6/9)

Section B: Hydrogen explosion in nuclear reactor building

Outline of investigation

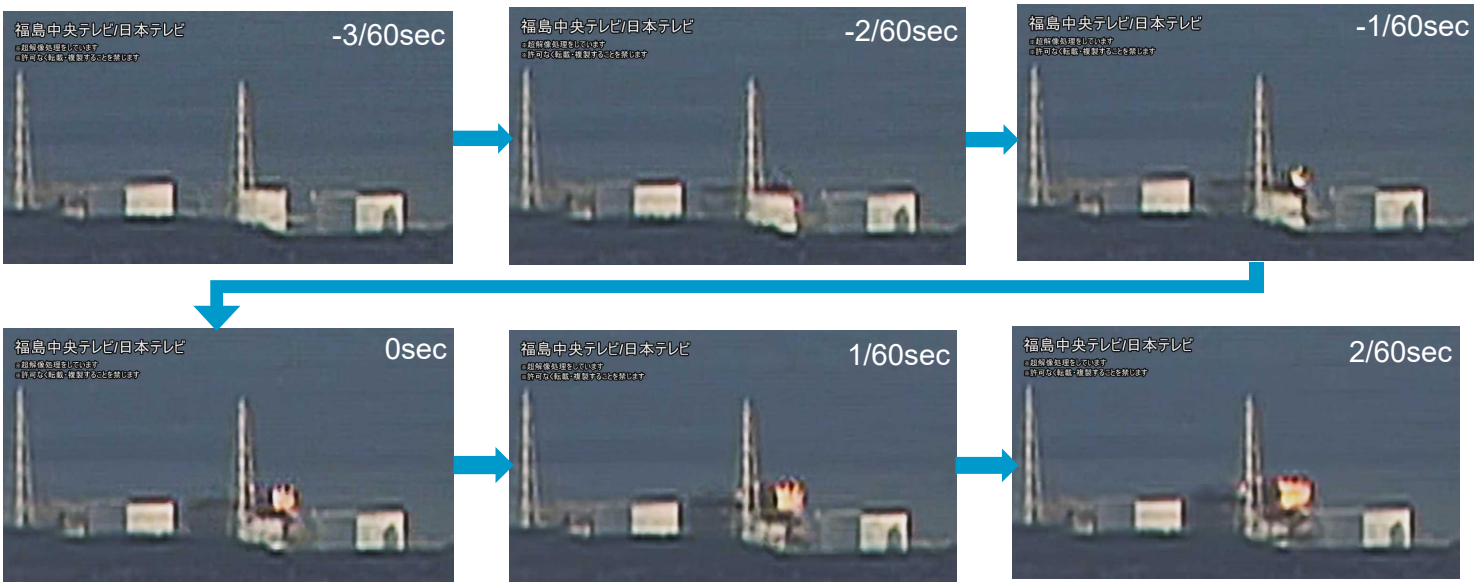
In order to investigate the behavior of hydrogen explosion in the reactor building and involvement of flammable gases, the NRA conducted the analysis below.
B-1: Video analysis of the explosion events
B-2: Survey of damage in the buildings
B-3: Cable heating analysis to identify flammable organic compounds

Investigation B-1 Video analysis of the explosion events

In order to investigate the behavior of hydrogen explosion in the reactor building the NRA analyzed the video at the accidents in March 2011 with the cooperation of Fukushima Central Television and Nippon Television.

(1) Comparison of the videos of hydrogen explosion of Unit 1 & Unit 3

(2) Analysis of the video of hydrogen explosion of Unit 3 flame by flame



Analysis of (1) shows that in case of Unit 3, it is observed that fragments from Unit 3 building are lifted up with black plume not like in case of Unit 1.
Analysis of (2) shows that the combustion of Unit 3 continued relatively long. Therefore, it is unlike that the fragments is lifted up only by first explosion energy because such large explosion will extinguish the fire.
The series of fire in the picture (2) is orange, so it is possible that there are organic compounds in the gases reacted.

The rising black smoke in the Unit 3 reactor building may not have been caused by the impact of the explosion but by the rising air currents caused by the combustion of flammable gases.

Source: the NRA report on FDNPSA investigation till 2021 March https://www.nra.go.jp/data/000345595.pdf

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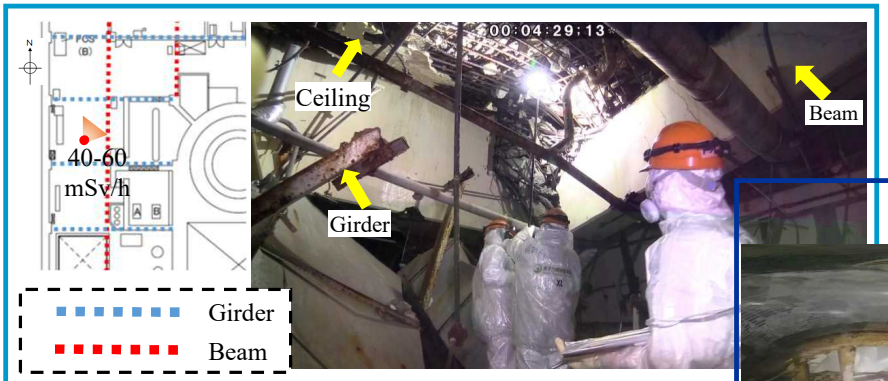
Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (7/9)

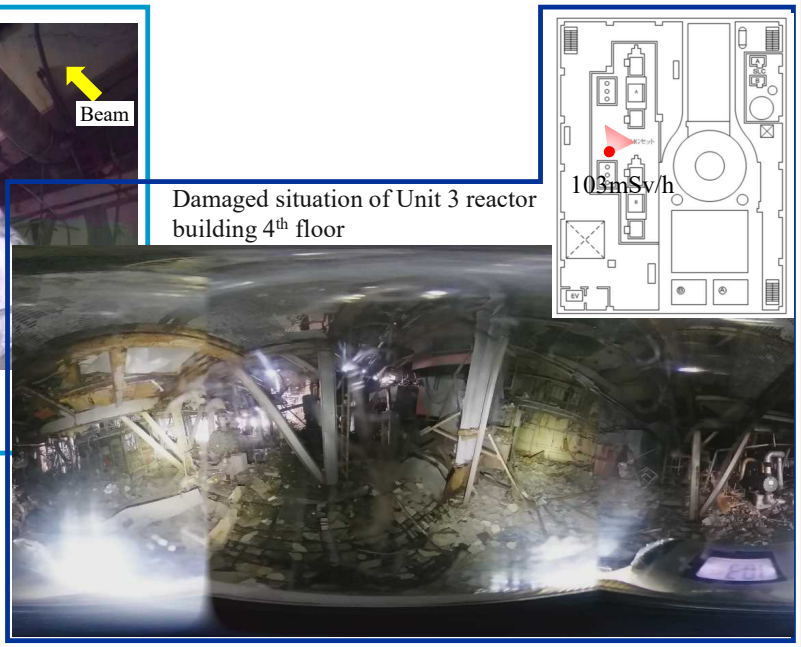
Section B: Hydrogen explosion in reactor building

Investigation B-2 Survey of damage in building

- The investigation team confirmed that some of the ceiling beams on the third floor of the Unit 3 reactor building were damaged. This suggests that the explosion occurred not only on operating floor (5th floor of the reactor building) but also on the 4th floor.
- The explosion at the time of the accident was not necessarily a detonation. However, even if it was a deflagration, it had enough energy to damage the reactor building.



Damage to ceiling beam on third floor of Unit 3 reactor building
https://www.youtube.com/watch?v=2ogtUCOnQDg around 6:15



Damaged situation of Unit 3 reactor building 4th floor

Regulatory action

The NRA decided to add hydrogen protection of the reactor building as an objective of PCV venting.
(At 38th FY2022 NRA, September 14, 2022)

Investigation B-3: Cable heating analysis to identify flammable organic compounds

In order to investigate deflagration by flammable gases (hydrogen and organic gases), heating tests were conducted on cables and other equipment used in the PCV. As a result, it was confirmed that pyrolysis product gases of organic materials were generated under high temperature conditions.
Hydrogen combustion tests are scheduled to be conducted in the future.

Offered sample	components	Pictures	Cross section image	Application
PN cable (insulator)	Flame-retardant ethylene propylene rubber			RPV bottom thermometer cable (140m)
PN cable (sheath)	Special chloroprene rubber			
CV cable (insulator)	Cross-linked polyethylene			RIP pump power cable
CV cable (sheath)	Flame-retardant heat-resistant vinyl			
Thermal insulator	Urethane			Thermal insulator of CCW system line (8m³, 320kg)

The following heating tests were conducted at JAEA.
1) Thermogravimetry (TG) mass spectrometry (MS)
2) Pyrolysis gas chromatography (GC)-mass spectrometry (MS)
Environmental conditions: Nitrogen atmosphere
Measuring range: Room temperature ≤ 1200°C
Temperature increase rate: 10°C/min

In the heating test under nitrogen environment, H_2O and CO_2 were detected, and toluene, an additive for cables, etc., was confirmed at the temperature of 400–500°C.
Oxygen and water vapor will be examined as environmental conditions for heating tests in the future.

Directions for future investigation

Hydrogen explosions have significant effects on progress after accidents, such as making subsequent accident management measures difficult. However, much remains unknown about hydrogen behavior, such as the occurrence and energy of deflagration, hydrogen leakage and retention in the reactor building, and the effects of combustible organic gases. The elucidation of these issues will help to improve the safety of nuclear facilities, and through hydrogen combustion tests and other tests and analyses related to hydrogen behavior, we will continue to expand knowledge and understanding of these issues.

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Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (8/9)

Section C: Damage to Unit 1 PCV pedestal

Outline of investigation

TEPCO has been conducting internal investigations on Unit 1 PCV since February 2022.
In the investigations, a remotely operated underwater vehicle (ROV) was deployed from the X-2 penetration on the west side of the Unit 1 PCV and moved in a counterclockwise direction, taking images of the area around the pedestal opening at the 180° circumferential point*.

* Videos of the surveys are available on TEPCO's website.
February survey: https://www.tepco.co.jp/library/movie/detail-j.html?catid=107299&video_uuid=k593g02e
March survey: https://www.tepco.co.jp/library/movie/detail-j.html?catid=107299&video_uuid=s19dq021
May survey: https://www.tepco.co.jp/library/movie/detail-j.html?catid=107299&video_uuid=og07od6u

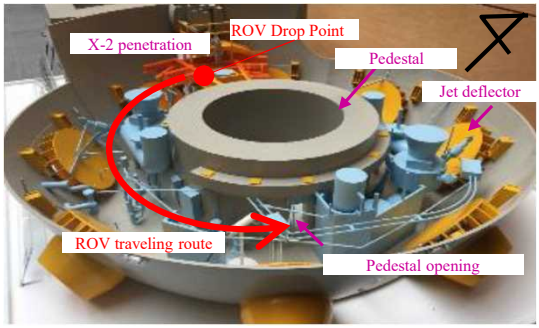
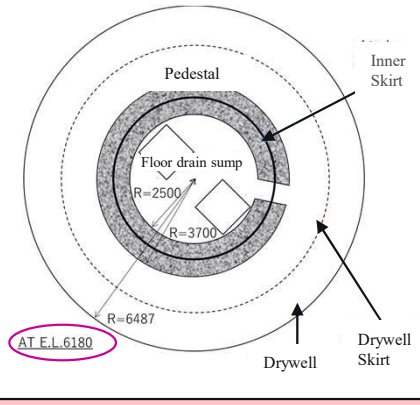
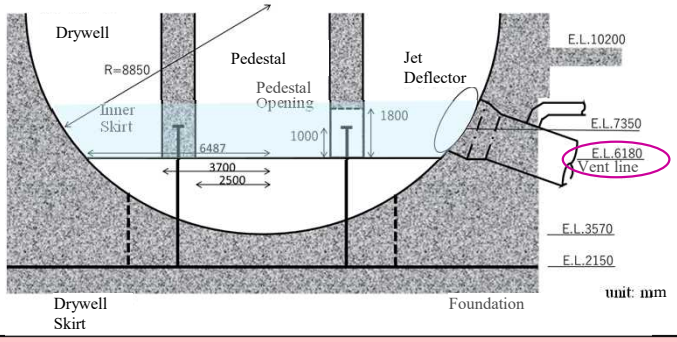
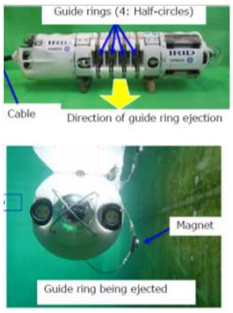


Figure 1 Structure model of PCV pedestal

Provision of reference: IRID & Hitachi-GE Nuclear Energy, Ltd.

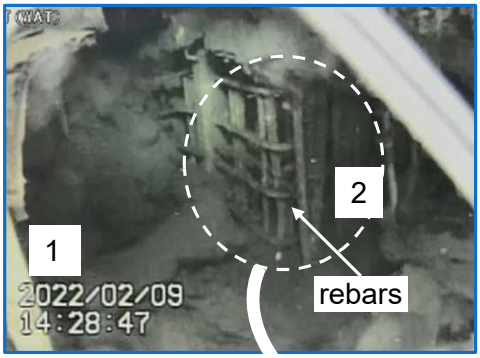


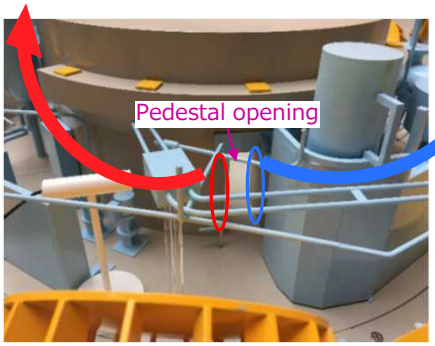


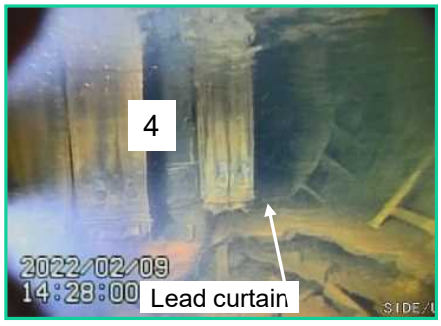


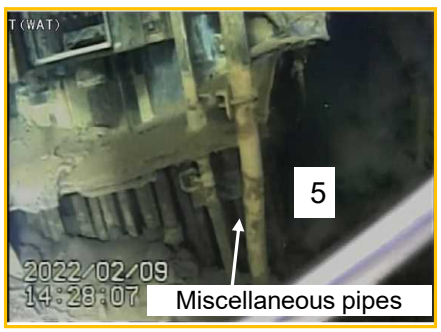
Damaged concrete of pedestal

1. Debris mound seems to exist near the pedestal opening. (not clear)
2. Loss of concrete at both sides of the opening. Rebars seems to be intact.
3. Concrete is lost only below the crust.
4. Lead net shield melted at a specific height.
5. Miscellaneous pipes are not affected severely.









Source of pictures: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 30th meeting Supplementary document 1, TEPCO, https://www.nra.go.jp/data/000395885.pdf

OECD/NEA International Conference on Regulator's Views and Priorities on Nuclear Safety and Radiation Protection 10 Years After TEPCO Fukushima Daiichi NPS Accident
Poster Exhibition, November 28th – 29th, 2022, Grand Nikko Tokyo Daiba

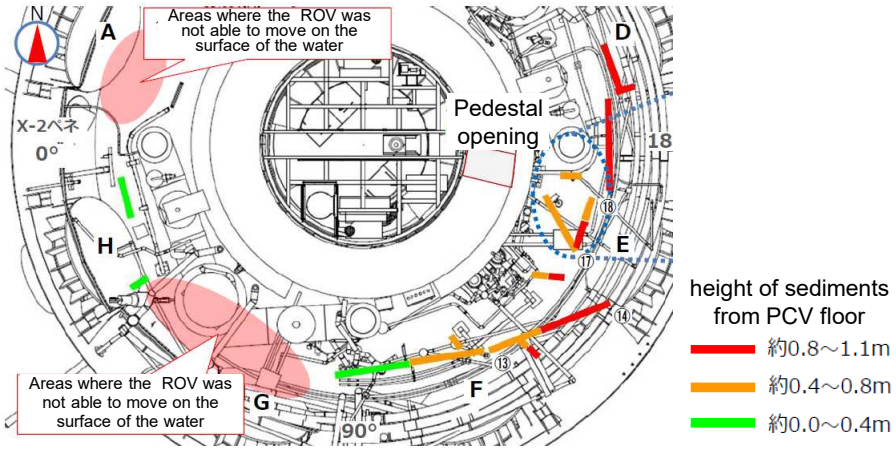
NRA JAPAN Nuclear Regulation Authority

Investigation and analysis of TEPCO's Fukushima Daiichi NPS Accidents (9/9)

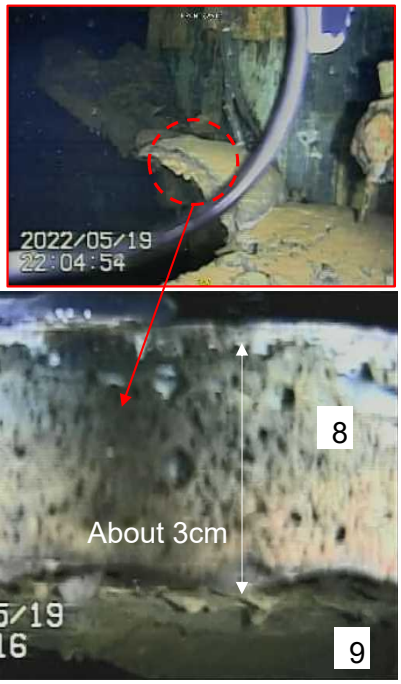
Section C: Damage to Unit 1 PCV pedestal

Crust (table-like sediments)

6. "Crust" exists from the area of opening to the other side.
7. "Crust" is the highest near the opening (~1.2m) and lowest at the other side (~0.3m).
8. "Crust" includes small bubbles. Its thickness is calculated around 3cm at a place.
9. Underside of the "Crust" seems to be smooth.



Source: "Investigation on the inside of Unit 1 PCV" P.5, TEPCO, 2022 Sept. 6, https://www.nra.go.jp/data/000403164.pdf



Situation near outer circumference of PCV (jet deflector)

10. Large bubble-like "Crust" exists under the opening ceiling.
    (The thickness is not known.)
11. No Damage is found out at the outer walls of the PCV.
12. Bubble-like image is observed on the surface of debris or crust on the PCV floor.
13. Exact situation of the PCV floor is not known.

Source of pictures: Committee of Accident Analysis of Fukushima Daiichi Nuclear Power Station 30th meeting Supplementary document 1, TEPCO, https://www.nra.go.jp/data/000395885.pdf

Major Questions

1. Why the debris dropped from the RPV did not spread out?
2. How was the concrete part alone of the pedestal wall damaged?
3. How was the "crust" formed?

Directions for future research

The findings of this study contribute to the estimation of the temperature and properties of the molten core. Based on the results of additional investigations conducted by TEPCO, including a reasonable explanation to the question above the mechanism of pedestal damage, behavior of molten core, and consistency with the conventional core-melting event progression model will be further investigated and analyzed.