（修士課程）
・原子炉廃止措置工学
Engineering for nuclear decommissioning
（博士課程）
・原子核システム安全工学特論
Advanced safety engineering of nuclear systems
（公開講座）
・軽水炉安全セミナー（原子炉廃止措置編）

福島第一の廃炉研究開発の現状と課題

Current Status and Challenges of R&D for Decommissioning of Fukushima Daiichi Nuclear Power Station

September 25, 2024

技術研究組合　国際廃炉研究開発機構
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Naoaki Okuzumi

The results are obtained under the Subsidy Project of Decommissioning and Contaminated Water Management granted by the Ministry of Economy, Trade and Industry.

Contents

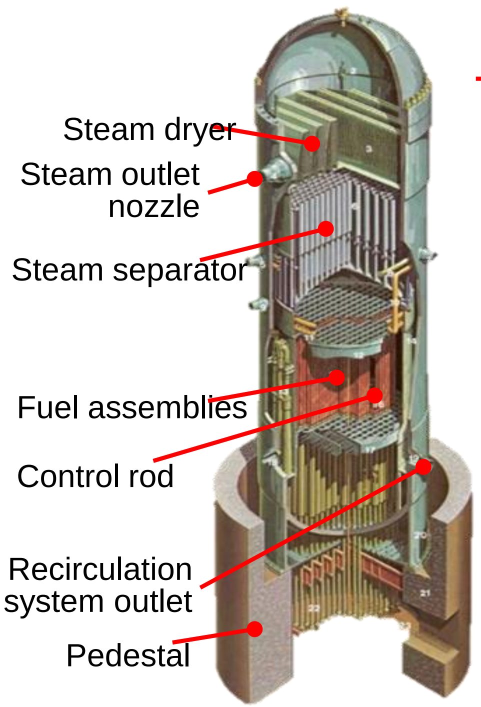
PCV: primary containment vessel

Contents

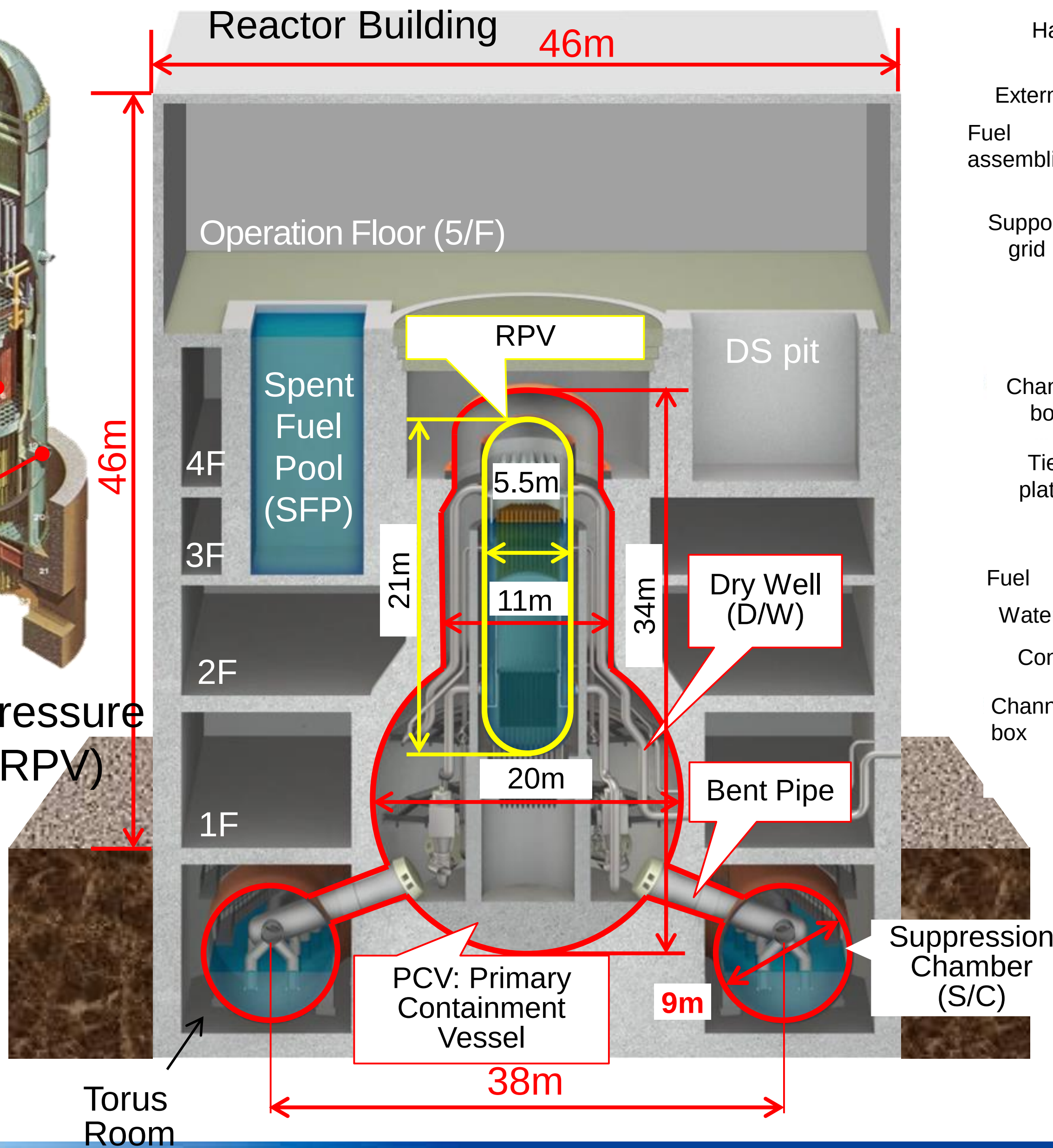
PCV : Primary containment vessel

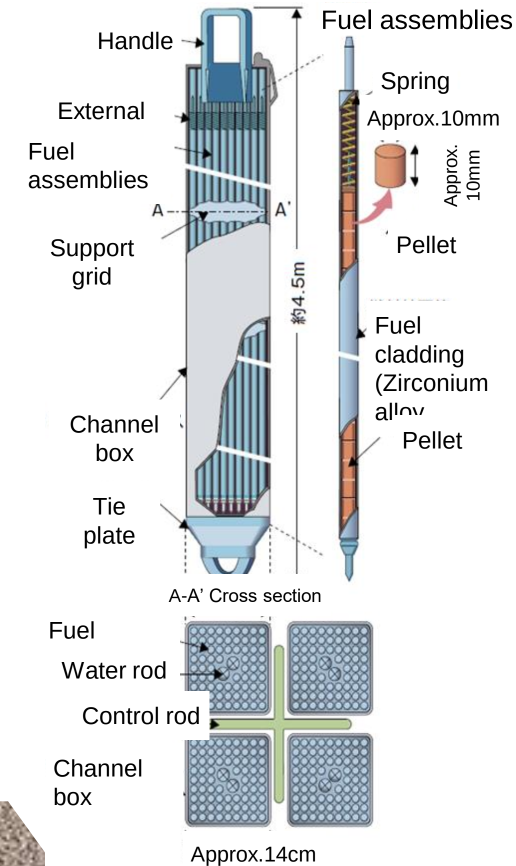
Video: Introduction of IRID

Boiling Water Reactor (BWR)



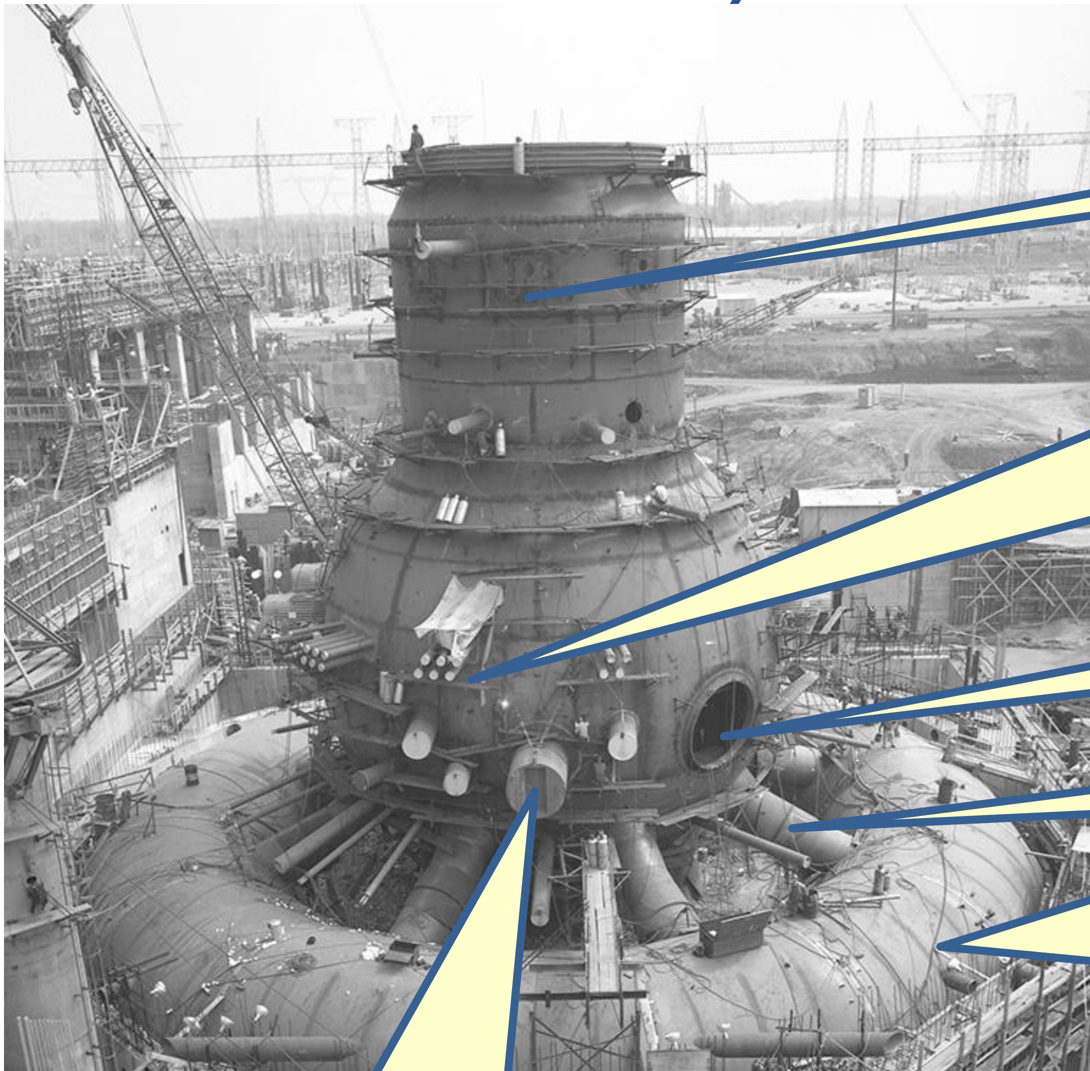
Reactor Pressure Vessel (RPV)





Fuel Assembly

Appearance of Primary Containment Vessel (PCV) (Photo of PCV under construction)



Dry well (D/W): Upper part of PCV above the S/C

PCV penetration： Penetrations of piping and electric wiring, etc.
Unit 1: Approx. 150 penetrations
Unit 2: Approx. 200 penetrations
Unit 3: Approx. 190 penetrations

Equipment hatch: Carry-in/out port of large equipment

Vent pipe: Connection pipe between D/W and S/C

Suppression Chamber (S/C): The S/C condenses water vapors generated when an accident occurs to suppress the increase of pressure in PCV.

Air lock: Entrance and exit for humans

"*Browns Ferry Unit 1 under construction 1966.Sep.*"
Tennessee Valley Authority – TVA's 75th Anniversary webpa

Outline of IRID

1. Name

International Research Institute for Nuclear Decommissioning (IRID)

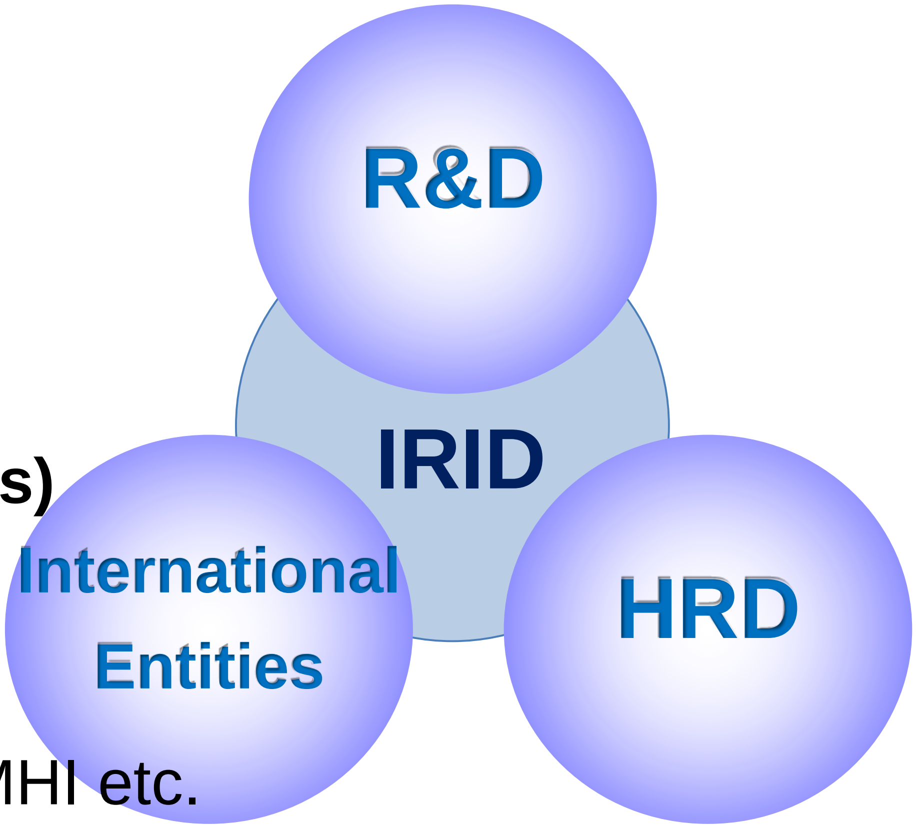
https://irid.or.jp/en/

2. Date of Establishment

August 1, 2013

3. Membership (19 organizations)

- 2 research institutes
  - JAEA etc.
- 4 manufacturers
  - Toshiba ESS, Hitachi-GE,MHI etc.
- 12 electric utilities, etc.
  - TEPCO Holdings etc.



Introduction: R&D projects conducted by IRID

1. R&D for fuel removal from spent fuel pool

- Evaluation of **Long-term Structural Integrity** of Fuel Assemblies Removed from Spent Fuel Pool — Completed in March 2016

3 R&D for Radioactive Wastes

- Technology for **Proceeding Process Methods** of Radioactive Wastes
- Treatment and **Disposal of Solid** Radioactive Wastes

Completed in March 2019

2 R&D for Fuel Debris Retrieval

Technology for Decontamination and Dose Reduction

- **Remotely Operated Decontamination** Technology in R/B

Completed in March 2016

Fuel Debris Retrieval Technology

- Retrieval Technology for Fuel Debris and Internal Structure: **Criticality Control/Fundamental Technology/ Small Neutron Detector**

Completed in March 2019

- **Development of Retrieval Technology and Method** For Fuel debris and Internal Structures
- **Dust collection System for Retrieval of Fuel debris and Internal structures**
- Technology for **Containment, Transfer And Storage** of Fuel Debris
- **Development of Safety System** for fuel Debris retrieval

Technology for Environmental Improvement

<Ensuring of the stable state>

- **Corrosion Control** Technology in RPV/PCV — Completed in March 2018
- **Full-scale test** for Repair Technology for PCV Leak Points — Completed in March 2018
- **Full-scale Test** for Water Circulation Technology in PCV — Completed in March 2019

Investigation and Analysis Technology

＜Indirect Investigation＞ ＜Direct Investigation＞

- **Fuel debris detection Technology for RPV** — Completed in March 2018
- Upgrading for **Identifying Conditions Insides the Reactor** — Completed in March 2018
- Technology for **Detailed Investigation Inside PCV** — Completed in March 2019
- **Investigation Technology** Inside the RPV
- PCV detailed Investigation: **Demonstration Through X-6 penetration**
- PCV Detailed Investigation: **Demonstration of Sediments**
- **Fuel Debris Characterization** and Analysis
- **Fuel Debris Sampling Technology/** /Increase of Retrieval Scale for Fuel Debris

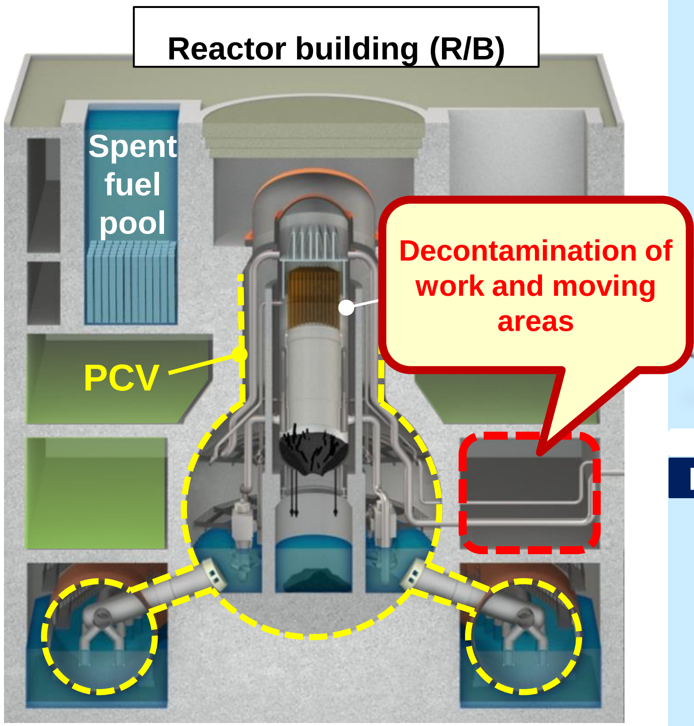
Contents

PCV : primary containment vessel

Remote Decontamination Technology

Needs for technological development

Humans cannot access the R/B because radiation levels are high in the R/B. It is necessary **to improve work environments (dose reduction).**



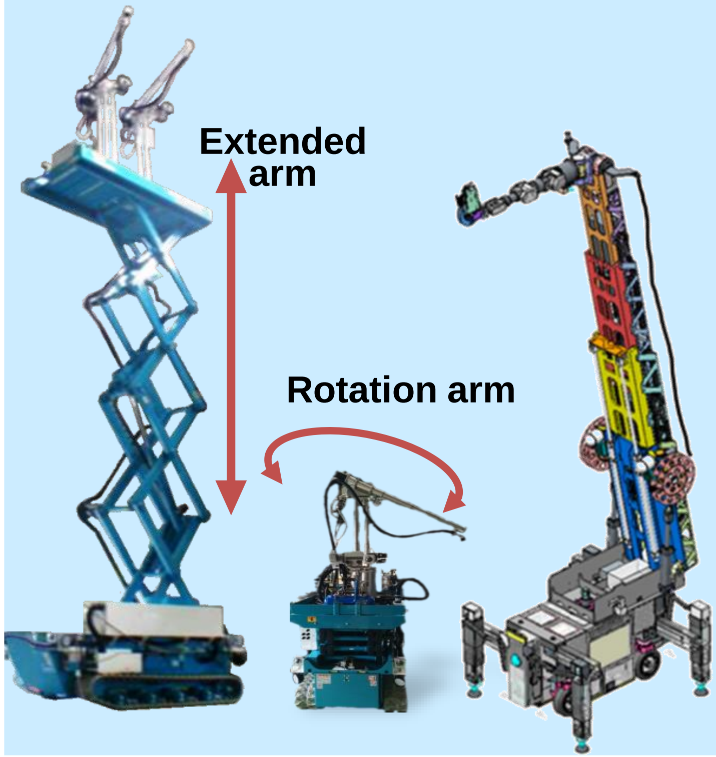
For low places (floors and lower part of walls)

Suction and blast

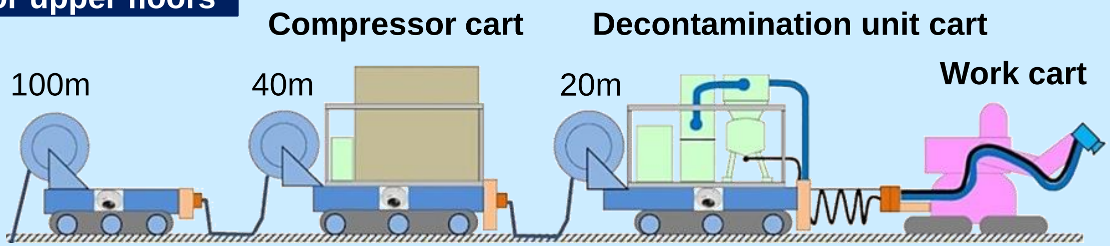
High pressure water injection

Dry ice blast

For high places



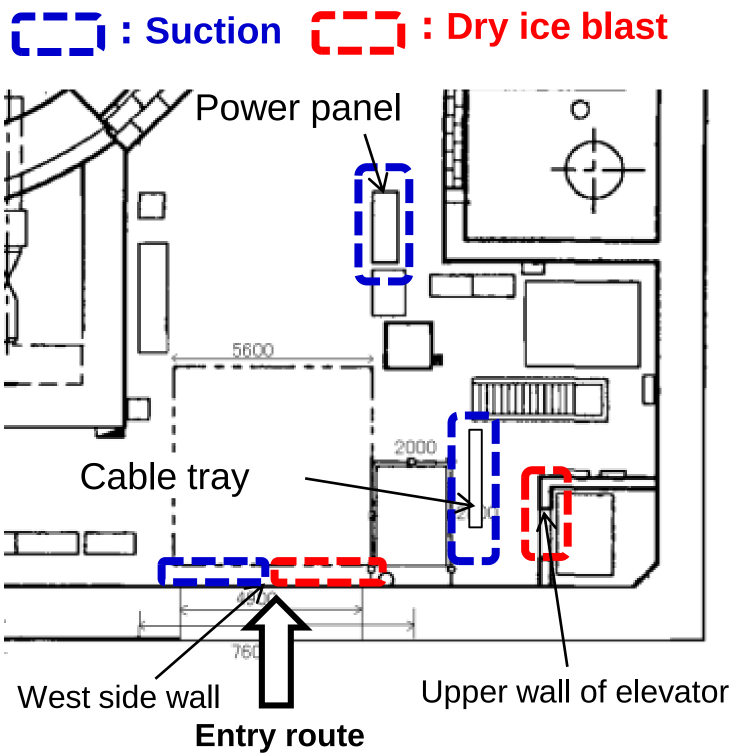
For upper floors



Remote Decontamination Technology

Site application (Unit 3)

Suction and dry ice blast decontamination was performed on 1st floor of the **Unit 3 R/B** from January 2016 to February 2016.



Photos of transporting decontamination equipment from a container

Photo of decontamination equipment moving to the Unit 3 R/B

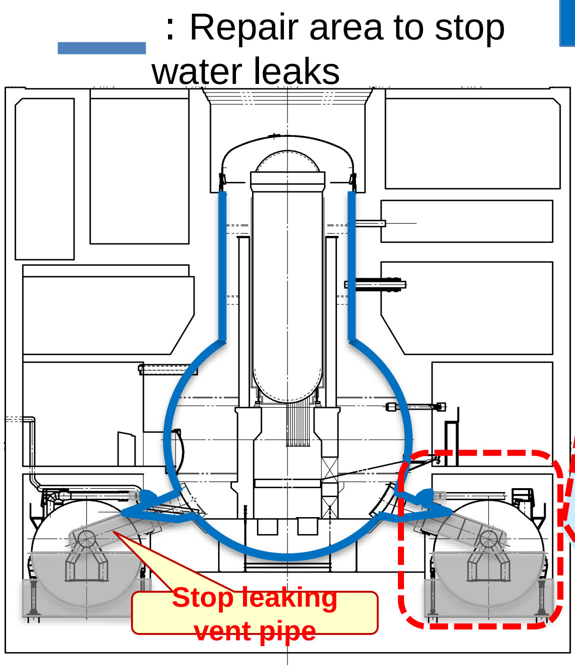
Contents

PCV : primary containment vessel

Repair Technology to Stop Water Leaks from Primary Containment Vessel (PCV)

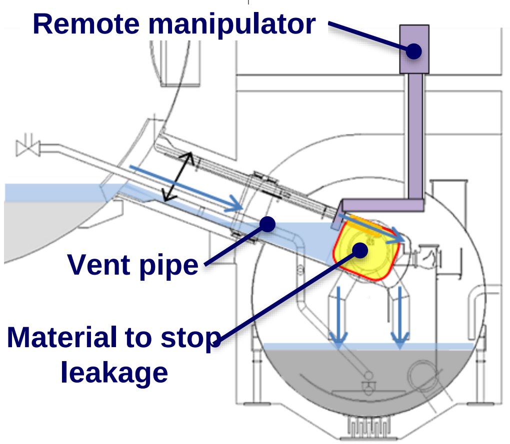
Test for stopping water leaks from vent pipe

Water stop performance was verified by using the 1/2 scale test facility (in factory).

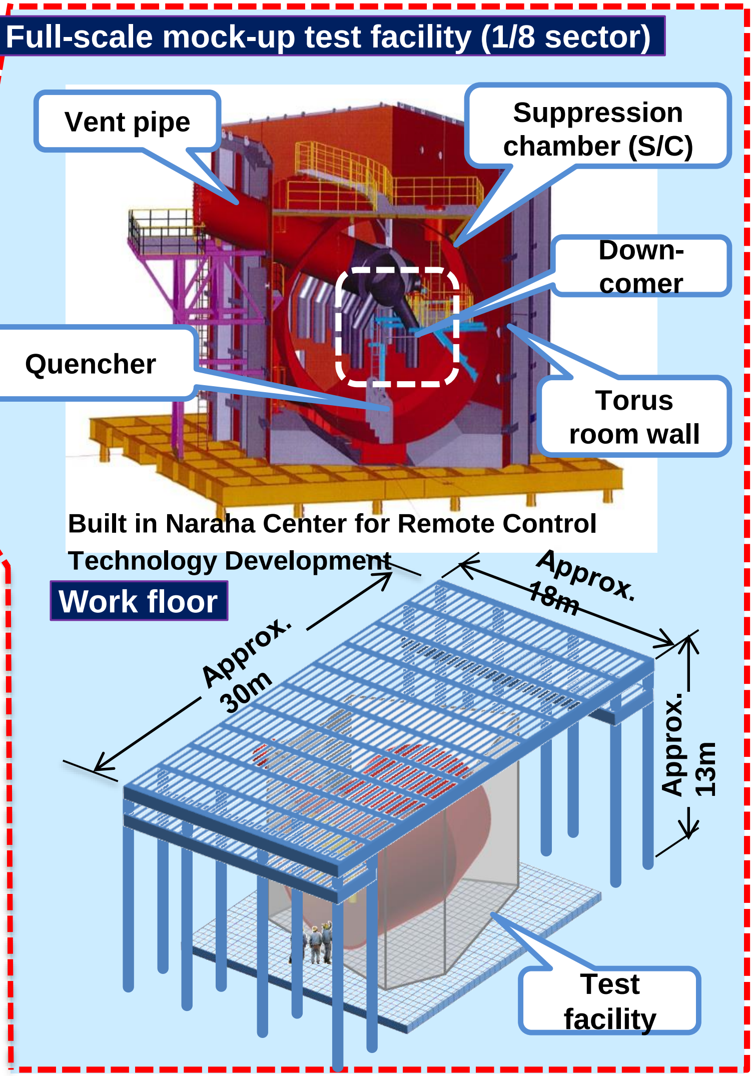


Test for stopping water leaks

Water stop performance of the material was verified by using the full-scale test facility (outdoor).



Full-scale mock-up test



Confirmation of Procedures for Full-scale Test Facility (JAEA Naraha Center for Remote Control Technology Development)

Purpose

- Creating of procedure manual by using a full-scale test facility considering actual onsite work to **determine the applicability of the actual equipment.**

Major work

- The procedures of the following three methods for water stops are tested to verify workability and performance of concrete placing.
  ① Stop water leaks from vent pipes
  ② Stop water leaks in the S/C by injecting filling
  ③ Strengthen the S/C support column

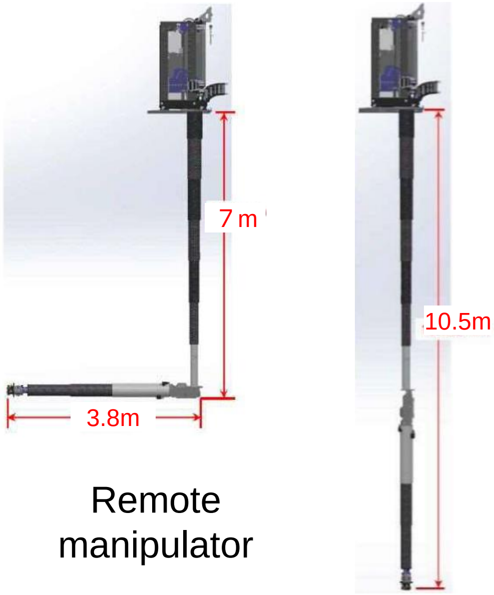
Test period

Nov. 2016 – March 2018

Appearance of test facility

Inside of the test facility (in the S/C))

Verification test of workability to strengthen the S/C support column



Remote manipulator

Contents

PCV : primary containment vessel

Muon Transmission Measurement

- Muons are secondary cosmic rays, which generate when radiation from space collides with the atmosphere of the Earth. The cosmic ray muons are high-energy particles and can pass through materials.

- Muon tomography can measure the number of muons that pass through the reactor building to image the density of materials such as X-ray. It can be used to image the distribution of fuel debris in the reactor pressure vessel (RPV). (Smaller number of muons will pass through high density regions so higher density regions show dark shadow).

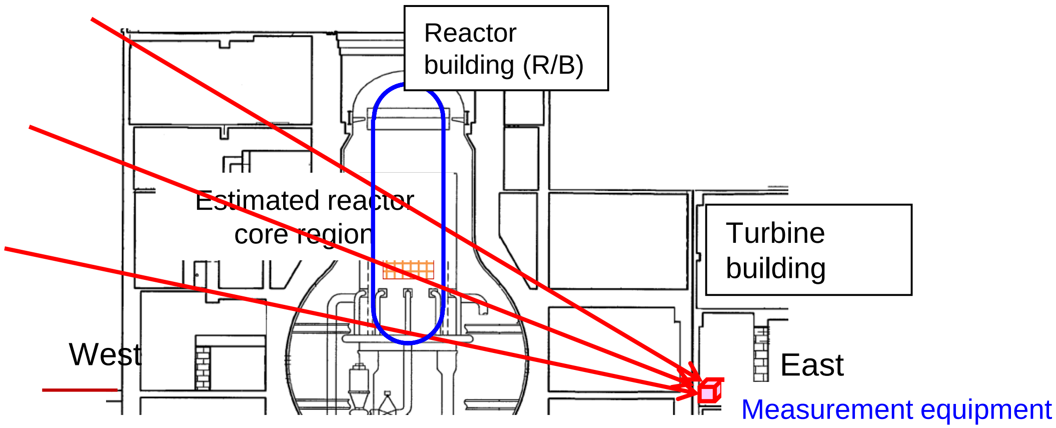


Illustration of measuring muons passing through the reactor building (horizontal cross section)

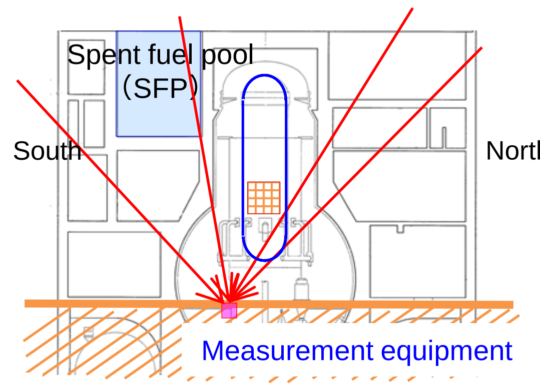
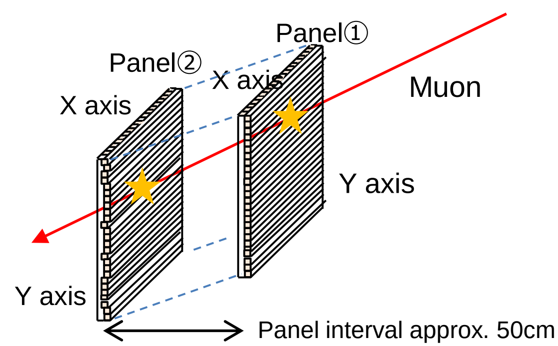


Illustration of measuring muons passing through the reactor building (vertical cross section)

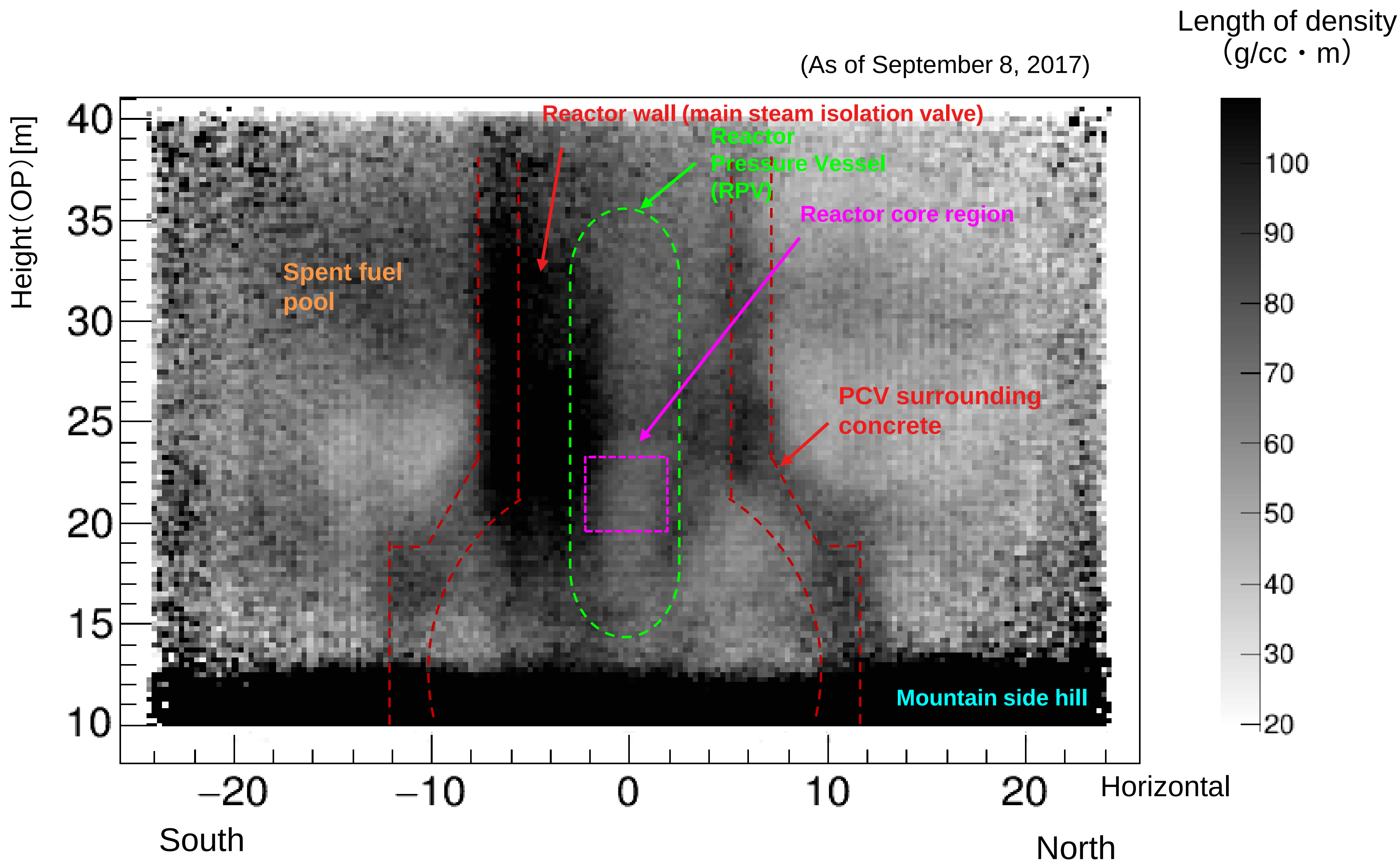
<Measurement principle of the muon transmission method (illustration)>

Two panel detectors (plastic scintillator) that are placed in the measurement equipment can detect muons falling from space and calculate their trace on where they have passed through from the coordinates (X and Y axes) on the panel.



Quoted from a material of TEOCO Holdings, Inc. website

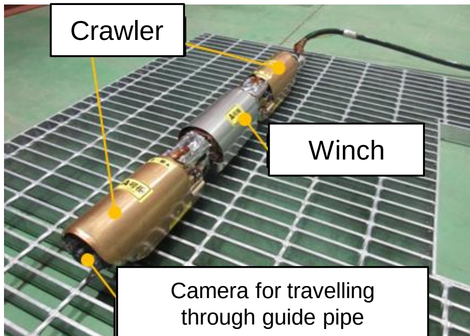
Measurement Result of the Muon Transmission Method for Unit 3



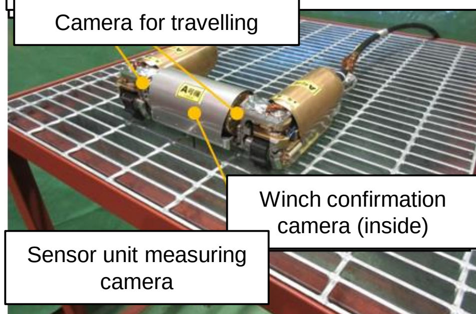
Quoted from report released from the TEPCO Holding Inc. website.

Robot Investigation of the PCV interiors

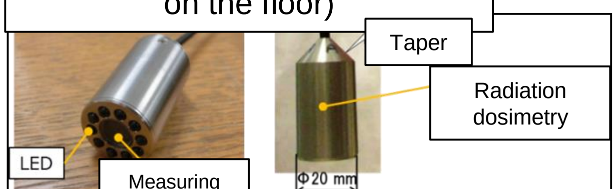
Investigation of outside the pedestal (Unit 1)



Type Ⅰ (when travelling through guide pipe)

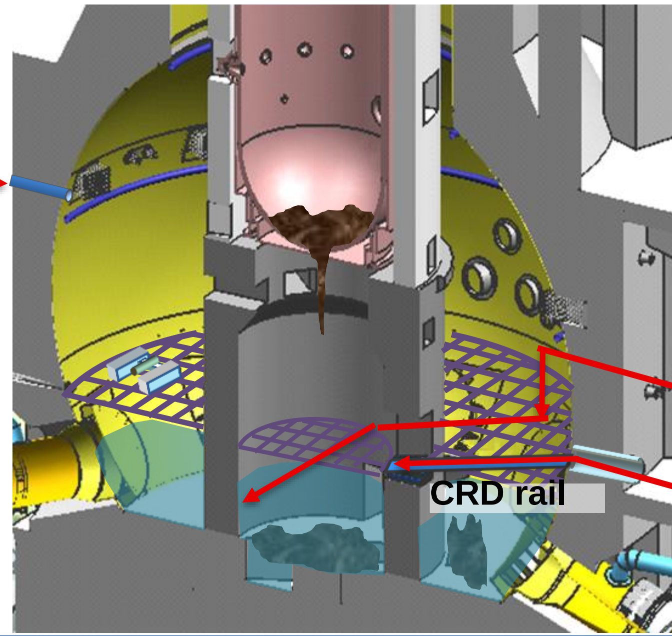


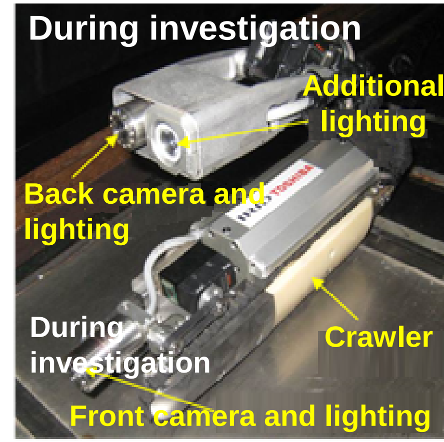
U-shape type (when travelling on the floor)



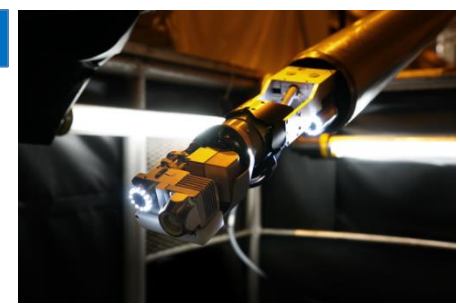
Investigation of inside the pedestal (Unit 2)

○ Remote-operated crawler robot for investigation

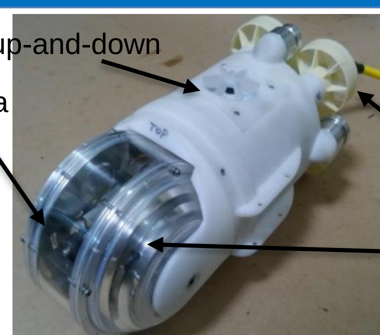




○Suspension type investigation equipment (A2' investigation)

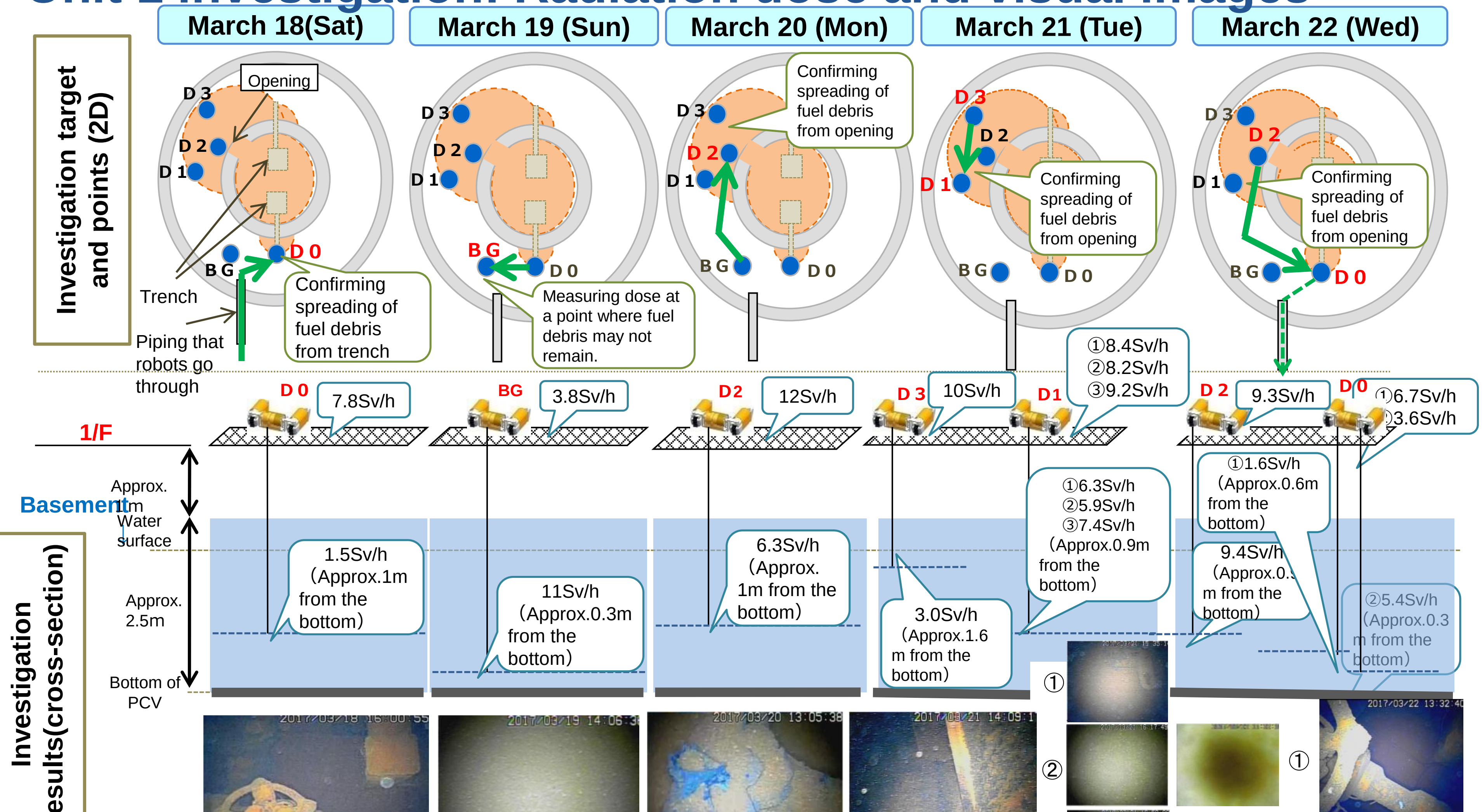


Investigation of inside the pedestal (Unit 3)



○Submersible Crawling Robot

Unit 1 investigation: Radiation dose and visual images



Investigation point | Investigation route | Images of fuel debris spreading (simulation examples)

* Radiation at the site boundary remains unchanged in approx. 0.5～2μSv/h during investigation. No effect on surrounding environment.
* Radiation dose and distance from the bottom will be evaluated.
* Radiation dose on 1/F is almost same dose as the previous measurement (4.1～9.7Sv/h in April 2015).

Investigation of the Unit 2 upper pedestal interior

(A2 investigation: January – February 2017)

【Investigation method】

- Photographing by camera

【Implementation period】

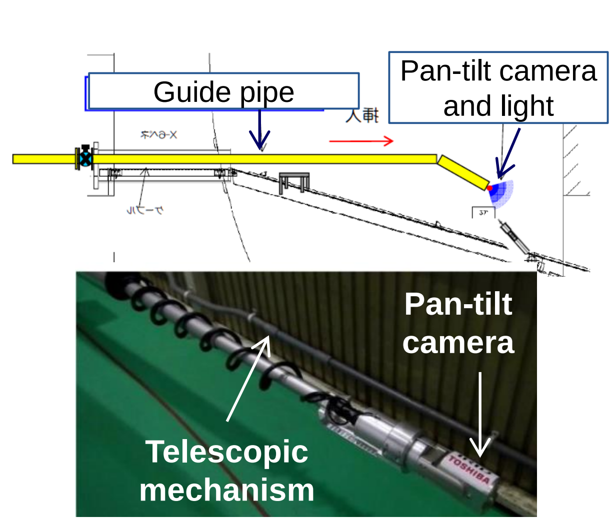
- Jan. – Feb. 2017

Investigation procedure

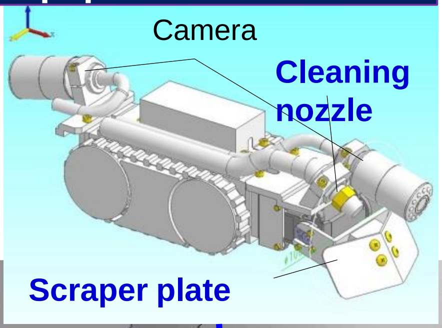
Pre-confirmation for the penetration interior

1. Pre-confirmation for the pedestal interior — Conducted on 30 Jan. 2017
2. Removal of deposition on the rail — Conducted on 9 Feb. 2017
3. A2 investigation — Conducted on 16 Feb. 2017

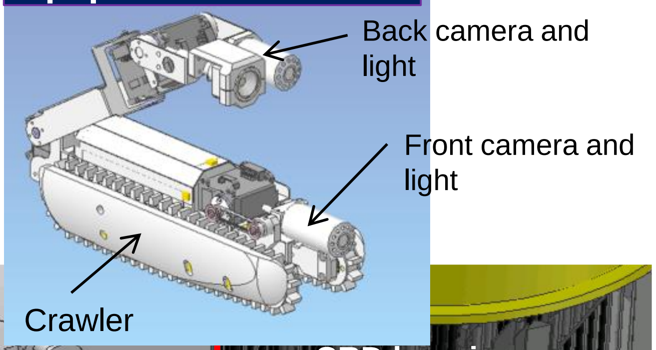
1. Pre-confirmation system

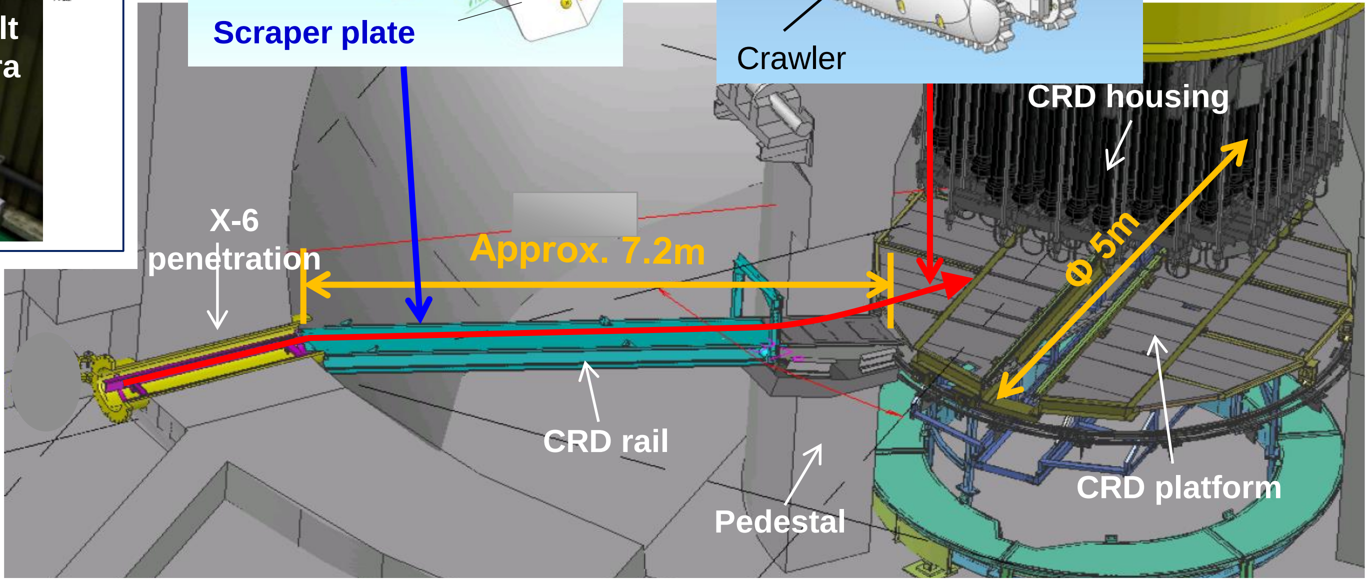


2. Deposition removal equipment



3. A2 investigation equipment

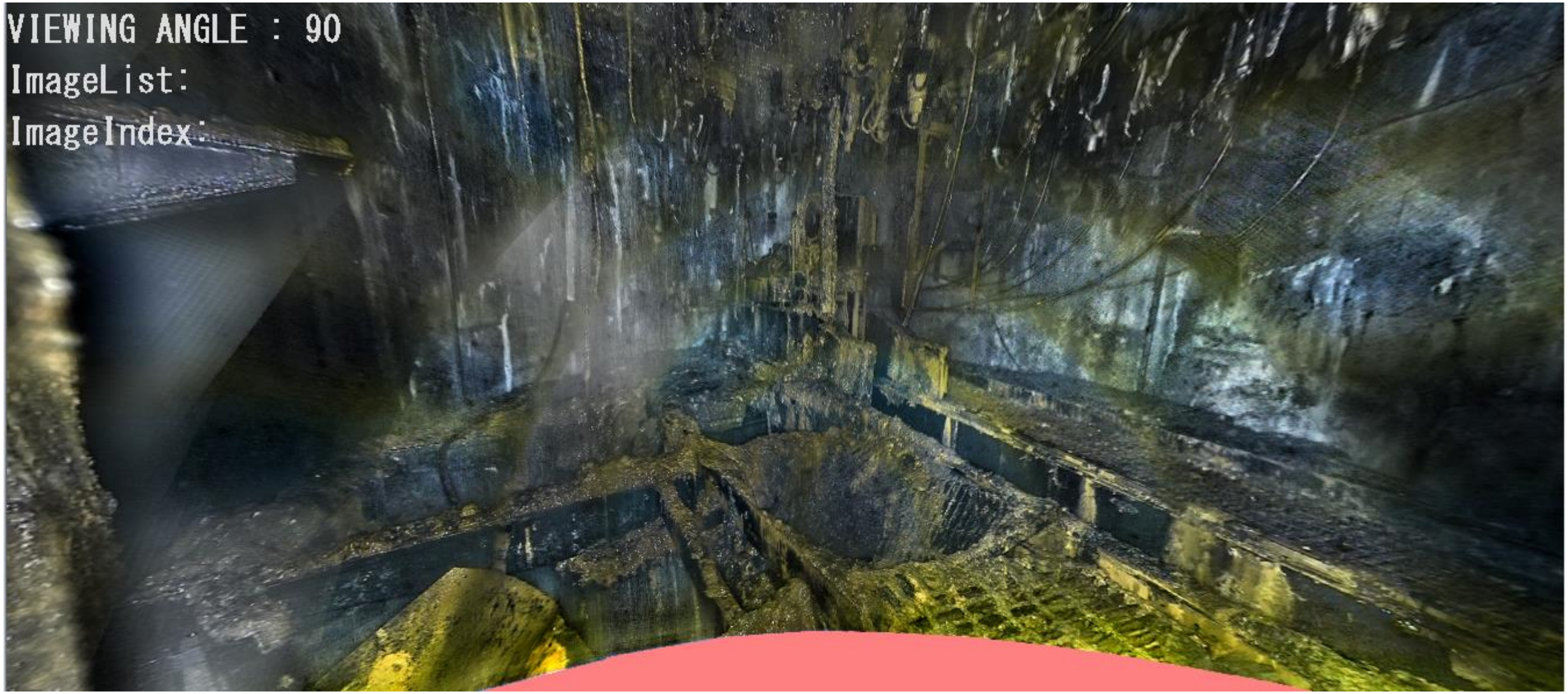




Investigation of the Unit 2 upper pedestal interior

(A2 investigation: January – February 2017)

Upper pedestal interior (after image processing)



Investigation of the lower pedestal interior

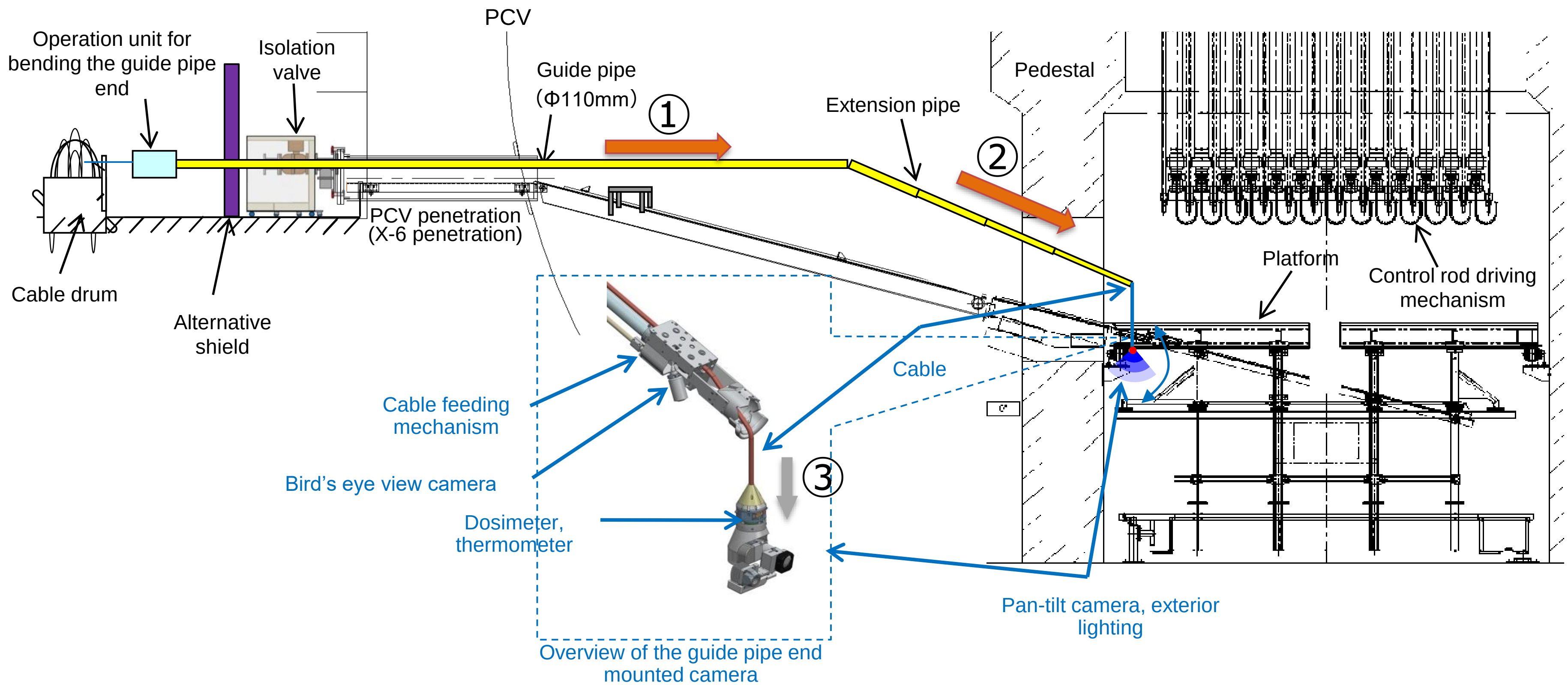
(A2' investigation in January 2018)

■ Purpose of investigation

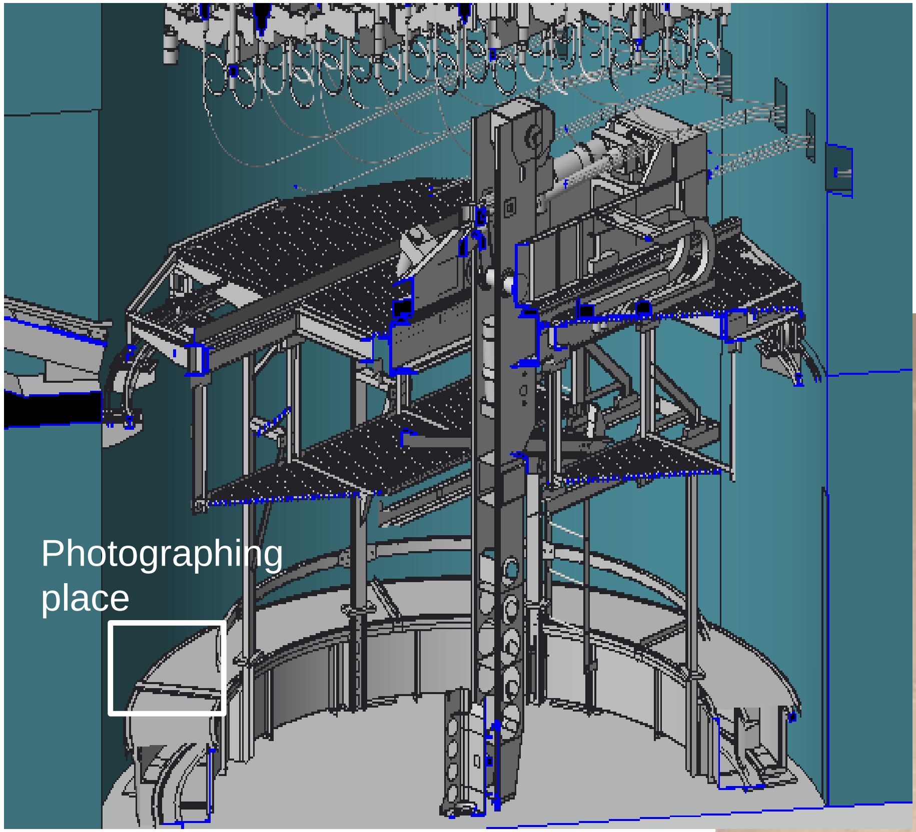
Confirmation of the state below the platform

■ Investigation procedure

①Inserting a guide pipe ⇒ ②Extending a pipe ⇒
③Suspending a pan-tilt camera ⇒ ④Investigation



Unit 2 investigation: Pedestal Floor



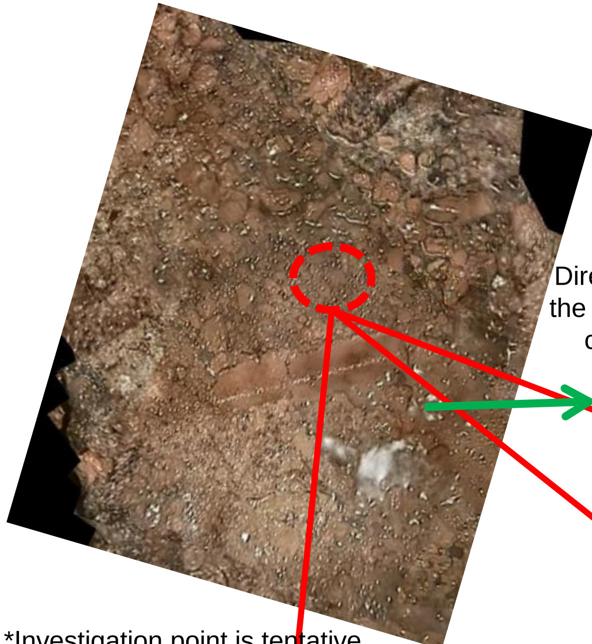
Bottom of the Unit 2 PCV
(An overhead image)

Pedestal floor and wall
Fuel debris? and a fuel assembly handle

Investigation of the Lower Pedestal Interior

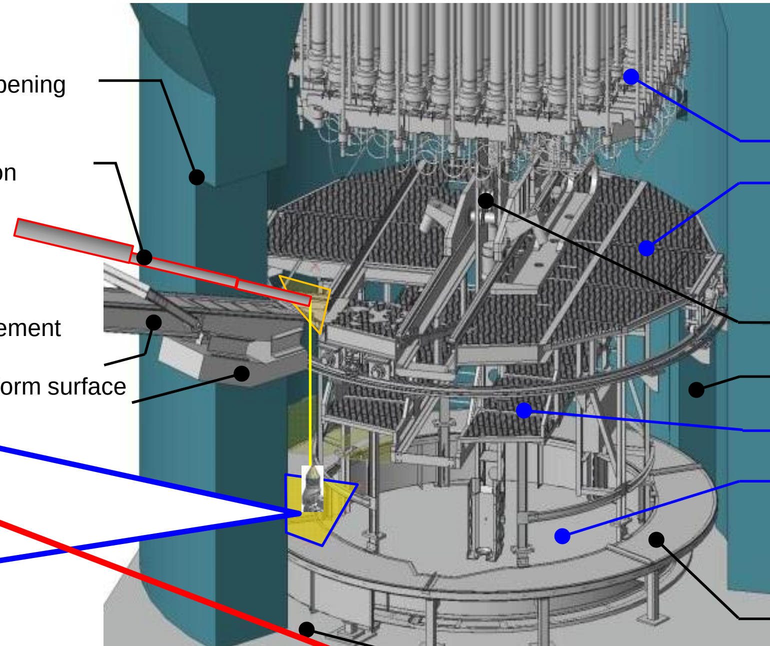
(A2' investigation in February 2019)

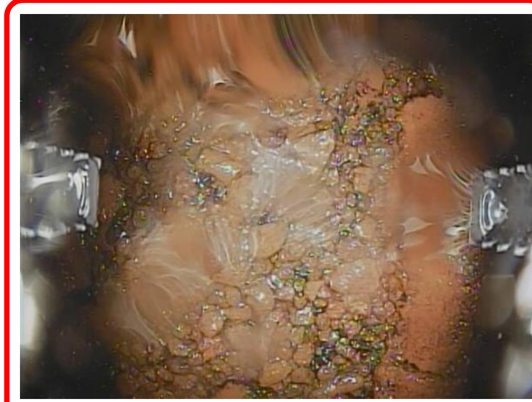
TEPCO



*Investigation point is tentative.

Investigation area (A photo taken in Jan. 2018)





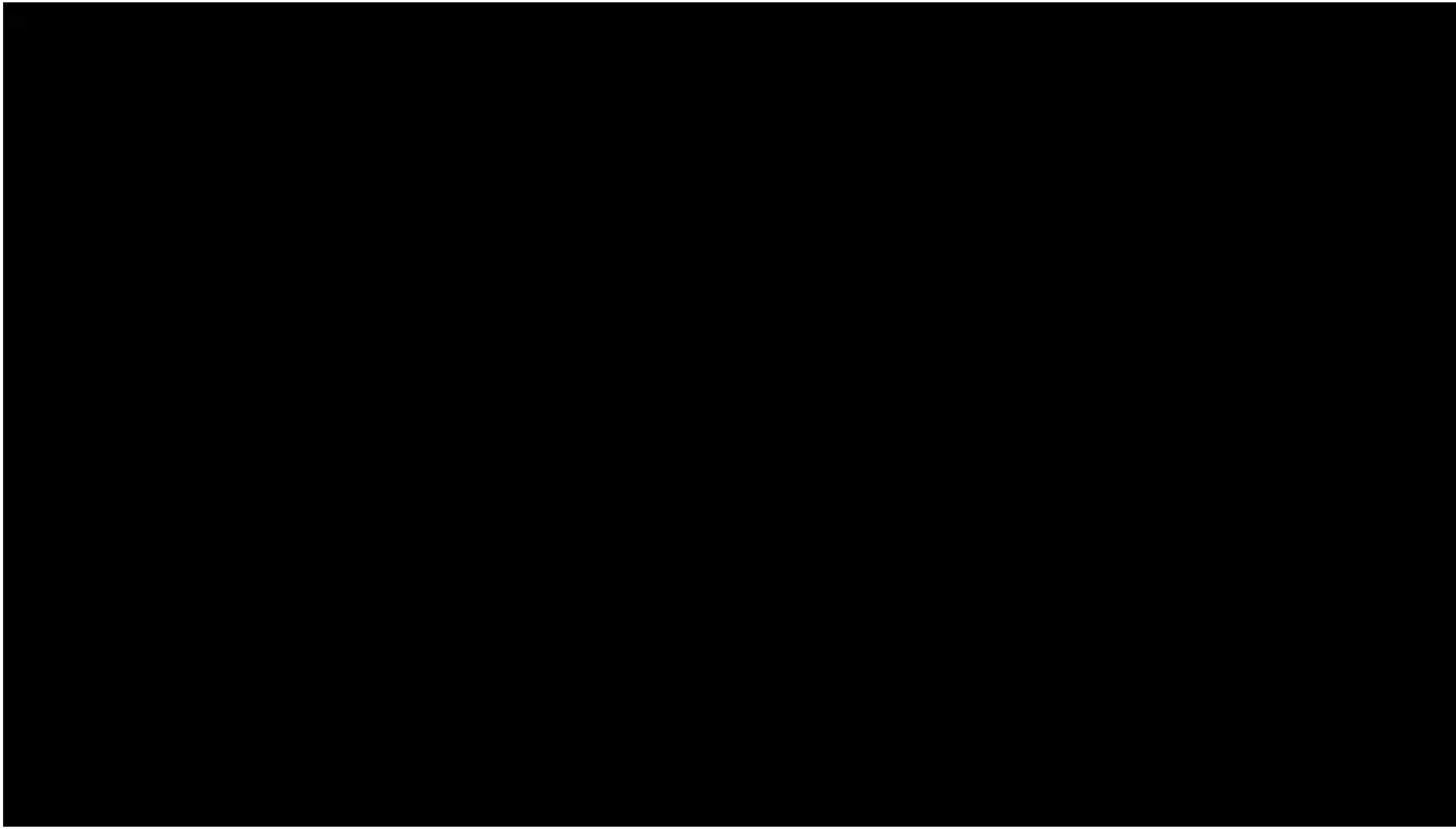
Before touching deposition

Touching deposition

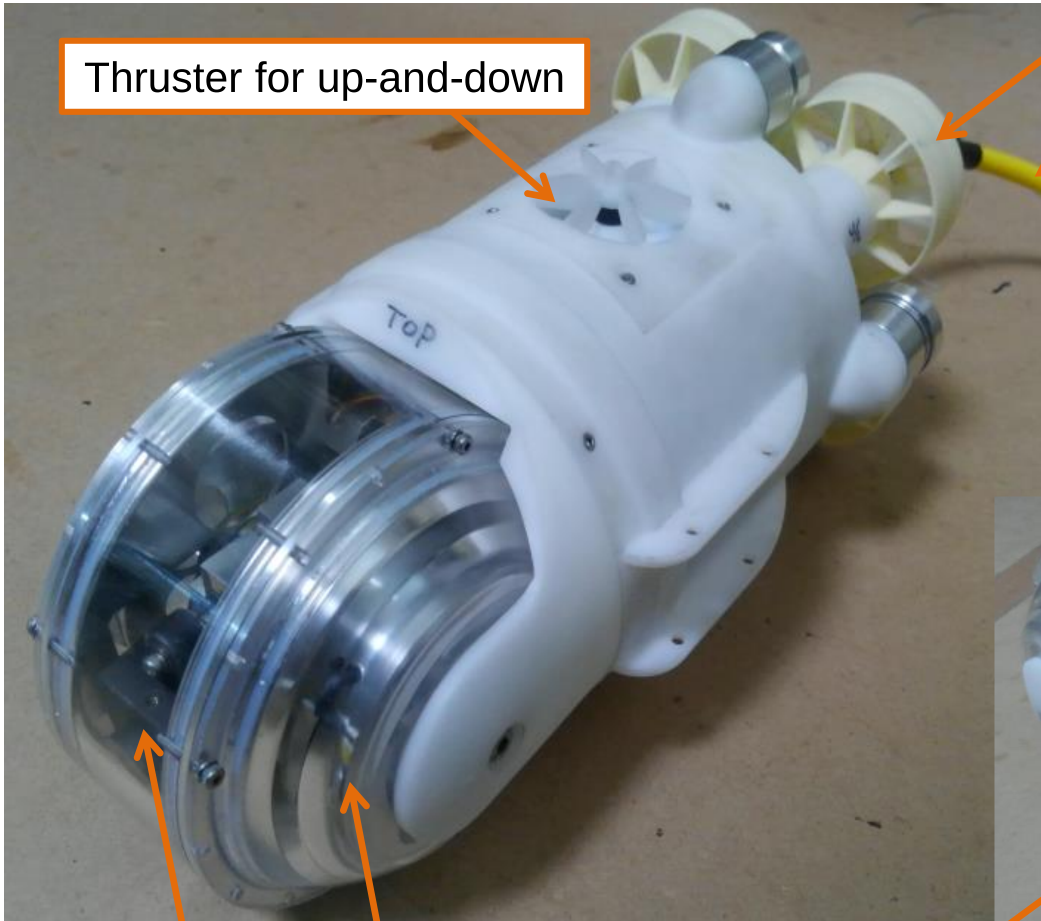
After touching deposition

Source: TEPCO Holding Inc. website

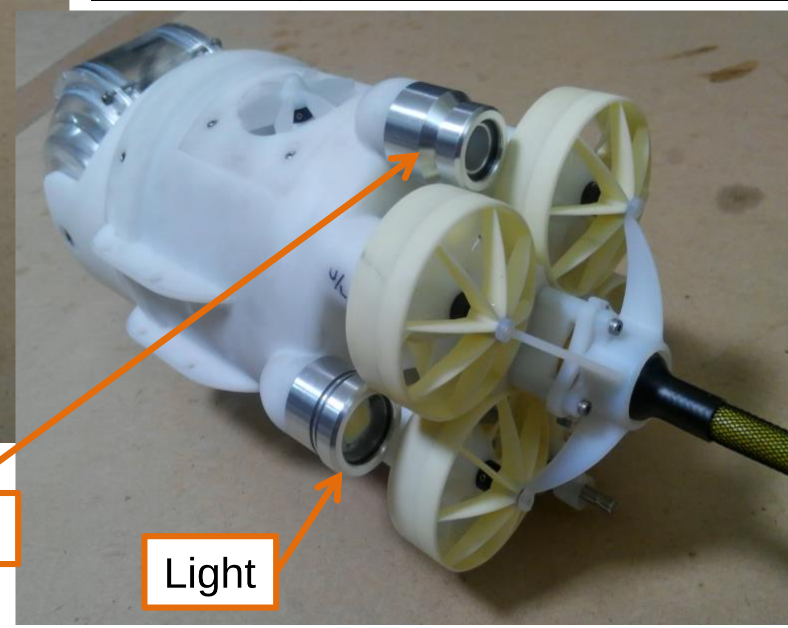
Investigation of the Unit 2 Lower Pedestal Interior
(A2’ investigation in February 2019)
Video: Unit #2 deposition at the lower pedestal area



Submersible Remote Operated Vehicle (ROV) (mockup vehicle)



Items	Specifications
Outer size	Outer diameter：φ125mm Overall length：Approx.300mm
Weight	Approx. 2000g (in air)
Radiation resistance	200Gy



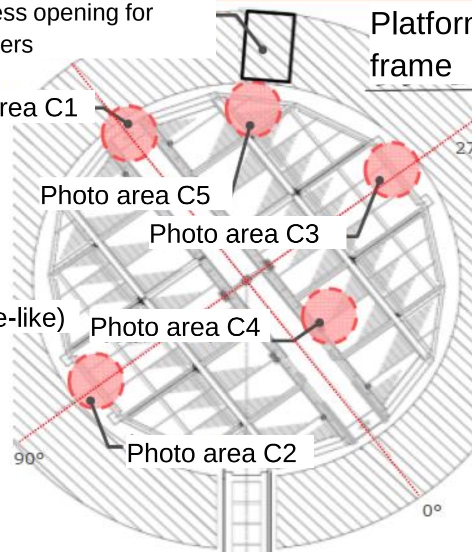
Results of investigation for the Unit 3 PCV

2. Investigation results

2.3. The lower pedestal

IRID TEPCO

Area C1 where a photo was taken
<Camera position: Lower>



Area C5 where a photo was taken
<Camera position: Lower>

Area C2 where a photo was taken
<Camera position: Horizontal>

Area C3 where a photo was taken
<Camera position: Upper>

Area C4 where a photo was taken
<Camera position: Lower>

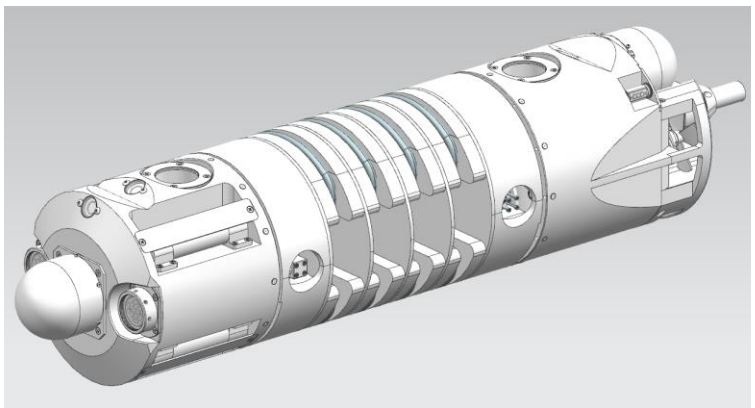
- The investigation has revealed that deposition in sandy, pebble-like and massive form has accumulated.
- The access opening for workers was not confirmed visually (deposition was visually seen nearby).

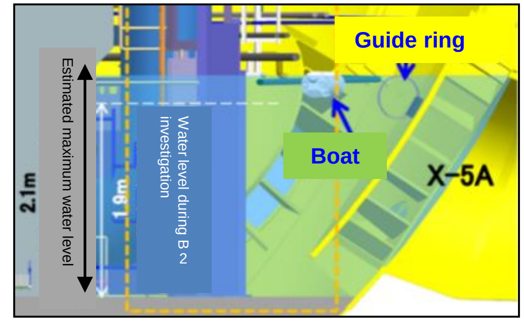
「3号

* Reference: Investigation result of the Unit 3 PCV interior (report of the 48th Team Meeting and Countermeasures for Decommissioning and Contaminated Water Treatment Conference on Nov. 30, 2017)

Boat Type Access Equipment

- Boat type access equipment which can move on a wide range of the water surface in the primary containment vessel (PCV) was developed.

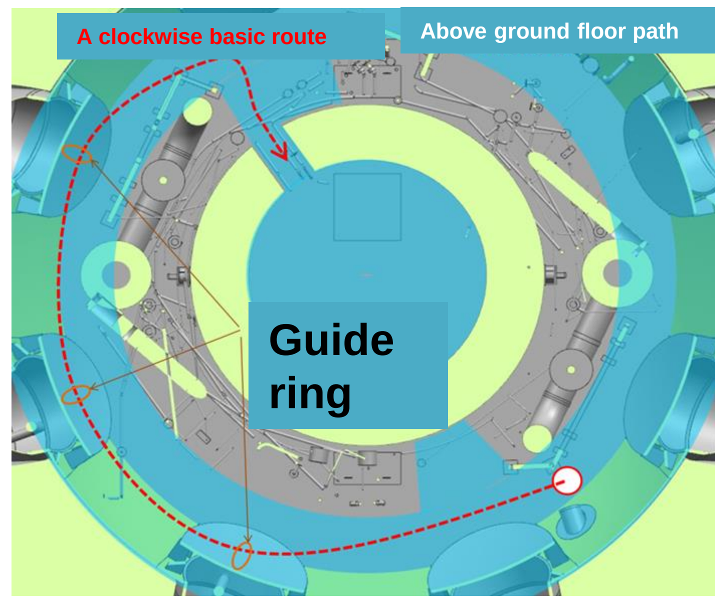




Example: Guide ring installation

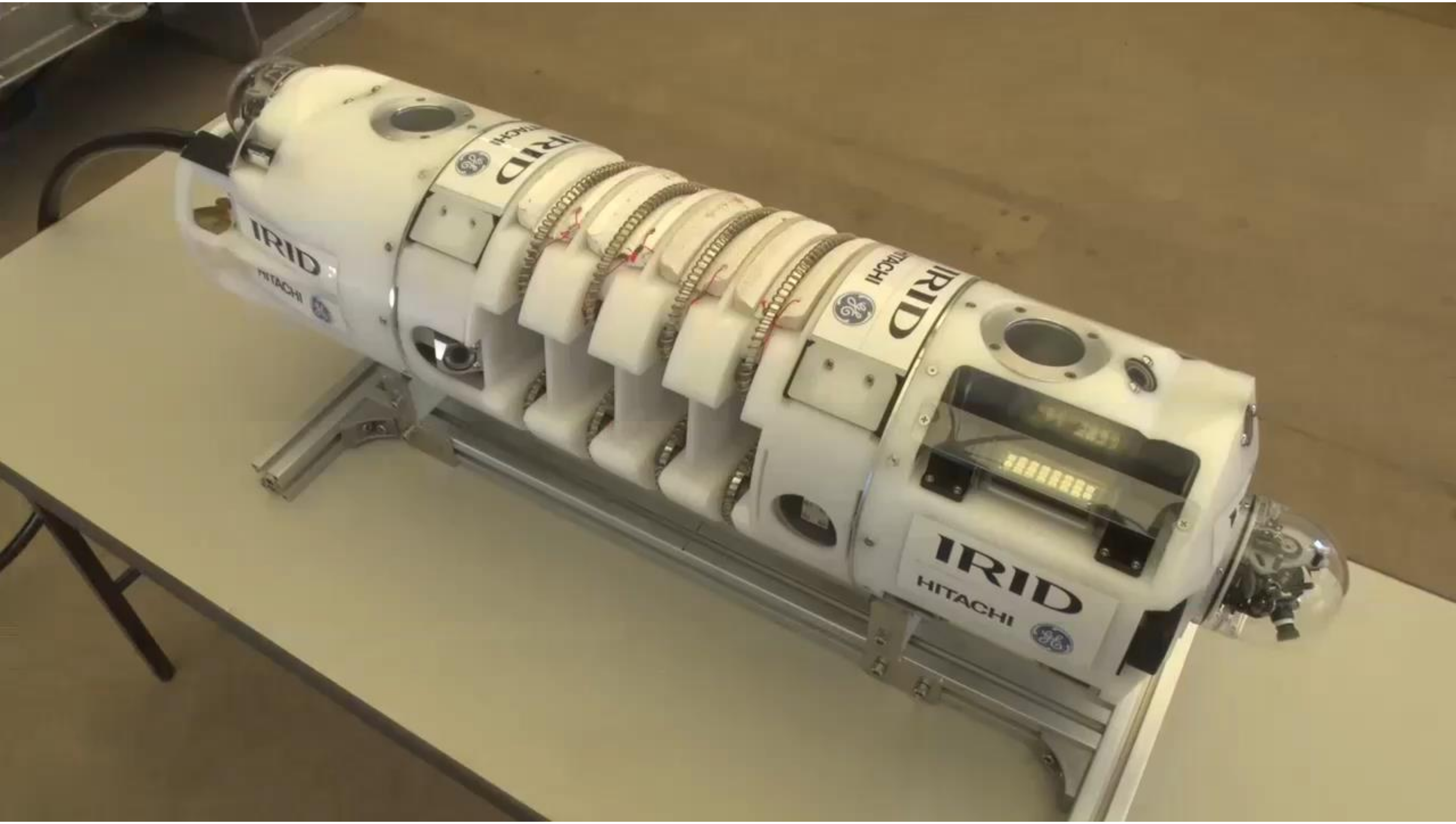
- Diameter: φ25cm
- Length: Approx. 1.1m
- Thrust: Over 25N

Appearance of the boat type access equipment



Travelling line of the equipment

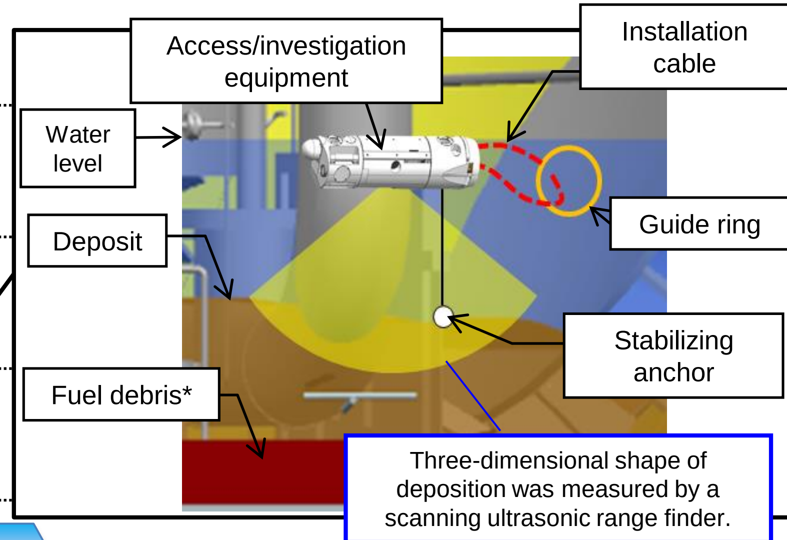
Boat Type Access Equipment (Video)

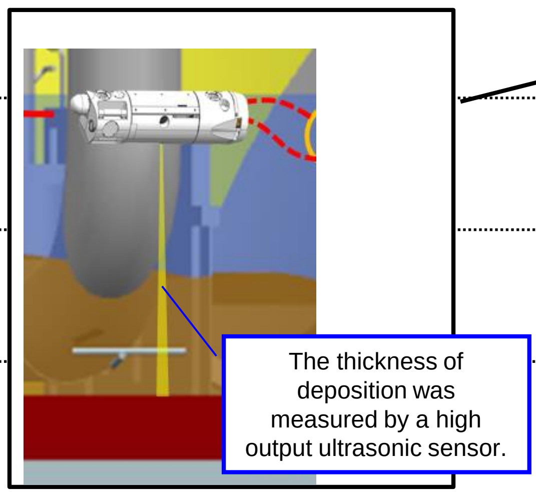


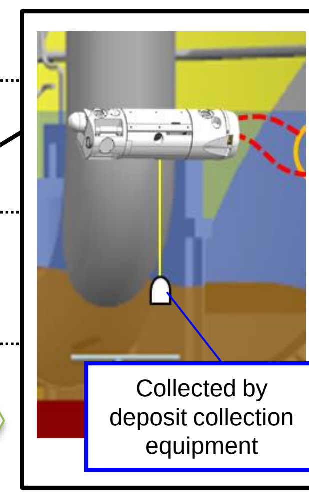
Boat Type Access Equipment (Investigation inside PCV through X-2 penetration)

- Six kinds of boat type access and investigation equipment with submersible functions will be prepared for each function.

Installation items	Work flow (image flow)
Install equipment Seal box equipment	
Guide ring installation (Installation for cable entanglement prevention)	ROV-A
Visual observation (Confirmation of PCV conditions by pan-tilt camera)	ROV-A2 (Small-size ROV)
Deposit three-dimensional shape measurement (Measured by scanning ultrasonic range finder)	ROV-B
Deposit thickness measurement (Measured by high output ultrasonic sensor)	ROV-C
Neutron flux measurement (Deposit surface measurement by detector)	ROV-D
Small amount of deposit sampling	ROV-E
Removal of install equipment and seal box	







*Thickness and existence of deposition and fuel debris are uncertain. The above figures are image descriptions.

【Reference】Panoramic photo images taken from the pedestal opening

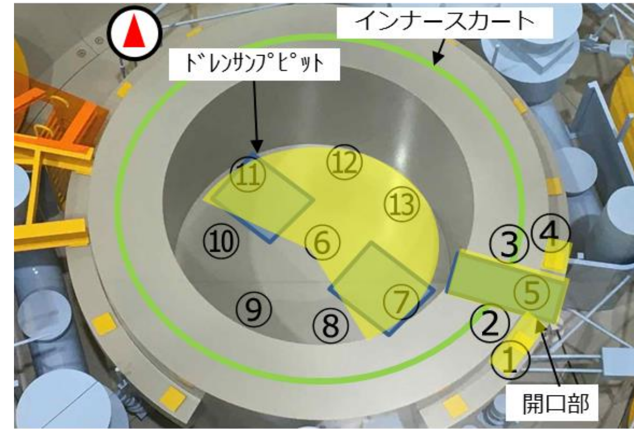


Image processing by TEPCO Holding, Inc.

【Reference】Concrete remains of the right pedestal opening (1/2)

TEPCO

- Tokyo Electric Power Company (TEPCO) Holdings, Inc. investigated the Unit 1 pedestal to confirm the concrete that likely remain outside the pedestal (Bolts that were installed before the accident were confirmed to be fixed). The investigation on March 2023 confirmed the inside of the pedestal wall.
- TEPCO assumes that the lost concrete of the pedestal outer wall opening in right side would be limited.
- The investigation found that reinforcing steels of the outside pedestal have remained 7 pieces in the right opening part and 11 pieces in the left side. The earthquake resistance should be evaluated based on 64° that is equivalent to the angle in accordnce with the opening angle.

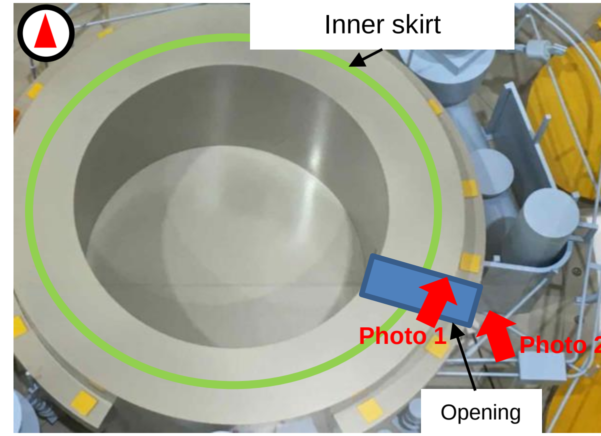


Photo 1: Concrete remains can be seen from the pedestal opening

Photo 2: Concrete remains can be seen from the pedestal opening

Photos processed by TEPCO Holdings Inc.

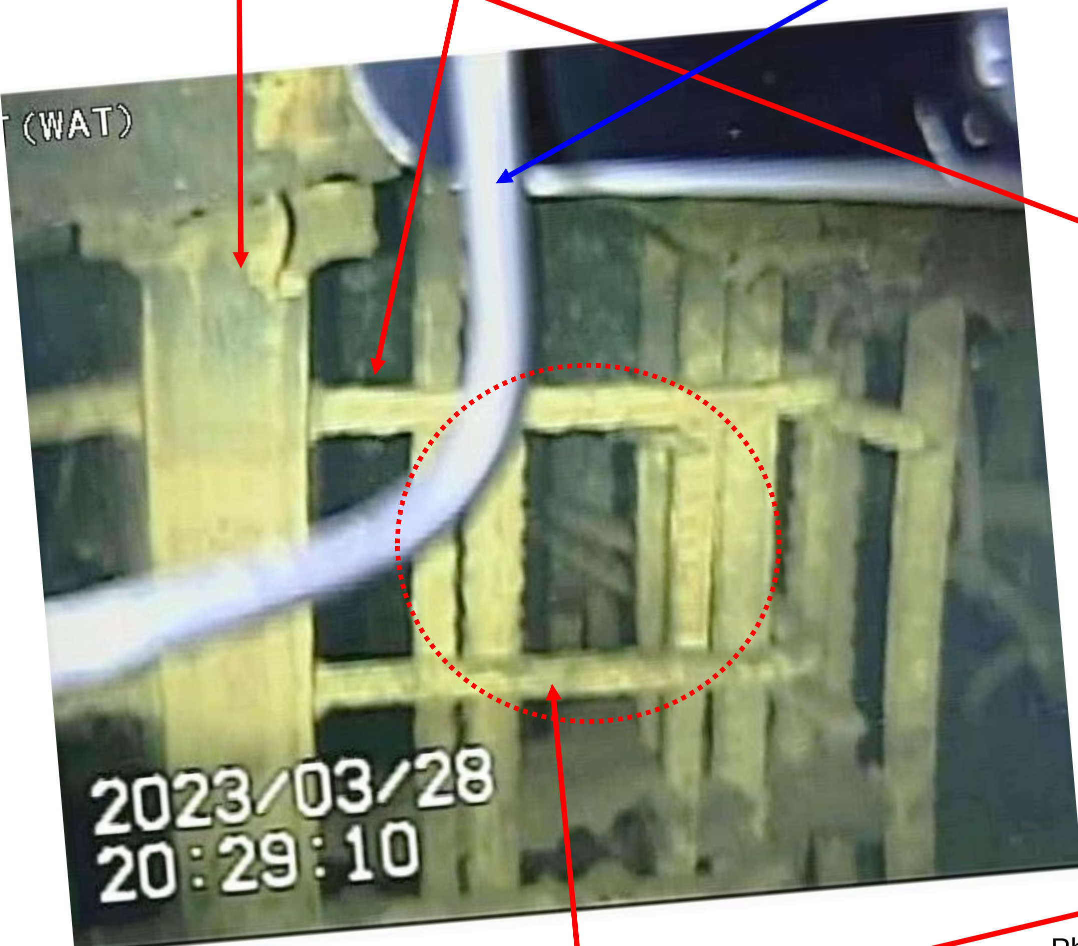
【Reference】Concrete remains of the right pedestal opening (2/2)

TEPCO

Inner skirt

First reinforcing steel

Shown the ROV frame



*The brightness of the original image is increased by 30%.

Second reinforcing steel

Figure 1: Remains of the pedestal outer wall of the right opening

*The brightness of the original image is increased by 50%.

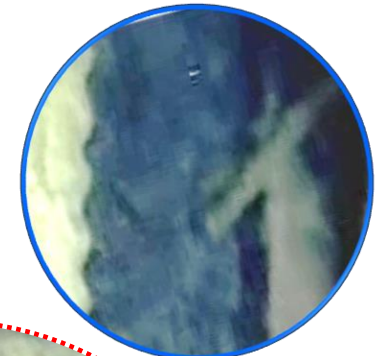
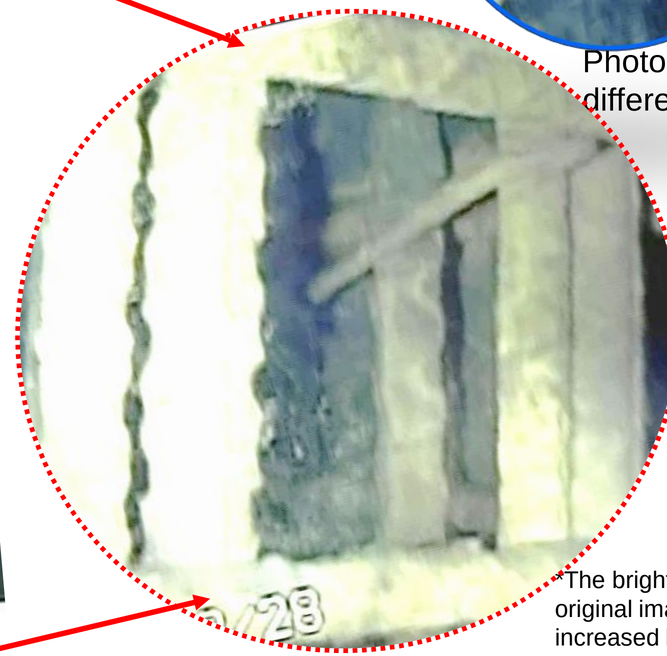


Photo taken from different angle



*The brightness of the original image is increased by 50%.

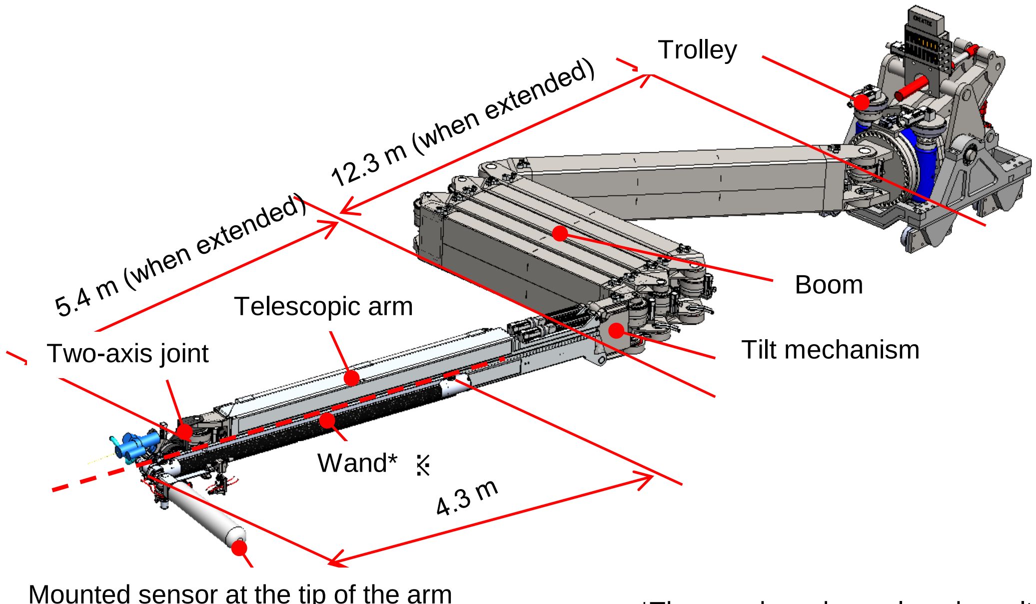
Photo of left red-circled part taken from different angle

Figure 2: Visual image taken from different angle of the remains

Photos processed by TEPCO Holdings Inc.

Arm Type Access Equipment

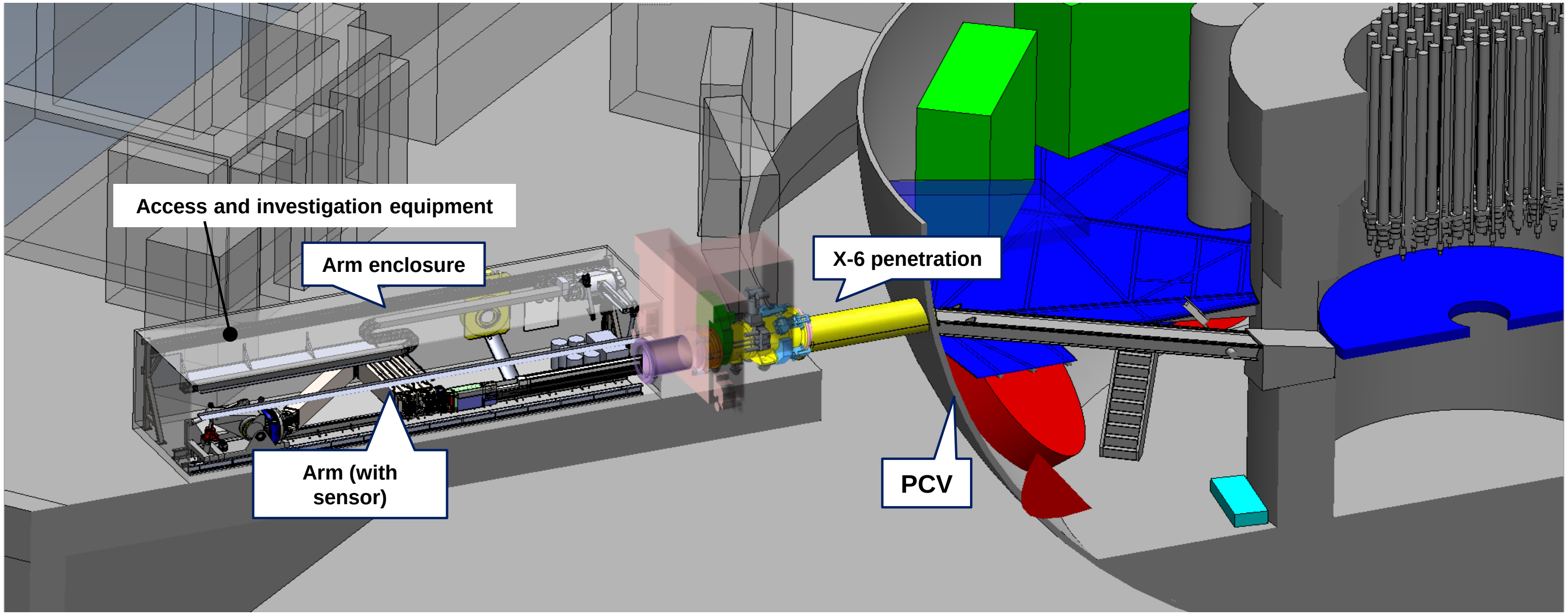
- The arm type access equipment was manufactured which can access on a wide range through the PCV penetration for maintenance of control rod drive mechanism.
  - Total length of the arm: Approx. 22m
  - Investigation equipment up to 10kg can be loaded.



*The wand can be replaced an alternative tool.

Arm type access equipment

Configuration of Access Equipment



IRID

Arm Type Access Equipment (video)

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1. Introduction
2. Development of Remotely Operation Equipment for Dose Reduction
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4. Development of Investigation Technology for inside PCV
5. Development of Technology for Fuel Debris Retrieval
6. Nuclear Safety Enhancement

PCV : primary containment vessel

Development of the Large Scale Fuel Debris Retrieval Method

To increase the retrieval scale, large-scale apparatus was installed.

- Fuel debris retrieval methods are being developed:

  Three side-access retrieval methods and two top-access methods.

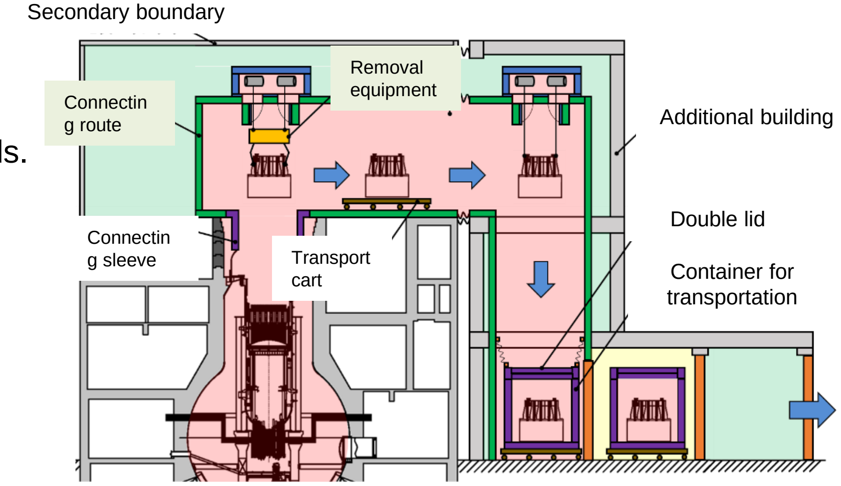
- The retrieval amount of fuel debris will be gradually increased to

  up to 300 kg per day.

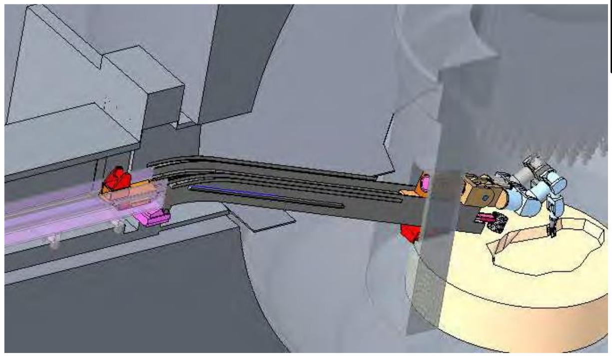
- NDF assessed that Unit 3 is an appropriate unit to start fuel

  debris retrieval (by side-access method).

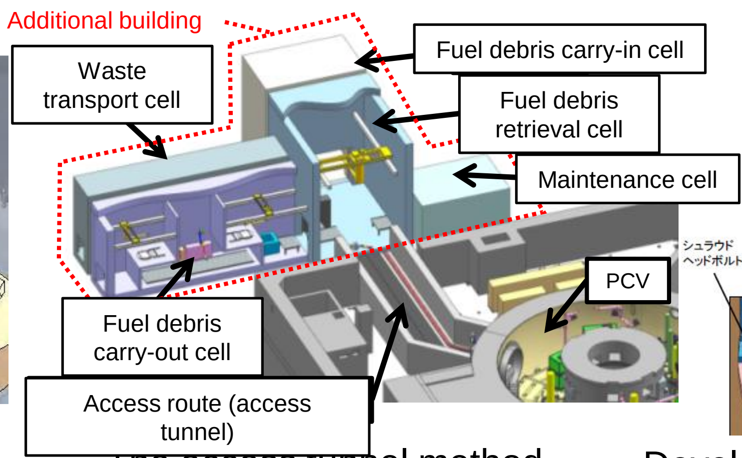
- The obtained technology, know-how, organization structure, experiences and lesson-learnt will be expected to be utilized for design, procurement, construction and operation.



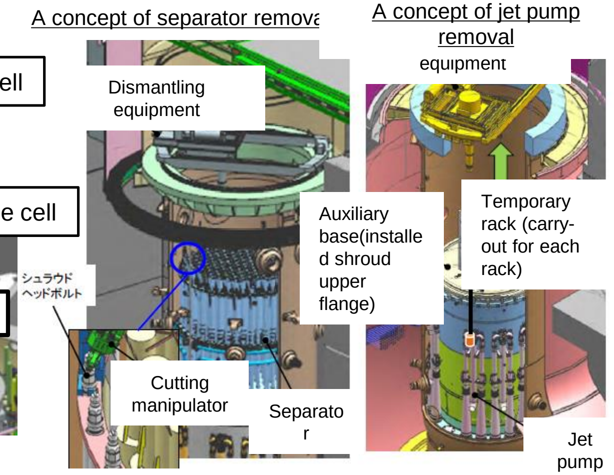
Carry-out and removal of the whole structure



The access rail method

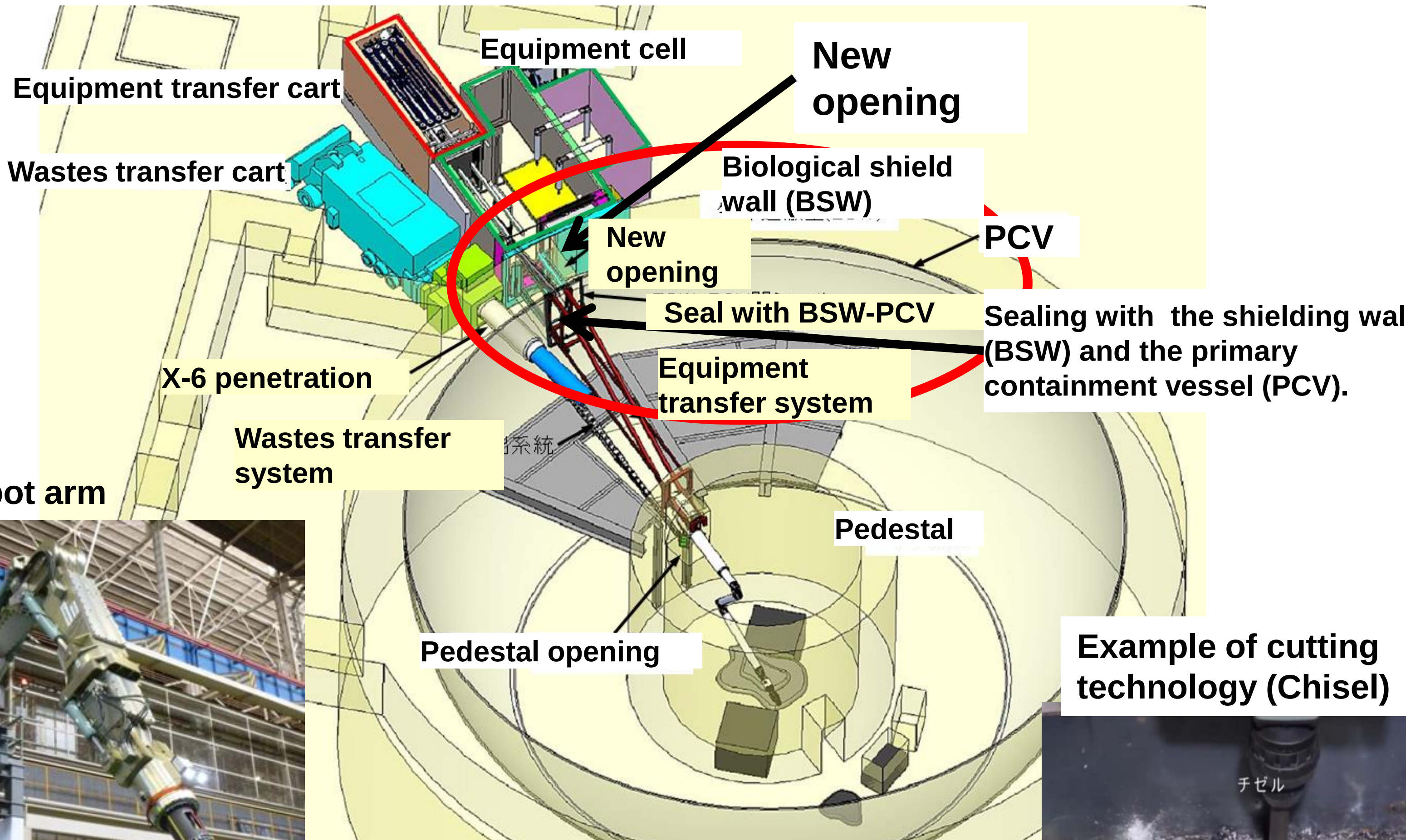


The access tunnel method



Development of the removal method for the reactor internal structure

Fuel Debris Retrieval Technology



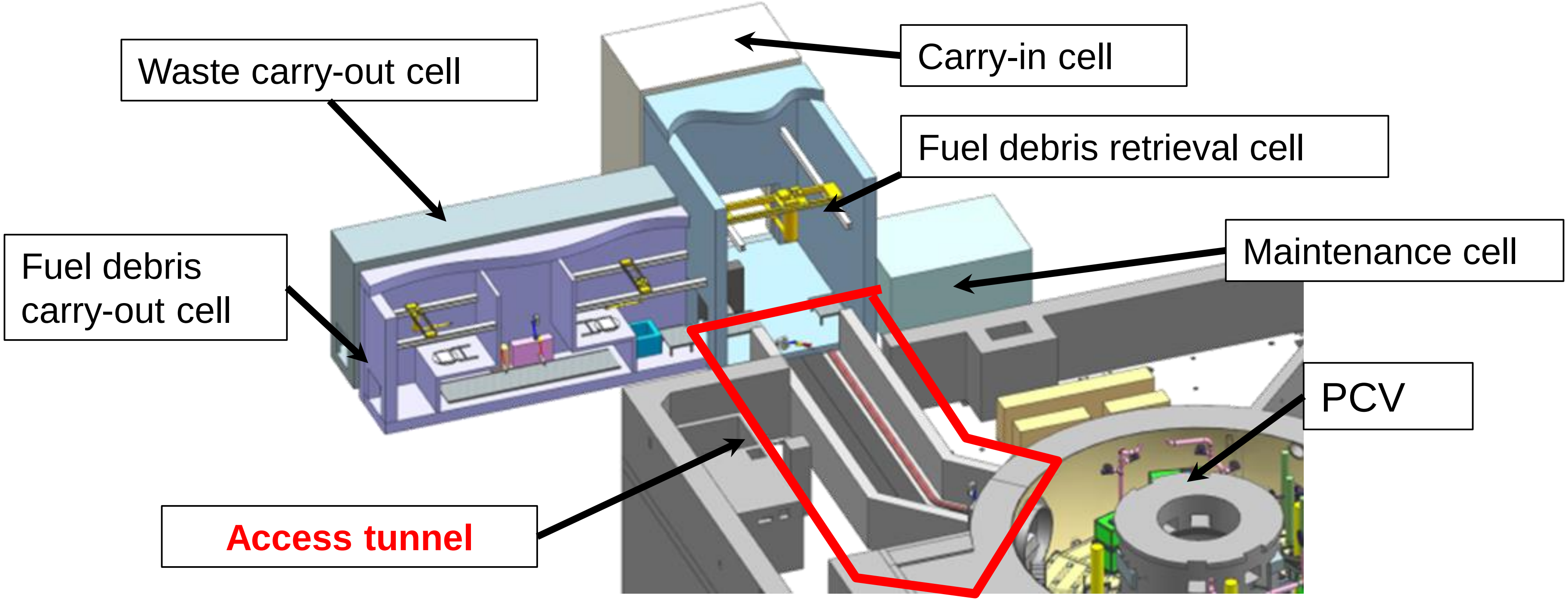
Example of robot arm

Example of cutting technology (Chisel)

Example of the side access method (illustration)

Access Tunnel Method

- The access tunnel method is required **to connect a heavy-lift tunnel (approximately 800 ton)** with the primary containment vessel (PCV) from outside the reactor building **through the precise position control system**.
- **Delivery technology for curved heavy-lift tunnel in narrow spaces** has been developed with applied heavy delivery technology experienced in bridge constructions.



A layout image of the access tunnel method

Element test of tunnel building technology

Example of the delivery method

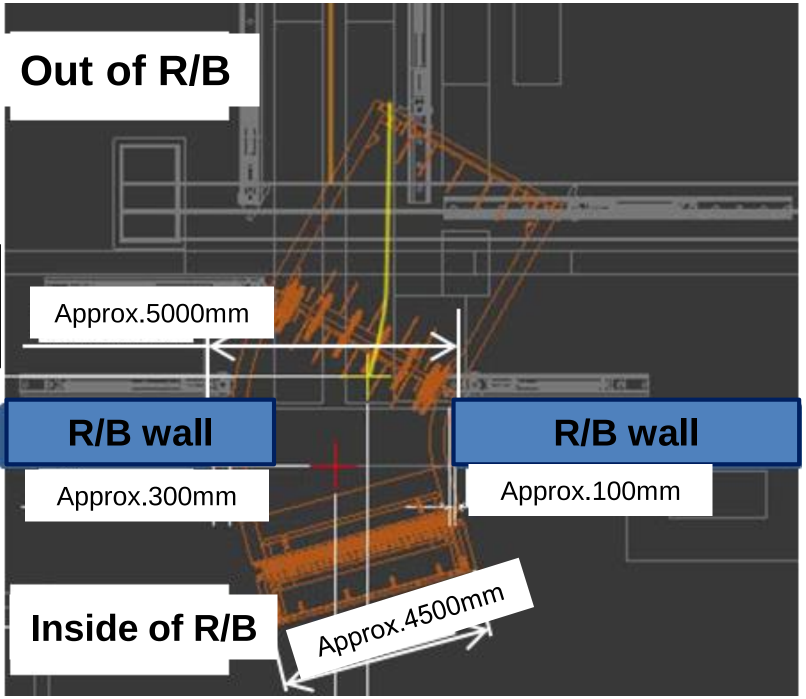


Illustration of work in narrow areas

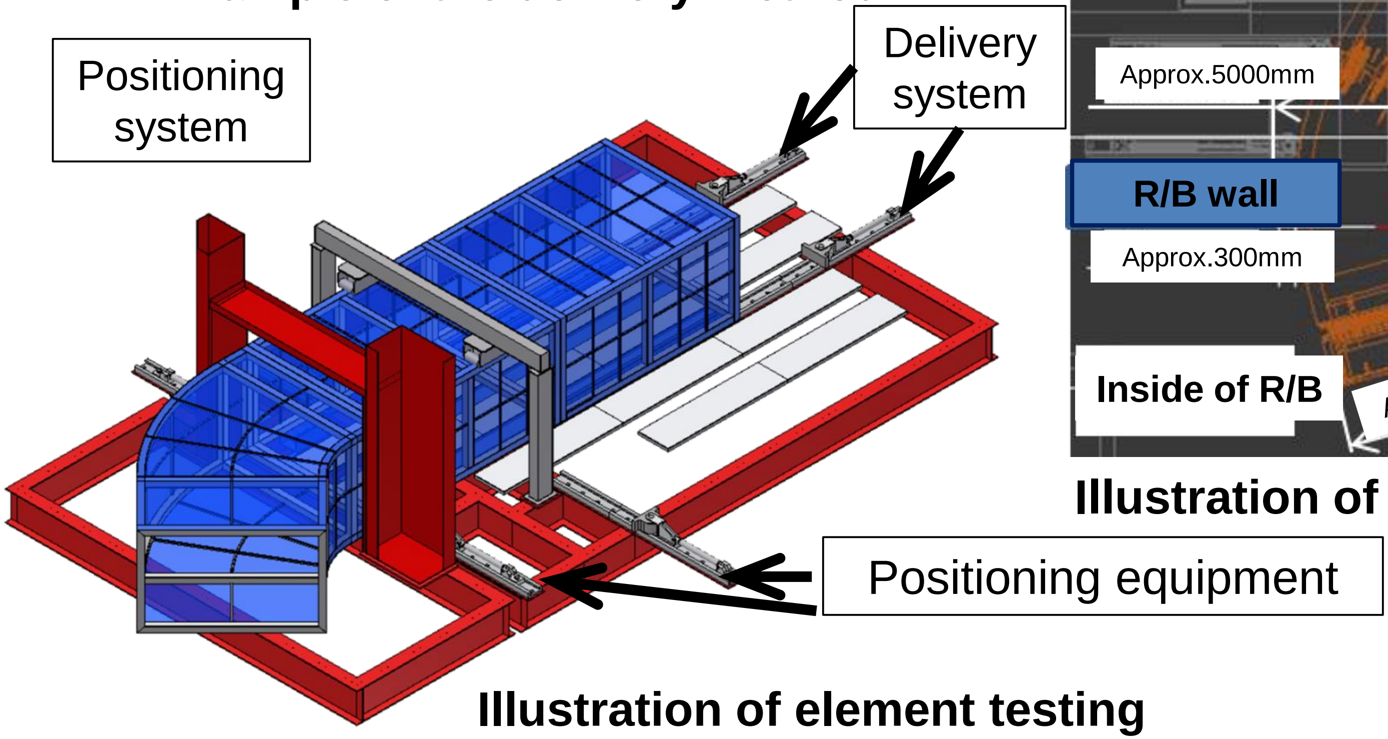
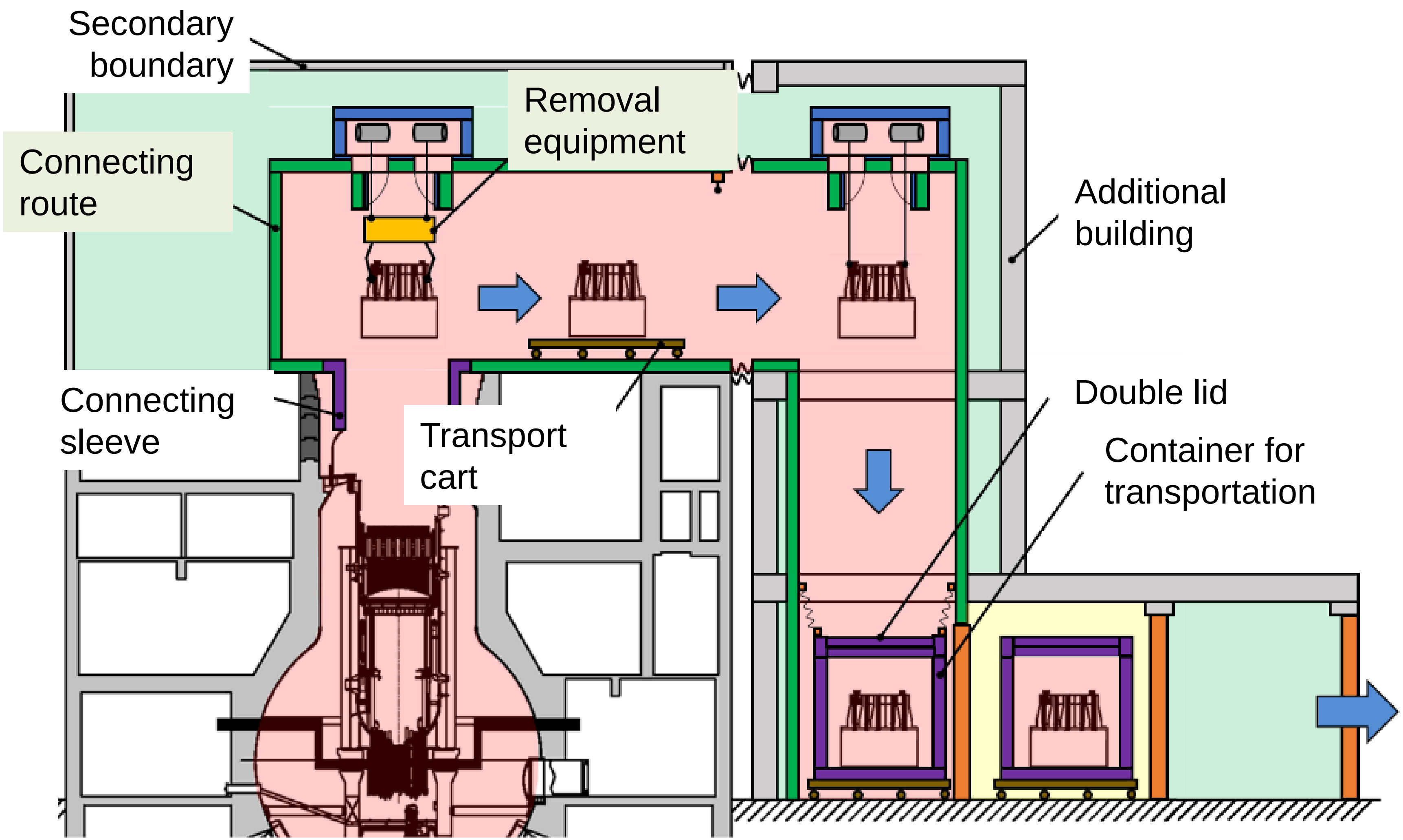


Illustration of element testing

*R/B: Reactor building

【Example of the top-access method】: Methods for Removing and Transporting the Entire Structures

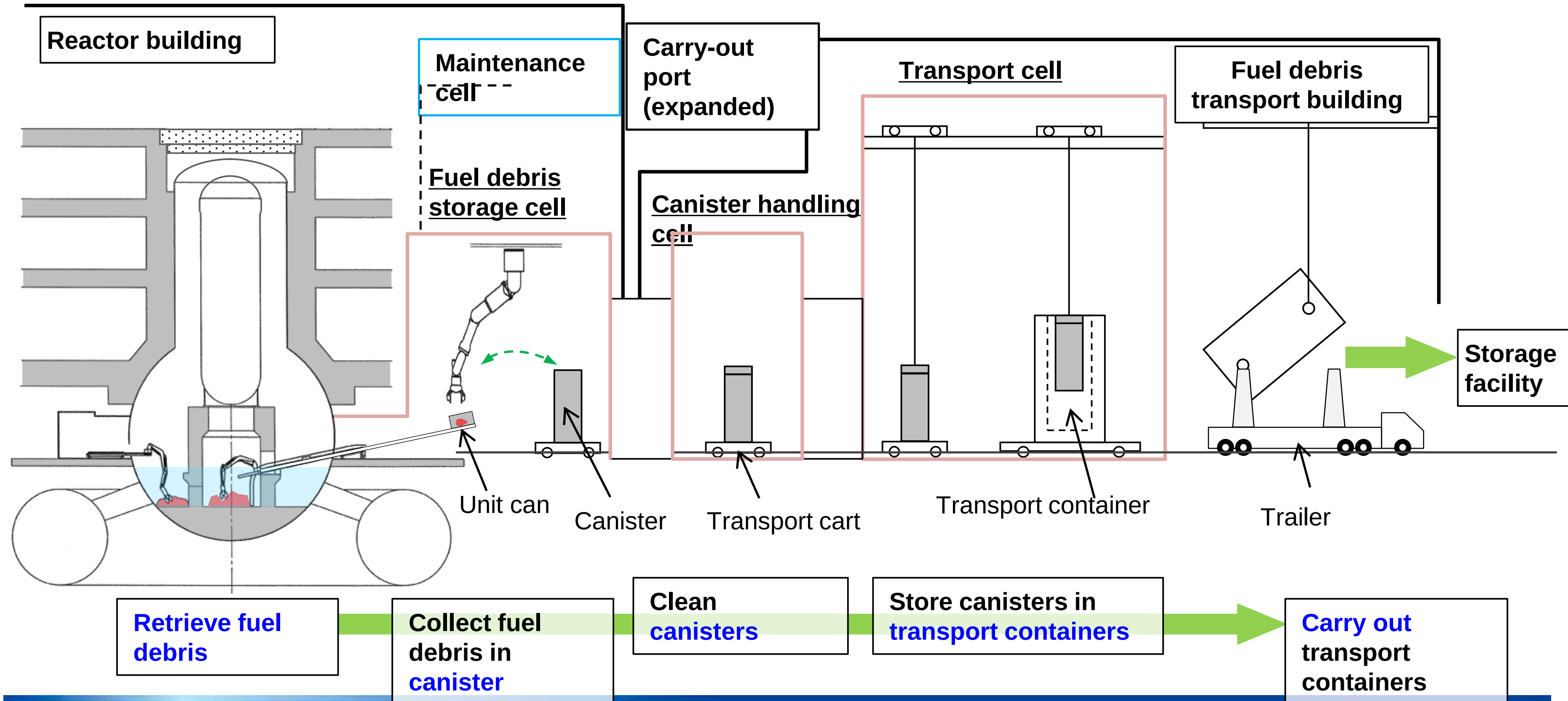


Technology for Containing, Transferring and Storing Fuel Debris

Design of canister ⇒**Responding to issues specific to the Fukushima Daiichi**

- High-burnup and the enrichment→ **High reactivity**
- Molten products mixed with concrete→ **Hydrogen generation** caused by radiolysis of moisture containing concrete
- Molten products with sea water injected and instrumental cables,etc. → Impact of **salt** and contamination of **impurities**

Transport method (Ex. Partial submersion side-access method



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PCV : primary containment vessel

Ensuring the Safety When Retrieving Fuel Debris

Risks necessary to be considered

1. Cooling
   ・・・Decay heat has decreased over a long time after the accident, however it must be cooled for a certain period of time. There is a risk of losing its functions.

1. Confinement
   ・・・There is a risk of releasing dust to be generated when cutting and chipping debris.

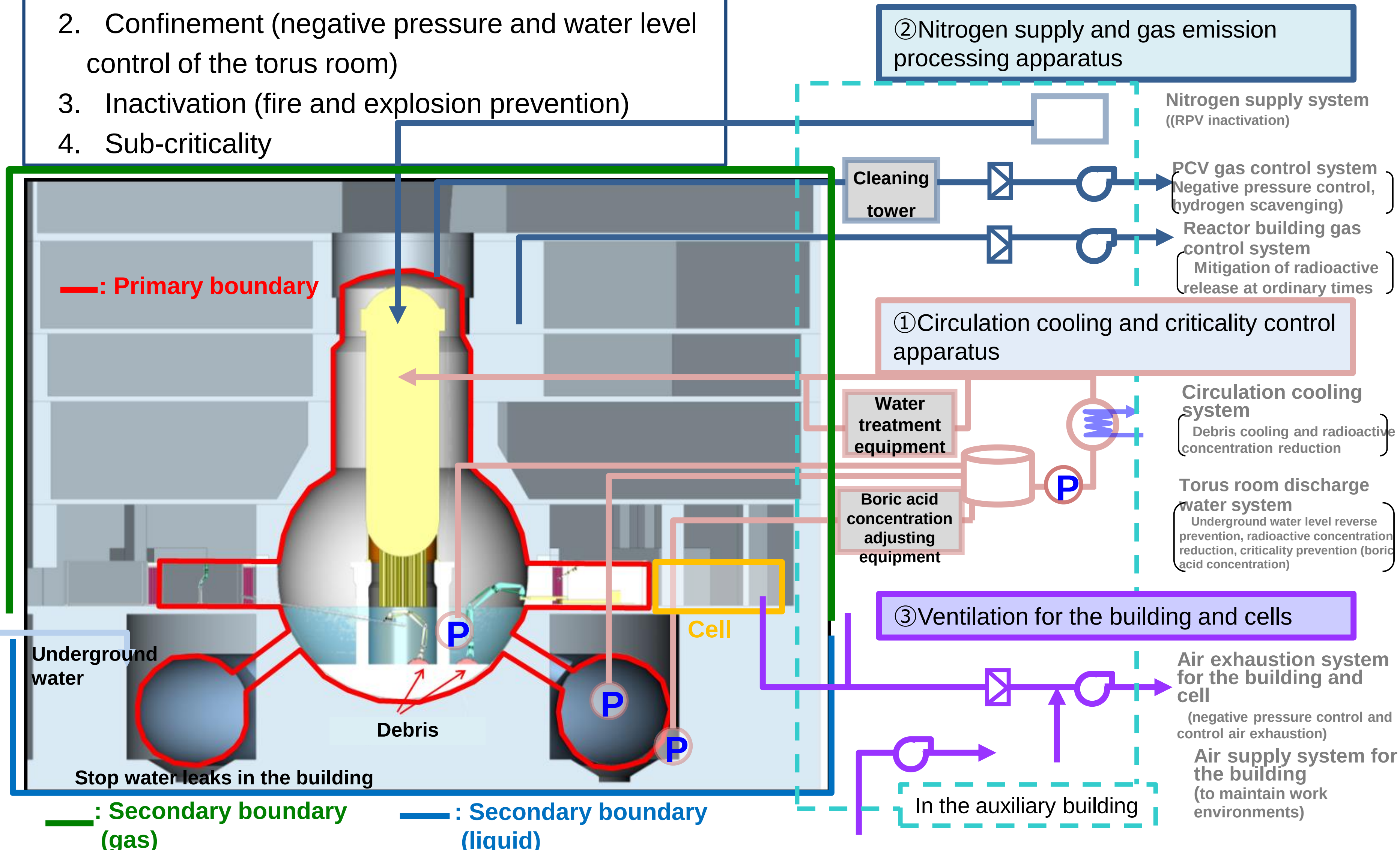
2. Fire and explosion (inactivation)
   ・・・There is a risk of fire and hydrogen explosion when cutting and chipping debris.

3. Criticality
   ・・・There is a risk of criticality caused by changing the shape of debris during fuel debris retrieval.

Ensuring the Safety When Retrieving Fuel Debris

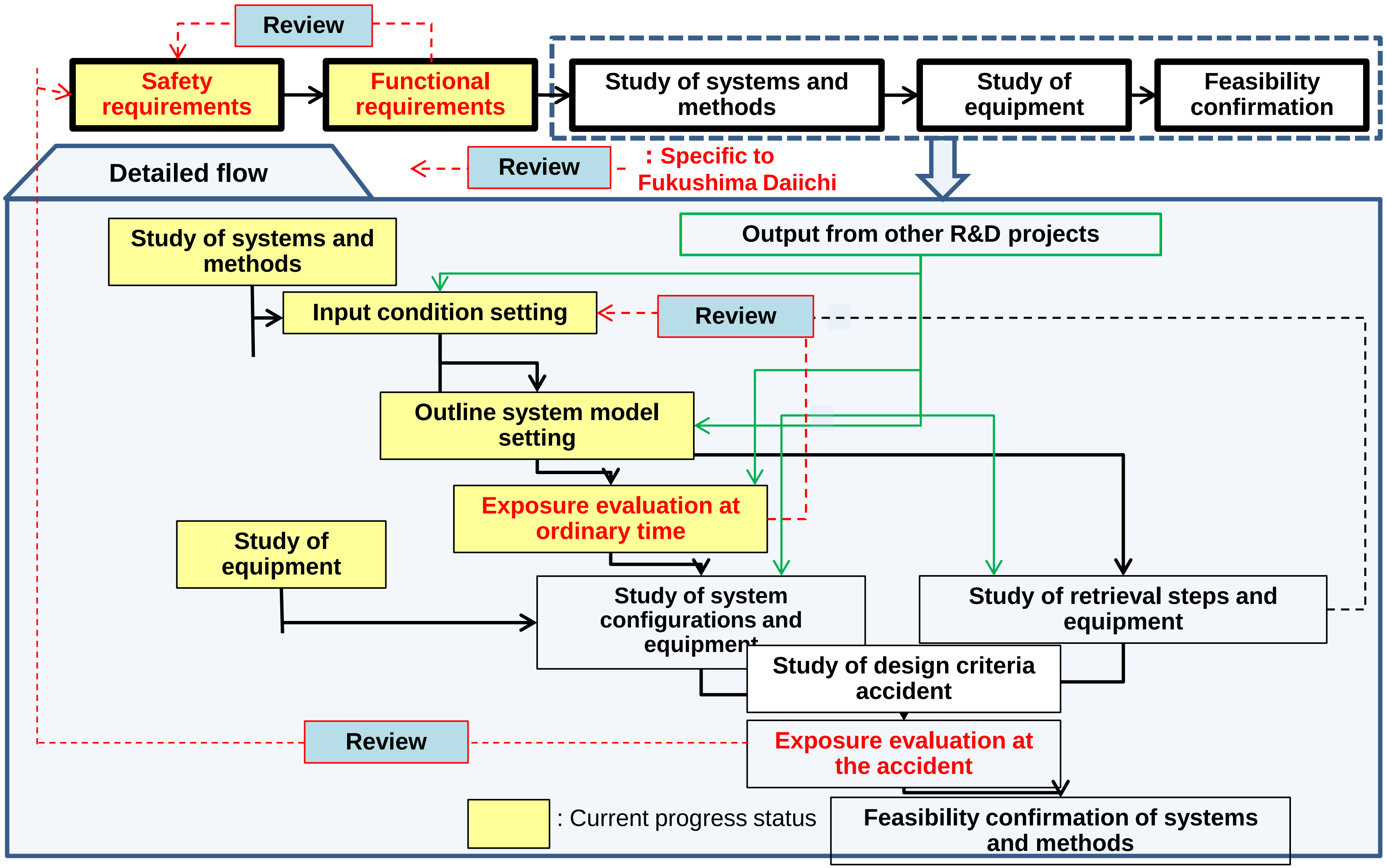
Necessary safety functions

1. Cooling
2. Confinement (negative pressure and water level control of the torus room)
3. Inactivation (fire and explosion prevention)
4. Sub-criticality



Concepts of Study: Procedures and Feasibility of System Design

- On the basis of the safety requirement setting (tentative), functional requirements from the throughput will be added.
- The safety requirements should be basically unchangeable, however potential current risks an work risks (i.e. work dose of radioactivity) may be reviewed depending on estimated work and evaluation.

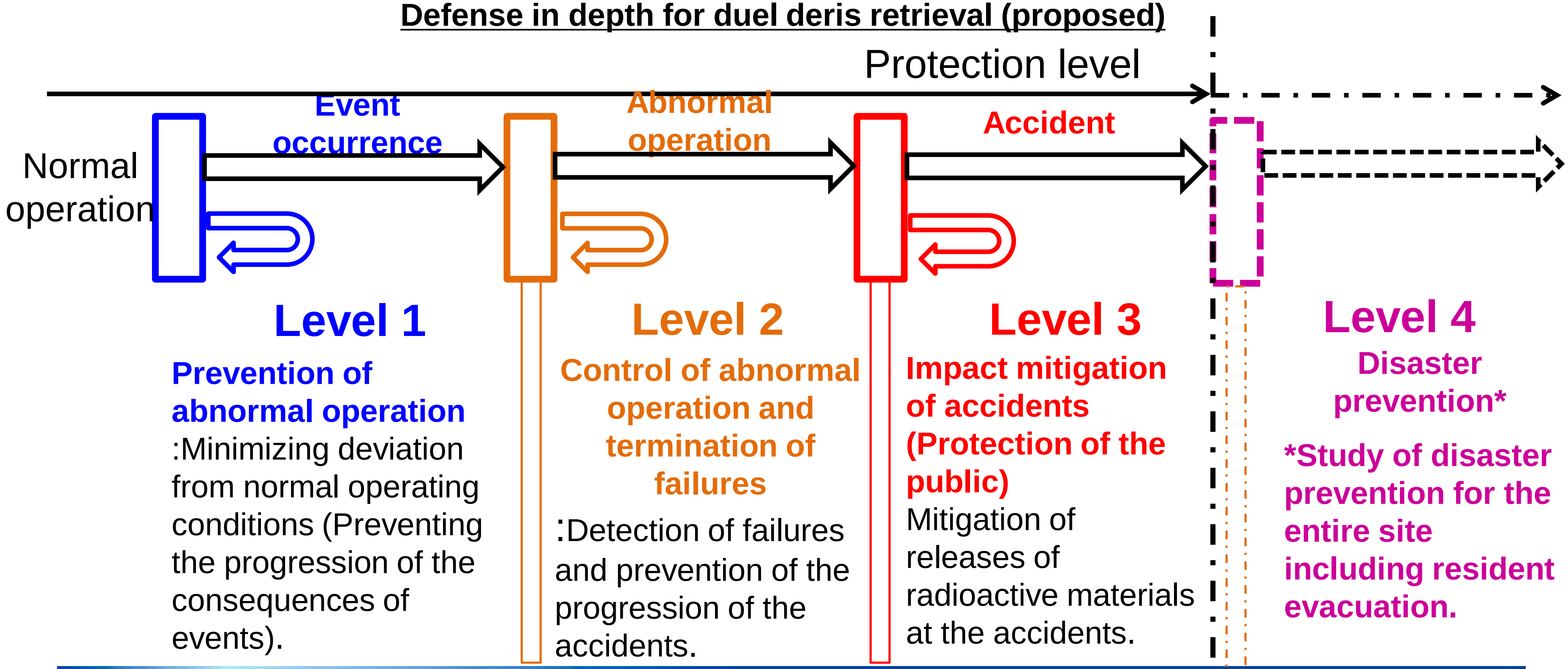


Concepts of Defense in Depth (proposed) (1/2)

- Regardless five levels of defense in depth for the light water reactor, an additional defense level was newly determined for fuel debris retrieval.

- Specifically, **three defense levels**, "**Prevention of abnormal operation,**" **"Control of abnormal operation and termination of failures" and "Impact mitigation of accidents of the public"** were determined and organized depending on the safety functions.

Defense in depth for duel deris retrieval (proposed)



Concepts of Defense in Depth (proposed) (2/2)

- The decommissioning of the Fukushima Daiichi differs from the one of normal plants. Considering a special circumstance of the Fukushima Daiichi that the **decommissioning of the accident plant (work in high radiation environments) will maintain for a long period of time and has a potential hazard of the final level.** The following items were considered to establish the defense in depth.

【Exposure of workers】

- **The effects of worker's exposure associated with installation work should be also considered** in addition to effects of the exposure during fuel debris retrieval and exposure reduction of the public. The purpose of exposure reduction is to totally reduce exposure for the public and workers.

【Event progression】

- At the time of functional loss, existing facilities will respond to events that rapidly progress. **Transportable equipment will also be utilized for slow-progression-events.**

【Robustness of existing facilities】

- The robustness of the facility is required for events that rapidly progress and its function is expected to be used. **In case that the function is expected to be used for only normal time and is not significant even though it takes time to restore the function at the time of functional loss, the robustness will not be required.**

Summary

- In the development of debris retrieval work technology, detailed on-site surveys are important for ensuring safety and earlier decommissioning work.

- Preparations for detailed investigation in the containment vessel and the taking out of small amounts of debris are underway.

- Risk assessment and defense in depth have been examined, and the conceptual design of debris retrieval systems has been advanced.

- Technology development concerning nuclear safety such as criticality control and hydrogen generation control are also being advanced.

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End of presentation