IRID
International Research Institute
for Nuclear Decommissioning

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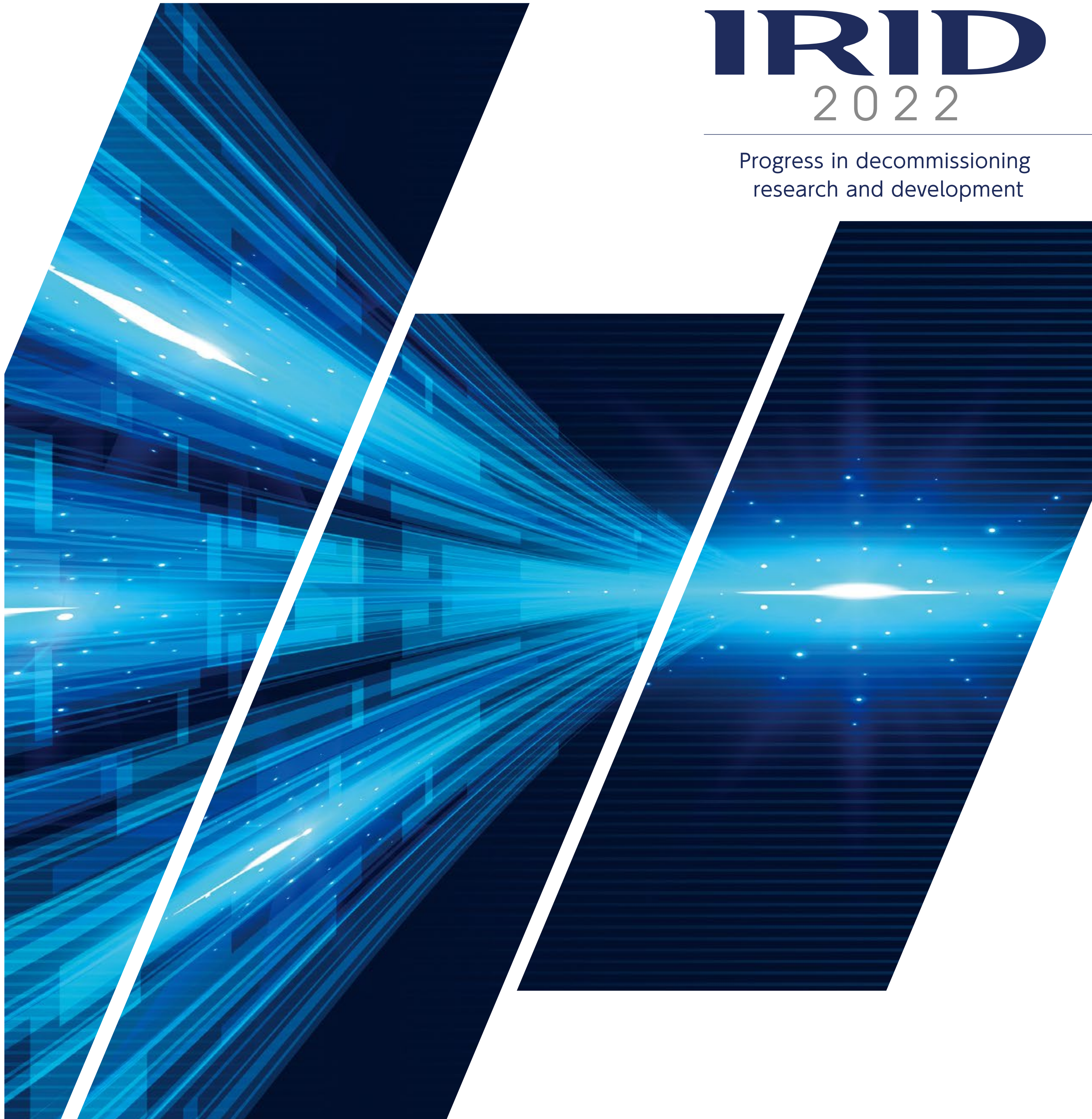
https://www.irid.or.jp/en/

IRID 2022

Unprecedented Challenges to Explore an Unknown Field and Gathering Wisdom from Around the World

IRID
2022

Progress in decommissioning
research and development



IRID commits to R&D for the nuclear decommissioning by working together as one team while gathering knowledge wisdom from around the world.

The decommissioning of Fukushima Daiichi is an extremely difficult task that is unprecedented worldwide. IRID is developing technologies based on accumulated knowledge and wisdom to overcome technological challenges.

Toyoaki Yamauchi
President of IRID

Greeting

The International Research Institute for Nuclear Decommissioning (IRID) was established as a non-profit mutual benefit corporation in August 2013, with the purpose of conducting tests study for the decommissioning of nuclear power station (NPS), and improvement and practical application of technological standards in accordance with the Act on Technology Research Associations.

Since its establishment, IRID has been engaged in research and development (R&D) of technologies necessary for decommissioning based on the needs of Tokyo Electric Power Company (TEPCO) Holdings, Inc., which is undertaking onsite work in accordance with the Mid- and Long-Term Roadmap for Decommissioning Fukushima Daiichi NPS of TEPCO Holdings Inc.; the Technical Strategic Plan for Decommissioning Fukushima Daiichi NPS of TEPCO Holdings, Inc.; and the R&D Mid-and-Long-Term Plan, which are issued by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF).

The reactors of Fukushima Daiichi NPS were damaged by the accident, and the surrounding area is a severe environment that humans cannot approach. To proceed with the decommissioning work in this environment, IRID has made it our mission to challenge technological development with the courage and wisdom necessary for this unprecedented decommissioning task.

So far, the technologies developed by IRID for use in the decommissioning include confirming the conditions inside the primary containment vessel (PCV) through robotic investigation and a tomography technique uses cosmic-ray muons to identify the location of fuel debris. Currently, IRID is researching and developing the technologies needed to perform detailed investigations within the PCV and retrieve fuel debris.

IRID is committed to the reconstruction of Fukushima as well as technological contributions that transform Japan into a technology-driven nation. We also would like to cultivate young talent for the next generation involved in decommissioning technology.

Our visions

Purpose

To conduct testing and research for the decommissioning of nuclear power stations and to implement projects aimed at improving the technological prowess of IRID member organizations with the goal of producing technologies for practical application.

Basic principles

From the standpoint of strengthening the foundation of nuclear decommissioning technology, we devote ourselves to research and development (R&D) of technology for the current and most urgent challenge: the decommissioning of the Fukushima Daiichi Nuclear Power Station (NPS).

Our Principles in Action

1. We work on R&D projects effectively and efficiently while advancing integrated project management to develop and propose the best technologies and systems for rapid onsite deployment at the Fukushima Daiichi NPS as we face numerous extremely difficult technological challenges.
2. We build the optimal R&D structure by cooperating with relevant organizations and gathering knowledge from Japan and abroad.
3. We actively promote efforts to develop and secure the human resources that will comprise the next generation of workers for nuclear decommissioning and related technologies, including efforts to collaborate with universities and research institutions.
4. We strive to release information on our R&D activities and results to reassure and reach an understanding with Japanese citizens, including those in Fukushima, as well as the international community.
5. We form an international research hub (center of excellence) through our R&D activities, thus contributing to the decommissioning of the Fukushima Daiichi NPS and rapid restoration of Fukushima and the improvement of technological capabilities in the international community.

Contents

Overview of IRID

Organizational Profile

1.Name

International Research Institute for Nuclear Decommissioning (IRID)

2.Location

5F, Toyokaiji Building No.3, 2-23-1 Nishishimbashi,
Minato-ku Tokyo 105-0003, Japan
Phone: +81 3 6435 8601

3.Date of Establishment

August 1, 2013
The establishment of IRID was approved by the Minister of Economy, Trade and Industry in accordance with the Research and Development Partnership Act.

4.Scope of Work

- R&D for nuclear decommissioning
- Cooperation with overseas organizations
- Human resource cultivation in R&D

5.Members (18 organizations)

National research and development agency:
Japan Atomic Energy Agency
National Institute of Advanced Industrial Science and Technology

Plant manufacturers, etc.:
Toshiba Energy Systems & Solutions Corporation
Hitachi-GE Nuclear Energy, Ltd.
Mitsubishi Heavy Industries, Ltd.
ATOX Co., Ltd.

Electric utilities, etc.:
Hokkaido Electric Power Co.,Inc.
Tohoku Electric Power Co., Inc.
Tokyo Electric Power Company Holdings, Inc.
Chubu Electric Power Co., Inc.
Hokuriku Electric Power Company
The Kansai Electric Power Company, Inc.
The Chugoku Electric Power Co., Inc.
Shikoku Electric Power Company, Inc.
Kyushu Electric Power Company, Inc.
The Japan Atomic Power Company
Electric Power Development Co., Ltd.
Japan Nuclear Fuel Limited

6.Board of Directors

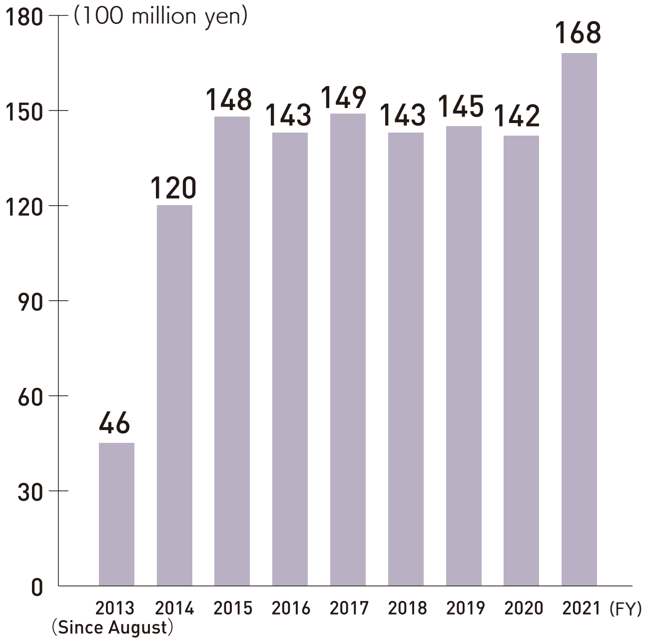
President: Toyoaki Yamauchi
Vice President: Tamio Arai
Managing Director: Akihisa Heike
Directors: Shunji Yamamoto, Hiroshi Arima, Satoshi Ueda, Satoshi Sekiguchi, Masaru Taniguchi, Kentaro Funaki, Noritoshi Maeda, Junichi Matsumoto
Auditor: Masao Nakanishi

7.Personnel

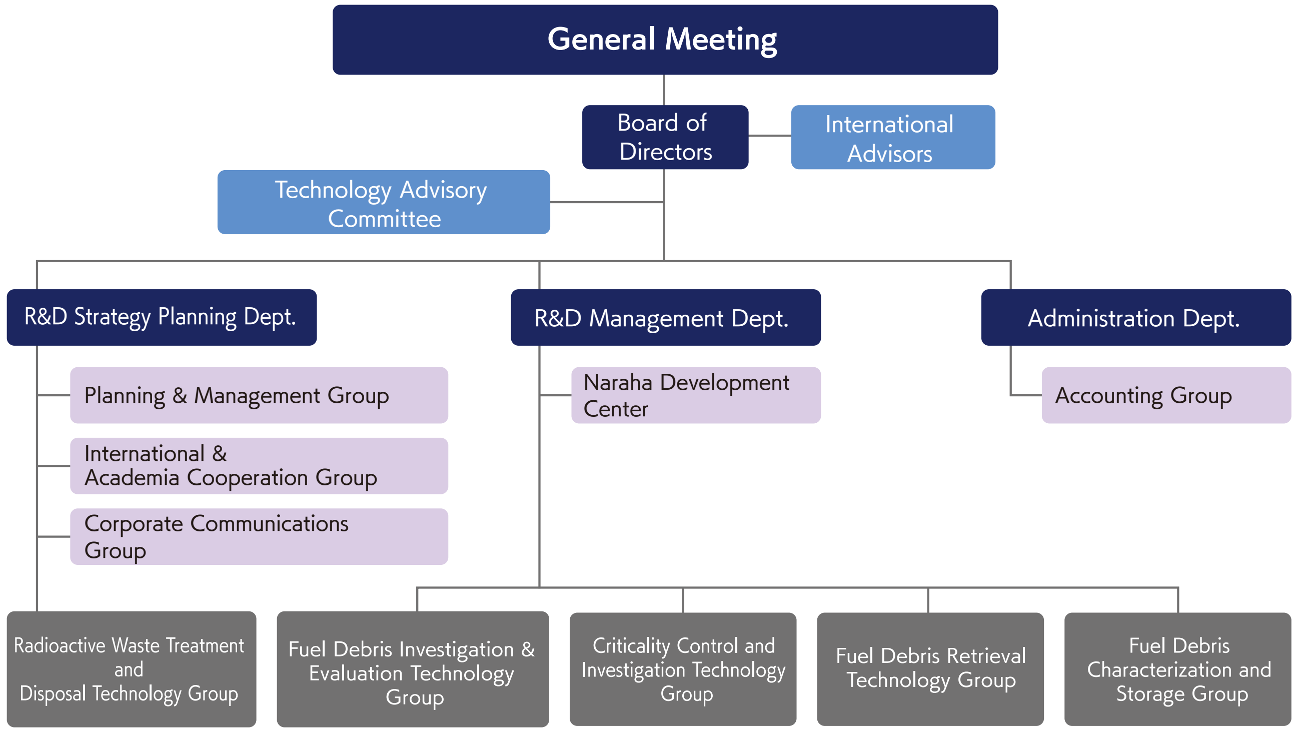
681 people* (Excluding directors)

*Including members of the above membership organizations who engage in research projects. (As of March 31, 2022)

Project costs



Organizational Structure

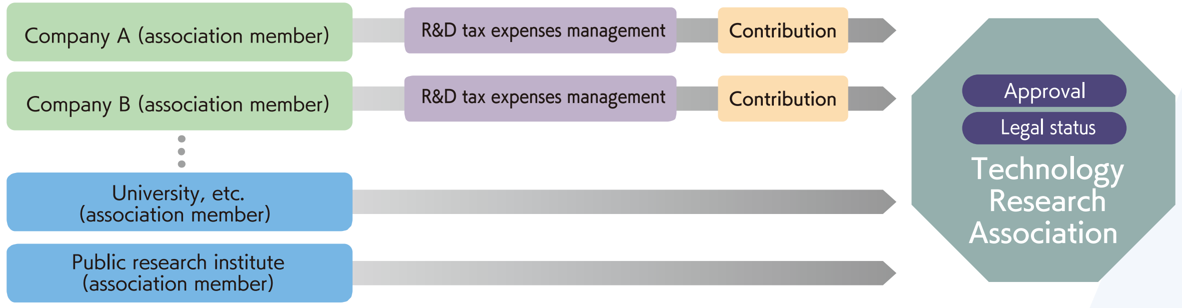


(As of April 1, 2022)

Reference: Technology Research Association

Technology Research Associations are mutual aid organizations (non-profit mutual benefit corporation) that conduct joint research on technologies for use in industrial activities, for the benefit of association members. IRID was established as a Technology Research Association to rapidly systemize its activities and take advantage of the transparency and flexibility in terms of running the organization.

Overview of the Technology Research Association Model



Features of Technology Research Association

- Each association member provides researchers, funds, and facilities for use in joint research. The result of the research are jointly managed and utilized by all members.
- Technology Research Associations are joint research organizations that have a legal identity independent of association members.
- Transparency and reliability of the association's management can be increased with the approval of the minister in charge and by holding regular member meetings as well as meetings of the board of directors.
- Those who directly or indirectly utilize the results of joint research (including corporations, individuals, foreign companies, and foreign nationals) can become association members.
- Since universities, R&D institutes, technical schools, local governments, and foundations primarily engaged in testing and research can participate as association members, the Technology Research Association serves as a conduit for collaboration between industry, academia, and government.

*Source: "Technology Research Association" on the Ministry of Economy, Trade and Industry website.

Roles of IRID

IRID works on R&D for decommissioning based on a major policy of the Japanese government while closely cooperating with other organizations involved in the decommissioning of Fukushima Daiichi NPS.

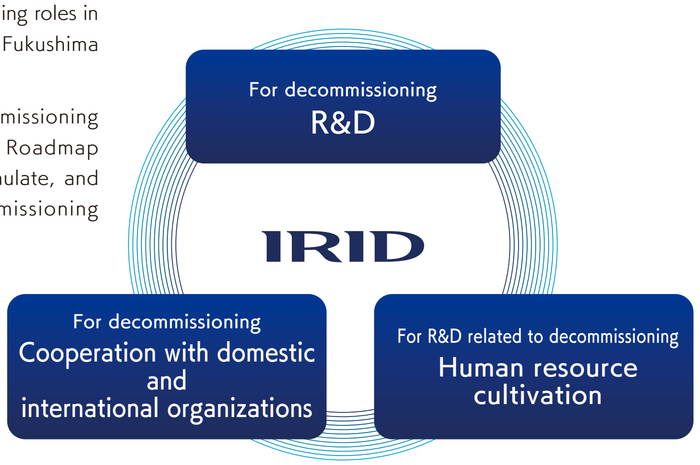
Activities of IRID

IRID has a three-pronged strategy: R&D on decommissioning, cooperation with domestic and overseas organizations, and the cultivation of human resources.

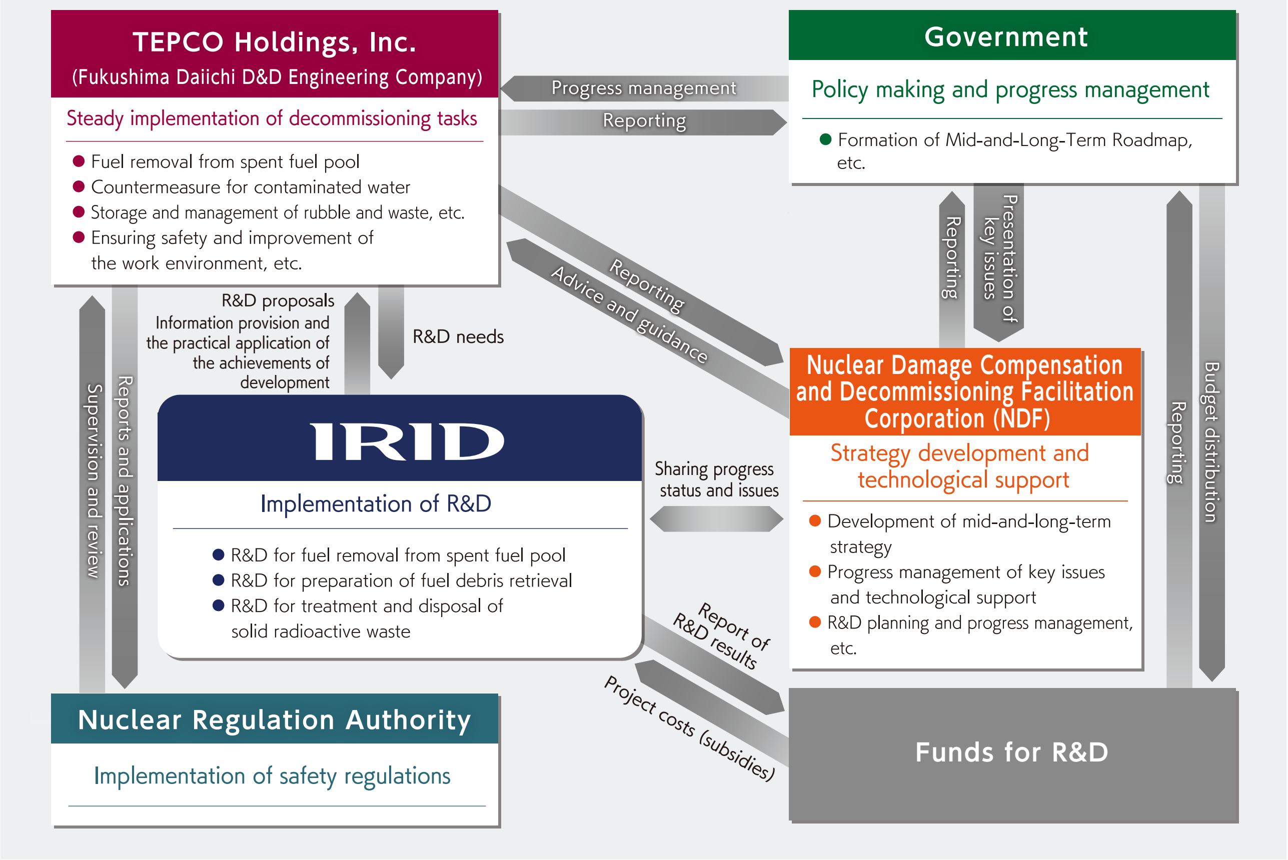
IRID is an organization composed of 18 corporations that play leading roles in research and development (R&D) on the decommissioning of Fukushima Daiichi Nuclear Power Station (NPS).

Currently, IRID conducts R&D on the urgent issue of decommissioning Fukushima Daiichi NPS based on the Mid- and Long-Term Roadmap developed by the government while aiming to cultivate, accumulate, and upgrade technologies necessary for future nuclear decommissioning throughout Japan.

In addition, it is essential to amass knowledge from within Japan and abroad to proceed with the decommissioning of Fukushima Daiichi NPS, a globally unprecedented and extremely difficult task; therefore, IRID is promoting collaboration with related domestic and international organizations. Moreover, IRID commits to the cultivation of the human resources needed to continue the decommissioning of Fukushima Daiichi NPS.



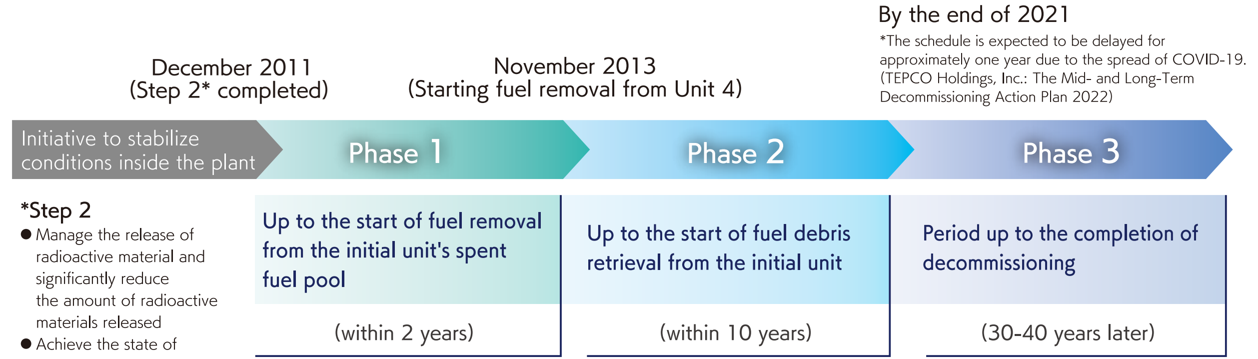
Roles of Organizations in the Decommissioning of Fukushima Daiichi NPS



Overview of Mid-and-Long-Term Roadmap (Revised on December 27, 2019)

The decommissioning of Fukushima Daiichi Nuclear Power Station (NPS) is proceeding based on the "Mid-and-Long-Term Roadmap for Decommissioning of Fukushima Daiichi NPS of Tokyo Electric Power Company (TEPCO) Holdings, Inc." (the "Mid-and-Long-Term Roadmap") formulated by the Japanese government.

Phases in the Mid-and-Long-Term Roadmap



*Numbers in parentheses indicate the period of time after the completion of Step 2

IRID has been engaged in various R&D projects under the Mid-and-Long-Term Roadmap. These R&D projects produced sucessful results in investigating the inside of the primary containment vessel (PCV) by using remote-operated robots and imaging the inside of PCV using cosmic-ray muons radiography, while clarifying technical challenges that must be overcome.

IRID will continue to tackle these issues as it commits to the R&D needed to begin retrieving fuel debris from the initial unit.

Scope of R&D conducted by IRID

Decommissioning work

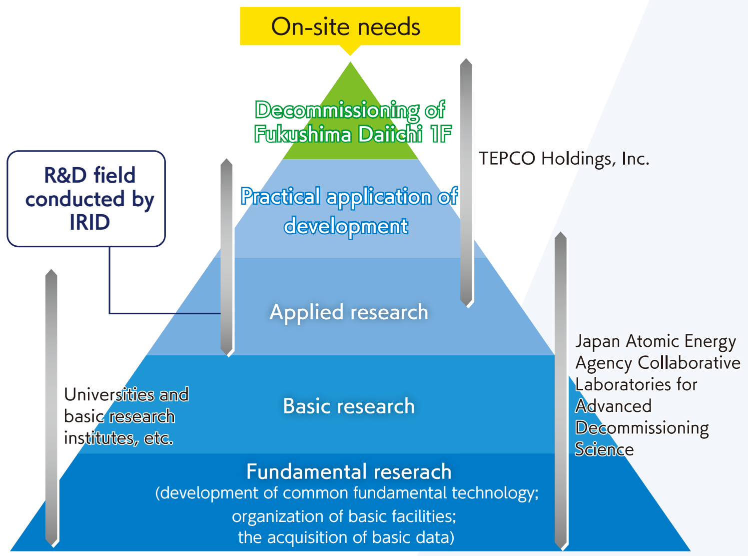
- Continue to maintain the cold shutdown state of the reactor
- Process the accumulated water (countermeasures for contaminated water)
- Reduce radiation dosages throughout the plant and prevent the spread of contamination

- Remove fuel from spent fuel pool
- Retrieve fuel debris
- Plan for the storage, management, and disposal of solid waste

- Plan for the decommissioning of nuclear facilities

R&D field conducted by IRID

Overview of R&D



Partially revised by reference to the NDF Technical Strategic Plan 2021

IRID' s R&D Projects

To advance the decommissioning strategies, IRID has been considering appropriate approaches and methods of reducing risks, focusing on the end state (the most appropriate state).

Three R&D Projects for Nuclear Decommissioning

IRID has three major R&D projects: R&D related to removing fuel from spent fuel pool, R&D related to preparing for the retrieval of fuel debris, and R&D on the treatment and disposal of solid radioactive waste. IRID will further advance its R&D based on the Fuel Debris Retrieval Policy issued in 2017.

IRID

R&D 1
R&D for removing fuel from the spent fuel pool

R&D 2
R&D for preparing to retrieve fuel debris

R&D 3
R&D for treating and disposing of solid radioactive waste

Policy for Fuel Debris Retrieval and the Current Approach

IRID will proceed with fuel debris retrieval based on the following policy, taking into account feasibility evaluations and proposals for fuel debris retrieval methods that were studied in the Technical Strategic Plan issued by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF).

1. Step-by-step approach

Start fuel debris retrieval at a small scale then gradually increase the retrieval scale of fuel debris while working flexibly

2. Optimization of the entire decommissioning process

Consider a comprehensive plan aimed at total optimization of the entire decommissioning process, including preparation work, and retrieval, transport, processing, storage of fuel debris until clean-up of the site

3. Combination of multiple methods

Study multiple methods of retrieving fuel debris under the assumption that the primary containment vessel (PCV) will be accessed from the bottom and the reactor pressure vessel (RPV) will be accessed from the top.

4. Initiative focused on the partial-submersion method

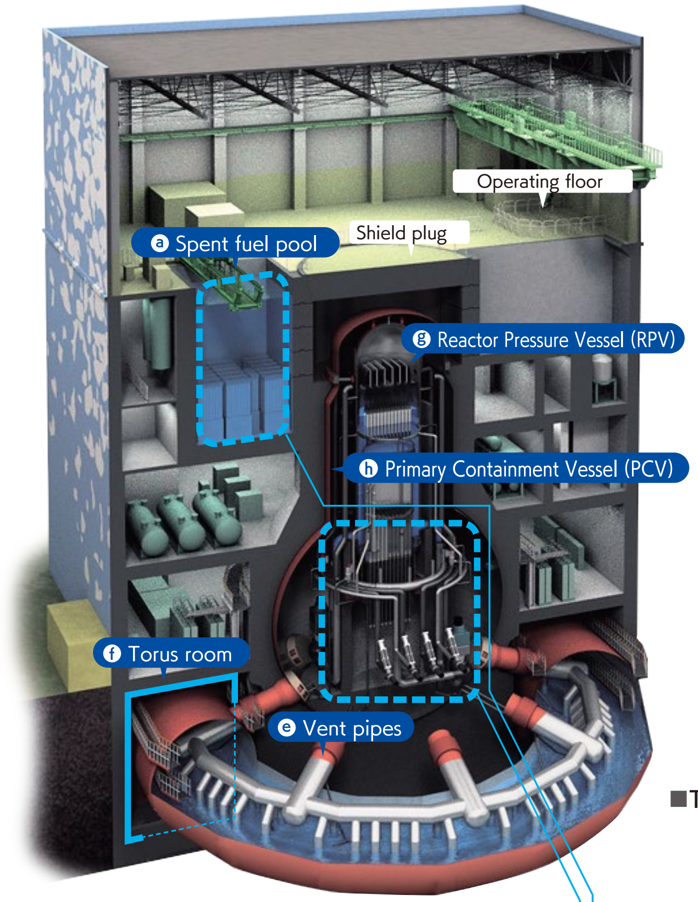
Currently, the submersion method is problematic due to the difficulty in preventing leaks as well as the amount of radiation exposure during retrieval work.

* The submersion method does have some advantages such as its shielding effect, so it may be reexamined in the future.

5. Prioritizing the method of accessing the bottom of the PCV from the side

Fuel debris is located both at the bottom of the PCV and within the RPV of each reactor.
To swiftly reduce risks and minimize the increased danger associated with retrieval, the method for accessing the bottom of the PCV from the side is prioritized in consideration of the following:
① it offers the best accessibility to the bottom of the PCV, which helps build knowledge through investigations of the interior;
② retrieval can begin at an earlier stage; and
③ the work can proceed simultaneously with the removal of spent fuel.

Overview of the Reactor Building



Explanation of technical terms related to the reactor building

ⓐ Spent fuel pool

Located on the top floor of the reactor building, this tank holds the water used to store racks of spent fuel until the heat generated by the decay of fission products has lessened.

ⓑ Fuel debris

This subtance is formed when high-temperature fuel melts along with control rods and structures inside PRV then cools and resolidifies.

ⓒ Drywell (D/W)

A safety structure comprised of a flask-shaped container that houses equipment such as RPV; contained radioactive material at the time of the accident.

ⓓ Suppression chamber (S/C)

Located in the basement of the reactor building, this doughnut-shaped device stores water. The S/C condenses vapor generated if there is a break in the reactor's piping to prevent excess pressure from building up. It also serves the important function of providing a water source for the Emergency Core Cooling System (ECCS) during incidents of coolant loss.

ⓔ Vent pipes

These connecting pipes transport vapor generated in the D/W by a break in a reactor pipe to the S/C. Eight vent pipes are installed in PCVs of Units 1-3 at Fukushima Daiichi NPS.

ⓕ Torus room

A room containing the torus-shaped (doughnut-shaped) S/C in the basement of the reactor building.

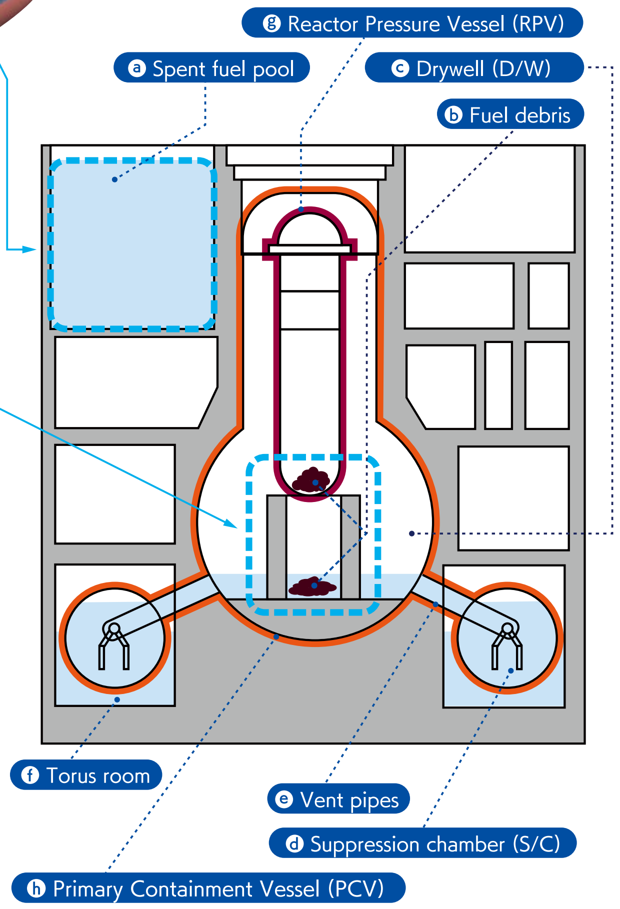
ⓖ Reactor Pressure Vessel (RPV)

A cylindrical steel container that houses the fuel assemblies. This container can withstand the high-temperature water and high-pressure steam generated by nuclear-fission energy inside the RPV, which is housed within the PCV along with cooling equipment etc.

ⓗ Primary Containment Vessel (PCV)

A steel container that houses RPV, cooling equipment, and other apparatus that perform important functions. This prevents radioactive material from being released outside under abnormal plant conditions, such as when an accident occurs or the cooling equipment breaks down. Each of PCVs in Units 1-3 of Fukushima Daiichi NPS consists of a flask-shaped drywell, a doughnut-shaped suppression chamber, and vent pipes connecting the drywell to the suppression chamber.

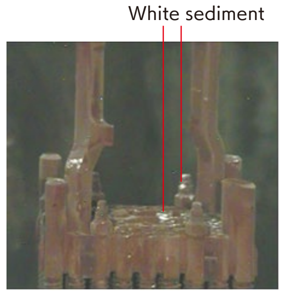
■Two-dimensional figure of the reactor building



Contents

Ⅰ Spent Fuel Management

19 Evaluation of long-term integrity of fuel assemblies removed from spent fuel pool and study of methods to process damaged fuel



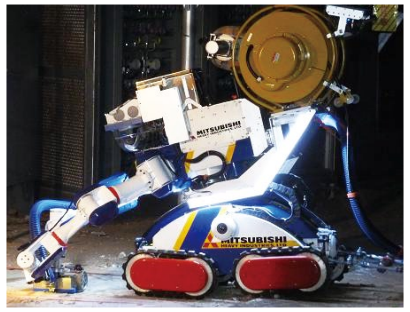
Appearance of spent fuel from Unit 4

Integrity assessments for the long-term storage of removed fuel
as well as studies on the processing of damaged fuel.

Ⅱ Decontamination and Dose Reduction

23 Development of technology for remotely operation in the reactor buildings

Technology for decontaminating reactor buildings
with remote-operated equipment in preparation
for the retrieval of fuel debris.

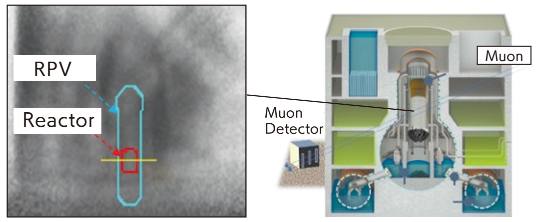


Suction/Blasting decontamination equipment

Ⅲ Investigating and Analyzing inside PCV/RPV

27 Development of technology for detection of fuel debris in the reactor

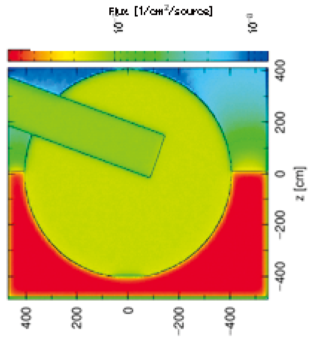
Technique of measuring muons to
more promptly estimate the distribution of
fuel debris in the reactor.



Muon measurement

29 Development of technology for non-destructive detection of radioactive materials accumulated in the suppression chamber

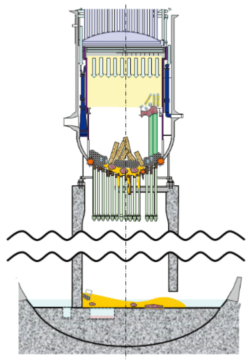
Methods of estimating and measuring the accumulation
of radioactive material within the suppression chamber (S/C) etc.



Distribution of fuel-originating radiation in
the vicinity of Unit 1's S/C

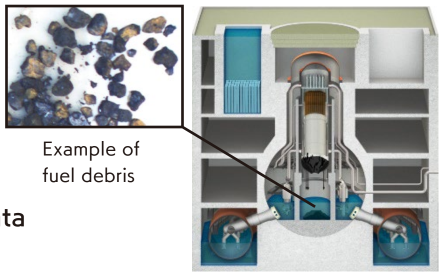
31 Upgrading for identifying comprehensive conditions inside the reactor

Analysis and evaluation techniques for inferring the conditions
inside the RPV and PCV, which is essential for studying technology for
fuel debris retrieval.



Understanding a reactor's internal conditions

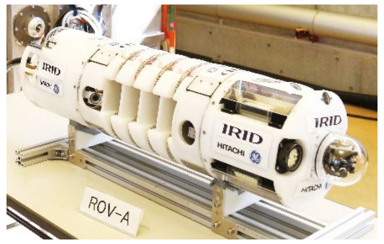
35 Development of analysis and detection technology for characterization of fuel debris



Example of fuel debris

Development of analysis technology and the acquisition of data
for ascertaining the properties of fuel debris,
which is needed to study fuel debris retrieval technology.

43 Development of technology for detailed investigation inside the primary containment vessel (PCV)

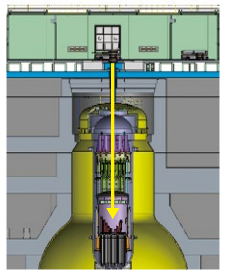


The Unit-1 submersible robot

Investigations of the inside of the PCV to
obtain detailed information for use in fuel debris retrieval.

53 Development of technology for investigation inside the reactor pressure vessel (RPV)

Technology used to investigate inside the PCV in preparation
for fuel debris retrieval.



Investigating inside the RPV

58 Integrity evaluation of PCV/RPV and development of corrosion control technology

Testing the durability of the RPV pedestal

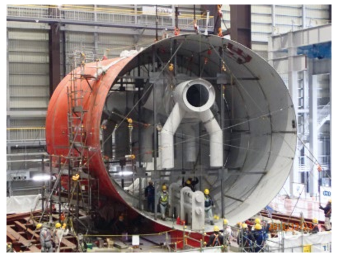
Development of anti-corrosion technology as well as
integrity assessments of the PCV and RPV based on
an earthquake-resistance assessment that considers corrosion and other factors.

Contents

Ⅳ The Water Circulation System and Repairing the PCV

63 Development of repair technology for PCV and full-scale test

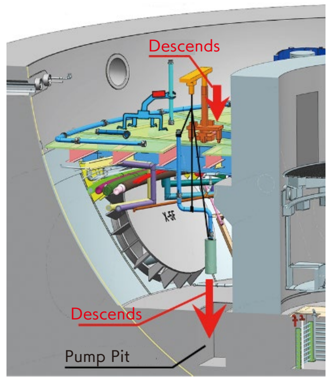
Technology for repairing leaks in the primary containment vessel (PCV) prior to fuel debris retrieval.



The S/C shell and downcomer assembly

71 Development of technology for establishing the water circulation system in the primary containment vessel (PCV) (development / full-scale test)

Systems that pump water into the dry well (D/W) and suppression chamber (S/C).

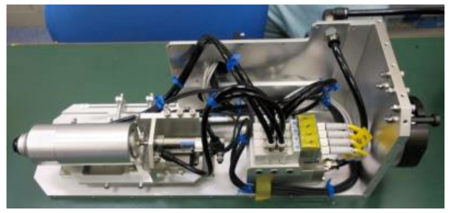


The dry-well intake line

Ⅴ Retrieving Fuel Debris

75 Development of trial retrieval and technology for increasing the retrieval scale of fuel debris

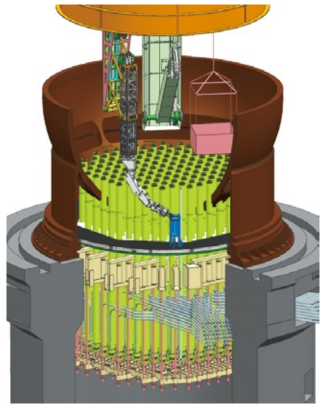
Development of methods for experimentally retrieving fuel debris and for continuing to gradually increase the scale of the retrieval.



Collection equipment (prototype)

79 Development of technology for retrieval of fuel debris and reactor internals

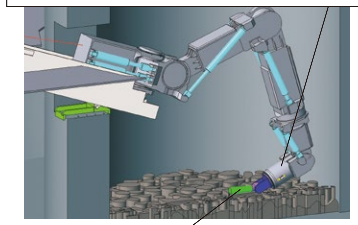
Research and development aimed at manufacturing the equipment required for fuel debris retrieval.



Removing obstacles from the bottom of the reactor

95 Development of technology for criticality control of fuel debris

Research and development for detecting and controlling abnormalities promptly to prevent criticality during fuel debris retrieval.

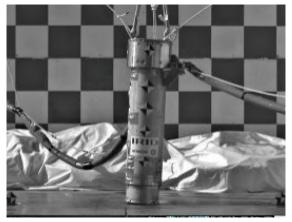


Detector installed next to the processing tool to continuously monitor the processing work and to watch for approaching criticality before and after debris processing

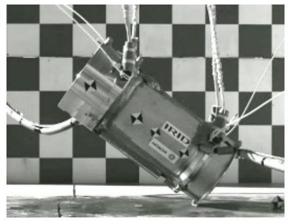
Detector installed on the arm to measure subcriticality

101 Development of technology for containing, transfer and storage of fuel debris

Development of canisters for containing, transporting, and storing fuel debris safely over the long term.



Structural test
(dropped vertically)

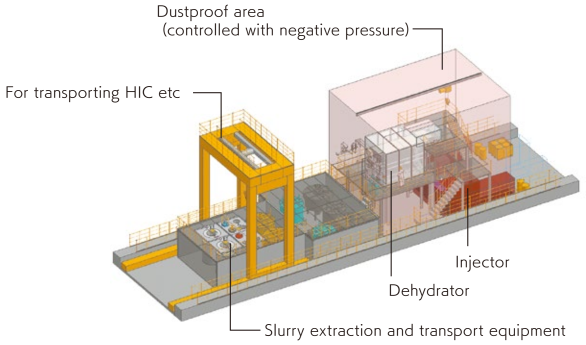


Structural test
(dropped at an angle)

Ⅵ Treatment and Disposal of Solid Waste

109 Research and development of treatment and disposal of solid radioactive waste

Research and development related to the treatment and disposal of solid waste, covering everything from understanding the properties of waste to handling its disposal.



Pressurized filtration method

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107 【 IRID Research and Development 】 IRID's History in Photos

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115 R&D Cooperation with Oversea Organizations

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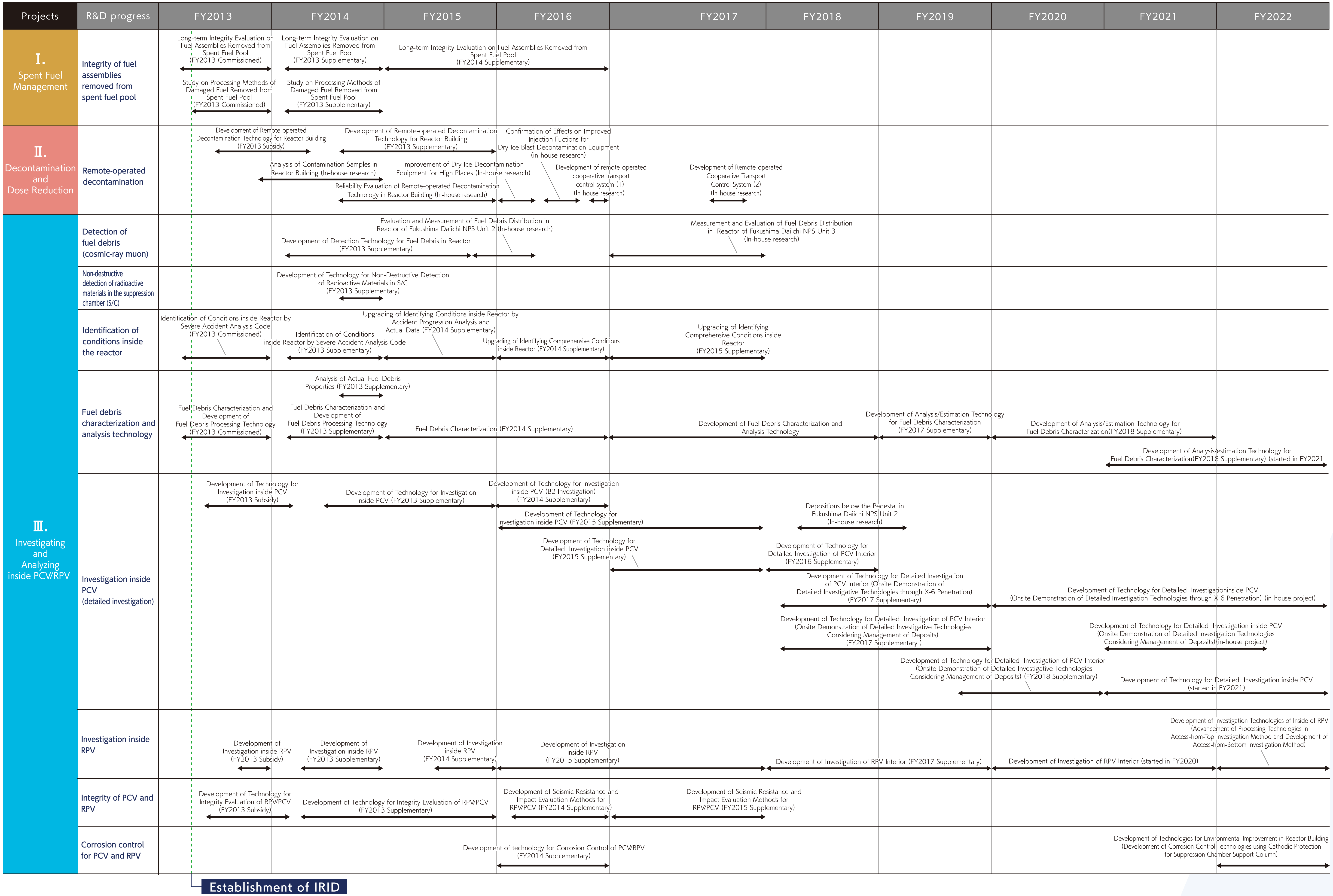
117 Human Resource Cultivation in R&D

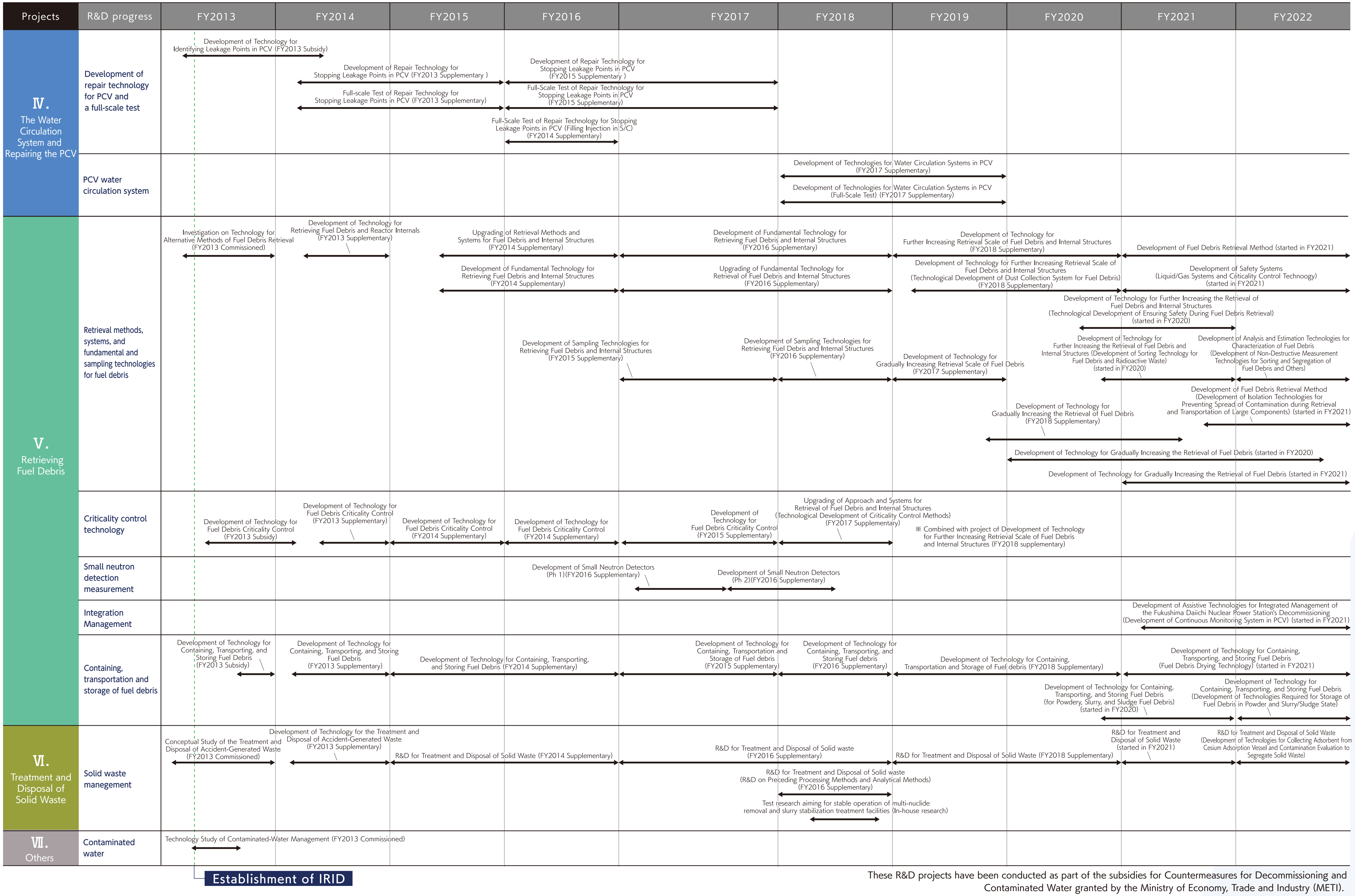
IRID R&D Progress in 10 years



Projects	R&D progress	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022
I. Spent Fuel Management	Integrity of fuel assemblies removed from spent fuel pool	Long-term Integrity Evaluation on Fuel Assemblies Removed from Spent Fuel Pool (FY2013 Commissioned) Study on Processing Methods of Damaged Fuel Removed from Spent Fuel Pool (FY2013 Commissioned)	Long-term Integrity Evaluation on Fuel Assemblies Removed from Spent Fuel Pool (FY2013 Supplementary) Study on Processing Methods of Damaged Fuel Removed from Spent Fuel Pool (FY2013 Supplementary)	Long-term Integrity Evaluation on Fuel Assemblies Removed from Spent Fuel Pool (FY2014 Supplementary)							
II. Decontamination and Dose Reduction	Remote-operated decontamination	Development of Remote-operated Decontamination Technology for Reactor Building (FY2013 Subsidy) Analysis of Contamination Samples in Reactor Building (In-house research)	Development of Remote-operated Decontamination Technology for Reactor Building (FY2013 Supplementary) Reliability Evaluation of Remote-operated Decontamination Technology in Reactor Building (In-house research)		Improvement of Dry Ice Decontamination Equipment for High Places (In-house research) Confirmation of Effects on Improved Injection Fuctions for Dry Ice Blast Decontamination Equipment (in-house research) Development of remote-operated cooperative transport control system (1) (In-house research)	Development of Remote-operated Cooperative Transport Control System (2) (In-house research)					
III. Investigating and Analyzing inside PCV/RPV	Detection of fuel debris (cosmic-ray muon)		Development of Detection Technology for Fuel Debris in Reactor (FY2013 Supplementary)	Evaluation and Measurement of Fuel Debris Distribution in Reactor of Fukushima Daiichi NPS Unit 2 (In-house research)		Measurement and Evaluation of Fuel Debris Distribution in Reactor of Fukushima Daiichi NPS Unit 3 (In-house research)					
	Non-destructive detection of radioactive materials in the suppression chamber (S/C)		Development of Technology for Non-Destructive Detection of Radioactive Materials in S/C (FY2013 Supplementary)								
	Identification of conditions inside the reactor	Identification of Conditions inside Reactor by Severe Accident Analysis Code (FY2013 Commissioned)	Identification of Conditions inside Reactor by Severe Accident Analysis Code (FY2013 Supplementary)	Upgrading of Identifying Conditions inside Reactor by Accident Progression Analysis and Actual Data (FY2014 Supplementary)	Upgrading of Identifying Comprehensive Conditions inside Reactor (FY2014 Supplementary)	Upgrading of Identifying Comprehensive Conditions inside Reactor (FY2015 Supplementary)					
	Fuel debris characterization and analysis technology	Fuel Debris Characterization and Development of Fuel Debris Processing Technology (FY2013 Commissioned)	Analysis of Actual Fuel Debris Properties (FY2013 Supplementary) Fuel Debris Characterization and Development of Fuel Debris Processing Technology (FY2013 Supplementary)	Fuel Debris Characterization (FY2014 Supplementary)		Development of Fuel Debris Characterization and Analysis Technology		Development of Analysis/Estimation Technology for Fuel Debris Characterization (FY2017 Supplementary)	Development of Analysis/Estimation Technology for Fuel Debris Characterization(FY2018 Supplementary)	Development of Analysis/estimation Technology for Fuel Debris Characterization(FY2018 Supplementary) (started in FY2021	
	Investigation inside PCV (detailed investigation)	Development of Technology for Investigation inside PCV (FY2013 Subsidy)	Development of Technology for Investigation inside PCV (FY2013 Supplementary)		Development of Technology for Investigation inside PCV (B2 Investigation) (FY2014 Supplementary) Development of Technology for Investigation inside PCV (FY2015 Supplementary)	Development of Technology for Detailed Investigation inside PCV (FY2015 Supplementary)	Depositions below the Pedestal in Fukushima Daiichi NPS Unit 2 (In-house research) Development of Technology for Detailed Investigation of PCV Interior (FY2016 Supplementary) Development of Technology for Detailed Investigation of PCV Interior (Onsite Demonstration of Detailed Investigative Technologies through X-6 Penetration) (FY2017 Supplementary) Development of Technology for Detailed Investigation of PCV Interior (Onsite Demonstration of Detailed Investigative Technologies Considering Management of Deposits) (FY2017 Supplementary)	Development of Technology for Detailed Investigation of PCV Interior (Onsite Demonstration of Detailed Investigative Technologies Considering Management of Deposits) (FY2018 Supplementary)	Development of Technology for Detailed Investigationinside PCV (Onsite Demonstration of Detailed Investigation Technologies through X-6 Penetration) (in-house project)	Development of Technology for Detailed Investigation inside PCV (Onsite Demonstration of Detailed Investigation Technologies Considering Management of Deposits)(in-house project) Development of Technology for Detailed Investigation inside PCV (started in FY2021)	
	Investigation inside RPV	Development of Investigation inside RPV (FY2013 Subsidy)	Development of Investigation inside RPV (FY2013 Supplementary)	Development of Investigation inside RPV (FY2014 Supplementary)	Development of Investigation inside RPV (FY2015 Supplementary)		Development of Investigation of RPV Interior (FY2017 Supplementary)		Development of Investigation of RPV Interior (started in FY2020)		Development of Investigation Technologies of Inside of RPV (Advancement of Processing Technologies in Access-from-Top Investigation Method and Development of Access-from-Bottom Investigation Method)
	Integrity of PCV and RPV	Development of Technology for Integrity Evaluation of RPV/PCV (FY2013 Subsidy)	Development of Technology for Integrity Evaluation of RPV/PCV (FY2013 Supplementary)		Development of Seismic Resistance and Impact Evaluation Methods for RPV/PCV (FY2014 Supplementary)	Development of Seismic Resistance and Impact Evaluation Methods for RPV/PCV (FY2015 Supplementary)					
	Corrosion control for PCV and RPV				Development of technology for Corrosion Control of PCV/RPV (FY2014 Supplementary)						Development of Technologies for Environmental Improvement in Reactor Building (Development of Corrosion Control Technologies using Cathodic Protection for Suppression Chamber Support Column)

Establishment of IRID

IRID R&D Progress in 10 years



Projects | R&D progress | FY2013 | FY2014 | FY2015 | FY2016 | FY2017 | FY2018 | FY2019 | FY2020 | FY2021 | FY2022

Ⅳ. The Water Circulation System and Repairing the PCV

Development of repair technology for PCV and a full-scale test

- Development of Technology for Identifying Leakage Points in PCV (FY2013 Subsidy)
- Development of Repair Technology for Stopping Leakage Points in PCV (FY2013 Supplementary)
- Development of Repair Technology for Stopping Leakage Points in PCV (FY2015 Supplementary)
- Full-scale Test of Repair Technology for Stopping Leakage Points in PCV (FY2013 Supplementary)
- Full-Scale Test of Repair Technology for Stopping Leakage Points in PCV (FY2015 Supplementary)
- Full-Scale Test of Repair Technology for Stopping Leakage Points in PCV (Filling Injection in S/C) (FY2014 Supplementary)

PCV water circulation system

- Development of Technologies for Water Circulation Systems in PCV (FY2017 Supplementary)
- Development of Technologies for Water Circulation Systems in PCV (Full-Scale Test) (FY2017 Supplementary)

Ⅴ. Retrieving Fuel Debris

Retrieval methods, systems, and fundamental and sampling technologies for fuel debris

- Investigation on Technology for Alternative Methods of Fuel Debris Retrieval (FY2013 Commissioned)
- Development of Technology for Retrieving Fuel Debris and Reactor Internals (FY2013 Supplementary)
- Upgrading of Retrieval Methods and Systems for Fuel Debris and Internal Structures (FY2014 Supplementary)
- Development of Fundamental Technology for Retrieving Fuel Debris and Internal Structures (FY2016 Supplementary)
- Development of Technology for Further Increasing Retrieval Scale of Fuel Debris and Internal Structures (FY2018 Supplementary)
- Development of Fuel Debris Retrieval Method (started in FY2021)
- Development of Fundamental Technology for Retrieving Fuel Debris and Internal Structures (FY2014 Supplementary)
- Upgrading of Fundamental Technology for Retrieval of Fuel Debris and Internal Structures (FY2016 Supplementary)
- Development of Technology for Further Increasing Retrieval Scale of Fuel Debris and Internal Structures (Technological Development of Dust Collection System for Fuel Debris) (FY2018 Supplementary)
- Development of Safety Systems (Liquid/Gas Systems and Criticality Control Technoogy) (started in FY2021)
- Development of Technology for Further Increasing the Retrieval of Fuel Debris and Internal Structures (Technological Development of Ensuring Safety During Fuel Debris Retrieval) (started in FY2020)
- Development of Sampling Technologies for Retrieving Fuel Debris and Internal Structures (FY2015 Supplementary)
- Development of Sampling Technologies for Retrieving Fuel Debris and Internal Structures (FY2016 Supplementary)
- Development of Technology for Gradually Increasing Retrieval Scale of Fuel Debris (FY2017 Supplementary)
- Development of Technology for Further Increasing the Retrieval of Fuel Debris and Internal Structures (Development of Sorting Technology for Fuel Debris and Radioactive Waste) (started in FY2020)
- Development of Analysis and Estimation Technologies for Characterization of Fuel Debris (Development of Non-Destructive Measurement Technologies for Sorting and Segregation of Fuel Debris and Others)
- Development of Fuel Debris Retrieval Method (Development of Isolation Technologies for Preventing Spread of Contamination during Retrieval and Transportation of Large Components) (started in FY2021)
- Development of Technology for Gradually Increasing the Retrieval of Fuel Debris (FY2018 Supplementary)
- Development of Technology for Gradually Increasing the Retrieval of Fuel Debris (started in FY2020)
- Development of Technology for Gradually Increasing the Retrieval of Fuel Debris (started in FY2021)

Criticality control technology

- Development of Technology for Fuel Debris Criticality Control (FY2013 Subsidy)
- Development of Technology for Fuel Debris Criticality Control (FY2013 Supplementary)
- Development of Technology for Fuel Debris Criticality Control (FY2014 Supplementary)
- Development of Technology for Fuel Debris Criticality Control (FY2014 Supplementary)
- Development of Technology for Fuel Debris Criticality Control (FY2015 Supplementary)
- Upgrading of Approach and Systems for Retrieval of Fuel Debris and Internal Structures (Technological Development of Criticality Control Methods) (FY2017 Supplementary)

※ Combined with project of Development of Technology for Further Increasing Retrieval Scale of Fuel Debris and Internal Structures (FY2018 supplementary)

Small neutron detection measurement

- Development of Small Neutron Detectors (Ph 1)(FY2016 Supplementary)
- Development of Small Neutron Detectors (Ph 2)(FY2016 Supplementary)

Integration Management

- Development of Assistive Technologies for Integrated Management of the Fukushima Daiichi Nuclear Power Station's Decommissioning (Development of Continuous Monitoring System in PCV) (started in FY2021)

Containing, transportation and storage of fuel debris

- Development of Technology for Containing, Transporting, and Storing Fuel Debris (FY2013 Subsidy)
- Development of Technology for Containing, Transporting, and Storing Fuel Debris (FY2013 Supplementary)
- Development of Technology for Containing, Transporting, and Storing Fuel Debris (FY2014 Supplementary)
- Development of Technology for Containing, Transportation and Storage of Fuel debris (FY2015 Supplementary)
- Development of Technology for Containing, Transporting, and Storing Fuel debris (FY2016 Supplementary)
- Development of Technology for Containing, Transportation and Storage of Fuel debris (FY2018 Supplementary)
- Development of Technology for Containing, Transporting, and Storing Fuel Debris (Fuel Debris Drying Technology) (started in FY2021)
- Development of Technology for Containing, Transporting, and Storing Fuel Debris (for Powdery, Slurry, and Sludge Fuel Debris) (started in FY2020)
- Development of Technology for Containing, Transporting, and Storing Fuel Debris (Development of Technologies Required for Storage of Fuel Debris in Powder and Slurry/Sludge State)

Ⅵ. Treatment and Disposal of Solid Waste

Solid waste manegement

- Conceptual Study of the Treatment and Disposal of Accident-Generated Waste (FY2013 Commissioned)
- Development of Technology for the Treatment and Disposal of Accident-Generated Waste (FY2013 Supplementary)
- R&D for Treatment and Disposal of Solid Waste (FY2014 Supplementary)
- R&D for Treatment and Disposal of Solid waste (FY2016 Supplementary)
- R&D for Treatment and Disposal of Solid Waste (FY2018 Supplementary)
- R&D for Treatment and Disposal of Solid Waste (started in FY2021)
- R&D for Treatment and Disposal of Solid Waste (Development of Technologies for Collecting Adsorbent from Cesium Adsorption Vessel and Contamination Evaluation to Segregate Solid Waste)
- R&D for Treatment and Disposal of Solid waste (R&D on Preceding Processing Methods and Analytical Methods) (FY2016 Supplementary)
- Test research aiming for stable operation of multi-nuclide removal and slurry stabilization treatment facilities (In-house research)

Ⅶ. Others

Contaminated water

- Technology Study of Contaminated-Water Management (FY2013 Commissioned)

Establishment of IRID

These R&D projects have been conducted as part of the subsidies for Countermeasures for Decommissioning and Contaminated Water granted by the Ministry of Economy, Trade and Industry (METI).

Research and Development of Nuclear Decommissioning

The decommissioning of Fukushima Daiichi Nuclear Power Station is often compared with the Asteroid Explore Hayabusa project. The two share many similar features, including the usage of remote-controlled robots in unknown environments. They also require the stable operation of element components in severe environments and systems that can respond to various events. A single prototype was subjected to mock-up testing then be applied in the site at an appropriate timing. In addition, all hopes were necessarily pinned on that first unit.

This creates the need for various technologies—not only those for retrieving and transporting fuel debris, decontamination and investigation of the inside of the reactor but also storage methods developed by analyzing the properties of retrieved material and the construction and connection of earthquake-resistance structures. IRID has striven to ensure safety from many angles by treating the entire decommissioning process as a single system and by sharing information during the development phase. We achieved this through the activities of working groups for each technical field; the groups operated in parallel with each project but in ways that extended beyond the project's framework.

Since 2015, IRID has also been conducting the design review meeting through the participation of external experts. A total of 345 review meetings have been conducted as of late March 2022. These review meetings identify technical issues such as insufficient technical study, the potential for new risks, and on-site challenges. Collaborating with Tokyo Electric Power Company Holding, Inc., which understands the on-site conditions, site surveys were also carried out to confirm details about the state of the worksite.The participants were engineers involved in a wide range of technological development, so the meetings proved useful in terms of on-the-job training and cultivating talent for the field of nuclear decommissioning.

I am proud of the fact that IRID has successfully eliminated barriers between its organizational members, especially between engineers engaged in research and development. Each organization has its own terminology and way of thinking, and the nuclear industry is no different. Through our many meetings where we explained technical documentation to one another, we've attained a shared understanding that extends to the conceptual level.Furthermore, we believe that decommissioning technology is "social technology", and have worked hard to publicize technology so that people in surrounding communities can understand the direction it is heading.

I greatly hope that many people read this pamphlet and learn about our research and development.

Dr. Tamio Arai
Vice President
International Research Institute for Nuclear Decommissioning (IRID)

I

Decommissioning Research and Development

Spent Fuel Management

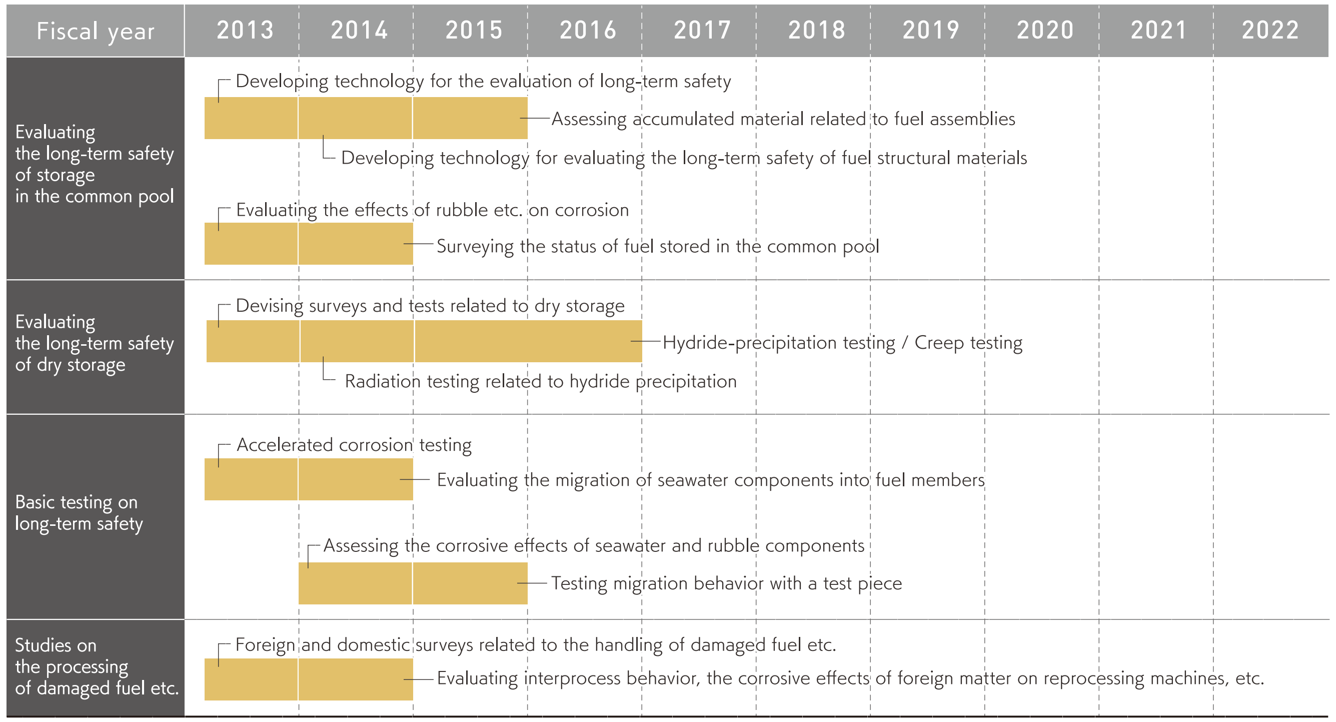
Impact assessment was carried out to obtain verified data related to the integrity (i.e. anti-corrosion, etc.) of the fuel assemblies removed from the spent fuel pool when they are stored in the common pool, etc. for a long period of time. Considering the possibility of physical damage from rubble fragments and salt adhesion from the seawater, criteria for judging the reprocessing possibility of the removed damaged fuel were created.

Evaluation of long-term integrity of fuel assemblies removed from spent fuel pool and study of methods to process damaged fuel

IRID assessed the integrity of the long-term storage of removed fuel and conducted studies on the processing of damaged fuel

- Evaluated the long-term integrity of storing fuel that was exposed to seawater, water mixed with rubble, etc. in the common pool for long periods of time
- Assuming that dry storage will also be used, assessed the long-term integrity of damaged fuel as well as the effects of moisture content within pieces of rubble that are wedged into crevices
- As a basic test, looked at the migration of seawater components to fuel materials and evaluated the effects of the radioactive environment on corrosion from seawater and other substances
- Assessed the technical challenges in reprocessing fuel that may have sustained damage and conducted evaluations for use in determining whether fuel can be reprocessed

Research and development progress



Background

The plan is to store fuel assemblies that are removed from the spent fuel pools of Unit 1 through 4 in the common pool within the power station until a future decision is made regarding their processing or disposal. However, these fuel assemblies have been exposed to a unique environment since they mixed with incoming seawater and falling rubble during the accident.

Therefore, the long-term integrity of fuel assemblies must be verified after they have been transported to the common pool. Whether potentially damaged fuel has any effect on future processing or disposal procedures must also be determined.

Purpose

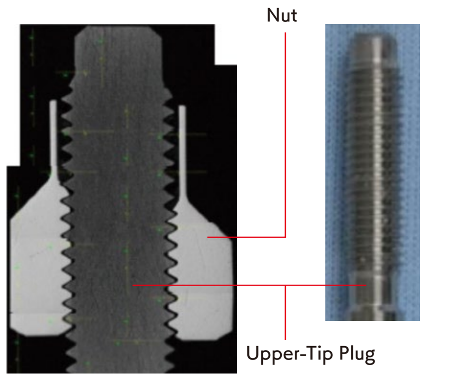
Corrosion and strength tests designed to simulate actual storage conditions were conducted in order to evaluate whether the common pool can be used to safely store fuel that may have been damaged or deformed by contact with rubble or changes in the water quality of the spent fuel pool due to the influx of seawater. Because some level of dry storage is also being considered to ensure that the common pool has sufficient capacity, simulations to determine the safety impact of using dry storage for fuel were also conducted.

And to confirm the technical feasibility of reprocessing fuel—which is one of the measures for disposing of fuel that may be damaged—the technical challenges faced in reprocessing were worked out and conducted a basic impact assessment for determining whether reprocessing is possible.

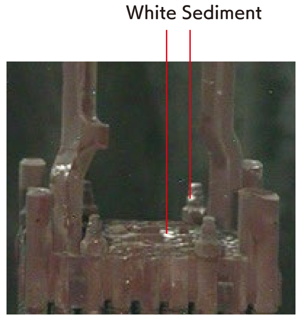
1 Evaluating the long-term safety of fuel stored in the common pool

Regarding fuel safety, one of the most important things is the safety of the fuel's upper and lower portions, which are placed under a great deal of stress when the fuel is handled. Therefore, a strength test as well as an immersion test were conducted on materials in a simulated environment that contains rubble etc. (Figure 1).

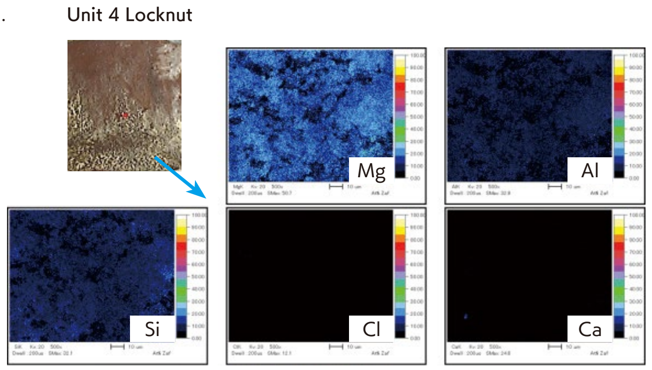
The tests did not reveal any corrosion or deterioration in physical strength that could impact safety. A visual inspection of fuel retrieved from Unit 4's pool was performed and the thickness of the oxide film on the cladding was measured. Although the presence of white sediment was confirmed, anything that would have an impact on safety was not observed. This white sediment is composed primarily of Mg, and Al and Si levels half of Mg, with Cl levels falling below detectable limits (Figure 3). Considering the results of the electrochemical test as well, it was concluded that there is virtually no effect on corrosion.



▲Cross-sectional view of test piece that simulates the upper end of a fuel assembly (left) and results of visual inspection (right) (90 ℃ , chlorine-ion concentration of 2500 ppm, 1,000 hours of immersion followed by 60 ℃, chlorine-ion concentration of 100 ppm, and 7,409 hours of immersion) (Figure 1)



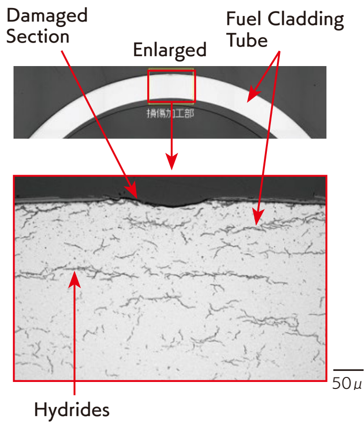
◀Results of visual inspection of spent fuel from Unit 4 (upper tie plate of fuel mixed with rubbles) (Figure 2)



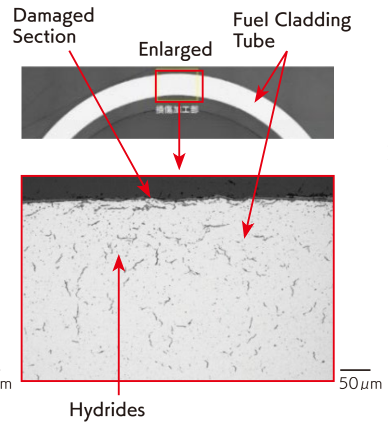
▲Chemical analysis of white sediment on Unit 4 locknut (Figure 3)

2 Evaluating the long-term integrity of fuel in dry storage

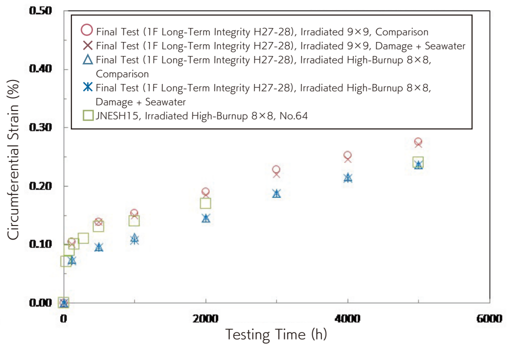
Assuming that dry storage will be used for some fuel assemblies removed from the spent fuel pool, the safety of using dry storage for fuel assemblies that were being affected in multiple ways (such as by falling rubble or seawater) was evaluated by conducting a hydride precipitation test and a creep test to ascertain the impact of Fukushima Daiichi NPS's unique circumstances on the properties of the material. The hydride precipitation test revealed no impact on the behavior (reorientation) of hydrides even when multiple factors, such as damage from rubble and seawater adhesion, are present (Figures 4 and 5). In addition, only a small impact on creep behavior was observed (Figure 6).



▲Results of hydride precipitation test (300 ℃, cooling rate of 0.3 ℃/h, circumferential stress of 70 MPa, damaged) (Figure 4)



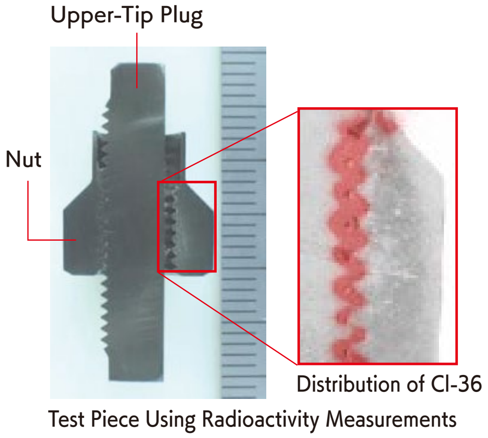
▲Results of hydride precipitation test (irradiated test piece, 300 ℃, cooling rate of 0.04 ℃/h, circumferential stress of 70 MPa, damaged, seawater adhesion, rubble adhesion) (Figure 5)



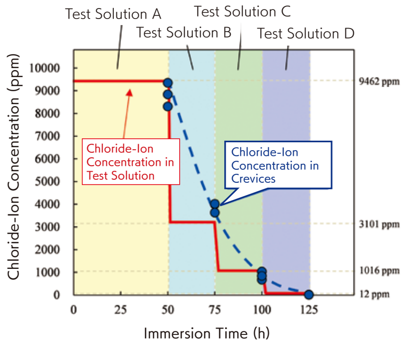
▲Results of creep speed test (irradiated test piece, 360 ℃, circumferential stress of 170 MPa, damaged, seawater adhesion, testing time of 5,000 h) (Figure 6)

3 Basic testing on the long-term safety of removed fuel

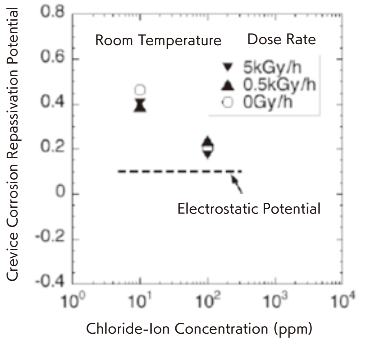
IRID has tested the behavior of seawater components as they move into the structural crevices of fuel materials. The results showed that while seawater components do migrate into structural crevices, improvements to water quality decrease the concentration of chlorine ions (Figures 7 and 8) and there is no accumulation within the structural crevices. It was also confirmed that seawater components do not significantly penetrate the oxide film that is formed on the surface of fuel-rod cladding. In an electrochemical test conducted using a crevice-corrosion test piece, the repassivation potential for crevice corrosion was higher than the electrostatic potential in a water environment that contains a chloride-ion concentration of 100 ppm or less, confirming that crevice corrosion does not occur (Figure 9).



▲Distribution of Cl-36 on the screw at the plug of the fuel's upper section (80 ℃, after 50 hours of immersion in twice-diluted artificial seawater) (Figure 7)



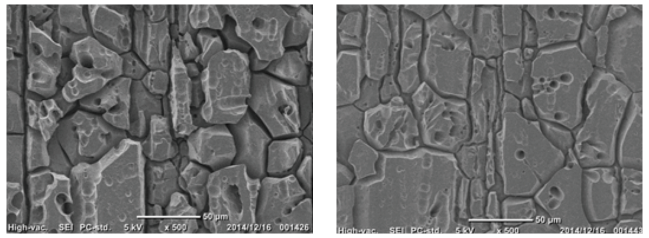
▲ Results of evaluating the concentration of chloride ions in structural crevices of the upper plug material (Figure 8)



▲Connection between crevice-corrosion repassivation potential and chloride-ion concentration (Figure 9)

4 Studying methods for processing damaged fuel

IRID studied the impact of damaged fuel when it is handled at a reprocessing facility, taking into account foreign substances such as seawater. By evaluating items like the corrosive effect on reprocessing equipment (the primary endpoint; Figure 10), the behavior during processing (Figure 11), and the effects on the final waste product, it was confirmed that foreign substance has no impact. It was also decided that confirmation of the state of the removed fuel would be the basis for determining whether to launch more detailed investigations in the future.

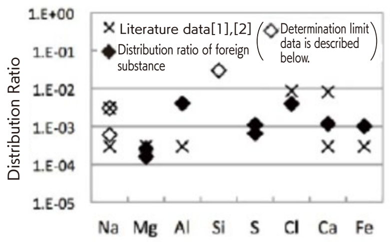


Simulated waste liquid from
Rokkasho Nuclear Fuel
Reprocessing Facility
(chloride ions: 0 g/L)

Simulated waste liquid from
Rokkasho Nuclear Fuel
Reprocessing Facility
(chloride ions: 20 g/L)

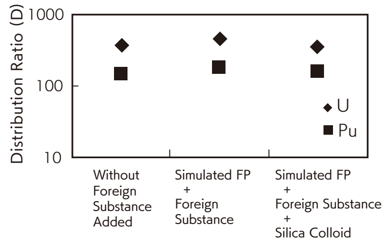
▲Immersion test in high-level waste liquid tank (surface of immersed test piece, 960 hours of immersion) (Figure 10)

No pitting corrosion due to chloride ions etc. was observed; if anything, the rate of corrosion was slower, and it was determined that there was no equipment corrosion caused by foreign substance.



[1]Data of Inorganic Solvent Extraction (1) JAERI1047
[2]PUREX Technical Manual (1980)

(a) Distribution of foreign substance during the presence of simulated FP
FP = fission product



D = organic phase (water-phase total for five times back extraction) / water phase (total for two times extraction)

(b) Distribution ratio of U / Pu during the presence of foreign substance

▲ Assessing the behavior of foreign substance during processing (Figure 11)

It was found that the distribution ratio of foreign substance was on the order of 10-2 to 10-3, making it difficult to extract with a solvent, and that the presence of foreign substance did not cause a significant change in the U / Pu distribution ratio.

II

Decommissioning Research and Development

Decontamination and Dose Reduction

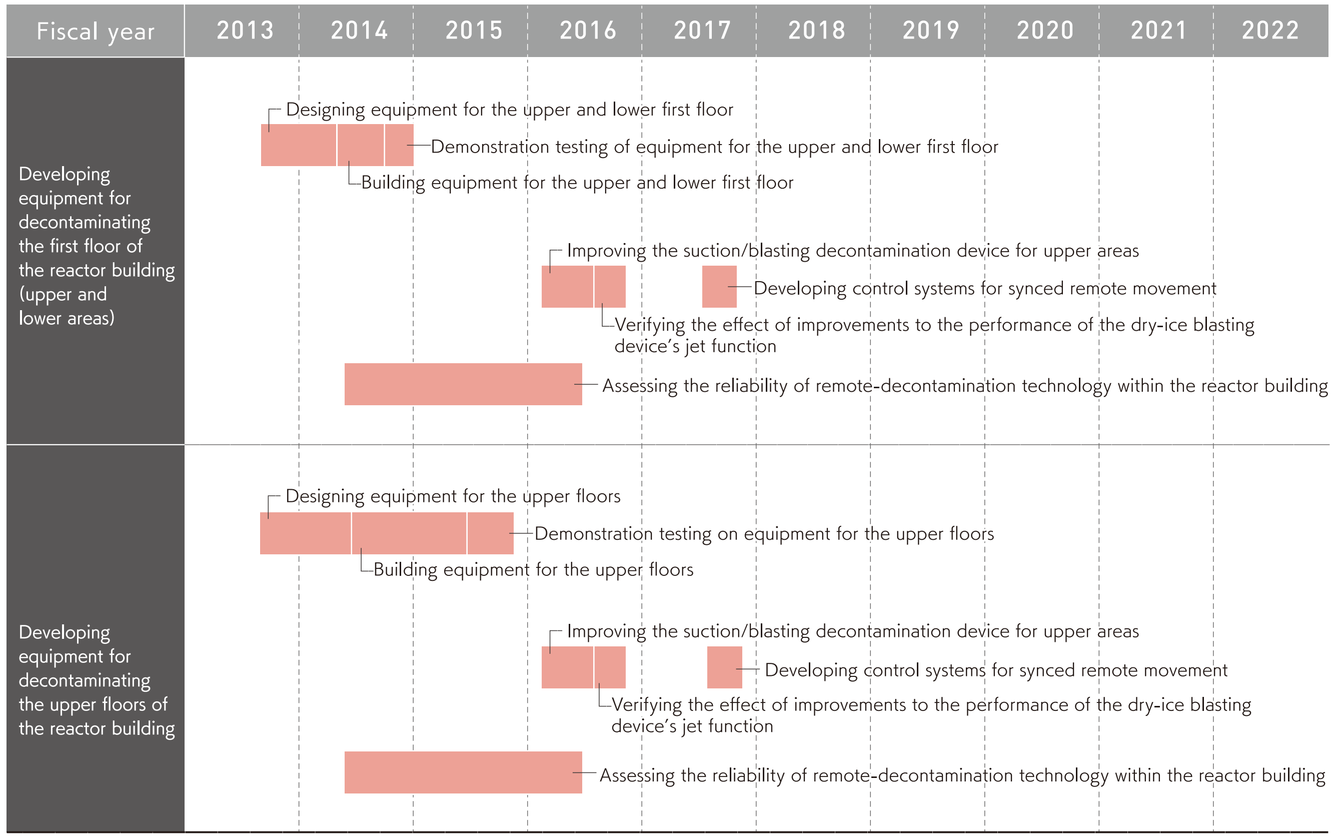
To improve the work environment when investigating inside PCV for fuel debris retrieval, remote-operated decontamination equipment was developed suited for the level of on-site contamination. Comprehensive measures for the reduction of worker exposure were studied in combination with remote-decontamination technology (equipment) and radiation shielding.

Development of technology for remotely operation in the reactor buildings

Prior to retrieving fuel debris, decontaminate the reactor buildings with remote-operated equipment

- Developed equipment for decontaminating the first floor of the reactor building (upper and lower areas)
- Developed equipment for decontaminating the upper (second and third) floors of the reactor building

Research and development progress



Background

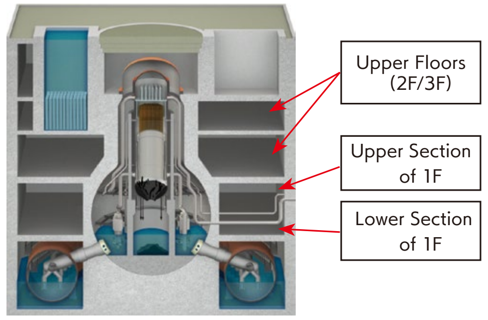
To work towards retrieving fuel debris from Unit 1–3 at Fukushima Daiichi NPS, the preparation work for the first floor and upper floors of the reactor building were planned; however, the highly radioactive environment was an impediment to those operations. To ensure that the work could proceed smoothly, the radiation dose had to be reduced and improve the work environment by developing remote decontamination technology.

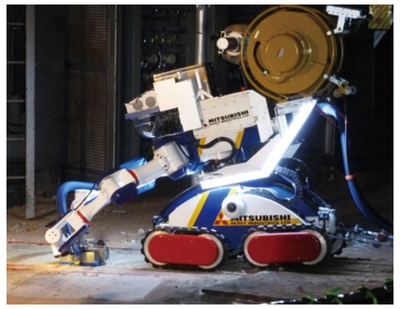
Purpose

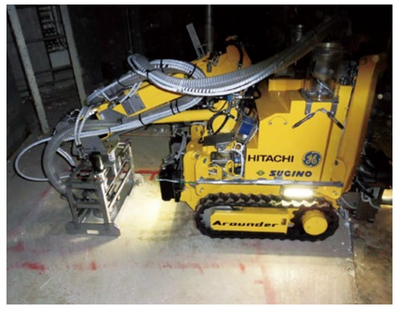
To reduce the dose inside the reactor building so that fuel debris can be retrieved, some decontamination equipment on the first floor and upper floors of the reactor building were designed and manufactured, then verified that it was functioning properly by verification tests. Based on the results of those tests, the equipment was aimed to be improved and develop a remote-operating system. Through this process, the remote decontamination technology was established.

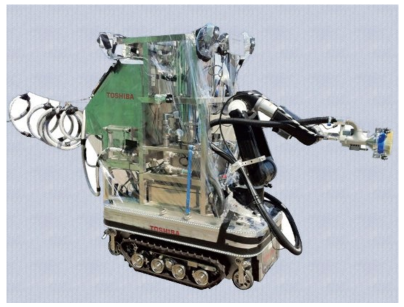
1 Equipment for decontaminating the lower section of the first floor

IRID developed equipment for decontaminating the floor as well as the walls and other surfaces up to 1.8 meters above the floor.
To accommodate the various contaminated forms and objects, equipment that uses three different methods was designed: suction and blasting, high-pressure water jets, and dry-ice blasting (Figures 1 through 3).




▲Suction and blast decontamination equipment (Figure 1)


▲High-pressure water jet decontamination equipment (Figure 2)


▲Dry-ice blast decontamination equipment (Figure 3))

2 Equipment for decontaminating the upper section of the first floor (height of 5–8 m)

The three equipment created in 2013 for decontaminating the lower section (the suction and blasting device, the high-pressure water jet decontamination equipment, and the dry-ice blast decontamination equipment) were redesigned and remanufactured so that they could be used to decontaminate the upper section.

Performance was confirmed by conducting demonstration tests at the mock-up testing facility manufactured for this purpose. Regarding the mock-up location, target facilities that approximate the environment were selected that the actual machines will be operated in, and factors such as variation within the facilities and operational priority when building the mock-ups were considered. In the demonstration test, whether the devices have the required features were confirmed and evaluated in terms of decontamination performance, safety, and operability and ease of use when operated remotely.

Among other things, the results confirmed the effective range of the high-pressure water jet decontamination equipment and dry-ice blast decontamination equipment in terms of decontaminating the upper section. The workability of the suction and blasting equipment on the walls were verified after the removal of obstacles, which is the primary target for that work. As a result, the goal of applying what had been learned to the actual machines was achieved.

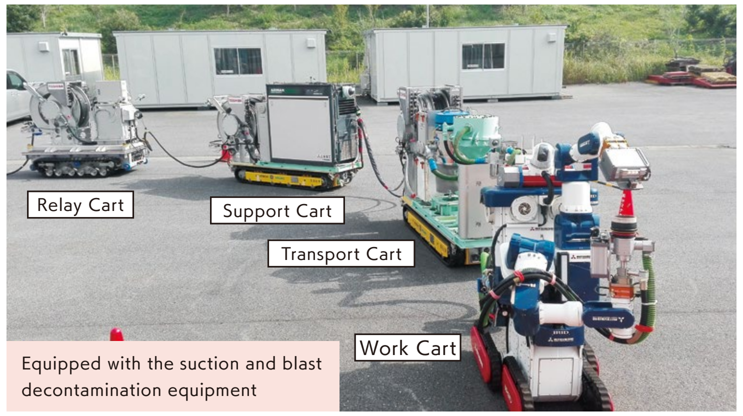

▲Suction and blast decontamination equipment for high places (Figure 4)


▲High-pressure water jet decontamination equipment for high places (Figure 5)


▲Dry-ice blast decontamination equipment for high places (Figure 6)

3 Equipment for decontaminating the upper (second and third) floors

The decontamination equipment for the upper floors uses a elevating work platform that extends from the equipment's hatch to access the upper floors (2F/3F) of the reactor building and decontaminate the floors and the walls up to a height of 2 meters. The machines were developed so that they could be executed on the same set of machines as the decontamination equipment build for the lower sections (suction and blasting, high-pressure water, and dry ice) so that the work could be completed using a single, customizable set of machines.



Work began on building each piece of equipment based on the method for accessing the upper floors and the design of each device. The shared set of machines includes a work cart, a transport cart, a support cart, a relay cart, and the various decontamination units (Figure 7).

The decontamination equipment was completed in FY 2015 and then a verification test was conducted using a mock-up unit.

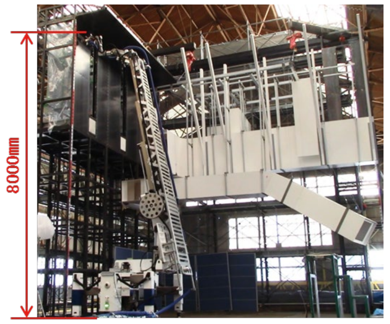
◀Decontamination equipment for the upper floors (Figure 7)

4 Demonstration test (example)

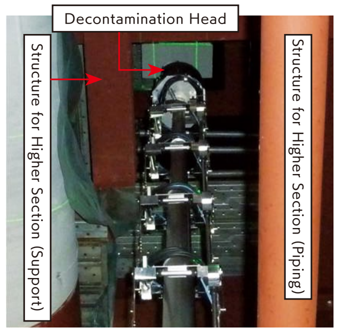
IRID developed separate decontamination equipment for the lower sections of the first floor, the higher sections of the first floor, and the upper floors. How effective the machines are on each form of contamination were confirmed and a demonstration test was conducted to verify the overall effectiveness and applicability of the equipment (Table 1; Figures 8–12).

▼Decontamination methods (Table 1)

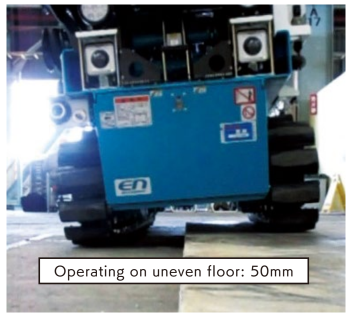
Decontamination Method		Suction	Blasting	High-Pressure Water Jet	Dry-Ice Blasting
Summary		Suctions up air and contamination in the air	Sprays compressed air on a steel grid to cut and collect	Sprays high-pressure liquid to collect contamination along with water	Sprays compressed air on a steel grid to chip away and collect
Contamination Form	Separating	○	—	○	—
	Adhering	—	○	○	○
	Penetrating	—	○	(○) [Under Very High Pressure]	—



▲Mock-up test facility (Figure 8)

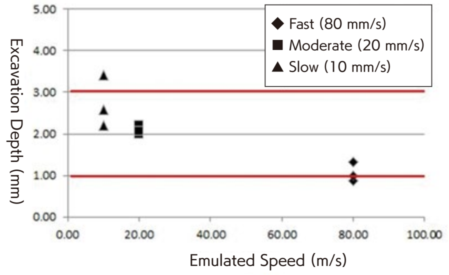


▲Checking positioning (Figure 9)



▲Verifying operation (Figure 10)

▲Test piece after blasting (20 mm/s) (Figure 11)



▲ Checking target-decontamination performance (Figure 12)

Ⅲ

Decommissioning Research and Development

Investigating and Analyzing inside PCV/RPV

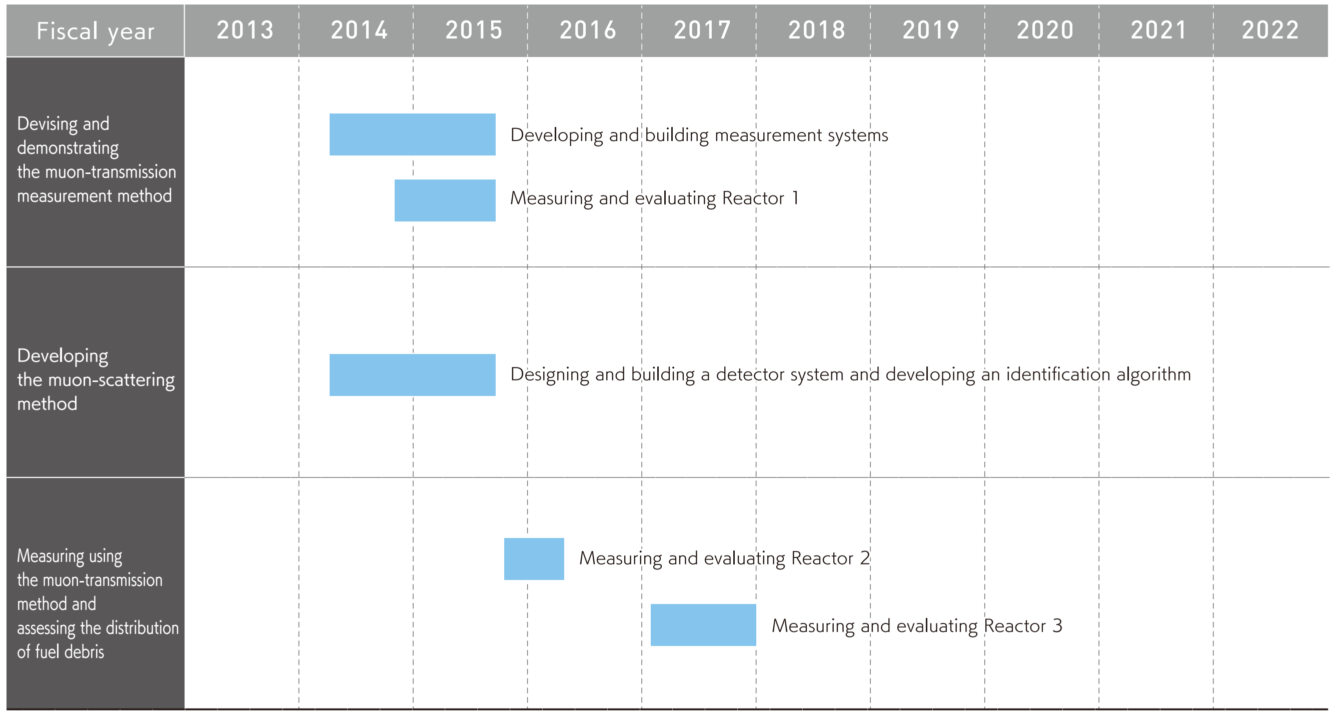
Investigation technology has been developed for ascertaining the distribution of fuel debris and the status of the structures in PCVs for fuel debris retrieval. Understanding the properties of the fuel debris is essential for developing technologies to retrieve, contain, transport, and store fuel debris as well as for studying the processing and disposal methods, therefore, analysis and estimation technologies have been developed.

Development of technology for detection of fuel debris in the reactor

Using muon measurement to estimate the distribution of fuel debris in the reactor at an early time

- Within a highly radioactive environment, a measuring system based on the muon-transmission method was established
- A detection system that utilizes the muon-scattering method (which can identify objects with a high degree of accuracy) was produced and established an identification algorithm
- Muon measurements using the transmission method was conducted at Unit 1 of Fukushima Daiichi NPS and demonstrated internal imaging technology that uses tomography
- The distribution of fuel debris at Unit 3 was measured using the experimentally verified transmission method.

Research and development progress



Background

The goal of this project is to ascertain the location and the amount (distribution) of fuel debris in the reactor and to contribute to the selection of methods for efficiently retrieving that fuel debris so that the initiatives for decommissioning Fukushima Daiichi NPS can proceed as planned.

After the accident, radioactivity was high inside the reactor and throughout the premise of Fukushima Daiichi NPS, which made investigating the inside of the reactor difficult. Although cameras and other equipment have been placed inside the containment vessel and are slowly gaining glimpses of its interior, the inside of the reactor pressure vessel (RPV) have not yet been seen. At the time, muon tomography was focused as a method that could be used to ingestigate the inside of the RPV sooner rather than later, so there were collaborations research institutions* both foreign and domestic to peer within the RPV.

* High Energy Accelerator Research Organization (KEK); Los Alamos National Laboratory, U.S.

Purpose

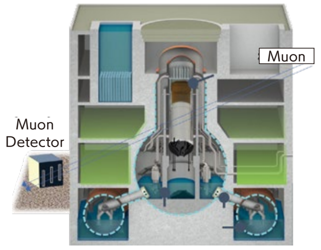
There are two techniques for internal imaging using muons: the transmission method and the scattering method.

The transmission method measures the amount of muons that pass through the reactor, tracking the path taken by those particles to estimate the size of objects. IRID developed this measuring technology within the highly radioactive environment that is characteristic of Fukushima Daiichi NPS, performing actual measurements on Unit 1 to demonstrate that it can be used to assess the distribution of fuel debris. Then, the technology was further developed for use on Units 2 and 3.

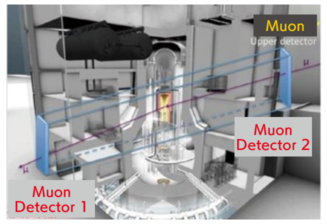
The scattering method tracks muons before and after they pass through the reactor, estimating their angles of scattering to predict the distribution of matter within the three-dimensional space of the reactor interior. This method is superior to transmission for discerning objects, so a detector was designed and produced, then an algorithm to identify specific materials was developed.

1 Investigating the inside of the reactor with muons

Cosmic-ray muons are constantly bombarding the Earth’s surface, with about one muon passing through an area the size of the human hand every second. Muons pass through matter, but differences in how they do so and the angles at which they are scattered by that matter can be used to visualize the inside of an object. The transmission method (Figure 1) can obtain internal information using a single detector for a short time. The scattering method (Figure 2) uses two detectors to discern objects with a high degree of accuracy. Measurements in Fukushima were only performed with the transmission method due to on-site limitations and other factors.



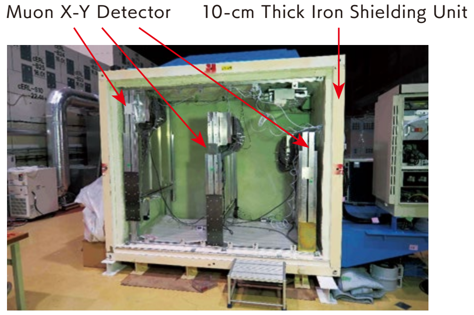
▲ Transmission method (Figure 1)



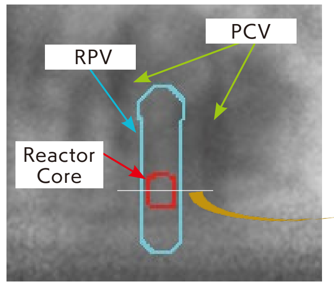
▲ Scattering method (Figure 2)

2 Demonstration test of transmission method on Unit 1

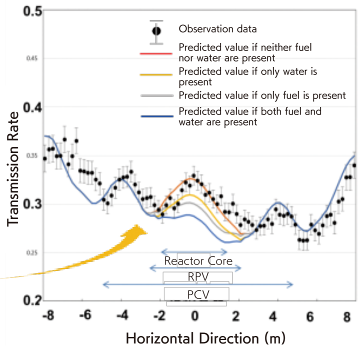
The measuring equipment (Photo 1) was enclosed in an iron shielding frame so that muons could be measured even in highly radioactive environments. The unit consists of three layers to eliminate errors when counting muons during measurement. This equipment was placed outside the building of Unit 1 and allowed to measure for a period of approximately three months. By comparing the measured transmission distribution (Figure 3) to the values predicted by simulations (Figure 4), it was concluded that there is almost no fuel at the location of the reactor's core.



▲Muon-transmission measuring device (Photo 1)
(Dimensions: approx. 2.5m×2.0m×2.1m [height])



▲ Distribution of muon-transmission rate (Figure 3)
(Reactor 1; measured February–May 2015)



▲Comparison of actual transmission rates and those predicted by simulations (Figure 4)

3 Measuring and evaluating the distribution of fuel debris at Units 2 and 3

Based on our demonstration test at Unit 1, a smaller transmission-method equipment (Photo 2) that was easier to handle on-site was manufactured, then used it to perform measurements on Units 2 and 3 and obtain the following results.

{Unit 2: measured March–July 2016 (Figure 5)}

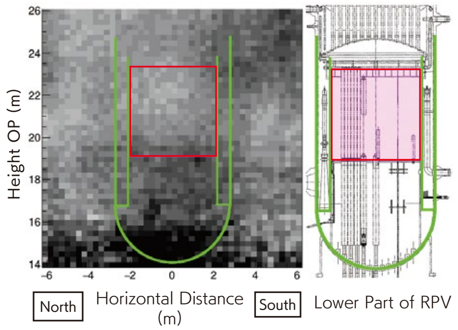
- Verified the presence of high-density material believed to be fuel debris at the bottom of the RPV
- Some amount of high-density material is also present in the lower part and perimeter of the reactor core

{Unit 3: measured May–July 2017}

- There are no large clumps of high-density material in the original core area
- There may still be some fuel debris at the bottom of the RPV

▲Small muon-transmission measuring equipment (Photo 2)
(Dimensions: approx. 1 m × 1 m × 1.3 m [height])

*One pixel is equivalent to approx. 25 cm of reactor cross-section



▲ Distribution of matter at the bottom of the RPV (Unit 2) (Figure 5)
(measurements taken on July 22, 2016)

Development of technology for non-destructive detection of radioactive materials accumulated in the suppression chamber

Estimating and developing methods of measuring the accumulation of radioactive material within the suppression chamber (S/C) etc.

- Studied scenarios for the migration of radioactive material to the S/C and torus room
- Evaluated the effects of radioactive material on water seals etc.
- Evaluated the nuclide composition of radioactive material and the distribution of radiation; assessed background radiation; selected the optimal methods for detecting radioactive material; and studied methods for estimating the accumulation of material inside the S/C

Research and development progress

Fiscal year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Formulating a plan for development and operation		Identifying the task items for development								
Constructing migration scenarios for radioactive material		Scenarios for the migration of radioactive material into the S/C and torus room								
Assessing the effects of radioactive material on water seals etc.		Evaluating the weight of uranium produced through the deterioration of cement due to heat generated within sealants								
Developing technology to detect radioactive material		•Evaluating the nuclide composition of radioactive material and the distribution of radiation •Assessing background radiation •Selecting the optimal method for detecting radioactive material •Studying methods for estimating the amount of material accumulated in the S/C								

Background

To repair and stop leaks in the S/C and other structures, the state of radioactive material accumulated within them must be understood; however, no method for performing such an evaluation has been developed. Non-destructive measurement would be ideal for this evaluation, but it is unclear whether the accumulated radioactive material that needs to be detected can be evaluated through non-destructive measurements. In addition, developing a method that can be used to identify the accumulated material throughout the entire S/C etc. has become quite the challenge.

Purpose

To acquire the information needed to repair and stop leaks in the S/C and other areas, methods for measuring and estimating the amount of radioactive material accumulated in those areas will be developed.

There appears to be a low chance that radioactive material exceeding the permissible dose has flowed into the S/C or torus room, and it has been determined that it is technically feasible for non-destructive detection to confirm the presence or absence of such material under the assumed conditions. Moving forward, measuring systems and access equipment will be continually manufactured based on the development of methods for making repairs and plugging leaks.

1 Migration scenarios for radioactive material

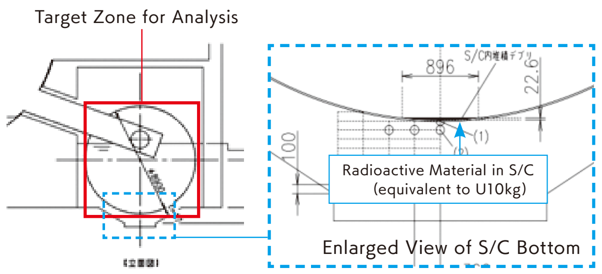
IRID has studied various scenarios for the migration of radioactive material into the S/C and torus room (Table 1). Since the results of that study show there to be a low chance that fuel debris exceeding the maximum permissible dose has flowed into these areas, measurements at the bottom of the S/C and in the vicinity of the sand-cushion drain pipe's exhaust port can be performed—areas where there should be relatively low amounts of accumulated radioactive material — to verify that there is no material exceeding the permissible dose.

▼Scenarios with a relatively high possibility of inflowing radioactive material

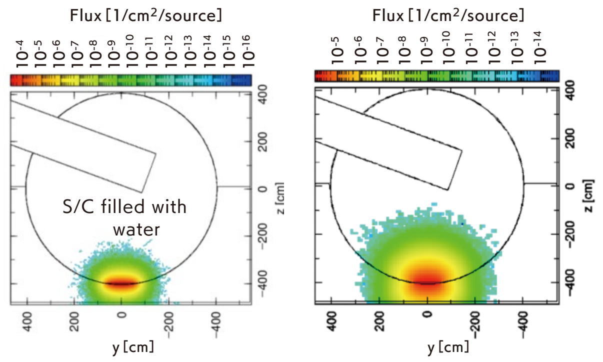
Form	S/C	Torus Room
Melted radioactive material	Radioactive material in the dry well reaches the S/C vent pipe intake port and flows into the S/C.	Radioactive material in the dry well corrodes the PCV shell and sand cushion then flows in through the drain pipe.
Powdery radioactive material	The inflow of coolant etc. causes material to migrate in through the S/C vent pipe.	The inflow of coolant etc. causes material to migrate in through the sand-cushion drain pipe.
Aerosol	The flow of gas causes the material to migrate in through pathways such as the SR intake pipe (primarily from the release of steam) and the S/C vent pipe.	The flow of gas causes the material to migrate in through the S/C and the damaged vacuum break line etc.

2-1 Evaluating the nuclide composition of radioactive material and the distribution of radiation

The nuclides originating from fuel (the measurement targets (Cm-244, Eu-154), background nuclides, and shielding-material nuclides) were evaluated according to their ORIGEN codes. The mixture ratio of fuel-originating nuclides and structural materials was set based on the results of analyzing MAAP codes. Regarding the computational model for the S/C and torus room (Figure 1), a three-dimensional system that simulates those areas at a 1:16 scale was used, assessing the neutron flux and γ-ray flux around the bottom of the S/C (Figure 2). Setting the fuel debris as the radiation source, the neutron flux and γ ray flux at the bottom of the S/C was then evaluated. The results confirmed that Cm-244 (neutrons) and Eu-154 (γ rays) can be measured even within the background environment.



▲Calculation system (Figure 1)



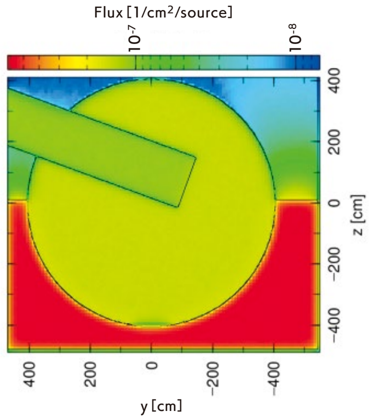
Calculation results for Eu-154 Calculation results for Cm-244

▲Distribution of fuel-originating radiation in the vicinity of Unit 1's S/C (Figure 2)

2-2 Assessing background radiation

IRID has assessed the background γ radiation (Cs-134 and Cs-137) of the accumulated water (Figure 3).

That assessment confirmed that there is a high amount of radiation coming from water accumulated within the torus room (the red region is about 10^{-7}/cm^2/source). Also, γ ray flux was observed to be roughly uniform in both the S/C and the torus room.



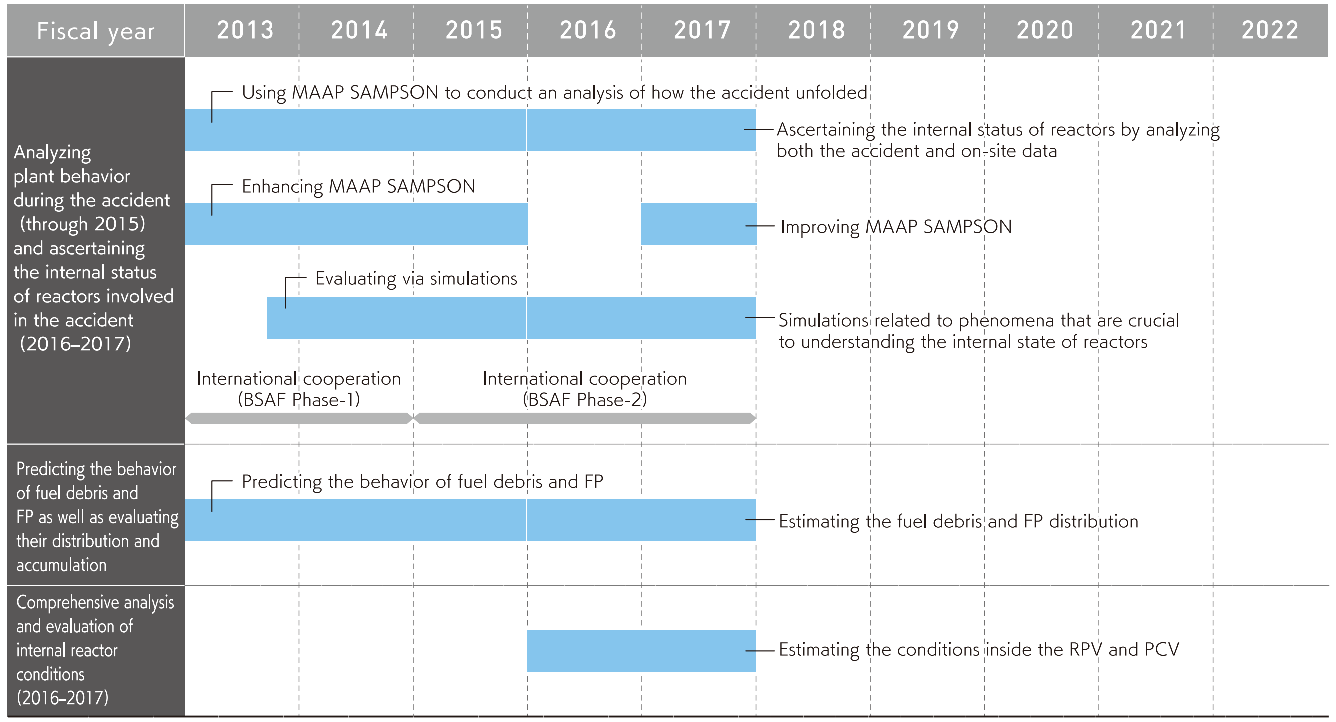
▲Distribution of fuel-originating radiation in the vicinity of Unit 1's S/C (Figure 3)

Upgrading for identifying comprehensive conditions inside the reactor

Estimating the conditions inside the RPV and PCV, which is essential for studying technology for fuel debris retrieval

- Collated data from a variety of sources, including actual on-site data, simulations of how the accident unfolded, and the results of other projects, then analyzed in detail and evaluated the internal conditions of the RPV and PCV
- Estimated and evaluated the behavior and predicted accumulation/distribution of fuel debris as well as the behavior and distribution characteristics of fission products (FP) for use in comprehensive analysis and assessment
- Utilized knowledge both from within and outside of Japan through international joint research with OECD/NEA
- Comprehensive analysis and evaluation has continued at Tokyo Electric Power Company (TEPCO) Holdings, Inc. after the completion of this project in FY 2017

Research and development progress



Background

Estimating the conditions inside the RPV and PCV as accurately as possible is essential to developing safety measures and studying methods for the retrieval of fuel debris that will commence in the near future. However, the extremely radioactive environments in Units 1–3 at Fukushima Daiichi NPS make direct investigations and observation difficult. Remote-operated equipment has been used to investigate some areas, but it is still exceedingly difficult to gain a sufficient understanding of the conditions inside the reactors.

Purpose

In an effort to ensure that the decommissioning of Fukushima Daiichi NPS proceeds as planned, this project aimed to estimate the conditions within the RPV and PCV through a comprehensive analysis and evaluation of various sources of information, including on-site data (internal observations and knowledge obtained from decommissioning work conducted around the reactor building), plant data from the time of the accident (water levels, temperature, pressure, radiation dose, etc.), simulations of how the accident unfolded (including simulations conducted by this project through improvements to MAAP and SAMPSON), past knowledge gained from events like the TMI-2 incident and mock-up testing on severe accidents, and insights gleaned from mock-up testing conducted primarily in Japan following the accident at Fukushima Daiichi NPS, including the mock-up testing done during this project. This project was conducted under a joint proposal with the Institute of Applied Energy.

1 Assessing what happened during the accident

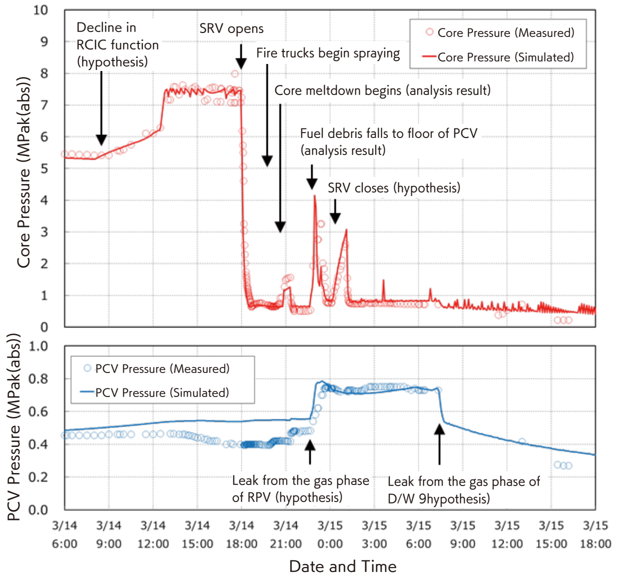
Based on a comprehensive review by a group of experts, the element models of MAAP and SAMPSON were improved, then studied and assessed accident scenarios that can rationally explain plant data from the time of the accident. The most credible scenarios regarding fuel debris fallen within the RPV, damage to the RPV boundary, and migration of debris to the pedestal were compiled at the time of project implementation.

● What is MAAP?

The Modular Accident Analysis Program is computer code that simulates severe accidents. Owned by the Electric Power Research Institute (EPRI), it is widely used both in Japan and overseas for checking the safety of nuclear power plants.

● What is SAMPSON?

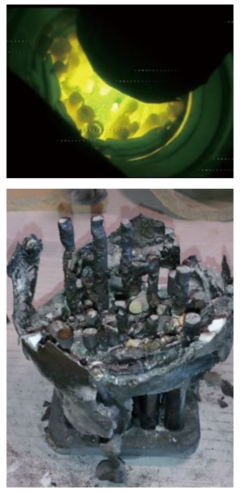
"Severe Accident analysis code with Mechanistic, Parallelized Simulations Oriented towards Nuclear fields" or SAMPSON is computer code that uses multidimensional models established from mathematical and theoretical frameworks to illustrate physical phenomenon in detail. It is well-suited for simulating things like the characteristics and distribution of fuel debris.



▲Using MAAP codes to reproduce the events of the Unit 2 accident progression

2 Studying how to reduce the uncertainty of simulation techniques

IRID conducted large-scale mock-up testing to obtain experimental data on areas that were identified through simulations as being unique to the accident at Fukushima Daiichi NPS (the transparency of steam within the reactor as the accident unfolded; debris infiltrating inside the control-rod drive mechanism in the lower section of the RPV; the mixing of metallic debris and oxide debris at the bottom of the RPV; etc.). The factor models of MAAP and SAMPSON were enhanced and had a group of experts conduct a comprehensive review.



▲ Plasma-heating test on simulated fuel assembly (during heating and the test piece after)

▲Test apparatus

3 Assessing the chemical properties of fission products (FP)

Along with investigating the inside of the reactors, samples collected from sediment near the fuel debris were analyzed and knowledge that can be used to assess things such as how the accident progression process and the status of accumulated fuel debris were compiled. The photo below is an example of the many particles containing uranium that were detected within a sample collected from the protective sheet covering the operating floor of Unit 2. While that analysis and detailed assessment are currently ongoing, early results have shown that these uranium particles were theoretically created in one of two ways: by transitioning to a gas then condensing, or by transitioning to a liquid and congealing. In the latter case, compositional information about the fuel debris itself may have been preserved. In addition, studies are underway to determine whether this knowledge could be applied to estimating the path by which the uranium particles migrated from the RPV to the operating floor during the accident.

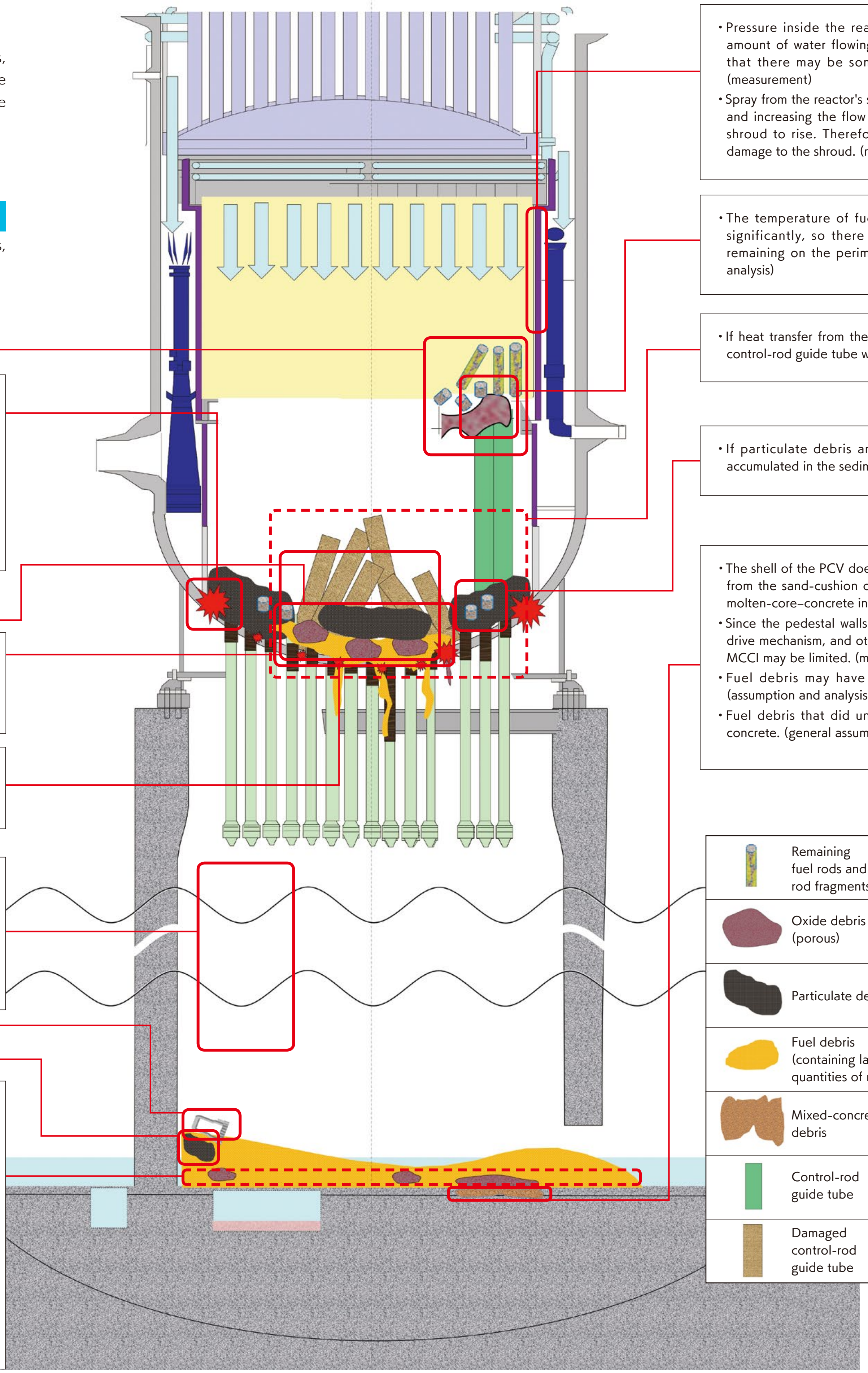
▲The protective sheet, an analysis target obtained from the fifth floor of the reactor building of Unit 2

4 Comprehensive Analysis and Evaluation of Reactor Pressure Vessel (RPV) and Primary Containment Vessel (PCV) Interior

Based on a comprehensive evaluation by a group of experts, a detailed diagram was created depicting the estimated locations of accumulated debris in each reactor unit as well as its distribution patterns and information about damage to the RPV and PCV. When conducting this evaluation, the debris and damaged material were organized into several categories depending on its characteristics, and the basis for those determinations when listing the objects were stated. This fundamental knowledge was then used to make decisions about methods of fuel debris retrieval.

Estimated Distribution of Fuel Debris and Other Conditions in the RPV and PCV of Unit 2

Rev. 15 (March 29, 2019), These are the results of continued analysis and evaluation by Tokyo Electric Power Company (TEPCO) Holdings, Inc. even after the project ended in FY2017.



- After estimating the amount of energy based on the increase in PCV pressure due to hydrogen generation, it is assumed that most of the fuel is damaged or has collapsed. (measurement and analysis).
- Temperature decreased when the reactor was sprayed with water, so it is predicted that there is fuel present at the perimeter of the reactor in areas struck by the water sprayed from the low-volume sprinkler system. (Even if molten fuel falls then solidifies on the fuel supports or control-rod guide tube, it behaves similarly as a heat source, so the exact positioning of debris cannot be determined.) (measurement)
- Measurements with muons indicate that fuel may be present at the perimeter of the reactor. (measurement)
- If fuel rods are present, some of them are around the perimeter (general assumption)
- There is typical oxide debris formed from molten fuel that has hardened (general assumption).

- During an inspection of the PCV's interior, the control-rod drive mechanism was observed. And since the grating is partially missing, there are presumably (small) holes in and around the center portion of the RPV. (assumption based on measurement)
- Although strength varies depending on the location, water droplets falling all over the pedestal floor has been observed. This means that there may be small perforations in the vicinity of the housing for the control-rod drive mechanism at the bottom of the RPV. (assumption based on measurement)
- Some of the debris that fell through the holes is presumably stuck to things like the control-rod drive mechanism housing. (general assumption)

- The upper tie plates etc. fell to the floor of the pedestal. The sediment in that area, which is believed to have fallen through the same hole in the RPV is assumed to be fuel debris. (measurement)

- Sediment of various sizes, such as pebbles and rocks, was observed on the pedestal floor. Since pooled water was found around the rock-sized sediment, such sediment may be impermeable. Pooled water was also observed here and there around the pebble-sized sediment, indicating that rock-sized sediment may lay underneath pebble-like sediment. (measurement)

- Since upper tie plates have fallen around the pedestal's perimeter, there may be perforations in the RPV there. (assumption based on measurement)
- The holes are presumably as least large enough for the upper tie plates to fall through. (measurement)
- Parts of the control-rod guide mechanism and tube in the perimeter may have been melted or destroyed by fuel debris that accumulated in the bottom of the RPV. (assumption based on measurement)

- Muon measurements revealed the silhouette of a high-density substance believed to be fuel debris in the bottom of the RPV. Fuel that fell onto the lower plenum may still remain at the bottom of the RPV. (measurement)

- As a result of damage to the control-rod guide tube and the control-rod guide housing, fuel debris and molten metal may have penetrated to the housing's interior.

- Enhanced images reveal a large amount of water droplets falling on the left side of the platform, as viewed from the CRD transfer rail. In addition, the positions of the PIP cable and other objects in that area cannot be verified, and grating is missing from the platform. Therefore, water that flooded the reactor may be dripping through perforations in the RPV. (measurement)

- Radiation dose and temperature were measured from the platform to the bottom of the pedestal. While radiation increased somewhat toward the bottom, there was generally no significant variation in temperature (a slight decrease in temperature was observed). And since no obvious damage to the pedestal substructure was found, the fuel debris on the floor of the pedestal is believed to be generating a relatively low amount of radiation and decay heat, and it may contain large quantities of metal. (assumption based on measurement)
- Sediment that contains fuel debris is presumably scattered across the entire pedestal floor (measurement).
- If water has pooled on the bottom of the PCV, then particulate debris has presumably formed. (general assumption)
- If particulate debris is present, it may have accumulated in the sediment layer. (general assumption)

- Pressure inside the reactor's recycling system rose when the amount of water flowing into the reactor increased, suggesting that there may be some level of water outside the shroud. (measurement)
- Spray from the reactor's sprinkler system lowered the temperature, and increasing the flow rate caused the water level outside the shroud to rise. Therefore, there is presumably no large-scale damage to the shroud. (measurement)

- The temperature of fuel on the perimeter has not increased significantly, so there may be pellets and broken fuel rods remaining on the perimeter. (general assumption, testing, and analysis)

- If heat transfer from the high-temperature fuel debris is low, the control-rod guide tube will not melt. (general assumption)

- If particulate debris and pellets are present, they may have accumulated in the sediment layer. (general assumption)

- The shell of the PCV does not appear to be damaged (no leakage from the sand-cushion drainpipe), so there was presumably little molten-core–concrete interaction (MCCI). (measurement)
- Since the pedestal walls, cable ties, supports for the control-rod drive mechanism, and other components are intact and unmelted, MCCI may be limited. (measurement and general assumption)
- Fuel debris may have solidified without undergoing MCCI. (assumption and analysis based on measurement)
- Fuel debris that did undergo MCCI may have mixed with the concrete. (general assumption)

Remaining fuel rods and rod fragments	Control-rod drive mechanism
Oxide debris (porous)	Control-rod drive mechanism (containing debris)
Particulate debris	Shroud
Fuel debris (containing large quantities of metal)	Pellet
Mixed-concrete debris	RPV perforation
Control-rod guide tube	Upper tie plate
Damaged control-rod guide tube	Sediment (unknown material)

Provided by TEPCO Holdings, Inc.

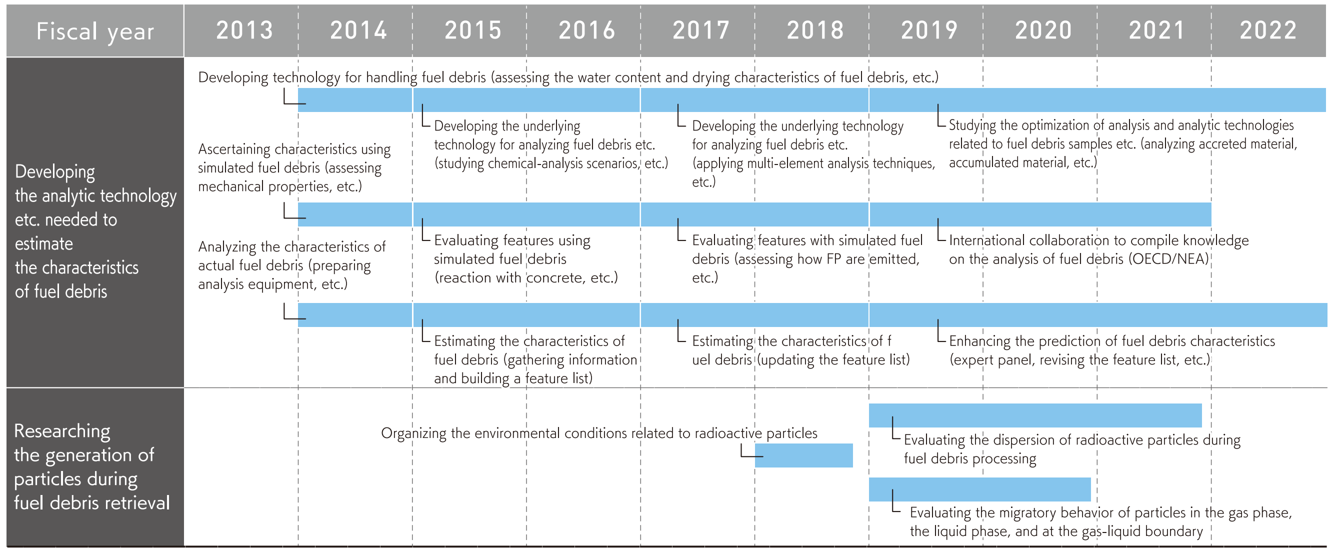
Development of analysis and detection technology for characterization of fuel debris

Understanding the characteristics of fuel debris, which are essential for studying technology for fuel debris retrieval

Currently, there is little data on the characteristics of fuel debris—data which would serve useful in selecting methods for retrieving fuel debris from Fukushima Daiichi NPS (Hereinafter "1F") as well as transporting and storing it. Therefore, IRID is developing analysis and estimation technologies based on the following three points to estimate these characteristics.
The most important results thus far are discussed below.

- Development of technologies for estimating the properties of fuel debris existing in the PCV/RPV from test data by preparing domestic and international knowledge and simulated fuel debris samples
- Development of analytical techniques for fuel debris using simulated fuel debris samples and acquisition of attributes necessary for fuel debris management
- Acquisition of analytical data of sediment and adhered materials collected from 1F, and creation of a database for estimation of fuel debris properties based on the evaluation of the data.

Research and development progress



Background

There is almost no knowledge about the fuel debris formed from the melted nuclear fuel with reactor structural materials during the melt-down accident of Fukushima Daiichi, so it is necessary to uncover such knowledge and to achieve the globally unprecedented task of the decommissioning of a damaged reactor caused by an accident. While on-site visual images of some areas have been obtained, information is still limited. Fuel debris is a heterogeneous material that contains a great variety of radioactive elements; it is assumed to be a complex mixture which also includes some hard-to-melt components. The needed information must be extracted and organized and acquire test data related to the many tasks that decommissioning entails, such as the handling of highly radioactive material and the accuracy of the analysis methods employed. This will prove useful for enacting radiation safety policies and developing the tools and equipment needed for fuel debris retrieval as well as the equipment used to transport and store it after it is retrieved.

Purpose

To develop analytic and other technology, IRID will create simulated fuel debris that simulates the form of debris in 1F, based on similar examples found in domestic and international research. Then, upon verifying the suitability of the analysis methods, the results of that verification through the analytical process will be disclosed. Material that adheres to the tools and equipment used to conduct actual investigations of the inside of the 1F PCV will be analyzed, then the suitability of the developed analytic technology will be verified. From those analysis results, hardness and other physical characteristics for use in selecting tools for processing fuel debris will be estimated; water content, which is needed to assess hydrogen generation during storage; and the volatilization of radioactive elements due to heat applied for drying purposes. In addition, there will be an enhancement of IRID's ability to predict the behavior of the fine particles that will presumably be generated when processing fuel debris. Those results will be provided in a database that is easy for people involved in decommissioning work to use.

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1 Utilize domestic and international knowledge to create simulated fuel debris and estimate its characteristics

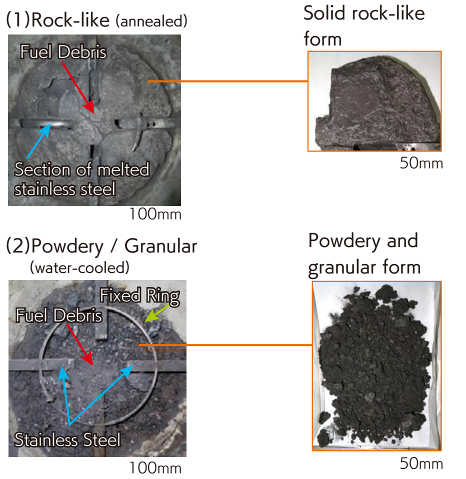
The fuel debris created during the accident at Three Mile Island's Unit 2 ("TMI-2") consisted primarily of nuclear fuel and internal structures in the reactors. However, the fuel debris from the 1F accident is unique, due to its interactions with concrete. Information about the product of this molten core-concrete interaction (MCCI) is therefore needed.

Figure 1 depicts a test conducted using condensed-light heating. A method for creating simulated MCCI product was created by placing simulated corium (a disk made from Zr, which is an element in fuel cladding etc., and stainless steel (SUS), which is used in other component material) on top of concrete fragments then melting it with condensed-light heating. This allowed use of debris with different characteristics as test parameters when obtaining data with IRID's simulated MCCI fuel debris.

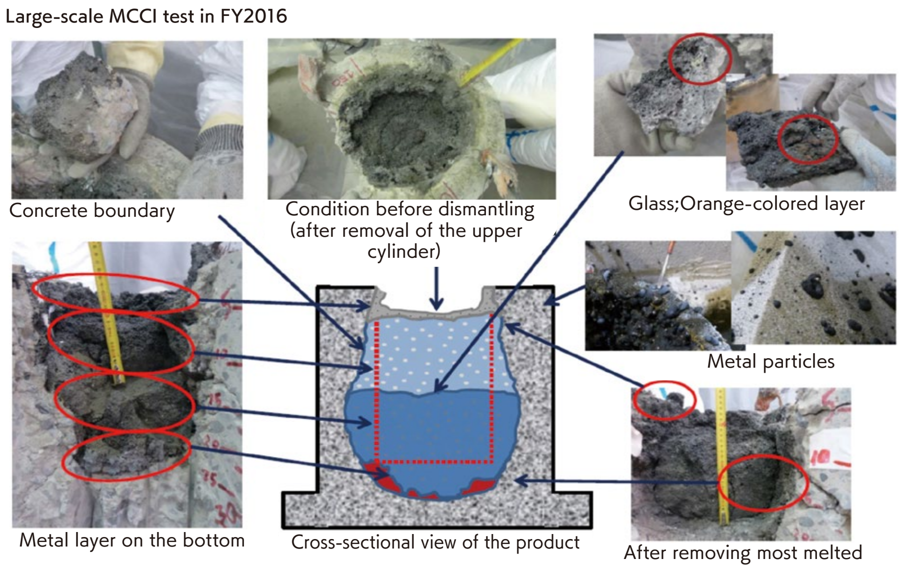
At the National Nuclear Center in Kazakhstan, UO2 was used to test the large-scale production of a metallic/ceramic substance that has melted and resolidified (Figure 2). In the test at the NNC, about 10 kg of UO2, Zr, and B4C was heated and melted then made to fall onto a stainless-steel bowl, thus producing the simulated fuel debris. Through this, detailed information was obtained about generating simulated fuel debris that has a granular or clumpy surface; the characteristics of a metallic/ceramic mixture; and related boundary regions.


Before Heating
After Heating

▲ Creating simulated MCCI product via condensed-light heating (Figure 1)



▲ Test production of melted and hardened metallic/ceramic mixture at the NNC in Kazakhstan (Figure 2)

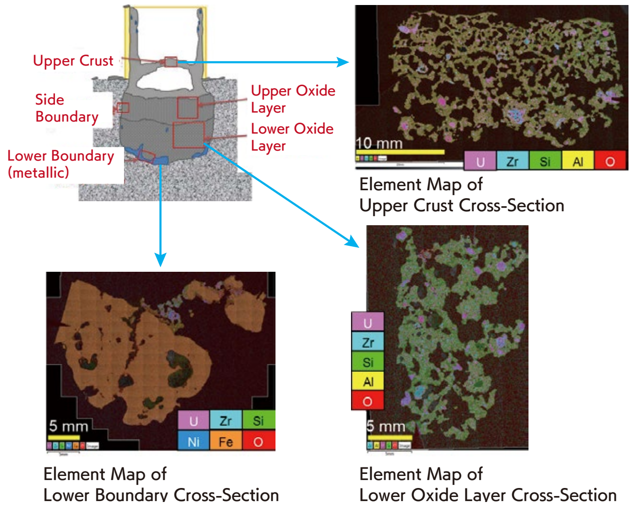

Large-scale MCCI test in FY2016

▲Large-scale MCCI test: appearance of the results (Figure 3)

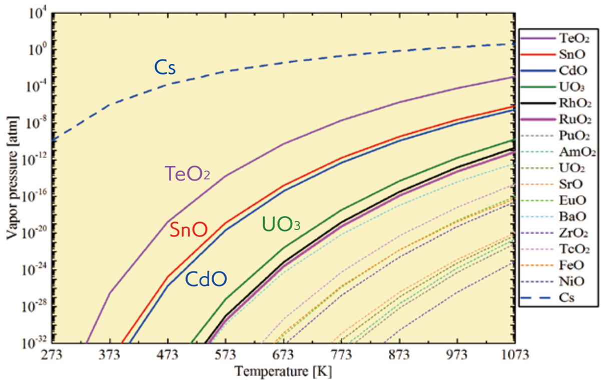
Meanwhile, at the French Alternative Energies and Atomic Energy Commission (CEA), IRID conducted a large-scale MCCI production test that took into account the melted components at 1F and the type of concrete used in Japan (Figure 3). By deconstructing the resulting simulated fuel debris and taking samples from its various sections, information about things like the depth of corrosion in concrete and the characteristics of MCCI product was obtained.

IRID also analyzed the product to obtain an element map for each structural region (Figure 4). The analysis revealed a non-uniform composition with porous sections and areas with metallic properties. As for the layers formed from oxides, it became apparent that substances such as U-Zr oxides form a precipitate in the parent phase, when silicon content is high.

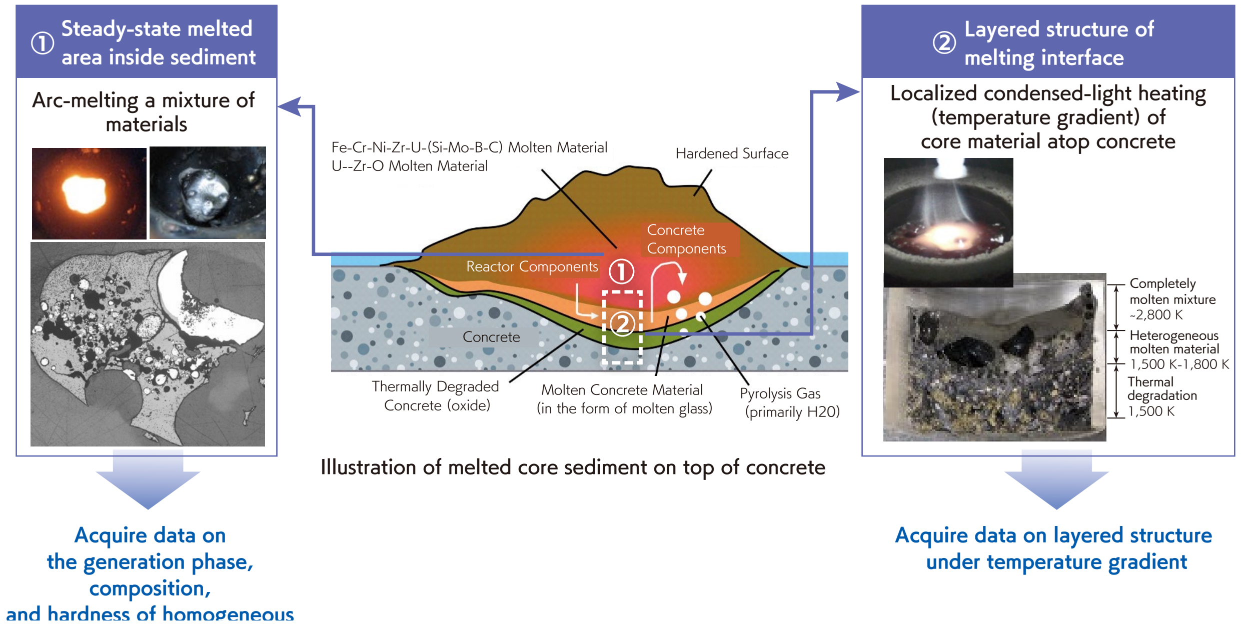
It was confirmed that the metallic layer at the bottom is an alloy composed primarily of iron. Conditions that were estimated from previous basic tests were reaffirmed, with no major changes detected. Figure 5 depicts the relationship between temperature and the vapor pressure calculated for the fission products (FP) and actinide oxides that were presumably generated. This implies the presence of Te, Sn, and Cd — which have higher vapor-pressure curves than UO3—in addition to the highly volatile Cs. This suggests that fission products within the fuel debris may have volatilized.



▲Distribution of elements in large-scale MCCI products (Figure 4)



▲Calculated results for oxide vapor pressure (Figure 5)



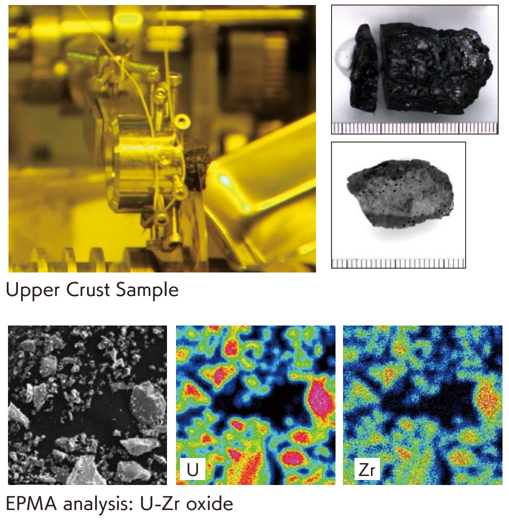
▲Producing two types of simulated MCCI product (Figure 6)

To obtain data on the little-known attributes of the MCCI product, simulated MCCI fuel debris that is suitable for testing purposes must be created (Figure 6). The left side of Figure 6 depicts the test in which information about composition, hardness, etc. was acquired by using arc melting to produce a uniform molten substance. The right side of the figure shows the test that was conducted to obtain data on the behavior of Gd and fission-product elements within the MCCI product by applying condensed-light heating in a localized manner. This was done to acquire data on the heterogeneous, layered structure under a temperature gradient. Attribute data on oxide fuel debris that contains potentially meltable FP elements etc. was compiled and added it to the Debris Wiki, which will be discussed later.

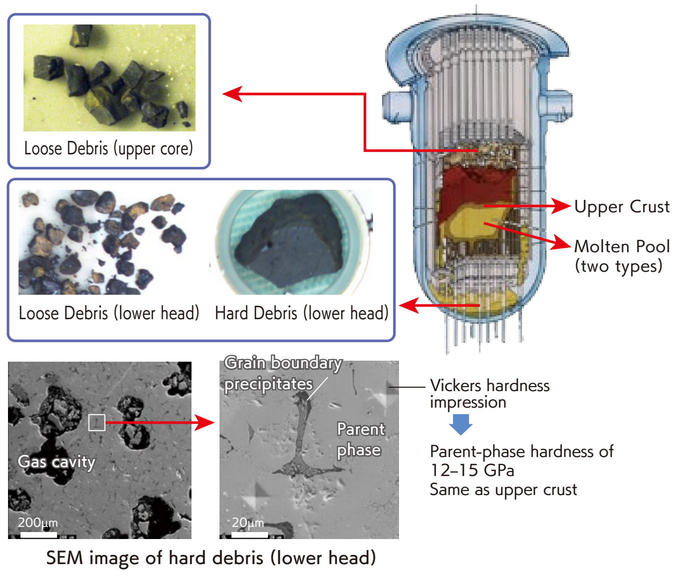
2-1 Establishing methods for analyzing fuel debris and understanding the characteristics that affect the retrieval and management of fuel debris

−Studying protocols for analyzing fuel debris as well as those used at TMI-2−

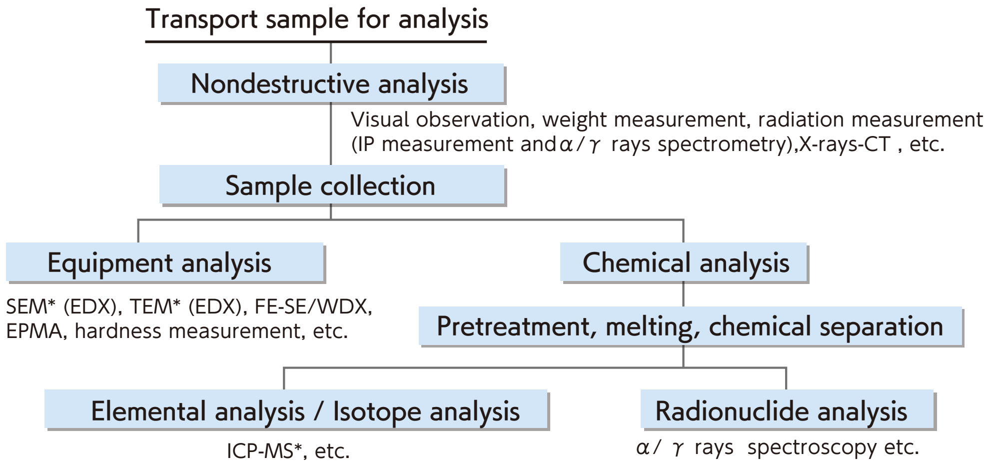
As part of IRID's efforts to develop technology for analyzing fuel debris, a cutting test on the TMI-2 fuel debris stored was conducted by the Japan Atomic Energy Agency (JAEA) (Figure 7). In addition to making metallographic observations and performing a Vickers hardness test, a severed piece of test fuel was observed using a scanning electron microscope (SEM) and it was analyzed with an electron probe microanalyzer (EPMA). The severed fuel is displayed at the top of Figure 7, with the results of the EPMA analysis shown at the bottom of the figure. It was found that the debris collected from the crust section is comprised primarily of oxides that contain U and Zr. TMI-2 fuel debris samples collected from three different locations were also analyzed (Figure 8). The sample from the lower head contained U, Zr, Fe, and Cr oxides in the parent phase, while the grain-boundary sample contained deposited oxides of the iron family/ iron and similar elements; the same degree of hardness was observed in both the upper and lower sections.



▲Cutting test on TMI-2 debris (Figure 7)



▲Appearance of TMI-2 fuel debris and SEM image of cut section (Figure 8)



*SEM: Scanning Electron Microscope *TEM: Transmission Electron Microscope
*Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

▲Analysis procedures (Figure 9)

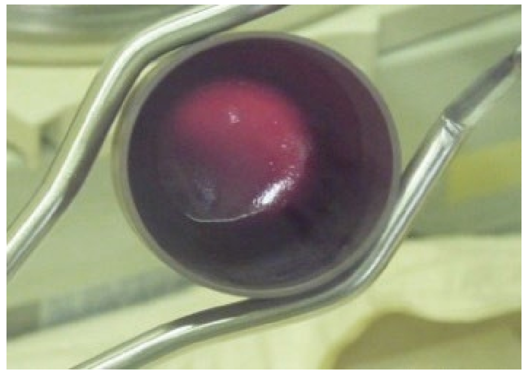
The Okuma Analysis and Research Center is planned to spearhead analysis of the fuel debris from 1F. As part of IRID's development of the technology for that analysis, a case study on the analysis process was conducted (Figure 9). Since the plan is to gradually increase the scope of fuel debris retrieval, for this scheme it was assumed the analysis of a very small amount of test fuel; however, it is believed that the flow of analysis will be updated in accordance with the actual retrieval process and the policies for storing and managing fuel debris.

2-2 Establishing methods for analyzing fuel debris and understanding the characteristics that affect the retrieval and management of fuel debris

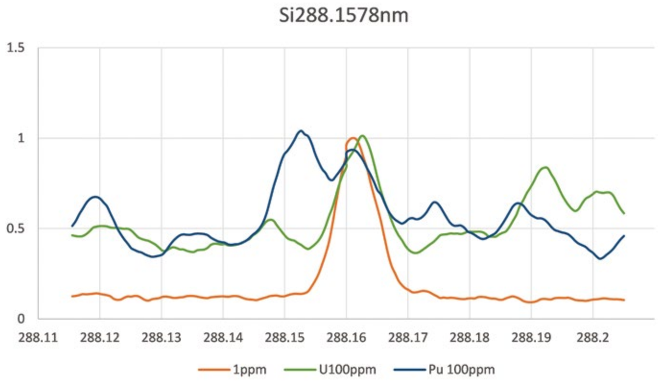
—Obtaining data for analyzing the chemical composition of fuel debris and assessing the generation of hydrogen during storage—

IRID studied methods of melting fuel debris as a preparatory step for analyzing its elemental composition. Fuel debris is created when internal core structures and concrete interact under high-temperature conditions, so it is presumably difficult to dissolve in water. Therefore, the alkali dissolution method was employed, which is known for its ability to dissolve insoluble material. Using an electric furnace, the simulated fuel debris reacted with sodium peroxide at 850 ℃ , after which the material was able to be completely dissolved using concentrated nitric acid (Figure 10).

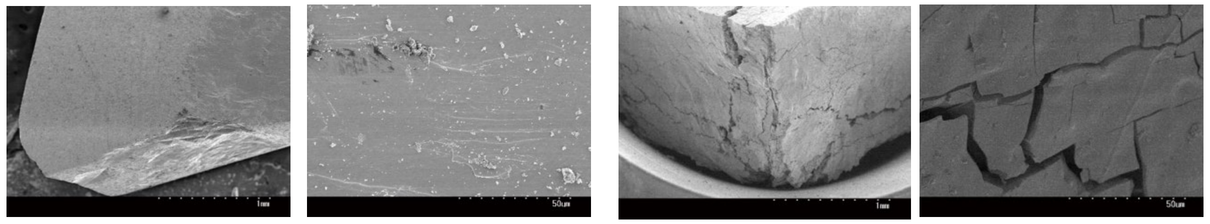
The challenges with applying analytic technology to insoluble fuel debris that has been dissolved via alkali dissolution or another method was summarized. One of the issues with performing chemical analysis on a dissolved solution is the interference that occurs with inductively coupled plasma atomic emission spectroscopy. If the fuel debris contains large amounts of uranium, there will be interference when trying to analyze other elements, so the impact on factors such as the minimum detection limit of the target element was evaluated. Figure 11 depicts the interference pattern for the intensity of light emitted by U and Pu and how it affects the analysis of Si. Emission peaks for U and Pu are present near 288.16 nm — the analysis wavelength for Si—which means interference for the Si analysis.



▲Alkali dissolution testing on simulated fuel debris (Figure 10)



▲Interference of U and Pu on the elemental analysis of Si (Figure 11)



①After 15 hours of heat treatment at 300 ℃ in a low-oxygen environment (no cracks have formed)

②After 11 hours of heat treatment at 600 ℃ in a low-oxygen environment (cracks are visible)

▲Appearance of simulated fuel debris after heat treatment (Figure 12)

One of the goals of understanding fuel debris characteristics is to obtain attribute data that can be used to evaluate safety related to the storage and management of fuel debris after it has been retrieved. One of the challenges of highly radioactive fuel debris is that hydrogen can be generated through the radiolysis of the material's water content.

IRID thus obtained data on the drying properties of fuel debris when water is removed for the purpose of preventing hydrogen generation. For this, IRID focused on the estimated temperature of 300 ℃ , also taking into account information about the behavior of volatile radionuclides that was obtained in this study. In addition to the drying characteristics of concrete, which is one of the components of MCCI product, the drying behavior of various particle sizes was also evaluated, under the assumption that particulate fuel debris is hard to dry. As seen in Figure 12's images, there was no change in the surface condition of fuel debris dried at 300 ℃, so this could be a good guideline as far as temperature is concerned.

2-3 Establishing methods for analyzing fuel debris and understanding the characteristics that affect the retrieval and management of fuel debris

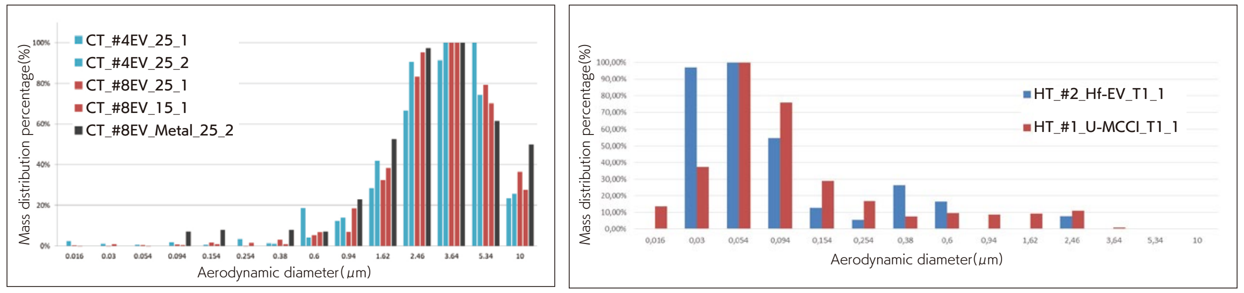
—Obtaining data on the generation of particles and evaluating their behavior—

The dispersion of radioactive particles during the retrieval of fuel debris is a challenge. IRID has conducted testing to explore the relationship between the processes used to retrieve fuel debris and the radioactive particles that are generated. For the test piece, simulated fuel debris was used, which contained U or Hf that was included in the material obtained during the MCCI test that was conducted previously in France. A mechanical cutting test and a heating test tailored to the assumed retrieval process was performed and the generation and behavior of particles was evaluated.

Figure 13 indicates the diameter distribution of generated particles. Compared to the mechanical cutting shown on the left graph, the average diameter of particles generated during the heating test was smaller, as is depicted on the right graph. These generated particles are composed mainly of U and Zr, which is different than the composition of the simulated fuel debris in the heating test. Since the primary mechanism that generates particles during heating is evaporation and condensation, this is believed to be the result of the different vapor pressures for each component within the test piece. It also suggests that particles generated during the heating test could be affected by oxygen in the atmosphere.

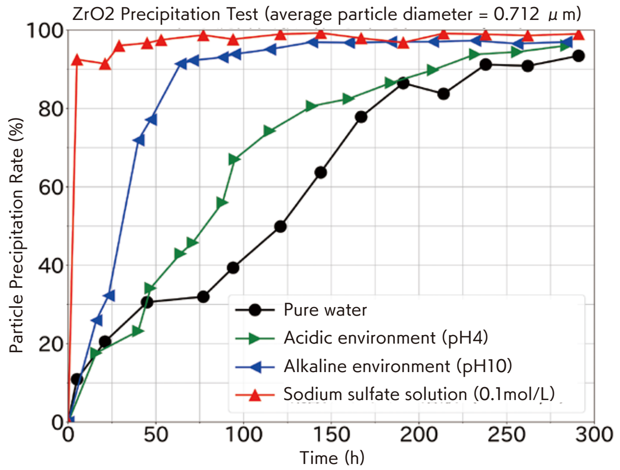
Of the processes for retrieving fuel debris, the method that involves applying heat under water (the laser method) is believed to produce particles that either travel through the water and are released at the surface of the gas or are transported through the water while in the liquid phase. To investigate things such as the phase change of particles from gas to liquid and how particles migrate while in the liquid phase, simulations using CFD codes were conducted in addition to basic testing that simulates particle behavior (Figure 14) as well as a precipitation test (Figure 15).

Applying the data from the aforementioned heating test to the simulations, the gas-to-liquid migration rate was estimated for the simulated 1F fuel debris particles that were predicted to be generated by the heating test.



▲Test results on the generation and behavior of particles using simulated fuel debris that contains uranium from the testing in France (Figure 13)

▲Testing particle migration at the gas-liquid boundary (Figure 14)



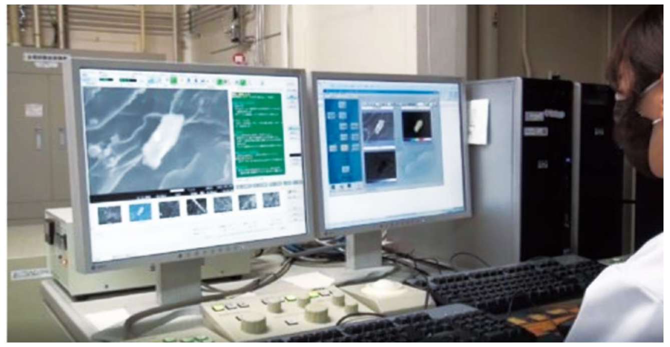
▲Changes in the ZrO2 particle precipitation rate over time for different dissolved substances (Figure 15)

3 Estimating fuel debris characteristics through the analysis of sediment then providing them in a database

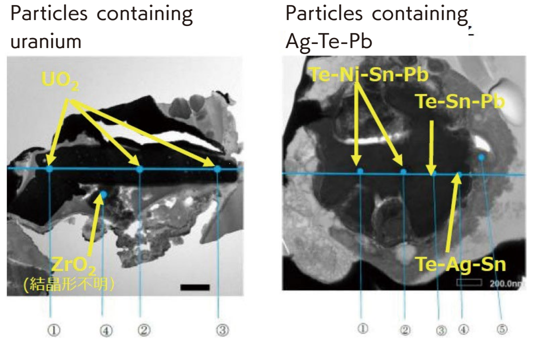
A variety of equipment have been used to investigate the inside of the primary containment vessel at 1F. To augment IRID's analytic data and experience, efforts were coordinated with multiple agencies that sampled the material accreted on those equipment as well as the sediment that they collected.

Figure 16 depicts the SEM analysis taking place at the JAEA Oarai Research and Development Institute. At other analysis agencies, a compound analysis with a transmission electron microscope (TEM) was performed. Figure 17 depicts how the existence of uranium-containing particles in the sample were verified, and the evaluation of characteristics of the fuel debris that will presumably generate those particles.

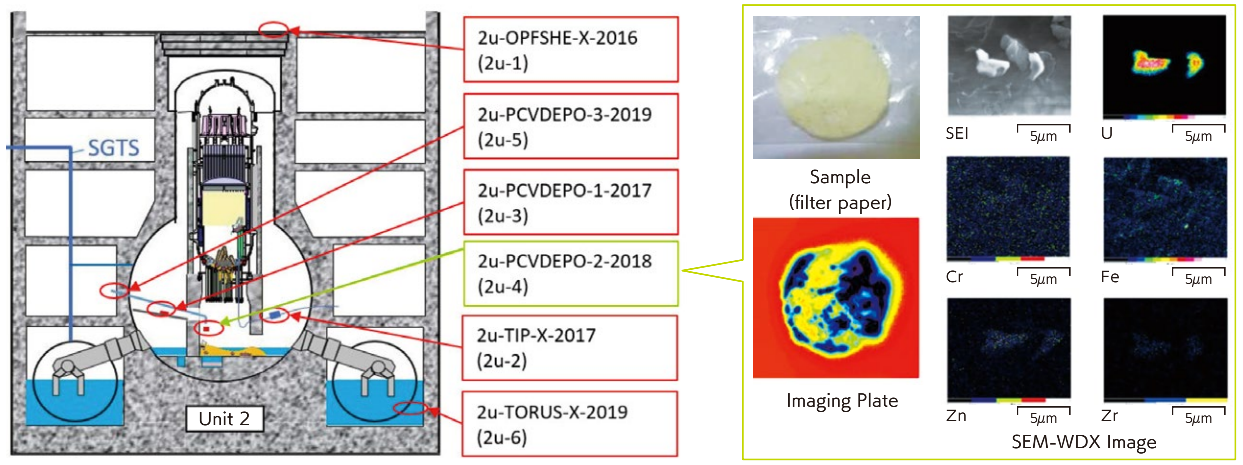
Collection locations for the Unit 2 samples as well as an analysis example are shown in Figure 18. Uranium that is believed to originate from fuel was detected in the sample collected from the operating floor inside the reactor (2u-1) and the sediment smear (2u-5). Also detected were Zr, which presumably originated from fuel cladding and similar material; Zn, which is believed to be from paint; and Pb, which is thought to be from shielding materials. Based on the presence or absence of each element at the various locations, IRID estimated the state of conditions in the reactor.



▲Conducting a SEM* analysis on the sample of accreted material collected inside the reactor (Figure 16)
At the JAEA Oarai Research and Development Institute
*SEM: scanning electron microscope

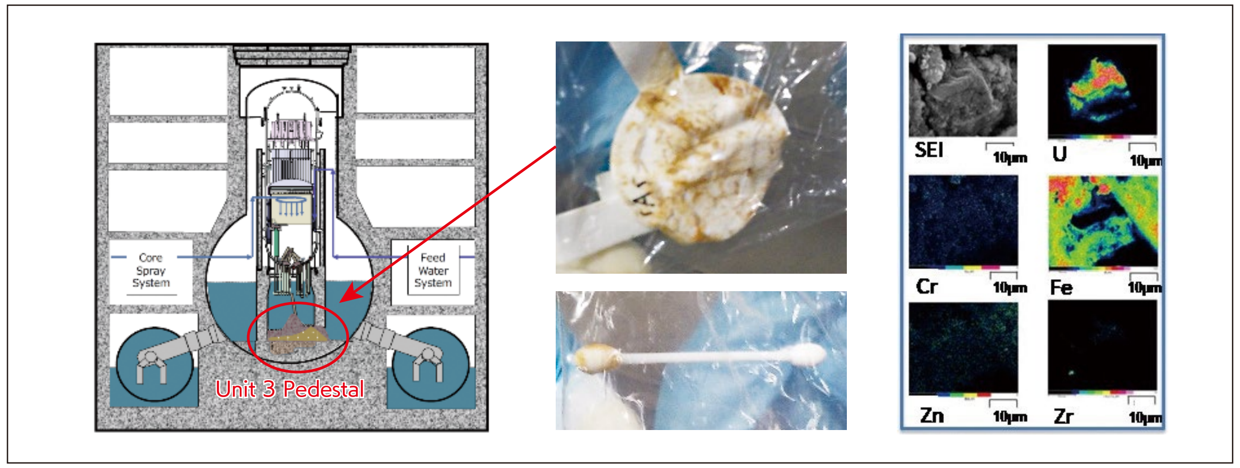


▲TEM* analysis of fine-powder sample collected from within the SGTS intake pipes of Units 1 and 2 (confirmation of particles containing uranium) (Figure 17)
*TEM: transmission electron microscope



▲Collection locations for Unit 2 samples and analysis example (Figure 18)

IRID used smear tabs and cotton swabs to collect and analyze material adhered on the surface of robots returning from internal investigations of the pedestal. The photographs in the center of Figure 19 show the outward appearance of those samples. IRID conducted an analysis of elements such as U and Fe then evaluated that data's connection to not only analysis methods but also the results of prior projects (such as studies to ascertain conditions within the reactors) and the results of internal investigations and accident simulations conducted by Tokyo Electric Power Company Holdings Inc. (TEPCO). All of the data was compiled as fuel debris characteristics for each area of Units 1–3.

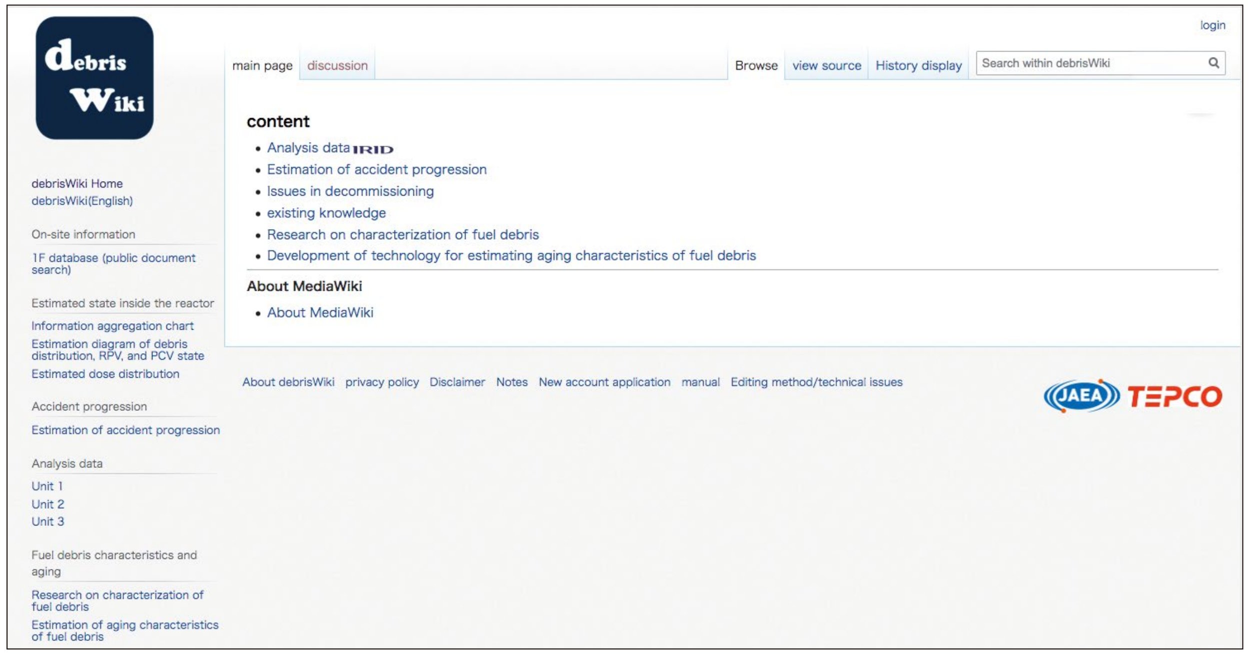


▲Result of analyzing adhered material (Figure 19)

The fuel debris data collected by this project covers a lot of areas, including the various physical properties of fuel and other materials, analysis results of fuel debris from TMI-2 etc., operational information about 1F, the results of internal reactor investigations, and the results of sample analysis. Therefore, a database has been created in conjunction with the JAEA and TEPCO so that the data can be utilized in an organized manner.

To make the data more accessible, a Wiki-style database platform has been created, that systematically organizes it with links to other information such as sample-collection location, accident information for each reactor, and the results of internal reactor surveys. IRID's plan is to continue inputting the data acquired by IRID thus far and integrating future analysis data and other information into the database.

https://fdada-plus.info/wiki/index.php



debrisWiki Home
debrisWiki(English)

On-site information
1F database (public document search)

Estimated state inside the reactor
Information aggregation chart
Estimation diagram of debris distribution, RPV, and PCV state
Estimated dose distribution

Accident progression
Estimation of accident progression

Analysis data
Unit 1
Unit 2
Unit 3

Fuel debris characteristics and aging
Research on characterization of fuel debris
Estimation of aging characteristics of fuel debris

content
- Analysis data IRID
- Estimation of accident progression
- Issues in decommissioning
- existing knowledge
- Research on characterization of fuel debris
- Development of technology for estimating aging characteristics of fuel debris

About MediaWiki
- About MediaWiki

About debrisWiki privacy policy Disclaimer Notes New account application manual Editing method/technical issues

▲Example of the database (Figure 20)

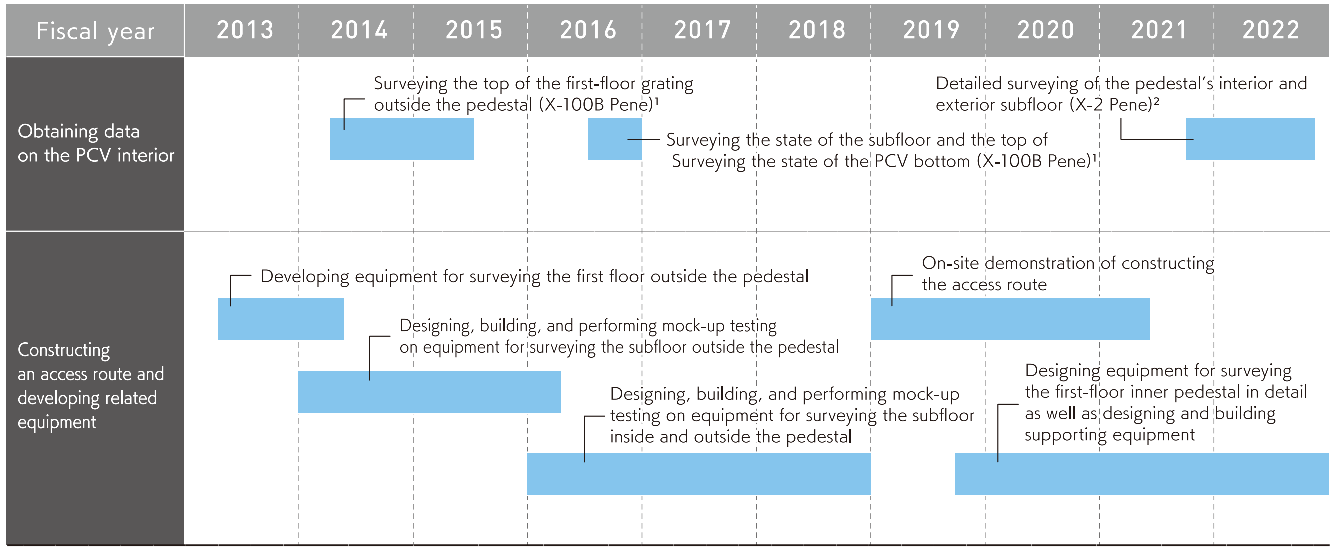
Development of technology for detailed investigation inside the primary containment vessel (PCV)

Investigating inside the PCV to obtain detailed information for fuel debris retrieval

- Detailed information about the PCV interior is needed for future fuel debris retrieval
- IRID is developing equipment and conducting detailed investigations in the PCV
- Equipment for the trial retrieval of fuel debris is being developed
- Equipment for creating access routes to the PCV interior is also under development

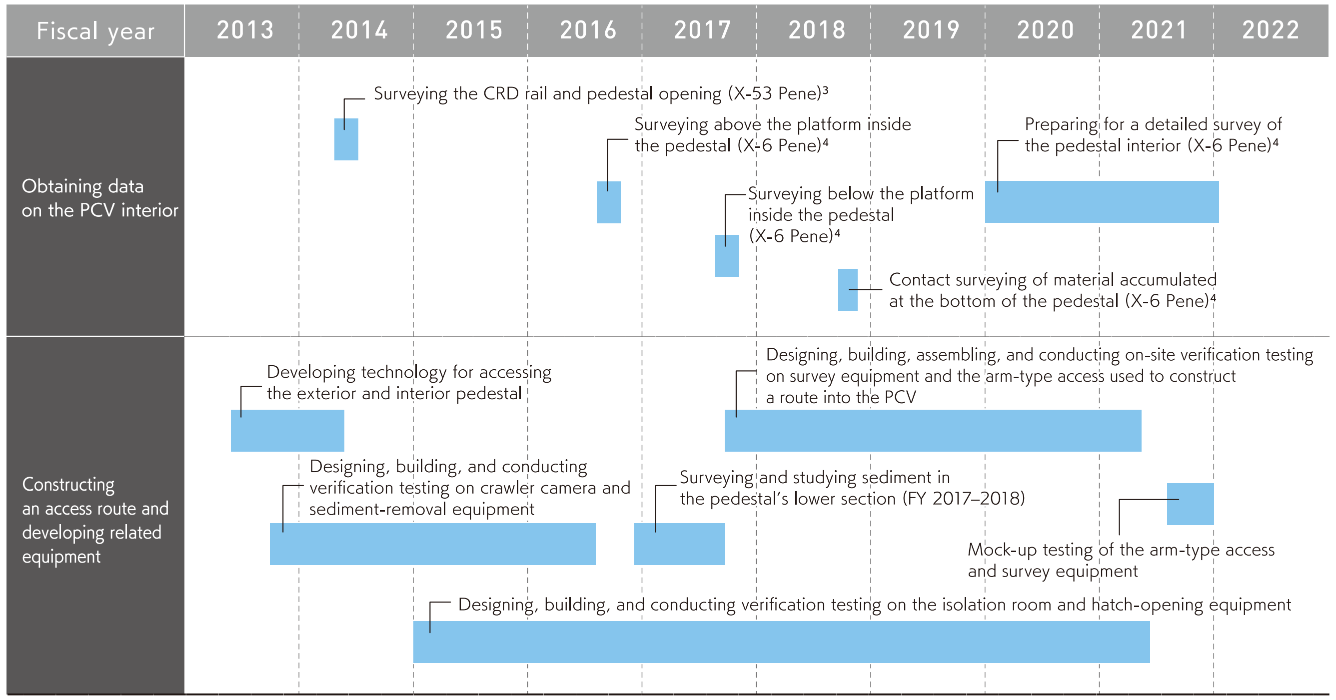
Research and development progress

【Unit 1】



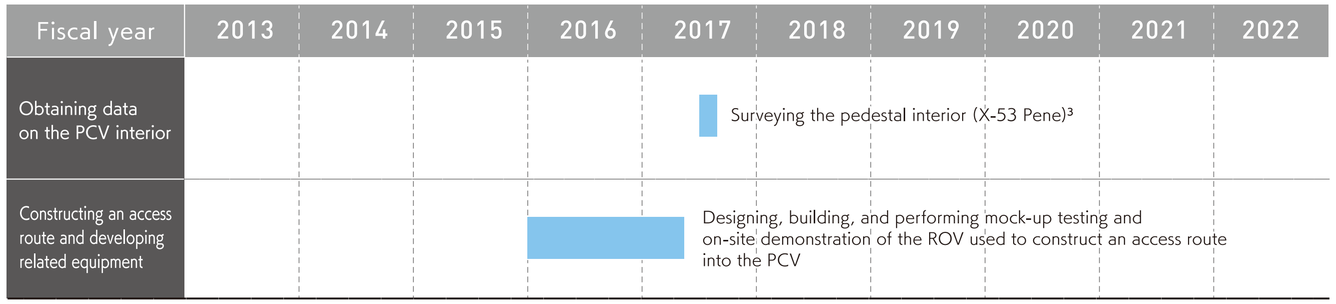
[1] X-100B Pene: X-100B Penetration [2] X-2 Pene: X-2 Penetration

【Unit 2】

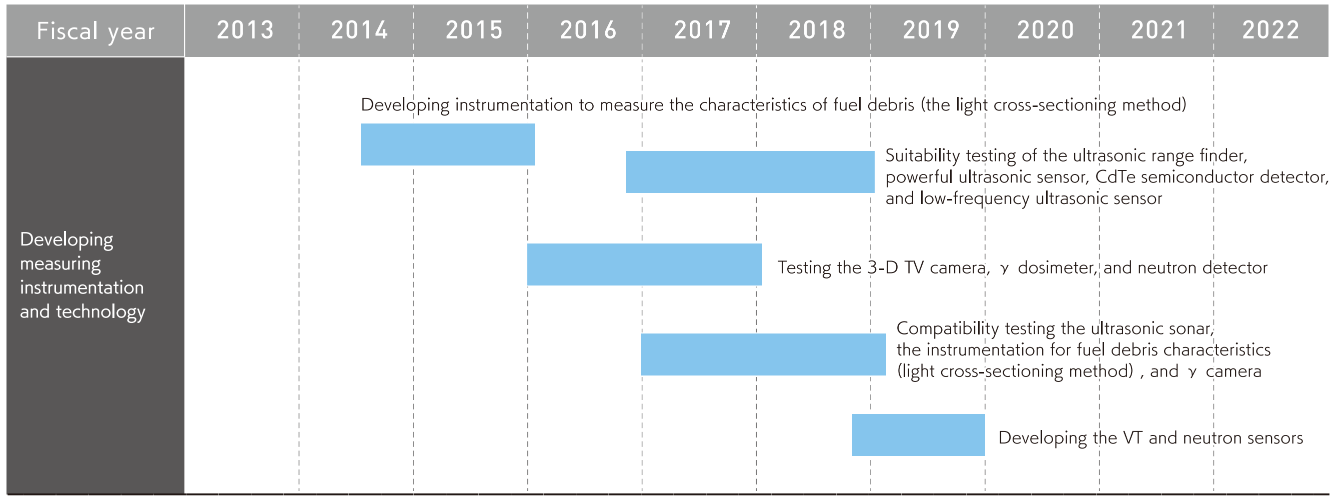


[3] X-53 Pene: X-53 Penetration [4] X-6 Pene: X-6 Penetration

【Unit 3】



【Units 1–3】



Background

To establish methods for retrieving fuel debris, it is necessary to understand the distribution and characteristics of fuel debris within the PCV and the status of the structures. Investigation of the inside PCVs have been conducted on Units 1, 2, and 3.

While these surveys provided valuable information, they were limited by factors such as the radioactive environment and the size of existing access points. In addition to updating and finalizing plans for further investigation and development, there are the additional challenges of creating access routes, and verifyig detailed design of the investigation equipment.

Purpose

It is believed that virtually all the melted fuel in Unit 1 fell into the pedestal, with some of that fuel spreading outside the pedestal via openings in the basement floor. To prepare for investigating this fuel debris, the environment outside the pedestal on the first floor was investigated as well as the general situation on the basement floor. Based on those results, a plan was developed to conduct investigation and obtain information about the fuel debris inside and outside the pedestal and the status of accumulated sediments. In that investigation, the spread and depth of accumulated sediments in and around the pedestal as well as the existence of fuel debris and its characteristics will be explored. At the same time, equipment to investigate the conditions inside the pedestal is underway.

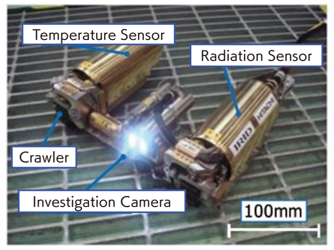
In the case of Unit 2, the existence of pebbles and clay sediment throughout the entire bottom of the pedestal's interior has been confirmed. To gain a more accurate understanding of the state of fuel debris and sediment as well as the shape and dimensions of the pedestal and its attached structures, a larger-diameter hole (approximately 550 mm) will be created in the X-6 penetration ("X-6" below) then a suitable combination of equipment and technology will be used to access the PCV interior and conduct a detailed investigation of the pedestal's interior and exterior. The aim is to collect some fuel debris using experimental retrieval equipment.

Unit 3 is believed to have high water levels within its PCV along with a variety of obstructions inside its pedestal. Due to these factors, a small submersible robot (ROV) has been developed that can access confined areas within the pedestal and navigate underwater while avoiding obstacles. After a mock-up test, it was used to investigate the inside of the pedestal. Fallen objects and damage to structures were observed throughout nearly the entire area, so a 3-D map is being developed for use in studying fuel debris retrieval policies.

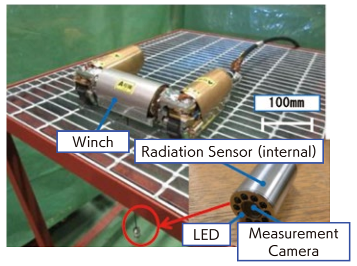
Unit 1

1 Investigation for the basement floor and the first floor of outside the pedestal

IRID developed the PMORPH1, which enters the PCV via a pipe with an internal diameter of 100 mm then transforms so that it can travel reliably across the top of the grating to investigate the area (Figure 1-1). By investigating the first-floor grating in the PCV of Unit 1, it was learned that factors such as the degree of equipment damage and the dose-rate distribution. Based on the above equipment, the PMORPH2 was developed, which is capable of lowering an array of sensors (a camera and dose rate meter) through the cracks in the grating to a depth of approximately three meters (Figure 1-2). Through the investigation of the PCV basement floor in Unit 1, the level of accumulated water was verified and the presence of sediment up to one meter in size was confirmed.



▲PMORPH1 for investigating the first-floor pedestal exterior (Figure 1-1)

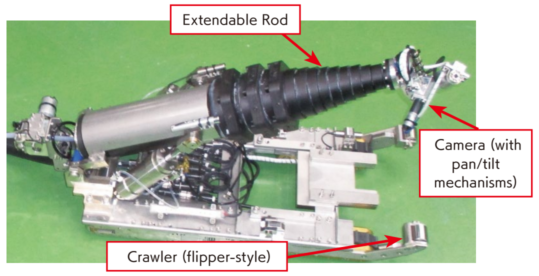


▲PMORPH2 for investigating the subfloor outside the pedestal (Figure 1-2)

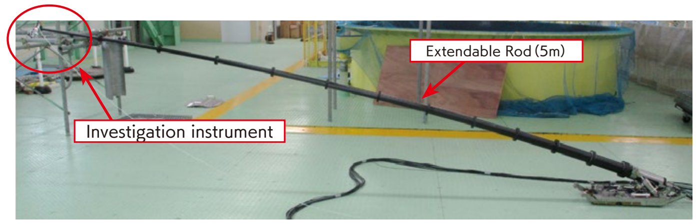
2 Detailed investigation of inside/outside of the first-floor pedestal

To investigate the inside of the PCV pedestal in Unit 1, IRID is developing equipment that will enter through an existing opening and move to the top of the grating, then access the pedestal's interior through the CRD opening to investigate the area by capturing images and obtaining radiation dose information (Figures 2-1, 2-2, and 2-3). The investigation was conducted in stages: first the primary investigation, which explored the conditions from in front of the CRD opening to outside the pedestal, then the secondary investigation, which investigated the above-water sections inside the pedestal.

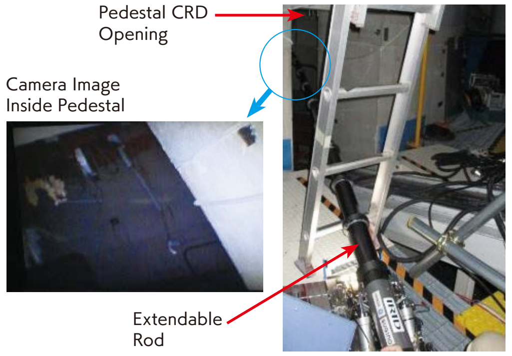
For the primary investigation, a roughly 70-cm extendable rod was attached to the crawler equipment then operated it while performing measurements; in the secondary investigation, the rod was extended to approximately 5 meters then gathered data with the camera and radiation sensors on its tip. Support equipment such as a cable-feeding equipment that grips, moves, and feeds out cable for the investigation equipment and monitors conditions behind it, is being developed.



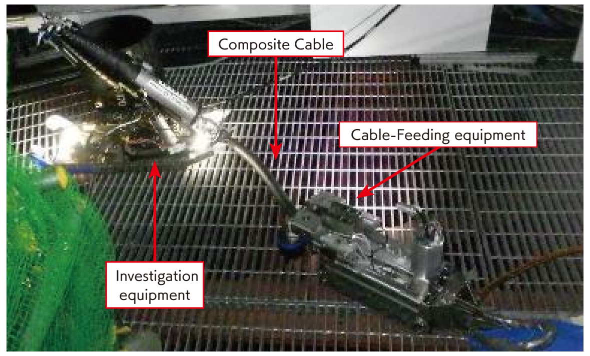
▲Survey equipment (with rod collapsed) (Figure 2-1)



▲Investigation equipment (with rod extended) (Figure 2-2)



▲Validation test for continuous operation (Figure 2-3)

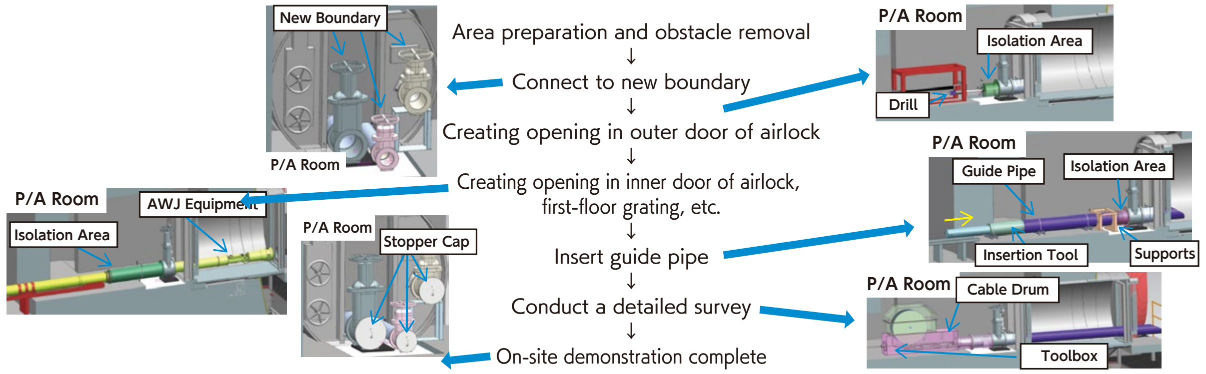


▲Releasing cable from the cable-feeding equipment (Figure 2-4)

3 Detailed investigation for the basement floor of inside/outside of the pedestal (creating an access route)

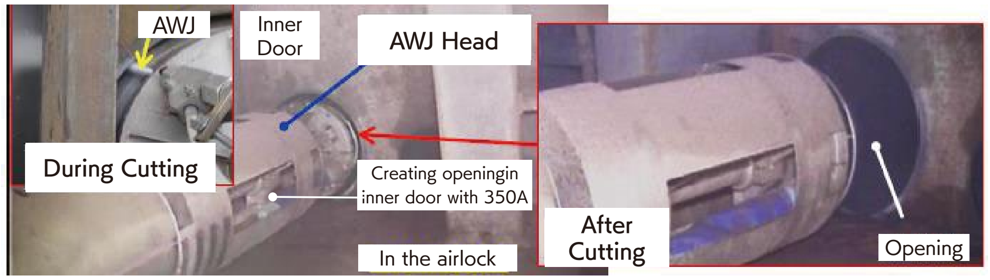
To investigate the inside of the PCV in detail, the investigation equipment was entered through the X-2 penetration (air lock) of Unit 1. Technology was developed for creating opening, establishing boundaries, and remote monitoring in order to create that access route (Figure 3-1). The opening technology included equipment for making a hole in the exterior door of the air lock with a diamond cutter (Figure 3-2) and for making a hole in the inner door of the air lock, the grating, and other surfaces with an abrasive water jet (AWJ) (Figures 3-3 and 3-4).

All operations were monitored remotely and maintained the PCV boundaries.

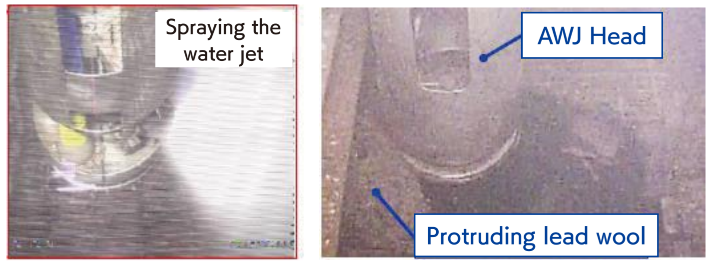


▲Steps to create the access route (Figure 3-1)

▲Creating opening in outer door of airlock with core opening equipment (Figure 3-2)



▲Creating opening in the inner door of the airlock (Figure 3-3)



▲Creating opening in the grating (Figure 3-4)

4 Detailed investigation for the basement floor of inside/outside of the pedestal

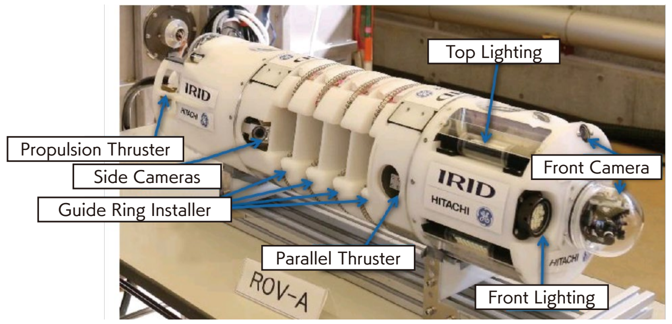
Since water has accumulated in the lower section of the PCV and the basement floor of the reactor building, a submersible robot is needed to investigate those areas. Therefore, IRID developed the submersible IRIDOLPHIN (Figure 4-1) to investigate the basement flor inside and outside the pedestal.

Five types of submersible boat (Figure 4-2) and a single type of small submersible boat (Figure 4-3) were developed. One of the first five types can attach magnetic guide rings to the basement floor structure to prevent it from getting tangled up in the boat cables. The other four types are equipped with various features such as the ability to create 3-D sediment maps, measure the thickness of sediment, measure fuel debris using neutron detectors or other methods, or collect samples of sediment. The small boat will submerge to enter the pedestal and survey its interior. In FY 2021, guide rings were attached along the route the boats will take (Figure 4-4); moving forward, IRID will continue to conduct actual investigations with the other boats as well.

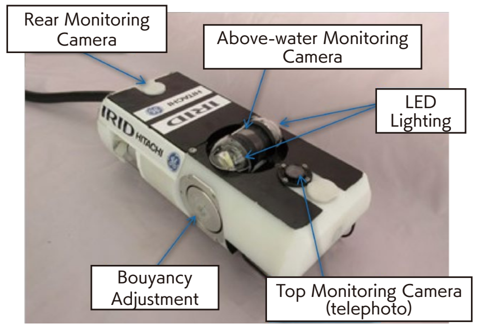
Investigation Equipment	Instrumentation	Operational Details
IRIDOLPHIN-A with guide rings	To protect the ROV (fiber-optic γ dosimeter)	Guide rings were installed on the jet deflector to prevent the cable from tangling in structural members
IRIDOLPHIN-A2 Detailed visual observation	To protect the ROV (fiber-optic γ dosimeter and improved small-scale B10 detector)	Accesses the pedestal' s interior and conducts a visual inspection of the CRD housing, fuel debris, accumulated material, etc.
IRIDOLPHIN-B 3-D mapping of sediment	• Scanning ultrasonic range finder • Water temperature gauge	Uses a scanning ultrasonic range finder to check the height distribution of accumulated material
IRIDOLPHIN-C Measures the thickness of accumulated material	• Powerful ultrasonic sensor • Water temperature gauge	Uses a powerful ultrasonic sensor to measure the thickness of accumulated material and the state of the objects underneath for the purpose of estimating the height and distribution of fuel debris
IRIDOLPHIN-D Detects accumulated fuel debris	• CdTe semiconductor detector • Improved small-scale B10 detector	Drops a fuel debris detection sensor onto the surface of accumulated material and verifies the composition of fuel debris by analyzing nuclides and measuring neutron flux
IRIDOLPHIN-E Samples accumulated material	• Suction sampler	Drops a sampling equipment onto the surface of accumulated material and collects samples from that surface

• Dimensions of IRIDOLPHIN-A through E: ϕ25 cm × approx. 110 cm long; Dimensions of IRIDOLPHIN-A2: ϕ20 cm × approx. 45 cm long

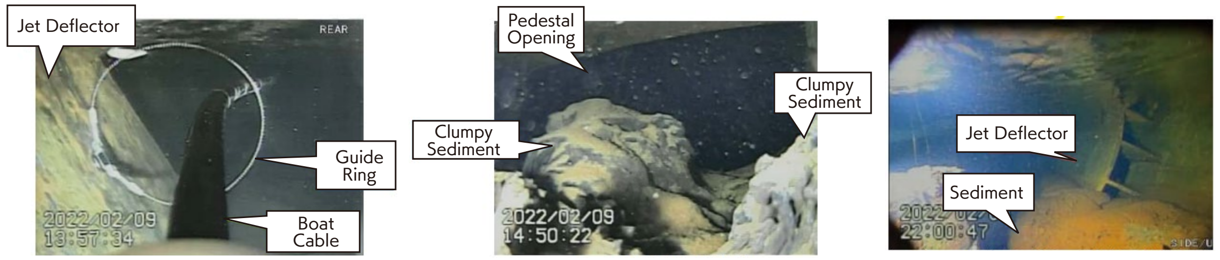
▲ List of IRIDOLPHIN submersible boats (Figure 4-1)



▲The submersible robot [IRIDOLPHIN-A] (Figure 4-2)



▲The small submersible robot [IRIDOLPHIN-A2] (Figure 4-3)



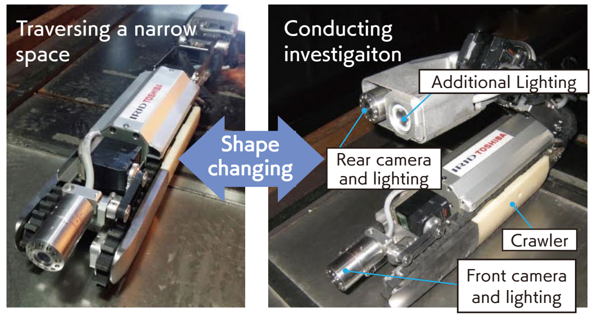
▲Images of submersible robot [IRIDOLPHIN-A] in action with installed guide rings (Figure 4-4)

Unit 2

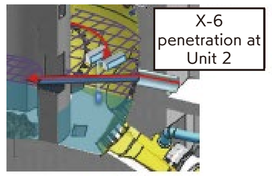
1 Developing crawler-type robots for conducting remote-operated investigations (FY 2014–2016)

The goal of the remote crawler robot (Figure 1-1) is to access tight spaces and provide visibility. When entering the PCV, the robot is long and straight so that it can pass through a guide pipe with an internal diameter of Φ 100 mm. Once inside, it unfolds like a scorpion to present its rear camera, which it uses in conjunction with the front-facing camera to achieve strong spatial recognition of its environment. To allow the robot to operate in extreme environments, it was made highly resistant to radiation (over 1,000 Gy [cumulative]) and improved visibility in hazy conditions by adding some highly concentrated illumination.

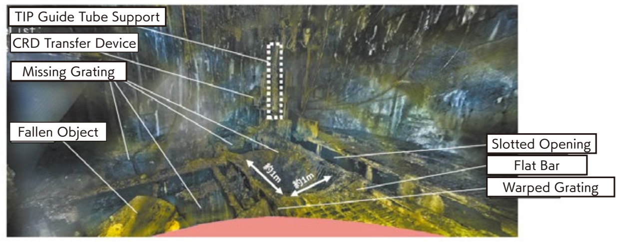
With this robot and a camera attached to a telescoping guide pipe, it was successful in investigating inside the pedestal and capturing images of it and the CRD rail.



▲Remote-operated crawler investigation robot (Figure 1-1)



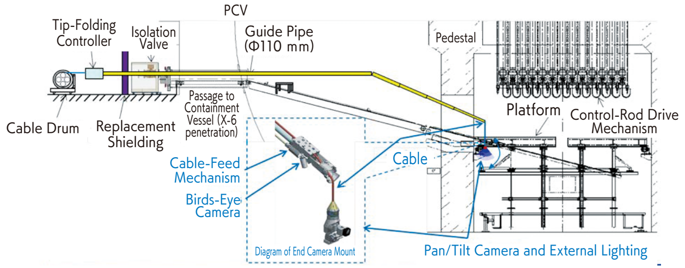
Enter the pedestal via the CRD rail



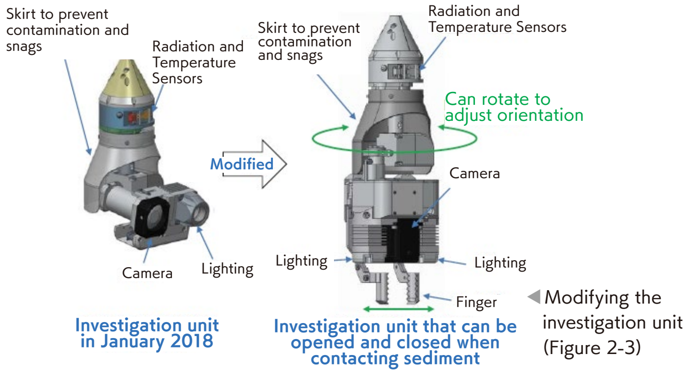
▲Internal pedestal images after processing (Figure 1-2)

2 Investigating and studying sediment in the pedestal’s lower section (FY 2017–2018)

IRID's investigations revealed that the original plan of operating a small, self-driven crawler inside the pedestal (as in section 1 above) would be difficult and that there is a hole where sections of the CRD platform’s grating has fallen. Thus, an access and investigation equipment with a telescoping guide pipe (Figure 2-1) was manufactured, which was then verified in January 2018 via an on-site demonstration test that captured images inside the pedestal and produced data on the temperature and dose rate in that environment (Figure 2-2). In February 2019, the TEPCO Member Research Project converted the equipment to an investigation unit (Figure 2-3) with an additional finger that can mechanically work with sediment. The unit was then used to verify changes in the status of accumulated material. That investigation confirmed movement in the pebble-shaped sediment at the bottom of the pedestal (Figure 2-4).



▲Investigating the inside of Unit 2's PCV using a guide pipe (Figure 2-1)



◀Modifying the investigation unit (Figure 2-3)

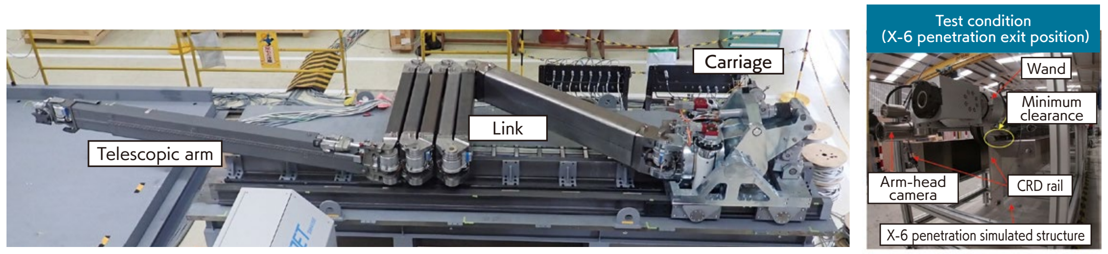
▲Investigating the bottom of the pedestal (Figure 2-2)

◀Examining sediment through direct contact (Figure 2-4)

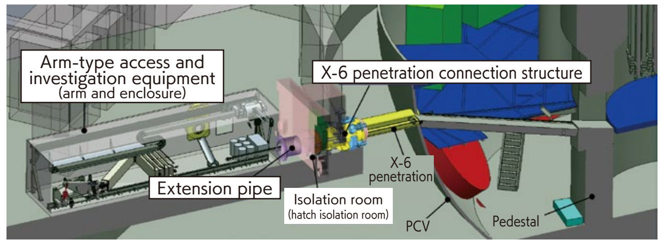
3 Developing arm-type access and investigation equipment

With the arm-type access and investigation equipment (Figure 3-1), an articulated arm is housed within an enclosure (a rectangular steel container) then extended during internal investigating or the test retrieval of fuel debris to establish a connection with the PCV via the equipment for creating an access route (the X-6 penetration connection structure etc.) (Figure 3-2).

The arm-type access and investigation equipment was unit tested in Kobe, where it was verified that it can pass through the narrow sections within the X-6 penetration (right side of Figure 3-1). Mock-up testing is currently underway at JAEA's Naraha Center for Remote Control Technology Development, and the plan is to conduct on-site demonstrations after some operational training on the equipment.



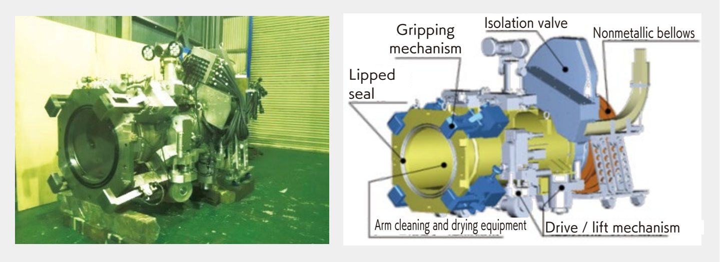
▲Arm unit test (X-6 penetration test) (Figure 3-1)



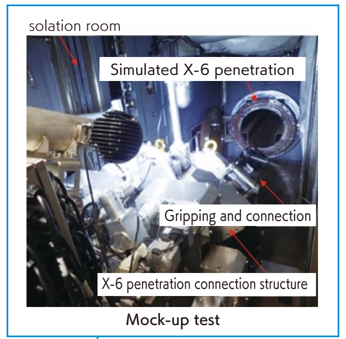
◀Site layout of arm access and investigation equipment (Figure 3-2)

4 Creating an access route: the X-6 penetration connection structure

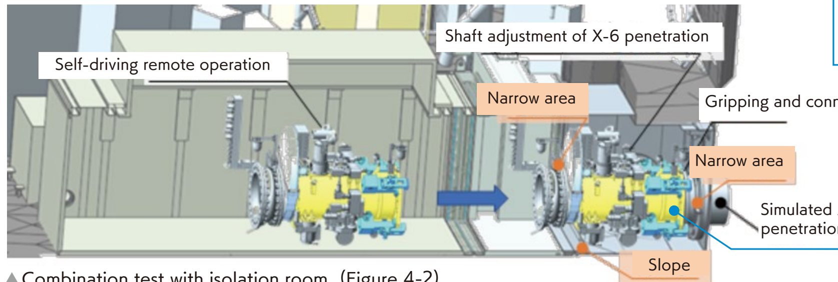
The X-6 penetration connection structure has the PCV isolation function (an isolation valve) (Figure 4-1) and is designed so that investigation arms can pass through the structure's interior, and it is one of the equipment to create an access route into the PCV. Self-driven through remote operation, the structure uses a gripping mechanism to connect to the flange of the X-6 penetration. The connection structure's various functions have already been verified through unit testing, mock-up testing, and testing in conjunction with the isolation room (Figure 4-2), and on-site demonstrations are currently being prepared.



▲Overview of the X-6 penetration connection structure (Figure 4-1)



Mock-up test



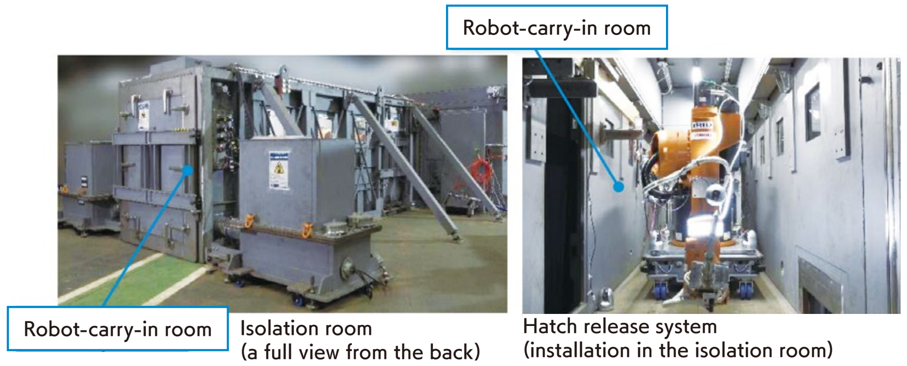
▲Combination test with isolation room (Figure 4-2)

Direction to the reactor ➡

5 Creating an access route: hatch-opening equipment and the isolation rooms

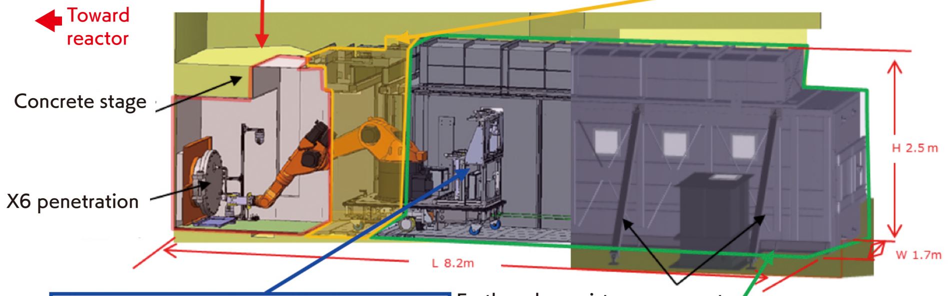
The purpose of this machine is to create a route for accessing the PCV interior through the X-6 penetration of Unit 2 by remotely opening the X-6 penetration hatch (Figure 5-2) via the isolation rooms (the general term for the stage isolation room, the hatch isolation room, and the robot deployment room) (Figure 5-1) while maintaining the PCV boundary.

IRID has already completed the design, manufacturing, and mock-up testing of the isolation rooms and the hatch-opening equipment, and task training is currently being carried out so that on-site demonstrations can commence.



【Isolation room in the stage】
○ Functions:
Formation of boundary to cover inside the concrete stage from the X-6 penetration sleeve to the hatch isolation room.
○Specifications:
Approx.1 ton/W1.2×L1.7×H1.8m

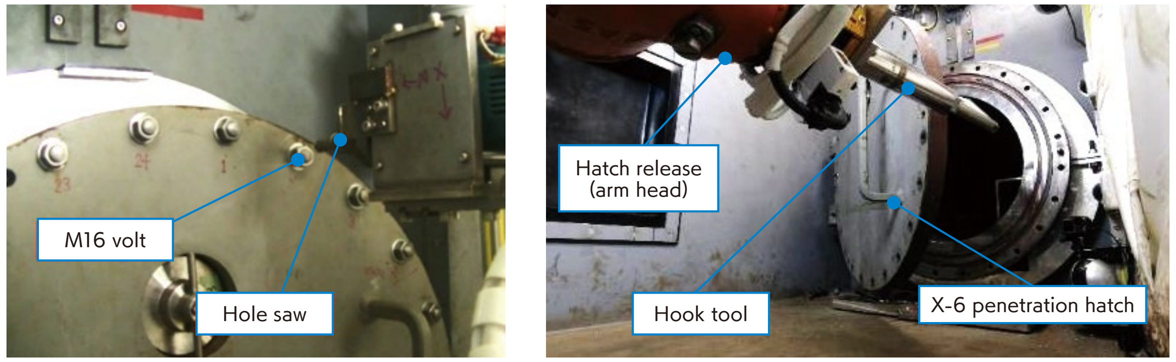
【Hatch isolation room】
○ Functions:
Boundary formation when opening the hatch. Formation of boundary and shielding with air-tight door after opening the hatch.
○Specifications:
Approx. 5.5 ton / W1.7×L5.3×H2.5m



【Hatch release】
○ Functions:
Opening of the X-6 penetration hatch
○Specifications:
Approx. 2.3 ton / W1×L2×H1.6m

【Robot carry-in room】
○ Functions:
Boundary formation when opening the hatch and carrying equipment in and out
○Specifications:
Approx. 8 ton / W1.7×L5.3×H2.5m

▲Overview of the isolation room and the hatch release (Figure 5-1)



▲Test setup of hatch release operation (Figure 5-2)

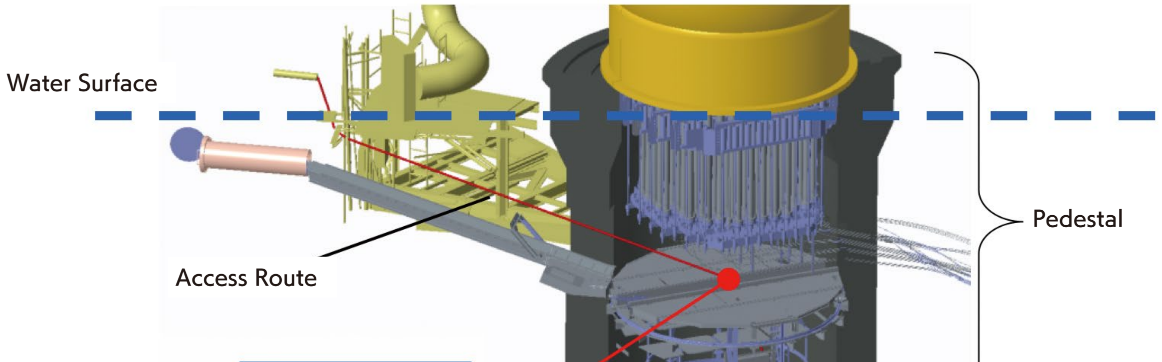
Unit 3

1 Investigating inside PCV with a submersible robot (ROV)

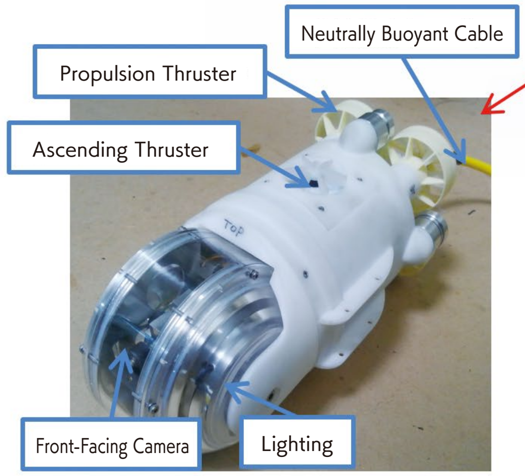
IRID developed a submersible robot (the "Little Sunfish" in Figure 6-2) to access Unit 3's PCV through the X-53 penetration (Figure 6-1) and investigate the inside of the pedestal. An actual investigation was conducted inside the pedestal as a demonstration test for the equipment. The demonstration test revealed damage to multiple structures, the accretion of what appears to be material that melted then resolidified in the pedestal's interior, and the presence of lumpy sediment accumulated in several places inside the pedestal.

These results are being further developed to create a 3-D map of the pedestal's interior that can be used to study policies for retrieving fuel debris.

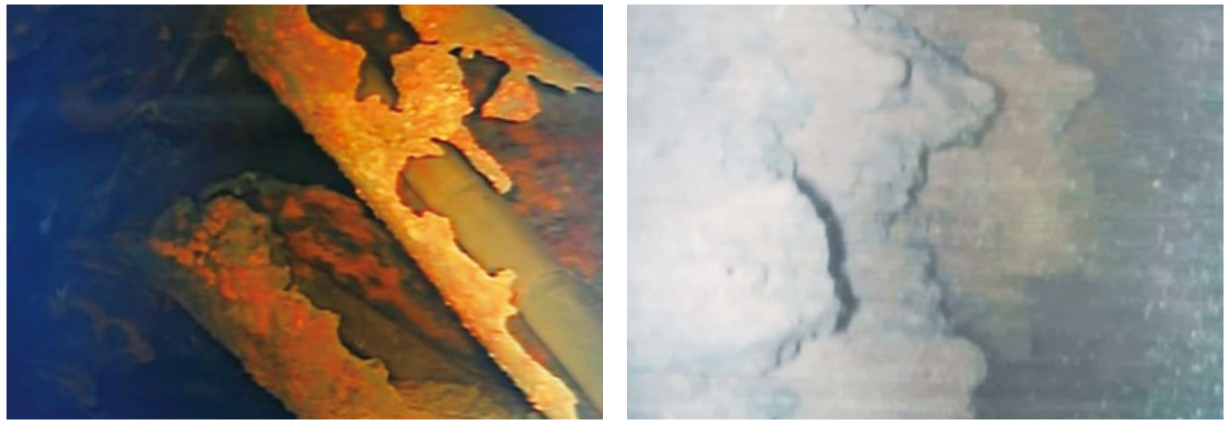
ROV Entry Point (PCV penetration)



▲Underwater ROV access route (Figure 6-1)
* ROV: Remotely Operated Vehicle



▲Exterior of ROV (Figure 6-2)



(damaged structures) (lumpy sediment)

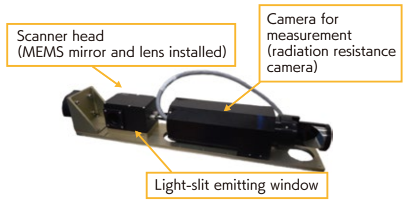
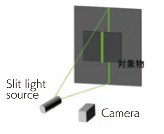
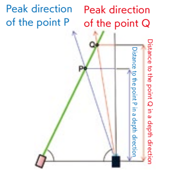
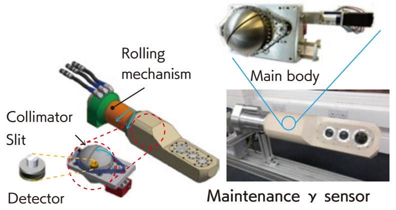
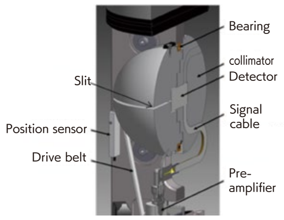
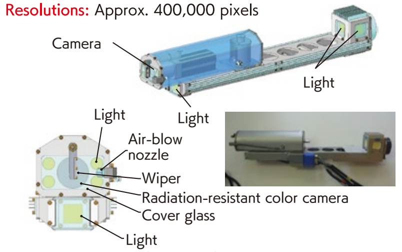
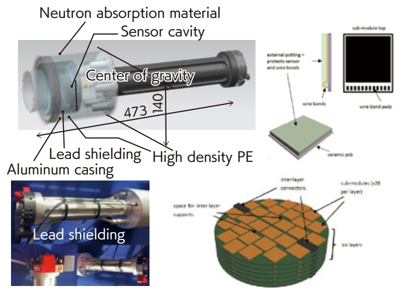
▲ Investigating the pedestal interior with the ROV (Figure 6-3)

Units 1-3

1 Developing measurement technology

Measurement technology (sensors) are currently being developed for detailed investigation inside PCV. Refer to Figure 4-1 for an overview of each sensor.

All sensors are designed to be installable on the arm-type access equipment or other investigation equipment, and each of them has already been tested and had its functionality verified. Next, a combination test is planned to for the sensors installed on the arm. On-site verification test is also being prepared.

Sensor	Measurement items	Overview	Principles of measurement	Use of obtained data
Laser scanner	Structures inside PCV Shape of sediment (debris)	**Mass:** Approx. 8 kg **Dimensions:** Width 135 mm × Length 515 mm × Height 145 mm **Measuring accuracy:** Errors ± 30 mm  Appearance of the sensor	Slits of light are beamed onto the target object, then the reflections are detected by light-receiving elements (the lasor scanner method). The method of measurements uses the principle of triangulation; variations in distance in the depth direction appear as unevenness in the slits of light, and that unevenness information is converted to distance.  Layout of the measuring equipment and a target object  Peak directions when irradiating slit lights	·To prevent the survey arm from colliding with structures inside the PCV, acquire data about the internal shape of the PCV after the accident and reflect that in the arm's operational system ·Combine with γ-ray data obtained from the γ sensor to estimate the distribution of γ-ray sources
γ sensor	γ ray dose inside PCV (including debris)	**Mass:** Approx.10 kg **Dimensions:** Approx. ϕ140 × Approx. 700 mm  Maintenance γ sensor	γ rays are measured by installing a high-radiation detector (silicon diode) inside a tungsten collimator then using the collimator's slits to control the incident γ rays. 	·Understanding the amount of γ rays originating from each direction in the PCV ·Combine with the shape data obtained with the laser scanner to estimate the distribution of γ-ray sources
VT camera	Structures inside PCV Images of sediment (fuel debris)	**Mass:** Approx. 7kg **Dimensions:** Approx. ϕ140 × Length 775 mm **Resolutions:** Approx. 400,000 pixels  Surface of camera (enlarged)	Applies a charge injection device (CID) as the camera element. The CID converts the light's wavelength to an electrical signal.	·Use as investigation images ·Use to monitor when operating the arm (to avoid collisions)
Neutron sensor	Neutrons originating from the fissile material within the sediment (debris) or fission products (pulse measurement)	**Mass:** Approx. 8kg **Dimensions:** Approx. ϕ140 × Length 500 mm 	·A thin SiC semiconductor is doped with the neutron convertor 10B. α rays (10B(n,α) reaction) generated when a reaction occurs between the convertor and a neutron (the 10B(n,α) reaction) excites charged particles, which are then read as electrical pulses. ·The thin SiC semiconductor makes γ ray sensitivity relatively low, allowing γ rays to be removed. ·To assess the distribution of fission products (nuclear fuel) within the fuel debris, use a neutron adsorbent that can measure the neutrons originating from fuel debris with a relatively high sensitivity to maintain directionality.	·Create a distribution of the number of neutrons in any direction ·Contribute to estimates of the distribution of radioactive material in fuel debris based on the results of future sampling of the fuel debris

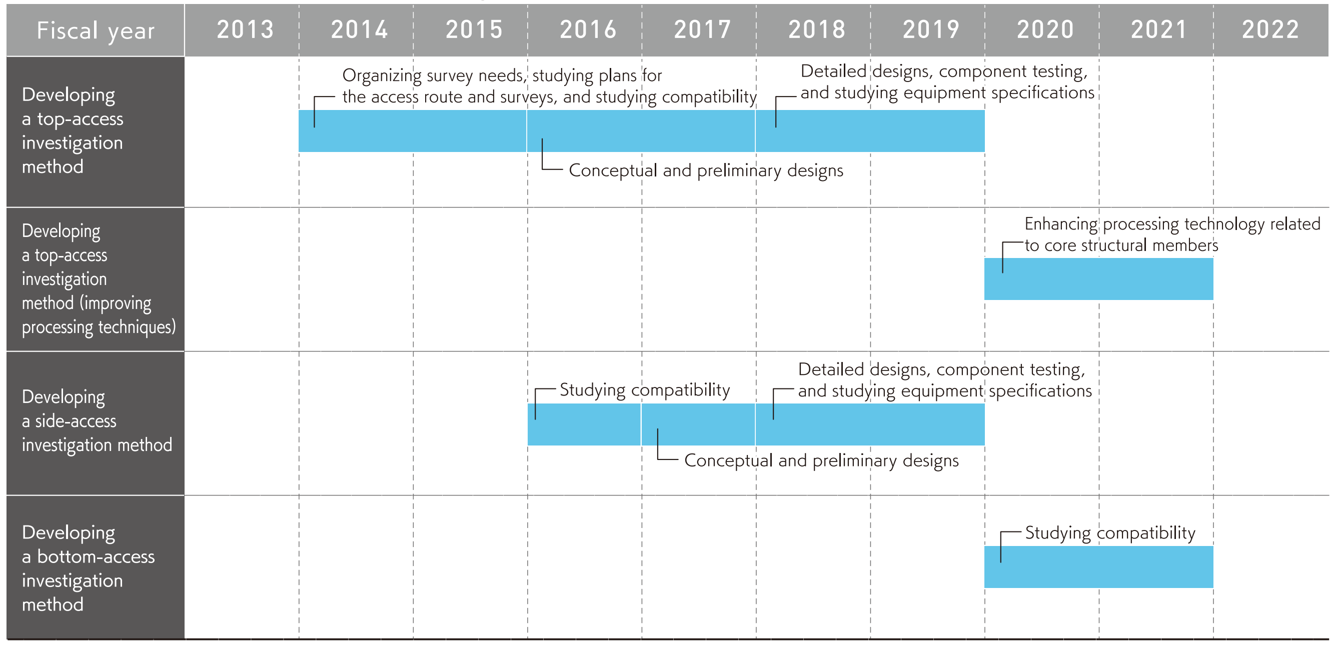
▲Lists of measurement technology (sensors) (Figure 4-1)

Development of technology for investigation inside the reactor pressure vessel (RPV)

Investigating inside the RPV to prepare for the retrieval of fuel debris

- Developing a top-access investigation method: Design a method for creating a hole in the operating floor at the top of the reactor building to ascertain conditions inside the reactor pressure vessel (RPV)
- Developing a top-access investigation method (improving processing technology): Create processing techniques that can reduce the secondary waste generated during processing
- Developing a side-access investigation method: Design a method for gaining access by opening a hole on the side to avoid interfering with work being done on the operating floor etc.
- Developing a bottom-access investigation method: Access via the hypothetical holes in the bottom of the RPV to promptly ascertain the RPV's internal conditions

Research and development progress



Background

To dismantle Fukushima Daiichi NPS, the fuel debris and the reactor internal structures in the RPVs must be safely retrieved. However, the location and condition of the debris and ithe reactor internals are currently completely unknown. To prepare for retrieving fuel debris and structural materials, it is necessary to gain access to the RPV interiors so that where those materials are and what shape they are in can be learned. But accessing the RPV is difficult due to the complex structures in and around it—not to mention the extremely radioactive environment. For this, a new investigation method that can gain access is needed while providing shielding from afar and preventing the radioactive dust generated during processing from being thrown up into the air.

Purpose

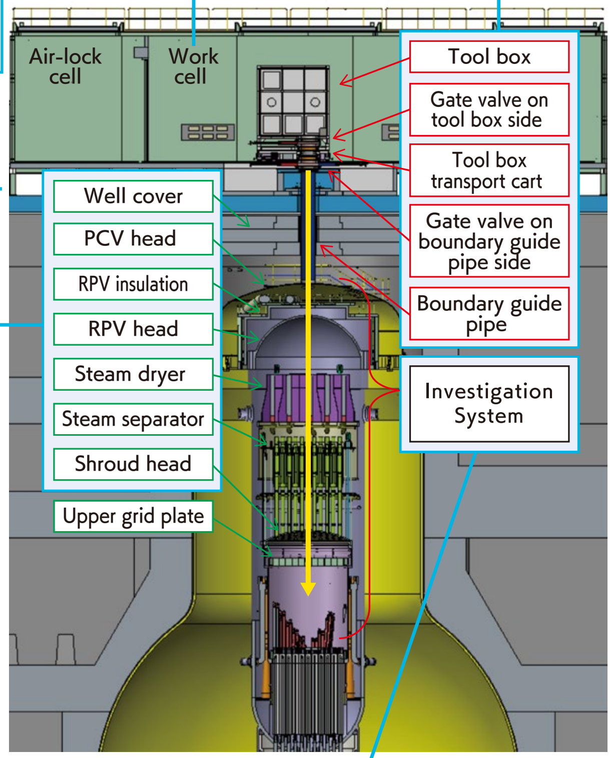
When developing a new investigation method, it is necessary to first consider the access route, or how to gain entry to the RPV. In this project, it was decided after much deliberation to access the RPV from the top, side, and bottom. For the top and side access, the goal was to reach the core from outside the primary containment vessel (PCV) by opening holes; for the bottom, the RPV interior would be accessed through the access route created in a different project for investigating the inside of the PCV.

The goal of this project is develop technology that will enable these routes to conduct investigations while providing remote shielding and preventing the radioactive dust generated during processing from being thrown up into the air.

1 Developing a top-access investigation method

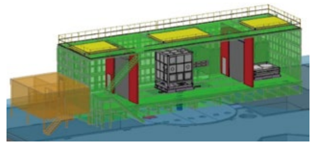
IRID considered how to access the RPV interior from above and what such investigations would need. A method of access was then developed by opening a hole in the operating floor. At the same time, investigation safety requirements and assessments of radiation exposure was used to determine the features needed on the investigation equipment, which was then reflected in the design specifications.

IRID conducted element testing on the core technologies for the top-access investigation method: ① the work cell, ② the boundary preservation equipment, ③ the processing equipment, and ④ the investigation system. The feasibility of those elements were also verified and obtained design information that can be used to determine equipment specifications.



Work Cell

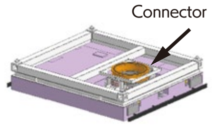
- Negative pressure to prevent the spread of contamination
  Study maintenance and management systems
- Study equipment and methods for carrying it in and out



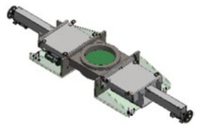
Boundary Maintenance Equipment

- Study the tool box
- Develop the gate valve
- Study the sealing structure (resin packing) etc.

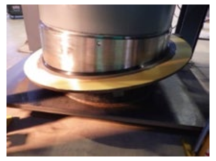
▲Tool box



▲Tool box transport cart



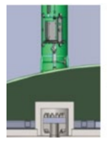
▲Gate valve on the boundary guide pipe side



▲ Boundary guide pipe (PCV head cconnecting part)

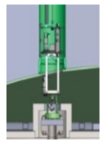
Processing Equipment

- Development of hole-opening equipment
- Development of t small-diameter equipment for opening holes etc.



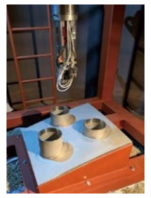
▲PCV head machining unit

▲Opening hole for RPV insulating material



▲ Flange release with spare nozzle in RPV head

▲Access equipment for processing the reactor internals

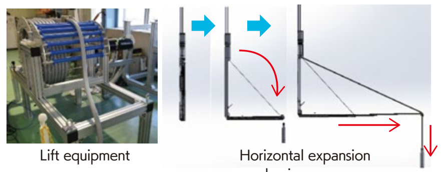


▲AWJ tool head

AWJ: Abrasive Water Jet

Investigation System

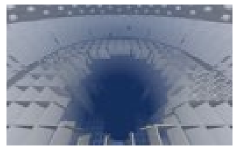
- Developing investigation system
- Developing investigation equipment
- Developing access equipment
- Visibility simulation
- Study horizontal expansion mechanism etc.



Lift equipment

Horizontal expansion mechanism

▲Access equipment



▲Superposition simulation of obtained images

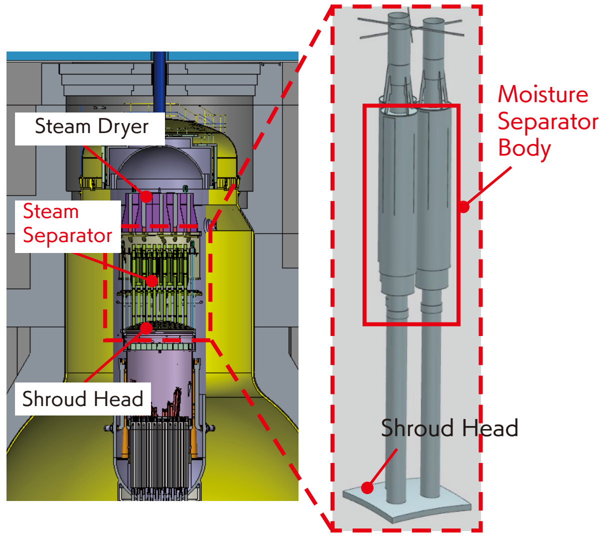
For prior confirmation

Full-scale investigation

▲Investigation equipment

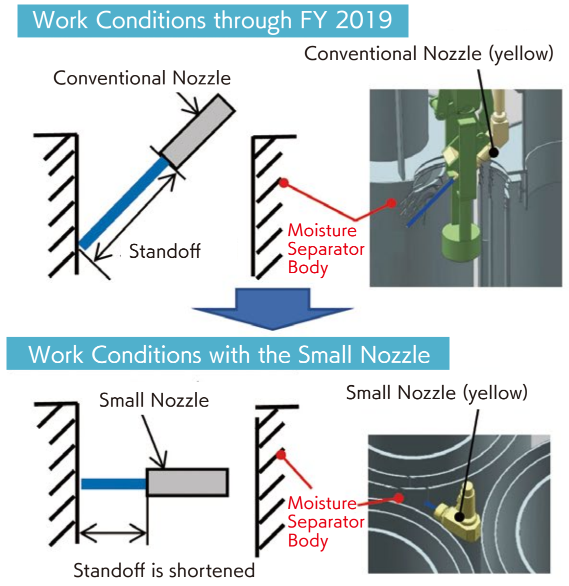
2 Developing a top-access investigation method (improving processing techniques)

Of the core technology for the top-access investigation method, IRID has made some improvements related to processing techniques. In FY 2020, sights on the body of the water separator were set (see Figure 1) inside the reactor internal structure, which is one of the targets for processing. The cutting nozzle of the abrasive water jet (AWJ) was made smaller then worked to determine the optimal parameters (spray angle, cutting location, etc.) as processing techniques were studied that can reduce secondary waste (material that was abraded etc.) (refer to Figure 2 and Table 1). Preliminary estimates show that approximately 8 tons of material was abraded in FY 2019. However, this number was only 0.33 tons in FY 2020, so being able to drastically reduce the amount of abraded material is anticipated.



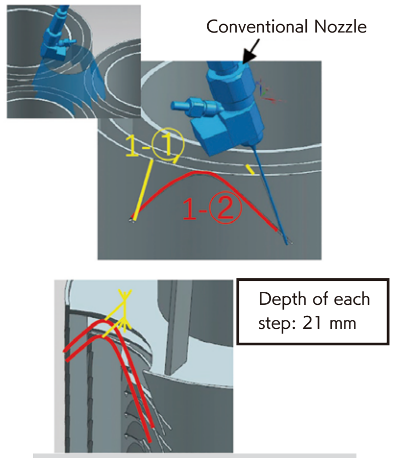
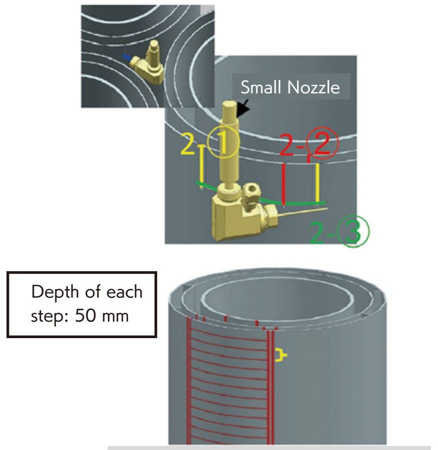
Moisture Separator (only three cylinders displayed)

▲Moisture Separator (Figure 1)



▲Optimization of spray angle etc. (Figure 2)

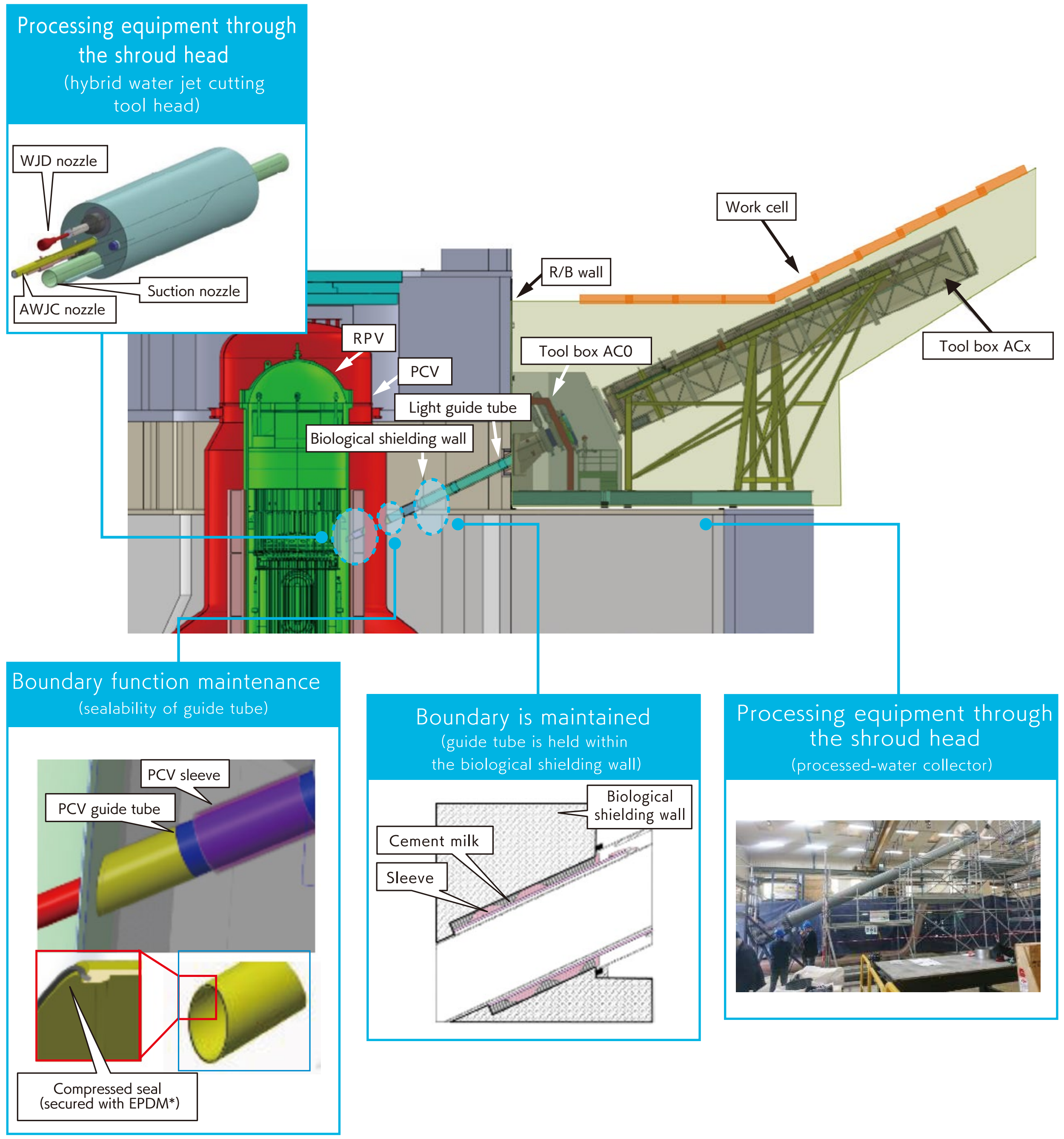
▼Comparison of AWJ cutting procedures (Table 1)

Item	Cutting Procedure through FY 2019	Cutting Procedure with Small Nozzle
Cutting Shape	•The AWJ sprays diagonally downward from the steam separator and makes repeated cone-shaped cuts down the entire length of the separator.  Cutting the Steam Separator	•The AWJ is sprayed from directly above the center of the steam separator's three cylinders as the number of steps are increased to cut the entire separator.  Cutting the Steam Separator
Number of Steps	78 (depth of 21 mm)	33 (depth of 50 mm)
Length of Cuts	75mm	31mm

3 Developing a side-access investigation method

When using the top-access investigation method, there could be delays in the investigation due to interference with other work being conducted on the operating floor and in other areas. Therefore a goal of conducting this investigation at an earlier date than the top-access investigation method was set. Regarding the method for accessing the core from the side, IRID studied access routes, assessed work risks, and considered the applicability of the method from the viewpoint of each unit. As a result, it was chosen to create an access route at Unit 2 by making a hole in the top of the core via the roof of the air-conditioning room on the east side of the reactor building. Holes were created in surfaces such as the biological shield wall, the PCV, and the RPV and developed equipment that inserts the investigation equipment into the reactor. All this was done while maintaining the PCV boundary.

IRID conducted element testing on the core technologies for the side-access investigation method: ① the processing equipment up to the shroud head, ② the treatedwater collection equipment, ③ the tools for the guide tube, and ④ the guide-tube retention mechanism within the biological shield wall. The feasibility of those elements were verified and design information that can be used to determine equipment specifications was obtained.



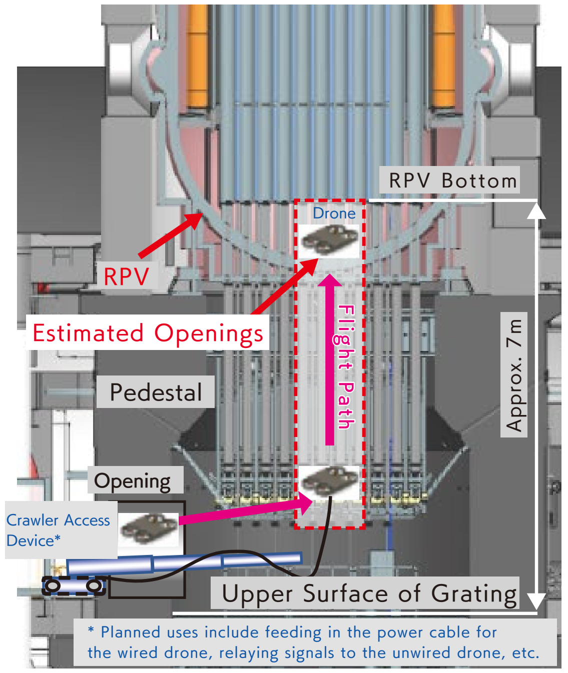
*EPDM: Ethylene propylene diene monomer rubber

4 Developing a bottom-access investigation method

IRID studied a bottom-access investigation method to obtain data earlier than the top- and side-access investigation methods, which involve the creation of holes; to apply the results of existing technological development as much as possible; and to obtain visual data and dose-rate information. For this study, the technologies from completed and ongoing development projects were compiled as well as data on the environmental conditions that can be inferred from the results of surveys of the PCV interior and other work. The technologies that need to be developed for each unit were then identified.

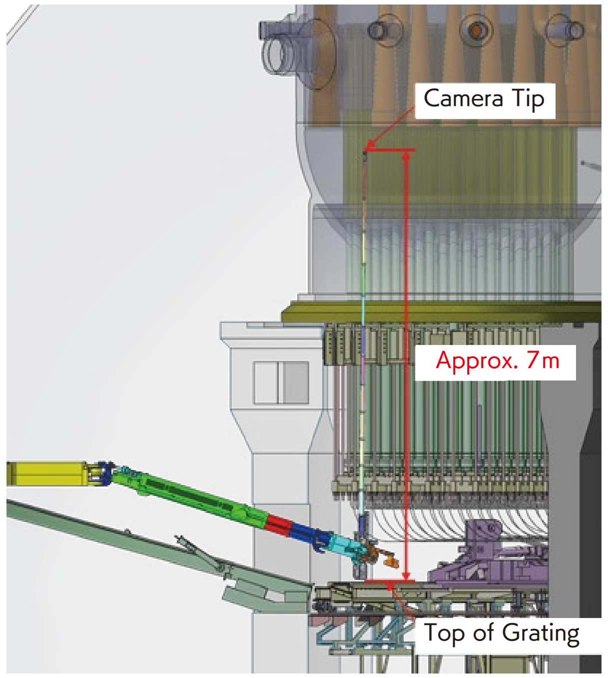
Since the holes in the bottom of Unit 1's RPV are believed to be large in diameter, it was decided to utilize the crawler access equipment currently being developed by the PCV detailed investigation project as methods for using drones were developed (wired and wireless) to gain access to the RPV (Figure 1). To assess the feasibility of using drones to access the RPV interior, several simple flight tests were conducted. For the wired drone, a drone and a cable drum was chosen, while the wireless drone would have an extendable rod attached to it (Figure 2).

The holes at the bottom of Units 2 and 3 are thought to be small, so it was decided to establish a plan for developing methods of accessing the RPV and to give telescoping capabilities to the arm-type access equipment that will be used to perform the gradually expanding retrieval of fuel debris (Figure 3). Several simple testing was conducted to determine feasibility and evaluated the possibility of a telescopic-type access equipment (Figure 4).

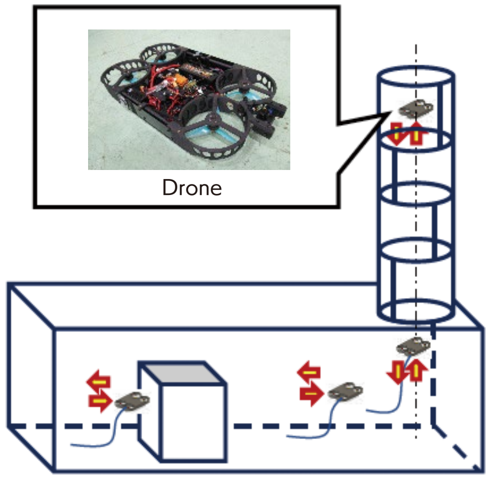


* Planned uses include feeding in the power cable for the wired drone, relaying signals to the unwired drone, etc.

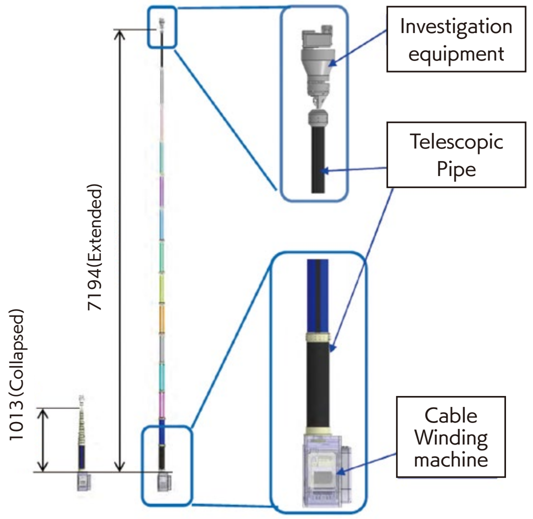
▲Accessing Unit 1 with a drone (Figure 1)



▲2Accessing Units 2 and 3 with a telescoping pipe (Figure 3)



▲Drone flight test at Unit 1 (Figure 2)



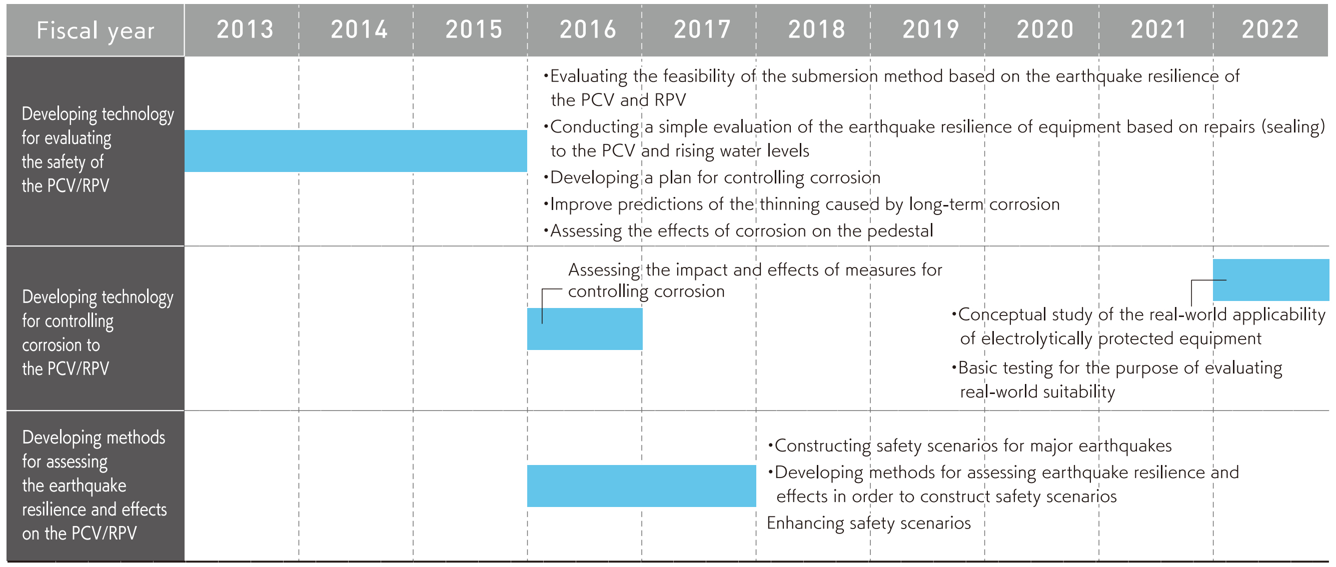
▲Telescoping equipment (Figure 4)

Integrity evaluation of PCV/RPV and development of corrosion control technology

Based on an earthquake-resistance assessment that considers factors such as corrosion, evaluate the integrity of the PCV/RPV and develop technology that prevents corrosion

- ■ Evaluated the integrity of PCV/RPV based on an assessment of earthquake resistance that considers the impact of falling fuel debris and aged deterioration caused by corrosion
- ■ In order to determine the feasibility of the full-submersion method, IRID developed a simple evaluation method to quickly assess earthquake resistance based on the various on-site conditions that are expected
- ■ Developed a corrosion inhibitor as a replacement for the nitrogen enclosure and evaluated its applicability for practical use
- ■ Identified the damage to critical equipment inside the PCV/RPV when a powerful earthquake occurs as well as aftereffects
- ■ Considered countermeasures for preventing or controlling the above effects and confirmed their validity through an assessment of earthquake resistance

Research and development progress



•Evaluating the feasibility of the submersion method based on the earthquake resilience of the PCV and RPV
•Conducting a simple evaluation of the earthquake resilience of equipment based on repairs (sealing) to the PCV and rising water levels
•Developing a plan for controlling corrosion
•Improve predictions of the thinning caused by long-term corrosion
•Assessing the effects of corrosion on the pedestal

Assessing the impact and effects of measures for controlling corrosion

•Conceptual study of the real-world applicability of electrolytically protected equipment
•Basic testing for the purpose of evaluating real-world suitability

•Constructing safety scenarios for major earthquakes
•Developing methods for assessing earthquake resilience and effects in order to construct safety scenarios
Enhancing safety scenarios

Background

The severe events caused by the Great East Japan earthquake exposed the reactor pressure vessels (RPVs) and primary containment vessels (PCVs) at Fukushima Daiichi NPS to high temperatures, seawater, falling fuel debris, and other hazards. There are concerns that structural materials have degraded as a result. A plan is needed to maintaining the structural integrity of the PCV and RPV over the long term, while fuel debris is being retrieved from the reactor core.

Purpose

IRID evaluated the structural integrity of the PCV/RPV based on an assessment of earthquake resistance that considered the impact of falling fuel debris and aged deterioration caused by corrosion. In addition to studying the retrieval of fuel debris and the repair and sealing of the PCV from the viewpoint of earthquake resistance, countermeasures for preventing or controlling corrosion were examined and applied that knowledge to preserving the structural integrity of the PCV and RPV.

The damage to critical equipment inside the PCV/RPV and their aftereffects when a major earthquake strikes were identified while working to understand the conditions that will be encountered when retrieving fuel debris, such as the water level inside the PCV and the location of essential machinery within the reactor building. Furthermore, IRID considered countermeasures for preventing or controlling those effects and confirmed their validity through an assessment of earthquake resistance.

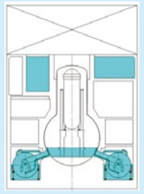
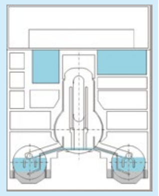
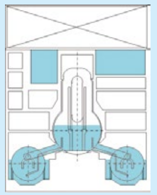
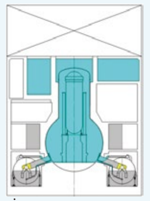
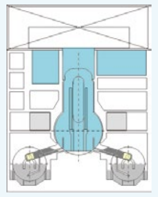
1 Evaluating the feasibility of the ful-submersion method based on the earthquake resistance of the PCV and RPV

As for plant conditions that reflect the latest repairs and other planned work, an Earthquake Response Analysis Model for the reactor building and large equipment was created, taking into account two different cases: retrieving fuel debris above water (at the current water level) and retrieving it while completely submerged (Table 1). Using this model, the earthquake load (shear and moment forces etc.) was calculated on specific points of the PCV and RPV at each plant to assess the earthquake resilience of those vessels.

The feasibility of retrieving fuel debris while above water and while completely submerged (top access) was studied, then a detailed earthquake evaluation was conducted for points that had weak results.

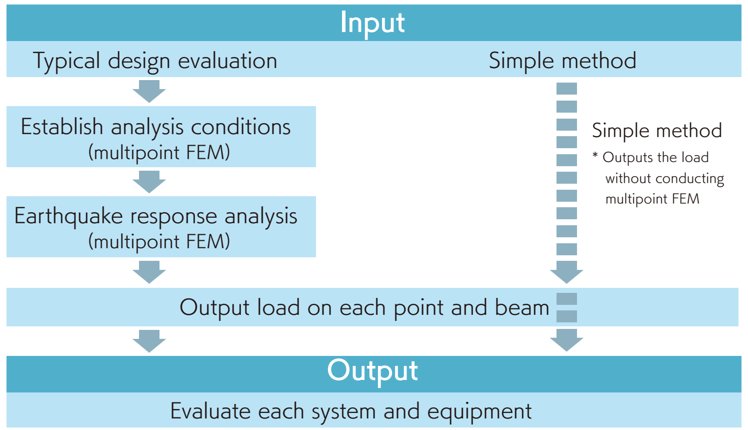
A detailed earthquake assessment that assumed the suppression chamber (S/C) support columns will not be reinforced was also conducted.

▼Case study on earthquake resistance including the latest updates on repairs and other conditions at the plant (Table 1)

Unit / Case example	Unit 1	Unit 2	Unit 3
Case 1 (Partial submersion: current water level)	 •Future estimates: parameters (10 years, 15 years, and 40 years later) •Damage model of reactor building •D/W water level: Approx. 2.9 m •In S/C: Full submersion •Torus room: OP3680 •Vent pipes: Full submersion •Vacuum-break pipes: Full submersion •Additional facilities on the operation floor: Parameters (N/A, approx. 5,100 t and approx. 6,100 t) •Cell installation: N/A •Damping constant: Parameters (1) Concrete: 7%, steel 4% (regulatory guide) (2) Concrete 5%, steel 1% (for building design) •Seismic waves: Currently Ss	 •Future estimates: Parameters (15 years and 40 years later) •Damage model of reactor building •D/W water levels: Approx. 0.6 m •In S/C: Concrete OP-1050 Water levels OP3100 •Torus room: Concrete (pin position of the upper column support: OP.-100) •Vent pipes: Water flows in lower section •Additional facilities on the operation floor: Approx. 4,710 t •Cell installation: N/A •Damping constant: Parameters (1) Concrete 7%, steel 4% (regulatory guide) (2) Concrete 5%, steel 1% (for building design •Seismic waves: Currently Ss	 •Future estimates: Parameters (10 years, 15 years, and 40 years later) •Damage model of reactor building •D/W water level: Approx. 6.5 m •In S/C: Fully submerged •Torus room: OP.3200 •Vent pipes: Fully submerged •Additional facilities on the operation floor: Parameters (N/A, approx. 4,710 ton) •Cell installation: N/A •Damping constant: Parameters (1) Concrete 7%, steel 4% (regulatory guide) (2) Concrete 5%, steel (for building design) •Seismic waves: Currently
Case 2 (full submersion)	 •Future estimates: Parameters (15 years and 40 years later) •Damage model of reactor building •D/W water level: Full submersion in the well •In S/C: Concrete OP. 3570 : Concrete (pin position of the upper column support: OP. 2140) •Vent pipes: consider repairs •Vacuum-break pipes: consider repairs •Additional facilities on the operation floor: Approx. 6,100 •Cell installation: Yes •Damping constant: Parameters (1) Concrete 7%, steel 4% (regulatory guide) (2) Concrete 5%, steel 1% (for building design) •Seismic waves: Currently Ss	•Future estimates: Parameters (15 years and 40 years later) •Damage model of reactor building •D/W water level: Full submersion in the well (approx. 35 m, OP. 39920) •In S/C: Concrete OP1900 •Torus room: Concrete (pin position of the upper column support: OP.-100) •Vent pipes: consider repairs •Additional facilities on the operation floor: Approx. 4710 t •Cell installation: Yes •Damping constant: Parameters (1) Concrete 7%, steel 4% (regulatory guide) (2) Concrete 5%, steel 1% (for building design) •Seismic waves: Currently Ss	Exemplified by Unit 3 

2 Simple assessment of earthquake resistance based on PCV repairs (plugging leaks) and rising water levels

After identifying and selecting the parameters that affect the earthquake response analysis (the water level inside the PCV etc.), analyses for the different parameters were conducted, determining how the response to earthquake load changed as the parameters were adjusted. IRID also developed a simple method for evaluating the earthquake resistance of equipment based on these combinations of factors (Figure 1). The results of this simple method were compared to those of a typical dynamic response analysis; the results were generally identical, confirming the validity of the simple evaluation method.



▲Evaluation process for typical earthquake assessments and the simple method (Figure 1)

3 Developing countermeasures for preventing corrosion

IRID has developed technology (a corrosion inhibitor) for controlling corrosion and evaluated its applicability for practical use.

- **Using electrochemical analysis to evaluate the localized anti-corrosion properties of the corrosion inhibitor**

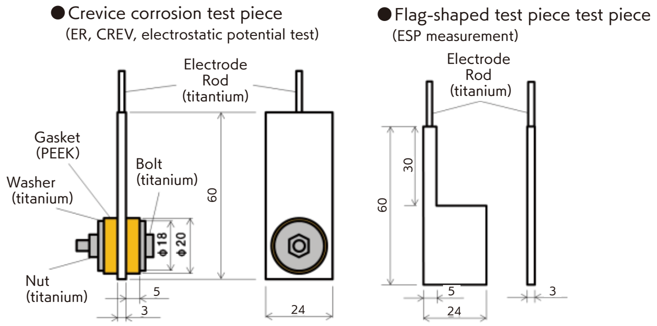
To evaluate the anti-corrosion properties of the main carbon-steel structural materials, electrochemical analyses (measurement of the repassivation potential for crevice corrosion, the rest potential, and the electrostatic potential for crevice corrosion) was conducted in an environment with γ radiation and one with no radiation, then selected a corrosion inhibitor that does not allow localized corrosion to form (Figures 2 and 3).

- **Evaluating the effects of a phosphorous-based corrosion inhibitor adhering to high-temperature surfaces**

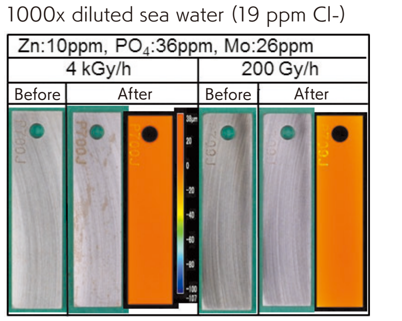
To evaluate the effects of a phosphorous-based corrosion inhibitor adhering to high-temperature surfaces, a batch test and a flush test was conducted to verify things such as the temperature at which the substance adheres. What happens when a phosphorous-based corrosion inhibitor is combined with a sterilizing agent was tested, verifying that doing so has no negative effects.

- **Assessing the impact on water-treatment equipment**

IRID has evaluated the effects of the corrosion inhibitor on water-treatment equipment, confirming that reducing those effects will require to dilute or filter collected water to bring the concentration of corrosion inhibitor in the processed water lower than what it is when it enters the PCV.



▲Construction of electrode for corrosion test piece (Figure 2)



Corrosion Inhibitor: Zinc/Sodium molybdate mixed with phosphate

▲Testing the effectiveness of the corrosion inhibiter under γ radiation (Figure 3)

4 Assessing the effects of corrosion on the pedestal

IRID tested the exposure to the cylinder test piece, the scaled-down test piece (Figure 4), and the block test piece both in and out of the water and under high-temperature heating. Data was acquired from concrete strength tests, rebar corrosion tests, and other sources and valuable knowledge for future study was gained.

A load was applied to the cylindrical test piece that simulated the RPV pedestal after the accident, when it was exposed to high temperatures and was inundated with coolant. Through this, we verified things like the durability of concrete structures degraded by high temperatures and the effects on their damage characteristics.

(The cylindrical test piece was dried, heated for a long period of time at 400 ℃ and 800 ℃, then immersed in water) Outer Diameter: 1,240 mm; Inner Diameter: 834 mm; Thickness: 200 mm

▲Testing the durability of the RPV pedestal (miniaturized testing equipment) (Figure 4)

5 Improve predictions of the thinning caused by long-term corrosion

To improve the accuracy of predicting the amount of thinning due to corrosion, IRID conducted a long-term corrosion test over a period of 10,000 hours (Figure 5). The liquid components that originated in fuel debris and core concrete as well as their corrosive effects were studied, acquiring new knowledge in those areas.

▲Conducting the long-term corrosion test (Figure 5)

6 Establishing safety scenarios for large earthquakes

Addressing the potential risks that can occur from damage to heavy equipment during a large earthquake, the dynamic responses that must be prepared and the facility policies that are needed prior to the start of fuel debris retrieval were organized then created safety scenarios (protocols for maintaining safety or responding to accidents). To create these scenarios, the following methods for assessing earthquake resistance and effects were also developed.

---

①Developed methods for assessing the earthquake resistance and effects on the suppression chamber (S/C) support columns

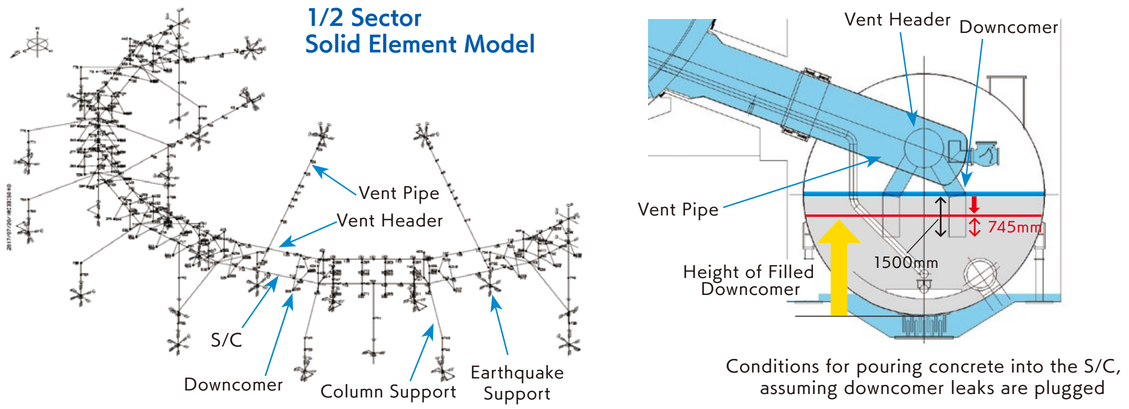
To evaluate the earthquake resistance after plugging leaks in the S/C, an analytical model that links the vent pipe and the S/C system (Figure 6) was created then a time-history response analysis was performed.

For the critical evaluation points — the column supports, earthquake supports, and vent headers—an FEM model was also created and an elasto-plastic analysis was conducted to verify the conditions for filling the downcomer.

②Developed methods for assessing the earthquake resistance and effects on the pedestal

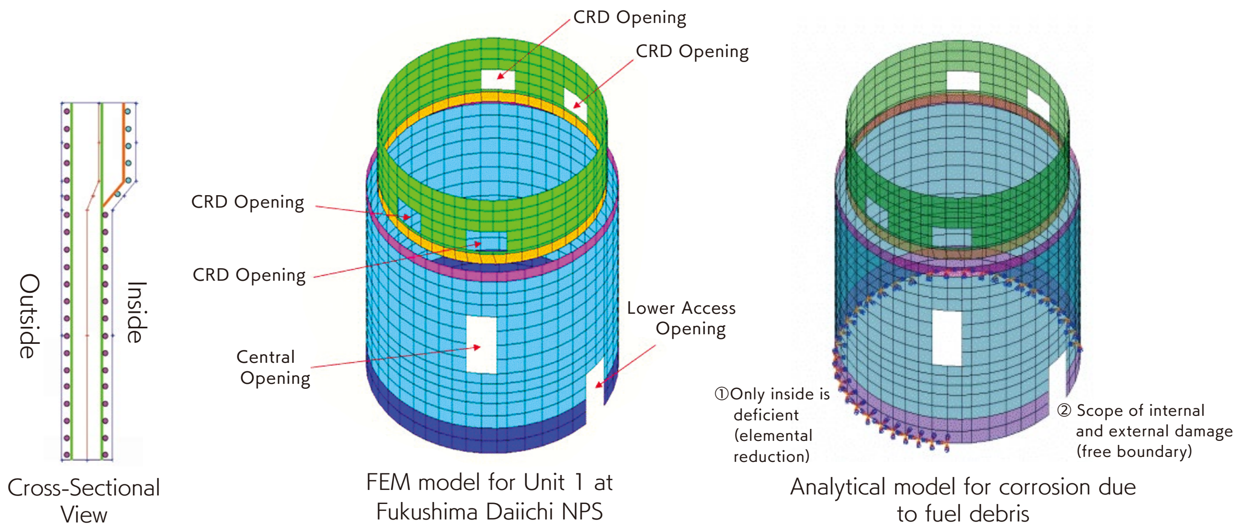
IRID developed the assessment methods below and obtained material data to evaluate the presumed history and distribution of the pedestal's temperature as well as the effects of fuel debris on corrosion.

- A method that combines a simple assessment which uses the amount of corrosion of RPV pedestral as a parameter and a detailed assessment which uses a 3-D FEM elasto-plastic analytical model (Figure 7)
- A method that assesses earthquake response using a model that links the reactor building and large equipment and sets as its parameter the decline in rigidity presumed to occur due to corrosion of the RPV pedestal
- IRID also studied plans for verifying (through analysis, testing, etc.) high-temperature corrosion and strength degradation in order to estimate the weakening of rebar inside concrete and to improve the above assessment methods. The following detailed analysis and material testing was then performed.
- Time-history analysis of earthquake response for the S/C support columns in Unit 1
- Obtained data via PCV material testing that considered the temperature history during the accident



Conditions for pouring concrete into the S/C, assuming downcomer leaks are plugged

▲Time-history earthquake response model (Units 2 and 3) and conditions for linkage analysis of vent pipe and S/C system (Figure 6)



Cross-Sectional View

FEM model for Unit 1 at Fukushima Daiichi NPS

Analytical model for corrosion due to fuel debris

▲Development of a method for assessing the earthquake resistance of the RPV pedestal through fuel debris corrosion (Figure 7)

IV

Decommissioning Research and Development

The Water Circulation System and Repairing the PCV

This research aims to provide confinement functions in PCV and maintain the stability state for preventing the spread and dispersion of radioactive material, radiation shielding and maintaining cooling functions, therefore, the repair technology for leakage points of PCV was developed.

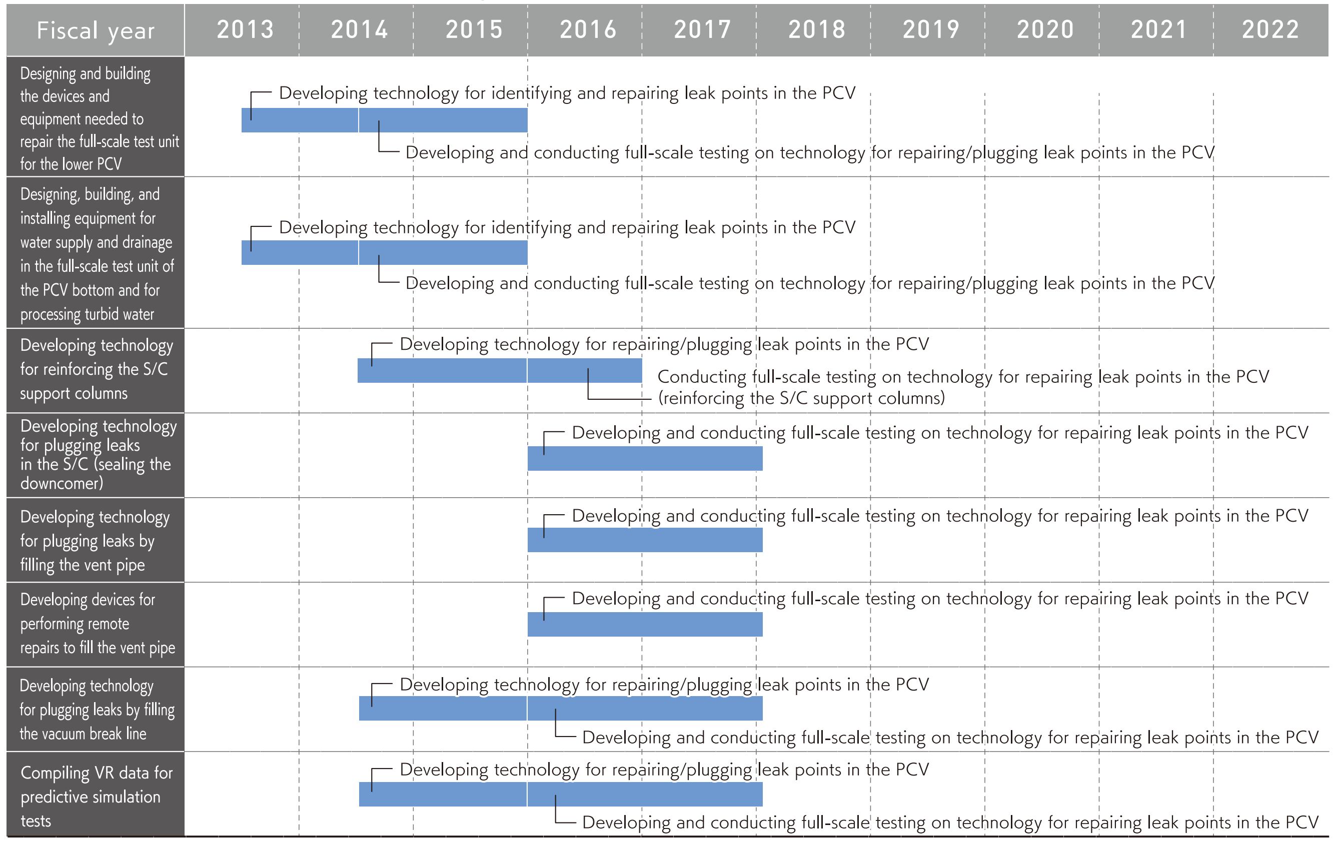
Additionally, various technical issues have been studied and revised technological specifications for monitoring of the water circulation system in the suppression chamber (S/C), the safety functions required to establish an access route to stop water leakage in S/C, reliability, feasibility of confinement function test, earthquake resistance and long-term integrity, etc.

Development of repair technology for PCV and full-scale test

Repairing leaks in the PCV in preparation for fuel debris retrieval

- Designed and manufactured equipment and system required to repair the full-scale test unit of the PCV bottom
- Designed, manufactured, and installed equipment for water supply and drainage in the full-scale test unit of the PCV bottom and for processing slurry
- Developed technology for reinforcing the suppression chamber (S/C) support columns
- Developed technology for injecting fillings to stop leaks in the S/C
- Developed technology for injecting fillings in the vent pipe to stop leaks
- Developed remote-operated repair equipment for filling vent pipes
- Developed technology for filling the vacuum break line to stop leaks
- Compiled VR data for predictive simulation tests

Research and development progress



Background

To decrease the radiation dose during the retrieval of fuel debris, a full-submersion method to submerge the PCV was considered. Since the PCV was leaking due to damage sustained during the accident, it had to be repaired and sealed; however, the interior of the reactor building is highly radioactive and narrow environment. Therefore methods and equipment for repairing the PCV remotely needed to be developed.

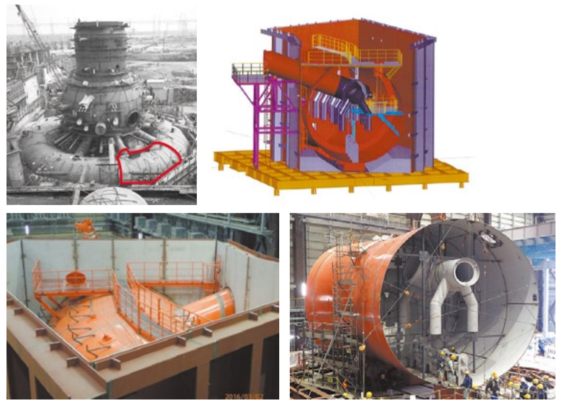
Purpose

A goal of this project was to develop technology that could repair and seal locations in the lower PCV—the S/C and the vent pipe—that would presumably leak if the PCV was flooded with water. Since filling the S/C with water will greatly increase its weight, it was also aimed to develop technology for reinforcing the S/C support columns to alleviate concerns about earthquake resistance.

In addition to developing element technology, this project also verified that the developed technology (such as procedures and remote equipment) can be applied at the site and performed a full-scale test for the purposes of operational training etc. This project was conducted at the Naraha Center for Remote Control Technology Development under a joint proposal with the Japan Atomic Energy Agency.

1 Designing and building the devices and equipment needed to repair the full-scale test unit for the lower PCV

IRID designed and manufactured a full-scale test unit that simulates the bottom of Unit 2's PCV at Fukushima Daiichi NPS. The test unit were assembled at the Naraha Center for Remote Control Technology Development (Photo 1) . To confirm the workability of the equipment for injecting concrete to reinforce the S/C support columns (which was developed as part of the repairs to PCV leaks), a full-scale test using water was also conducted (Photo 2).



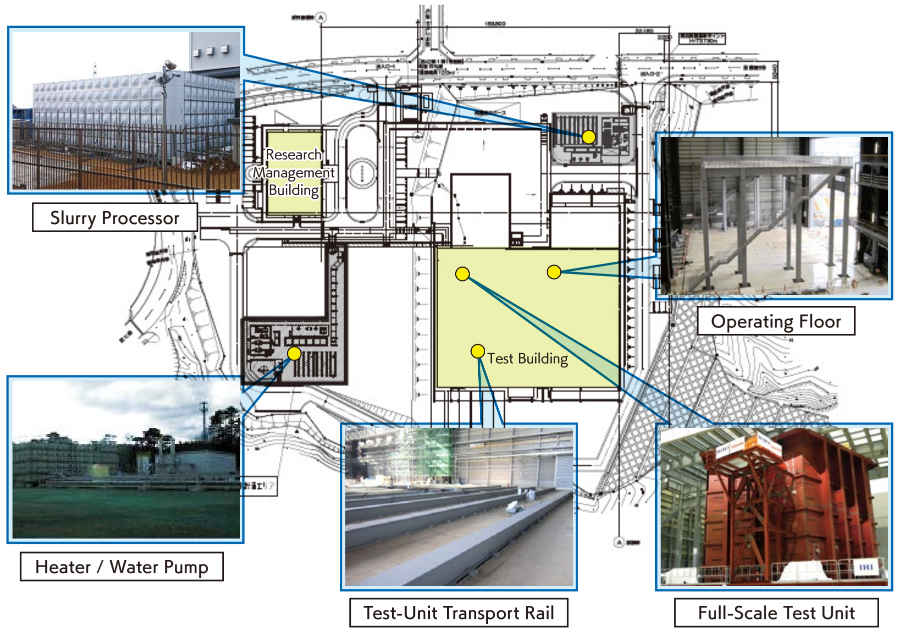
▲Upper left: primary containment vessel (when building Unit 1; simulated S/C is in the red box); Upper right: full-scale S/C (1/8 sector) CAD drawing; Lower left: vent pipe and S/C; Lower right: assembled S/C shell and downcomer (Photo 1)

▲ Upper left: concrete-injecting equipment; Upper right: image from end monitoring camera on concrete-injecting equipment; Lower left: mixer; Lower right: effect of nozzle on concrete-injecting equipment (Photo 2)

2 Designing, building, and installing equipment for water supply and drainage in the full-scale test unit of the PCV bottom and for processing turbid water

For the full-scale test, the following equipment were installed to simulate the range of possible dimensions, temperatures, etc. in the environments within Units 1–3 of Fukushima Daiichi NPS (Figure 1).

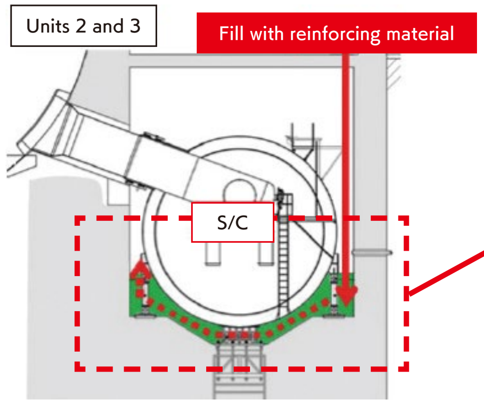
- Increasing temperature and supplying water: equipment that supplies accumulated water at its actual temperature
- Treating turbid water: equipment for processing drainage water that includes sealer (a grout containing cement)
- Operating floor: a workspace for installing the various machinery needed to seal leaks
- Test-unit transport rail: a rail system for transporting the test unit (which weighs approximately 5,400 tons)



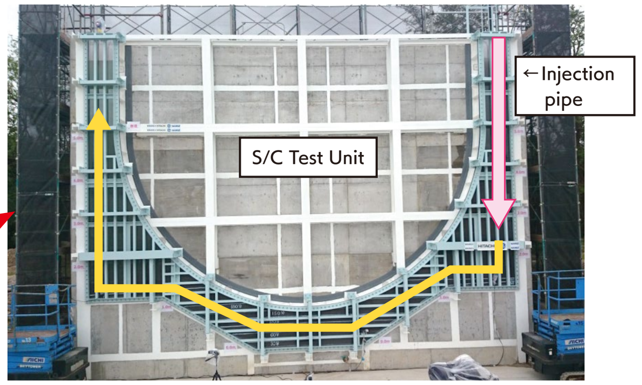
◀Various equipment assembled for the full-scale test (Figure 1)

3 Developing technology for reinforcing the S/C support columns

For the S/C support columns, the plan is to fill them with concrete to prevent the S/C from leaking. However this will increase their weight, so they must be filled with mortar that has high fluidity to ensure resilience to earthquakes. Various tests were conducted that highly fluid mortar material were poured into six to eight insertion points in the first subfloor of the reactor building, so that it flows throughout the entire perimeter of the torus room. Flow tests were conducted with a maximum distance of 20 meters, build-up tests, simulations, etc. then a 1:1 scale test was performed which showed that the target features can be expected to be achieved (Figures 2–7).

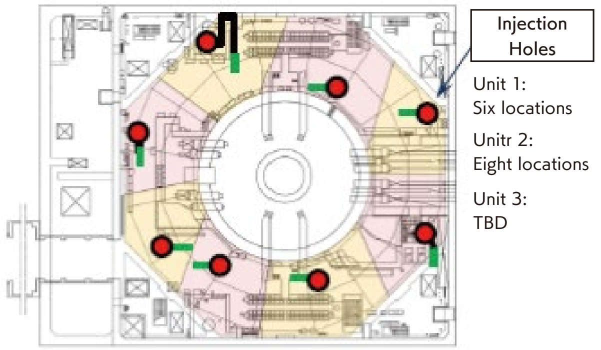


▲Fill area for reinforcing S/C support columns (Figure 2)



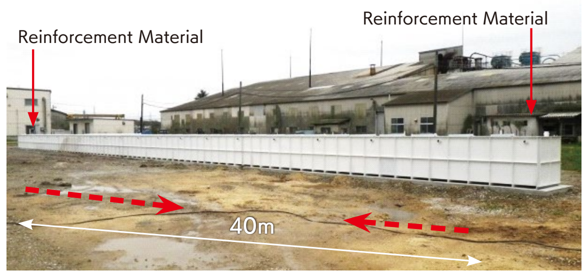
▲S/C support column validation test (1:1 scale; simulates Units 2 and 3) (Figure 3)

It was confirmed that the reinforcement material flows through the fill pipe and wraps around the bottom of the S/C to uniformly fill the opposite side.



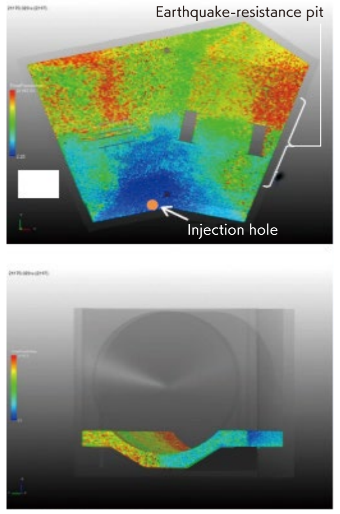
▲Injection hole locations imagined for the reactor building's first floor (Figure 4)

Maximum interval between injection holes: approximately 20 meters



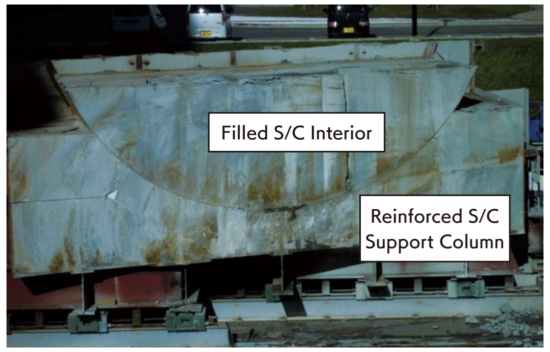
▲Long-distance flow test (Figure 5)

It was confirmed there to be no change in the reinforcement material's quality even after it was inserted from both ends and allowed to flow for 20 meters.



◀Simulation analysis of filling with reinforcement material (Figure 6)

Taking into account both the results of the full-scale fill test and a fluid analysis (complete enclosure model), a strength distribution map was created. This revealed that the compressive strength of the reinforcement material in all areas satisfies that required by assessments on earthquake resistance.

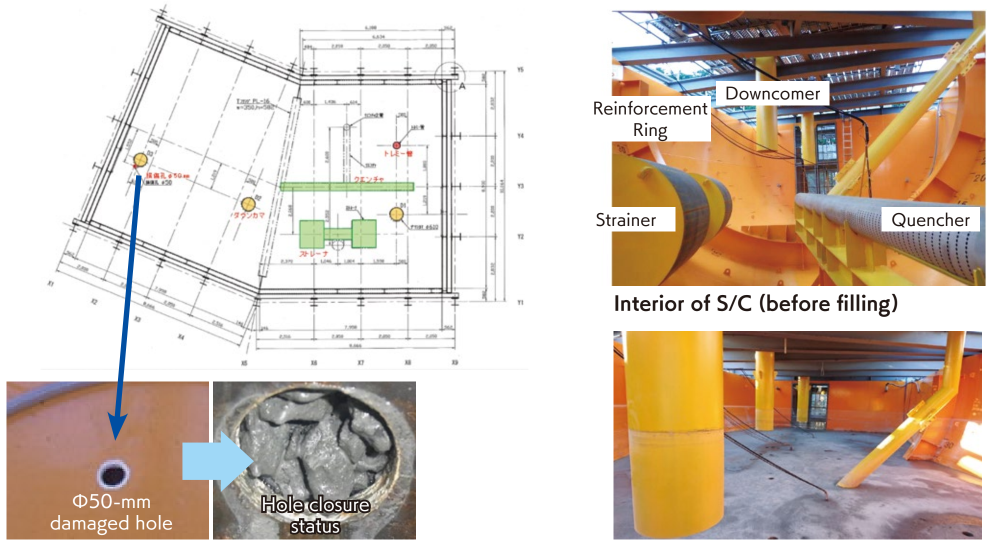


▲Results of filling test at 1:1 scale (Figure 7)

It was verified the state of the filler by making a cross-sectional cut on the test piece after the S/C had been filled.

4 Developing technology for plugging leaks in the S/C (sealing the downcomer)

To inject filling to stop the leaks in the downcomer, quencher, strainer, and other locations within the S/C as well as the Φ50-mm holes that are believed to exist in Unit 2, fill tests, long-distance force feeding tests of the underwater-inseparable concrete, etc. were conducted and a composite material that possessed the required properties was developed. Using the developed material, a seal test on a 1:1 scale model was conducted and its sealing capacity and workability was verified (Photos 8–10).



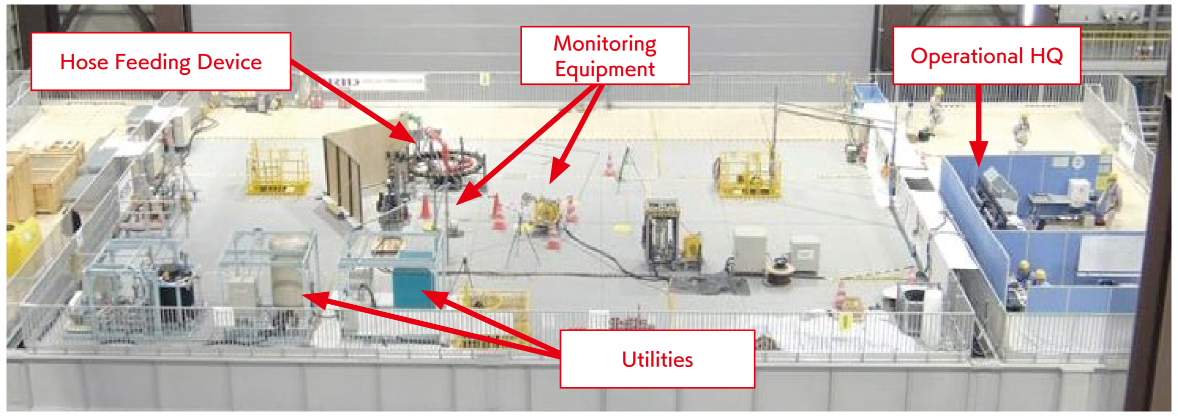
S/C damaged holes (before and after filling)

Interior of S/C (before filling)

Interior of S/C (after filling)

▲Results of S/C water-seal test at 1:1 scale (Photo 8)

To inject filling to stop leaks in the S/C, holes were opened in its upper surface and concrete was injected in. It was verified that the concrete moves over the reinforcement ring and buries the damaged holes, quencher, and strainer to prevent water from flowing out of the S/C.



▲Verifying workability and remote operation (Photo 9)

Filling the S/C interior was conducted remotely from the first floor of the reactor building.

①Hose feeding and collection device

②Hose coiling device

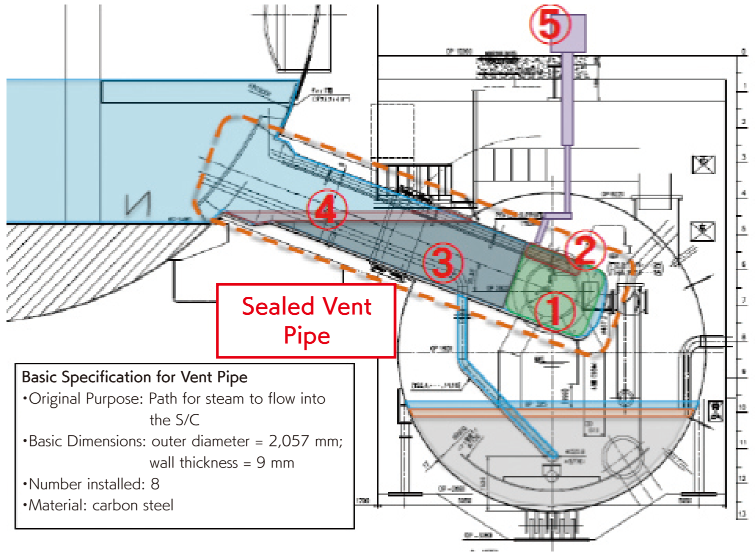
③Hose feed mechanism

▲Equipment for filling the S/C (Photo 10)

To fill the S/C interior, the hose feeding and collection device and other equipment was set up on the first floor.

5 Developing technology for plugging leaks by filling the vent pipe

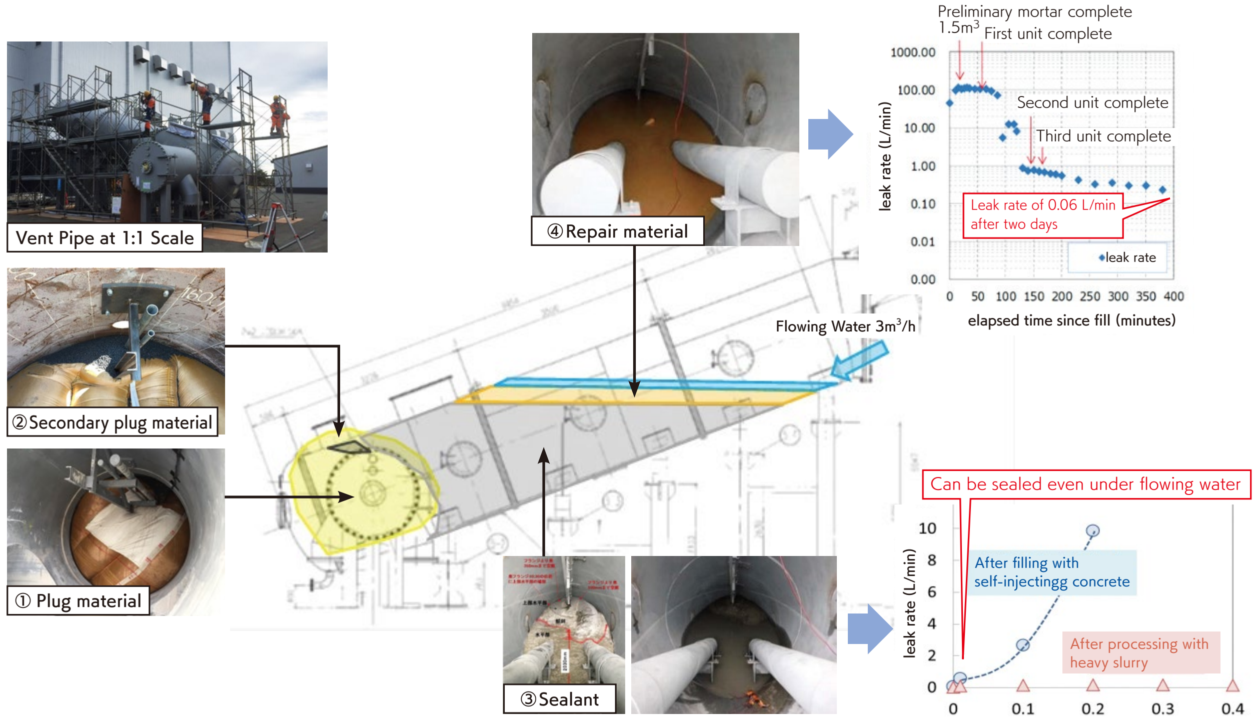
Each of the elements needed to stop leaks in the vent pipe (the main path by which water leaks from the PCV), to prevent contaminated water from entering the S/C, and to create a water level inside the D/W were developed separately then combined and seal tested on a 1:1 scale model: ① the plug material (an inflatable seal), ② the secondary plug material, ③ the sealant (self-compacting concrete that does not separate in water), ④ the repair material (heavy bentonite slurry), and ⑤ the remote-operated repair equipment. Those test results showed that the surfaces no longer leaked when water flowed over them, and we verified via a pressure test that the repaired locations were leakproof up to 0.4 MPa (Figures 11 and 12).



Basic Specification for Vent Pipe
- Original Purpose: Path for steam to flow into the S/C
- Basic Dimensions: outer diameter = 2,057 mm; wall thickness = 9 mm
- Number installed: 8
- Material: carbon steel

▲Overview of the vent-pipe seal test (Figure 11)

① Plug material: forms a temporary barrier for insertion of the sealant. ② Secondary plug material: fills any cracks that remain after the plug material is installed. ③ Sealant: flows into the crevices of the plug material to form a waterproof barrier. ④ Repair material: repairs small cracks etc. caused by external factors and long-term degradation. ⑤ Remote-operated repair equipment: creates holes in the S/C and vent pipe, removes obstacles, and inserts the plug material, secondary plug material, and sealant through remote operation.
Sealing the vent pipe is done through the following process: Using the remote-operated repair equipment (⑤) from the first floor of the reactor building, the plug material (①), secondary plug material (②), sealant (③) and repair material (④) are utilized in turn.

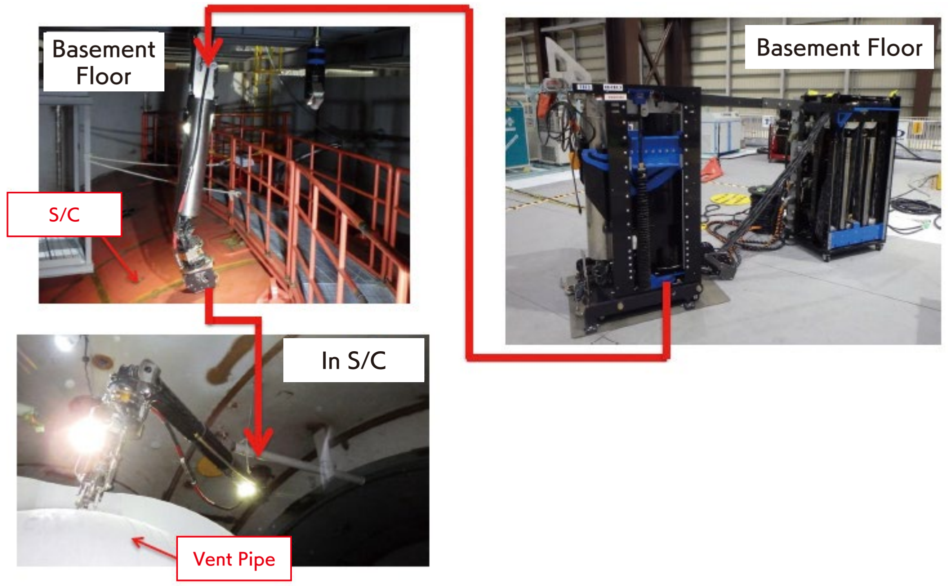


▲Results of seal test with 1:1 scale vent pipe (Figure 12)

Using the remote-operated repair tools and monitoring cameras, the ① plug material and ② secondary plug material was installed in the 1:1 scale test unit then filled it with self-compacting concrete that does not separate in water (the ③ sealant) and verified that it is capable of stopping leaks even under water flowing at a rate of 3 m3/h. The ④ repair material was added and a water-resistance test was conducted in which it was confirmed there to be virtually no leaks at 0.4 MPa.

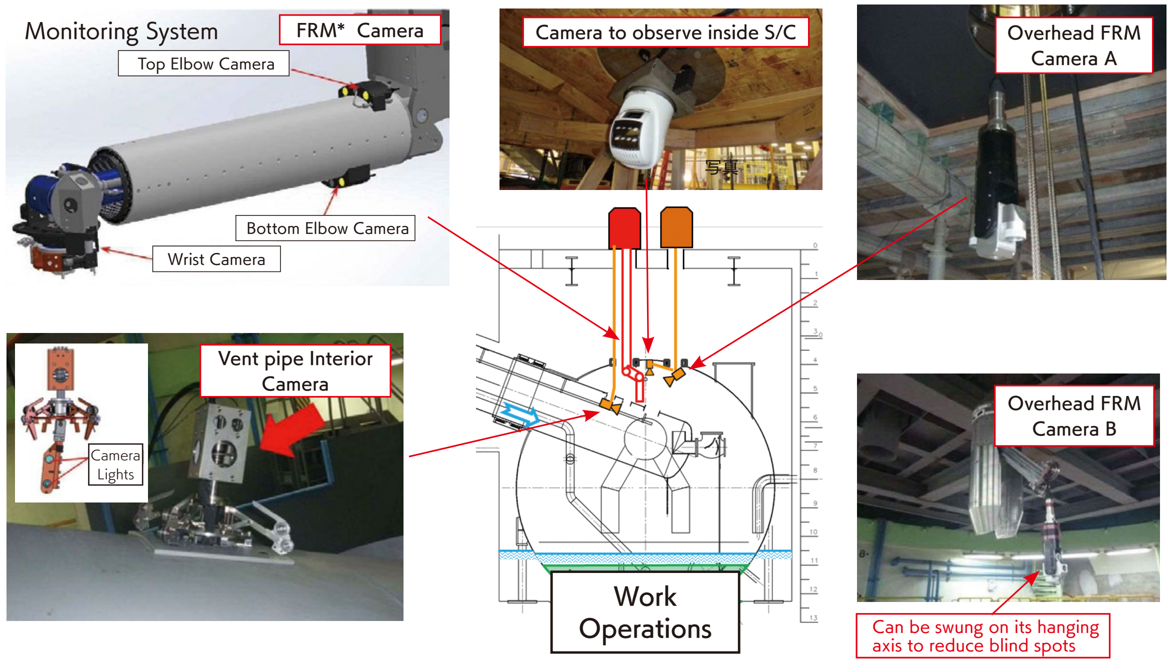
6 Developing devices for performing remote repairs to fill the vent pipe

To achieve a waterproof seal by filling the inside of the vent pipe, IRID first developed remote-operated repair equipment that could complete tasks such as removing obstacles or opening holes in the vent pipe. After designing and assembling the equipment, their workability tests were conducted to verify that they can access the work targets within the real-world environment. Mock-up tests using the remote-operated repair equipment as well as other tools and cameras were conducted, confirming various improvements to areas such as visibility, reliability, and ease of use during installation and collection work.



▲Verifying the workability of remote-operated repair equipment (Photo 3)

The workability test showed that each task unit in the manned work should be completed within 20 minutes and that a series of steps can be accomplished.
The following was achieved.
■ Drafted procedure manual for onsite application, ■ completed a test to verify workability, ■ verified the capability for remote operation,
■ verified the establishment of the procedure manual, and ■ identified challenges in onsite application



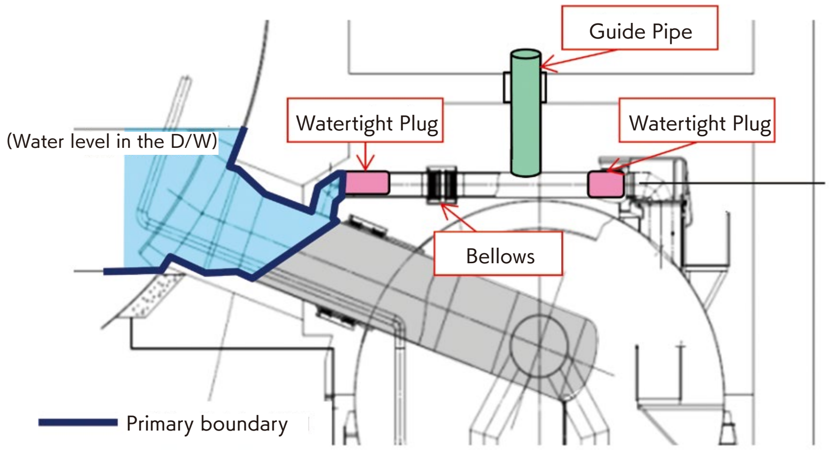
*FRM: Fukushima Repair Machine (remote-operated repair equipment)

▲Monitoring cameras installed on remote-operated repair equipment (Photo 4)

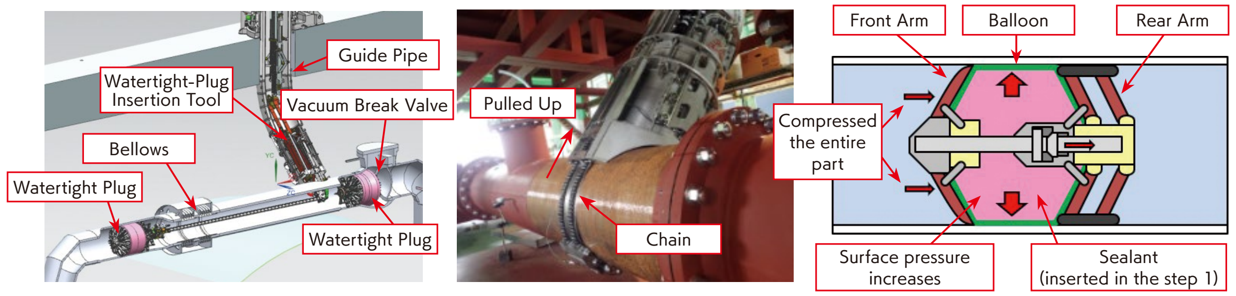
The plan is to use a combination of at least two surveillance systems—the overhead cameras and the cameras attached to the remote-operated repair equipment—to monitor work while it is being performed.
This will allow to understand the three-dimensional positional relationships from multiple angles.

7 Developing technology for plugging leaks by filling the vacuum break line

There are confirmed leaks in the bellows of Unit 1's vacuum break line. As we cannot enter just above the first floor of the reactor building, a full-scale test was conducted in which watertight plugs were inserted via a flexible guide pipe that can enter at an angle. Workability and feasibility was verified by installing a guide pipe, creating a hole in the vacuum break line, and inserting watertight plugs then testing the resistance to pressure (Figures 13–15).



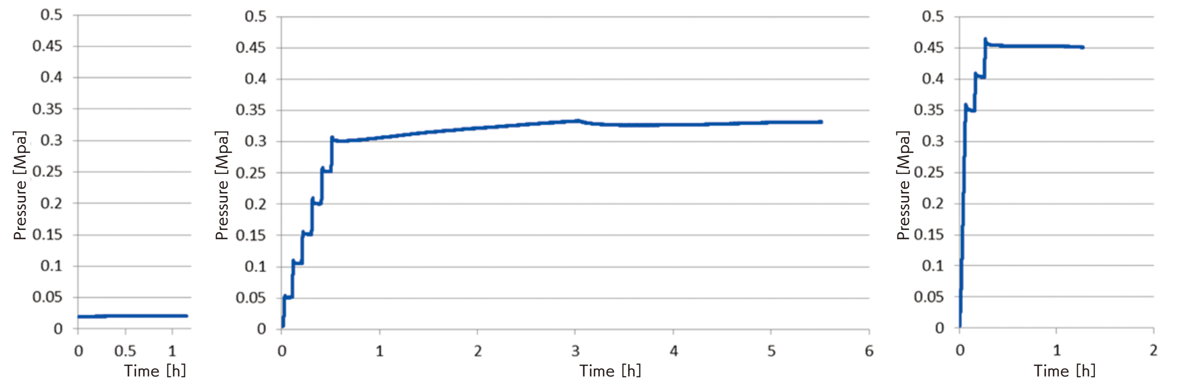
▲Conceptual image of a method to stop leaks from the vacuum break line (Unit 1)



①Drawing of the watertight plugs in the vacuum break line ②Fixing the flexible guide pipe ③Overview of a watertight plug

▲Conceptual drawing of the method to stop leaks from the vacuum break line (Figure 14)

IRID developed a guide pipe that can access the vacuum break line at an angle, since a hole cannnot be opened directly above the line and there are obstacles around the perforations in the ground of the first floor.
The installation performance was also improved, with which the watertight plugs and accompanying insertion tool can be installed via the flexible guide pipe.



0.02 Mpa
Results of water and pressure tests

0.3 Mpa
Results of water and pressure tests

0.45 Mpa
Results of water and pressure tests

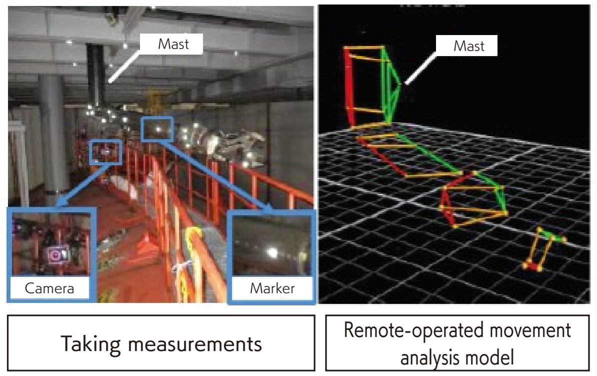
▲Results of pressure test (Figure 15)

Using the flexible guide pipe and improved watertight plugs, a workability test using the 1:1 scale test unit was conducted to verify the method's workability and waterproofing capabilities.
In the leak pressure test, no leaks were observed at 0.45 MPa (completely submerged conditions).

8 Compiled VR data for predictive simulation tests

IRID established an environment that allows operation of the remote manipulator used to stop leaks in the vent pipe to be reproduced on a virtual-reality (VR) system for training purposes. Through that process, the movement of the remote equipment was confirmed by using motion capture and other methods, comparing the movement to that of a VR system that reflected the collected data, then the effectiveness of the VR system was verified through operational training (Photos 5–6 and Figures 16–17).

▲VR system with three-dimensional screen (Photo 5)



▲Measuring movement of remote-operated equipment (photo 6)

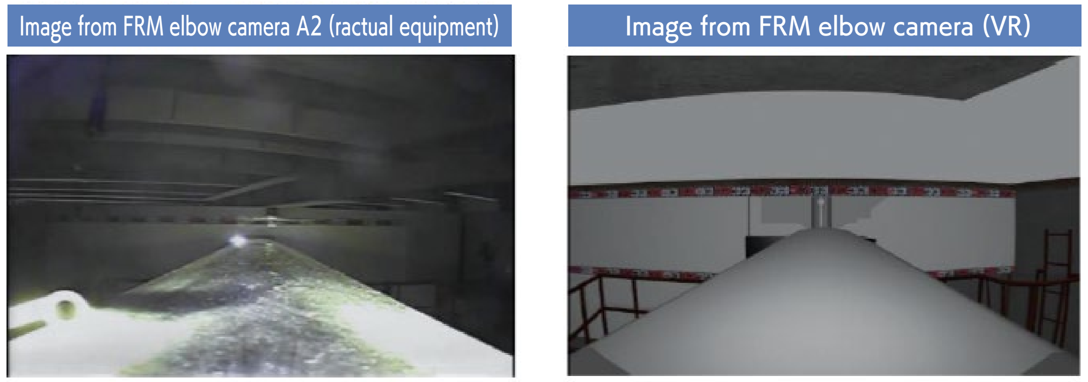
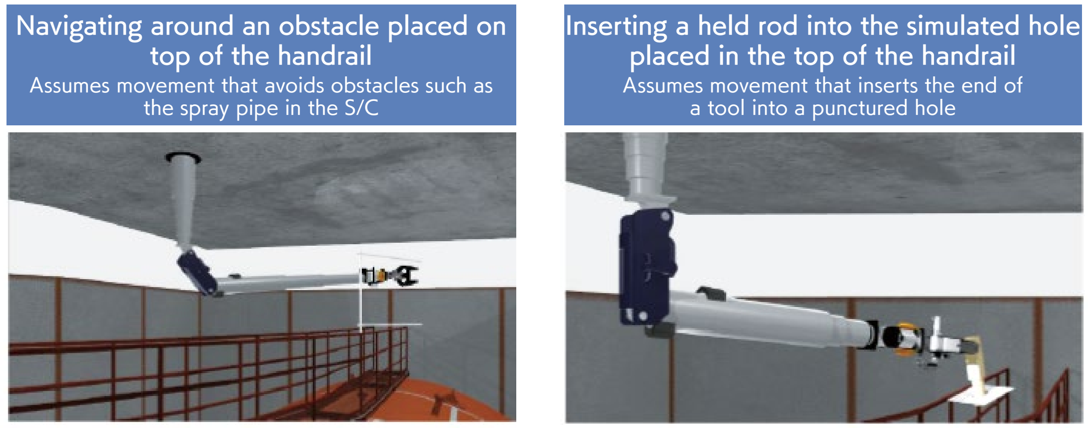


Image from FRM elbow camera A2 (ractual equipment)

Image from FRM elbow camera (VR)

▲Compiling VR data for the predictive simulation test (comparison of actual equipment and VR cameras) (Figure 16)



Navigating around an obstacle placed on top of the handrail
Assumes movement that avoids obstacles such as the spray pipe in the S/C

Inserting a held rod into the simulated hole placed in the top of the handrail
Assumes movement that inserts the end of a tool into a punctured hole

▲Movement test to verify VR operation (Figure 17)

A verification test comparing the performance of the actual machine and the VR system showed that there are no major differences in movement and behavior and that the latter is sufficient for application in operational training.

Development of technology for establishing the water circulation system in the primary containment vessel (PCV) (development / full-scale test)

Establishing and verifying the water intake structure for the dry well (D/W) and suppression chamber (S/C) to establish the water circulation system inside the PCV

- Organized technical specifications for improving the water circulation system inside the PCV; studied work plans and created a development plan
- Developed and verified element technology for connecting to and accessing the PCV interior etc.
- Verified through full-scale testing the technology for connecting to and accessing the PCV etc.

Research and development progress

Fiscal year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Studying technologies related to the water circulation system inside the D/W						▨ Organizing technical specs using the D/W; constructing an access route and planning its maintenance; identifying development challenges and formulating development plans				
Developing and testing technologies related to the water circulation system using the S/C						▨ Organizing technical specs using the S/C; constructing an access route and planning its maintenance; identifying development challenges and formulating development plans				
Developing and testing component technology for connecting to and accessing the PCV interior, etc.						▨	▨	Formulating and executing plans for testing the component technology needed to connect to and access the D/W and S/C, etc.		
Verification through full-scale testing the technology for connecting to and accessing the PCV etc.						▨	▨	Designing, building, and full-scale testing the S/C water intake		

Background

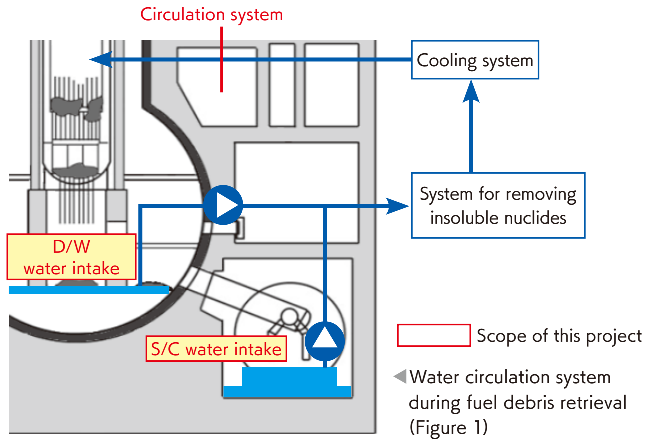
Coolant continues to be circulated into the primary containment vessel (PCV) at Fukushima Daiichi NPS to steadily cool fuel debris, and the retrieval of fuel debris will begin in the near future. That retrieval work will also require to continue to safely manage the water within the PCV. In particular, the work to build circulation lines for continually pumping coolant in during fuel debris retrieval must be done in and around the PCV, so it is needed to develop technology for connecting to and accessing the PCV to complete remote-operated tasks while still keeping it sealed off and safely managing the water inside it.

Purpose

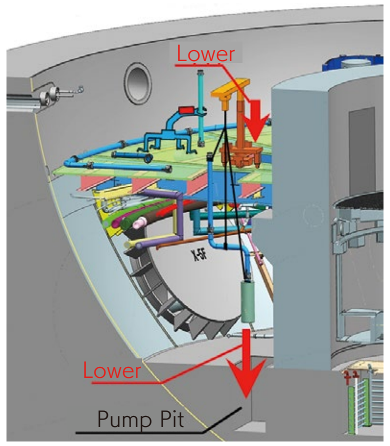
There are issues regarding the water intake of the water circulation system, such as the sealing function of liquid/gas, its safety over the long term, and the possibility of remote installation and operation under a highly radioactive environment. The goal of this project is to develop applicable technology that can connect to and access inside the PCV for the intake of water to the water circulation system.

1 Organized technical specifications for the water circulation system inside the PCV

- When studying technology that can be used to create an access route for water to flow into the D/W and S/C, the actual conditions inside and outside the PCV (the environmental dose rate on the first floor of the reactor building (R/B), predictions of the state of the core, sediment accumulated within the PCV, the water level in the PCV (currently, during work, and when operating the water circulation system) were compiled for each Unit based on the results of investigations conducted thus far.
- Establishing the examination of a water circulation system (Figure 1) that improves the work and systems for retrieving fuel debris and other core structures, the technical specifications related to constructing a PCV access route (shared by the D/W and S/C) as well as design specifications for the D/W water intake was organized, then the candidate locations for the D/W water intake in each Unit were selected.
- After looking at existing technology for creating an access route into the PCV, it was found that it would be possible to utilize methods that were already used to enter the PCV during the on-site verification tests conducted in other projects (Figure 2). At that point, the challenges to creating the route up to the water-intake point (pump pit etc.) in the PCV were 1) how to lower the pump (pipe) to the basement floor via remote operation and 2) how to remotely connect and exchange the pipe (hose).



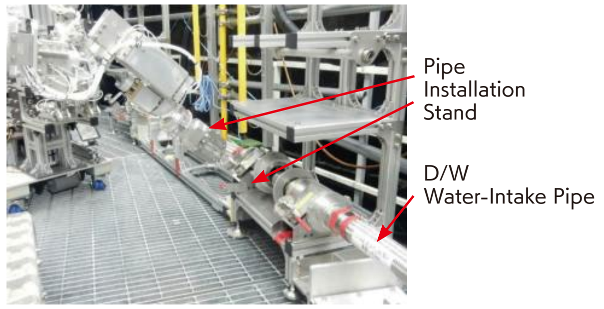
◀Water circulation system during fuel debris retrieval (Figure 1)



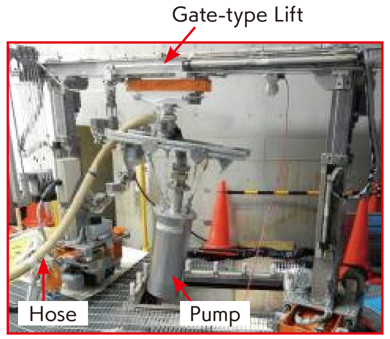
◀Creating the D/W water-intake line (Figure 2)

2 Developing and verifying element technology for connecting to and accessing the PCV interior etc.

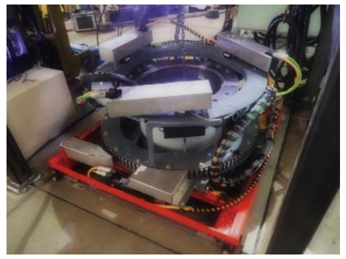
- IRID performed element testing related to the remote deployment of the pipe (hose) in the D/W (Figure 3) as well as the insertion, installation, and collection of the hose at the bottom of the D/W (Figure 4), confirming that such a setup is feasible. At the same time, the engineering challenges that needed to be solved were identified, and plans for dealing with them were studied.
- In addition to developing a plan for testing the application of devices during work and maintenance of the S/C water intake (Figure 5), which was one of the development goals, this project developed prototypes of the necessary equipment: an positioning system (Figure 6), an extension pipe to S/C auto-welder (Figure 7), a bead-removal equipment, and equipment for creating a temporary seal.
- IRID performed element testing on each equipment or unit testing on each prototype and verified that they have the required functionality (Figure 8).



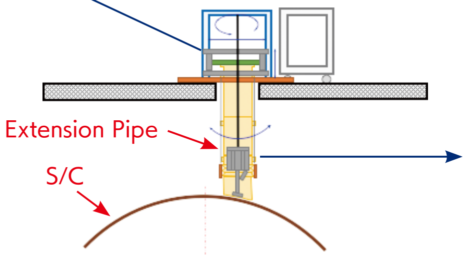
▲Connection of D/W water-intake pipe (Figure 3)



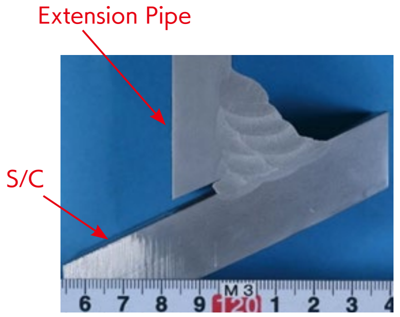
▲Inserting the pump into the D/W basement floor (Figure 4)



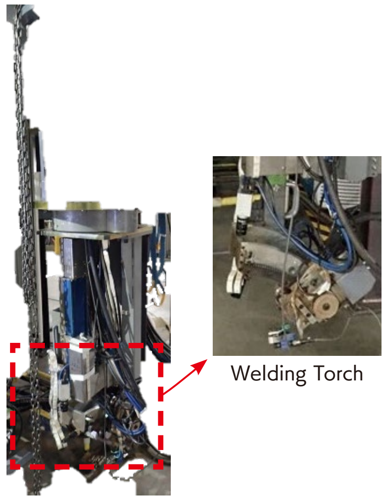
▲Positioning system for extension pipe (Figure 6)



▲Structure of the S/C water intake (Figure 5)



▲Macro cross-section of weld (3 layers, 8 passes) (Figure 8)

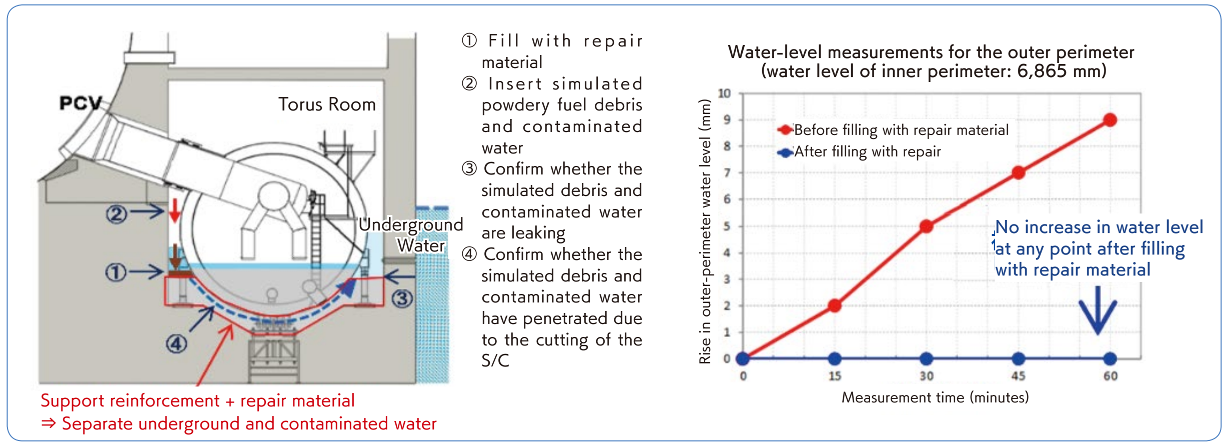


▲Extension pipe to S/C fitting auto-welder (Figure 7)

3 Verifying through full-scale testing the technology for connecting to and accessing inside the PCV etc.

- Using the auto-welder prototype developed from work on the S/C water intake (Figure 7), a series of full-scale tests via remote operation (positioning the extension pipe and welding it to the S/C fitting) were conducted. This testing showed that remote operation of the S/C water intake is feasible.

- As part of the plan for preventing Unit 1's D/W from leaking into its torus room and S/C inner perimeter, the effectiveness of establishing a liquid boundary was tested by inserting repair material. To do this, the full-scale test unit was installed at the JAEA's Naraha Center for Remote Control Technology Development. This unit was manufactured to test technology for repairing leak points in the PCV by filling the S/C structures and the torus-room floor with mortar. This test confirmed that the torus room and the inner perimeter of the S/C could be used as a boundary for contaminated water and powdery fuel debris (Figure 9).



① Fill with repair material
② Insert simulated powdery fuel debris and contaminated water
③ Confirm whether the simulated debris and contaminated water are leaking
④ Confirm whether the simulated debris and contaminated water have penetrated due to the cutting of the S/C

▲Boundary-effectiveness testing and results (Figure 9)

V

Decommissioning Research and Development

Retrieving Fuel Debris

The inside of PCVs and RPVs are contaminated with radioactive material and their radiation levels are high. As information about each PCV/RPV is limited and uncertain, equipment and system for fuel debris retrieval have been developed while carefully verifying the feasibility of the system.

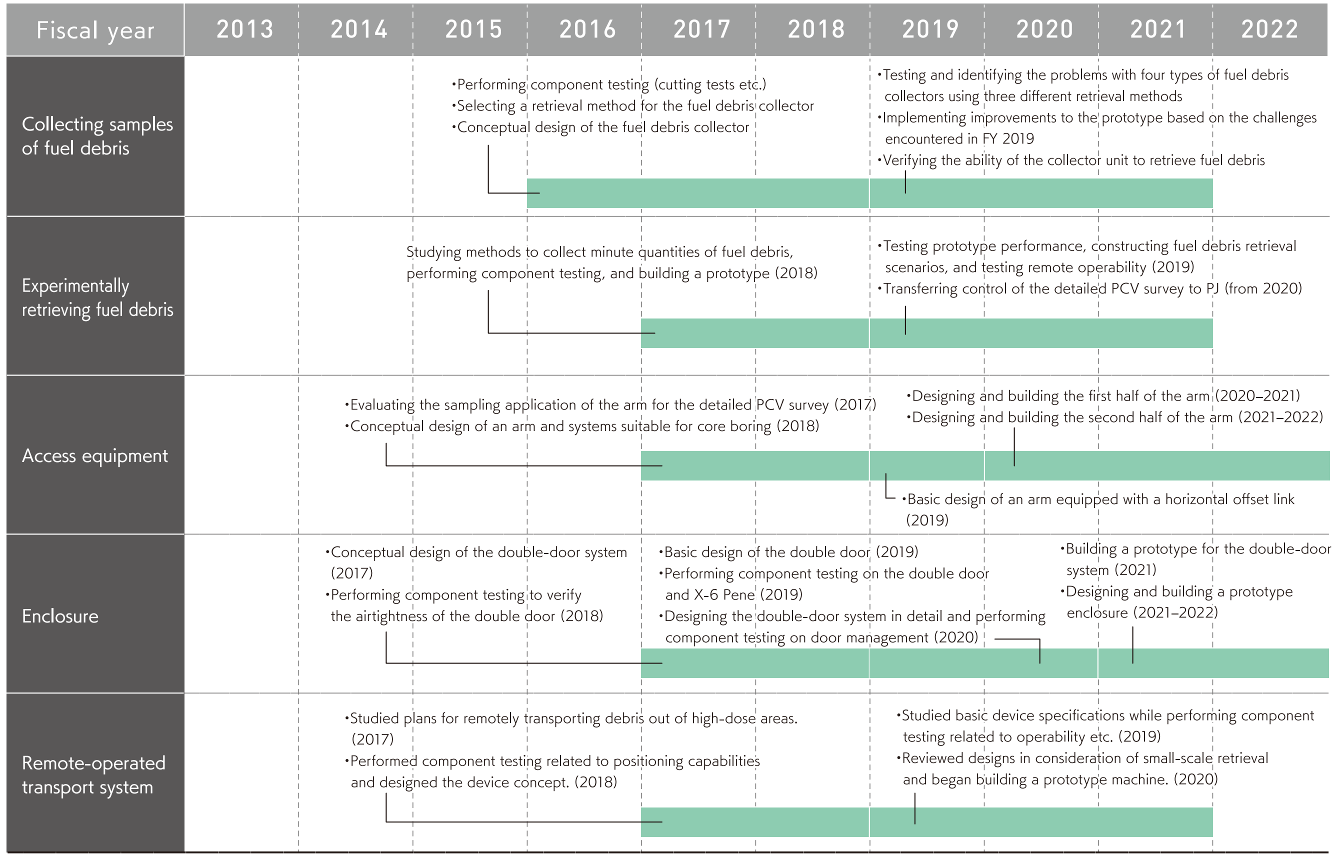
Due to the differences of the reactor structure and response to the nuclear accident, Fukushima Daiichi NPS has never-before-seen characteristics. Therefore, the fuel debris retrieval systems has also been developed to ensure safely containing, transporting and storing retrieved fuel debris.

Development of trial retrieval and technology for increasing the retrieval scale of fuel debris

Trial-retrieving of fuel debris then gradually increasing the scale of the retrieval

- IRID is studying methods for trial retrieval of fuel debris and the gradual increase of the retrieval scale
- Creating sampling scenarios that involve collecting fuel debris and bringing it to analysis facilities
- Capitalizing on the results of PCV interior investigations and the development of the arm for detailed investigation inside the PCV, this project is designing, manufacturing, and testing equipment for collecting, accessing, and transporting of the arm.

Research and development progress



Collecting samples of fuel debris

- Performing component testing (cutting tests etc.)
- Selecting a retrieval method for the fuel debris collector
- Conceptual design of the fuel debris collector

- Testing and identifying the problems with four types of fuel debris collectors using three different retrieval methods
- Implementing improvements to the prototype based on the challenges encountered in FY 2019
- Verifying the ability of the collector unit to retrieve fuel debris

Experimentally retrieving fuel debris

Studying methods to collect minute quantities of fuel debris, performing component testing, and building a prototype (2018)

- Testing prototype performance, constructing fuel debris retrieval scenarios, and testing remote operability (2019)
- Transferring control of the detailed PCV survey to PJ (from 2020)

Access equipment

- Evaluating the sampling application of the arm for the detailed PCV survey (2017)
- Conceptual design of an arm and systems suitable for core boring (2018)

- Designing and building the first half of the arm (2020–2021)
- Designing and building the second half of the arm (2021–2022)

- Basic design of an arm equipped with a horizontal offset link (2019)

Enclosure

- Conceptual design of the double-door system (2017)
- Performing component testing to verify the airtightness of the double door (2018)

- Basic design of the double door (2019)
- Performing component testing on the double door and X-6 Pene (2019)
- Designing the double-door system in detail and performing component testing on door management (2020)

- Building a prototype for the double-door system (2021)
- Designing and building a prototype enclosure (2021–2022)

Remote-operated transport system

- Studied plans for remotely transporting debris out of high-dose areas. (2017)
- Performed component testing related to positioning capabilities and designed the device concept. (2018)

- Studied basic device specifications while performing component testing related to operability etc. (2019)
- Reviewed designs in consideration of small-scale retrieval and began building a prototype machine. (2020)

Background

For the appropreate safety management and equipment design for fuel debris retrieval, it is significant to collect some fuel debris from the bottom of the PCV and ascertain its composition and mechanical properties. IRID is studying methods for collecting fuel debris and bringing it to analysis facilities so that data that cannot be gleaned from camera investigation or similar approaches can be obtained.

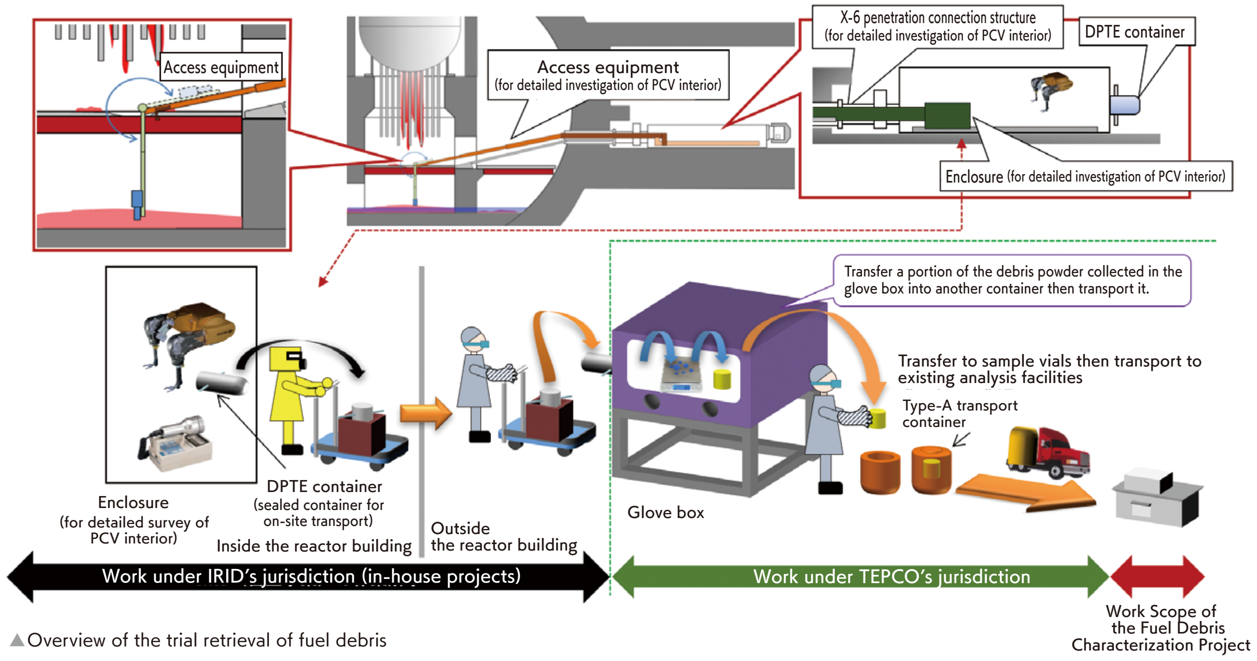
Purpose

Technology for accessing the lower PCV is currently being developed as part of the detailed investigation of the PCV interior. It was decided to incorporate that same concept for the development of technology that can gradually increase the scale of fuel debris retrieval. To collect fuel debris and retrieve from the PCV, however, it is needed to take steps to prevent the leakage of radioactive material throughout the entire route traversed by the debris. The retrieval of fuel debris involves bringing highly radioactive material into the enclosure, so even more than shielding the equipment itself from radiation, systems that account for improving our ability to seal the enclosure need to be established. A system for remotely transporting collected fuel debris samples from the highly radioactive environment in the reactor building to the analysis facility must also be established.

1-1

Trial retrieval I of fuel debris

Utilizing some equipment from the project that investigated the PCV interior in detail—the enclosure, the equipment for creating an access route, the arm-type access equipment, etc.—sample collectors were attached to the end of the arm and the retrieval of an extremely small amount of fuel debris will be conducted.

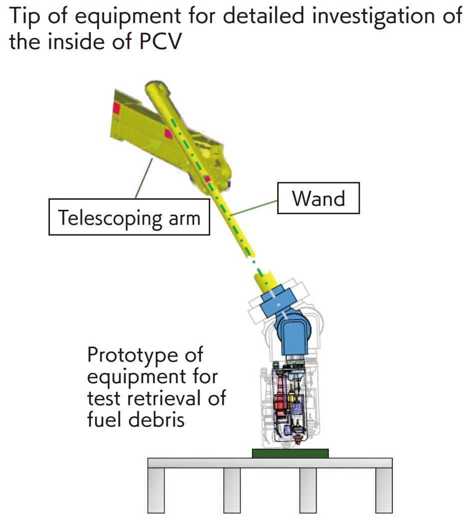


▲Overview of the trial retrieval of fuel debris

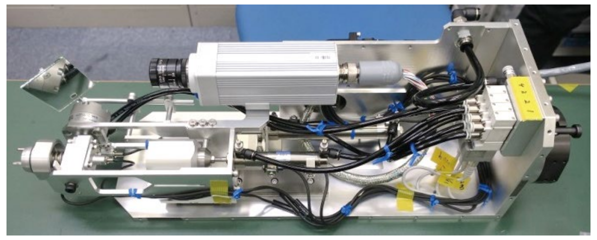
1-2

Sample collectors for fuel debris (test retrieval)

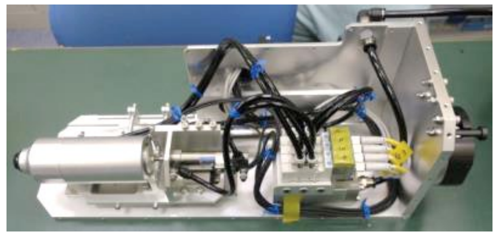
IRID designed two types of fuel debris sample collection equipment (equipment for the testl retrieval of fuel debris) to attach to the arm-type access equipment: a brush with very fine bristles and a vacuum chamber. A wand was installed and a combination test was conducted to verify the behavior of the units.



▲Conceptual image of combination test with the arm for detailed investigation inside PCV



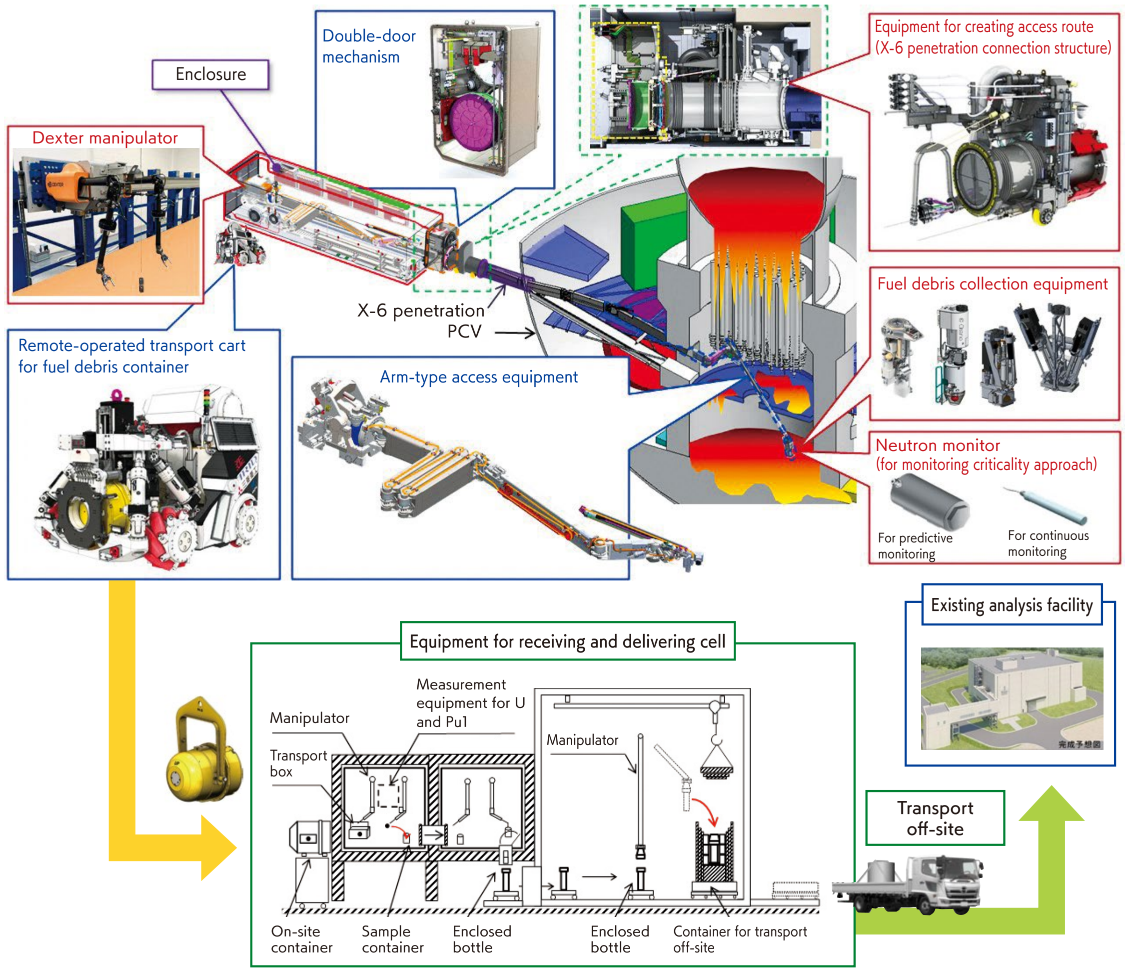
▲Prototype: Ultrafine metal brush method



▲Prototype: Vacuum tube method

2-1 Developing technology for gradually increasing the scale of fuel debris retrieval

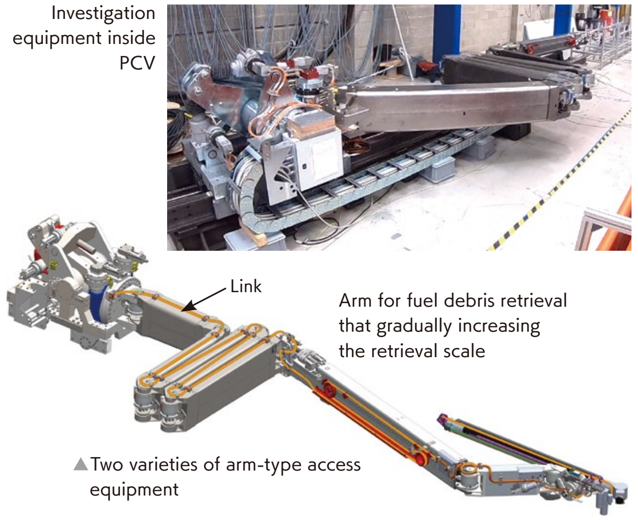
Using the structure of equipment in the detailed PCV internal investigation as a base, IRID made some modifications so that the retrieval of fuel debris can be gradually increased. In addition to enhancing the hardness of the arm's front half in order to improve its payload, the tip's range of access was extended and a double door in the connecting section was installed so that the contaminated surfaces of the enclosure do not travel outside the PCV when the enclosure is withdrawn.



2-2 The arm-type access equipment

IRID is designing and manufacturing the front half of the arm to include the following improvements for gradually increasing the scale of fuel debris retrieval.

- Reduce the number of links in the arm (shortening the length) and increase the payload (from approximately 10 kg to 20 kg)
- Use a link with a horizontal offset mechanism to improve the arm's ability to pass through openings on the pedestal platform

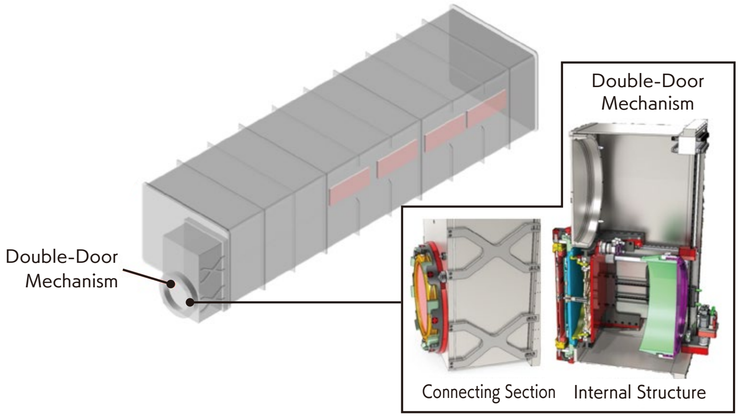


▲Two varieties of arm-type access equipment

2-3 Enclosure (isolation room)

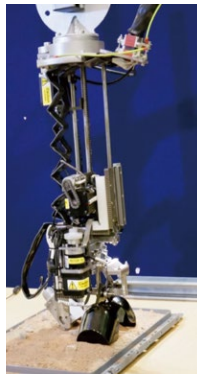
IRID has developed a double-door mechanism that maintains an airtight connection between the junction and the PCV opening while maintaining the opening safely sealed in an emergency. The prototype for an enclosure that allows to perform tasks such as attaching and removing the fuel debris collection equipment on the end of the access arm is currently being designed and manufactured as well as remote maintenance on the access equipment itself.

▲Prototype of double-door system



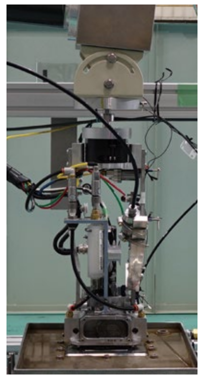
2-4 The fuel debris collection equipment

IRID identified the issues faced when performing actual work with the various equipment for collecting fuel debris — those for pebble-shaped and granular debris (buckets and flexible grippers), those for powdery debris, and those for slicing and collecting cylindrical debris—and made design modifications to improve their utility. tests to collect simulated debris and cutting tests are being conducted, and improvements are being made to address the issues.

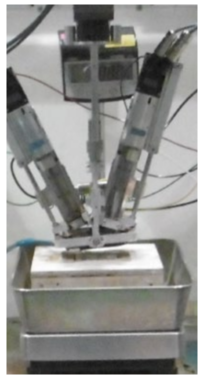


▲For collecting sandy and pebble-shaped fuel debris (bucket)

▲For collecting sandy and pebble-shaped fuel debris (flexible gripper)



▲For cutting and collecting powdery fuel debris

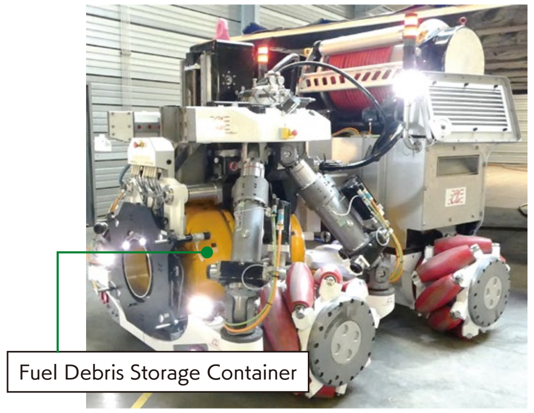


▲For cutting and collecting cylindrical fuel debris

2-5 Remote-operated transport system

For fuel debris collected with the access equipment, the plan is to transport it from the enclosure using a storage container. IRID has developed a "remote transport cart" that can load and unload fuel debris storage containers in the highly radioactive enclosure then transport them to lower-radiation areas via remote operation.

Element testing was performed related to the capability to adjust positioning when connecting to the enclosure and maneuverability in narrow area. Based on those results, the equipment was designed, prototype units were manufactured, and plant verification tests were conducted.



▲Remote transport cart with fuel debris storage container

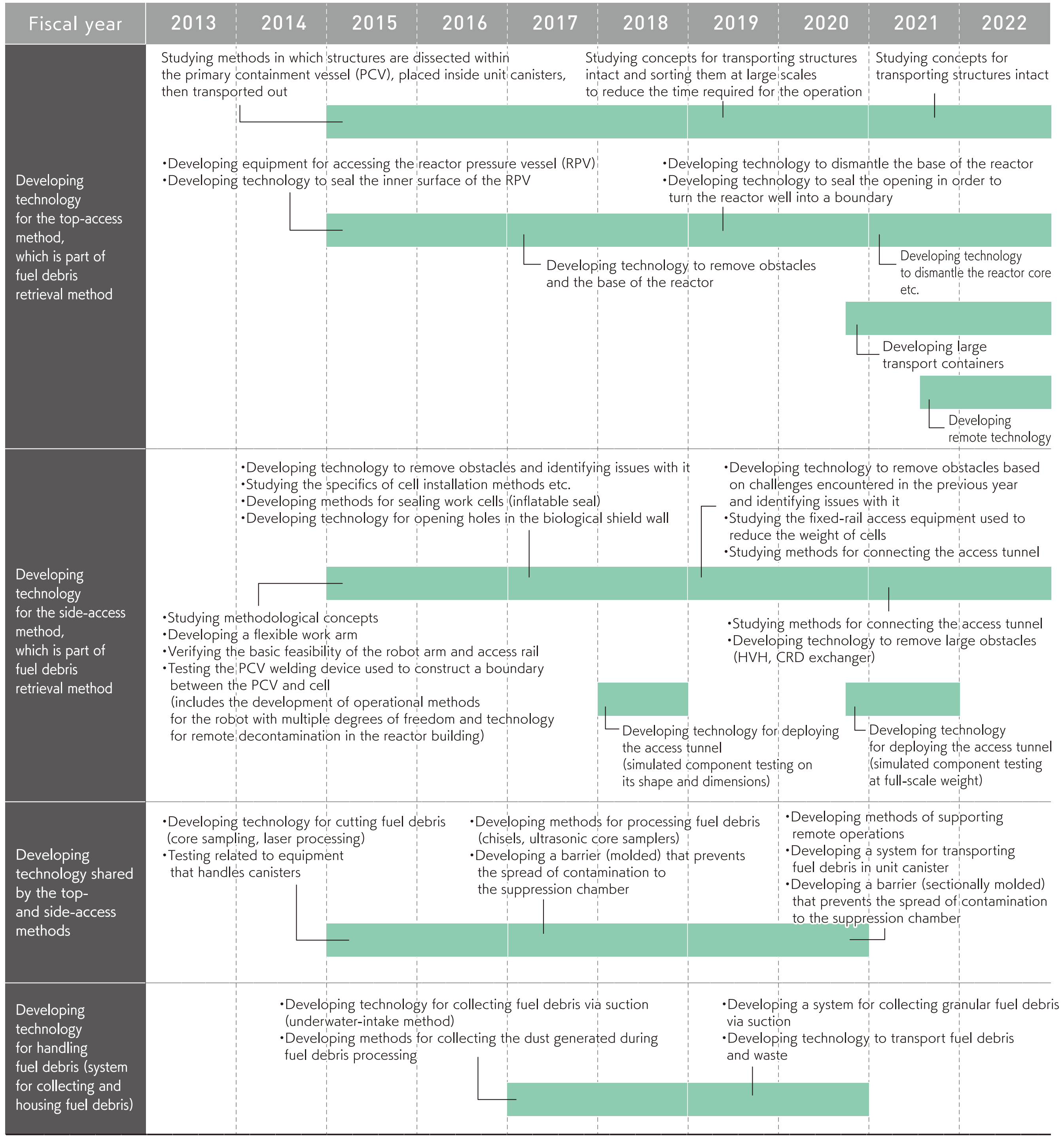
Development of technology for retrieval of fuel debris and reactor internals

Conducting research and development (R&D) for manufacturing the equipment required for fuel debris retrieval

Below are some of the challenges faced when retrieving fuel debris. To respond to these issues so that work can be completed safely and promptly , IRID is conducting the R&D necessary to manufacture equipment for fue debris retrieval.

- The work must be done entirely from a remote location, since it is a highly radioactive environment that humans cannot enter
- Radioactive material must be confined to prevent its dispersion while the work is being conducted
- For fuel debris retrieval to be conducted safely, criticality needs to be prevented, limit the radiation exposure of workers, and prevent the structures from falling or being damaged
- As the work will be conducted in the dark and narrow spaces within the reactors, its efficiency through remote operation must be improved

Research and development progress



Developing technology for the top-access method, which is part of fuel debris retrieval method

Studying methods in which structures are dissected within the primary containment vessel (PCV), placed inside unit canisters, then transported out

Studying concepts for transporting structures intact and sorting them at large scales to reduce the time required for the operation

Studying concepts for transporting structures intact

- Developing equipment for accessing the reactor pressure vessel (RPV)
- Developing technology to seal the inner surface of the RPV

- Developing technology to dismantle the base of the reactor
- Developing technology to seal the opening in order to turn the reactor well into a boundary

Developing technology to remove obstacles and the base of the reactor

Developing technology to dismantle the reactor core etc.

Developing large transport containers

Developing remote technology

Developing technology for the side-access method, which is part of fuel debris retrieval method

- Developing technology to remove obstacles and identifying issues with it
- Studying the specifics of cell installation methods etc.
- Developing methods for sealing work cells (inflatable seal)
- Developing technology for opening holes in the biological shield wall

- Developing technology to remove obstacles based on challenges encountered in the previous year and identifying issues with it
- Studying the fixed-rail access equipment used to reduce the weight of cells
- Studying methods for connecting the access tunnel

- Studying methodological concepts
- Developing a flexible work arm
- Verifying the basic feasibility of the robot arm and access rail
- Testing the PCV welding device used to construct a boundary between the PCV and cell (includes the development of operational methods for the robot with multiple degrees of freedom and technology for remote decontamination in the reactor building)

- Studying methods for connecting the access tunnel
- Developing technology to remove large obstacles (HVH, CRD exchanger)

Developing technology for deploying the access tunnel (simulated component testing on its shape and dimensions)

Developing technology for deploying the access tunnel (simulated component testing at full-scale weight)

Developing technology shared by the top- and side-access methods

- Developing technology for cutting fuel debris (core sampling, laser processing)
- Testing related to equipment that handles canisters

- Developing methods for processing fuel debris (chisels, ultrasonic core samplers)
- Developing a barrier (molded) that prevents the spread of contamination to the suppression chamber

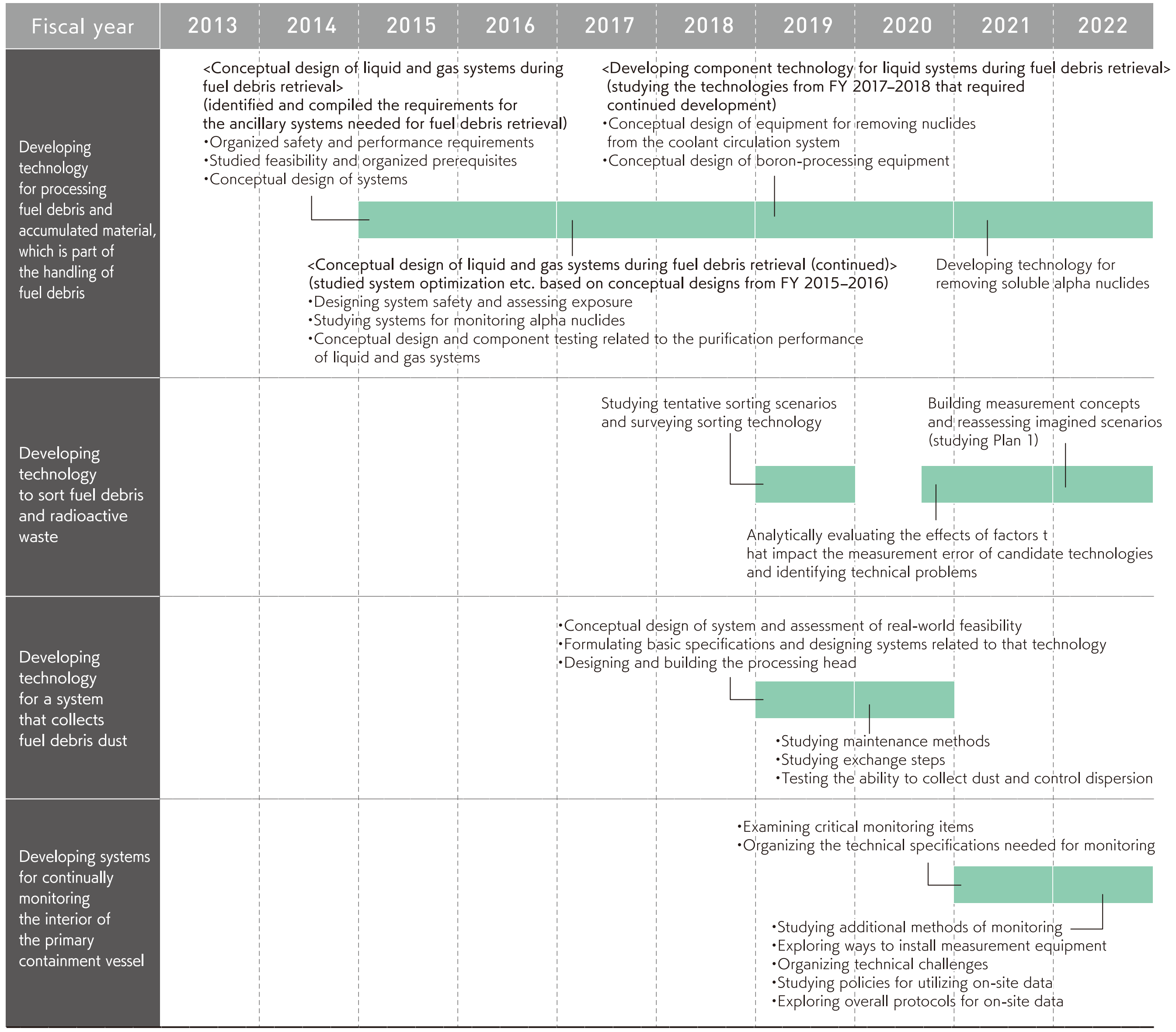
- Developing methods of supporting remote operations
- Developing a system for transporting fuel debris in unit canister
- Developing a barrier (sectionally molded) that prevents the spread of contamination to the suppression chamber

Developing technology for handling fuel debris (system for collecting and housing fuel debris)

- Developing technology for collecting fuel debris via suction (underwater-intake method)
- Developing methods for collecting the dust generated during fuel debris processing

- Developing a system for collecting granular fuel debris via suction
- Developing technology to transport fuel debris and waste

Research and development progress



Developing technology for processing fuel debris and accumulated material, which is part of the handling of fuel debris

<Conceptual design of liquid and gas systems during fuel debris retrieval>
(identified and compiled the requirements for the ancillary systems needed for fuel debris retrieval)
- Organized safety and performance requirements
- Studied feasibility and organized prerequisites
- Conceptual design of systems

<Developing component technology for liquid systems during fuel debris retrieval>
(studying the technologies from FY 2017–2018 that required continued development)
- Conceptual design of equipment for removing nuclides from the coolant circulation system
- Conceptual design of boron-processing equipment

<Conceptual design of liquid and gas systems during fuel debris retrieval (continued)>
(studied system optimization etc. based on conceptual designs from FY 2015–2016)
- Designing system safety and assessing exposure
- Studying systems for monitoring alpha nuclides
- Conceptual design and component testing related to the purification performance of liquid and gas systems

Developing technology for removing soluble alpha nuclides

Developing technology to sort fuel debris and radioactive waste

Studying tentative sorting scenarios and surveying sorting technology

Building measurement concepts and reassessing imagined scenarios (studying Plan 1)

Analytically evaluating the effects of factors t hat impact the measurement error of candidate technologies and identifying technical problems

Developing technology for a system that collects fuel debris dust

- Conceptual design of system and assessment of real-world feasibility
- Formulating basic specifications and designing systems related to that technology
- Designing and building the processing head

- Studying maintenance methods
- Studying exchange steps
- Testing the ability to collect dust and control dispersion

Developing systems for continually monitoring the interior of the primary containment vessel

- Examining critical monitoring items
- Organizing the technical specifications needed for monitoring

- Studying additional methods of monitoring
- Exploring ways to install measurement equipment
- Organizing technical challenges
- Studying policies for utilizing on-site data
- Exploring overall protocols for on-site data

Background

The fuel debris inside the reactor pressure vessel (RPV) and primary containment vessel (PCV) at Fukushima Daiichi NPS is currently being maintained in a stable, cool state. But when the accident occurred, areas including the reactor building, RPV, and PCV were damaged, so the plant itself was experiencing instability. For this reason, a goal of the project is to retrieve fuel debris safely without dispersing radioactive material and while achieving the objectives below.

- Ensure confinement function for radioactive dust
- Establish remote-operated technologies that work in highly radioactive environments
- Establish technologies that reduce radiation exposure and prevent the spread of contamination

Purpose

IRID will conduct the following R&D to manufacture the equipment required for fuel debris retrieval, including technology for creating the access routes (both top- and side-access) needed to retrieve the fuel debris located in the RPV and PCV; technology for handling fuel debris; and element technology related to confinement functions.

- Perform element testing etc. as needed to study conceptual methods (both top- and side-access) for retrieving fuel debris and assess their feasibility
- Develop technologies related to the retrieval of fuel debris (remote-operated assistance, transport methods, dust-collection systems, sorting fuel debris and radioactive waste, etc.)
- Develop technology for handling fuel debris (collection and disposal)
- Develop element technology related to confinement functions
- Develop systems for continually monitoring the inside of the primary containment vessel

Retrieving fuel debris: Developing technology for the top-access method

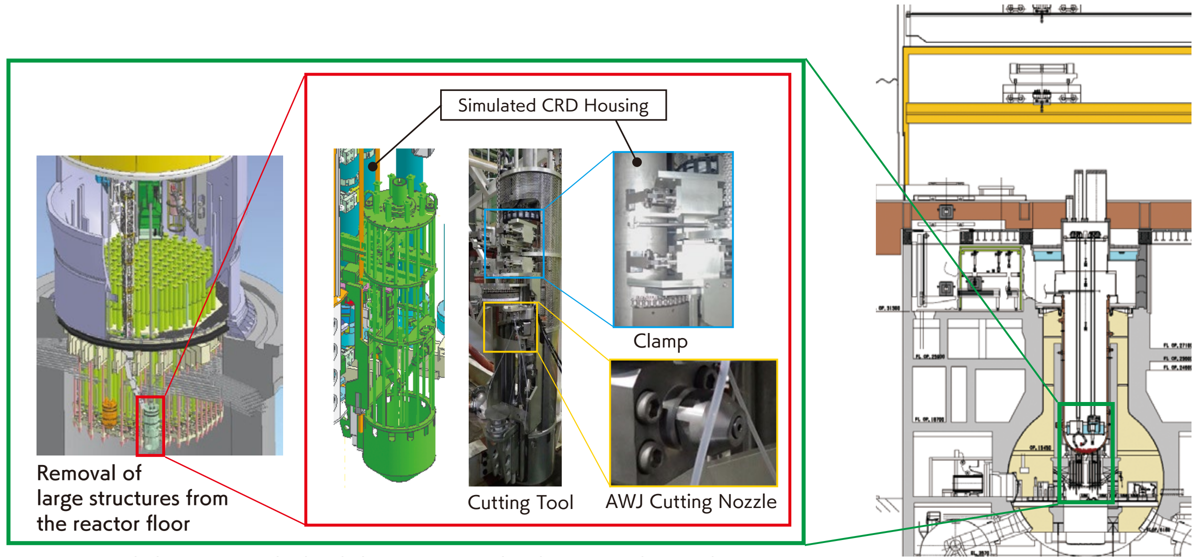
Plan 1 Removal and transport of the entire structure

In its subsidy projects through FY 2018, IRID studied methods for cutting up the structures inside the PCV then placing them into unit cans for transport, with the goal of reducing the scope of highly radioactive and contaminated areas by providing shielding around the fuel debris and preventing the dispersion of dust. Element testing related to cutting up the CRD housing was performed, which are obstacles on the reactor bottom.

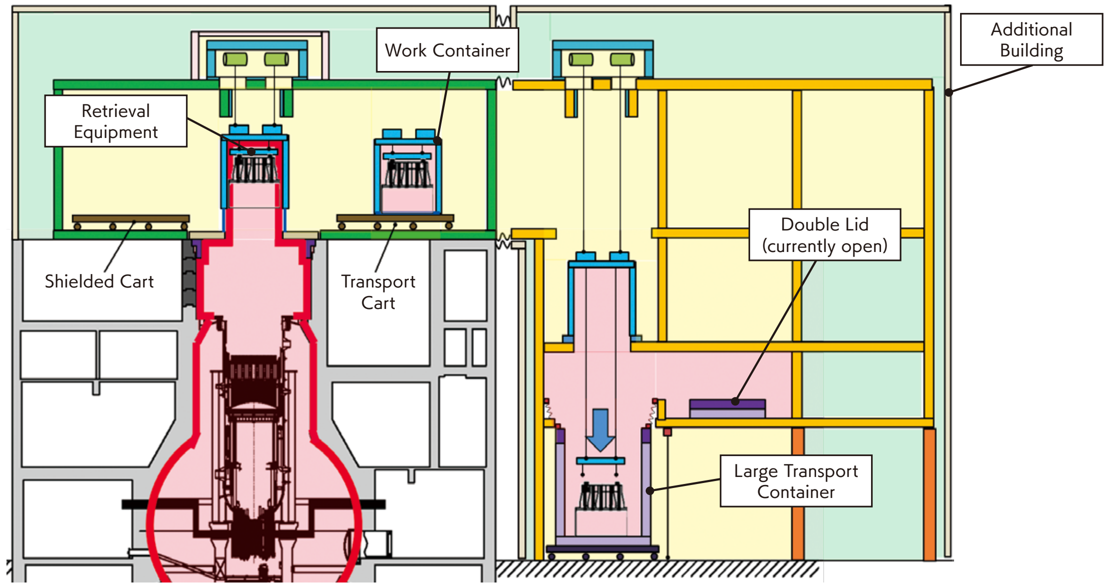
This research revealed tremendous difficulties from the perspective of workability and operational hours (throughput), and ways to make improvements and to transport large-sized structures as possible have been searched for since 2019. As Plan 1 of that strategy, the basic policies on the removal and transport of the entire structure was organized.

[Basic Methodology]

- Transport each structure as one unit to a newly built facility away from the reactor building, then cut it up and store it in containers. Minimize cutting operations inside the hazardous environment of the core to improve throughput while lowering the difficulty of remote work.
- When transporting the structures, use large, dedicated containers so that maintaining the objects shielded and airtight can be handled via the containers, the passageway, or some combination of the two.



▲Transport with the cutting method and element testing related to cutting the CRD housing



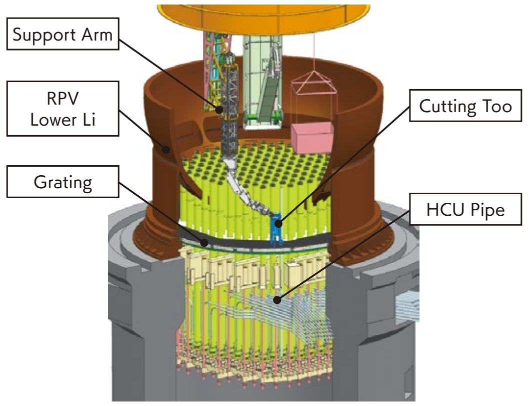
▲Removal and transport of the entire structure

Retrieving fuel debris: Developing technology for the top-access method

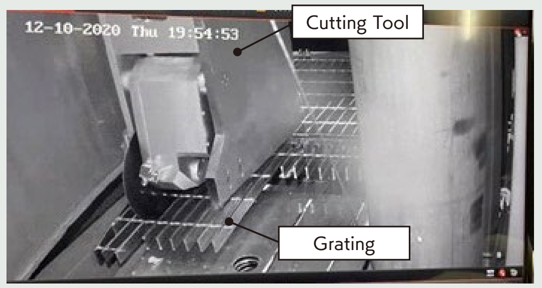
Plan 1 Removal and transport of the entire structures

IRID has continued to study various methods based on the policies in the previous pages. In FY 2019 and 2020, element testing was performed to verify the manual procedures for cutting and disassembling objects on the reactor floor and reflected those results in the throughput calculations. Specific issues to this process were also identified. Since FY 2021, disassembly methods for the reactor core parts etc. have been studied and their feasibility through element testing are being confirmed.

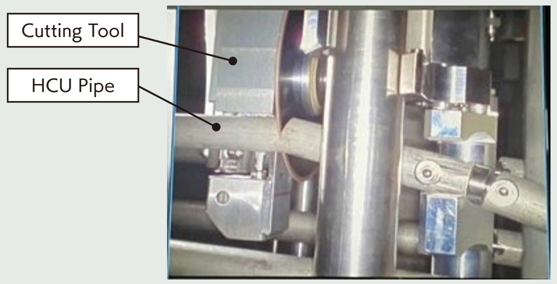
In addition, examination was conducted on the function of preventing the spread of contamination (airtight construction) of the dedicated transport container (large carry-out container) used to carry out the structure removed in one unit, and it was decided to use a double-lid structure for the lid part of the container. The feasibility of the double-lid structure is being confirmed through elemental tests starting in FY 2020 to see if airtightness can be ensured by studying the operational steps of the double-lid structure.



▲Removing obstacles from the bottom of the reactor

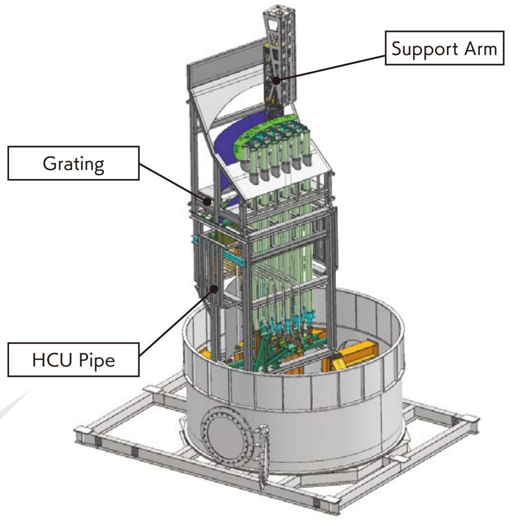


Testing the removal of simulated grating



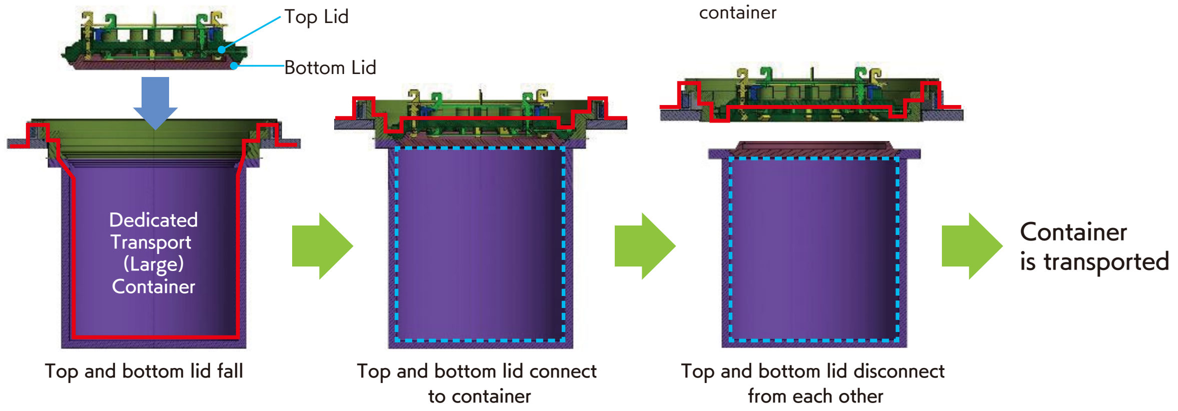
Cutting test on simulated HCU* pipe

*HCU: hydraulic control unit



▲Simulated the reactorbottom

▲Testing the top lid of a dedicated (large) transport container



▲Moving a dedicated (large) transport container

Retrieving fuel debris: Developing technology for the top-access method

Plan 2 Combination of dividing into the structual components and decontamination

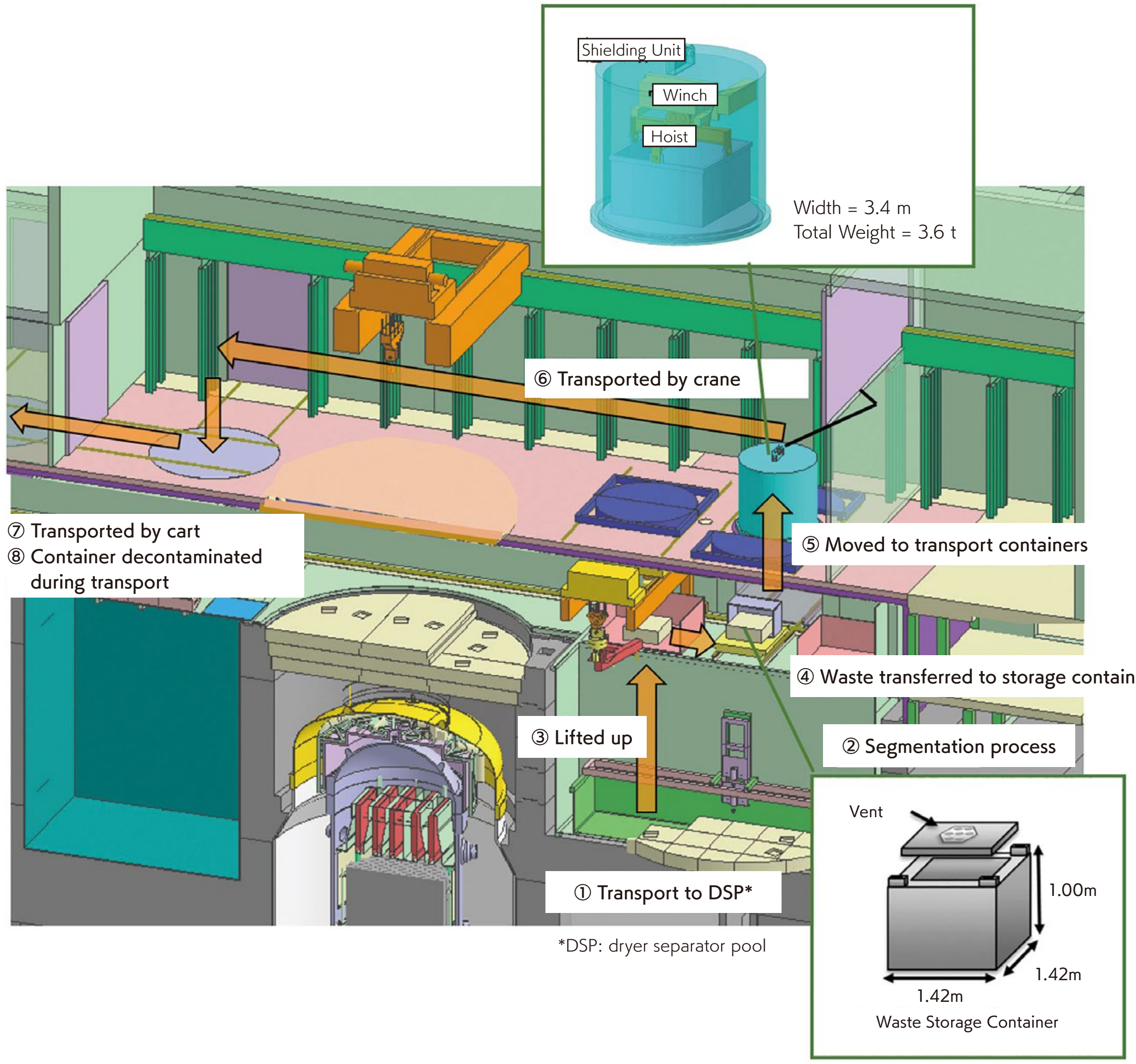
In an effort to improve work efficiency and reduce operational hours (throughput), IRID compiled and studied basic policies that aim to divide and decontaminate the structures at the same time to reduce the load that needs to be transported. This was Plan ②, which was executed separately from Plan ①.

[Basic Methodology]

1) Structural waste and fuel debris will be loaded into containers as close to the RPV as possible then transported.
  - Drying, sorting, transfer to containers, and other work done in preparation for storage will take place in a separate facility, away from the reactor building (R/B). The goal is to reduce the weight of the cell by removing some functionality.
  - Obstacles will be cut down to a transportable weight using a combination of decontamination and shielding.

2) A confinement area (boundary) separate from the existing reactor building will be newly created with containers. The area will be double-sealed by a primary boundary surrounded by a secondary boundary, and negative pressure will be used to form an additional dynamic boundary. The primary boundary is further subdivided into three stages with different levels of contamination and radiation dose.

3) Containers will be gradually moved from the highly radioactive areas in the primary boundary to the less radioactive secondary boundary then transported out.



*DSP: dryer separator pool

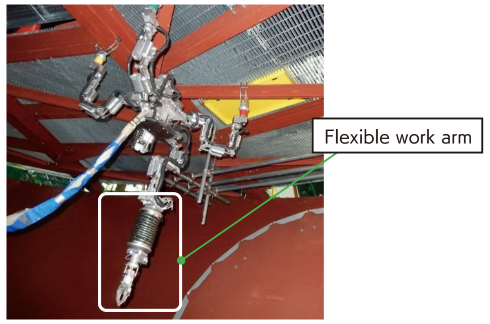
Retrieving fuel debris: Developing technology for the side-access method

Removing obstacles (flexible work arm)

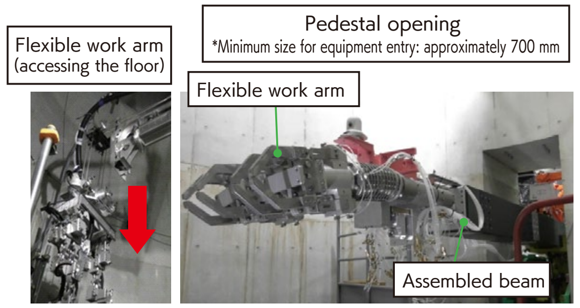
There are likely to be many changes throughout the course of fuel debris retrieval due to unknowns in the work environment and the progress of operations there. However, it can be assumed that the radiation dose rate will be high for work done within the PCV. IRID thus developed a lithe remote-operated arm that is highly resistant to radiation and that can flexibly respond to these on-site changes. That concept was then applied to the equipment for removing obstacles in the inner-pedestal, which combines the design of the equipment for removing obstacles in the outer-pedestal (basement floor) with assembled beams.

In FY 2019–20, a smaller equipment for removing obstacle that could be used to clear interfering objects and monitor conditions in the PCV was developed while working in narrow environmentss. Element testing was performed on the equipment, such as maneuvering around a simulated pedestal interior and cutting a simulated ICM (incore nuclear instrumentation) housing. This testing showed the device to be capable of performing such tasks.

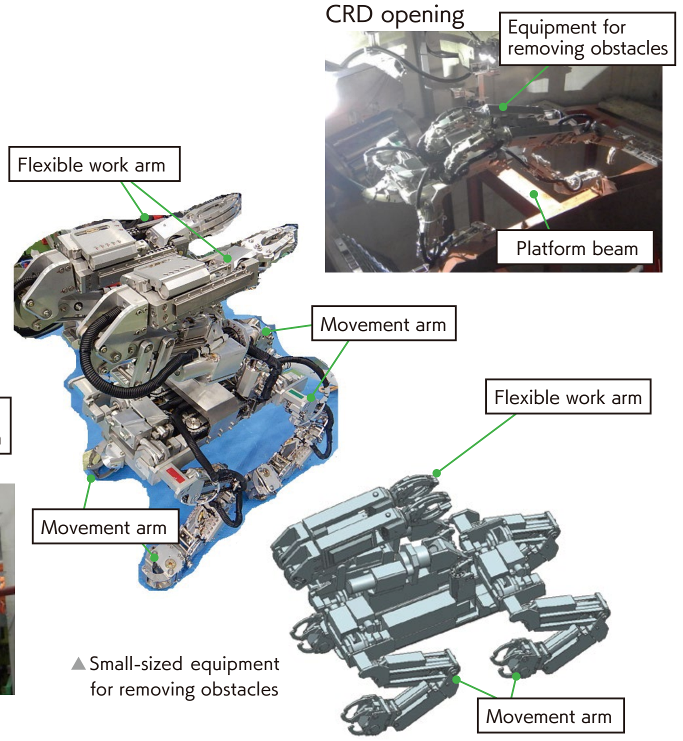
Since FY 2021, IRID has been studying methods to remotely remove large obstacles that will significantly hinder the retrieval of fuel debris, such as HVH (heating ventilating handling) units and CRD exchangers.



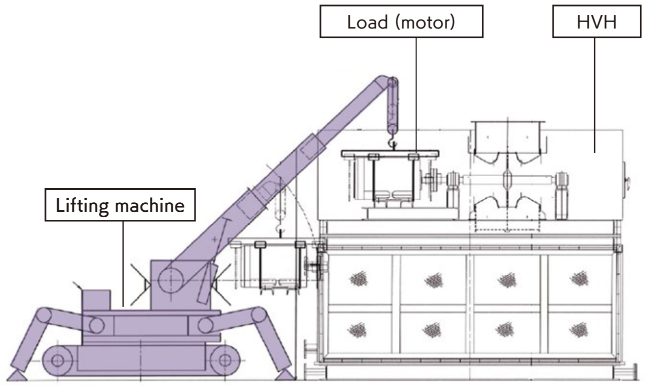
▲Equipment for removing obstacles in the outer-pedestal (basement floor)



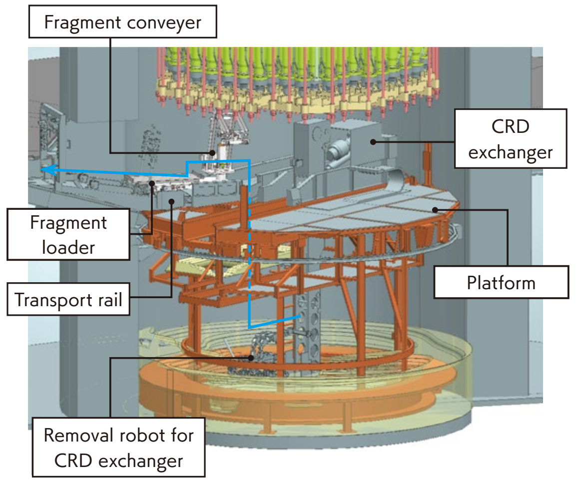
▲ Equipment for removing obstacles in the Inner-pedestal with assembled beam



▲Small-sized equipment for removing obstacles



▲Lifting machine used in HVH dismantling



▲Dismantling with CRD exchanger

Retrieving fuel debris: Developing technology for the side-access method

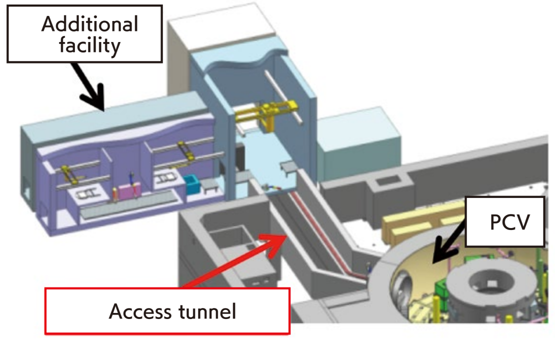
Access tunnel

To retrieve fuel debris, a variety of equipment needs to be transported into the PCV and move extracted obstacles and fuel debris outside the PCV. IRID is studying how to create a transport route by connecting the reactor building (R/B) to an additional facility via a shielded access tunnel and how to support the load of the access tunnel with the R/B outer wall and biological shield wall so that the weight limits of the 1st floor of the R/B are not exceeded.

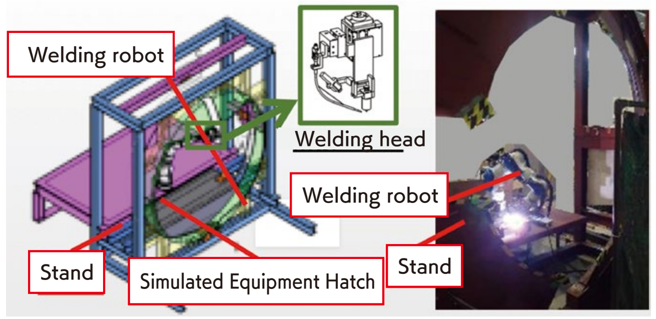
IRID's plan was to assemble the access tunnel outside the R/B to reduce the radiation exposure of workers, after which it would be carried into the R/B and set up through remote operation. In FY 2018, element testing was used to verify the design's feasibility by sending in a prototype with the correct shape and dimensions.

In FY 2019–20, research and testing related to the welded connection between the access tunnel and PCV was conducted, determining the welding requirements and protocols while identifying potential issues. Based on those results, IRID has been conducting full-scale welding tests and exploring methods for remotely installing the section that connects the PCV and access tunnel (the PCV connection sleeve) since FY 2021.

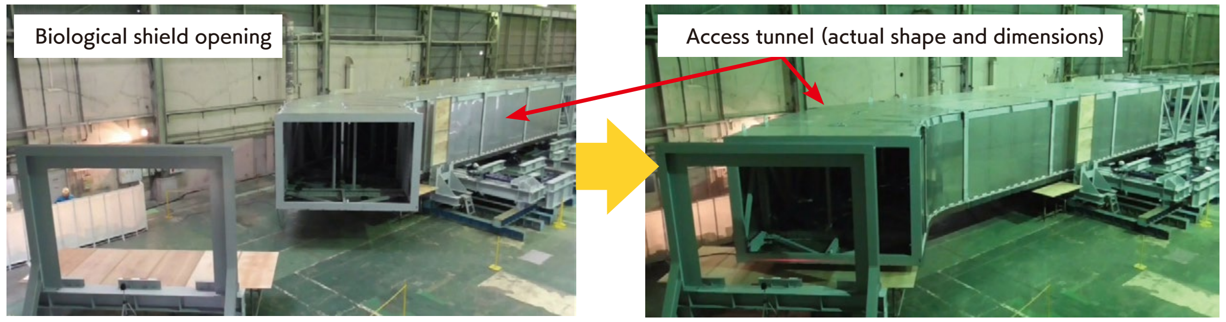
Since the access tunnel must be able to turn (slide) near the R/B, the slide section is also being studies and element testing is being performed on the slide of a full-weight simulated test unit to confirm its feasibility.



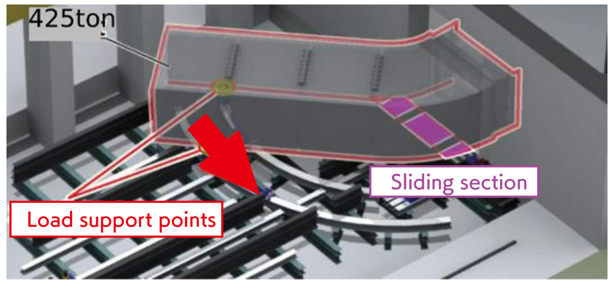
▲Conceptual drawing of access tunnel



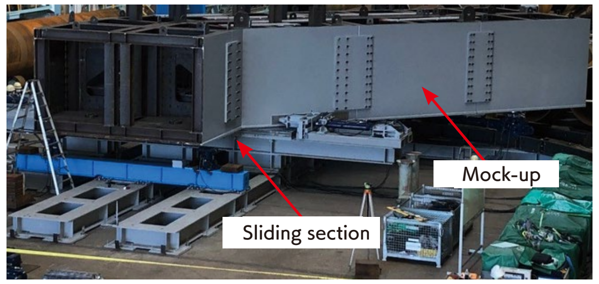
▲Test welding the access tunnel connection



▲Element testing for delivery of the access tunnel



▲Turning the access tunnel



▲Full-scaled weight simulated access tunnel

Retrieving fuel debris: Developing technology for the side-access method

Access rail and robot arm

Retrieving fuel debris requires us to process and collect it without knowing its properties or distribution. While processing methods will be selected during the internal investigation conducted later, IRID has already developed a six-axis robot arm and a three-stage extendable access rail to guide that arm into the pedestal. This will allow to flexibly respond to a great variety of fuel debris processing methods.

[Overview of the method]

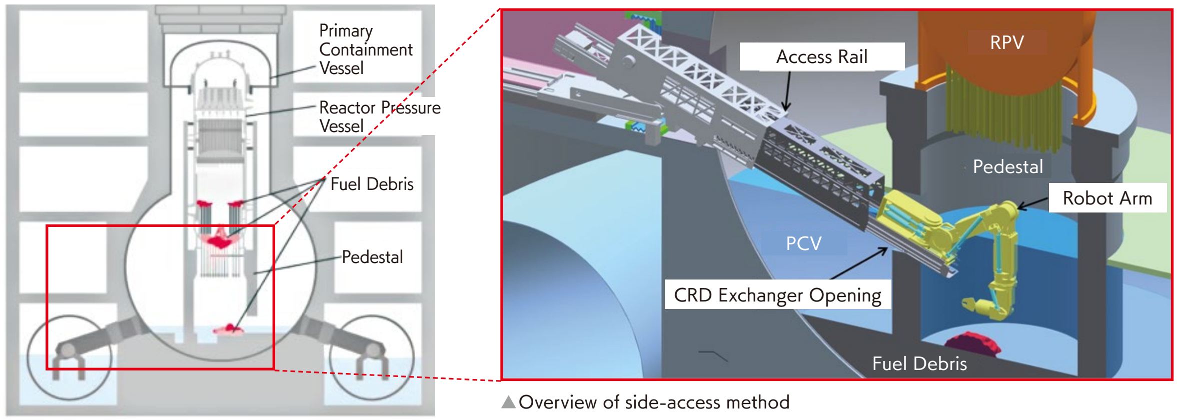
- The biological shield wall near the existing X-6 penetration passage will be removed and the hole in the PCV wall widened to gain linear access to the pedestal interior.
- An access rail equipped with the robot arm will be aimed toward the CRD exchanger opening then extended at a downward angle.
- The robot arm will move down the access rail and into the pedestal, where it will process and collect fuel debris.

[Access Rail]

- A three-stage extendable design is used to reduce the size of the cell.
- The rail is equipped with a feature that guides the robot arm into the pedestal.
- The rail is equipped with a feature that transports unit canisters for the purpose of fuel debris collection.
- Dimensions: Width = 1,900 mm
  Length = 8,700 mm
  (when contracted) / 17,000 (when extended)
  Height = 2,500 mm
- Weight = approximately 24 tons

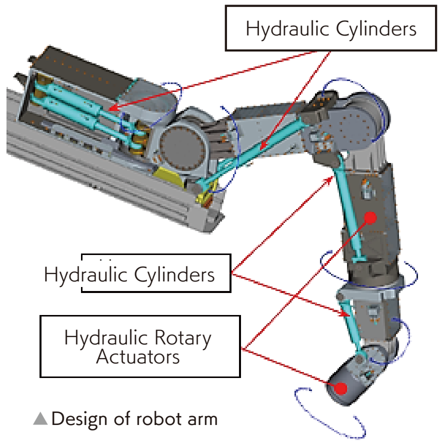
[Robot Arm]

- The processing tool on the end of the arm can reposition along six axes.
- Has redundant hydraulic cylinders and supply lines in case of failures.
- Uses hydraulic power to achieve strong processing capabilities in a compact form factor.
- Cables and hydraulic hoses are housed inside the equipment, preventing damage from contact with surrounding obstacles.
- Develop methods for controlling the hydraulic cylinders and rotary actuators for each axis so that the tip can be repositioned with a precision of ±5 millimeters.
- Dimensions: Width = 700 mm
  Arm Length = 7,100 mm
  Height = 920 mm
- Weight = approximately 4 tons
- Load of Tip = 2 tons in the downward direction



▲Overview of side-access method

▲Access rail and robot arm



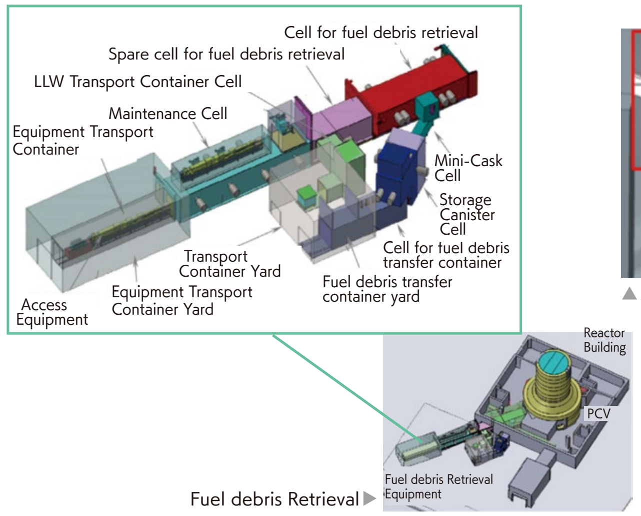
▲Design of robot arm

Retrieving fuel debris: Developing technology for the side-access method

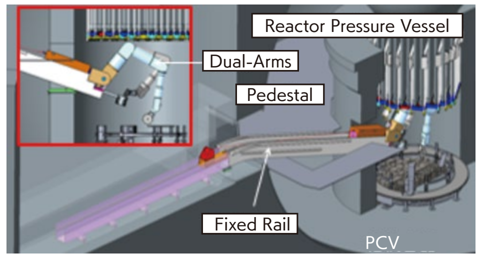
Studying installation of the cell

IRID is working to develop a side-access method in which the biological shield wall will be removed to widen the existing X-6 penetration opening so that retrieval equipment can be installed and the fuel debris within the pedestal can be accessed through a short distance.

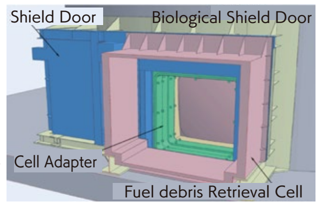
- To solve the issue of the shielded debris-retrieval cell exceeding the weight limit of the floor when installed in the reactor building, the installation was adopted that both minimizes the size and weight of the cell and reinforces the floor beams and walls of the reactor building with supporting materials. The feasibility of this plan was then verified.
- To reduce cell size and weight, the access equipment for debris retrieval was changed to a fixed rail type and the height of the equipment itself was loweredby scaling down the rail's transport capabilities. At the same time, the thickness of shielding was optimized to decrease weight.
- IRID also designed a series of steps for installing the massive cells—ranging from preparation work through mounting and installation — and verified the feasibility of that installation procedure.



Fuel debris Retrieval ▶



▲Access equipment with fixed rail



Installing cells and other large structures ▶

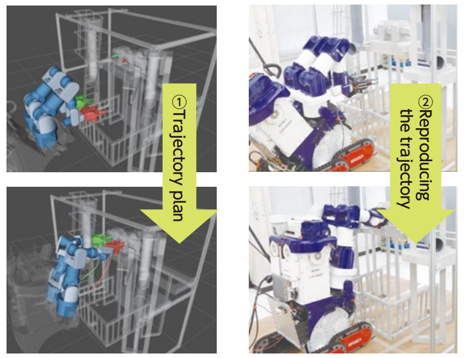
Developing common technology shared by the top- and side-access methods

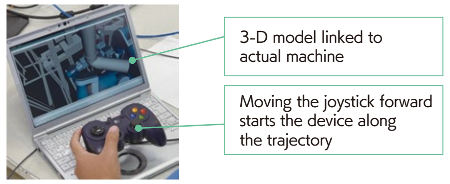
Remote-operation support

IRID has developed a technique for supporting remote operation (a trajectory plan) to increase operational efficiency and reduce the work load on operators who remotely operate the robots through narrow environments with poor visibility.

① By setting a goal (position and direction) for the fingers in relation to two manipulators, a trajectory that avoids obstacles can be calculated automatically[1] (in 1–2 minutes).

② This automatically calculated trajectory is then reproduced on the actual machine. While this is taking place, the operator can adjust the joystick in the forward and back directions to control the speed at which the trajectory is reenacted. It requires several minutes to achieve the goal positioning for beginner and veteran operators alike; however, the time was able to be reduced by 90% compared to manual operation[2] by a veteran operator.





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[1] For this, the movement plan technique was utilized for the robot with multiple degrees of freedom that was developed under the project to enhance the foundational technology for retrieving fuel debris and the reactor internals.

[2] In addition to adjusting the position and attitude of the fingers, this also includes redundant-axis movement developed as part of the project to create technology for remotely decontaminating the building's interior.

Developing common technology shared by the top- and side-access methods

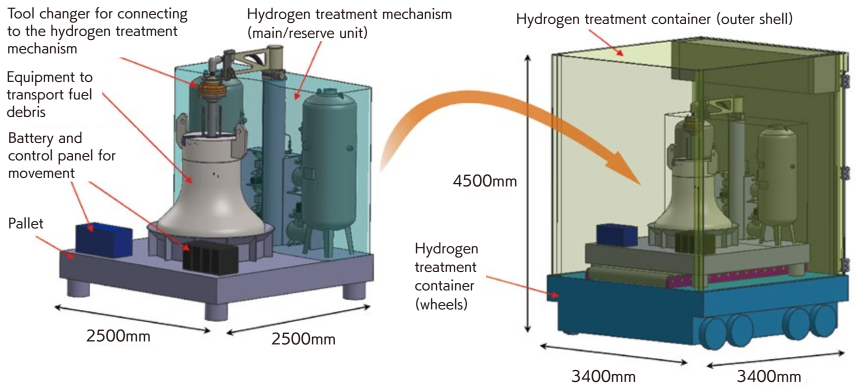
Equipment to transport fuel debris

- Anticipating cases where the drying facility for fuel debris cannot be near the reactor building, IRID developed equipment for transporting unit canss containing undried fuel debris to a facility located away from that building.
- Using the top-access method as the model case, the following feasibility assessments was conducted.

■ Established basic design requirements based on safety and handling demands
■ Studied concepts for equipment that fits the layouts used by fuel debris retrieval methods
■ Throughput assessment
■ Explored additional methods for monitoring whether safety functions remain intact
■ Evaluated the radiation exposure of workers
■ Considered scenarios for rescuing devices based on a defense of depth

- In conjunction with the above assessments, IRID also studied and tested the theoretical validity of essential element technologies such as the hydrogen treatment mechanism and the double door structure used to transfer unit cans.

The fuel debris transport equipment that houses the unit can is connected to the hydrogen treatment mechanism installed on the pallets. To continuously maintain a static double boundary with fuel debris, it is stored in the hydrogen treatment containers during on-site transport, which takes place after loading onto the cart. All steps in the process through container storage are completely unmanned.

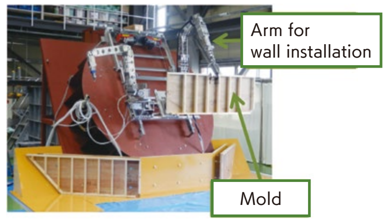


Developing technology shared by the top- and side-access methods

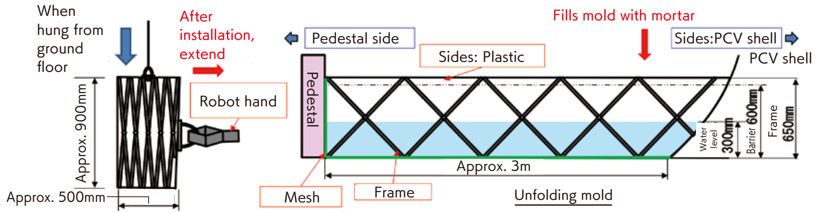
Preventing contamination from spreading to the S/C

One concern with fuel debris retrieval is that fuel debris and contaminated water will spread to the suppression chamber (S/C) or other locations when the debris is processed, which would expand the range of debris collection and increase the risk and time required for retrieval. IRID is currently exploring whether barriers can be erected inside the PCV to prevent the dispersion of fuel debris.

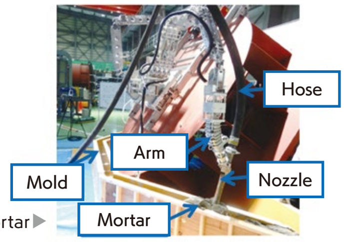
To build such barriers, installing molds then filling them with mortar was considered, and element testing has shown this to be a highly feasible option. However, it was found that remotely installing a mold then positioning a hose to fill it with mortar is difficult. To get around this issue, IRID is considering a method in which the wall is built by filling a folding mold with dry mortar; through the element testing, it has been verified that this strategy can be accomplished through remote operation.



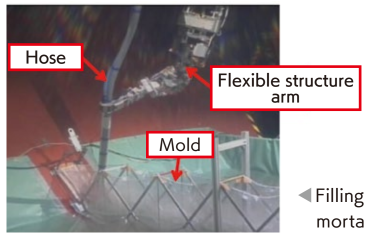
▲Installing the mold



▲Illustration of folding mold



Filling the mold with mortar ▶



◀Filling the folding mold with mortar

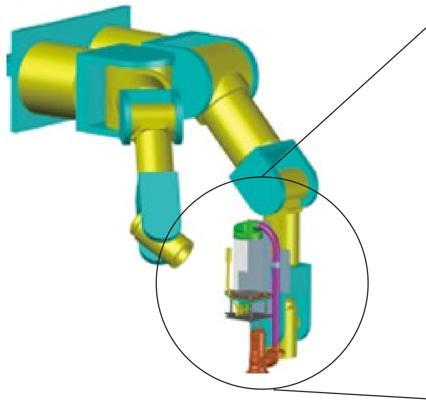
Developing technology for handling fuel debris (system for collecting and containing fuel debris)

Collecting granular fuel debris through suction

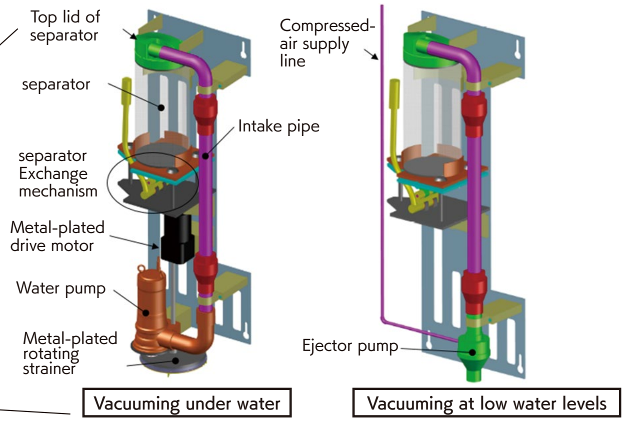
Suction is an effective method for improving throughput when collecting fuel debris that is granular (0.1 mm to 10 mm). IRID has identified and responded to the following requirements regarding the vacuum collection equipment.

- Consider what shape of pump strainer applicable to this system
- Study methods for detecting when a unit can (separator) is full
- Investigate methods for exchanging a unit can (separator)
- Explore which type of pump is applicable for vacuuming underwater and at low water levels

To meet these requirements, a vacuum collection equipment that can collect approximately 40 kg to 300 kg per hour was developed, depending on factors such as the relative density of the target material and the water level in the environment.



▲Installation on the access equipment



▲Vacuum collection equipment for granular fuel debris

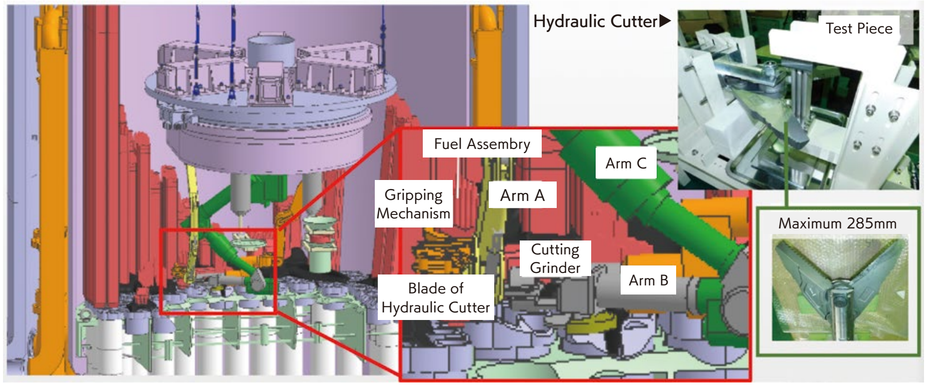
Developing technology for handling fuel debris (system for collecting and containing fuel debris)

Transport processes applicable to debris characteristics

Methods for collecting fuel debris will be selected according to the size and other properties of the debris.

- For clumps of material that melted and resolidified, we will prioritize use of a chisel (spiky hammer), which is fast and easy to use; brittle sections will be torn down with a bucket. IRID anticipate scenarios in which the target object cannot be demolished due to its physical properties or accessibility. Cutting grinders, laser gouging, and other methods will be employed in such cases.
- Fuel rods turn brittle due to the radiation generated when a reactor is running, so we should be able to tear off that material with a bucket or hydraulic cutter. If cutting or breaking it with a cutter is difficult, a cutting grinder or similar tool will be used before the hydraulic cutter is damaged.

- A collection equipment that combines multiple robot arms will be used for collection work. The end of the robot arm will be equipped with a gripper, various processors, a vacuum collection equipment, or other implements.

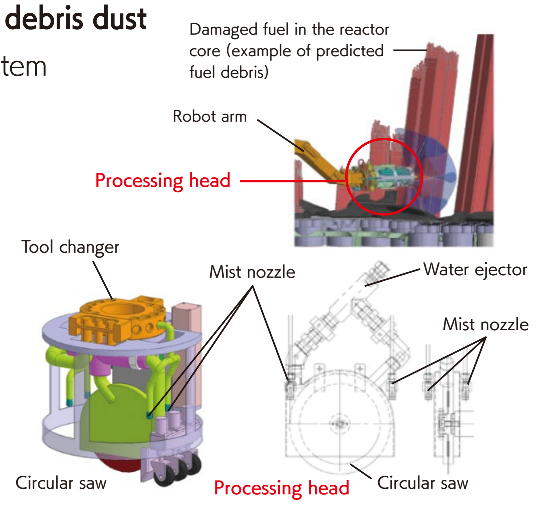


Developing technology for a system that collects fuel debris dust

Designing the dust-collection and dispersion-control system

There are concerns that processing nuclear fuel which contains fuel debris will cause dust to be dispersed into the air, worsening the work environment and placing a tremendous burden on the operation and maintenance of equipment. To address this, IRID has designed and manufacture a system for controlling the dispersion of dust in the vicinity of processing work. For the purpose of preventing the spread of dust and other material during the processing of fuel debris, the area around the processing sites could be structured to stop dispersion was examined for the applicability of a system that achieves efficient dust-collection and dispersion control based on existing technologies.

- Conceptual design of system and assessment of applicability for practical use
- Create basic specifications and system design; design and manufacture processing head



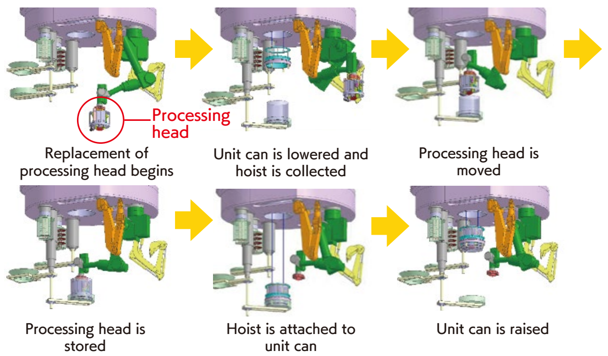
▲Conceptual drawings of circular-saw tool for the dust-collection and dispersion-control system

Developing technology for a system that collects fuel debris dust

Designing remote-maintenance technology for the dust-collection and dispersion-control system

As the equipment and systems used to retrieve fuel debris (systems for cutting fuel debris and collecting dust; work tables; monitoring systems; robot arms that manipulate tools; etc.) will be installed in highly radioactive areas, they must generally be maintained remotely. IRID has therefore organized the various approaches for maintaining such equipment, taking into account that they will be handling fuel debris. The maintenance methods and their feasibility, identified issue areas were studied, and logical policies for responding to those areas on the actual machines were considered.

- Study maintenance methods as well as procedures for exchanging parts



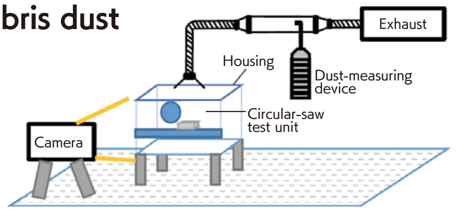
▲Concept for replacing parts with a remote-maintenance tool

Developing technology for a system that collects fue debris dust

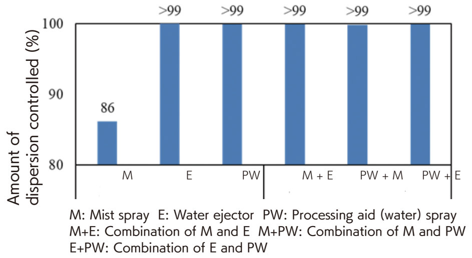
Evaluation test to collect dust and control dispersion

IRID manufactured a test unit to evaluate dust dispersion then conducted testing in the vicinity of a processing area.

Of the processing methods that are anticipated to have the highest throughput as determined by the project that developed technology for further expanding the scope of retrieving fuel debris and the reactor internals, IRID selected those that are expected to generate relatively large amount of dust. First, test elements that could be applied to all processing methods were considered. Then, the processing head was designed, manufacture and installed on the dust-collection and dispersion-control system, which would serve as our prototype for element testing. Finally, how well it can cut the simulated fuel debris was tested, which mimics the predicted properties of the fuel debris. IRID also tested the rate at which dust migrates into air and water in the space around the processing head and evaluated the efficiency of dust collection to verify the applicability of the system to control the dispersion of dust.



▲Testing dust dispersion



M: Mist spray E: Water ejector PW: Processing aid (water) spray
M+E: Combination of M and E M+PW: Combination of M and PW
E+PW: Combination of E and PW

▲Relationship between spray type and dust-collection efficiency (processed with ceria)

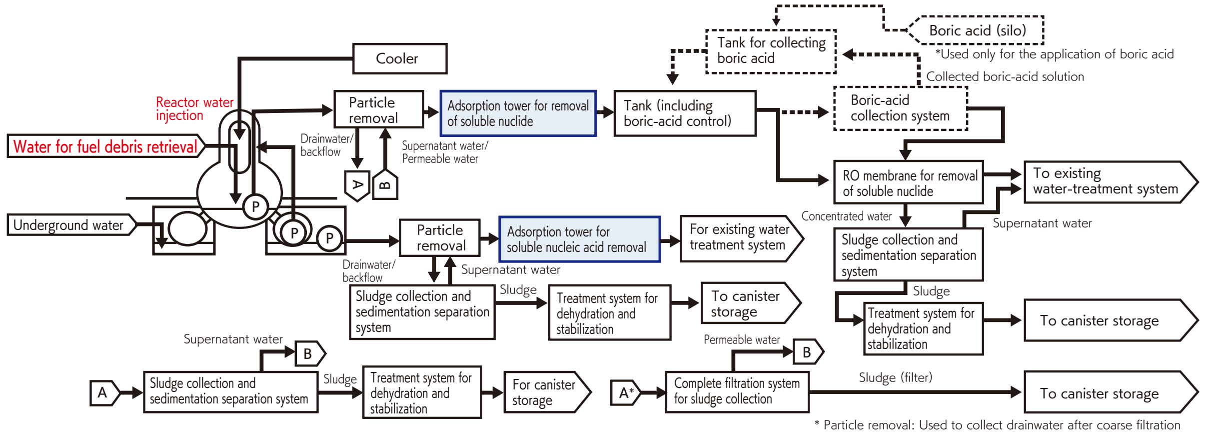
Developing technology for handling fuel debris (disposal of fuel debris and accumulated material)

Equipment for removing nuclides from circulated coolant

The coolant-circulation system depicted in the diagram below is being considered for use during the retrieval of fuel debris. Large numbers of α nuclides and other radioactive nuclides originating in fuel debris are expected to dissolve in the circulated coolant due to increases in surface area resulting from fuel debris processing, changes in the quality of water accumulated within the PCV, and other factors. To reduce the risk of leaks and decrease the effects of radiation exposure on the public, the coolant-circulation system may need to be continuously operated while these nuclides are removed.

Development through FY 2020 focused on first designing the overall concept of the liquid system and determining the requirements for each of its components. Next, the literature study and adsorption tests for the α nuclides that must be removed were conducted to select the candidate material for adsorbing the nuclides. Based on those results, the concept for a system that removes soluble nuclides was designed and the challenges involved in applying that concept to an actual machine were identified.

Since FY 2021, IRID has been studying plans for conducting suction tests in a simulated gas phase environment and one that uses actual coolant to further assess suction performance within the above-water sections of the PCV as well as the impact that coolant components have on suction performance.



* Particle removal: Used to collect drainwater after coarse filtration
Ⓟ···pump

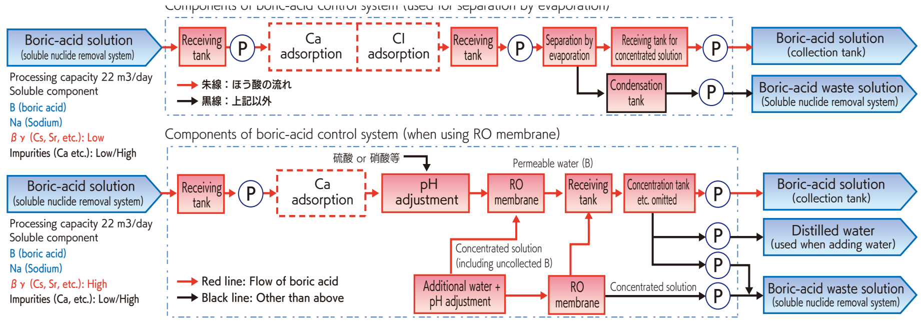
▲Flow chart of the liquid phase system (example)

Developing technology for handling fuel debris (disposal of fuel debris and sediment)

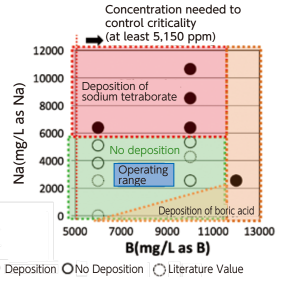
Boron-adjusting equipment

This research explored the issues with using a sodium-pentaborate solution to evaluate criticality, a method that was developed under a subsidy project as part of establishing methods for evaluating criticality and developing technology for controlling it. The results of this study are summarized below.

- Obtained deposition data on concrete components, substances in underground water, and boron then determined a rough guide for managing concentrations.
- To collect the boron, evaporative separation and a reverse-osmosis (RO) membrane was chosen. The theory behind the points at which boron passes through the RO membrane within a slightly acidic environment was confirmed.



▲Boric acid collection technology



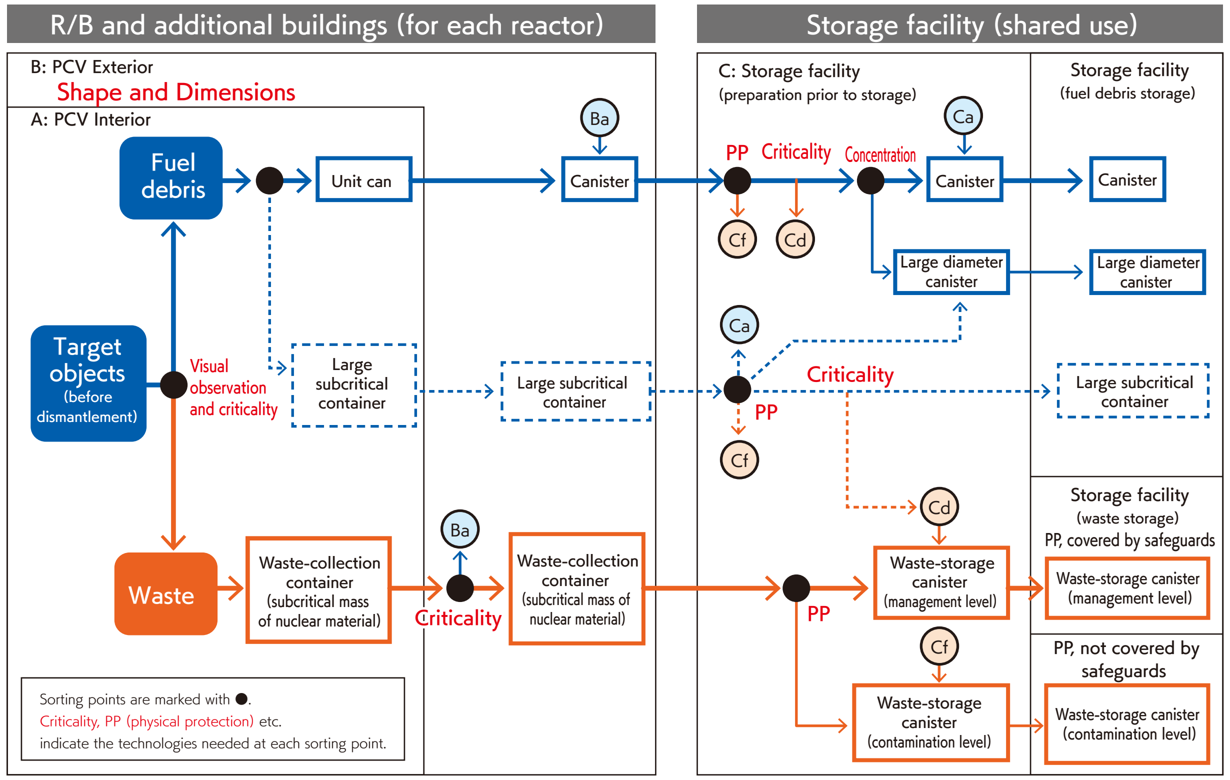
▲Scope of operational adjustments (under continuous use of boric acid)

Developing technology to sort fuel debris and radioactive waste

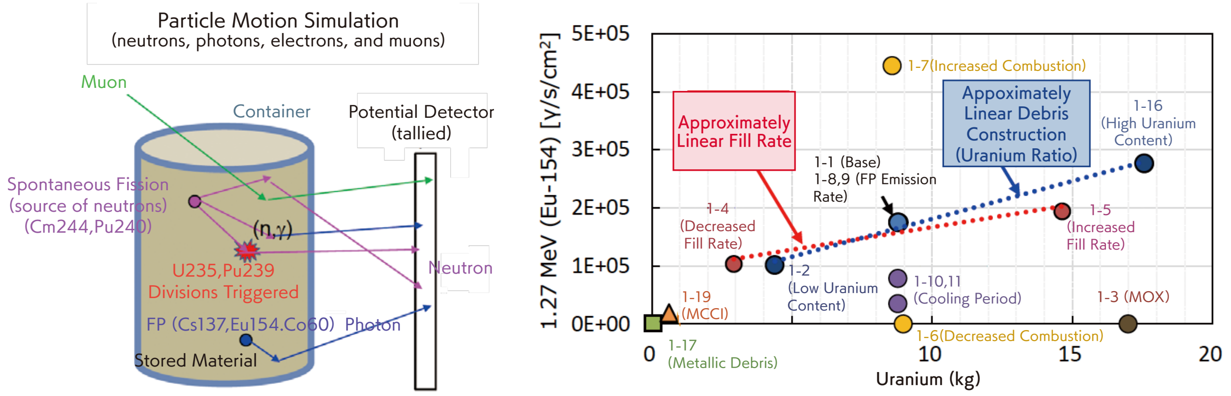
Studying sorting scenarios and evaluating measurement technology

If we can measure the amount of nuclear fuel in the material retrieved from the primary containment vessel during the decommissioning of Fukushima Daiichi NPS then sort it into fuel debris and radioactive waste, it should be possible to streamline everything from the retrieval of fuel debris to its storage, which will help stabilize Fukushima Daiichi as soon as possible. Unfortunately, the technology for doing so does not currently exist anywhere in the world. Thus, IRID studied multiple sorting scenarios (Figure 1-1) and conducted the technical investigations needed for each sorting point.

Through this process, the following measurement techniques that could be applied to sorting were identified: the active neutron method, passive neutron method, passive γ method, muon scattering method, and high-energy X-ray CT method. In FY 2020–2021, IRID used simulations to evaluate how much the properties, compositional diversity, and other characteristics of fuel debris affect measurements taken; this was done to identify the challenges in developing each of these measurement techniques (Figure 1-2). Moving forward, aiming for on-site application, it is necessary to develop measurement systems, reassess sorting scenarios, conduct verification tests using simulated debris, and take other action according to plan.



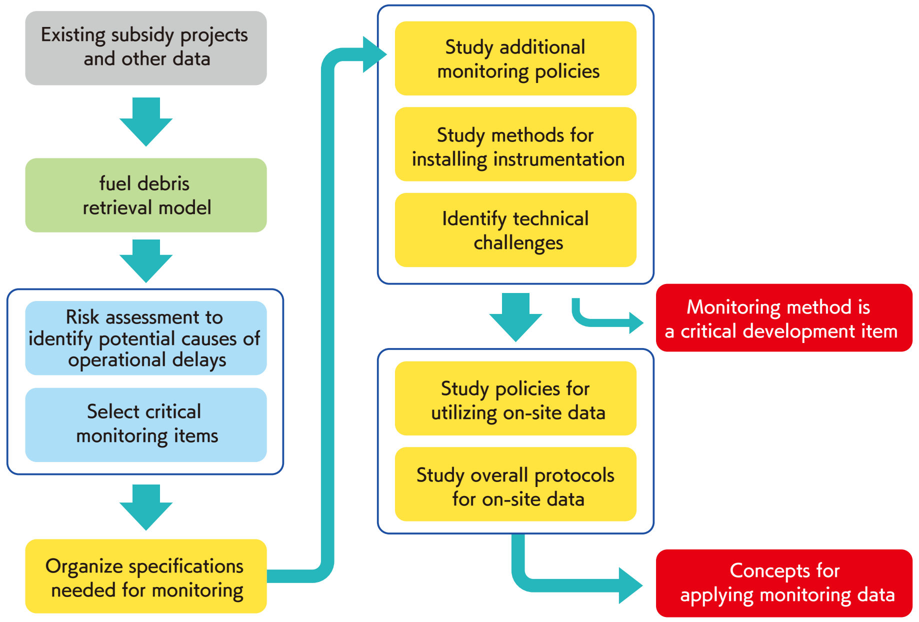
▲Sorting scenario plan (Figure 1-1)



▲Simulation of passive γ measurements (Figure 1-2)

Developing systems for continually monitoring inside the primary containment vessel (PCV)

When further expanding the scope of fuel debris retrieval, necessary technology is to continually monitor environmental changes in the PCV over long periods of time during retrieval work; this is to ensure safety and maintain throughput while remotely operating machines within a highly contaminated and radioactive environment that contains many unknowns. To continuously monitor the environmental changes in the PCV interior that occur due to fuel debris retrieval work, this project will organize and select monitoring items (taking into account safety requirements and whether operations are continuous) as well as compile and study the underlying concepts of various monitoring methods while considering on-site feasibility. The overall development process is indicated in Figure 1.



▲Development process for a continuous monitoring system inside the PCV (Figure 1)

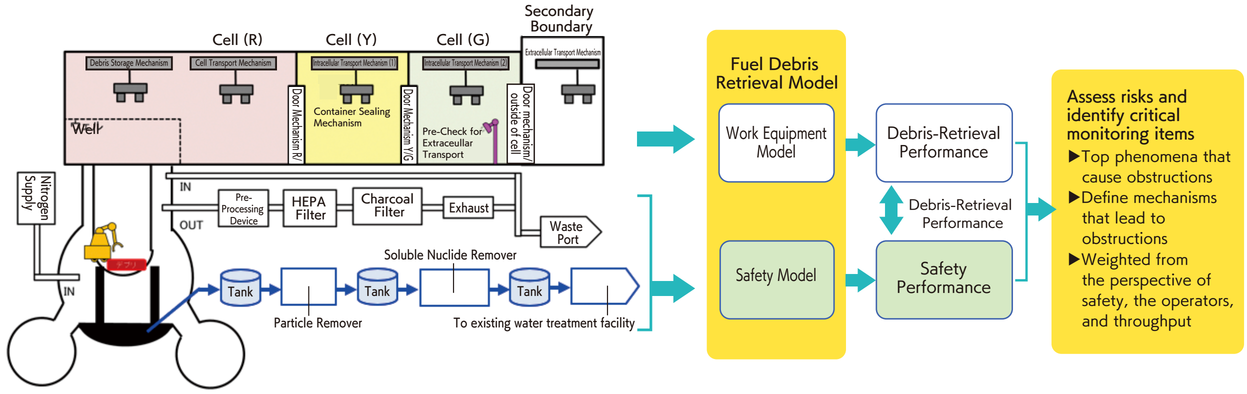
❶Investigating the monitoring items for the PCV interior

・Examining the critical monitoring items

IRID determined the critical monitoring items by creating models of the processes for retrieving and transporting fuel debris, including additional safety features, and assessing the risks identified as causing operational delays. For the risk assessment, we devised a weighted method that takes safety, operators, and throughput into account (Figure 2). Also, Figure 3 depicts an example of the results for critical monitoring items.

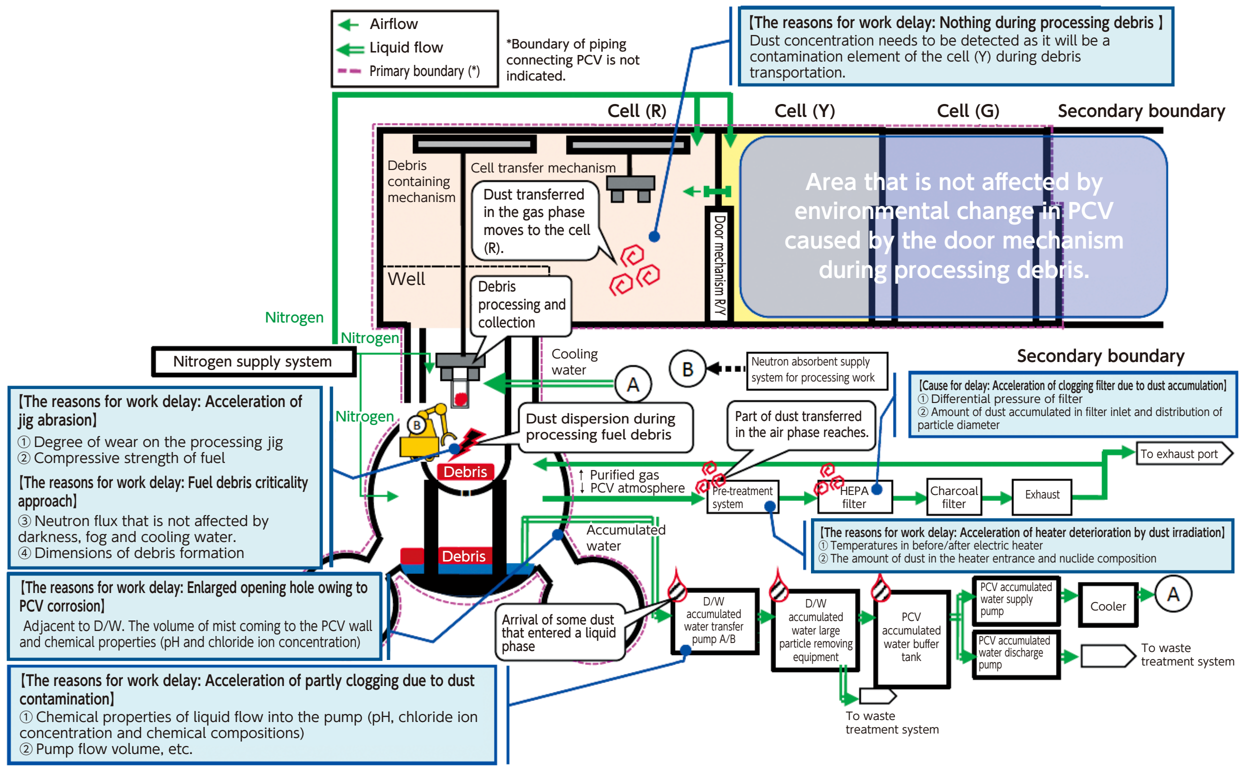
・Organizing the technical specifications needed for monitoring

Our critical monitoring items included things like measured physical quantities (such as dust concentration and pressure differential), the environment (status of fuel debris processing etc.), and whether something needs to be monitored continuously.



▲Protocol for identifying critical monitoring items for the PCV interior (Figure 2)

Developing systems for continually monitoring inside the PCV (Proposal)



▲An example of the extraction result of important monitoring items (Figure 3)

❷Exploring monitoring methods

IRID analyzed the trends in the results for the risk assessments described in ❶ and selected the following areas to study in earnest moving forward:

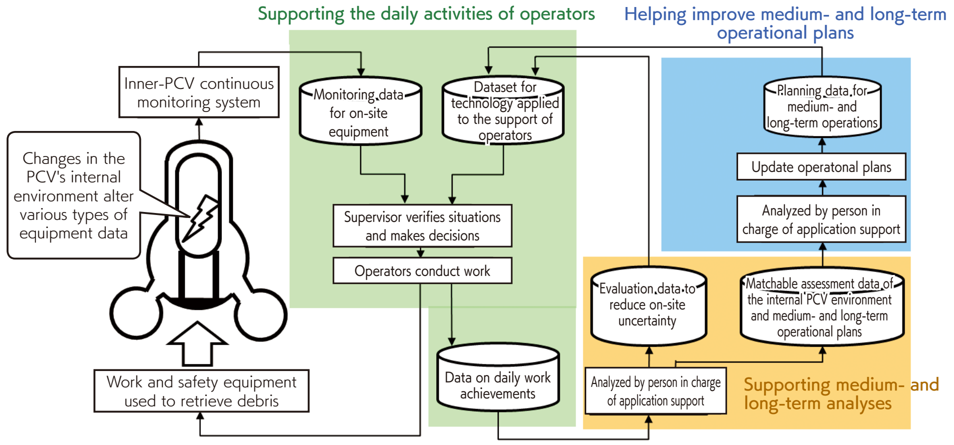
- Study additional methods of monitoring
- Explore ways to install measurement equipment
- Identify technical challenges

❸Examining management method of integrated management support technologies

So that operators can more rapidly and appropriately respond to on-site conditions each day, IRID studied concepts of the operation for plant data supplied by a continuous monitoring system within the PCV. This was done from the perspective of supporting the daily activities of operators and helping with analysis and the planning of work improvements over the medium and long term.

Moving forward, these concepts will be applied to the following areas:

- Studying policies for utilizing on-site data
- Exploring overall protocols for on-site d



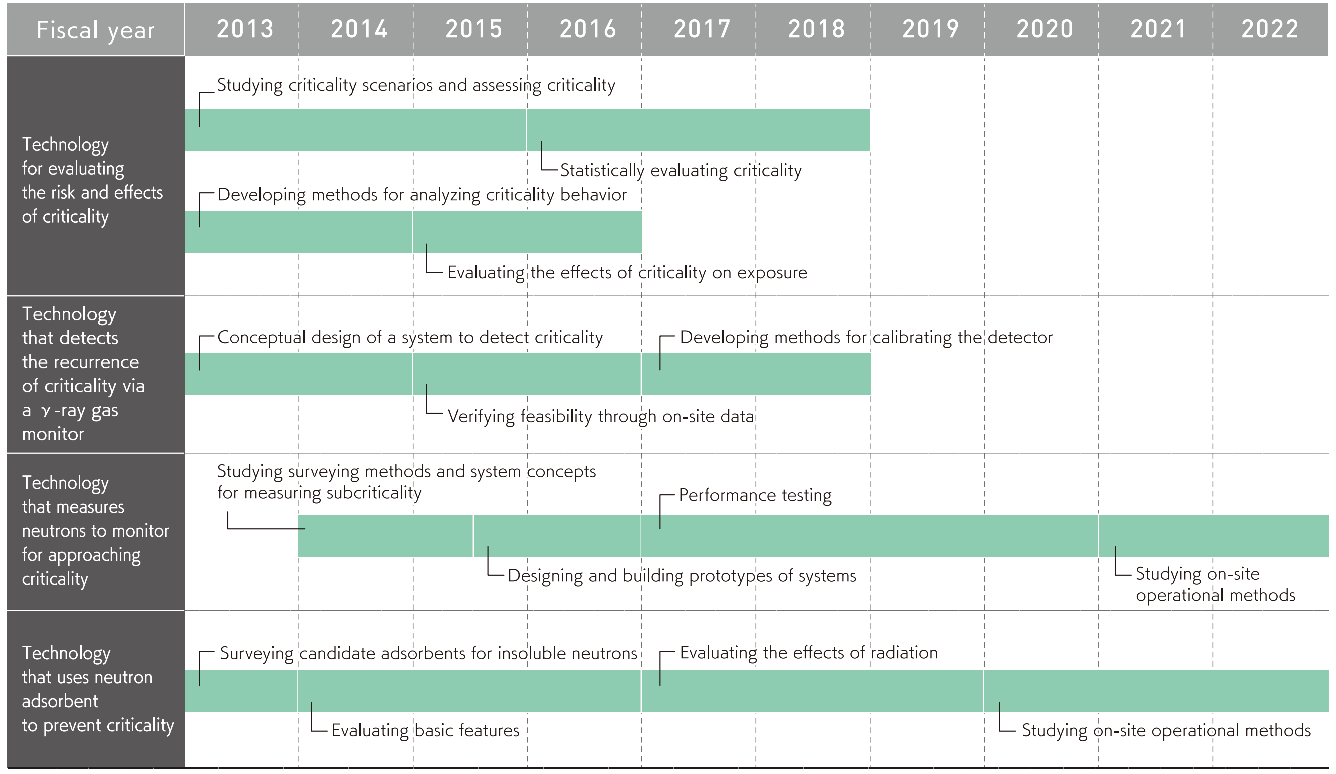
▲Concept for on-site application of a continuous monitoring system inside the PCV (Figure 4)

Development of technology for criticality control of fuel debris

Detecting and controlling abnormalities promptly to prevent criticality during fuel debris retrieval

- Determine the risks of criticality occurring in fuel debris; understand the effects of radiation exposure on criticality; develop technology for appropriately managing criticality
- Monitor approach to criticality and develop methods to prevent criticality
- Develop methods to swiftly detect and halt criticality if it occurs
- Finalize methods for applying the developed criticality-control technology to the on-site environment

Research and development progress



Background

Monitoring data from the plant has revealed that the fuel debris is currently in a subcritical state. As the properties and water content of fuel debris can be expected to change as debris retrieval and other operations are conducted, however, criticality needs to be properly managed so that it does not occur in the future. This will allow fuel debris retrieval to be completed safely and without issue.

Purpose

To ensure the safety of workers and the general public and to prevent them from being exposed to radiation during the retrieval of fuel debris, IRID has worked to develop technology for avoiding criticality as well as detecting and suppressing it in the rare chance that it occurs.

Specifically, the goals are to:

① determine the risks of criticality occurring in fuel debris and the effects of radiation exposure caused by criticality;

② develop techniques to detect if criticality is near and prevent it from occurring;

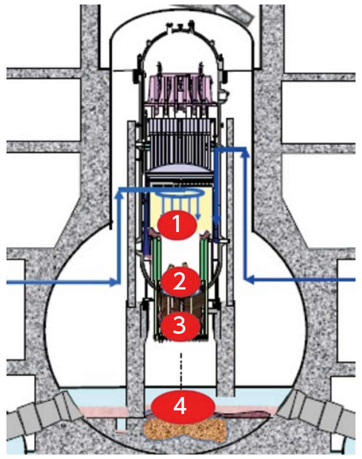
③ develop techniques to detect if criticality has occurred and to halt it; and

④ devise ways to apply the developed criticality-management technology to specific on-site environments.

1 Criticality scenarios and risks based on the estimated distribution of fuel debris

Overall, there is believed to be little risk of criticality occurring due to fuel debris becoming submerged or undergoing changes during retrieval. Although there remains a significant amount of fuel debris with relatively large exposed sections, the risk of criticality should still be low considering what it could possibly be composed of.

Nevertheless, there is currently a lack of information on the detailed distribution, composition, and properties of fuel debris, which is why IRID is developing technology to prevent and mitigate criticality if it does happen to occur.



▲Locations where fuel debris is assumed to exist

Location	Criticality Scenario	Unit 1	Unit 2	Unit 3
1 Reactor Core	• Submerging of remaining fuel	Minimum (almost no remaining fuel)	Medium (Fuel could remain in and around the core)	Small (Fuel could remain around the core)
2 Lower RPV	• Submerging of fuel debris • Change of state during retrieval	When submerged: small During retrieval: minimum (small remaining amount)	When submerged: medium During retrieval: small (large amounts of remaining and exposed fuel)	When submerged: medium During retrieval: small (large amounts of remaining and exposed fuel)
3 CRD※ Housing	• Submerging of adhered fuel debris	Small to minimum (small risk due to amount and form of adhered material)	Small to minimum (small risk due to amount and form of adhered material)	Small to minimum (small risk due to amount and form of adhered material)
4 PCV Bottom	• Submerging of exposed fuel debris • Change of state during retrieval (content; winding)	When submerged: small During retrieval: small (large remaining amount, low exposure amount)	When submerged: small During retrieval: small (somewhat small remaining amount with somewhat high exposure)	When submerged: small During retrieval: small (large remaining amount but small exposure)

*CRD: Control-rod drive mechanism

2 General overview of technology for controlling criticality during fuel debris retrieval

To maintain subcriticality, IRID is studying plans for managing criticality based on multi-stage protection.

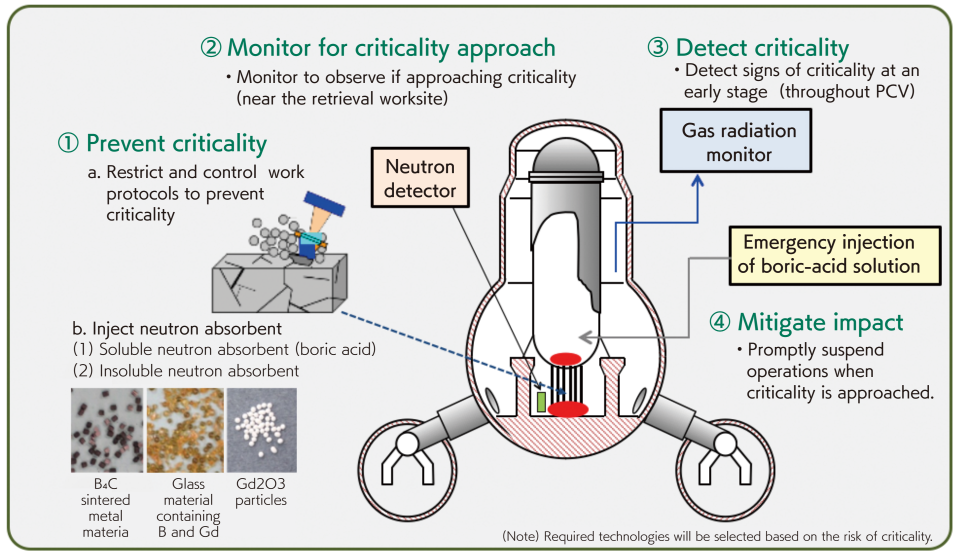
This includes:

① restrictions placed on work protocols so that reactivity stays low, and if necessary, technology that prevents criticality through the use of a neutron adsorbent;

② monitoring technology used to ensure that criticality is not imminent while work is being performed;

③ technology that can quickly detect a state of criticality; and

④ halting criticality through an emergency injection of boric acid in the unlikely event that it occurs.



(Note) Required technologies will be selected based on the risk of criticality.

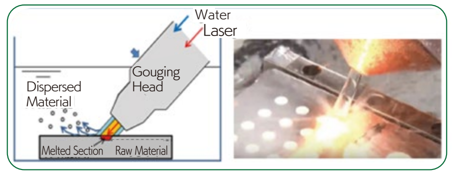
3 Technology for preventing criticality (restriction and control of work protocols)

It is possible to imagine scenarios in which criticality is approached due to a perfect combination of fuel debris consistency and water content.

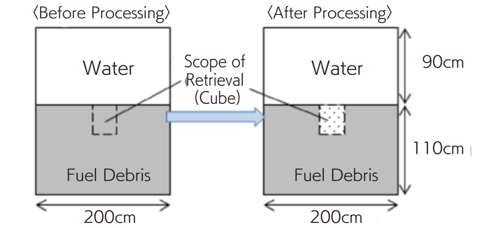
By limiting the amount of fuel debris that can be retrieved per shift, unexpected increases in reactivity from leading to a state of criticality can be prevented (for example, the graph up to 16 cubic centimeters in Figure 1).

▲Core boring; accumulation of water fine debris powder and in the cored hole

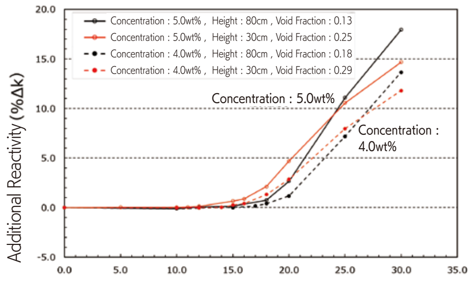
▲Pulverizing debris with a chisel; mixture with water due to crevice expansion



▲Laser gouging; dispersed material accumulated in specific locations



▲Evaluation system (added reactivity due to the perfect mixture of water and fine fuel debris powder)

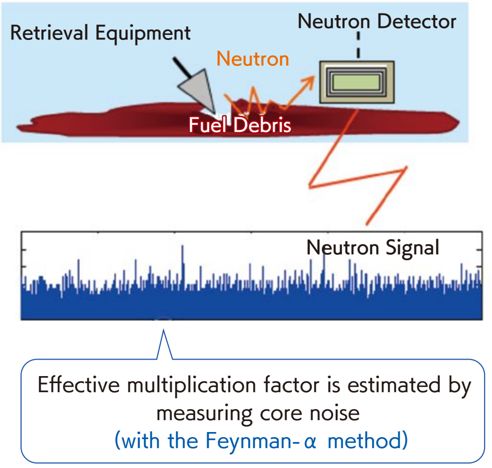


▲Relationship between additional reactivity and the amount of debris retrieved per shift (Figure 1)

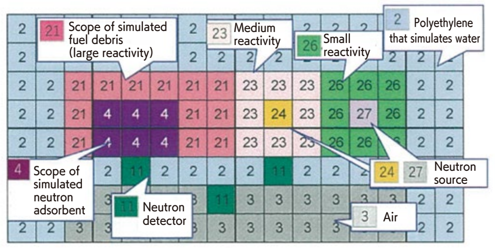
4 Technology that measures neutrons to monitor for approaching criticality

To monitor for approaching criticality, neutrons will be measured in the vicinity of fuel debris retrieval work.
In testing conducted at KUCA*, IRID learned that the effective multiplication factor can be estimated by analyzing neutron signals (core noise measurement by Feynman-alpha method), even for fuel debris that is unevenly distributed (Figure 2).

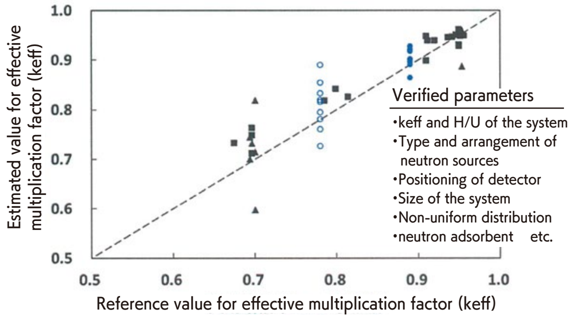
*Kyoto University Critical Assembly



▲Estimating effective multiplication factor by measuring core noise with the Feynman-α method



▲Example of testing system that simulates fuel debris at KUCA (reactor core simulating the neutron adsorbent and an uneven debris distribution)

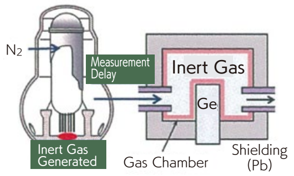


▲Results of evaluating effective multiplication factor with the Feynman-alpha method (Figure 2)

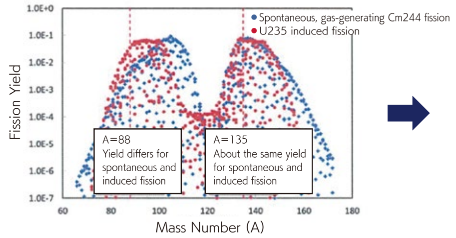
5 Technology that detects the recurrence of criticality via a PCV gas radiation monitor

The PCV gas-management system is continuously measuring the radioactive concentration of nuclides to monitor how much is released into the environment.

At present, Xe-135 (which has a primary peak at 250 keV) is being measured to detect the recurrence of criticality; however, making improvements (such as a highly sensitive germanium detector) that allow Kr-87 and Kr-88 to be measured will speed up the detection process and enable estimation of the degree of subcriticality.

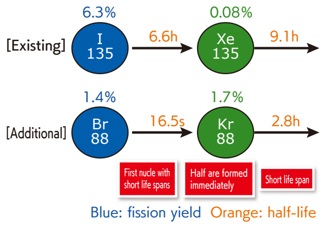


▲PCV gas-management system

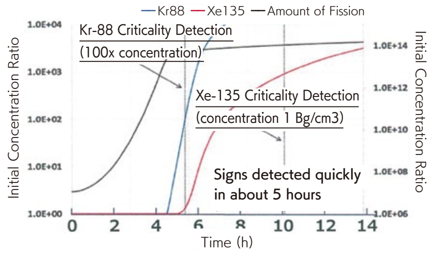


▲Yields for spontaneous and induced fission

Estimation of neutron source coefficient in Reactor 1 as calculated from detailed long-term measurement using the difference between spontaneous and induced fission yields: 0.5 to 0.7



▲Behavior of monitored nuclides



Detection of approaching criticality via Kr-87 and Kr-88 in about half of the 5 hours required for Xe-135 measurement (in an actual case) (Figure 3)

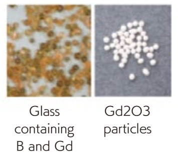
▲Evaluating criticality detection when a criticality event is suspected (Figure 3)

6 Technology that uses an insoluble neutron adsorbent to prevent criticality

n order to differentiate fuel debris according to its properties, IRID studied absorption material with different characteristics: a solid (granular) type and a solidified (water glass) type.

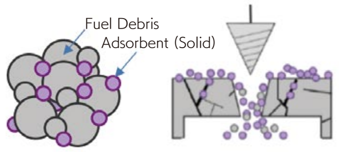
A variety of tests related to basic material properties, adhesion and miscibility, secondary effects due to radiation (hydrogen generation, changes in water quality or structural materials, etc.), workability, and other areas were conducted to select the candidate material.

- **Verifying the miscibility of fuel debris and adsorbent (Figure 4)**
- **Confirming that the material can be injected underwater at a stable speed (Figure 5)**



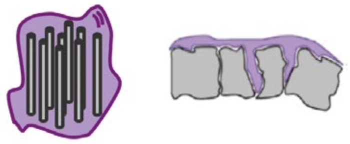
▲Solid Adsorbent

▲Solidified Adsorbent



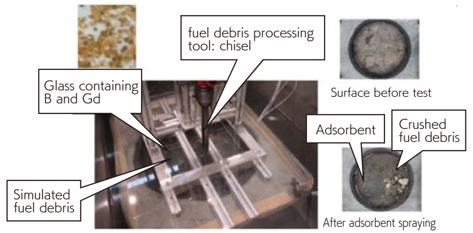
▲Applying the solid-type adsorbent

Adheres to surface of pebble- and rock-like debris then penetrates into crevices



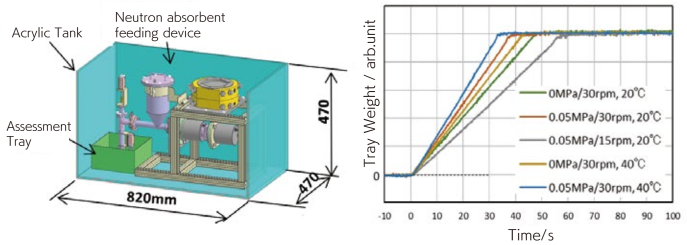
▲Applying the solidified-type adsorbent

High viscosity, so it covers the surface of fuel debris as it changes shape



a) Underwater testing with chisel (simulated lower pedestal)
b) Surface appearance before and after testing

▲Injection/Crushing test on fuel debris with insoluble adsorbent (Figure 4)



(a) The test setup
(b) Changes over time in the amount of adsorbent injected

▲Verifying the performance of underwater injection (Figure 5)

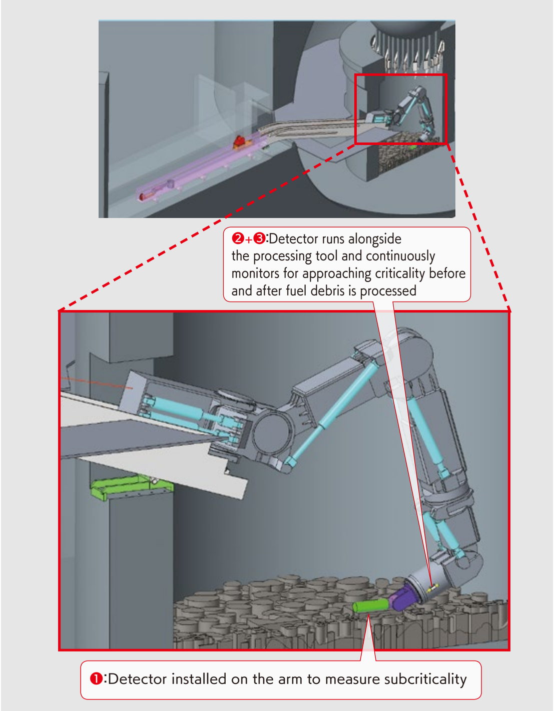
7 Methods for criticality approach monitoring technology in the on-site environment

IRID has established protocols for monitoring if criticality is being approached during fuel debris retrieval and formalized methods for the on-site application of such technology. Monitoring for approaching criticality involves three steps: ① understanding the state of conditions prior to retrieval work, ② monitoring both before and after the processing of fuel debris, and ③ continuous monitoring of fuel debris processing. Protocols are followed as necessary depending on how factors such as the work location and operational steps affect the risk of criticality.

Different neutron detectors will be used to suit each of those purposes, and they will be set in a way that avoids interfering with retrieval work as much as possible.

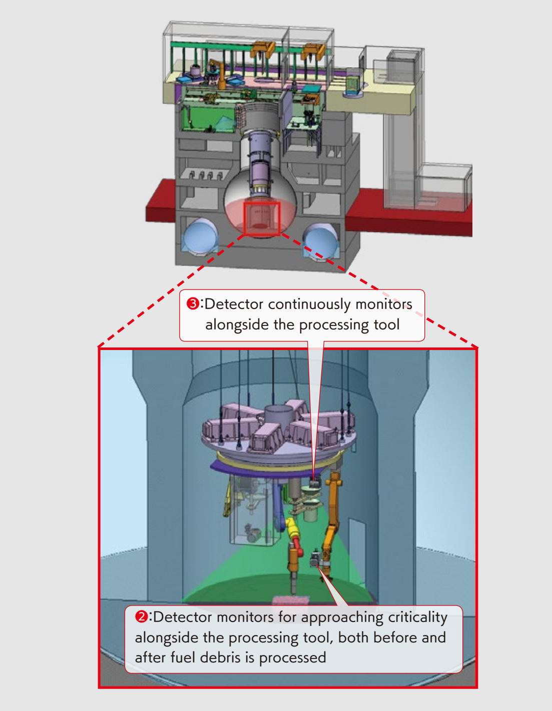
Monitoring Protocol (Objective)		❶ Ascertain conditions prior to retrieval work	❷ Monitor before and after fuel debris processing (determine when processing begins/continues)	❸ Monitor neutron flux during fuel debris processing (detect unforeseen changes)
Neutron Detector	Name	Subcriticality detector	Criticality detector	Continuous-monitoring detector
	Type	Arm-type device positioned above debris	Arm-type device installed alongside processing tool	Installed alongside processing tool and above fuel debris
	Weight	30～100kg	30～50kg	Less than 30kg
Monitoring and Measurement Methods	Method	Measure the degree of subcriticality (Feynman-alpha method) only once prior to the start of fuel debris retrieval to establish the initial state. ★Absolute-value measurement of the neutron multiplication factor	Measure neutron flux before and after the processing of fuel debris (for each fixed volume of processing such as 4,000 cm3) to determine if criticality is approaching (or if processing can continue). ★Absolute-value measurement of the neutron multiplication factor	Monitor neutron flux during processing. Detect signs of criticality (a sustained increase in neutron flux) and use them to determine if the criticality danger has passed. ★Absolute-value measurement of the neutron multiplication factor
	Measurement Time	Several hours to one week (depending on site conditions)	About 10 minutes	Continuously during processing
	Measurement Points	One point in the vicinity of the retrieval work	Move with processing location as appropriate	Same as left as well as places that overlook processing locations
Application points and stages for each monitoring protocol				
When retrieving accumulated material from inside the pedestal and around the lower RPV head		Applied	Applied	Applied
When removing obstacles from within the PCV		–	Applied	Applied
When retrieving from the core		–	Applied	Applied

Example of Side-access Retrieval



▲Monitoring for approaching criticality when retrieving PCV fuel debris from the side

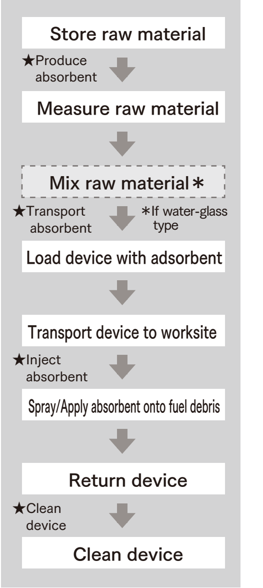
Example of Top Retrieval



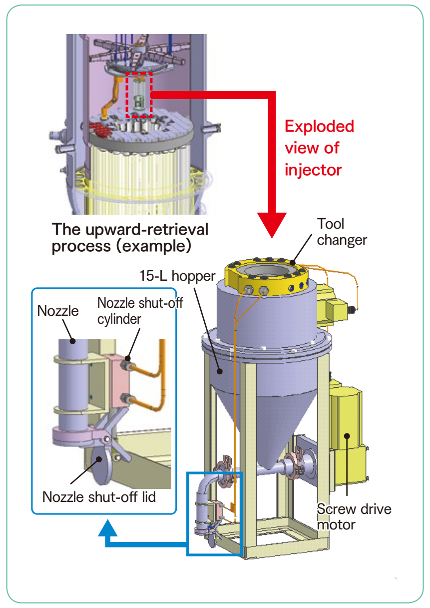
▲Monitoring for approaching criticality when retrieving PCV fuel debris from the top

8 Using insoluble neutron absorbent at the plant

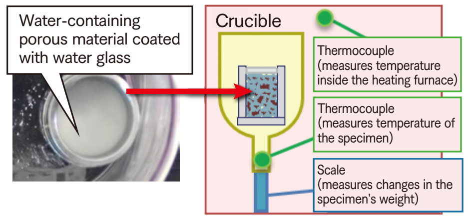
Based on the developmental progress of equipment for processing and collecting fuel debris, IRID has formalized protocols for using an insoluble absorbent in spraying and injecting devices. There were concerns that a water-glass absorbent would solidify on the surface of fuel debris and negatively affect its drying behavior (the debris will be dried to prevent the generation of hydrogen). Therefore, its drying characteristics using simulated fuel debris were tested.



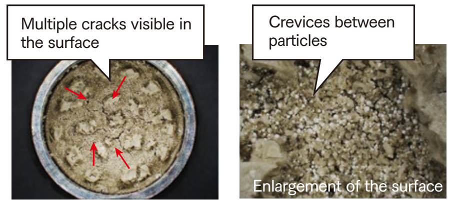
▲Example protocol for the on-site injection of insoluble neutron absorbent



▲Injector for granular Gd absorbent



(a) Overview of drying test conducted in the crucible



(b) Observations of water-glass appearance after drying test

Heating causes cracks to form between chunks and particles of the water-glass material, which suggests that the water content of the porous material could be sufficiently dried out. Moving forward, IRID will investigate this process further.

▲Drying test of porous material coated with water glass

9 Proposals for applying criticality-control technology applicable to the fuel debris retrieval work

The table below contains several ideas for applying the developed criticality-control technology, taking into account factors such as the amount of fuel debris extracted and the criticality risk for each retrieval method. Retrieval methods that extract large amounts of fuel debris and cause significant changes in its state have a relatively higher risk of criticality, so IRID will strive to make a variety of criticality-control technologies available for selection.

Small　Degree of change in fuel debris　Large

Retrieval work		Internal investigations	fuel debris retrieval			
			Scope of retrieval gradually expanded			Full-scale retrieval
Retrieval amount		Tiny (a few g)	Small (a few kg)		Small (several to ten kg)	Full (several hundred kg per day)
Retrieval method		Gripping, suction, etc.	Gripping, suction, etc.	Core boring etc.	Core boring etc.	Core boring, chisels, etc.
①Prevent criticality	Work restrictions (①a.)	Method has no effect on fuel debris	Method has no effect on fuel debris	･Limit the amount of processing per shift ･Limit the distance between retrieval sites	･Limit the amount of processing per shift	･Limit the amount of processing per shift (expanded)
		–	–	Monitor neutron flux	Monitor neutron flux	Monitor neutron flux
②Monitor for approaching criticality	Monitor for approaching criticality (②)	–	–	–	–	Measure degree of subcriticality 1
	Insoluble neutron absorbent (①b.(2))	–	–	–	–	Insolube neutron absorbent 2
	Soluble neutron absorbent (①b.(1))	–	–	–	–	Sodium-pentaborate solution 3 (6000 ppm)
③Detect criticality	Detect criticality	Monitor PCV radioactive gas	Monitor PCV radioactive gas	Monitor PCV radioactive gas and neutron flux	Monitor PCV radioactive gas and neutron flux	Monitor PCV radioactive gas and neutron flux
④Alleviate effects	Resolve criticality	Inject sodium-pentaborate solution	Inject sodium-pentaborate solution	Inject sodium-pentaborate solution	Inject sodium-pentaborate solution	Inject sodium-pentaborate solution

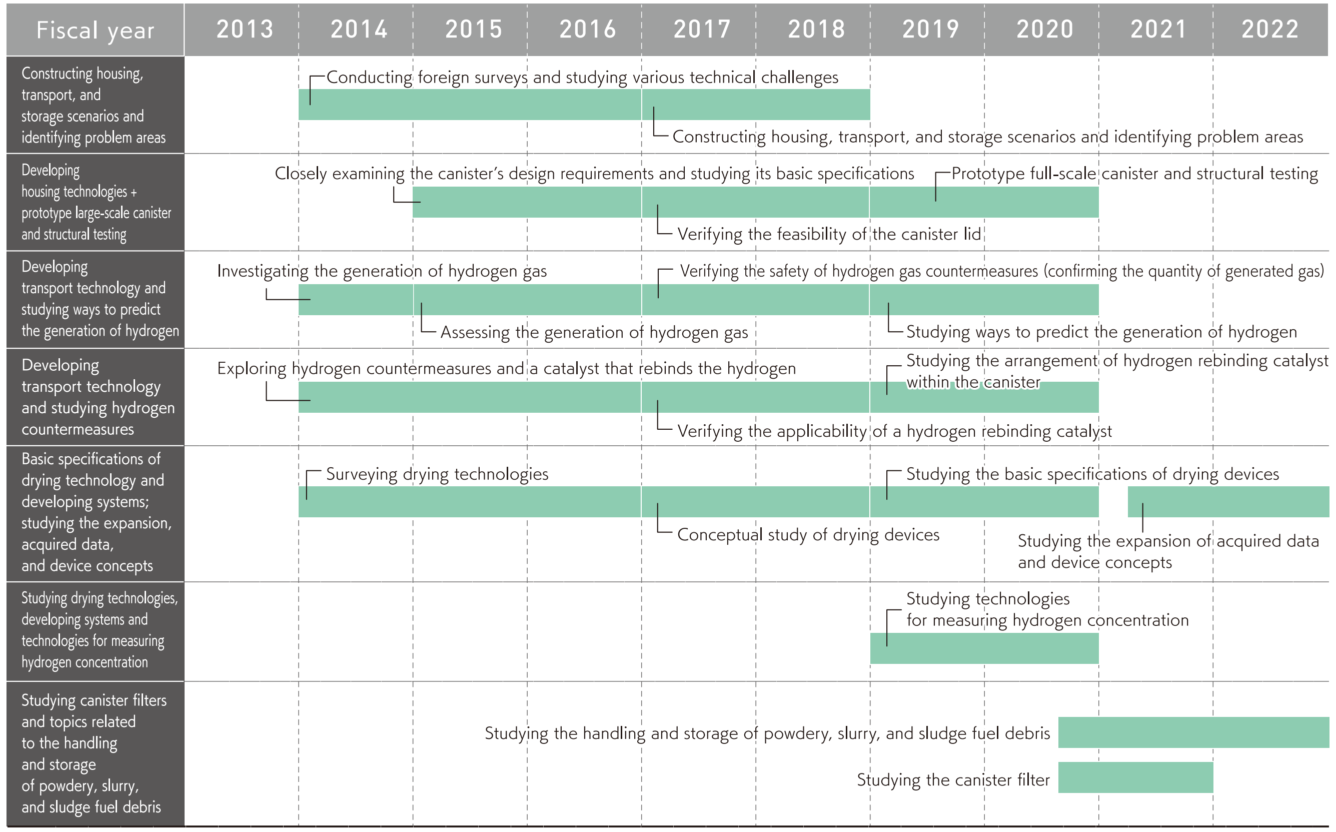
1, 2, 3 Can be selected based on the specifics of retrieval work and on-site conditions. * The numbers ① through ④ correspond to the figure on page 96-2).

Development of technology for containing, transfer and storage of fuel debris

Developing canisters forcontaining, transport, and storage so that fuel debris can be stored safely over the long term

- Constructed containing, transport, and storage scenarios and identified problem areas
- Developed containing technologies (prototype full-scale canister and structural testing)
- Developed transport technology (studied ways to predict the generation of hydrogen and deal with the gas)
- Developed drying technology and systems (studied the expansion of basic specifications, acquired data, and device concepts for drying equipment as well as technology for measuring hydrogen concentration)
- Studied canister filters and topics related to the handling and storage of powdery, slurry, and sludge fuel debris

Research and development progress



Background

To decommission Fukushima Daiichi NPS, technology that allows to safely and logically contain, transport, and store retrieved fuel debris is needed. Because fuel debris contains nuclear fuel, it is particularly important that radioactive material (to prevent the spread of contamination) is sealed and handled so that it remains in a subcritical state.

During the decommissioning of the Unit 2 at Three Mile Island (TMI-2) in the U.S., collected fuel debris was contained and handled in special containers (canisters) while using existing technology for transporting and storing spent fuel and for managing radioactive waste to keep the material sealed, logically achieving the safety requirements. Employing existing technology by utilizing canisters that fit the individual realities of each situation should thus be an effective approach.

Purpose

There are differences between TMI-2 and Fukushima Daiichi NPS. The latter was inundated with seawater at the start of the accident, and pieces of its melted core have reached the bottom of the reactor pressure vessel. Due to this additional complexity, those such as the requirements for canisters and methods for transporting fuel debris are also different. For that reason, IRID has been working to develop special canisters and related technology so that fuel debris can be contained, transported, and stored safely and logically at Fukushima Daiichi NPS .

1 Developing containing, transport, and storage scenarios and identifying issues

IRID developed scenarios covering everything from the sorting of fuel debris to managing facilities for its long-term storage. This was done to develop technology related to developing and using special canisters for safely and logically containing, transporting, and storing fuel debris at Fukushima Daiichi NPS. Each scenario was developed by establishing hypothetical conditions based on the actual situation at the plant, taking into account the handling of radioactive material and safety design (subcriticality, heat removal, quarantining, shielding, structures (consideration of usability; resilience against possible phenomena), materials (long-term integrity), hydrogen measures, fire prevention, throughput (processing capabilities) for the estimated amount of fuel debris, layout (required space), ease of maintenance, etc.). In addition to overseas studies and investigations on this topic conducted through FY 2016, other related developmental data when creating the scenarios were used.

As a result of the study, it was confirmed that long-term dry storage of fuel debris is a promising storage method compared to wet storage (pool storage) in terms of safety, the need for long-term water quality maintenance, and the fact that existing pool facilities are not expected to be diverted, and a scenario was tentatively established as the goal of this technology development. Therefore several scenarios were created with the goal of achieving that technological development. Based on the imagined scenarios, IRID then studied the flow of debris handling up through its dry storage (Figure 1).

From that process, challenges (technological development) that must be addressed to achieve the containing, transport, and storage of fuel debris were also identified. Finally, the results of all these investigations to select the areas that require continued study (as technological development items) after FY 2019, from the viewpoint of the safety designs studied thus far (subcriticality, heat removal, confinment, shielding, structures, materials, hydrogen measures, fire prevention, etc.) were used.

Those problem areas are listed below. For the results of technological development that addressed the below challenges, please refer to the pages that follow.

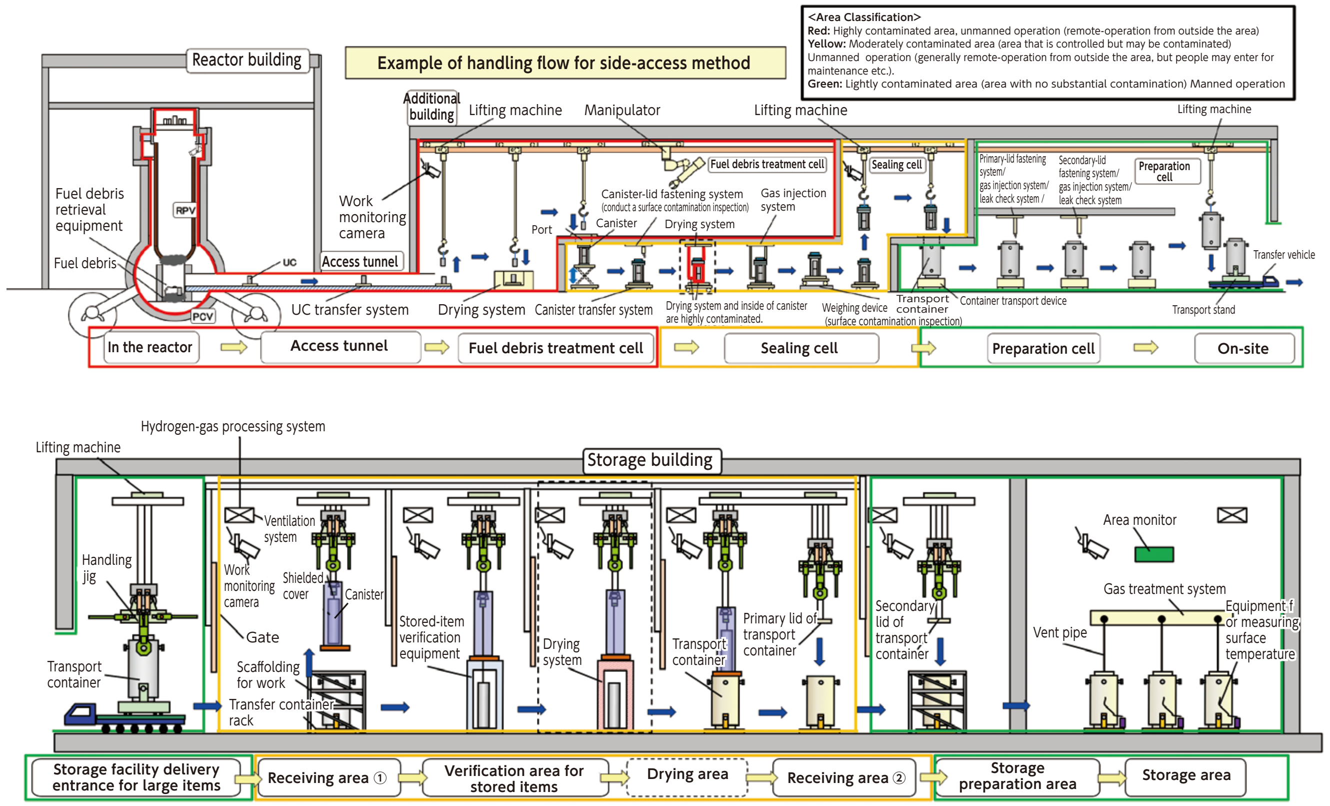
Challenges (Technological Development Items)

[Structural integrity of canisters] — Develop storage technology (prototype large-scale canister and structural testing)

[Measures for hydrogen generated by fuel debris] — evelop transport technology (study ways to predict the generation of hydrogen and deal with the gas)

[Plan to reduce the hydrogen generated by fuel debris] — Develop drying technology and systems (study the expansion of basic specifications, acquired data, and device concepts for drying equipment as well as technology for measuring hydrogen concentration)

[Measures for powdery, slurry, and sludge fuel debris] — Study the handling and storage of fuel debris as well as the canister filter

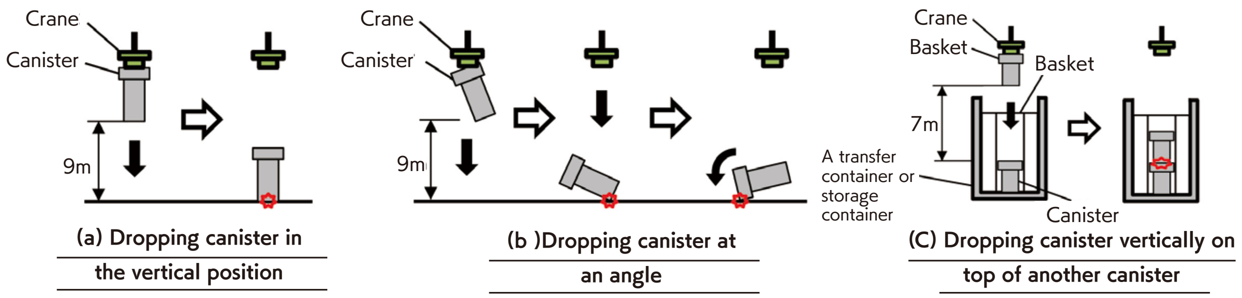


▲Example flow based on a scenario that involves containing, transferring, and storing fuel debris (figure 1)

2 Developing containing technologies + prototype large-scale canister and structural testing

Based on the safety requirements for canisters, IRID developed housing technology by designing structural drop tests (Figure 2), manufacturing prototype canisters (Figure 3), and conducting structural tests (Figures 4 and 5).
The results of the structural drop test on a full-scale canister confirmed that the canister specifications and structural designs developed by IRID are capable of maintaining safe conditions (quarantining and subcriticality).

In addition, comparing the results of structural testing and analyses allowed to verify the behavior when dropped, the relative offset of the lid and flange with regard to maintaining safety, the inner diameter of the canister body, and the fact that deformation was generally consistent. In this way, the applicability of the analysis method was confirmed.

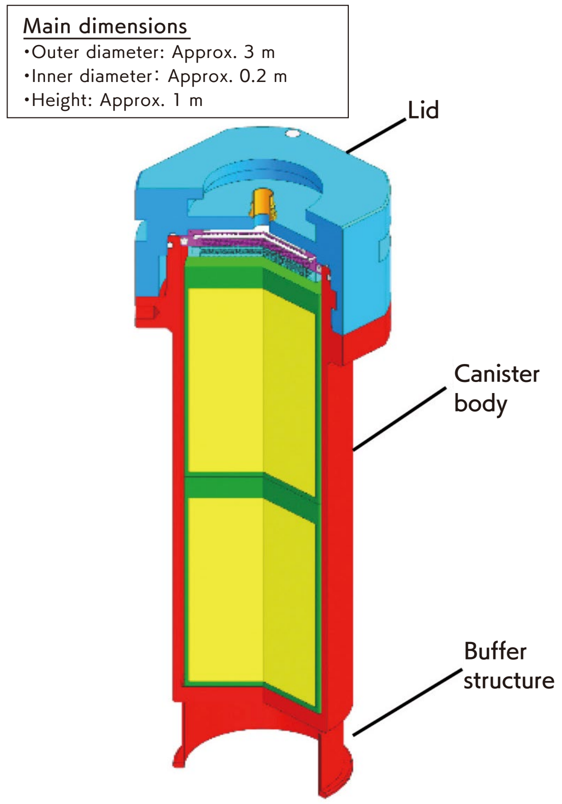


(a) Dropping canister in the vertical position

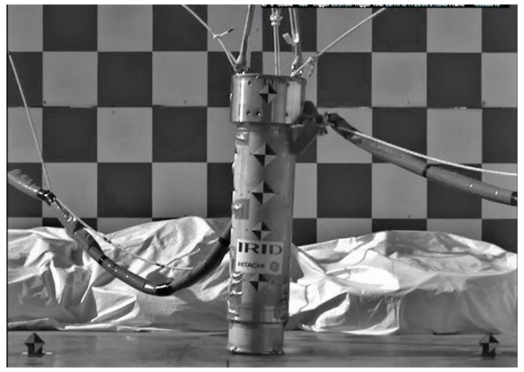
(b)Dropping canister at an angle

(C) Dropping canister vertically on top of another canister

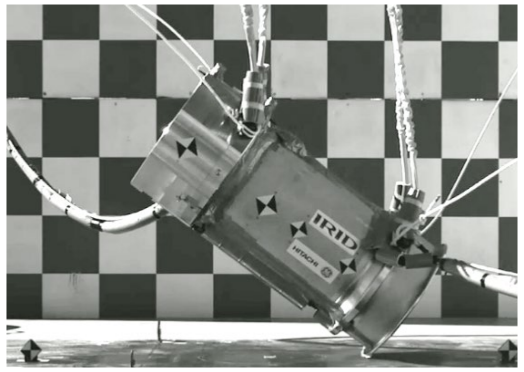
▲Conceptual images of drop events (figure 2)
A structural verification test was planned, in which a canister dropping event was simulated during handling.



▲Proposed canister structure (figure 3)
A prototype canister was designed and created to verify its structural integrity.



▲Structural test (dropped vertically) (figure 4)

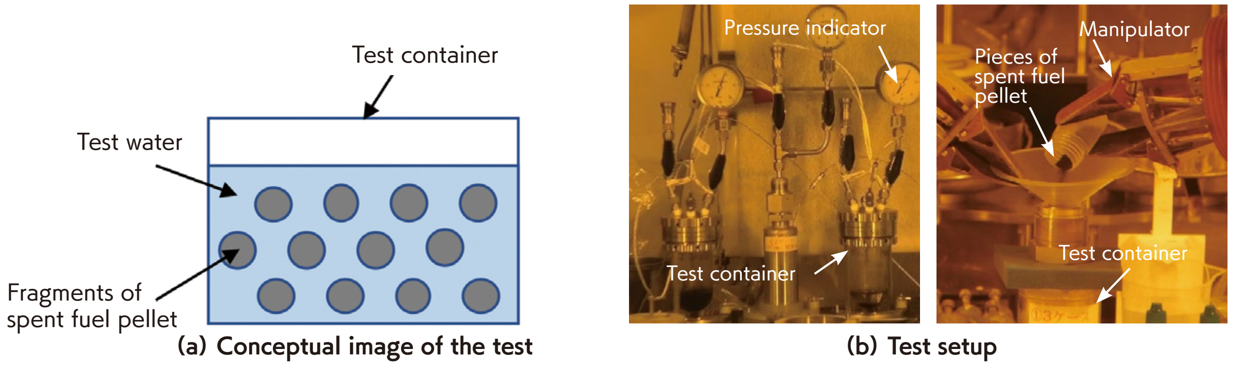


▲Structural test (dropped at an angle) (figure 5)
The structural tests were conducted by using a full-scale canister (prototype) that were designed and manufactured.

3 Developing transport technology and studying methods to predict the generation of hydrogen

To develop transport technology, IRID acquired knowledge from Japan and overseas about hydrogen-generation prediction methods and exchanged the opinions from experts while studying the items that must be considered before transport requirements can be established. Hydrogen generation using spent fuel (Figure 6) was tested and methods of predicting that generation to verify the suitability of a method (linear model) were studied for evaluating and confirming the validity of the energy-absorption rate.

Based on those results, a method for calculating the energy-absorption rate using a linear model and particle-transport formula was proposed to arrive at a predictive method appropriate for fuel debris. The amount of hydrogen generated in a canister was estimated and the transport requirements that will facilitate safe transport were considered.



(a) Conceptual image of the test

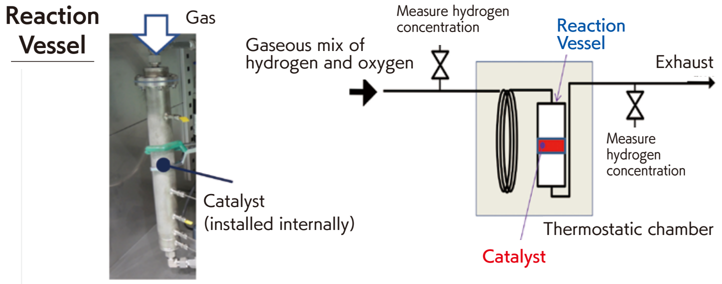
(b) Test setup

▲Hydrogen-generation test using spent fuel (figure 6)
A hydrogen-generation test using pieces of spent fuel pellet was conducted to verify the feasibility of the hydrogen prediction method.

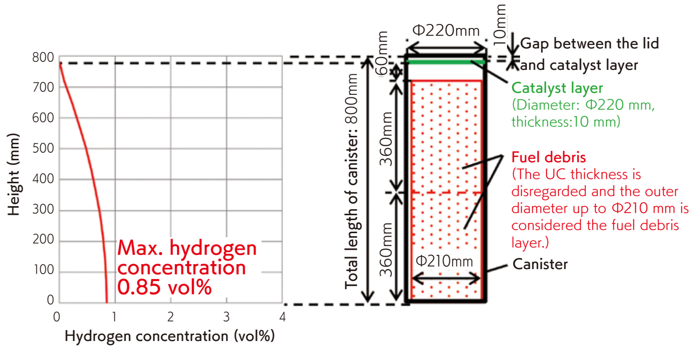
4 Developing transport technology and studying hydrogen measures

The accumulation of hydrogen is a problem when transporting fuel debris between buildings to the storage facility, and IRID has been studying methods of drying the debris to reduce the amount of hydrogen generated. As a backup plan, however, techniques that involve the use of a catalyst to rebind the hydrogen to oxygen was also studied.

The catalyst was subjected to a circulation-style reaction velocity test (Figure 7) to obtain data on its performance at different environmental temperatures, the presence or absence of water vapor, the dependence on hydrogen concentration, toxicity effects, and other areas. This testing verified that the catalyst is an effective way to deal with hydrogen. Even under the hypothesized conditions of temperature, water vapor, and strong internal hydrogen generation, the catalyst's performance was more than enough, with the hydrogen concentration staying sufficiently below the lower threshold for explosion (4 vol%). Based on the acquired catalyst data, the concentration distribution within a canister was also evaluated and the best catalyst arrangement for each quantity of generated hydrogen (Figure 8) was determined.



▲Concept for testing flow reaction velocity (figure 7)
We tested the flow reaction velocity to verify the performance of the catalyst.



▲Distribution of hydrogen concentration in canister (figure 8)
Taking into account the catalyst performance obtained in the test, the distribution of hydrogen concentration was evaluated with regard to the arrangement of catalyst within the canister.

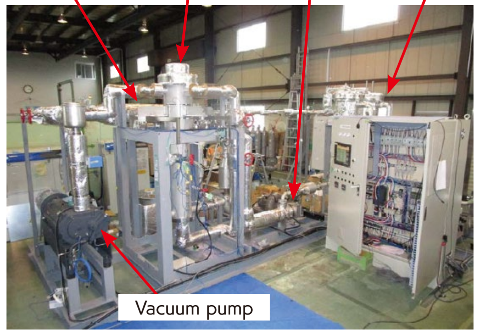
5 Developing drying technology and systems; studying the expansion of basic specifications, acquired data, and concepts of equipment

A technical issue that occurs when transporting fuel debris between buildings to a storage facility is the accumulation of hydrogen inside the hermetically sealed containers due to water within the debris. Removing that water content via drying is thus an effective way to reduce hydrogen generation.

Since the case of TMI-2 in the United States revealed that fuel debris is porous in nature, IRID focused on the drying behavior of porous material. Parameters that were effective for drying were defined, component testing to obtain data on drying behavior was performed, and a full-scale drying test (Figures 9 and 10) was conducted. Through this, the effects that drying method and operational requirements have on drying behavior was verified.

IRID then studied proposals regarding basic specifications for equipment to dry the fuel debris at Fukushima Daiichi NPS, taking into account the aforementioned results as well as other factors such as retrieving fuel debris and maintaining equipment within contaminated zones.

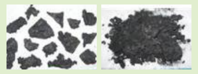
Based on the fact that there is great diversity among fuel debris and its byproducts, the data needed for technology that can handle material that is difficult to dry (Table 1) was also expanded and supplemented and plans for testing that would ascertain the drying properties as needed were devised to establish drying device concepts and operational requirements that reflect the target water content and drying speed.



▲Appearance of full-scale drying test equipment (figure 9)
To verify the effects on drying behaviors affected by the drying method and operational conditions, a full-scale drying system was manufactured and verified.

▲Test piece in drying test (Figure 10)
Drying tests were conducted using zeolite, a porous material.

▼Data acquisition for drying target candidates (Table 1)
The following table lists drying target candidates. A test plan was designed to understand drying characteristics, particularly for materials that are difficult to dry.

Type	Generated By	Details	Conceptual images	Status of data acquisition (-2020)			
				Zeolite	SUS	Slurry	Concrete
Unmelted fuel debris	fuel debris retrieval process	Unmelted fuel assemblies that remained in the reactor.		○	–	–	–
Lumpy fuel debris and MCCI		Molten fuel that formed lumps by slow cooling.		○	–	–	Not yet acquired
Pebble-shaped and particulate fuel debris		Molten reactor-core materials that became fragmented pieces due to rapid cooling.		○	○	–	–
Structural materials with adhered nuclear fuel		Fuel debris adhered to structures that remained unmelted		○	○	–	–
Slurry and sludge	Water treatment system	Powdered and fine particulate debris		–	–	1 set of conditions (ZrO2) 1	Not yet acquired
Water treatment filter		Filters with powdered and fine particulate debris adhered to them		–	–	Not yet acquired	Not yet acquired
Gas treatment filter	died	Filters with dry debris powder adhered to them		–	–	Not yet acquired	–

1 Data for one set of conditions was acquired by FY2020.Additional data will be collected in FY2021-2022.

🟥 Scope of data expansion in FY2021-2022

6 Developing drying technology and systems and studying technology for measuring hydrogen concentration

With regard to measuring the hydrogen concentration within a canister prior to transporting it to the additional building, IRID studied constant monitoring in which the concentration is continuously measured as well as periodic monitoring that measures the hydrogen concentration when a process allows such measurements to be performed. From this research, it was learned that constant monitoring is possible once debris has been stored in a transport container and that observing differences in the thermal conductivity of gas species is a suitable measurement method. It was also found that periodic monitoring can be accomplished during the drying process and when inert gas is being injected; in both instances, applicable measurement methods include proton conduction by way of a ceramic material that selectively allows hydrogen to pass through it as well as gas chromatography that utilizes differences in the adsorption and desorption rate of a vaporized sample (Table 2).

▼Classifications of measurement points (work stages) for hydrogen concentration and assumed environments (Table 2)
Measurement points for hydrogen concentration were selected, then measurement methods were studied based on each assumed atmosphere.

Monitoring method	Selected measurement points (work stages) for hydrogen concentration	Assumed atmosphere	Assumed range of hydrogen concentration	Measurement method
Continuous monitoring	Transfer container (processes after storage in the transfer container)	Room temperature and pressure Nitrogen, water vapor, and hydrogen	0–4 vol%	Sensor installed on the transfer container
Sequential monitoring	•Drying chamber •Canister (drying process)	Below room temperature and pressure Nitrogen, water vapor, and hydrogen	0–100 ppm	Gas sampling via a pump from the object of measurement point or sensor installed on piping
Sequential monitoring	•Canister •Cavity of transfer container (inert gas injecting process)	Approximately room temperature and pressure Nitrogen, water vapor, and hydrogen	100 ppm and above	Gas sampling via a pump from the object of measurement point or sensor installed on piping

7 Studying the handling and storage of powdery, slurry, and sludge fuel debris

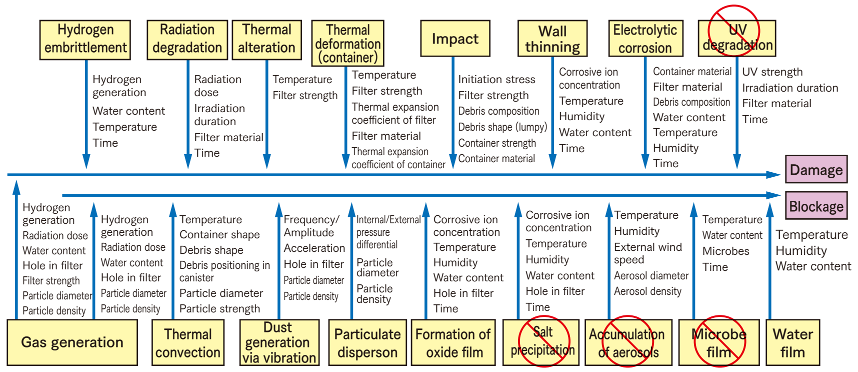
IRID researched examples of powdery nuclear material and radioactive waste being handled and stored within Japan and abroad, then analyzed the experience, expertise, and data needed to construct a system for housing, transporting, and storing powdery, slurry, and sludge fuel debris (collectively referred to as "powdery debris" below), including factors to keep in mind when handling powdery debris, approaches for maintaining safety, and ways to reflect what we know in designs. Problem areas and technology that must be developed for the dry storage of powdery debris (Table 3) were also identified, taking into account the results of case studies as well as a set of 32 processes (the aforementioned Figure 1) which assume that canisters will be similarly used to house, transport, and store lumpy fuel debris.

▼Case study on storing powderized fuel debris (Table 3)
The technical issues were identified pertaining to the dry storage of powderized fuel debris and items for technological development were determined.

Issues	Technological development
When powderized fuel debris is dried, minute particles in the canister can be slung upward, clogging the filter installed on the canister lid.	•Evaluate clogging of the canister filter •Study measures for controlling the dispersion of minute particles
Because powderized fuel debris is viscous, the hydrogen can form clumps internally then be released suddenly. This could instantly increase the concentration of gaseous hydrogen inside the canister.	•Study methods for predicting the release of hydrogen gas by powderized fuel debris

8 Studying the canister filter

IRID examined the various environmental conditions and requirements for the canister filter, identifying 13 different causes of filter degradation (Figure 11). The effects that these causes have on the life span of the filter were studied and evaluated and the results of that examination were used to formulate a general strategy for testing filter life span.



▲Causes of degradation in the canister filter (Figure 11)
IRID examined the environmental conditions and requirements for the canister filter and identified 13 different causes of filter degradation.

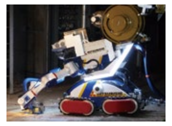
IRID Research and Development

IRID's History in Photos

2014

March

Conducted demonstration tests on the suction/blasting decontamination equipment



Suction/Blasting decontamination equipment▶

April

Conducted verification testing on low-lying decontamination equipment (dry-ice blaster)

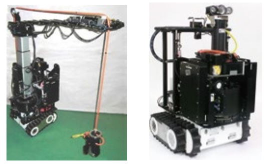
▲Dry-ice blaster

Conducted verification testing on low-lying decontamination equipment (high-pressure water sprayer)

High-pressure water jet decontamination equipment▲

May

Investigated Unit 1's suppression chamber with the upper-S/C investigation equipment



The upper-S/C investigation equipment▶

July

Surveyed the wall surfaces of Unit 2's torus room with a submersible robot and one that travels across the floor

Floor-traveling robot▶

Submersible robot▶

September

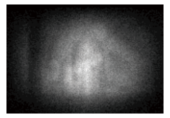
Investigated Unit 2's suppression chamber with the lower-S/C investigation equipment

The lower-S/C investigation equipment▶

2015

February–May, May–September

Measured Unit 1 with the muon transmission method



Unit 1 under observation▶

April

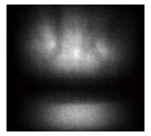
Investigated the PCV interior of Unit 1 with PMORPH 1

PMORPH 1▶

2016

March–July

Measured Unit 2 with the muon transmission method



Unit 2 under observation▶

April

Completed full-scale testing at JAEA's Naraha Center for Remote Control Technology Development

Full-scale test unit▶

May

Verification testing of the elevated decontamination equipment (a dry-ice blaster) on the first floor of Unit 3

Elevated decontamination equipment▶

2017

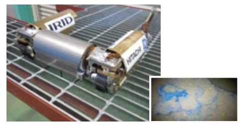
February

Investigated the PCV interior of Unit 2 with the Scorpion robot

Scorpion robot▶

March

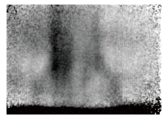
Surveyed the PCV interior of Unit 1 with PMORPH 2



PMORPH 2▶

May–September

Measured Unit 3 with the muon transmission method



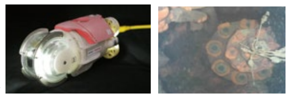
Unit 3 under observation▶

June

Conducted full-scale testing on technology for plugging leaks in the suppression chamber (S/C)

July

Surveyed the PCV interior of Unit 3 with a submersible robot (ROV)



The ROV▶

Conducted full-scale testing on reinforcement technology for the suppression chamber (S/C) support columns

2018

January

Investigated Unit 2's PCV with a telescoping investigation equipment

▲Telescoping investigation equipment

▲Inside Unit 2's PCV

2022

February

Conducted a detailed investigation Unit 1's PCV interior with IRIDOLPHIN

▲IRIDOLPHIN

VI

Decommissioning Research and Development

Treatment and Disposal of Solid Waste

IRID has studied safety evaluation methods and concepts of treatment and disposal for managing and storing solid waste in consideration of the characteristics of the waste generated from the accident. The goal was to develop plans for treatment and disposal approximately by the end of FY2021 and to make technical perspectives related to the safety of the waste treatment and disposal.

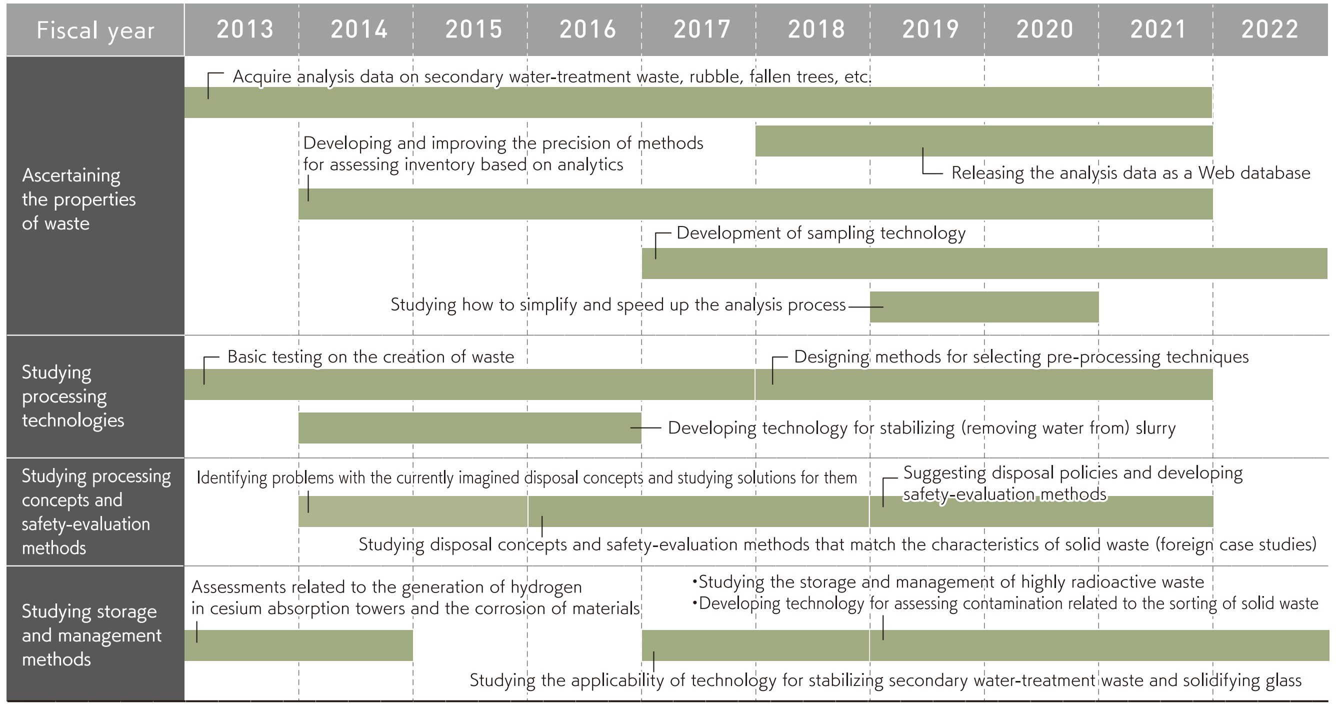
Research and development of treatment and disposal of solid radioactive waste

Safely managing and treatment of waste

IRID's research and development on the treatment and disposal of solid waste has focused on integrating the following four major areas of study, which cover everything from understanding the properties of waste to handling its disposal.

- Ascertain waste properties: Studying the solid waste generated during decommissioning activities requires to gather information on the properties of that waste. Develop technology for remotely collecting analysis samples, techniques for analyzing them, methods for evaluating that analysis data, and tools for publicizing the data
- Study disposal technology: Solid waste will be processed so that its radioactivity can be sealed away and it can be isolated (disposed of) in a place unaccessible by people. Study improvements to safety and confinement that can be implemented beforehand so that solid waste can be handled safely with an eye toward disposal
- Study disposal concepts and safety-assessment methods: Concepts for disposing of waste will be chosen based on the properties of that waste. Study disposal concepts and develop (safety-assessment) methods for determining if those concepts are suitable
- Study storage and management methods: Solid waste contains things like highly radioactive waste as well as material generated during the processing of contaminated water (secondary waste from water treatment). Study methods for safely storing such waste

Research and development progress



Background

Just as with regular waste, radioactive waste generated during the decommissioning (1F waste) must also be reduced as much as possible and handled so that the useful portions of it can be reused and the nonreusable portions can be disposed of properly. This 1F waste has different properties than the radioactive waste that originates from traditional nuclear power plants. For example, there are many types of 1F waste, including the rubble that was dispersed by a hydrogen explosion immediately after the accident, trees and shrubs that have radionuclides stuck to them, soil, etc. There is also secondary water-treatment waste such as the absorbent used to remove radionuclides from contaminated water. These circumstances make it difficult to study safety management and disposal policies for 1F solid waste.

Purpose

At the end of FY 2021, the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) published a technological forecast related to policies for processing and disposing of solid waste as well as the safety of those policies. At IRID, the goal was to work on developing processing and disposal methods so that 1F waste can be safely stored and disposed of. Progress has been made on a variety of technological development related to 1F waste with the goal of presenting the NDF with a technical foundation for understanding the properties of solid waste, processing/disposal, and storage/management.

* 1F: Fukushima Daiichi Nuclear Power Station

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1 IRID's research and development process for understanding the properties of solid waste as well as storage/management and treatment/disposal

Radioactive waste can be a solid, a liquid, or a gas. IRID has worked to ascertain the properties of solid waste and to research and develop the storage/management and treatment/disposal of such waste, with the goal of reducing the risk of radiation exposure. Compared to conventional radioactive waste for which there is a wealth of past experience, the waste generated by the 1F accident has never been dealt with before, and it has some unknown properties. It also has different types and comprises a large amount of material.

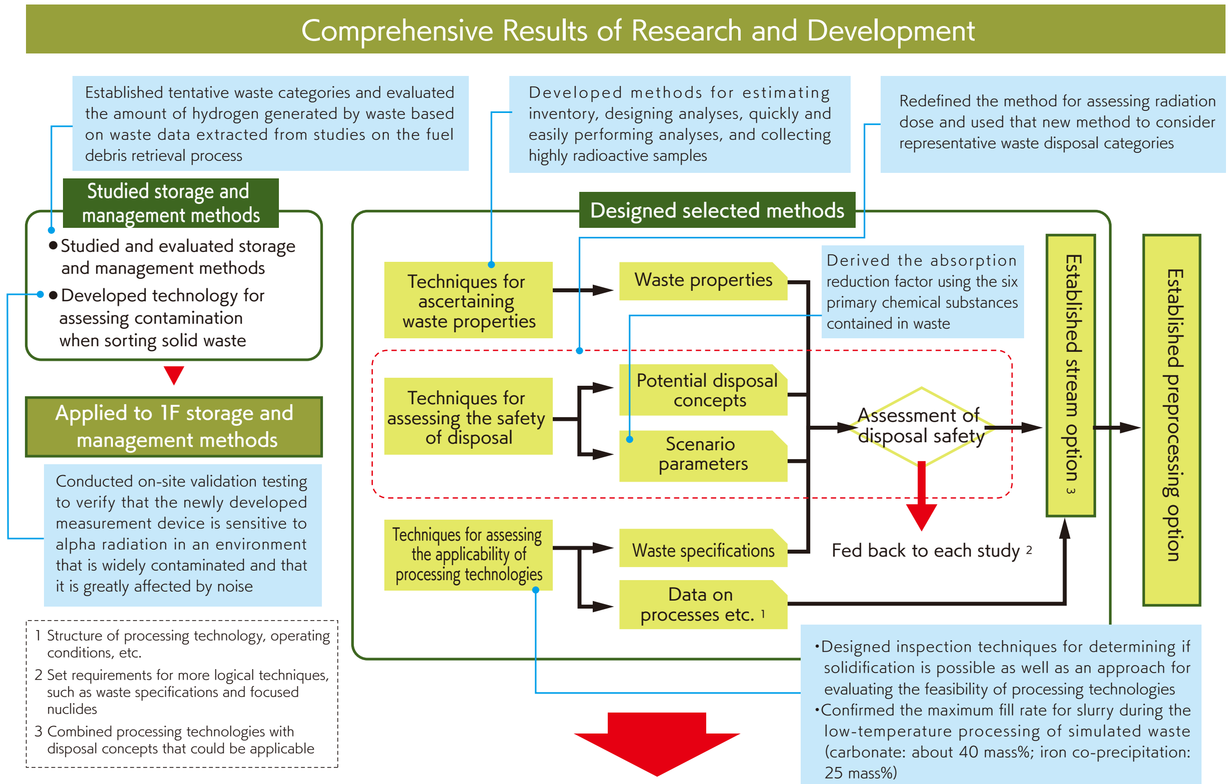
The areas where the results of all of IRID's research and development will be applied are systematically depicted in the figure below. First, traditional waste-management practices was referenced to apply existing disposal concepts such as estimating the solidified objects present and assessing the instantaneous release of radionuclides at the disposal site. There are clearly some issues, however, such as the large variance in waste properties and the increasing number of disposal categories. It is now apparent that it is needed to introduce pragmatic approaches that reflect overseas and domestic knowledge—such as the formation of solidified objects and the expansion of existing disposal concepts — in addition to the handling of storage and management.

To understand the waste's properties, IRID first created some general categories for waste, designed methods for estimating inventory and plans for identifying and analyzing quick and expedient analysis methods, and developed methods for collecting highly radioactive samples for analysis.

IRID designed a method for selecting the applicable solidification methods as a preprocessing technique. Methods for solidifying slurry waste were studied, which is unique to 1F for which there is little knowledge.
A basic safety assessment was conducted and existing data used by methods of assessing disposal safety was organized. Based on those results, potential disposal concepts were reexamined and investigating the utilized scenarios and parameters continued. The results of the safety assessment were then passed back to each R&D area. With waste categories, for instance, the most problematic waste were further narrowed and reestablished and the new knowledge needed for safety assessments were applied, such as selecting the important chemical substances in waste.

Meanwhile, data was gathered and prepared for future assessments while aiming to improve the analysis precision for understanding waste properties by analyzing collected samples. The collected data was made available worldwide as a database.

Through this process, an understanding of the waste's properties was gained, safe and rational methods for storing and managing waste based on those properties were presented, and a method for logically selecting the preprocessing method was designed. The main results will be introduced on the following pages.


Comprehensive Results of Research and Development

Established tentative waste categories and evaluated the amount of hydrogen generated by waste based on waste data extracted from studies on the fuel debris retrieval process

Developed methods for estimating inventory, designing analyses, quickly and easily performing analyses, and collecting highly radioactive samples

Redefined the method for assessing radiation dose and used that new method to consider representative waste disposal categories

Derived the absorption reduction factor using the six primary chemical substances contained in waste

Conducted on-site validation testing to verify that the newly developed measurement device is sensitive to alpha radiation in an environment that is widely contaminated and that it is greatly affected by noise

- Designed inspection techniques for determining if solidification is possible as well as an approach for evaluating the feasibility of processing technologies
- Confirmed the maximum fill rate for slurry during the low-temperature processing of simulated waste (carbonate: about 40 mass%; iron co-precipitation: 25 mass%)

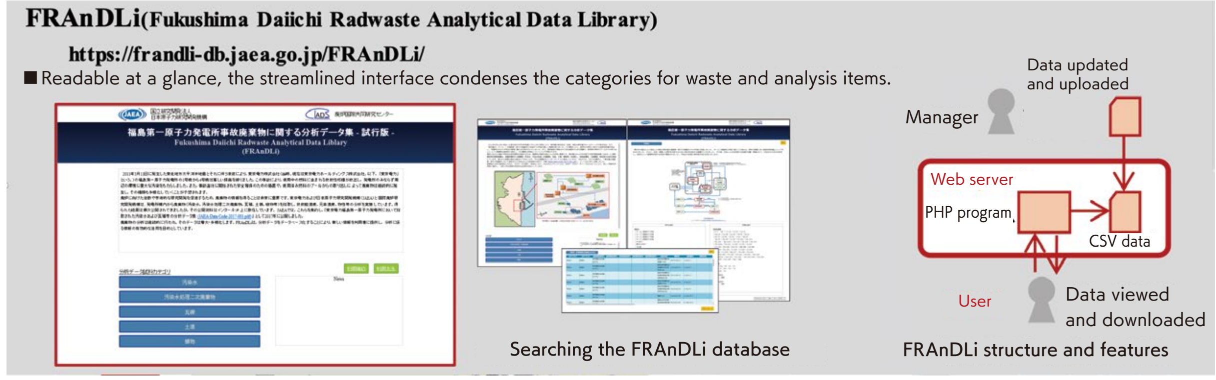
1 Structure of processing technology, operating conditions, etc.
2 Set requirements for more logical techniques, such as waste specifications and focused nuclides
3 Combined processing technologies with disposal concepts that could be applicable

- Proposed safe and logical storage and management methods based on waste properties
- Designed techniques for selecting preprocessing methods in a logical manner

2-1 Releasing data on the understanding of waste properties as a database on the web (understanding the properties of waste)

IRID analyzed waste and contaminated water with samples provided by Tokyo Electric Power Company Holdings Inc. (TEPCO), transporting them to analysis facilities located primarily in Ibaraki Prefecture. The analysis samples covered a wide range, including rubble, soil, vegetation, contaminated water (both accumulated water and treated water), secondary waste created through the treatment of contaminated water, and more. This project is notable for also attempting to analyze the so-called "difficult to measure" nuclides that emit alpha and beta radiation. Using existing methods as a foundation, appropriate improvements at each research facility were made to arrive at the analysis methods for 1F waste. The analysis results for the gained understanding of waste properties have been released via the Web-based FRAnDLi database (Figure 1) along with relevant data published by TEPCO. The approximately 12,400 data points amassed by the end of FY 2020 were put to use in areas such as IRID's study of the storage/management and processing/disposal of 1F waste.

For example, data on nuclides that contribute to the radiation dose and heat generation of waste is useful for evaluating hydrogen generation, which is an important factor in the storage of waste. Data on each nuclide that has a long half-life will also be instrumental in conducting safety assessments from the perspective of treatment and disposal.



FRAnDLi(Fukushima Daiichi Radwaste Analytical Data Library)

https://frandli-db.jaea.go.jp/FRAnDLi/

■ Readable at a glance, the streamlined interface condenses the categories for waste and analysis items.

Searching the FRAnDLi database

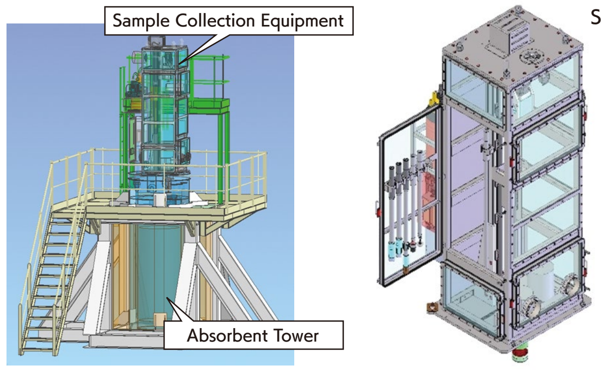
FRAnDLi structure and features

▲Overview and features of the FRAnDLi database (Figure 1)

2-2 Developing sampling technology by using equipment for collecting highly radioactive analysis samples (understanding the properties of waste)

This section introduces technology for collecting highly radioactive analysis samples, which is part of the initiative to understand waste properties.

As with the cesium adsorbent, collecting samples for analysis can be difficult because they are highly radioactive and inside a sealed container. Regarding the waste from the cesium adsorbent tower, the radionuclides included in the adsorbent and their concentrations are expected to undergo large changes depending on operating conditions such as the type of adsorbent, the operating time of the device, and the flush duration. This is why analyzing the adsorbent is essential for understanding the properties of 1F waste. IRID therefore developed equipment that collects samples while working to remotely reduce radiation exposure. Figure 2 depicts a drawing of the sample collector used to obtain samples of the cesium adsorbent tower. The sample collection equipment can create opening in the top of the absorbent tower, collect samples, then seal the opening.



◀The sample collection equipment for cesium adsorbent towers

3 Researching and developing the methods for stabilization and solidification processing that are expected to be applicable to actual processing (studying processing technology)

This section introduces the results of IRID's studies regarding technology for processing the secondary waste produced by water treatment, which is part of the solid waste that characterizes 1F.

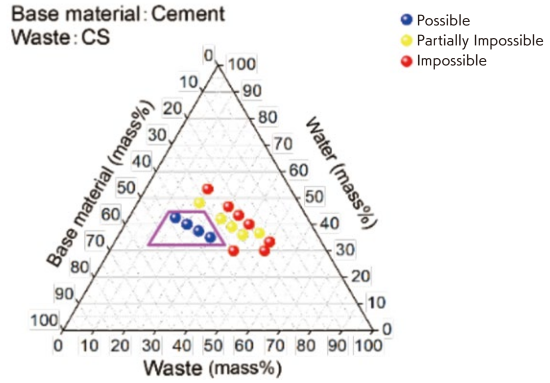
The primary materials currently being generated are slurry from the multi-nuclide removal system (ALPS) and waste zeolite produced by the cesium adsorbers. IRID has worked to develop a method for conducting versatile assessments of applicable solidification technology for these target materials. Four highly mature candidate technologies employed in domestic and overseas waste disposal were selected, keeping on-site installation in mind: cement, alkali activated materials (AAM), melting, and glass. Assessment criteria for comparing the technologies was also established (Table 1).

Referring to standards related to current regulations etc., information related to each piece of solidification technology was then examined, acquiring technical data through experimentation, and organized that data into a set of comparison charts (Table 2 and Figure 3). Through this, techniques that allow multiple technologies to be selected for the preprocessing disposal methods used with the secondary waste produced by water treatment were established.

The waste generated from now on will be nonuniform and contain a variety of materials. IRID has developed simple inspection techniques that allow to check whether cement or AA solidification is possible when actually processing on-site and to study which mixtures will ensure quality when performing solidification processing. The applicable scope of waste has been expanded and criteria for judging the quantitative applicability of processing technologies have been studied.

▼Established focus of evaluation (Table 1)

Evaluation Item	Evaluation Sub-Item
Technical Results	Development stage, operational achievements, etc.
Process Performance	Processing speed, Cs volatilization rate, etc.
Operability and Safety	Process risk, maintenance details, etc.
Cost-Effectiveness	Volume reduction, construction area, etc.
Properties of Solidified Matter	Impermeability, resistance to radiation, etc.



▲Comparison table for compiled technologies (possible scope of cement solidification for carbonate slurry) (Figure 3)

▼Comparison chart for compiled technologies (excerpted from the comparison chart for low-temperature solidification processing technologies) (Table 2)

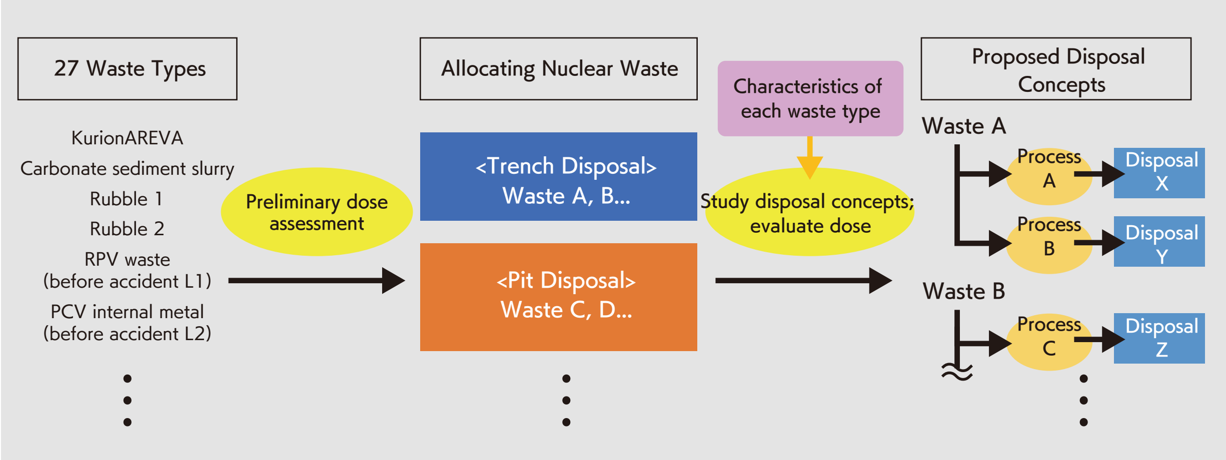
Technology		Cement Solidification (in drum)	Cement Solidification (outside of drum)	AAM Solidification (in drum)
Target Secondary Waste from Water Treatment → Solidified Product		Carbonate slurry → cement solidification	Carbonate slurry → cement solidification	Carbonate slurry → AAM solidification
Process Performance	Processing Temperature	Room temperature	Room temperature	Room temperature
	Processing Speed	0.12 t/h	0.24 t/h	0.12 t/h
	Cs Volatilization Rate	Does not volatilize in principle		
Maintenance Frequency and Details	Process Risk	Quickly hardens when cement contains 2% or more of sodium carbonate	Quickly hardens when cement contains 2% or more of sodium carbonate	None in particular
	Maintenance Frequency and Details	Maintain meter calibration and dustproof facilities	Maintain meter calibration and dustproof facilities	Maintain meter calibration and dustproof facilities
Cost-Effectiveness	Primary Solidification Equipment	Mixing facility (stirring blades, agitators)	Mixing facility (stirring blades, agitators, mixing container)	Mixing facility (stirring blades, agitators)
	Consumables	Stirring blades (per batch); dust filter (periodically)	Stirring blades (periodically); dust filter (periodically)	Stirring blades (per batch); dust filter
	Secondary Waste Generated	None	None (reused in cleaning water)	None in particular
Properties of Solidified Matter	Strength [Mpa, N/mm2]	7 (fill rate 30%; 28 days)		5 or more (fill rate 30%; 28 days)
	G value [1/100 eV]	0.16-0.17		0.05-0.28
	Impermeability	Cs: 96%, Sr: 5%, Sn: ND, Ce: ND (assess leaching rate with ANS/ANSI-16.1)		Cs: 24%, Sr: 0.5%, Sn: 5%, Ce: 0.5% (assess leaching rate with ANS/ANSI-16.1)
	Heat Resistance	Without decreasing in strength even at 80 ˚ C drying		40-50% decrease in strength even at R.H. 60%, which is less drying strength than 80 ˚ C drying

4 Developing disposal concepts and safety-assessment methods based on disposal technology that can be applied to solid waste (studying disposal concepts and safety-assessment methods)

This section discusses IRID's efforts to research and develop the task of disposal.

Since waste that cannot be reused will be disposed of in the future, disposal must be studied while simultaneously exploring other areas such as recycling as well as processes to stabilize and reduce the volume of waste, tasks which will be performed for the time being. The procedure for studying disposal concepts is depicted in Figure 4. First, IRID referred to the properties of accident waste that have already been identified then classified the waste into 27 comprehensive types. Next, a preliminary safety assessment was conducted, taking into account the hypothetical application of each of those waste types to one of our disposal categories such as trench, pit, burial at a medium depth, or deep geological disposal.

To investigate disposal concepts in more detail, eight representative types of waste was selected for further study. When making the selections, how much information about the radioactive concentration, physical traits, and chemical characteristics of the various waste types that are available was considered. The goal was to be able to suggest specific disposal concepts and safety-assessment methods for these eight waste types. As noted in section 1, the results of this disposal research were fed back into studies on understanding waste properties and techniques for storage and processing.

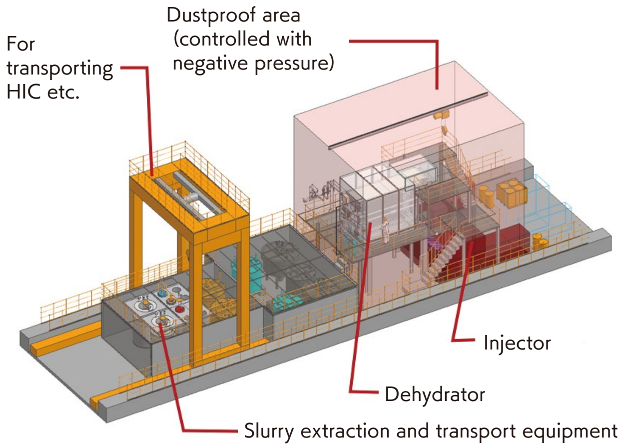


▲Process of studying disposal concepts (Figure 4)

5-1 Developing technology for stabilizing (removing water from) the slurry generated by the multi-nuclide removal system (studying storage and management methods)

Of the 1F waste, the secondary water-treatment waste carries a relatively high storage risk. In particular, the multi-nuclide remover generates large amount of slurry (ALPS slurry), a material characterized by its fluid nature and comparatively high radioactive concentration.

IRID thus studied the applicability of dehydration technology for reducing the storage risk of ALPS slurry, suggested some basic equipment designs, and demonstrated the feasibility of using pressurized filtration and disc drying in slurry stabilization processing (Figure 5). The results of this research were reflected in the design of the water-removal process that uses pressurized filtration, which was suggested as a candidate technology, as TEPCO works toward the actual on-site implementation of stabilization processing for ALPS slurry.



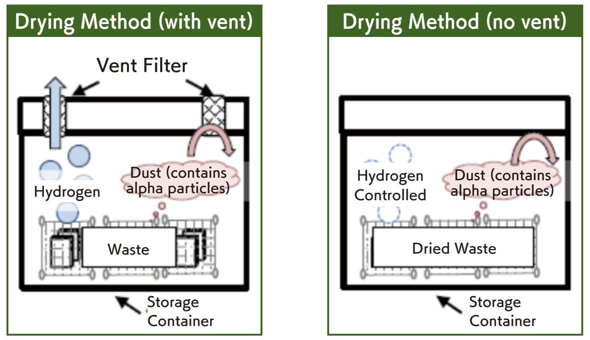
▲The pressurized filtration process (Figure 5)

5-2 Studying methods for storing and managing the highly radioactive waste generated during fuel debris retrieval (studying storage and management methods)

IRID studied methods for safely containing, transporting, and storing the highly radioactive waste (reactor internals etc.) that is produced when fuel debris is retrieved, then proposed hypothetical scenarios for the process of handling it up through storage. A list of desired features for the storage container was compiled and candidates that fulfill those requirements were considered.

This list of requirements includes measures for dealing with hydrogen generation, which has been identified as a major concern when it comes to safety assessments. Even in the case of conventional storage containers, ensuring that they remain sealed is an essential safety step for preventing the dispersion of radionuclides; the emission of hydrogen gas, however, requires to also keep them ventilated, so a plan that achieves both is needed. IRID looked at foreign and domestic examples of highly radioactive waste being stored, verifying that vent filters and pipes have been employed in cases where hydrogen gas is being generated (see Figure 6). The concept for a vent filter system as a storage method was also formalized.

The amount of hydrogen generated depends greatly on the water content, radioactivity, and how long radiation has been interacting with the water. However, assessing the amount of water that is contained within individual pieces of waste is difficult to do on the work site, thereby deciding that drying the solid waste is a logical strategy for preventing the production of hydrogen. The concept for how to dry the waste was then actualized.



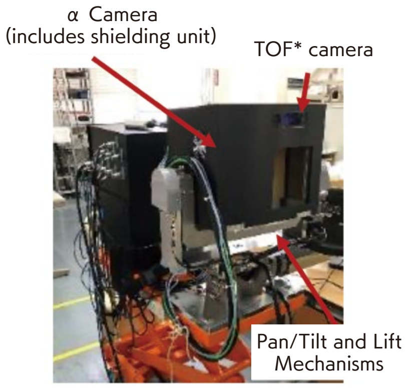
▲Foreign and domestic examples of storing highly radioactive waste (Figure 6)

5-3 Developing technology for assessing contamination with regard to the sorting of solid waste (studying storage and management methods)

Since α particles have severe effects on the human body when they enter it, waste that is contaminated with alpha radiation must be stored and managed with even more caution. It is therefore imperative that the presence and degree of alpha contamination for the waste generated during the demolition of structures and removal of equipment is ascertained — which are preliminary steps for the retrieval of fuel debris at Fukushima Daiichi NPS — and reflect that information in the operational plans and methods for managing the work.

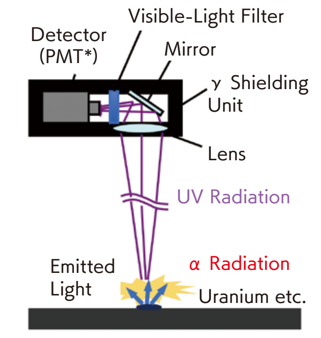
Alpha contamination is traditionally verified through a quantitative determination made with a smear sample. However, there is always the possibility that a hot spot etc. will be overlooked when using this method, so it is difficult to know the distribution of contamination across the entire area of measurement.

To make it easier to sort waste that is contaminated with α radiation, IRID is working to develop technology that can comprehensively measure the α contamination on a target surface in a short period of time. Efforts are now focused on improving the developed device (alpha camera), for example by bringing it into the 1F site and performing some test measurements. Figure 7 contains a photo of the machine, while the principles behind how it takes measurements are depicted in Figure 8.



▲The measurement device (Figure 7)

＊ TOF: time of flight



■ Measurement principles

- The interaction of α particles with nitrogen atoms produces ultraviolet radiation
- This UV radiation is focused with a lens to create an image; the distribution of the UV radiation that reaches the photodetector is then used to measure the distribution of α radiation
- Since γ radiation that reaches the detector would interfere with the measurement of alpha radiation, the equipment is shielded to prevent γ rays from entering

▲Principles of the alpha camera (Figure 8)

＊ PMT: photomultiplier tube

R&D Cooperation with Oversea Organizations

Based on our management policy of "open frameworks," IRID is striving to disseminate information such as the R&D results and development while strengthening our relationships with foreign experts and research organizations.

Strengthening relationships and cooperation with international organizations

IRID is accelerating our R&D with entities overseas, and constantly introducing the latest technology for the nuclear decommissioning.

Initiatives involving R&D with overseas organizations (list of main projects)

IRID engages in technological collaboration with overseas nuclear organizations that have experience in nuclear decommissioning and damaged fuel.

UK
- Sellafield Ltd: Handling and safe storage of damaged fuel; controlling criticality
- National Physical Laboratory: Developing technology for calibrating radioactive-gas monitors
- Currently developing a robot arm together with Veolia Nuclear Solutions (VNS)

France
- Atomic Energy and Alternative Energies Commission (CEA): MCCI testing

Hungary
- Paks Nuclear Power Plant: Handling and safe storage of damaged fuel

Kazakhstan

National Nuclear Research Center (NNC): Testing to ascertain the characteristics of fuel debris

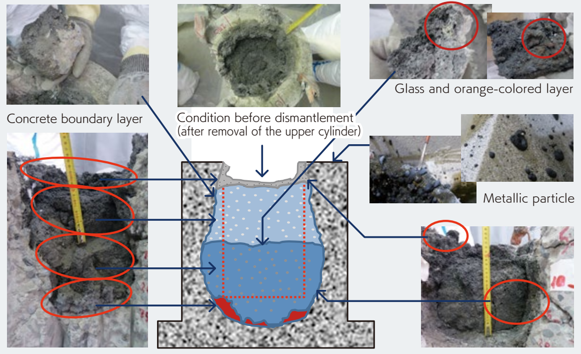
Austria
- IAEA: Compiling technical data

USA
- Pacific Northwest National Laboratory: Handling and safe storage of damaged fuel
- Hanford Facility: Handling and safe storage of damaged fuel; studying ventilation systems for fuel-debris dust
- Idaho National Laboratory: Gathering information on the experience gained from TMI-2
- Argonne National Laboratory: Exchanging information on our understanding of fuel-debris characteristics
- Los Alamos National Laboratory: Developing technology for detecting fuel debris
- University of California, Berkeley: R&D on the treatment and disposal of solid waste
- Mississippi State University: Studying ventilation systems for fuel-debris dust

French Atomic and Alternative Energies Commission (CEA)

Through our international joint research with the CEA, the MCCI simulated test was conducted to test for the reaction between molten fuel and concrete. The test revealed some of the characteristics of the MCCI test products, including its porous appearance and separate layers of oxides and metals.

Condition of MCCI test products



Idaho National Laboratory (INL), USA

As part of our projects to study safety requirements and specifications for containing, transporting, and storing fuel debris (under IRID's project, "Developing technologies for containing, transporting, and storing fuel debris"), a workshop was held at the INL to exchange information and engage in discussion. IRID thus gleaned a large amount of valuable data from the specific knowledge and lessons learned by US experts who had experience with TMI-2.

National Physical Laboratory (NPL), UK

IRID is working to develop detecting technology that uses Kr-88 to recognize approach signs at an earlier stage in the event that criticality is occurred when retrieving fuel debris. In order to improve the Kr-88 measurement accuracy, it is necessary to relate the concentration of Kr-88 and the amount of γ rays measured. At the NPL, a world-renowned authority that determines standards, actual Kr-88 was generated then methods for calibrating detectors were established.

The International Advisory Meeting

The International Advisory Meeting is comprised of three foreign nuclear experts to advise on organizational operation and management.

International Advisors

USA Mr. Lake Barrett

Independent consultant
(former site director for the Nuclear Regulatory Commission (NRC) during the Three Mile Island accident)

Spain Mr. Luis E. Echavarri

Former executive director of the OECD/NEA
(has experience with the IAEA's International Nuclear Safety Group (INSAG) etc.)

UK Prof. Melanie Brownridge

Technology and Innovation Director at the Nuclear Decommissioning Authority (NDA) in the UK

The 8th International Advisory Meeting

Date: May 25, 2021 Venue: Online

The international advisors reviewed the progress of IRID activities since FY2020 and provided advice regarding the status of the R&D design reviews that IRID is currently conducting, a framework for conveying knowledge, and the future activities.

▲Meeting of the International Advisory Meeting (IRID office)

Participating in international conferences

IRID has presented the results of our R&D via the forums hosted by international-relations organizations.

〈Japan〉
STSS / ISOFIC / ISSNP2021

Date: November 15, 2021
Venue: Okayama Convention Center (hybrid of online / in-person)

In Japan, a series of three international conferences were held—the STSS, ISOFIC, and ISSNP — related to interactions between humans and computers, cutting-edge systems for controlling instrumentation, and nuclear-power systems that share a relationship with society.

STSS:International Symposium on Socially and Technically Symbiotic Systems
ISOFIC: International Symposium on Future I&C for Nuclear Power Plants
ISSNP: International Symposium on Symbiotic Nuclear Power Systems

Attendees primarily from Japan, China, and Korea joined the conference virtually. Naoaki Okuzumi, a senior manager in IRID's R&D Planning Department, delivered a special lecture titled "Overview of IRID's Research and Development." During the lecture, approximately 120 attendees listened eagerly as Mr. Okuzumi discussed the current state of investigations inside PCV for the nuclear decommissioning as well as the status of technological development for retrieving fuel debris.

〈United States〉 American Nuclear Society (ANS)
ANS Winter Meeting

Date: December 2, 2021
Venue: Streamed from Washington DC (online)

The ANS Winter Meeting was an international meeting on nuclear engineering held online from November 30, 2021 through December 3, 2021 and organized by the American Nuclear Society (ANS). IRID's President Yamauchi and Senior Manager Okuzumi of the R&D Strategy Planning Department each participated in one of two panel sessions, giving presentations on the status of IRID's research and development. The meeting was attended by researchers and experts from around the world. Mr. Lake Barrett, one of IRID's international advisors, also participated in the panel sessions.

〈U.K.〉 International Commission on Radiological Protection (ICRP)
International Conference on Recovering After Nuclear Accidents

Date: December 1, 2020 (lasting through December 4)
Venue: Online

Led by the International Commission on Radiological Protection (ICRP) as the main organizer , this online meeting focused on "Radiological-Protection Lessons from Fukushima and Beyond." The meeting was held through the cooperation of a number of domestic and international organizations as well as the Japan Atomic Energy Agency (JAEA). President Yamauchi of IRID presented the current state of technological development with regard to retrieving fuel debris at Fukushima Daiichi NPS. The lecture was attended by over 190 people from various countries. In February 2022, a summary of the lecture was made available on the ICRP website **(https://icrp.org/index.asp).**

Human Resource Cultivation in R&D

The nuclear decommissioning is a long-term project that can span 30–40 years. Therefore, IRID hopes that the younger generation take more interest in the decommissioning and engage in the decommissioning industry.
IRID has been working to actively provide universities and other academic institutions that conduct research related to nuclear decommissioning with information about Fukushima Daiichi NPS, an urgent issue that IRID has faced, and advanced initiatives to lead caltivating human resources for the future.

The IRID Symposium

IRID Symposium 2021
"Challenges for Fuel Debris Retrieval IV"

Date: December 8, 2021
Venue: Exhibition Hall, Iwaki Business Innovation Center (LATOV), Fukushima Prefecture

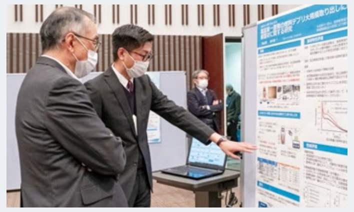
Organized by IRID, this symposium was held to report the latest research results and to cultivate young researchers and engineers, focusing on technological development aimed at the retrieval of fuel debris. Over 400 individuals participated in the FY2021 symposium, most of whom joined via internet. In the opening remarks, Mr. Toyoaki Yamauchi, President of IRID, expressed the desire to contribute to decommissioning, reconstruction, and technological development through the difficult task of retrieving fuel debris.

Reporting session

At the reporting session for IRID's R&D, Kenro Takamori, General Manager of IRID's R&D Strategy Planning Department, summarized overviews of R&D since the accident and described the development status of fuel debris containers.

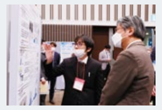
▲The reporting session

Decommissioning poster session



▲Panels at the exhibition hall

Panels presenting the latest information about IRID's R&D projects as well as results of student research were displayed in the exhibition hall. Engineers and students involved in R&D had the opportunity to engage in direct discussions with attendees.



Student presentations of research results

Many students present their research at the symposium every year. In FY2021, a total of seven students made such presentations.

◀Presentations by students

▲Audience member listening eagerly to student presentation

Student awards ceremonies / Site observation at the JAEA Naraha Center for Remote Control Technology Development (NARREC) and Fukushima Daiichi NPS

IRID presented awards to students selected by the judges for their research presentations. All attendees who presented at the symposium were invited JAEA NARREC, Fukushima Daiichi NPS and the Fukushima Robot Test Field for observation. The purpose of the site visit is to utilize technology for future research activities involving decommissioning.

▲On-site at the Fukushima Daiichi NPS

◀Awards ceremony

◀JAEA NARREC

Participation in various events

IRID actively participates in academic conferences, events, lectures organized by various organizations.

Robotics Society of Japan
129th Robotics Engineering Seminar
[Robots Utilized for Reconstruction of Fukushima]

Date: October 21, 2020　Venue: Online seminar only

Program

■**Session 1**: Robotic and remote-operation technologies required for decommissioning Fukushima Daiichi NPS
Prof. Hajime Asama, The University of Tokyo

■**Session 2**: Developing robots for decommissioning Fukushima Daiichi NPS: Challenges and required technology
Dr. Tamio Arai, IRID

■**Session 3**: Developing and field testing remote-imaging technology for visualizing the radioactive material dispersed by the Fukushima Daiichi NPS accident **Dr. Yuki Sato, JAEA**

■**Session 4**: Improving the monitoring of environmental radiation with drones: From the response to 1F to application as a nuclear-disaster tool **Dr. Yukihisa Sanada, JAEA**

Vice President of IRID, Dr. Arai gave a lecture

Developing robots for decommissioning Fukushima Daiichi NPS—Challenges and required technology

Dr. Tamio Arai, IRID

Many different robots have been introduced at TEPCO's Fukushima Daiichi NPS. Starting with investigation of primary containment vessel (PCV) including in the partial-submersion / submersion method, currently detailed investigation inside PCV has been conducted and then test retrieval of the fuel debris will be prepared as a next step. The robots to be used range from small investigation robots that can pass through the narrow pipes to access PCV and larger robots with large weight capacity. I would like to talk about the robotic technology and the peripheral equipment that help achieve their many functions, as demonstrated by the decommissioning processes of retrieving fuel debris and removing obstacles. I will then discuss the challenges with using robotics for decommissioning in the hope that the latest technology from the field of robotics can be introduced to the world of decommissioning as well.

Source: Excerpt from the Robotics Society of Japan website

Atomic Energy Society of Japan
ANSJ Fall Meeting 2021

Date: September 9, 2021
(online meeting)

▲N. Okuzumi,
Senior Manager of IRID.

At the ANSJ Fall Meeting 2021, Senior Manager Okuzumi of the R&D Strategy Planning Department gave a presentation on the current state of IRID's R&D as part of an activity report from the Fukushima Daiichi NPS Decommissioning Investigative Committee.

Japan Society of Applied Physics
82nd JSAP Autumn Symposium

Date: September 10, 2021 (online)

Senior Manager Okuzumi of IRID's R&D Strategy Planning Department reported the current status of IRID's R&D during an activity reported entitled "What can JSAP members do for the decommissioning of Fukushima Daiichi NPS and the recovery of the prefecture?"

Fukushima Prefecture
Fukushima Robot & Aerospace Festival 2021

Date: November 19–20, 2021
Venue: Big Pallete Fukushima (Koriyama, Fukushima)

Despite the restrictions by holding the event in the COVID-19 pandemic, around 4,500 ardent fans and their family members during the two-day event (as announced by Fukushima Prefecture, the event's host). Many of them also visited IRID's booth, which displayed panels introducing the current state of IRID's R&D on the decommissioning of Fukushima Daiichi NPS and played a video showing the submersible robots currently being developed as well as the Robot Arm that was developed in the UK and is now being tested in Japan.

▲At the IRID booth

Disseminating information to universities and research institutions

IRID is actively working to develop human resources by visiting entities such as universities and research institutions and providing them with information.

Nuclear Almanac Editorial Board
2022 Nuclear Almanac

Senior Manager of the R&D Management Department contributed an academic paper titled "IRID's technological development related to the containing, transport, and storage of fuel debris during the decommissioning of Fukushima Daiichi NPS" to this book.

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Editor: Nuclear Almanac Editorial Board
Publisher: Nikkan Kogyo Shimbun Ltd.

Tohoku University
FY2021
Light-Water Reactor Safety Seminar
(Nuclear Decommissioning Edition)

Date: September 16, 2021
Venue: Tohoku University (Sendai, Miyagi)

▲K.Takamori,
General Manager of IRID.

Mr. Takamori, General Manager of the R&D Planning Department, gave an online lecture in which he discussed an overview of IRID, the status of fuel debris investigation, and technological development for the retrieval of fuel debris as well as challenges and safety design.