Subsidy Project of Decommissioning and Contaminated Water Management in FY 2018 Supplementary Budget

Development of Technology for Containing, Transfer and Storage of Fuel Debris

FY 2020 Final Research Report

June 2021

International Research Institute for Nuclear Decommissioning (IRID)

Contents (1/2)

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1. Research background and purpose

1.1. Background

For decommissioning of Fukushima Daiichi Nuclear Power Station (hereinafter called the 1F), technology for containing, transfer and storage of fuel debris to be retrieved in a safe and effective manner is required.

Fuel debris contains nuclear fuel material, therefore, it is necessary to consider, in particular, confinement of radioactive materials (preventing the spread of contamination) and sub-criticality in the handling of the debris.

When the Three Mile Island Nuclear Power Station Unit 2 (TMI-2), in the US, was decommissioned, fuel debris was retrieved and put into specialized containers (canisters) and **handled by the canister**. This effectively fulfilled requirements, such as confinement of radioactive materials, **by using existing technologies for transfer and storage of spent nuclear fuel and management of radioactive waste**. This example led to the belief that it is **reasonable to use existing technologies effectively by developing canisters** to satisfy individual conditions. Based on this approach, it has been decided to focus the development of canisters for the decommissioning of the 1F.

The plant type of the 1F is different from that of TMI-2. In addition, seawater was injected during the initial phase of the accident, and the molten core reached the pedestal at the bottom of the reactor pressure vessel. Therefore, the requirements for the 1F canisters are more complex and advanced compared to TMI-2. Development of specialized canisters for the 1F is required to contain, transfer, and store fuel debris safely and effectively.

•1.2. Purpose

In this project, fuel debris canisters applicable to the 1F conditions and technology for handling the canisters will be developed. To do that, the information and requirements provided from the related IRID projects (input conditions) and those provided from this project to the related IRID projects (output conditions) will be organized and clarified by close cooperation with the related projects.

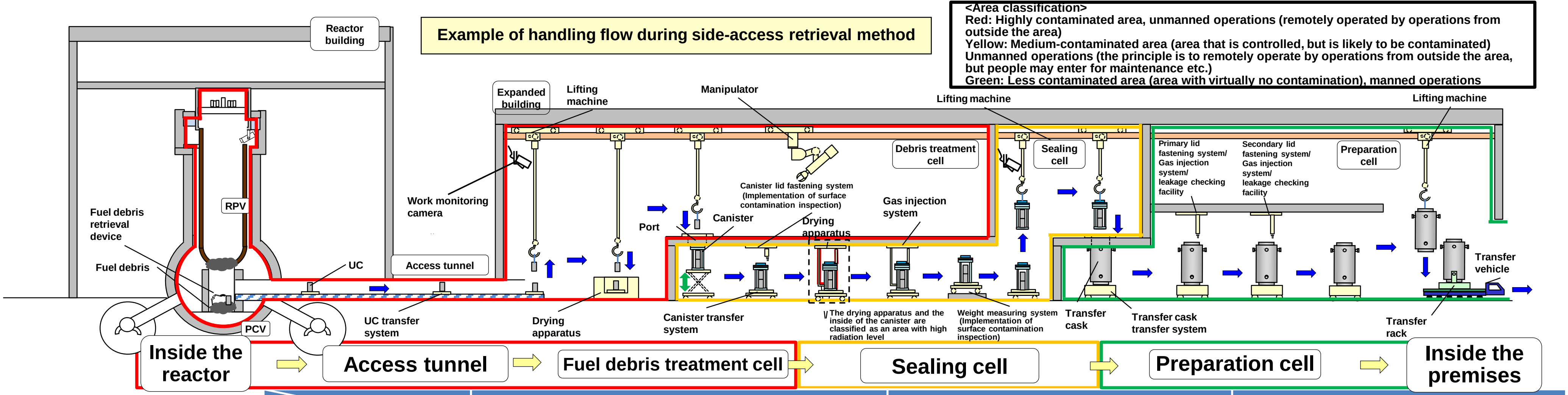
1. Research background and purpose

1.3 Previous studies and remaining issues (1/4)

The process for fuel debris containing, transfer and storage, and issues therein are shown below.

<Area classification>
Red: Highly contaminated area, unmanned operations (remotely operated by operations from outside the area)
Yellow: Medium-contaminated area (area that is controlled, but is likely to be contaminated)
Unmanned operations (the principle is to remotely operate by operations from outside the area, but people may enter for maintenance etc.)
Green: Less contaminated area (area with virtually no contamination), manned operations

Example of handling flow during side-access retrieval method



Black text indicates that technological development is not required based on past results, etc.

Blue text indicates study has been completed

Brown text indicates the items the study of which will be concluded in this subsidized project (and succeeded in the project at the actual site).

Red text indicates the items that need to be continuously studied. (To be studied in a succeeding subsidized project or suggested to be so)

Numbers in parentheses indicate the chapters that describe the preceding subject matters in detail.

Area / Canister		Sealing cell	Preparation cell (excluding drying apparatus	Inside the premises
Safety design	Subcriticality	Subcriticality can be maintained by the geometrical shape of canister	Subcriticality can be maintained by the geometrical shape of the canister and the arrangement inside the transfer cask	
	Heat removal	Canisters can be naturally cooled using normal in-cell ventilation	Each transfer cask can be naturally cooled by normal building ventilation	Each transfer cask can be naturally cooled by the outside air
	Confinement	Confinement using the sealing material of canister（6.2） /study of filter（6.2） /and sealing cell. (Gas is released in a controlled manner)	Confinement using the sealing material of canister (6.2), study of filter (6.2) and preparation cell. (Gas is released in a controlled manner)	Confinement using the sealing material of canister (6.2), study of filter (6.2) and transfer cask (Gas is released in a controlled manner)
	Shielding	Shielding in sealing cell	Shielding in preparation cell	Shielding in transfer cask
	Structure	Study to maintain safety function against damage caused by drop from up to 9m/ drop of canister within transfer cask (6.2)		Ability of withstanding accidents during transfers (Designed to be encapsulated during fall)
	Materials	Safety function can be maintained against aging (As a prerequisite, the corrosion of the metal is studied. Also, as the neutron flux density is small, irradiation does not affect the material)		
	Hydrogen	・Study on the vent diameter used for release of hydrogen from the canister's vent hole with filter to the cell (6.2)/the cell can control the hydrogen concentration to the lower explosion limit or lower by ventilation. ・Study on the reduction of water content of fuel debris by early drying of fuel debris, as hydrogen countermeasures during sealed transfer. (The top priority in debris treatment cell is the drying timing) (6.3) ・ Study of hydrogen concentration measurement inside transfer cask to ensure that the hydrogen concentration is 4 vol.% or less at the time of transfer (6.4).		・Drying for sealing the canister/ transfer cask for up to 7 days (6.3) ・ Study of method to predict hydrogen generation at the time of transfer (by evaluation formula) (6.3) ・ Study on recombination catalyst (6.3)
	Fire prevention	Ability of maintaining the inside of sealing cell/ preparation cell/ transfer cask at an inert atmosphere		
Handleability		Ability of remote transportation and closing a lid	Ability of remote transportation	Ability of storage in transfer cask
Improvement in storage workability		The storage work efficiency can be improved by expanding the inner diameter of the canister	None	

Note: Safety design and handleability from "inside the reactor to debris treatment cell" will be studied in the "Project of further increasing the scale of fuel debris retrieval"

Note: RPV (abbreviation for reactor pressure vessel)
PCV (abbreviation for primary containment vessel)
UC (abbreviation for unit can)

1. Research background and purpose

1.3 Previous studies and remaining issues (2/4)

The process for fuel debris containing, transfer and storage, and issues therein are shown below.

<Area classification>
Yellow: Medium-contaminated area (area that is controlled, but is likely to be contaminated) Unmanned operations (the principle is to remotely operate by operations from outside the area, but people may enter for maintenance etc.)
Green: Less contaminated area (area with virtually no contamination), manned operations

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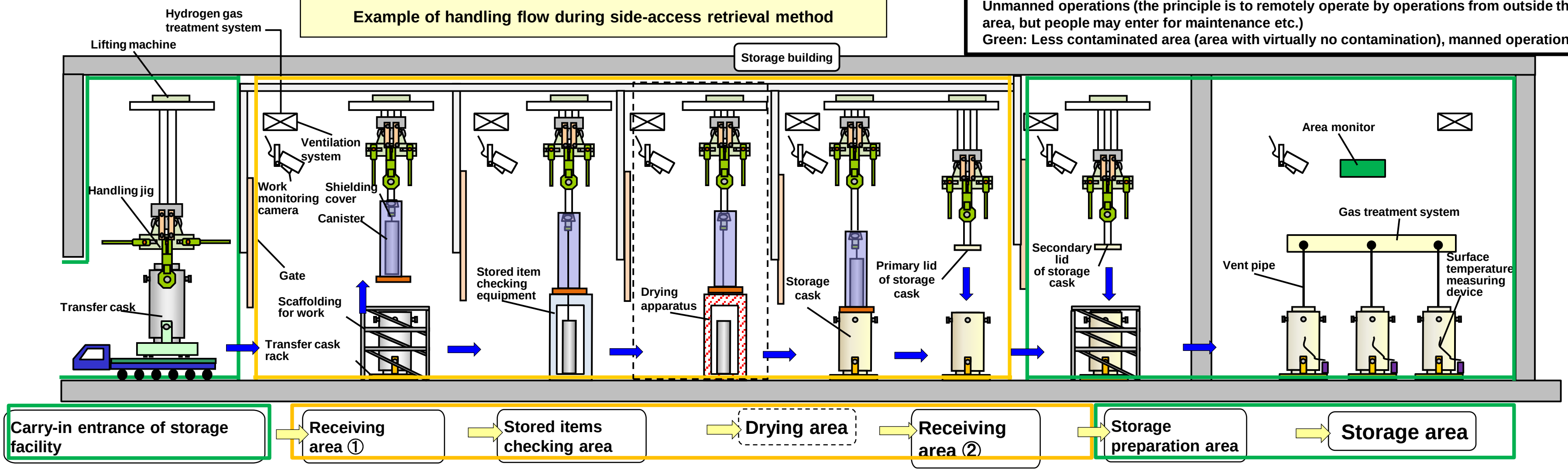


Black text: Indicates that technological development is not required based on past results, etc.

Blue text indicates the items in which development work was concluded (and succeeded in the project at the actual site).
Brown text indicates the items the study of which will be concluded in this subsidized project (and succeeded in the project at the actual site).
Red text indicates the items that need to be continuously studied. (To be studied in a succeeding subsidized project or suggested to be so)
Numbers in parentheses indicate the chapters that describe the preceding subject matters in detail.

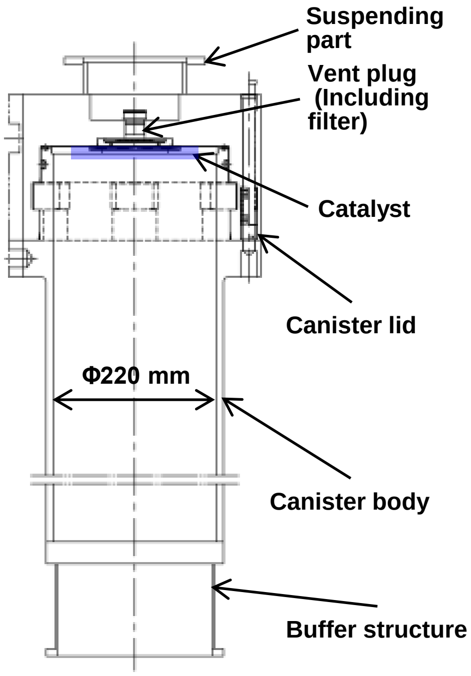
Note: Drying area shall be set up when drying apparatus cannot be installed inside the debris treatment cell

Area / Canister		Receiving area ① ~ Receiving area② (Excluding drying area)	Storage preparation area	Storage area
Safety design	Subcriticality	Subcriticality can be maintained by the geometrical shape of canister	Subcriticality can be maintained by the geometrical shape of the canister and the arrangement inside the storage cask	
	Heat removal	Can be naturally cooled using normal in-cell ventilation	Each storage cask can be naturally cooled using normal building ventilation	
	Confinement	Confinement using the sealing material of canister (6.2), study of filter (6.2) and building (Gas is released in a controlled manner)	Confinement using storage cask/ building (Gas is released in a controlled manner)	
	Shielding	Shielding in the cell	Shielding in storage cask/ building	
	Structure	Study to maintain safety function against damage caused by drop from up to 9m/ drop of canister within storage cask (6.2)		Can withstand accidents during storage (Designed to be encapsulated during fall)
	Material	Safety function can be maintained against aging including corrosion		
	Hydrogen	Study on the vent diameter used for release of hydrogen from the canister's vent hole with filter to the cell/(6.2) /Ability of scavenging inside the building		Can be vented/ scavenged inside the storage cask
	Fire prevention	Ability of maintaining the building/ inside of transfer cask at an inert atmosphere		
Handleability		Ability of remote operation		Can be stored in a storage cask
Improvement in storage workability		None		

1. Research background and purpose

1.3 Previous studies and remaining issues (3/4)

The table below shows the results of the study on safety design of fuel debris canister conducted up to FY 2018, and the remaining issues to be studied.



(Canister Material: SUS316L)

Figure: Structural plan for canister
(Provisional structural plan set in FY 2018)

Safety design		Canister specifications	
		Study up to FY 2018	Issues to be studied (in FY 2019 and FY 2020)
Subcriticality		・ The inner diameter of the canister was determined (φ220 mm) based on the subcriticality maintenance evaluation method considering the fuel debris particle size and water content, so that the canister itself can maintain subcriticality.	–
Cooling	Heat removal	・ No problem.	–
Confinement	Confinement	・ A filter and an outlet to prevent hydrogen retention (vent plug) are installed to prevent the spread of contamination during actual operation.	・ Study of sealing material/ filter (except during storage) (Studied under the project of “development of storage technology”)
	Shielding	・ No problem.	–
Others (Maintaining the shutdown, cooling and confinement functions)	Structure	・ The integrity was confirmed by conducting element tests for lid, body, and buffer structure against the impact load during the drop on the canister inside the transfer or storage cask, and during the tumbling or dropping while handling the canister.	・ It is necessary to confirm the structural integrity when the entire canister is integrated. (Studied under the project of “development of storage technology”)
	Material integrity	・ The validity of the canister material (SUS316L material) was confirmed assuming the water quality environment of 1F and the handling process, etc., of the canister.	–
	Hydrogen	・ Hydrogen generation amount： The validity of the G-value was confirmed through gamma irradiation test considering the 1F water quality (iodine, etc.). In addition, the effect of alpha rays was confirmed through a hydrogen generation test using spent nuclear fuel. ・ Catalyst： Identification of catalyst candidates capable of hydrogen recombination in a canister environment (presence of low temperature, high humidity and dose). ・ As a result of the drying element test conducted for porous bodies that may exist as a form of fuel debris, the phenomenon of equilibrium moisture content not reaching zero (drying stops with water remaining) was confirmed.	・ Study of method to predict hydrogen generation suitable for fuel debris condition in 1F. ・ Collection of detailed data on catalyst performance and evaluation of effectiveness when the catalyst is installed inside a canister. (Studied under the project of “development of transfer technology”) ・ Study on vent diameter (Studied under the project of “development of storage technology”) ・It is necessary to develop a drying method that keeps the equilibrium moisture content at or below the target moisture content within the target time. In addition, it is necessary to set the basic specifications of drying apparatus considering maintainability, etc. ・ As the purpose of drying fuel debris is to reduce the amount of hydrogen generation, a technology for measuring hydrogen concentration is required as a means of confirmation. (Studied under the project of “development of drying technology and systems”)
	Fire prevention	・ No problem.	–

1. Research background and purpose

1.3 Previous studies and remaining issues (4/4)

The table below shows the results of the study on the fuel debris canister specifications up to FY 2018, and the remaining issues to be studied.

Handleability/ rationalization	Canister specifications	
	Study up to FY 2018	Issues to be studied (In FY 2019 and FY2020)
・Remote lid closing and remote lifting of canister	・ Study on the structural plan for the lid fastening device and hanging jig required for remotely handling the canister	-
・Increasing the inner diameter of the canister	・As a mitigation measure, the conditions that allow the inner diameter to be expanded (φ400 mm) were set.	- (Decision on acceptance or rejection based on the actual fuel debris results)

2. Project Goals

The indicators for determining achievement of target at the end of FY 2020 are as follows.

1. Investigation and research plan of containing, transfer, and storage of fuel debris	
General	The latest study status and findings of related projects and actual projects have been collected, overseas safety-related technical requirements have been additionally analyzed and organized based on already obtained information, and have been reflected in the research plan along with the opinions of experts. (Not subject to TRL evaluation)
2. Development of containing technology for fuel debris	
① Study of specifications and structure for the canister	The structural integrity of the canister as per the tentatively set specifications and structural plans has been confirmed using structural verification tests or analysis. The specifications and structural plans for the canister have been proposed based on the results of structural integrity verification. (Target TRL at the end of the project: Level 6)
3.Development of transfer technology for fuel debris	
① Study on method to predict hydrogen generation	A method to predict hydrogen generation suitable for the fuel debris condition has been proposed. The transfer condition plan has been presented based on the evaluation results of the proposed method to predict hydrogen generation. (Target TRL at the end of the project: Level 6)
②Study on hydrogen measures	The resistance to chloride ion, which is a candidate catalyst and a typical toxic substance, etc., have been evaluated. The flow inside the canister has been evaluated, and the validity of hydrogen measures using catalyst, etc., has been evaluated. (Target TRL at the end of the project: Level 6)
4. Development of drying technology and systems	
① Study on the basic specifications of drying apparatus	The first draft of the basic specifications for the fuel debris drying system has been proposed. (Target TRL at the end of the project: Level 4)
② Study on hydrogen concentration measurement technology	Selection of candidates for hydrogen concentration measurement technology applicable to the canister has been completed. (Target TRL at the end of the project: Level 3)
5. Evaluation summary	• Participation in and cooperation with fuel debris and waste sorting technical surveys upon request. (Not subject to TRL evaluation)

3. Implementation items, their correlations, and relations with other research

3.1 Implementation Items

This subsidy project worked on the following technological development issues related to transfer and storage engineering of fuel debris in 1F.

(1) Investigation and research plan of containing, transfer and storage of fuel debris

To collect the latest study status and findings of related projects and actual projects, perform additional analysis and organize overseas safety-related technical requirements based on already obtained information, and to reflect this in the research plan.

(2) Development of technology for containing of fuel debris

To maintain and confirm the safety functions (criticality prevention and confinement) during evaluation events with the entire canister in an integrated state, through a structural verification test using a full-scale canister.

(3) Development of technology for transfer of fuel debris

・Study on method to predict hydrogen generation

To analyze the existing methods to predict hydrogen generation and the factors that impact the generation, etc., and to predict the amount of hydrogen generated by acquiring data by conducting tests, if necessary.

・Study on hydrogen measures

As catalyst-based hydrogen measures, acquire performance data for the candidate catalyst in consideration of the canister environment and confirm the effectiveness considering the diffusion of hydrogen inside the canister.

3. Implementation items, their correlations, and relations with other research

3.1 Implementation Items

(4) Development of drying technology and systems

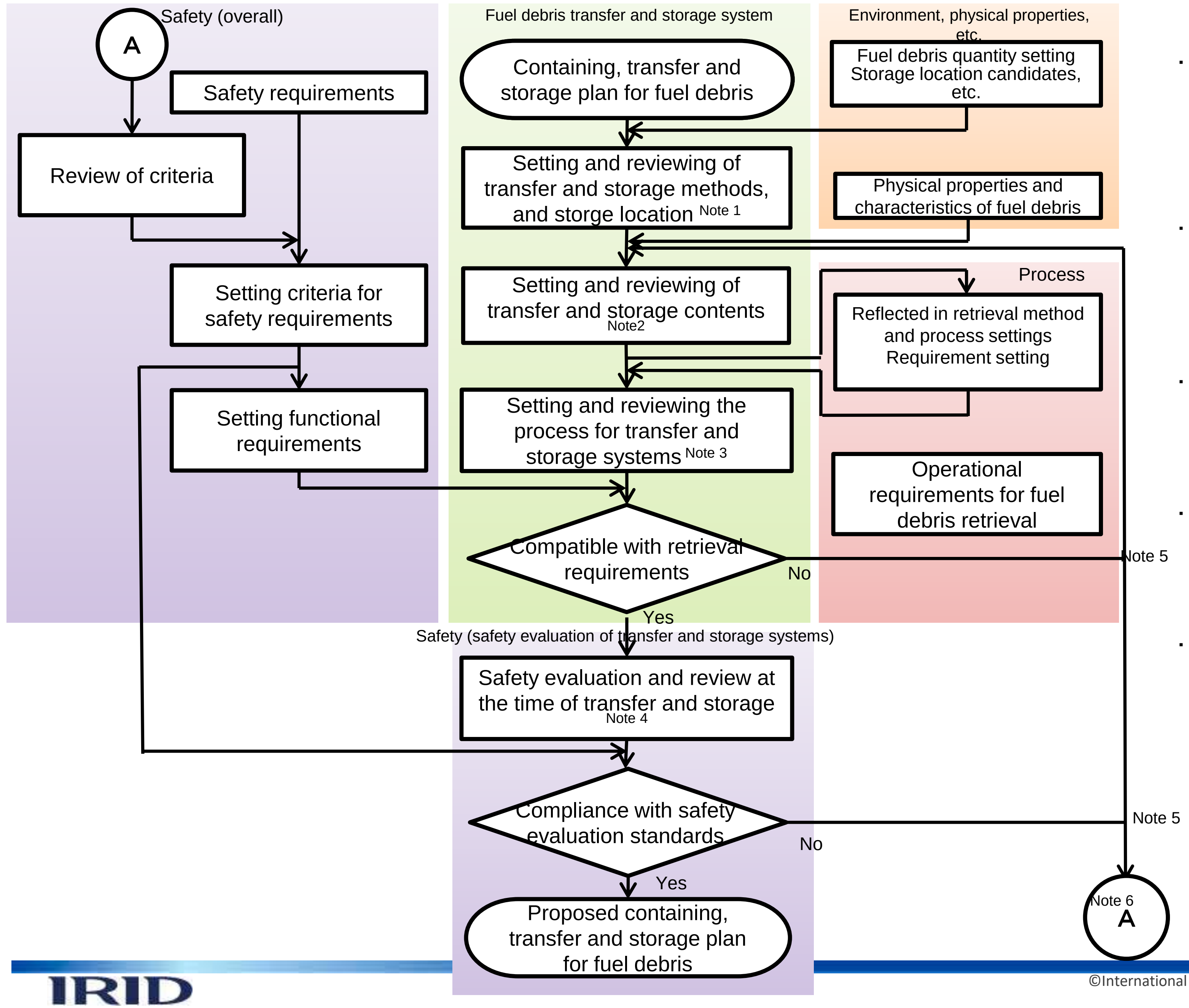
・Study on the basic specifications of drying apparatus

To propose a sample drying system arrangement for drying fuel debris, considering the basic concept of drying apparatus and its maintenance, by organizing the safety requirements of the drying system itself, identifying the applicable candidate technologies, and by collecting drying behavior data using a full-scale test device.

・Study on hydrogen concentration measurement technology

To ensure that the hydrogen concentration in the transfer cask does not exceed the lower explosion limit during the expected transfer period before allocating the transfer cask, investigate the hydrogen concentration measurement technology, and identify and propose the applicable candidate technologies for the canister.

3. Implementation items, their correlations, and relations with other research



Safety (overall)

A

Safety requirements

Review of criteria

Setting criteria for safety requirements

Setting functional requirements

Fuel debris transfer and storage system

Containing, transfer and storage plan for fuel debris

Setting and reviewing of transfer and storage methods, and storge location Note 1

Setting and reviewing of transfer and storage contents Note2

Setting and reviewing the process for transfer and storage systems Note 3

Compatible with retrieval requirements

No

Note 5

Yes

Environment, physical properties, etc.

Fuel debris quantity setting Storage location candidates, etc.

Physical properties and characteristics of fuel debris

Process

Reflected in retrieval method and process settings Requirement setting

Operational requirements for fuel debris retrieval

Safety (safety evaluation of transfer and storage systems)

Safety evaluation and review at the time of transfer and storage Note 4

Compliance with safety evaluation standards

No

Note 5

Yes

Proposed containing, transfer and storage plan for fuel debris

Note 6

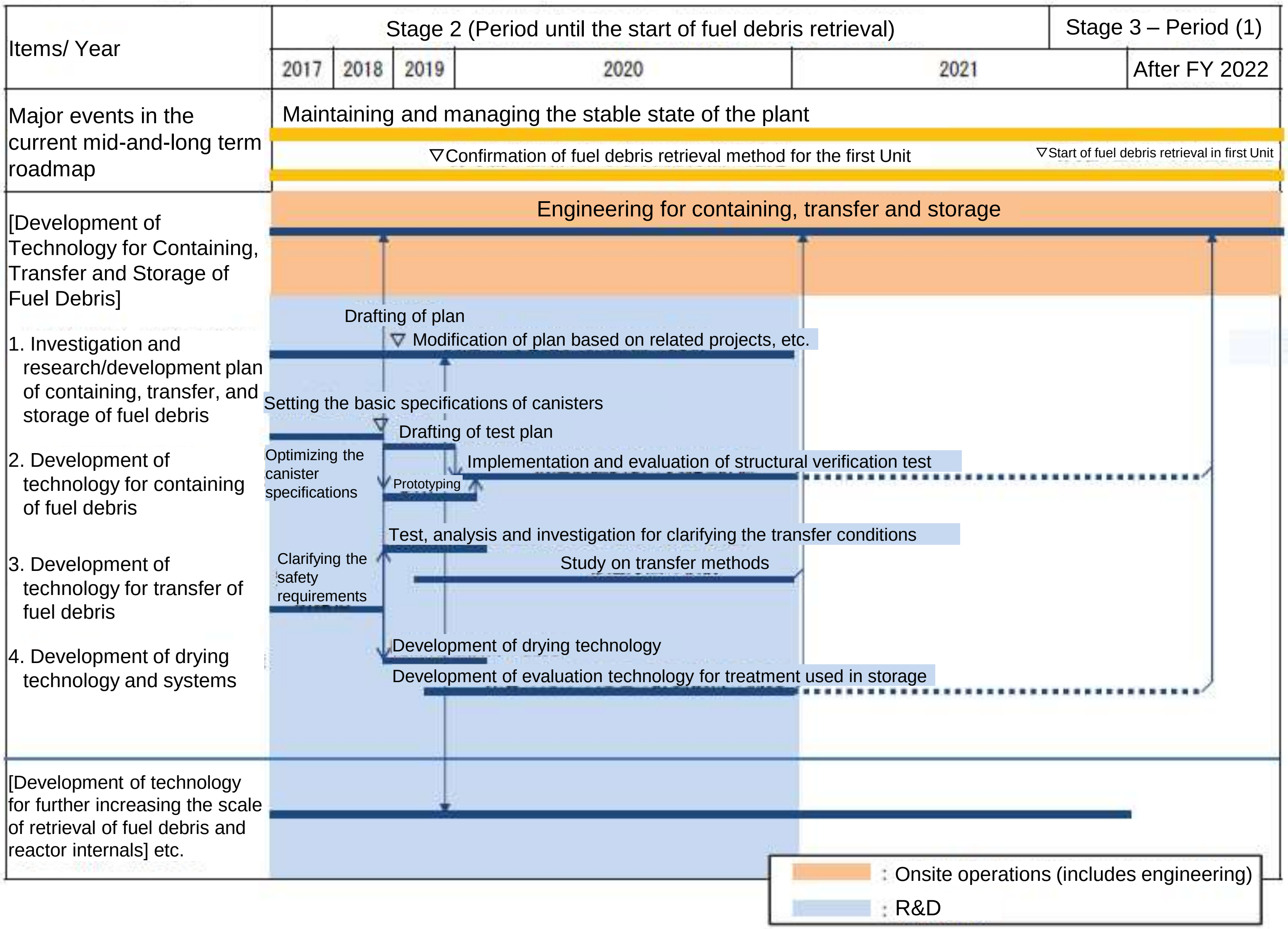
A

- Note 1：
  Setting basic storage policies such as wet storage and dry storage in new facilities
- Note 2：
  Specific storage methods such as dried-and-vented storage and dried-and-sealed storage:
    Related technology development:
    Hydrogen generation amount evaluation, Hydrogen measures
- Note 3：
  Processes such as drying that are required for transfer and storage
  Related technology development:
    Drying apparatus, Hydrogen measurement technology
- Note 4：
  Safety evaluations
  Related technology development:
    Structural evaluation, Hydrogen generation amount evaluation
- Note 5：
  Go up for “Setting and review of transfer and storage contents”, and go down for “Review of overall safety criteria”
  If it is both the cases, go up and down
- Note 6：
  When studying the overall safety by temporarily setting the criteria, the criteria for overall safety may be reviewed as necessary by enhancing knowledge through R&D and incorporating the progress of the study

3. Implementation items, their correlations, and relations with other research

3.2 Relation of Implementation Items (1/2)

(Target process) 2 - (3) Development of Technology for Containing, Transfer and Storage of Fuel Debris



Items/ Year

Stage 2 (Period until the start of fuel debris retrieval)

Stage 3 – Period (1)

2017 | 2018 | 2019 | 2020 | 2021 | After FY 2022

Major events in the current mid-and-long term roadmap

Maintaining and managing the stable state of the plant

▽Confirmation of fuel debris retrieval method for the first Unit

▽Start of fuel debris retrieval in first Unit

[Development of Technology for Containing, Transfer and Storage of Fuel Debris]

Engineering for containing, transfer and storage

1. Investigation and research/development plan of containing, transfer, and storage of fuel debris

Drafting of plan

▽ Modification of plan based on related projects, etc.

2. Development of technology for containing of fuel debris

Setting the basic specifications of canisters

▽ Drafting of test plan

Optimizing the canister specifications

Implementation and evaluation of structural verification test

Prototyping

3. Development of technology for transfer of fuel debris

Test, analysis and investigation for clarifying the transfer conditions

Clarifying the safety requirements

Study on transfer methods

4. Development of drying technology and systems

Development of drying technology

Development of evaluation technology for treatment used in storage

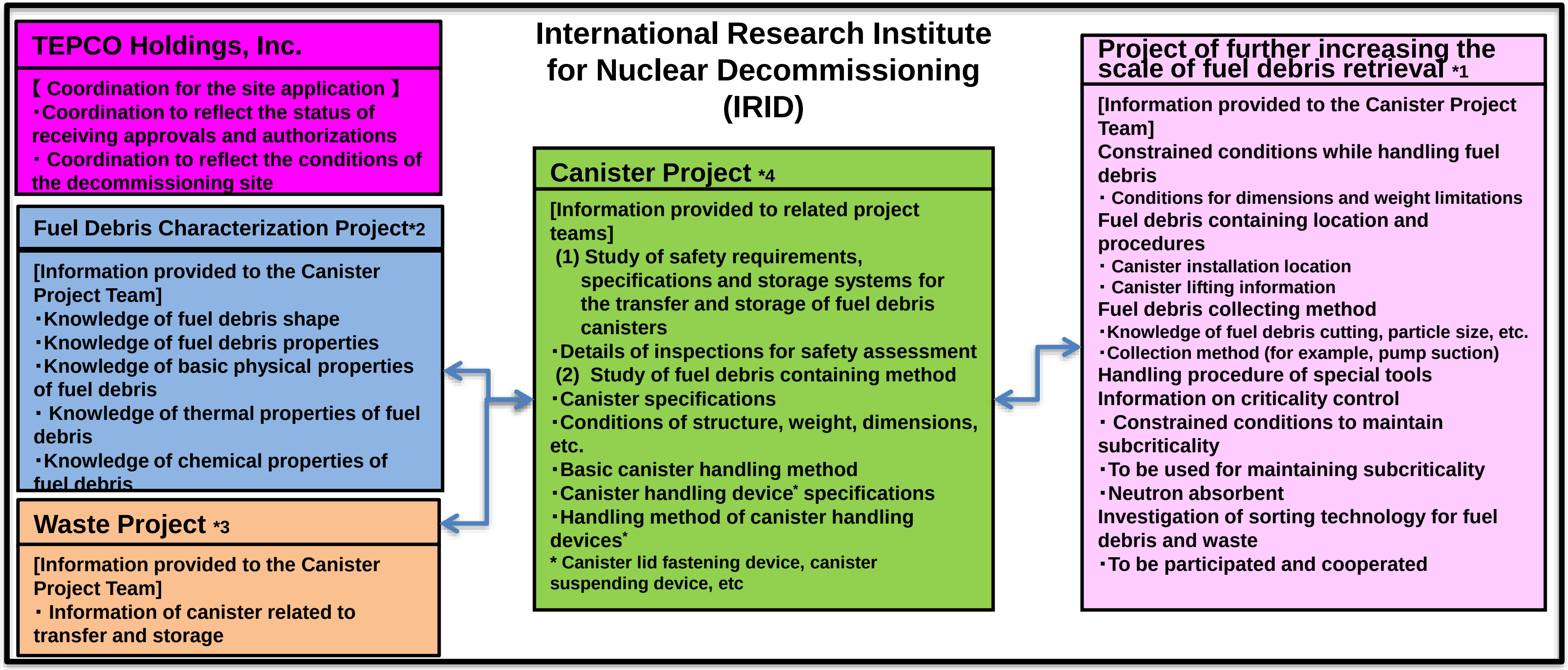
[Development of technology for further increasing the scale of retrieval of fuel debris and reactor internals] etc.

🟧 : Onsite operations (includes engineering)

🟦 : R&D

3. Implementation items, their correlations, and relations with other researches

3.2 Relation of Implementation Items (2/2)



TEPCO Holdings, Inc.

【 Coordination for the site application 】
- ･Coordination to reflect the status of receiving approvals and authorizations
- ･ Coordination to reflect the conditions of the decommissioning site

Fuel Debris Characterization Project*2

[Information provided to the Canister Project Team]
- ･Knowledge of fuel debris shape
- ･Knowledge of fuel debris properties
- ･Knowledge of basic physical properties of fuel debris
- ･ Knowledge of thermal properties of fuel debris
- ･Knowledge of chemical properties of fuel debris

Waste Project *3

[Information provided to the Canister Project Team]
- ･ Information of canister related to transfer and storage

International Research Institute for Nuclear Decommissioning (IRID)

Canister Project *4

[Information provided to related project teams]

(1) Study of safety requirements, specifications and storage systems for the transfer and storage of fuel debris canisters
- ･Details of inspections for safety assessment

(2) Study of fuel debris containing method
- ･Canister specifications
- ･Conditions of structure, weight, dimensions, etc.
- ･Basic canister handling method
- ･Canister handling device* specifications
- ･Handling method of canister handling devices*

* Canister lid fastening device, canister suspending device, etc

Project of further increasing the scale of fuel debris retrieval *1

[Information provided to the Canister Project Team]

Constrained conditions while handling fuel debris
- ･ Conditions for dimensions and weight limitations

Fuel debris containing location and procedures
- ･ Canister installation location
- ･ Canister lifting information

Fuel debris collecting method
- ･Knowledge of fuel debris cutting, particle size, etc.
- ･Collection method (for example, pump suction)

Handling procedure of special tools

Information on criticality control
- ･ Constrained conditions to maintain subcriticality
- ･To be used for maintaining subcriticality
- ･Neutron absorbent

Investigation of sorting technology for fuel debris and waste
- ･To be participated and cooperated

Note)

1: Project of further increasing the scale of fuel debris retrieval: Development of technology for further increasing the scale of retrieval of fuel debris and reactor internal structures

*2: Fuel debris characterization project: Development of technology for analysis and estimation of fuel debris characterization

*3: Waste Project: Research and development of treatment and disposal of solid waste

*4:Canister Project : Development of technology for containing, transfer, and storage of fuel debris

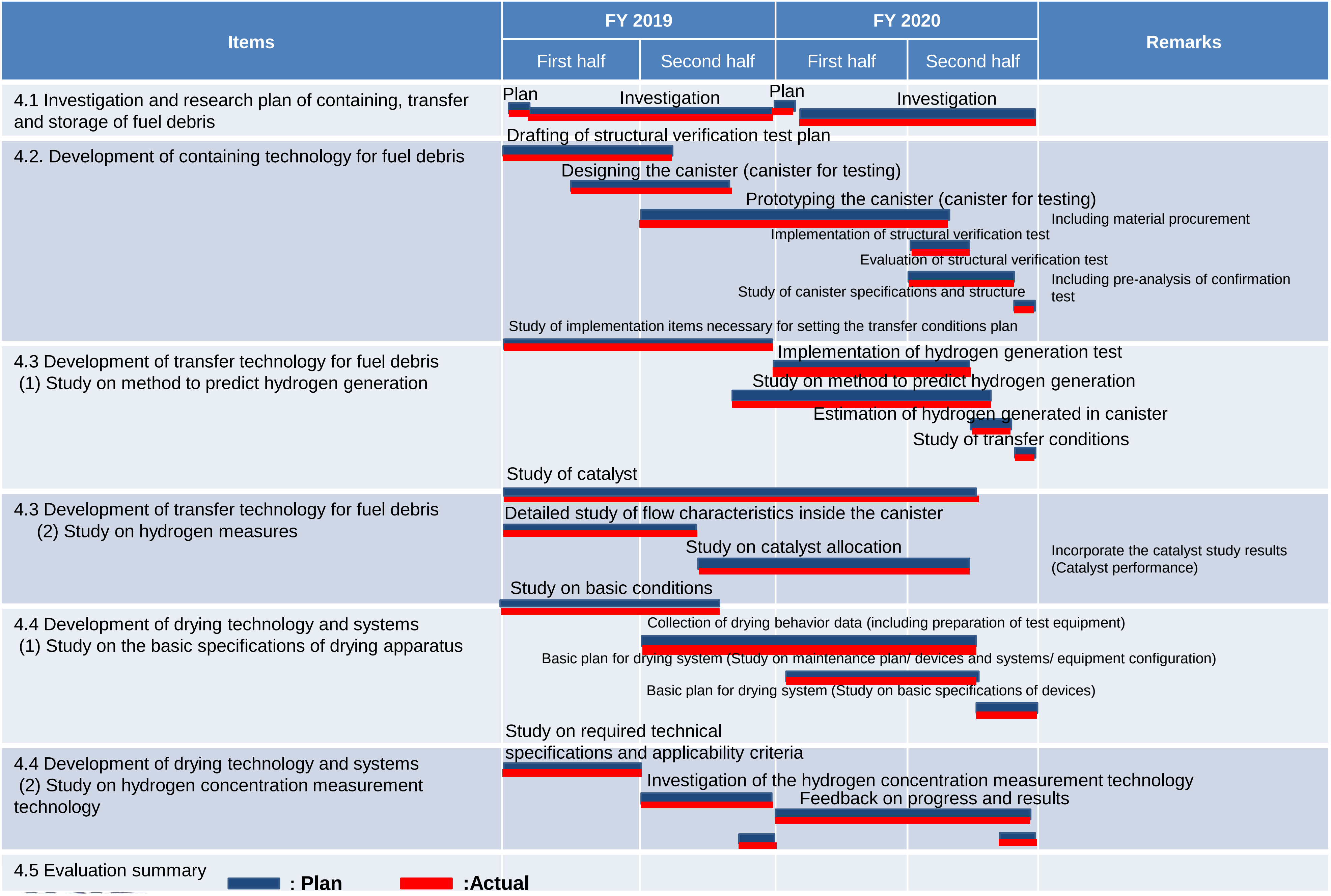
*This project *was* called as *Development of Technology for Retrieval of Fuel Debris and Internal Structure,* when the project started. According to the development plan of decommissioning research in FY 2020 disclosed at the 75th Secretariat Team Meeting for Countermeasures for Decommissioning and Contaminated Water Treatment, the project name was changed to *Development of Technology for Further Increasing the Scale of Retravel of Fuel Debris and Internal Structures*.

Consistent results should be obtained by sharing information provided from IRID's related projects as well as information delivered by this project, working in cooperation and coordinating with those projects.

4. Implementation schedule

Development of Technology for Containing, Transfer and Storage of Fuel Debris

No.14



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	

4.1 Investigation and research plan of containing, transfer and storage of fuel debris
- Plan
- Investigation
- Plan
- Investigation

4.2. Development of containing technology for fuel debris
- Drafting of structural verification test plan
- Designing the canister (canister for testing)
- Prototyping the canister (canister for testing) — Including material procurement
- Implementation of structural verification test
- Evaluation of structural verification test — Including pre-analysis of confirmation test
- Study of canister specifications and structure
- Study of implementation items necessary for setting the transfer conditions plan

4.3 Development of transfer technology for fuel debris
(1) Study on method to predict hydrogen generation
- Implementation of hydrogen generation test
- Study on method to predict hydrogen generation
- Estimation of hydrogen generated in canister
- Study of transfer conditions
- Study of catalyst

4.3 Development of transfer technology for fuel debris
(2) Study on hydrogen measures
- Detailed study of flow characteristics inside the canister
- Study on catalyst allocation — Incorporate the catalyst study results (Catalyst performance)
- Study on basic conditions

4.4 Development of drying technology and systems
(1) Study on the basic specifications of drying apparatus
- Collection of drying behavior data (including preparation of test equipment)
- Basic plan for drying system (Study on maintenance plan/ devices and systems/ equipment configuration)
- Basic plan for drying system (Study on basic specifications of devices)

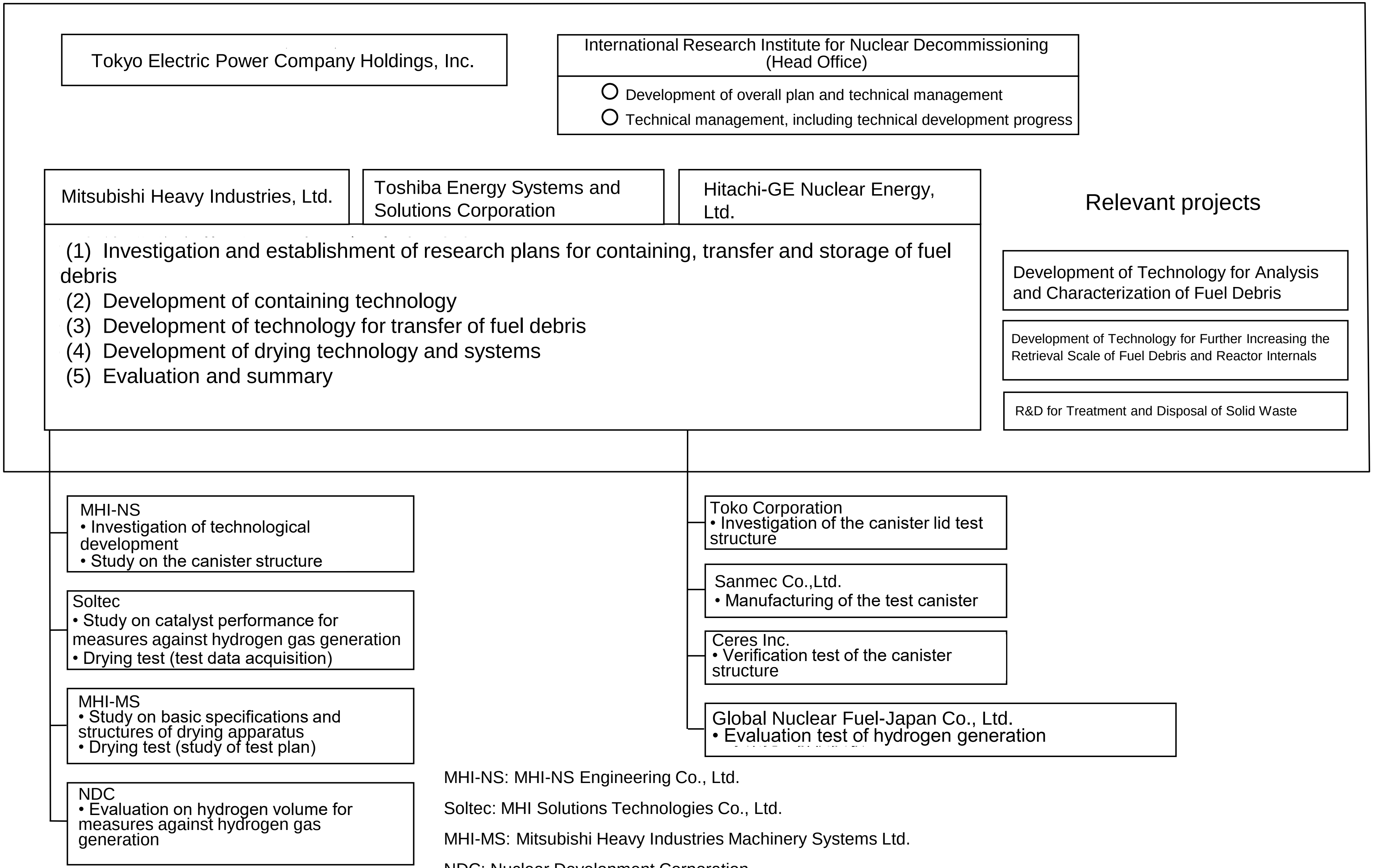
4.4 Development of drying technology and systems
(2) Study on hydrogen concentration measurement technology
- Study on required technical specifications and applicability criteria
- Investigation of the hydrogen concentration measurement technology
- Feedback on progress and results

4.5 Evaluation summary

🟦 : Plan 🟥 :Actual

5. Project Organization Chart

(as of the end of March 2021)



Tokyo Electric Power Company Holdings, Inc.

International Research Institute for Nuclear Decommissioning (Head Office)

○ Development of overall plan and technical management
○ Technical management, including technical development progress

Mitsubishi Heavy Industries, Ltd.

Toshiba Energy Systems and Solutions Corporation

Hitachi-GE Nuclear Energy, Ltd.

(1) Investigation and establishment of research plans for containing, transfer and storage of fuel debris
(2) Development of containing technology
(3) Development of technology for transfer of fuel debris
(4) Development of drying technology and systems
(5) Evaluation and summary

Relevant projects

- Development of Technology for Analysis and Characterization of Fuel Debris
- Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals
- R&D for Treatment and Disposal of Solid Waste

MHI-NS
- Investigation of technological development
- Study on the canister structure

Soltec
- Study on catalyst performance for measures against hydrogen gas generation
- Drying test (test data acquisition)

MHI-MS
- Study on basic specifications and structures of drying apparatus
- Drying test (study of test plan)

NDC
- Evaluation on hydrogen volume for measures against hydrogen gas generation

Toko Corporation
- Investigation of the canister lid test structure

Sanmec Co.,Ltd.
- Manufacturing of the test canister

Ceres Inc.
- Verification test of the canister structure

Global Nuclear Fuel-Japan Co., Ltd.
- Evaluation test of hydrogen generation

MHI-NS: MHI-NS Engineering Co., Ltd.

Soltec: MHI Solutions Technologies Co., Ltd.

MHI-MS: Mitsubishi Heavy Industries Machinery Systems Ltd.

NDC: Nuclear Development Corporation .

Contents

6. Implementation Details

6.1 Investigation and research plan for containing, transfer, and storage of fuel debris

① Purposes and goals

The latest information of related projects and the progress of the on-site operations will have to be collected and reflected to the plan so that the effective collaboration between the development tasks can be achieved. In addition, relevant information will have to be sought internationally so that the development tasks can be streamlined effectively.

② Comparison with existing technology (as necessary)

A comparison will be performed for each development task as needed basis, which is not mentioned in this section.

③ Action items and results (estimated and actual)

a. Fine tuning of research plans based on the latest technical trends

The research plans were fine tuned based on the latest information (including the progress of development) and knowledge from other projects, such as Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures, Characterization of Fuel Debris, and Waste Management, and the latest trends and information about the coordination of the on-site operations by TEPCO Holdings and coordination on permission and authorization, obtained in joint meetings and the like so that the development tasks would be performed toward the goals effectively linked with the goals of other projects and the outcomes of them would be applicable to on-site operations.

In FY2019, for example, the plan of fuel debris drying tests was developed based on the latest planning drawing of the unit provided from the project “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures.” In addition, development tasks in FY2020 were systematically performed according to the plans formulated based on information exchanged with TEPCO Holding.

b. International research on relevant information

To seek information useful for effective planning of development tasks in FY2019, documents on TMI-2 fuel debris drying obtained and examined before were re-examined. (Details are described in Section 6.4, “Development of drying technology and systems: (1) Study of the basic specifications of the drying apparatus”) There is no additional need of investigation in FY2020.

6. Implementation Details

6.1 Investigation and research plan for containing, transfer, and storage of fuel debris

④ Contribution of outcomes to relevant study areas

The outcomes of investigation and research will be incorporated into each development tasks of this subsidized project.

⑤ Analysis with respect to the on-site applicability

The applicability of the intended outcomes of each development task in on-site operations will be evaluated individually and separately. This section does not mention anything about the applicability.

⑥ Goal achievement level

Technical requirements for safety assurance imposed in other countries were additionally analyzed and organized into documents based on the information already obtained and the latest information on the progress of other projects including those conducted at the actual site and knowledge obtained in them that were additionally collected. The originally set goal that was to fine tune the plan of each development task based on the results of investigation and research along with advice from experts.

⑦ Issues to be addressed

Each technology will be evaluated as needed basis, which is not mentioned in this section.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of full-scale canister and structural verification test -

① Purposes and goals

The specifications and structural design of the canister are to be proposed. For this purpose, the plan of the specifications and structural design of the canister that was temporarily adopted in FY2018 is to be reviewed if necessary, and full-scale models of the canister will be prototyped. In addition, the full-scale prototype canisters will be subjected to structural verification tests to evaluate their safety functions (such as confinement and criticality prevention) in the evaluation events.

Further, the applicability of the method to simulate and analyze the structural integrity of the canister in various events is to be examined by comparing its calculation results with the results of the structural verification tests.

② Comparison with existing technology (as necessary)

There will not be any issues on the final design of the mechanism to fasten the lid of the canister since the design of the canister lid developed in FY2018 uses fixing bolts and it is within the applicable range of existing technology.

Meanwhile, the simple installation structure is a method of fastening the lid by turning the lid. Although it has a proven track record in ultra high-pressure vessels, there are concerns about the structural integrity of the entire canister (an integrated state with the lid structure, body, buffer structure, etc.) in the event of dropping, tumbling, etc. It is necessary to ensure the structural integrity based on the handling of canisters in 1F.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of full-scale canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (1/2)

(i) Selection of events to be tested

It was decided to extract events from each operation of the latest canister handling flow (side-access retrieval method, dry storage, storage in metal casks) as the subject of the event selection.

Among the identified design events and evaluation events, the events of the canister dropping in the vertical position, the canister dropping in the inclined position, and the canister dropping on top of another canister in the vertical position, which are considered to have a large impact on the structural strength, were selected as the events for which the structural verification test will be performed.

The dropping height was set in consideration of the dimensions of the building and transfer cask. The oblique angle was set to 60º, which has a large impact based on the preliminary analysis.

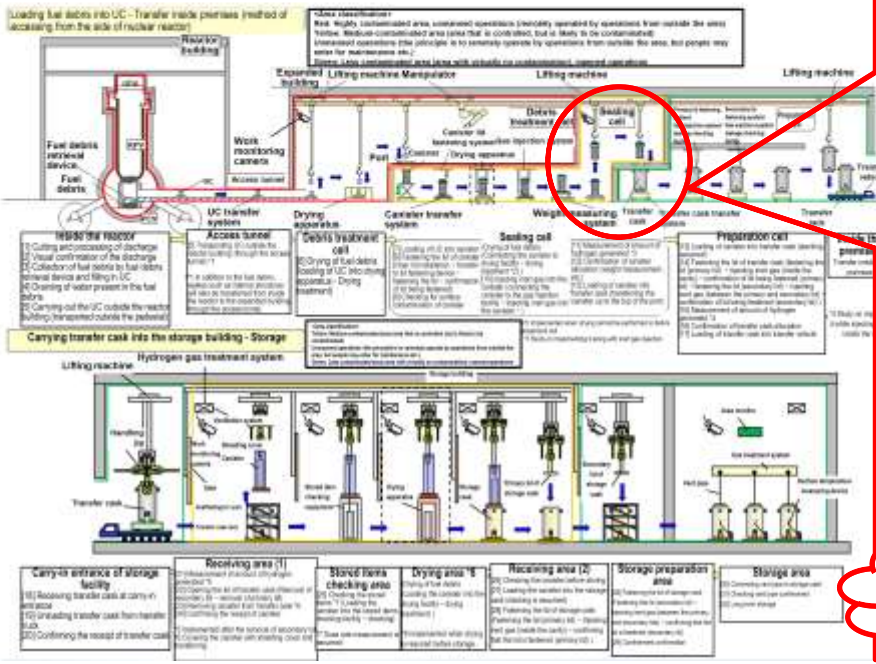


Figure. Canister handling flow plan

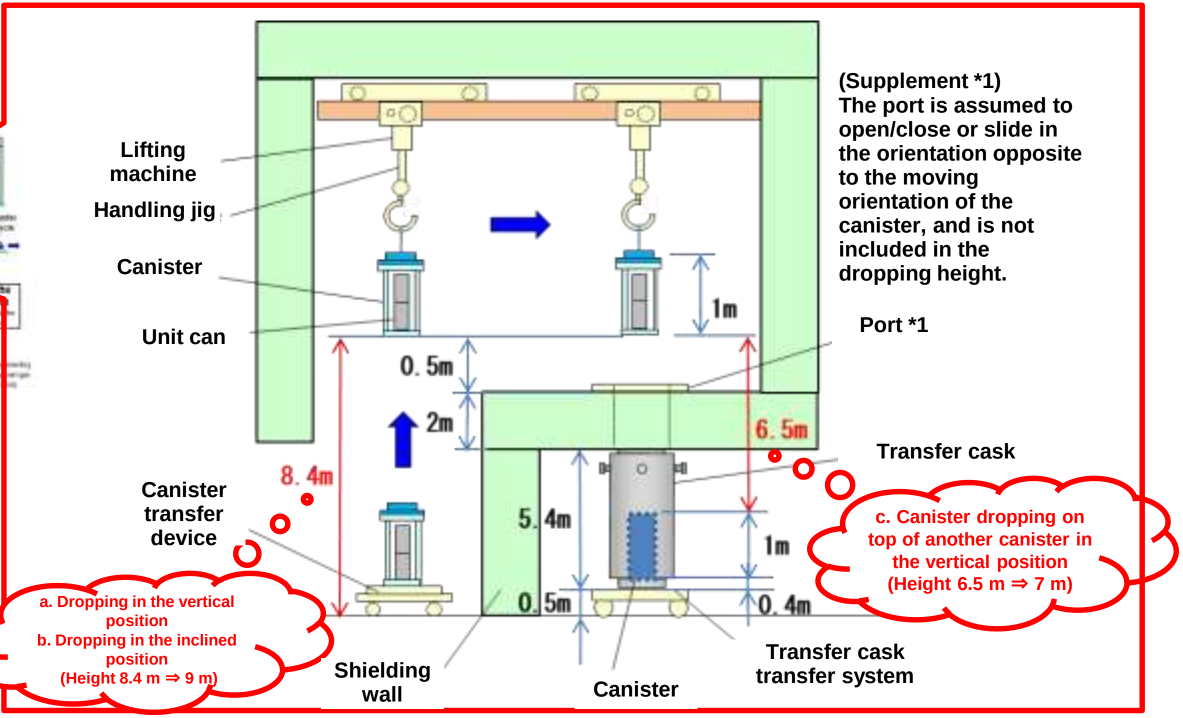


Figure. Approach to setting of the dropping height

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

a. Structural verification test planning (2/2)

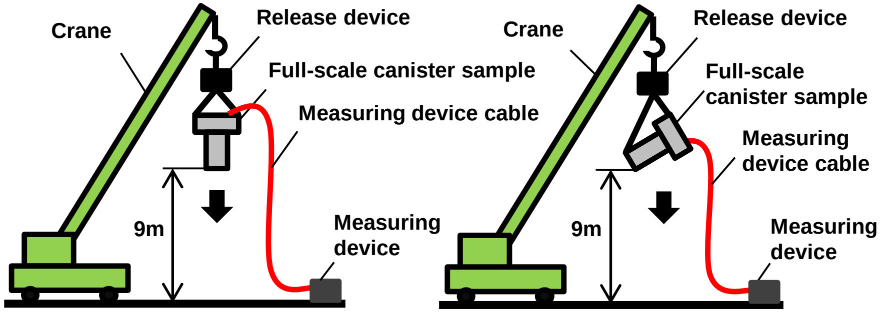
(ii) Test cases and test systems

A total of six structural verification test scenarios were developed for the three events by combining the test conditions and the structures of full-scale canister models (test samples).

The construction of the test systems illustrated below was planned to reproduce events that may occur in operations at the 1F and to be used for structural verification tests.

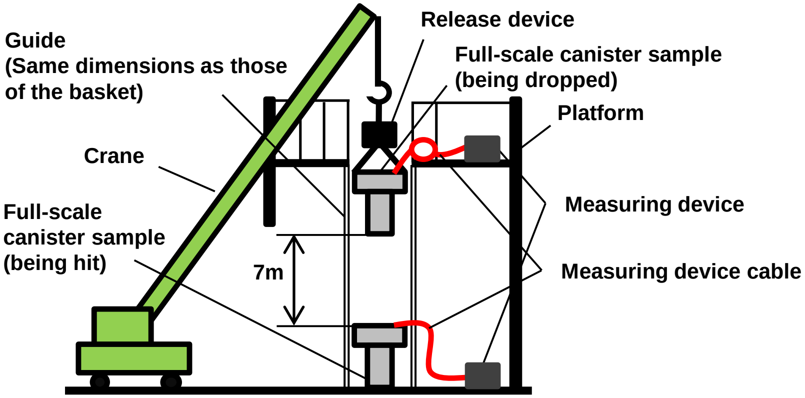
Table: Test cases (plan)

No.	Events	Test conditions			Structures of full-scale canister models (test samples)				Main test purposes
		Drop test height	Tilt angle	Number of tests	Lid structure	Body inner diameter	Air supply mechanism	Number of samples	
1	Dropping the canister in a vertical position	9m	0°	1	Simple mounting structure	400 mm	None	1	· The main test purpose is to check the impact of the impact load caused by the canister collision into the floor in a vertical position on its body (measuring a change in its inner diameter) and to validate the buffer structure (including the effect of preventing the contents of the canister from colliding against the inner surface of the lid)
2					Bolt structure	220mm	None	1	
3	Dropping the canister in an inclined position	9m	60°	1	Simple mounting structure	400 mm	Yes	1	· The main test purpose is to evaluate the impact of the canister dropping in an inclined position (including the impact of the canister collision into the floor in an inclined position) on its lid, bottom, and air supply mechanism, specifically, the sealing performance of the lid and the integrity of the air supply mechanism after the drop test.
4					Bolt structure	220mm	Yes	1	
5	Dropping a canister on another canister in a vertical position	7m	0°	1	Simple mounting structure	220mm	None	2	· The test purpose is to check the impact of the impact load caused by dropping a canister on another canister in a vertical position on their bodys (measuring a change in their inner diameters) and to validate the buffer structure (including validation of measures to prevent deformation of the lift hook and to prevent the buffer structure from interfering the lift hook)
6					Bolt structure	400 mm	None	2	



(a) Dropping the canister in a vertical position

(b) Dropping the canister in an inclined position



(c) Dropping a canister on another canister in a vertical position

Figure: Illustration of the test system for the structural verification of full-scale canister samples

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of full-scale canister and structural verification test -

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (1/4)

(i) Canister specification plan

The design conditions/ design policy for canister were re-organized, and the canister specification plan was set considering the latest canister handling flow and the status of study of project of further increasing the scale of fuel debris retrieval, etc.

Lid

・Two types of lids were designed as remotely operable structures: a simple installation structure that can be opened and closed by turning the lid, and a bolt structure that has a proven track record in remote controlled operation in TMI-2, etc.
・The structure does not cause detachment of the lid or damage leading to a large amount of leakage and does not generate continuous leakage from the seal even when it receives an impact load such as a drop in the vertical position.

Vent mechanism

The diffusion evaluation was conducted considering the coupler and filter for the amount of hydrogen generated based on actual measurements (assumed that the amount of hydrogen generation is reduced lower than actual measurements in the presence of water since it is dried), and setting of the coupler inner diameter was determined. Additionally, on basis of risk evaluation for vent opening/closing during handling canisters, a regular opening coupler was adopted.

Air supply mechanism

・When fuel debris is dried in the unit can, the air supply mechanism is not installed in the canister, but when fuel debris is dried in the canister, it was decided to install air supply mechanisms at two locations (couplers for air supply) on the body flange. A coupler that is normally-closed is installed in each air supply mechanism so that hot air flows from the bottom to the top of the canister in the order of air supply coupler (air supply port) ⇒ piping ⇒ inside the canister ⇒ air supply coupler (exhaust port). To prevent clogging, it was decided to install a filter on the system side equipment and not on the air supply coupler.

Body

・Two types of bodies were designed, inner diameter of 220 mm, which can maintain subcriticality, and 400 mm, which has an expanded inner diameter for improved workability.
・The internal height of the canister was set taking into account the catalyst case thickness (20 mm (temporarily set)) and height of two unit cans it will store (400 mm per can), in addition to considering a margin on the thermal expansion of the unit cans, the manufacturing tolerance, and the total dimension of the height when the unit cans are stored at an angle.
・A tapered portion is provided at the joint between the flange and the body, and the bottom plate to relieve stress when an impact load is applied.

Material

It was decided to use SUS316L in consideration of SCC resistance, procurement, workability, etc.

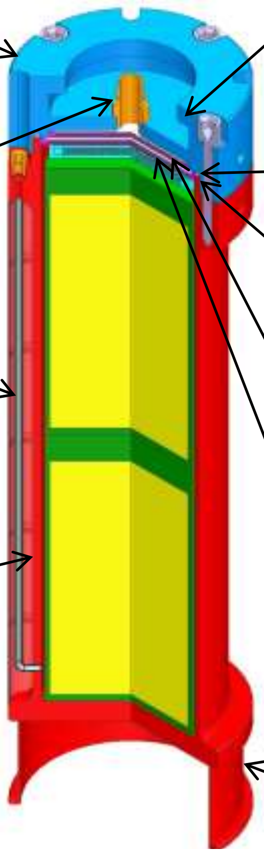


Figure. Canister specification plan Note 1
(Structural plan with bolt structure/ inner diameter 220 mm/ air supply mechanism)

Suspending part

・A structure that allows lifting without being affected by the shape of the storage space (square prism, cylinder, plate (drilled hole)), by providing a groove inside the lid of the canister for lifting and making the suspending device smaller than the outer diameter of the canister lid.
・A structure where the buffer structure does not enter the suspending part by not installing the suspending part that was earlier installed in the center of the upper surface of the lid.

Seal

To ensure the confinement function at the storage facility during storage, elastomer gasket (EPDM: ethylene propylene diene rubber) was used prioritizing on the storage efficiency (minimization of lid outer diameter), lid fastening workability, and applicability to a simple installation structure.

Method of sealing the port between cells and the canister

・To prevent contamination as much as possible at the boundary between cells, a sealing structure is to press the upper end plate of the canister against the seal part of the port between cells.
・To prevent contamination as much as possible during handling of the canister including fastening the lid between the port cells, an inner lid of the canister body(with a hydrogen venting filter) is installed on the canister.

Filter

・The hydrogen release was evaluated by using a method for hydrogen diffusion evaluation, and it was confirmed that the hydrogen concentration was less than 4 vol% when using a wire mesh type SUS316 filter having a mesh diameter of 0.3 μm . In addition, the structure is less affected by clogging as the filter diameter is increased to enlarge the surface area of the flow.

Catalyst

・Installation space is created, assuming that catalyst is placed at the lower of the inner lid.

Buffer structure

・A structure with a buffer structure installed to prevent collision of stored items with the inner surface of the lid due to shooting up during drop events, and to reduce deformation of the body of the canister. The DOE (skirt) type was selected because of its good manufacturability.

Note 1: In the cross-sectional view, the components are color coded for identification.

6. Implementation Details

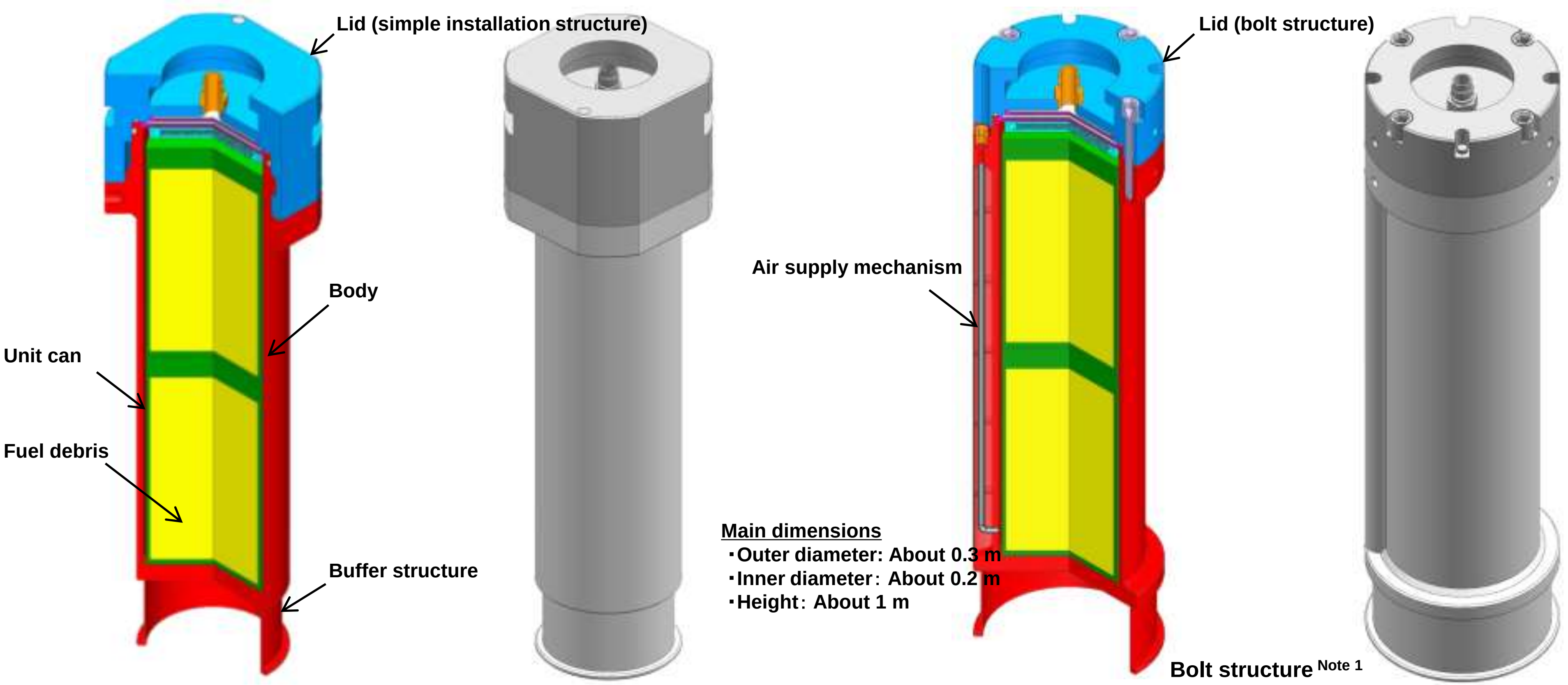
6.2 Development of technology for containing of fuel debris

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (2/4)

(ii) Canister structural plan

Eight types of structural plans were selected for the canister: two types of lid structures (simple installation structure and bolt structure), two types of inner diameter of body (220 mm and 400 mm), and with/ without air supply mechanism.



Main dimensions
- Outer diameter: About 0.3 m
- Inner diameter: About 0.2 m
- Height: About 1 m

Simple mounting structure Note 1
(Inner diameter of body is 220 mm/ without air supply mechanism)

Bolt structure Note 1
(Inner diameter of body is 220 mm/ with air supply mechanism)

Figure. Real-size canister structural plan

Note 1: In the cross-sectional view, the lid, body, unit can, fuel debris, etc. are color coded for identification of the components

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

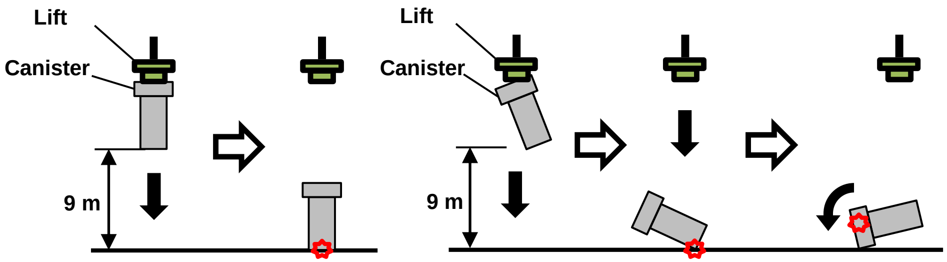
③ Action items and results (estimated and actual)

b. Designing the canister (canister for testing) (3/4)

(iii) Structural analysis evaluation (1/2)

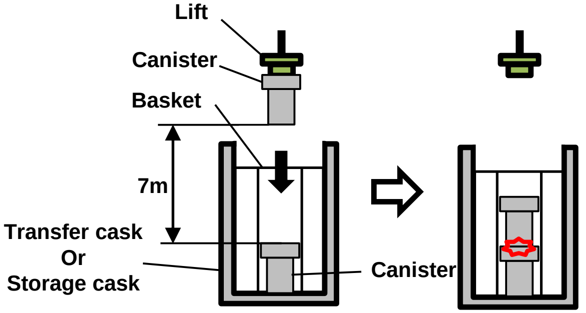
1) Analysis model and evaluation item

To evaluate the structural integrity of the canister, the following events were taken into consideration as those that cause the strongest impact on the structural strength of the canister among various events: a canister falling from a height of 9 m in a vertical position, falling from a height of 9 m in a 60° inclined position, and a canister falling from a height of 7 m and crashing onto the top of another canister in a vertical position. Then, models to simulate these events were created, and how the impact load caused in those events affects the canister was evaluated using general purpose finite element method analysis software, LS-DYNA. The simulation models were created based on the shape and dimensions of the canisters, and the impact load caused by the collision was calculated and given based on the theoretical terminal speed of a free fall as a collision velocity (e.g., $\sqrt{2gh}$ = 13.3 m/s for a fall from a height of 9 m).



Dropping the canister in a vertical position

Dropping the canister in an inclined position



Dropping a canister on another canister in a vertical position

Figure: Conceptual image of evaluation events

<Evaluation item>

(a) Confinement performance (effective plastic strain)

The calculated values of strain must prove that there is no risk of fracture in the joint of the lid and the body. (They must be less than the fracture equivalent plastic strain, for example, 30% for SUS316L.)

(b) Confinement performance (seal gap displacement)

A seal gap displacement must be within a range where proper compression dimensions are maintained for the O-ring (0.8 mm for the top and 0.9 mm for the side). The occurrence of an instant gap opening and closure is permissible as the duration of leakage is minimal.

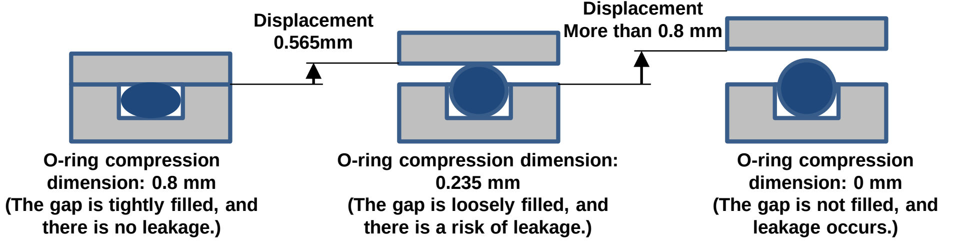


Figure: Relationship between seal gap displacement and risk of leakage (O-ring [top])

(c) Measures to maintain sub-criticality (maximum permissible change in the inner diameter of the body)

The deformation of the body of the canister (change in its inner diameter) must be within a range (245 mm or less, target is 232.5 mm or less) so that the geometric shape can maintain sub-criticality.

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

b. Designing the canister (canister for testing) (4/4)

(iii) Structural analysis evaluation (2/2)

2) Summary of structural analysis

As a result of the structural analysis evaluation, it was confirmed that all types of proposed structure design of a canister were robust enough to maintain their safety functions (such as confinement and criticality prevention) after being subjected in various events. In some test cases, a risk of the occurrence of an instant gap opening and closure was predicted at the O-ring seal. Despite such cases, the confinement performance will be maintained because the duration of the gap opening is so short that leakage can be minimally suppressed.

Table: Summary of structural analysis results

Events	Safety functions	Evaluation items of structural analysis	Simple mounting structure				Bolt structure			
			Inner diameter: 220 mm		Inner diameter: 400 mm		Inner diameter: 220 mm		Inner diameter: 400 mm	
			Air supply—No	Air supply—Yes	Air supply—No	Air supply—Yes	Air supply—No	Air supply—Yes	Air supply—No	Air supply—Yes
Dropping the canister in a vertical position	Confinement	Effective plastic strain	○	○	○	○	○	○	○	○
		Seal gap	○	○	○	○	○	○	○	○
	Maintaining sub-criticality	Body inner diameter change	○	○	○	○	○	○	○	○
Dropping the canister in an inclined position	Confinement	Effective plastic strain	○	○	○	○	○	○	○	○
		Seal gap	○	○	△ There is a risk of an instant gap opening and closure. (Max. 0.65 mm)	△ There is a risk of an instant gap opening and closure. (Max. 0.83 mm)	○	○	△ There is a risk of an instant gap opening and closure. (Max. 0.59 mm)	○
	Maintaining sub-criticality	Body inner diameter change	○	○	○	○	○	○	○	○
Dropping a canister on another canister in a vertical position	Confinement	Effective plastic strain	○	○	○	○	○	○	○	○
		Seal gap	○	○	○	○	○	○	○	○
	Maintaining sub-criticality	Body inner diameter change	○	○	○	○	○	○	○	○

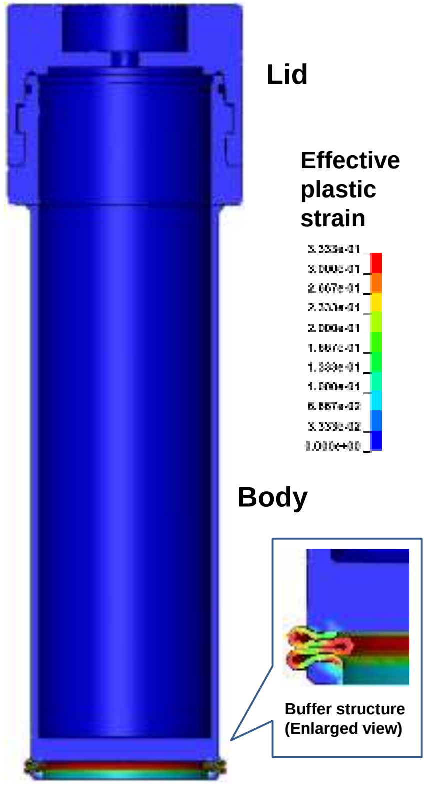


Figure: Contour figure of effective plastic strain

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

c. Prototyping the canister (canister for testing)

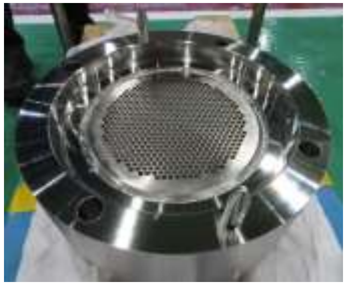
(i) Structure and prototypes of the canister (canister for testing)

A total of 8 units of full-scale canister models (canisters for testing) were prototyped with 6 different specifications. The specifications were configured to be the same as those of the canisters planned to be used in the actual site with respect to dimensions and structure based on the structural verification test plan and the result of the canister (canister for testing) design work. As to the contents of the canister (such as the unit can and fuel debris), simulants that simulated the external dimensions and weight of them were made. In addition, a cable entry flange was attached in each canister sample at a position that causes the minimum effect on the canister strength to guide the cables of a strain gauge and accelerometer installed inside the canister.

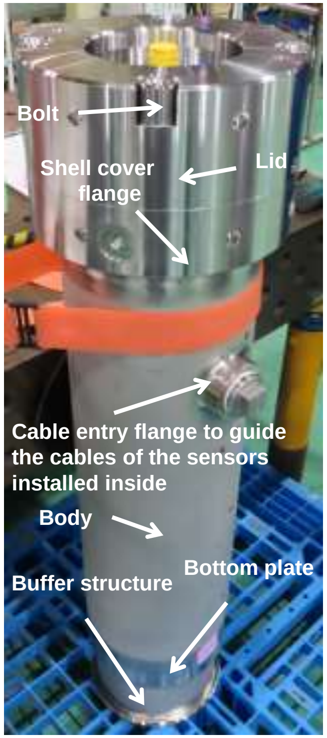
Table: Comparison between the canisters planned to be used at the actual site (assumed conditions) and the canisters for testing

Item			Dimensions of the canisters planned to be used at the actual site (assumed fuel debris removal plan)	Canister (test sample)	Basis of condition setting
Unit can (or canister content simulants)	Outer diameter	Inner diameter: 220 mm	Φ210mm(PLAN-A,C) Φ200mm(PLAN-B)	φ210mm	Based on the maximum dimensions among those used in each PLAN of the project "Development of Technologies for Retrieving Fuel Debris and Internal Structures"
		Inner diameter: 400 mm	Φ390mm(PLAN-B)	φ390mm	
	Height	Inner diameter: 220 mm	200 mm (PLAN-A) 325 mm (PLAN-B) 400 mm (PLAN-C)	400 mm	Based on the maximum dimensions among those used in each PLAN of the project "Development of Technologies for Retrieving Fuel Debris and Internal Structures"
		Inner diameter: 400 mm	400 mm (PLAN-B)	400 mm	
	Number of samples		4 (PLAN-A) 2 (PLAN-B, C)	2	Based on the first and second largest units in unit weight among those used in each PLAN of the project "Development of Technologies for Retrieving Fuel Debris and Internal Structures"
Fuel debris (or canister content simulants)	Filling rate		30%	50% (A canister content simulant with a weight equivalent to that of UO_2 that fills 50% of the canister's capacity was made.)	More conservative conditions were applied to ensure the structural strength of the canister.
	Density		2.5×10^{-6} Up to 11×10^{-6} kg/mm^3 (The minimum value is of concrete density, and the maximum value is of UO2 density)	11×10^{-6}kg/mm^3 (A canister content simulant with a density equivalent to that of UO2 was made.)	More conservative conditions were applied to ensure the structural strength of the canister.
Cable entry flange to guide the cables of the sensors installed inside			No	Yes	Prepared to guide the cables of a strain gauge and accelerometer

(a) Lid



(b) Lid (inner side)



(c) Appearance of a fully assembled canister sample

Figure: External appearance of a full-scale canister model (canister for testing)

(A sample model with the bolt structure, an inner diameter of 220 mm, and without air supply mechanism)

6. Implementation details

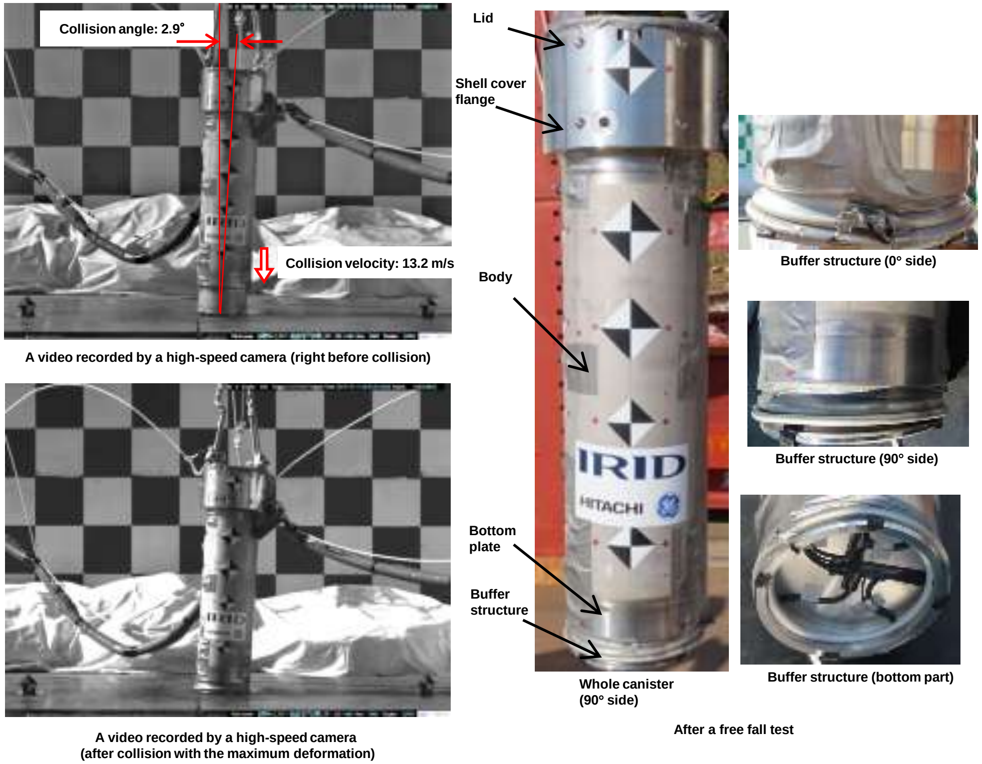
6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

d. Performing structural verification tests (1/3)

(i) Test results (typical examples: drop tests in vertical and inclined positions)

None of the canister samples showed a problem of the lid having come off the body or cracks in the lid or the body (including the flange, body, and bottom plate) that ran through the thickness of those parts and created a leakage path after the tests. Leakage rates were below the acceptance criterion. There was no noticeable deformation in the body either. There was a case where the lid could not be removed after a drop test in an inclined position. The sample canister that showed this problem was with the simple installation structure, an inner diameter of 400 mm and a ventilation mechanism. The cover of the air supply mechanism was bent and came to contact with the elbow. However, there was no damage in the piping.



A video recorded by a high-speed camera (right before collision)

A video recorded by a high-speed camera (after collision with the maximum deformation)

Whole canister (90° side)

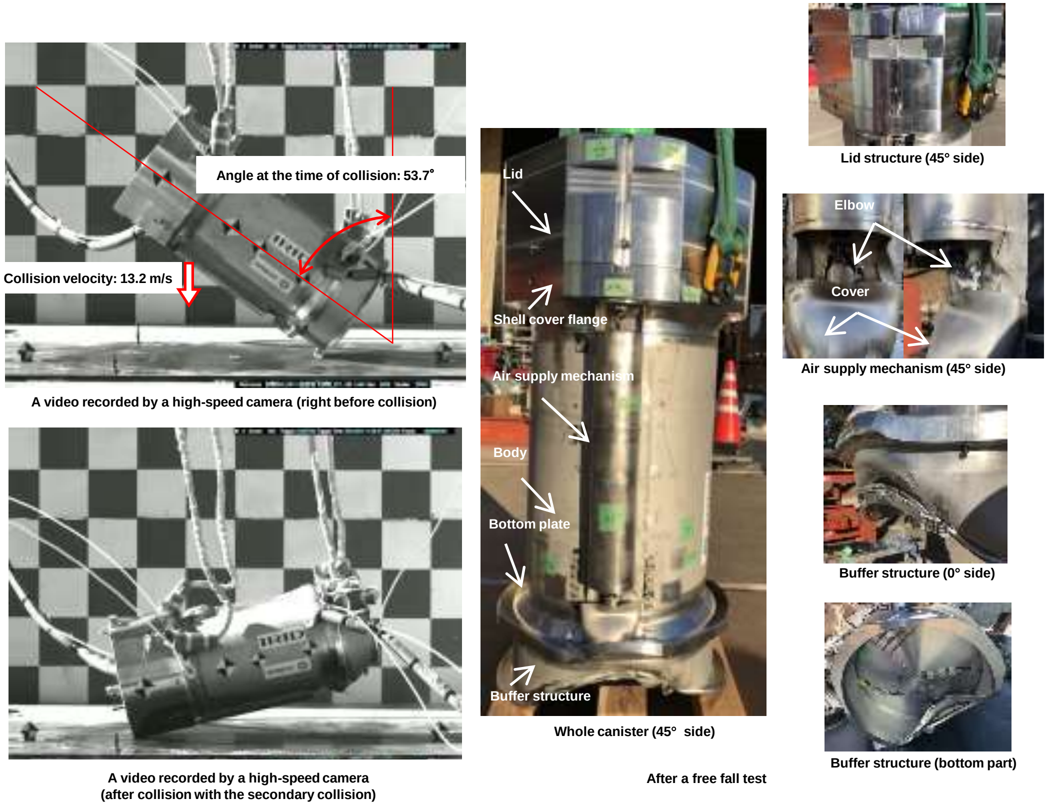
Buffer structure (0° side)

Buffer structure (90° side)

Buffer structure (bottom part)

After a free fall test

Figure: Result of the drop test of the canister with the bolt structure, inner diameter of 220 mm, and without air supply mechanism in a vertical position (external appearance after the test)



A video recorded by a high-speed camera (right before collision)

A video recorded by a high-speed camera (after collision with the secondary collision)

Whole canister (45° side)

Lid structure (45° side)

Air supply mechanism (45° side)

Buffer structure (0° side)

Buffer structure (bottom part)

After a free fall test

Figure: Result of the drop test of the canister with the simple installation structure, inner diameter of 400 mm, and air supply mechanism in an inclined position (external appearance after the test)

6. Implementation details

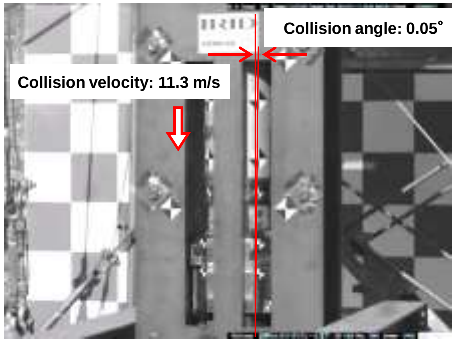
6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

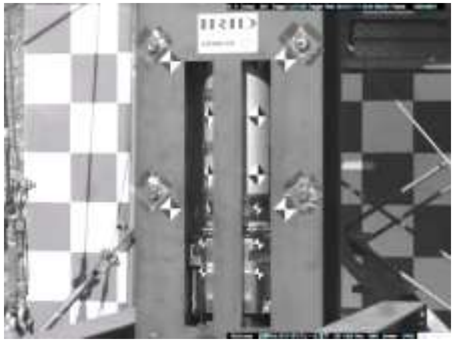
d. Performing structural verification tests (2/3)

(ii) Test results (typical examples: test to drop a canister on another canister in a vertical position)

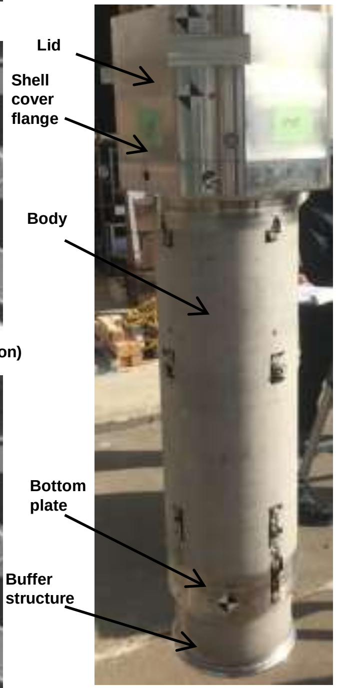
None of the canister samples showed a problem of the lid having come off the body or cracks in the lid or the body (including the flange, body, and bottom plate) that ran through the thickness of those parts and created a leakage path after the tests. Leakage rates were below the acceptance criterion. There was no noticeable deformation in the body either.



A video recorded by a high-speed camera (right before collision)



A video recorded by a high-speed camera (after collision with the maximum deformation)



Whole canister (180° side)

Lid structure (45° side)

Buffer structure (90° side)

Buffer structure (180° side)

Buffer structure (bottom part)

After a free fall test

Figure: Result of the test (external appearance of the canister after the test) of dropping a canister on another canister in a vertical position.
(The canisters used in the test were with the simple installation structure, inner diameter of 220 mm, and without air supply mechanism.)

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

d. Performing structural verification tests (3/3)

(iii) Summary of test results

As a result of the structural verification test, it was confirmed that all canister samples were robust enough to maintain their safety functions (such as confinement and criticality prevention) against the impact loads caused in the drop tests. In some test cases, an instant gap opening and closure may have occurred at the O-ring seal. Despite such cases, the confinement performance will be maintained because the duration of the gap opening is so short that leakage can be minimally suppressed. On the other hand, there was a case where the lid could not be removed after a drop test in an inclined position. The sample canister that showed such problem was with the simple installation structure. This result has raised the need for continuous engineering efforts on the lid mounting method.

Table: Summary of test results (all test cases)

Safety functions	Check items in tests	Test results							
		Drop test in a vertical position		Drop test in an inclined position		Test to drop a canister on another canister in a vertical position			
		Simple mounting structure Inner diameter: 400 mm	Bolt Inner diameter: 220 mm	Simple mounting structure Inner diameter: 400 mm	Bolt Inner diameter: 220 mm	Simple mounting structure Inner diameter: 220 mm Falling canister	Simple mounting structure Inner diameter: 220 mm Canister being hit	Bolt Inner diameter: 400 mm Falling canister	Bolt Inner diameter: 400 mm Canister being hit
Confinement	Leak test	○	○	○	○	○	○	○	○
	Visual inspection	○	○	○	○	○	○	○	○
	Strain time history measurement (Check plastic deformation around O-ring sealing surfaces)	○	○	- Missing data*1	- Missing data*1	○	○	○	○
	(Check instant gap opening and closure at the O-ring seal) (Measure the relative displacement of the lid to the body)	○	○	△ There is a risk of an instant gap opening and closure.	△ There is a risk of an instant gap opening and closure.	○	○	○	○
Criticality prevention	Dimension check (Measure the inner diameter of the body)	○	○	○	○	○	○	○	○
(Basic function)	Removal of the lid	○	○	× Unable to open the lid*2	○	○	○	○	○

Note 1: Though missing data occurred in strain time history measurement, it was concluded to pose no problem because the confinement performance was proven to be maintained based on other test results, such as leak tests.

Note 2: At present, the event of the canister falling is considered to be one of the evaluation events. It is our basic stance that the problem of the lid not being able to be opened due to a drop impact should be solved by preventing a falling by devising equipment and/or processes. In case of the occurrence of such a problem, there should still be a method to open the canister, such as cutting. The canister design can be changed, such as adding a buffer structure to the lid, to be prepared for cases where the occurrence of the canister falling cannot be avoided by devising equipment or processes. However, it will be a more reasonable solution to address this problem by devising equipment and/or processes, such as applying a buffer material on the floor surface and limiting the canister lifting height.

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (1/8)

(i) Method used in the structural analysis

A structural analysis (post-test analysis) that simulated the test conditions of the structural verification test was performed, and the result of the analysis was compared with the result of the test to evaluate the validity of the post-test analysis. It was conducted to evaluate the certainty of the analysis method (including analysis code, analysis model, and analysis conditions) that can simulate the structural integrity of the canister.

The floor of the model used for the post-test analysis was configured to simulate the properties of the floor of the actual test facility, and the position of the canister during falling was set to be the same as that at the time of collision that had been recorded by a high-speed camera in the test. A theoretical value was used for the collision velocity since collision velocities were nearly equal to theoretical values in all test cases.

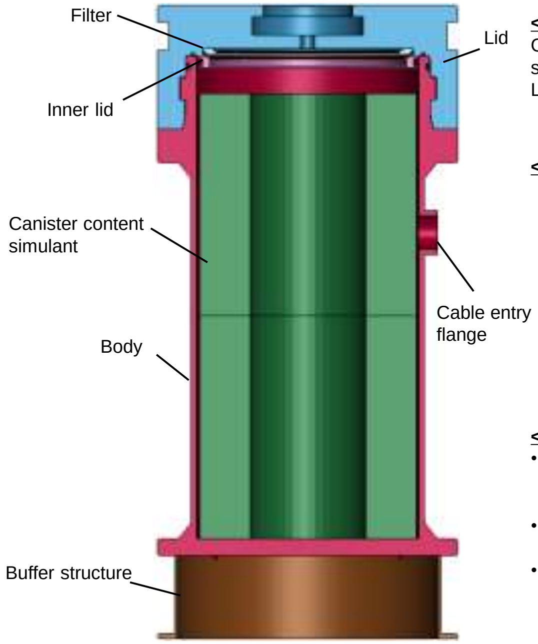


Figure: Analysis model (test sample)

(Drop test in a vertical position, the test sample was a canister with the simple installation structure, inner diameter of 400 mm, and without air supply mechanism.)

<Analysis code>

General purpose finite element method analysis software:
LS-DYNA

<Materials>

Part	Material	Temperature
Canister	SUS316L	Room temperature (25°C)
Metal filter	SUS316	
Canister content simulant	S45C	
Lid fixing bolt	SUS630	

<Other conditions to be considered>

- Gap between the lid and the flange in an axial direction
  (Use actual measurements of test samples)
- Eccentricity of the lid in a radial direction
  (Use actual measurements of test samples)
- Amount of bouncing of the canister content simulant
  (Use a theoretically calculated value)

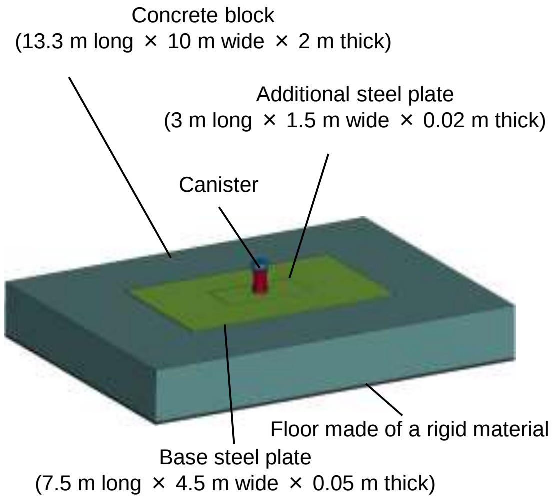


Figure: Analysis model (test sample and drop test floor)

<Initial conditions>

Test conditions	Test piece	Collision velocity	Position during falling (Collision angle)
Drop in a vertical position	Simple mounting structure Inner diameter: 400 mm	13.3m/s	0.7°
	Bolt structure Inner diameter: 220 mm	13.3m/s	-2.9°
Drop in an inclined position	Simple mounting structure Inner diameter: 400 mm	13.3m/s	53.7°
	Bolt structure Inner diameter: 220 mm	13.3m/s	60.8°
Dropping a canister on another canister in a vertical position	Simple mounting structure Inner diameter: 220 mm	11.7m/s	0°
	Bolt structure Inner diameter: 400 mm	11.7m/s	0°

<Contact conditions>

Friction coefficient: 0.3

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

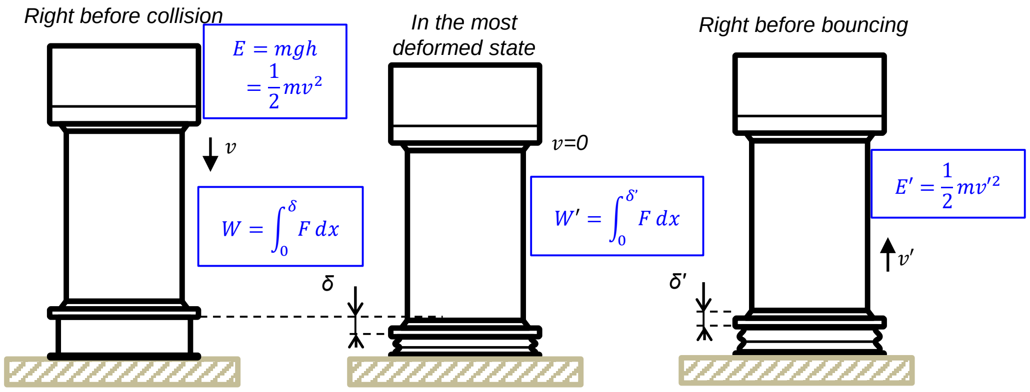
e. Evaluation methods used in the structural verification tests (2/8)

(ii) Results of the analysis of test sample movement in the drop test (1/3)

Among the parameters that describe the movement of a test sample in a drop test, those that are related to the evaluation of energy used for the deformation of the test sample were compared to evaluate the reproducibility of the movement in an analysis model.

1) Canister drop test in a vertical position (typical example: a canister with the bolt structure, inner diameter of 220 mm, and without air supply mechanism)

The following hypotheses were used: the kinetic energy of the canister right before the collision is all converted into the strain energy of the buffer structure in its most deformed state, and then it is converted into energy absorbed by the buffer structure due to its deformation and the kinetic energy of the canister's bouncing movement. The validity of the analysis of the load acting on the test sample was examined by comparing the amount of the deformation of the buffer structure δ' and the bouncing velocity v' obtained from the analysis with those obtained from the test.



E: Kinetic energy right before collision
h : Drop height
v: Collision velocity
W: Strain energy of the buffer structure

F: Load acting on the buffer structure (test sample)
x: Amount of the deformation of the buffer structure
δ: Amount of the deformation of the buffer structure in its most deformed state
W': Energy absorbed by the buffer structure

δ: Amount of the deformation of the buffer structure right after the canister's bouncing
v': Initial velocity of the canister's bouncing movement
E': Kinetic energy of the canister's bouncing movement

$$E = W = W' + E'$$

Figure: Canister movement in a vertical drop test

The amount of the deformation of the buffer structure and the velocity of bouncing right after the occurrence of its most deformed state, both of which are associated with the movement of the test sample in the drop test, were compared between those obtained from the test and from the analysis. Difference in the maximum bouncing velocity was approximately 2% between the results from the test and analysis, which suggests that the analysis accurately simulates the movement of the test sample in the drop test in a vertical position.

- **Bouncing velocity**

Comparative item	Test results	Results of post-test analysis	Difference
Maximum bouncing velocity after the most deformed state	Max.: 1.53 m/s	Max.: 1.56 m/s	2%

- **Amount of the deformation of the buffer structure**

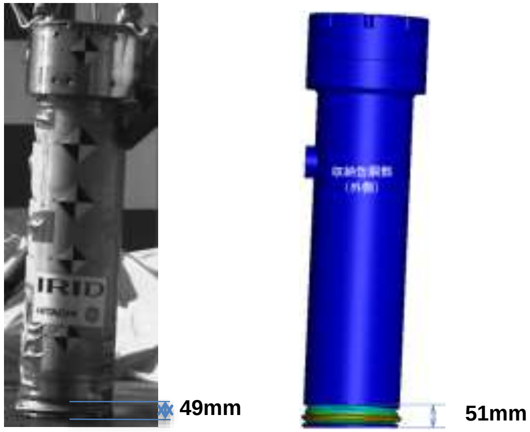


Figure: Comparison of the height of the buffer structure in its most deformed state between the test and post-test analysis

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

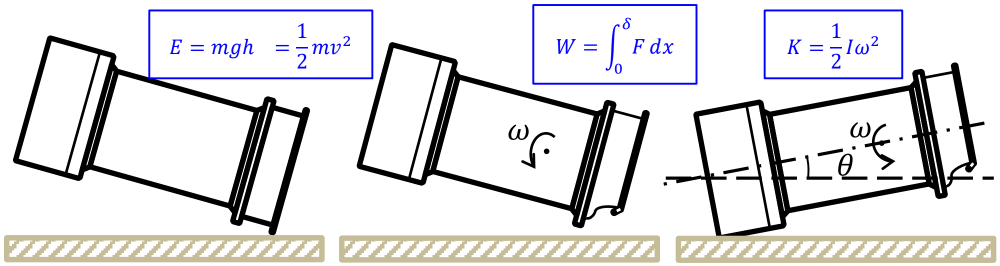
③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (3/8)

(ii) Results of the analysis of canister movement in the drop test (2/3)

2) Canister drop test in an inclined position (typical example: a canister with the simple installation structure, inner diameter of 400 mm, and air supply mechanism)

When the canister is dropped in an inclined position, the buffer structure absorbs the kinetic energy in the primary collision, and then the test sample turns to the inclined direction (rotational movement). It was hypothesized that the rotational kinetic energy of the test sample right before the secondary collision produced by this rotational movement would be the collision energy of the lid section against the floor.
The validity of the analysis of the energy transferred to the test sample was examined by comparing the angular velocity and collision angle obtained from the analysis with those obtained from the test.



Before the primary collision

$$E = mgh \quad = \frac{1}{2}mv^2$$

Between the primary and secondary collisions

$$W = \int_0^{\delta} F\,dx$$

Before the secondary collision

$$K = \frac{1}{2}I\omega^2$$

E : Kinetic energy right before collision
h : Drop height
v : Collision velocity
W : Strain energy of the buffer structure

F : Load acting on the buffer structure (test sample)
x : Amount of the deformation of the buffer structure
δ : Amount of the deformation of the buffer structure in its most deformed state
K : Rotational kinetic energy

ω : Angular velocity
I : Inertia moment
θ : Secondary collision angle

$$E - W = K$$

Figure: Canister movement in a drop test in an inclined position

The angular velocity of the test sample right before the secondary collision and the angle of the secondary collision, both of which are associated with the movement of the test sample in the drop test in an inclined position, were compared between those obtained from the test and from the analysis. Difference in the angular velocity was approximately 0.5% between the results from the test and analysis, and the angles of secondary collision were also nearly equal, which suggests that the analysis accurately simulates the movement of the test sample in the drop test in an inclined position.

- **Angular velocity before the secondary collision**

Comparative item	Test results	Results of post-test analysis	Difference
Angular velocity before the secondary collision	20.5 rad/s	20.6 rad/s	0.5%

- **Secondary collision angle**

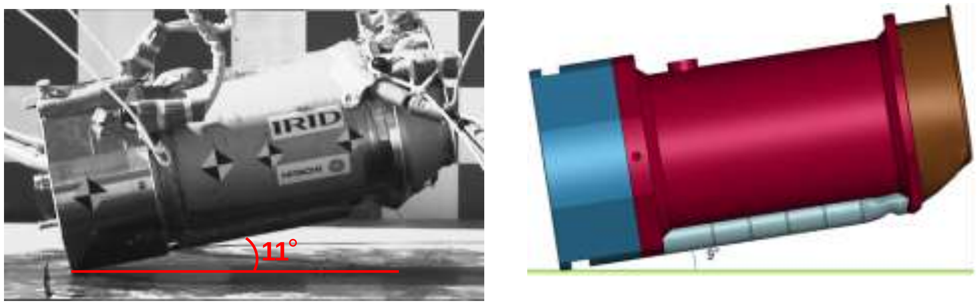


Figure: Comparison of the secondary collision angle between the test and post-test analyses

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

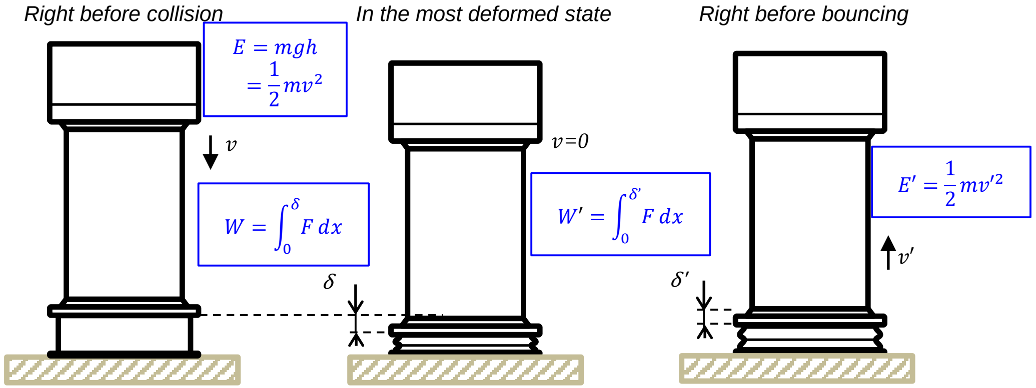
③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (4/8)

(ii) Results of the analysis of canister movement in the drop test (3/3)

3) Result of the test of dropping a canister on another canister in a vertical position (typical example: canisters with the simple installation structure, inner diameter of 220 mm, and without air supply mechanism)

The following hypotheses were used: the kinetic energy of the canister right before the collision is all converted into the strain energy of the buffer structure in its most deformed state, and then it is converted into energy absorbed by the buffer structure due to its deformation and the kinetic energy of the canister's bouncing movement. The validity of the analysis of the load acting on the test sample was examined by comparing the amount of the deformation of the buffer structure δ' and the bouncing velocity v' obtained from the analysis with those obtained from the test.



E: Kinetic energy right before collision
h : Drop height
v: Collision velocity
W: Strain energy of the buffer structure

F: Load acting on the buffer structure (test sample)
x: Amount of the deformation of the buffer structure
δ: Amount of the deformation of the buffer structure in its most deformed state
W': Energy absorbed by the buffer structure

δ': Amount of the deformation of the buffer structure right after the canister's bouncing
v': Initial velocity of the canister's bouncing movement
E': Kinetic energy of the canister's bouncing movement

$$\boxed{E = W = W' + E'}$$

Figure: Canister movement in a vertical drop test

The amount of the deformation of the buffer structure and the velocity of bouncing right after the occurrence of its most deformed state, both of which are associated with the movement of the test sample in the drop test, were compared between those obtained from the test and from the analysis. Difference in the maximum bouncing velocity was approximately 6% between the results from the test and analysis, which suggests that the analysis accurately simulates the movement of the test sample in the drop test in a vertical position.

- **Bouncing velocity**

Comparative item	Test results	Results of post-test analysis	Difference
Maximum bouncing velocity after the most deformed state	**Max.: 1.35 m/s**	**Max.: 1.43 m/s**	**6%**

- **Amount of the deformation of the buffer structure**

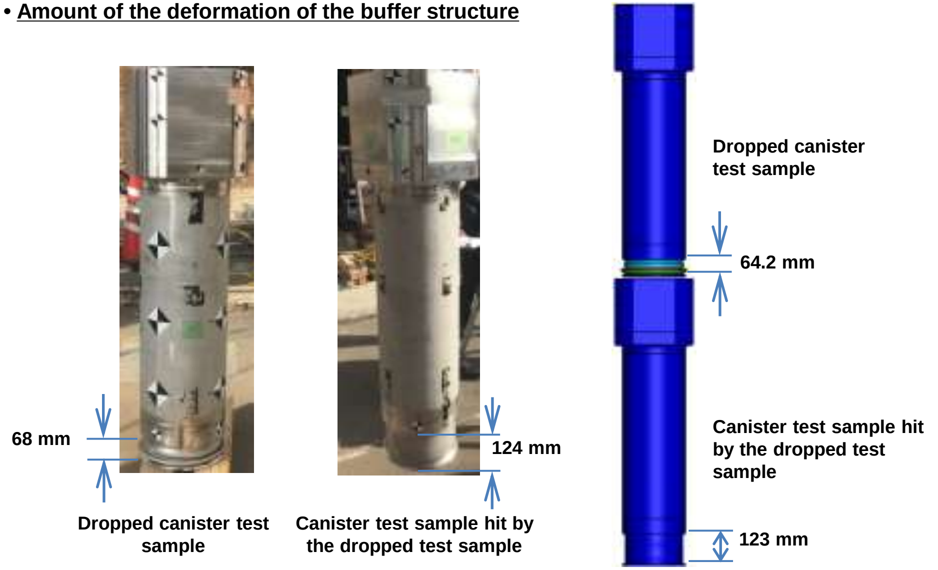


Figure: Comparison of the height of the buffer structure in its most deformed state between the test and post-test analysis

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (5/8)

(iii) Result of the evaluation of the certainty of analysis related to safety functions (1/4)

1) Canister drop test in a vertical position (typical example: a canister with the bolt structure, inner diameter of 220 mm, and without air supply mechanism)

The relative displacement of the lid to the flange in an axial direction, which relates to the confinement performance of the canister, was compared between those obtained from the test and from the analysis. The maximum difference in the relative displacement of the lid to the flange in an axial direction is approximately 14% of the acceptable value.

- **Relative displacement of the lid to the flange in an axial direction**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Relative displacement of the lid to the flange in an axial direction	Max.: 0.17 mm Residual displacement: No	Max.: 0.28 mm Residual displacement: No	0.11mm	0.8 mm

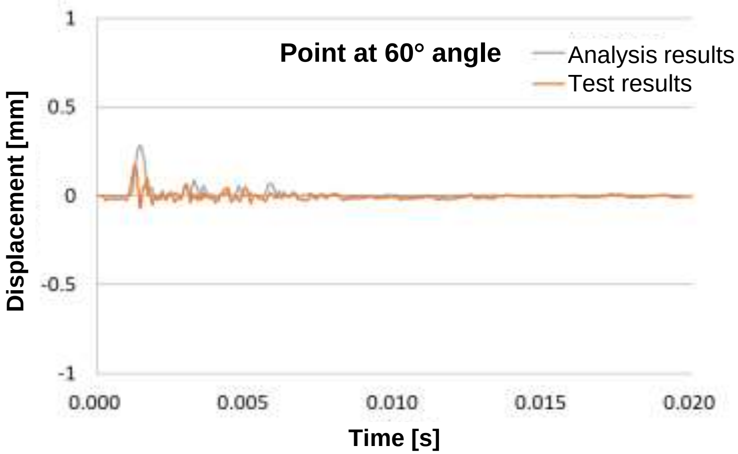


Figure: Comparison of the relative displacement of the lid to the flange in an axial direction between the test and post-test analyses

Changes in the inner diameter of the body and its strain, which relate to the criticality prevention performance, were compared between those obtained from the test and from the analysis.
A significant difference was not found in changes in the inner diameter of the body between the results of the test and of the analysis. Strains in the central part of the body in a circumferential direction also showed similar results between the test and analysis. These results suggest that the analysis can be used to evaluate the ability to maintain the criticality prevention performance.

- **Inner diameter of the body**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Inner diameter of the body	Max.: 223 mm	Max.: 220 mm	No significant difference	245 mm or less (Target: 232.5 mm or less)

- **Strain of the body**

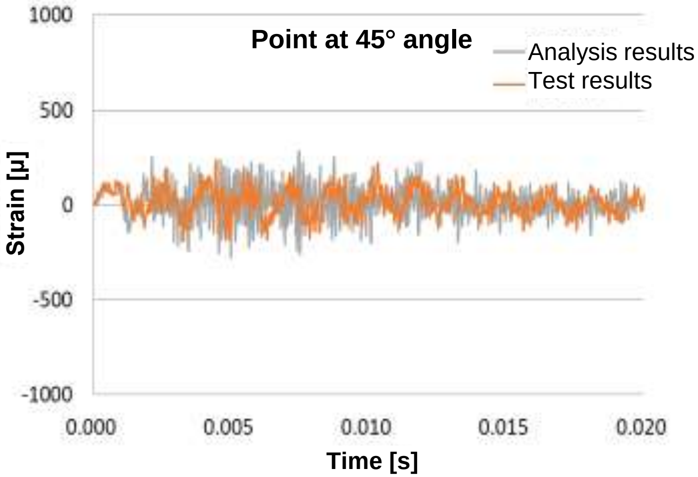


Figure: Comparison of the strain of the body in a circumferential direction between the test and post-test analyses

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (6/8)

(iii) Result of the evaluation of the certainty of analysis related to safety functions (2/4)

2) Canister drop test in an inclined position (typical example: a canister with the simple installation structure, inner diameter of 400 mm, and air supply mechanism)

The relative displacements of the lid to the flange in an axial direction and in a radial direction, which relate to the confinement performance of the canister, were compared between those obtained from the test and from the analysis. The maximum differences in the relative displacement of the lid to the flange were approximately 44% of the acceptable value in an axial direction and approximately 11% of the acceptable value in a radial direction. The wave forms and the timings of displacement peak occurrence in the test result and post-test analysis result well accord with each other, which suggests that the post-test analysis accurately simulates the movement of the lid in both axial and radial directions. The margin for the acceptable value is small, therefore it will be necessary to set a reasonable margin when analysis evaluation is performed.

- **Relative displacement of the lid to the flange in an axial direction**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Relative displacement of the lid to the flange in an axial direction	Max.: 1.64 mm Residual displacement: 0.9 mm	Max.: 1.29 mm Residual displacement: 0.7 mm	Max.: −0.35 mm Residual displacement: −0.2 mm	0.8 mm

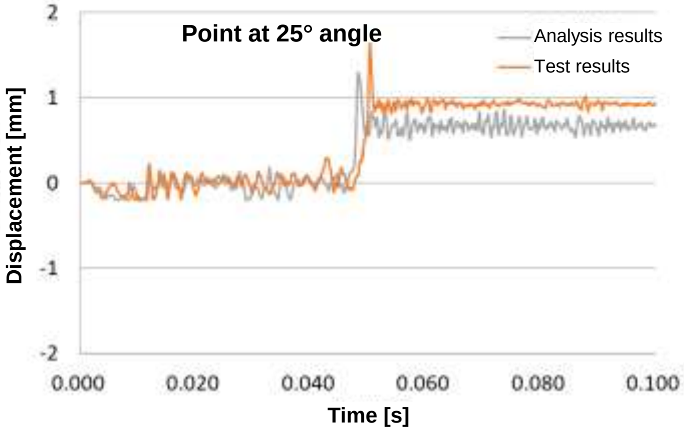


Figure: Comparison of the relative displacement of the lid to the flange in an axial direction between the test and post-test analyses

- **Relative displacement of the lid to the flange in a radial direction**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Relative displacement of the lid to the flange in a radial direction	Max.: 1.54 mm Residual displacement: 0.6 mm	Max.: 1.63 mm Residual displacement: 1.2 mm	Max.: 0.09 mm Residual displacement: 0.6 mm	0.8 mm

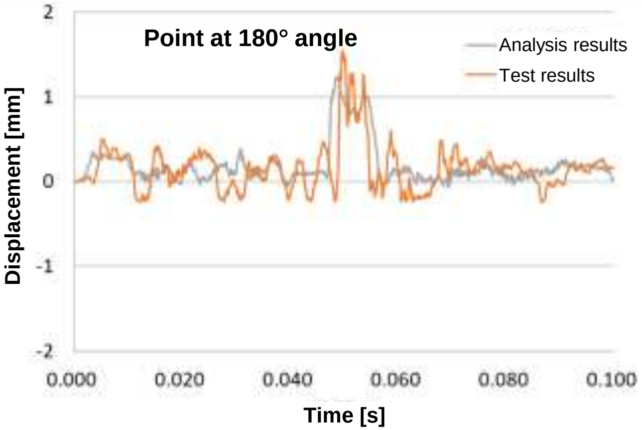


Figure: Comparison of the relative displacement of the lid to the flange in a radial direction between the test and post-test analyses

Changes in the inner diameter of the body and its strain, which relate to the criticality prevention performance, were compared between those obtained from the test and from the analysis. A significant difference was not found in changes in the inner diameter of the body between the results of the test and of the analysis. Strains in the central part of the body in a circumferential direction also showed similar results between the test and analysis. These results suggest that the analysis can be used to evaluate the ability to maintain the criticality prevention performance.

- **Inner diameter of the body**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Inner diameter of the body	Max.: 402 mm	Max.: 403 mm	No significant difference	425 mm or less (Target: 412.5 mm or less)*1

- **Strain of the body**

Note 1: This target value is temporary because a dimension that can maintain sub-criticality for 400 mm canister is not known yet

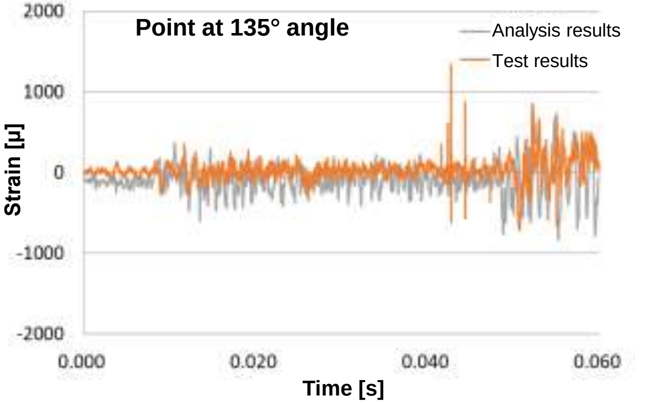


Figure: Comparison of the strain of the body in a circumferential direction between the test and post-test analyses

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (7/8)

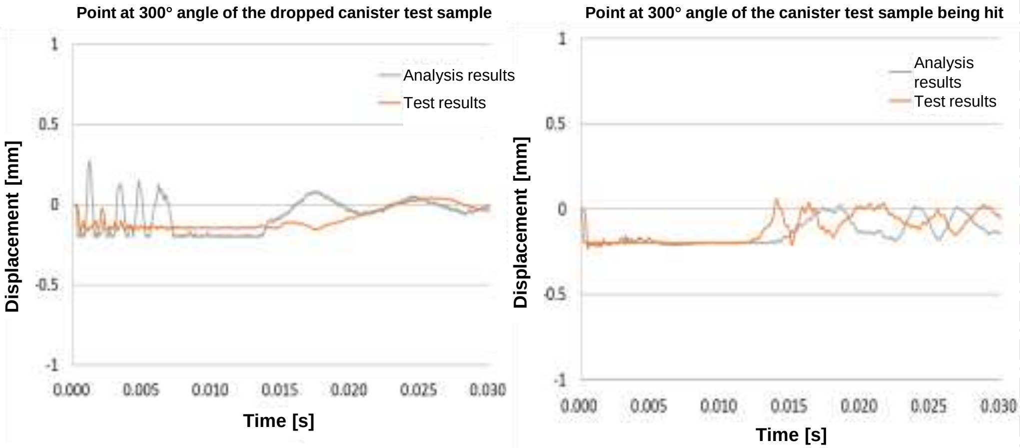
(iii) Result of the evaluation of the certainty of analysis related to safety functions (3/4)

3) Result of the test of dropping a canister on another canister in a vertical position (typical example: canisters with the simple installation structure, inner diameter of 220 mm, and without air supply mechanism)

The relative displacement of the lid to the flange in an axial direction and the strain of the lid fixing bolts in an axial direction, both of which relate to the confinement performance of the canister, were compared between those obtained from the test and from the analysis. The maximum difference in the relative displacement of the lid to the flange in an axial direction is approximately 14% of the acceptable value.

- **Relative displacement of the lid to the flange in an axial direction**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Relative displacement of the lid to the flange in an axial direction	Max. in the dropped sample: 0.04 mm Residual displacement: No Max. in the sample being hit: 0.06 mm Residual displacement: No	Max. in the dropped sample: 0.27 mm Residual displacement: No Max. in the sample being hit: 0.02 mm Residual displacement: No	Dropped sample: 0.23 mm Sample being hit: −0.03 mm	0.8 mm



Point at 300° angle of the dropped canister test sample

Point at 300° angle of the canister test sample being hit

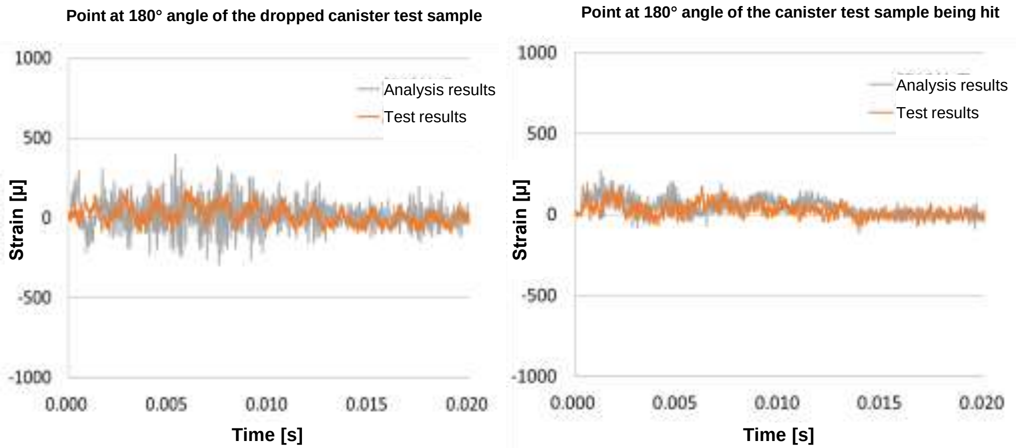
Figure: Comparison of the relative displacement of the lid to the flange in an axial direction between the test and post-test analyses

Changes in the inner diameter of the body and its strain, which relate to the criticality prevention performance, were compared between those obtained from the test and from the analysis.
A significant difference was not found in changes in the inner diameter of the body between the results of the test and of the analysis. Strains in the central part of the body in a circumferential direction also showed similar results between the test and analysis. These results suggest that the analysis can be used to evaluate the ability to maintain the criticality prevention performance.

- **Inner diameter of the body**

Comparative item	Test results	Results of post-test analysis	Difference	Acceptable value
Inner diameter of the body	Max. in the dropped sample: 222 mm Max. in the sample being hit: 223 mm	Max.: 220 mm (Same value for both samples)	No significant difference	245 mm or less (Target: 232.5 mm or less)

- **Strain of the body**



Point at 180° angle of the dropped canister test sample

Point at 180° angle of the canister test sample being hit

Figure: Comparison of the strain of the body in a circumferential direction between the test and post-test analyses

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

e. Evaluation methods used in the structural verification tests (8/8)

(iii) Result of the evaluation of the certainty of analysis related to safety functions (4/4)

4) Summary of evaluation results

The relative displacement of the lid to the flange, which relates to the confinement performance of the canister, was compared between those obtained from the test and from the analysis. It was confirmed that the maximum displacements and residual displacements from the two methodologies roughly accord with each other with a difference of 0.6 mm or less. However, it will be necessary to set a reasonable margin due to small margins for the acceptable values, when analysis evaluation is performed.

Changes in the inner diameter of the body and its strain, which relate to the criticality prevention performance, were compared between those obtained from the test and from the analysis. It was confirmed that the said values from the two methodologies roughly accorded with each other and the analysis could be used for the structural verification.

Table: Summary of the validity evaluation of structural analysis (comparison of test and analysis results)

Safety functions	Comparison items between test results and analysis results	Evaluation method	Drop in a vertical position		Drop in an inclined position		Dropping a canister on another canister in a vertical position	
			Simple mounting structure Inner diameter: 400 mm	Bolt structure Inner diameter: 220 mm	Simple mounting structure Inner diameter: 400 mm	Bolt structure Inner diameter: 220 mm	Simple mounting structure Inner diameter: 220 mm	Bolt structure Inner diameter: 400 mm
Confinement	Relative displacement of the lid to the flange in an axial direction	Max. value (Residual displacement)	0.09 mm (No residual displacement)	0.11 mm (No residual displacement)	-0.35 mm (−0.6 mm)	0.28 mm (0.2 mm)	Dropped sample: 0.23 mm (No residual displacement) Sample being hit: −0.03 mm (no residual displacement)	Dropped sample: 0.08 mm (No residual displacement) Sample being hit: 0.06 mm (No residual displacement)
	Relative displacement of the lid to the flange in a radial direction	Max. value (Residual displacement)	-	-	0.09 mm (0.6 mm)	0.00 mm*1 (0.4 mm)	-	-
Criticality prevention	Inner diameter of the body	Max. value comparison	No significant difference	No significant difference	No significant difference	No significant difference	No significant difference on both samples	No significant difference on both samples
	Strain of the body	Occurrence tendency comparison	Roughly accord with each other	Roughly accord with each other	Roughly accord with each other	Roughly accord with each other	Roughly accord with each other	Roughly accord with each other

Note 1: The result of comparison on this item will be used for reference purpose only as the bolt structure has no sealing function in a radial direction.

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

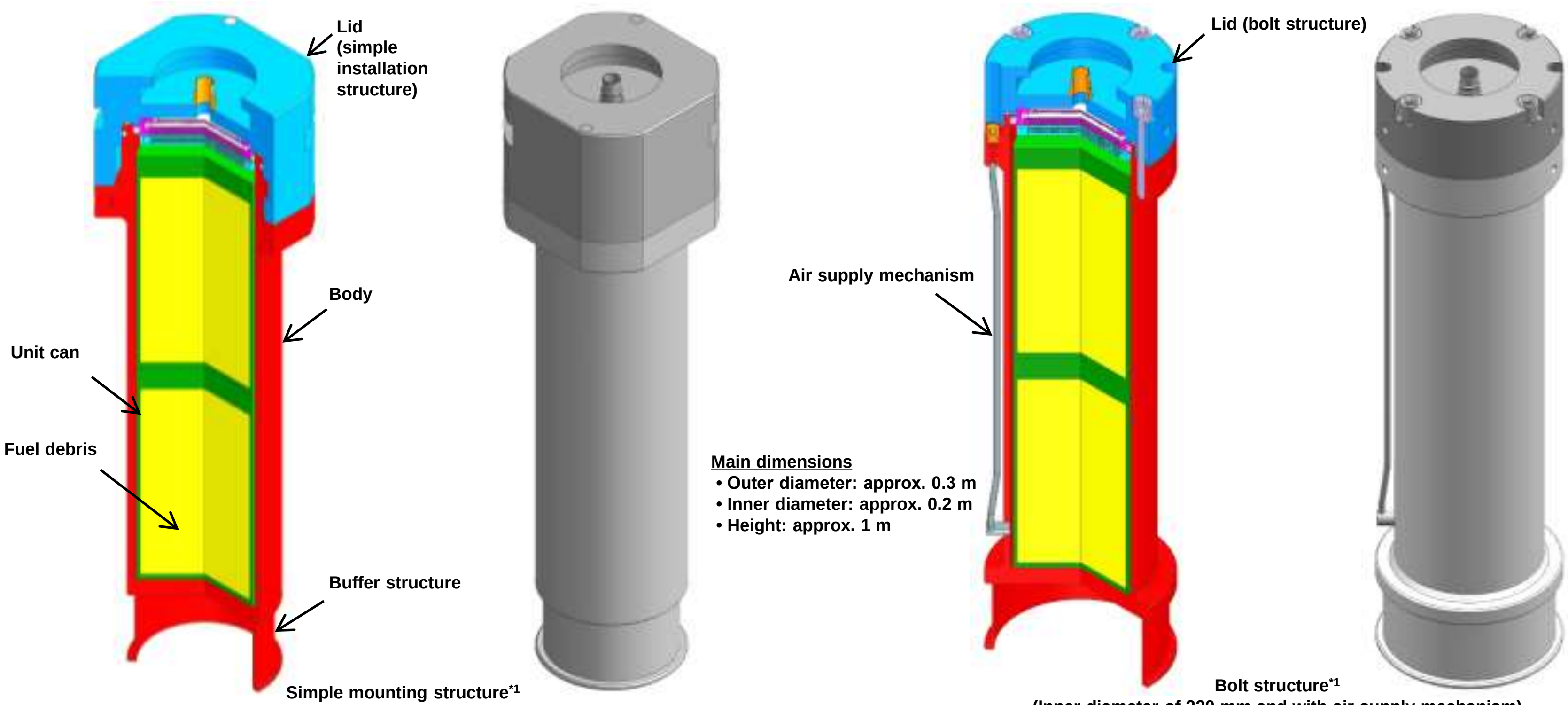
③ Action items and results (estimated and actual)

f. Study of the specifications and structural design of the canister (1/2)

(i) Proposal of the specifications and structural design of the canister

As a result of the drop tests and structural analysis, it was confirmed that all types of canister structure design that had been developed and proposed were robust enough to maintain their safety functions (such as confinement and criticality prevention). Therefore, it was concluded that the proposed specifications and structural designs did not have to be changed. As to the cover of the air supply mechanism, however, it was decided to be removed taking into account the risk of it causing damage in the piping when heavily deformed and the need of visual inspection.

The following two methods are proposed as the final design of the lid: the “simple installation structure” that uses a threaded lid that allows it to be opened and closed by turning itself and the “bolt structure” that uses fixing bolts as a popularly used fixing method and has a proven record in remote control at TMI-2 and other facilities.



Main dimensions
- Outer diameter: approx. 0.3 m
- Inner diameter: approx. 0.2 m
- Height: approx. 1 m

Simple mounting structure*1
(Inner diameter of 220 mm and without air supply mechanism)

Bolt structure*1
(Inner diameter of 220 mm and with air supply mechanism)

Figure: Proposed structure of a canister (typical example)

Note 1: In the cross-sectional view, the lid, body, unit can, fuel debris, etc. are color coded for identification of the components.

6. Implementation details

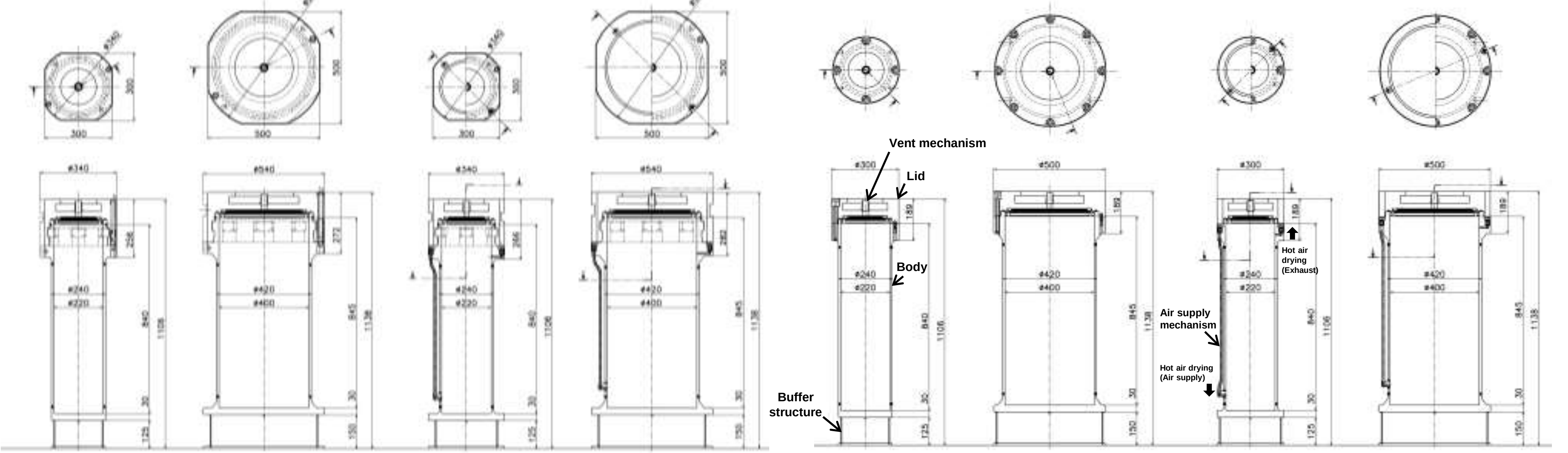
6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

③ Action items and results (estimated and actual)

f. Study of the specifications and structural design of the canister (2/2)

(ii) Proposed structural design of a canister

A total of 8 plans are proposed for the design of the canister. Those are the combinations of the following three options: type of the lid structure (simple installation structure or bolt structure), inner diameter of the body (220 or 400 mm), and with or without air supply mechanism.



Inner diameter: 220 mm Inner diameter: 400 mm

Simple mounting structure (without air supply mechanism)

Inner diameter: 220 mm Inner diameter: 400 mm

Simple mounting structure (with air supply mechanism*1, 2)

Inner diameter: 220 mm Inner diameter: 400 mm

Bolt structure (without air supply mechanism)

Inner diameter: 220 mm Inner diameter: 400 mm

Bolt structure (with air supply mechanism*1, 2)

Figure: Proposed structural design of a canister (total 8 types)

Note 1: The air supply mechanism is used as air supply and exhaust piping when fuel debris and other removed materials are dried by hot air after being packed in the canister. The proposed process flow of handling them specifies the method to dry them in unit cans as the main process.

Note 2: It was decided not to use the cover of air supply mechanism taking into account the risk of it causing damage in the piping when heavily deformed and the need of visual inspection.

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

④ Contribution of outcomes to relevant study areas

The proposed specifications and structure design of the canister are expected to contribute to facilitating the design and prototyping of the canisters applicable to operations at the 1F. They are also expected to contribute to the design of facilities related to the canister, such as the extended building, storage facility, and handling devices.

⑤ Analysis with respect to the on-site applicability

The proposed specifications and structure design of the canister have been developed and evaluated taking into account how it will be handled in the process from packaging to storage at the 1F and events that may occur on them during the process. Therefore, there should not be any issue in on-site applicability.

It must be noted that measures to prevent the fall of the canister or to limit its lifting height need to be taken by devising equipment and processes if the canister design with the simple installation structure is used in operations at the actual site because there was a problem of a lid with the simple installation structure not being able to be opened after a drop test in an inclined position.

⑥ Goal achievement level

It can be concluded that goals have been achieved since the following criteria were met:

- The structural integrity of the hypothetically proposed specifications and designs of the canister must have been verified by structural verification tests or analysis.
- The specifications and designs of the canister must have been proposed based on the result of structural integrity evaluation.

6. Implementation details

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

⑦ Issues to be addressed

Issues to be addressed toward the final design of the canisters used in operations at the 1F were listed based on the specifications and designs of the canisters proposed in this subsidized project.

Table: Issues to be addressed toward the use of the designed canisters in operations at the 1F

No.	Issues	When to work on[*1]	Concrete actions	Remarks
1	Containment of fuel debris in a powder, slurry, or sludge form	Development	The proposed specifications and designs of the canisters were developed based on the assumption that they would contain fuel debris in a particle or lump form with a size of 0.1 mm or more. Therefore, the specifications and designs may need to be changed if the canisters need to contain fuel debris in a powder, slurry, or sludge form.	Being studied in the succeeding subsidized project
2	Performance assessment of canister filters	Development	Fuel debris in a powder form may get airborne inside the canister during various operations and handling (such as drying) if it is mixed into the canister along with those in a particle or lump form. Such airborne powder may cause the degradation of the filter's hydrogen gas exhausting performance and filter clogging. The influence of fuel debris in a powder form on the filter performance (such as clogging and performance degradation) will need to be investigated.	Being studied in the succeeding subsidized project
3	Drying fuel debris and other removed materials while they are in the canister	Development or final design	The air supply mechanism will be used to supply and exhaust drying air when the method to dry fuel debris while it is in the canister is used. There is a concern that the process time of this method may be longer than that of the chamber method (drying fuel debris while it is in the unit can). When the process time of the in-canister drying method is found to be unacceptably long as a result of the drying apparatus performance test, the design of air supply mechanism will need to be changed.	
4	Verification of the calculation-based evaluation of hydrogen gas exhaustion performance	Development or final design	The evaluation of the performance of exhausting hydrogen gas generated by the radiolysis of water is performed by calculation based on Fick's first law, which is the basic law on the diffusion of substances. It is desirable to verify the result of the calculation by element tests or the like.	
5	Investigation on the port between cells (equivalent to a double door)	Final design	A design plan to add an inner lid to the main body of the canister was proposed as a measure to suppress the contamination as much as possible during handling of the canister from the port between cells to the fastening of the lid. It will be necessary to develop the specifications of the port between cells (equivalent to a double door) and its detailed design by reference to the double door technology used in existing products and developed in other subsidized project.	
6	Simplification of the canister	Final design or operation	A conservative approach was taken in the development of the proposed specifications and designs of canisters because the properties of fuel debris were not well known and the development and design of canister handling facility and equipment had not reached a detailing phase. Production costs will also need to be considered in the final design of the canisters. For example, the buffer structure may be eliminated if the falling accident of the canister can be avoided by devising canister handling equipment. Simplification of the canister will be possible by reexamining the requirements for the canister and devising alternative ways to handle it.	

Note 1: Development for technical development phase, final design for final design engineering phase, and operation for after actual use of the canisters at the 1F

6.2 Containment technology development: Prototyping full-scale canister models and structural verification tests

Summary

As part of the containment technology development, planning of the structural verification test, design and prototyping of canisters (test samples), and the structural verification test and the evaluation of the test results were performed based on the safety requirements for the canister.

In addition, the results of the structural verification tests were compared with the results of the structural analysis with respect to the movement of the test sample during a drop test, the relative displacement of the lid with respect to the flange and changes in the inner diameter and strain of the body, all of which relate to the maintenance of safety functions, to evaluate the applicability of the analysis. Both results showed reasonable agreement with each other, which suggested the applicability of the analysis method.

As the result of the structural verification tests and structural analysis, it was confirmed that the developed specifications and design of the canister were robust enough to maintain the safety functions (such as confinement and criticality prevention).

The final plan of the specifications and design of the canister was proposed based on the results of the structural verification tests and structural analysis.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

① Purpose and Goal

To propose a method to predict hydrogen generation suitable for 1F fuel debris conditions, to propose a predicted value of hydrogen generated in a canister using the method to predict hydrogen generation, and to propose a transfer condition plan based on the predicted value of hydrogen generation.

For this purpose, in addition to the results of studies conducted so far, the results of past research will be investigated and analyzed, the past methods to predict hydrogen generation will be analyzed, and the factors greatly affecting hydrogen generation gas will be analyzed. Moreover, as necessary, the data to be used for evaluation will be obtained by testing for hydrogen generation.

② Comparison with existing technology

The effect of alpha rays during the radiolysis of water has been confirmed, but there are few reported findings on a system coexisting with beta rays and gamma rays, including those from TMI-2. Therefore, a study must be conducted considering the conditions peculiar to 1F.

It is particularly necessary to study the method for setting the energy absorption rate and its validity verification method, since it is believed that this factor has a large effect on the evaluation of the hydrogen generation amount.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

a. Identification of actions necessary to clarify the conditions (tentative idea) of fuel debris transport (1/2)

The conventional methods[*1] to estimate a hydrogen generation amount use a conservative approach where all radiation energy is used for the radiolysis of water ($R_{H2(max)}$). It sets an excessively tough hurdle for the conditions of fuel debris transport.

In reality, not all radiation energy is used for the radiolysis of water due to the self-shielding effect of fuel debris. To set practical conditions for the design of a fuel debris transport system and process (which should be easier to meet), the self-shielding effect of fuel debris is taken into consideration in estimating a hydrogen generation amount. Specifically, the self-shielding effect of powder ($R_{H2(PHITS)powder}$) is used if fuel debris is in a form of fine particles. In addition, a particle size-dependent self-shielding effect ($R_{H2(PHITS)d}$) is used. Then, an energy absorption rate is derived by particle transport calculation using the said effect representing parameters.

It was decided to use "PHITS[*2]" developed mainly by JAEA as the code for particle transport calculation in the calculation of an energy absorption rate because it was not strictly bound by the laws and regulations of export control and easy to use with respect to calculation condition input and result output.

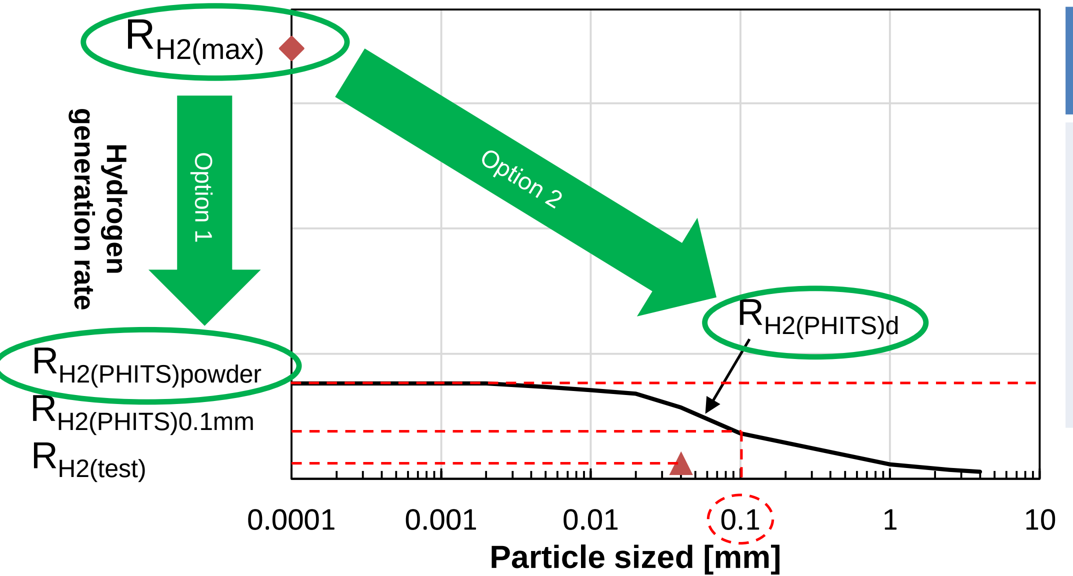


Figure: Illustrated relationship between hydrogen generation rate and particle size

Table: Energy absorption rates used in FY2018 project and the conditions of fuel debris transfer derived by them[*3]

Evaluation method	Energy absorption rate	Time for a hydrogen concentration to reach 4 vol%		Conditions of transport (Evaluation conditions: A hydrogen concentration must be less than 4 vol%, and time spent for transport is 7 days)		
		Canister	Transfer cask	Canister	Transfer cask	Restrictions[*4]
TMI-2 Evaluation formulas	Total absorption ($R_{H2(max)}$)	Approx. 0.04 day (Approx. 1.0 h)	Approx. 0.3 day (Approx. 7.1 h)	Vent opened	Sealed	The number of canisters in a transfer cask must be reduced to one, and the amount of fuel debris in the canister must be reduced to 50% of its capacity.
	Particle transport calculation ($R_{H2(PHITS)0.1mm}$)	Approx. 0.2 day (Approx. 5.5 h)	Approx. 1.7 days (Approx. 41 h)	Vent opened	Sealed	The number of canisters in a transfer cask must be reduced to two.
	Test results ($R_{H2(test)}$)	Approx. 5.8 days (Approx. 139 h)	Approx. 43 days (Approx. 1,029 h)	Vent opened	Sealed	No restrictions are imposed. In addition, the canisters can be completely sealed if the amount of fuel debris in the canister is reduced to approximately 80% of its capacity.

Note 1: Including the results of research in and outside Japan and the method to estimate a hydrogen generation amount used for the high-level waste tank of the U.S. Savannah River National Laboratory

Note 2: A Monte Carlo calculation code to simulate various radiation behaviors in substances using nuclear reaction models and nuclear data, cited from Tatsuhiko Sato, Yosuke Iwamoto, et al., "Features of Particle and Heavy Ion Transport code System (PHITS) version3.02," J. Nucl. Sci. Technol. 55 (5-6) (2018): 684–690

Note 3: FY2018 Accomplishment Report of the FY2016 Supplementary Budgets Based Subsidy Project, "Decommissioning and Contaminated Water Management: R&D for Fuel Debris Containment, Transfer, and Storage Technologies," published by the International Research Institute for Nuclear Decommissioning (IRID), a technology research association, in June 2019

Note 4: It was hypothesized that a transfer cask would accommodate 12 canisters.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

a. Identification of actions necessary to clarify the conditions (tentative idea) of fuel debris transport (2/2)

It was decided to evaluate how conservative the result of PHITS-based calculation was in comparison with actual phenomena by comparing energy absorption rates obtained from hydrogen generation tests with those obtained by PHITS-based calculation to assess the validity of the estimation of an energy absorption rate using PHITS.

There was an idea to use the result of a hydrogen generation test performed in FY2018 using spent fuel pellet particles as a reference for the validation. However, the said result was found not to be suitable for such use since the possibility of the contact of the pellet particles and air bubbles in the boundary layer between the pellet particles and test water, both of which are factors to reduce a hydrogen generation rate, having affected the test result was found in a reexamination. Therefore, the results of tests in FY2018 were considered not to be suitable for the assessment of the validation of energy absorption rate estimation due to the possibility of lack of conservativeness.

This issue raised the need for a hydrogen generation test described below. The basic concept of the test is to use particles whose size and radioactivity are known and to cause the particles to float in the test water by agitating the water to eliminate the influence of the contact of the particles and air bubbles in the boundary layer between the particles and the water.

【Hydrogen generation test with spent fuel pellets】

The purpose of this test is to prove that a hydrogen generation rate calculated using a linear model of α, β, and γ rays co-existing system that uses an energy absorption rate for each type of rays estimated by PHITS-based calculation as input values is fairly conservative compared with test results (hydrogen generation rate).

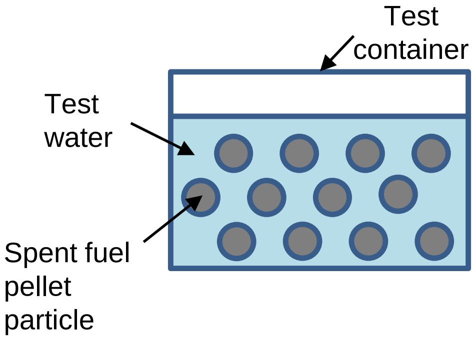


Figure: Illustration of a test system with spent fuel

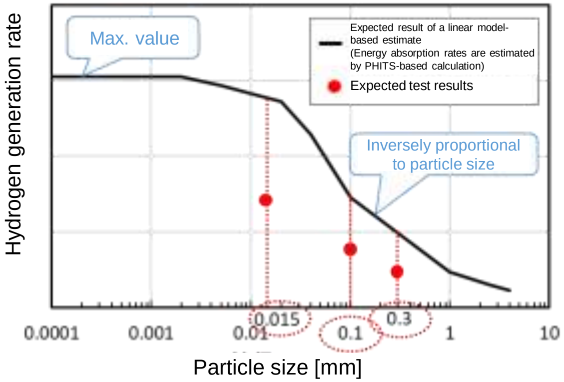


Figure: Illustration of the expected result of the test with spent fuel

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

b. Performing hydrogen generation tests (1/3)

(i) Conditions of hydrogen generation tests with spent fuel

Tests with spent fuel pellet particles of different particle sizes are planned to investigate the particle size dependence of hydrogen generation rate. To eliminate the influence of the contact of the particles and air bubbles in the boundary layer between the particles and water, the water will be agitated to cause the particles to float in it. In addition, two types of test water are prepared to investigate the influence of the recombination of generated hydrogen into water: one with recombination inhibitor halogen ions added in it and the other without such halogen ions. Further, tests with and without agitating the test water are planned to investigate the influence of agitation.

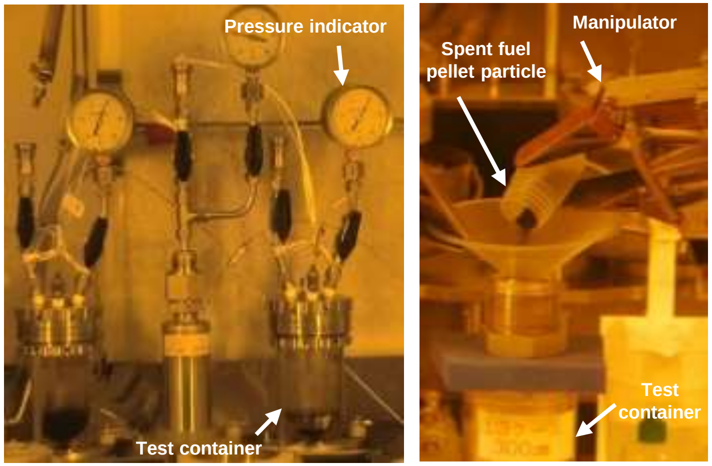


Figure: Photos of the hydrogen generation test with spent fuel

Table: Test conditions of the hydrogen generation tests with spent fuel

Case No.	Outlines	Spent fuel pellet particle		Test water		Agitation	Test environment	Test period	Number of tests
		Weight	Particle size[*1]	Amount of test water	Type of test water				
Case 1	Particle size: approximately 0.015 mm	Approximately 10 g	0.0085mm	Approximately 30 times of the total volume of pellet particles (Effective agitation must be provided)	Halogen ions—Yes[*2, 3]	Yes	Gas phase: air Initial inner pressure: approximately 1 atm Temperature: room temperature	10 and 20 days	4
Case 2	Particle size: approximately 0.1 mm		0.123mm					10 and 31 days	3[*4]
Case 3	Particle size: approximately 0.3 mm		0.415mm					10, 20, and 31 days	4
Case 4	Particle size: approximately 0.1 mm, pure water		0.123mm		Halogen ions—No[*3]			10 and 20 days	2
Case 5	Particle size: approximately 0.1 mm Agitation—No				Halogen ions—Yes[*2, 3]	No		31 days	1
Case 6	Blank test	No	-	Same as Cases 1–5		Yes		10 days	1

Note 1: Particle sizes below are volume average diameters derived from the results of SEM analysis performed on spent fuel pellet particles before the tests.
Note 2: Artificial seawater (equivalent to a chloride ion concentration of 5.6 × 10−4 mol/L, 20 ppm) and sodium iodide (1.0 × 10−4 mol/L in iodide ion concentration) are used as additives.
Note 3: The pH value of the test water is controlled between 9 and 10 by adding a pH adjusting agent (NaOH) to suppress the clumping of particles.
Note 4: The pellet particles used in the tests of cases 4 and 5 are reused.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

b. Performing hydrogen generation tests (2/3)

(i) Results of hydrogen generation tests with spent fuel

The results of the hydrogen generation tests with spent fuel demonstrated that the estimated hydrogen generation rates of fine particles based on a linear model that uses energy absorption rates estimated by PHITS-based calculation as input values ($R_{H2(PHITS)powder}$) were fairly conservative compared with the test results. Thus, the effectiveness of the hydrogen generation rate estimation by the PHITS-based calculation was demonstrated.

Meanwhile, the results of the tests to investigate the particle size dependency of a hydrogen generation rate showed a considerable variation with the upper limit of variation (1σ) exceeding $R_{H2(PHITS)d}$ at some particle sizes, whereas the estimated RH2(PHITS)d was demonstrated to be fairly conservative compared to the test results with respect to average values.

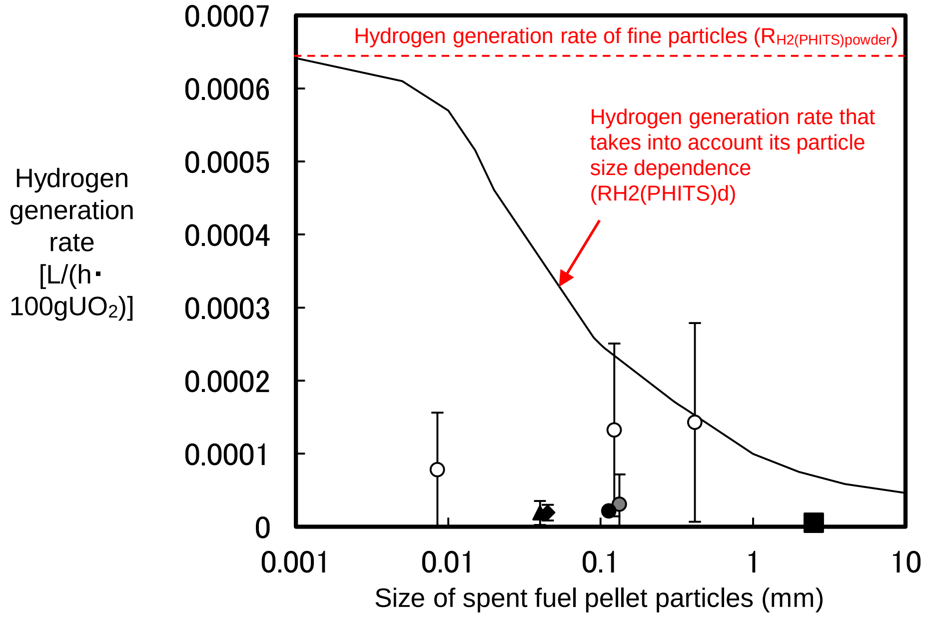


Table: Legends of plotted data

	Halogen ions	Agitation	Water/UO$_2$ volume ratio	Source
○	Yes	Yes	33	This study
⬤	None	Yes	33	
●	Yes	None	33	
▲	Yes	None	14	Results of hydrogen generation tests with spent fuel in FY2017–2018
◆	Yes	None	1	
■	Yes	None	1	

Figure: Test result: Relationship between hydrogen generation rate and particle size

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

b. Performing hydrogen generation tests (3/3)

(iii) Evaluation of the results of hydrogen generation tests with spent fuel

Cause analyses performed on the variation of the hydrogen generation rates obtained in the tests to investigate the particle size dependency of the said rate, which was so large that the upper limit of variation (1σ) exceeded the values of $R_{H2(PHITS)d}$ at some particle sizes, were investigated. Based on the result of the investigation, the hydrogen generation rates obtained by the tests were corrected and used for the evaluation of the validity of RH2(PHITS)d.

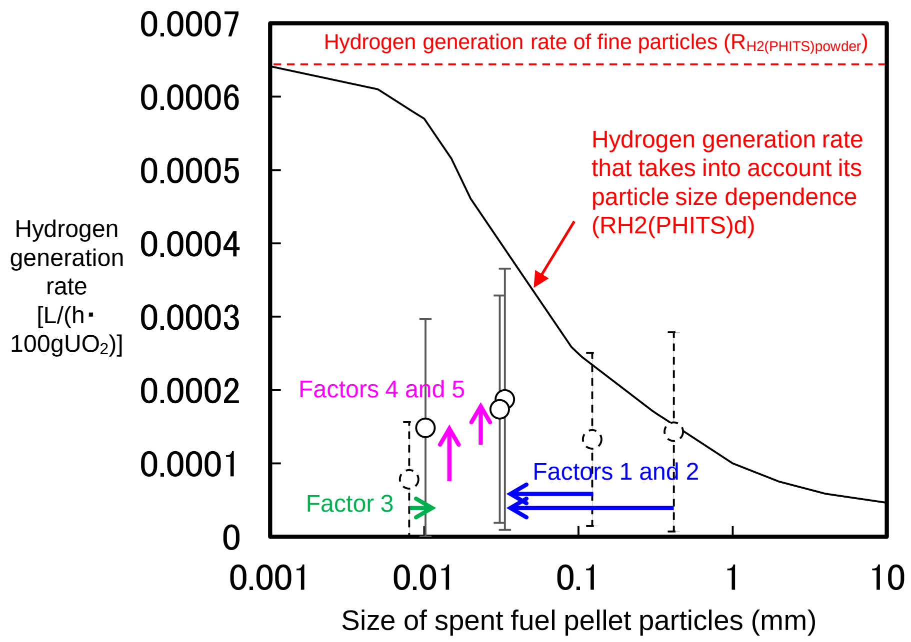


Figure: Test result (after correction): Relationship between hydrogen generation rate and particle size

Factor 1: Particle size reduction due to the fracture of particles

⇒ It was confirmed by SEM images taken after the tests that the particle size had reduced to a range of 0.005–0.256 mm. A particle size of 0.1 mm was adopted as the particle size after fracture to hypothetically estimate the effective particle size after fracture.

Factor 2: The occurrence of grain boundary widening to increase contact surface between particles and water (practically the same as the particle size reduction)

⇒ The SEM images of the particles' surface taken after the tests suggested the occurrence of grain boundary widening. A reduction of a particle size to one-third of the original size was adopted to hypothetically estimate the effective particle size after the occurrence of grain boundary widening.

Factor 3: Increase in the effective particle size due to the clumping of particles

⇒ The pH value of the test water was near the point of zero charge after the test, so there is a possibility that the particles had clumped due to a van der Waals force. An increase of a particle size to 1.2 times larger than the original size was adopted to hypothetically estimate the effective particle size after the occurrence of clumping.

Factor 4: Reduction in hydrogen generation rate due to the sedimentation and adhesion of particles

⇒ The test water was observed to be opacified at a level indicating a good agitation condition. Thus, the agitation of the test water can be considered appropriate. A reduction of a hydrogen generation rate by 10% was adopted to hypothetically estimate the influence of the particles' sedimentation and adhesion.

Factor 5: Reduction in hydrogen generation rate due to the recombination reaction of Pd and Rh

⇒ Pd and Rh contained in spent fuel is approximately 0.12 wt.%. A reaction rate constant k of 1.3 × 10^{-3}m/min[*1] × 1/477[*2] was adopted for Pd and Rh catalyzed recombination of hydrogen to hypothetically estimate the reduction of a hydrogen generation rate due to the presence of Pd and Rh.

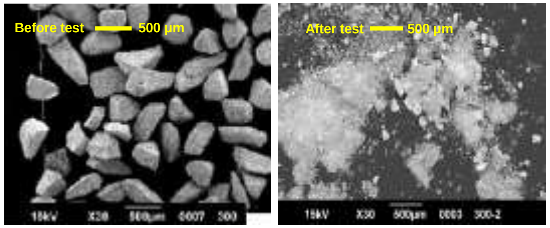


Figure: SEM image before and after test (particle size: 0.415 mm)

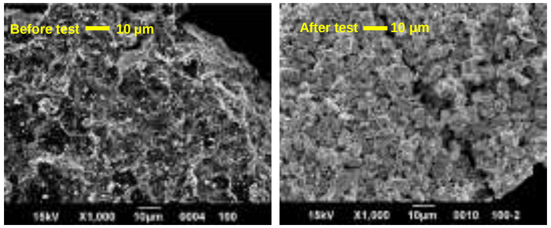


Figure: SEM image before and after test (particle size: 0.123 mm)

Note 1: Cited from S. Nilsson, M. Jonsson, J. Nucl. Mater, 372, p. 160 (2008)
Note 2: The ratio of the volume of the test water (30 mL) to the gas phase volume of the test container (279 cm³) was taken into account based on Henry's law.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

c. Study of methods to predict hydrogen generation

The canister is designed to contain fuel debris with a size of 0.1 mm or more as an approximate target. However, that with a size less than 0.1 mm will possibly be mixed in unintentionally. To stay on a safer side under limited information on the properties of fuel debris including its particle size, it is recommended to use $R_{H2(PHITS)powder}$, the estimate of the hydrogen generation rate of powder and the most conservative estimate.

Evaluation method: Linear model

$$R_{H2(PHITS)powder} = R_{H2(PHITS)powder(\alpha)} + R_{H2(PHITS)powder(\beta)} + R_{H2(PHITS)powder(\gamma)}$$

$$R_{H2(PHITS)powder(i)} = E_{(i)} \times P \times M \times C \times F_{(PHITS)powder(i)} \times G_{(i)}$$

$R_{H2(PHITS)powder}$: hydrogen generation rate; $R_{H2(PHITS)powder(i)}$: hydrogen generation rate for each type of rays; $E_{(i)}$: decay heat; P: peaking factor; M: weight of fuel debris; C: ratio of fuel contained in fuel debris; F(PHITS)powder(i): energy absorption rate; G(i): hydrogen generation G value; i: type of rays, α, β, and γ

The use of $R_{H2(PHITS)d}$, estimate of a hydrogen generation rate that takes into account the effect of a particle size, which makes it possible to estimate the volume of hydrogen generated from fuel debris with a particle size larger than powder, will be a practical method when the properties of fuel debris including its particle size are known from measurement in the fuel debris removal project, or the size of fuel debris contained in a canister is controlled by devising the design of the unit can (such as using a sieve to prevent fuel debris smaller than a certain size from remaining in the unit can) in the future.

Evaluation method: Linear model

$$R_{H2(PHITS)d} = R_{H2(PHITS)d(\alpha)} + R_{H2(PHITS)d(\beta)} + R_{H2(PHITS)d(\gamma)}$$

$$R_{H2(PHITS)d(i)} = E_{(i)} \times P \times M \times C \times \left(F_{(PHITS)powder(i)} \times \frac{a}{100} + F_{(PHITS)d\,(i)} \times \frac{b}{100}\right) \times G_{(i)}$$

$R_{H2(PHITS)powder}$: hydrogen generation rate; $R_{H2(PHITS)powder(i)}$: hydrogen generation rate for each type of rays; $E_{(i)}$: decay heat; P: peaking factor; M: weight of fuel debris; C: ratio of fuel contained in fuel debris; F(PHITS)powder(i): energy absorption rate of powder, G(i): hydrogen generation G value; i: type of rays, α, β, and γ; a: weight ratio of particle portion to powder portion, b: weight ratio of particles with a size of d to total fuel debris

6. Implementation details

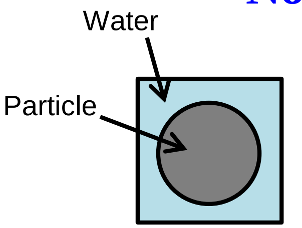
6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

d. Estimation of hydrogen generation amount in a canister

- The amount of hydrogen generated in a canister that contains fuel debris was estimated using a linear model.
- The following condition was used for fuel debris: it consists only of UO_2 fuel debris that originates in fuel loaded in the 1F-1 (a burnup of 40GWd/t and 10-year cooling period).
- 50 vol% for the volume of dewatering and 1.1 vol% (≒ 0.1 wt.%) for the volume of moisture to be dried were used for the volumes of water in PHITS calculation.



- A pellet particle is placed in the exact center of a cube.
- Each nuclide is uniformly distributed in the pellet particle.
- The target volume of moisture to be dried is simulated by placing a water film with the same volume around the particle.

Figure: PHITS calculation system

Table: Conditions and results of the estimation of

Estimation scenarios			P1	P2	P3	P4	P5
Estimation conditions	Energy absorption rate (Estimated by PHITS calculation)	Volume of water (Volume ratio)	Volume of dewatering (Particles:water = 1:1[*2])	Volume of dewatering (Particles:water = 1:1[*2])	Volume of dewatering (Particles:water = 1:1[*2])	Target volume of moisture to be dried (Particles:water = 91:1[*3])	Target volume of moisture to be dried (Particles:water = 91:1[*3])
		Particle size distribution	Powder	Particle size distribution (powder with 0.1 mm particles mixed in)[*4]	Particle size distribution (powder with 0.1 mm and a few mm particles mixed in)[*5, 6]	Powder	Particle size distribution (powder with 0.1 mm particles mixed in)[*4]
		Estimation results (F)[*1]	α-ray: 0.250 β-ray: 0.160 γ-ray: 0.158	α-ray: 0.133 β-ray: 0.142 γ-ray: 0.134	α-ray: 0.021 β-ray: 0.064 γ-ray: 0.058	α-ray: 0.004 β-ray: 0.002 γ-ray: 0.002	α-ray: 0.004 β-ray: 0.002 γ-ray: 0.002
	Decay heat (E)		Estimates based on burnup calculation results (α-ray: 0.113 W/kg UO2, β-ray: 0.383 W/kg UO2, and γ-ray: 0.221 W/kg UO2)*7				
	Peaking factor (P)		Estimates based on burnup calculation results (α-ray: 2.35, β-ray: 1.56, and γ-ray: 1.56)*8				
	Weight of fuel debris (M)		Design value (72.9 kg for the canister with an inner diameter of 220 mm)				
	Ratio of fuel contained in fuel debris (C)		Max. value (1)				
	Hydrogen generation G value (G)		Values cited from literature (α-ray: 1.3 molecules/100 eV and β-ray and γ-ray: 0.45 molecule/100 eV)*9				
Estimation results	Hydrogen generation rate (R_{H2})		1.6×10^{-16} L/h/Bq	1.1×10^{-16} L/h/Bq	3.4×10^{-17} L/h/Bq	2.3×10^{-18} L/h/Bq	2.2×10^{-18} L/h/Bq

Note 1: A margin of error of ±1% was set for estimates because calculation was performed so that the statistical error of PHITS calculation results was less than 1%.
Note 2: This ratio was set based on the result of dewatering tests in FY2016 (maximum amount of residual water).
Note 3: This volume ratio was set based on 0.1 wt.% for the target volume of moisture to be dried, 11 g/cc for the density of the pellet particles, and 1 g/cc for water density.
Note 4: It was assumed that particles with a size of 0.1 mm were placed in a canister to its maximum capacity and powder filled the gap between the particles. (The composition ratios of powder and 0.1 mm particles were 26% and 74%, respectively)
Note 5: This particle size distribution was hypothetically used based on the particle size distribution obtained from simulant fuel debris (the composition ratios of powder, 0.1 mm particles, 1 mm particles, and 4 mm particles being 4%, 8%, 12%, and 76%, respectively) that was reported in the Accomplishment Report of the FY2014 Supplementary Budgets Based Subsidy Project, “Decommissioning and Contaminated Water Management: Characterization of Fuel Debris,” published by the International Research Institute for Nuclear Decommissioning (IRID), a technology research association, in May 2017.
Note 6: It was considered to be difficult to validate the energy absorption rate of particles with a size of a few mm by tests.
Note 7: The calorific values of main nuclide in the 1F-1 for each type of rays were quoted from Tables 5, 8, 11, 43, 45, and 47 in the report below and summed up: Nishihara, K., Iwamoto, H. and Suyama, K., Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant, JAEA-Data/Code. 2012–18, published by the Japan Atomic Energy Agency in September 2012. Note that no margin of error was set because the values of decay heat used in the estimate were those for the maximum burnup by applying peaking factors to make the estimate conservative.
Note 8: These peaking factors were set for each type of rays taking into account those for each type of rays derived based on the data described in the report cited in Note 7 above. (The ratio of the maximum decay heat to the mean decay heat for α-ray and the ratio of the maximum burnup to the mean burnup for β- and γ-rays)
Note 9: hese G values were set by reference to Hilbert Christensen and Erling Bjergbakke, NUCLEAR AND CHEMICAL WASTE MANAGEMENT, Vol.6, pp. 265–270, TABLE 2, APPRICATION OF CHEMISIMUL FOR GROUNDWATER RADIOLYSIS (1986). Note that a margin of error of ±10% was set taking into account variation in data among different literatures.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

e. Study of the conditions of fuel debris transfer (1/2)

(i) Results of the estimation of hydrogen released from a canister through the vent port by diffusion

- The amount of hydrogen released from a canister through its vent port by diffusion was estimated to examine whether the hydrogen concentration in the canister could be maintained at 4 vol% or less. This estimation was conducted to evaluate the feasibility of canister design.
- Estimated hydrogen concentrations in the canister were less than 4 vol% in the estimation scenarios P3 (taking into account the particle size distribution extending to a few mm sizes) and P4 and P5 (given moisture content being equal to the target volume of moisture to be dried). In these scenarios, the feasibility of canister design was demonstrated.

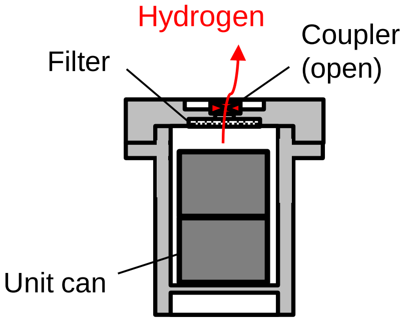


Figure: Diffusion evaluation model

Table: Results of the estimation of hydrogen released by diffusion

Estimation scenarios	Energy absorption rate					Hydrogen generation rate (L/h/Bq)	Estimated hydrogen concentration		Remarks
	Volume of water (Volume ratio)	Particle size distribution	Estimation results				Hydrogen concentration (vol%)	Result	
			α-ray	β-ray	γ-ray				
P1	Volume of dewatering (The ratio of particles to water is 1:1.)	Powder	0.250	0.160	0.158	1.6×10^{-16}	6.4	×	
P2	Volume of dewatering (The ratio of particles to water is 1:1.)	Powder with 0.1 mm particles mixed in	0.133	0.142	0.134	1.1×10^{-16}	4.4	×	
P3	Volume of dewatering (The ratio of particles to water is 1:1.)	Powder with 0.1 mm and a few mm particles mixed in	0.021	0.064	0.058	3.4×10^{-17}	1.4	○	
P4	Target volume of moisture to be dried (The ratio of particles to water is 91:1.)	Powder	0.004	0.002	0.002	2.3×10^{-18}	0.1	○	
P5	Target volume of moisture to be dried (The ratio of particles to water is 91:1.)	Powder with 0.1 mm particles mixed in	0.004	0.002	0.002	2.2×10^{-18}	0.1	○	
Total absorption (reference)[*1]			1.00	1.00	1.00	8.0×10^{-16}	22.8	×	An estimation scenario in which an energy absorption rate of 1 (total absorption) is used for all types of rays

Note 1: The energy absorption rates of total absorption were set to be 1 for α- and β-rays and 0.02 for γ-ray (values used in the estimation that took account of the particle size distribution) in the estimation in FY2018. Those rates were set to be 1 for all types of rays in the reestimation in FY2020 to provide a conservative and accountable result.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Action items and results (estimated and actual)

e. Study of the conditions of fuel debris transfer (2/2)

(ii) Results of time estimate allowed for canister/ transfer cask to be completely closed and sealed

- The feasibility of fuel debris transfer was examined using hydrogen generation rate estimates. If the canister and transfer cask could be completely sealed for 7 days (168 h) or longer, the feasibility was considered to be confirmed. If not, additional restrictions to be met were suggested.
- The feasibility of transfer was confirmed in estimation scenarios P4 and P5 (scenarios with fuel debris after dewatering).
- The feasibility of transfer was confirmed in estimation scenarios P1 to P3 subject to imposing additional restrictions (scenarios with fuel debris without dewatering).

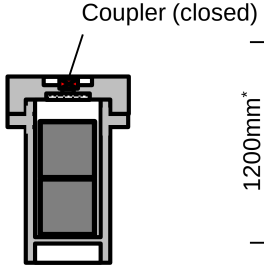


Figure: Conceptual image of time estimate allowed for real-size canister to be completely closed

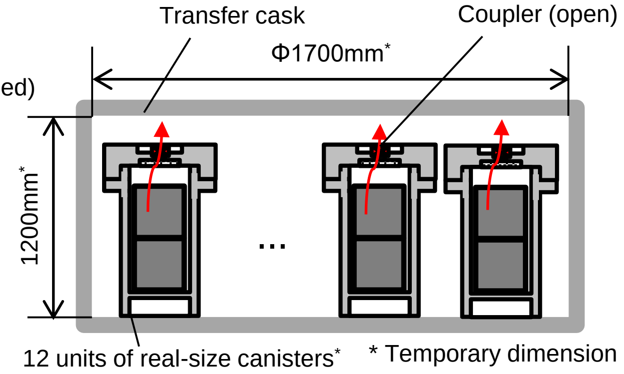


Figure: Conceptual image of a system to estimate a period allowed for a transfer cask to be completely sealed

Table: Results of the evaluation of transfer conditions (time allowed for complete closure and sealing)

Estimation scenarios	Volume of water (Volume ratio)	Particle size distribution	Hydrogen generation rate (L/h/Bq)	Time for a hydrogen concentration to reach 4 vol%		Conditions of transport (Evaluation conditions: A hydrogen concentration must be less than 4 vol%, and time for transport is 7 days.)		
				In the canister	In the transfer cask*1	Canister	Transfer cask	Additional restrictions to be met*1
P1	Volume of dewatering (The ratio of particles to water is 1:1.)	Powder	1.6×10^{-16}	Approx. 0.2 day (Approx. 6 h)	Approx. 2 days (Approx. 53 h)	Vent opened	Sealed	The number of canisters in a transfer cask must be reduced to three.
P2	Volume of dewatering (The ratio of particles to water is 1:1.)	Powder with 0.1 mm particles mixed in	1.1×10^{-16}	Approx. 0.3 day (Approx. 8 h)	Approx. 3 days (Approx. 710 h)	Vent opened	Sealed	The number of canisters in a transfer cask must be reduced to five.
P3	Volume of dewatering (The ratio of particles to water is 1:1.)	Powder with 0.1 mm and a few mm particles mixed in	3.4×10^{-17}	Approx. 1 day (Approx. 27 h)	Approx. 11 days (Approx. 259 h)	Vent opened	Sealed	None (note that the vent of the canister must be opened)
P4	Target volume of moisture to be dried (The ratio of particles to water is 91:1.)	Powder	2.3×10^{-18}	Approx. 17 days (Approx. 404 h)	Approx. 161 days (Approx. 3,853 h)	Completely closed	Sealed	No restrictions are imposed.
P5	Target volume of moisture to be dried (The ratio of particles to water is 91:1.)	Powder with 0.1 mm particles mixed in	2.2×10^{-18}	Approx. 17 days (Approx. 407 h)	Approx. 162 days (Approx. 3,882 h)	Completely closed	Sealed	No restrictions are imposed.
Total absorption (reference)*2			8.0×10^{-16}	Approx. 0.05 day (Approx. 1 h)	Approx. 0.5 day (Approx. 11 h)	Vent opened	Sealed	The number of canisters in a transfer cask must be reduced to one, and the amount of fuel debris in a canister must be reduced to 70% of its capacity.

Note 1: It was assumed that 12 canisters would be placed in a transfer cask as a basic plan. (See page 4/8 of Supplement-1: Basic conditions of development of the canister for details)

Note 2: The energy absorption rates of total absorption were set to be 1 for α- and β-rays and 0.02 for γ-ray (values used in the estimation that took account of the particle size distribution) in the estimation in FY2018. Those rates were set to be 1 for all types of rays in the reestimation in FY2020 to provide a conservative and accountable result.

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

④ Contribution of outcomes to relevant study areas

The results of the study described in this section, such as the estimates of hydrogen generation and the proposed additional restrictions on the fuel debris transfer system, are expected to contribute to the planning of operation procedures for the canister transport and storage, design and production of the vent port of the canister, and study on hydrogen gas process equipment, all of which are essential to fuel debris removal operations at the 1F.

⑤ Analysis with respect to the on-site applicability

It is necessary to find a way to combine the methods developed in this project effectively, including fuel debris dewatering methods to reduce hydrogen generation, gaining a margin by hydrogen catalyst, and the determination of the feasibility of fuel debris transfer based on the measurement of a hydrogen concentration before transfer, not to mention the method to estimate hydrogen generation, to apply the outcomes to operations at the 1F.

⑥ Goal achievement level

It can be concluded that goals have been achieved since the following criteria were met:

- A method to estimate hydrogen generation suitable for the conditions of fuel debris must have been proposed.
- Conditions for fuel debris transfer must have been presented based on the estimates obtained by the proposed hydrogen generation estimation method.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

⑦ Issues to be addressed

Issues to be addressed toward the final design of the canisters used in operations at the 1F were listed based on the method to estimate hydrogen generation proposed in this subsidized project.

Table: Issues to be addressed toward the use of the designed canisters in operations at the 1F

No.	Issues	When to work on[*1]	Concrete actions	Remarks
1	Provision of accurate data on particle size distribution	Final design Or the phase of operation process design	Once the particle size distribution of actual fuel debris becomes available by measurement, or the design of the unit can that can control the particle size of fuel debris placed in the canister (such as using a sieve to prevent fuel debris smaller than a certain size from remaining in the unit can) becomes specific, efforts should be made to reduce hydrogen generation by estimating it with a linear model using PHITS calculation-based particle size-dependent energy absorption rates.	
2	Characterization of fuel debris	Final design or operation	Once the decay heat, ratio of fuel contained in it, and source intensity of actual fuel debris become available by measurement, efforts should be made to reduce hydrogen generation by estimating it with a linear model using values based on the above-mentioned measurements as the inputs of the model.	

Note 1: Development for technical development phase, final design for final design engineering phase, and operation for after actual use of the canisters at the 1F

Summary

Items and procedures that affect the constrains imposed on the design of a fuel debris transfer system with respect to the permissible amount of hydrogen generation were studied as a part of the development of fuel debris transfer technology by studying hydrogen generation estimation methods including research of knowledge in Japan and overseas and hearing with experts. Hydrogen generation tests were also performed using spent fuel to validate energy absorption rates and applicability of a linear model used to estimate them, which affects the estimation of hydrogen generation.

Based on the results of the above-mentioned study, a method to estimate an energy absorption rate using a linear model and PHITS that fits the properties of fuel debris and is needed to estimate hydrogen generation, estimates of hydrogen generation in final design canisters using the said method, and conditions for safe fuel transfer were studied and proposed.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

① Purpose and Goal

- Studies are being conducted centering on early drying treatment in order to control the hydrogen generated from fuel debris during transfer, but as **a backup the method of recombining hydrogen with oxygen by means of a catalyst** will be studied.
- As per the studies conducted so far, it is necessary to consider the following as the environment inside the canister:
  ○ Humid environment: To continue the recombination reaction, it is necessary to promptly remove the moisture generated by hydrogen recombination.
  ○ Room temperature environment: The recombination reaction cannot take place easily.
  ○ High radioactivity: The water-repellent treatment for removing moisture tends to deteriorate easily.
- The studies conducted up to FY 2018 have revealed that the catalyst applied during the water-repellent treatment may be able to handle the environmental conditions inside the canister as well.
- Based on the above, **the hydrogen recombination performance of the catalyst (platinum-based catalyst with a particle size of about 3 mm and water-repellent treatment applied)** identified in the study last year, **will be evaluated mainly focusing on the flow velocity of the gas passing through the catalyst**.
- The amount of hydrogen generation or the internal structure of canisters, etc. was not determined in the recent studies, but **case studies were conducted in accordance with the hydrogen generation amount** for the current canister design and **the effectiveness of hydrogen measures has been exhibited**.

② Comparison with existing technology

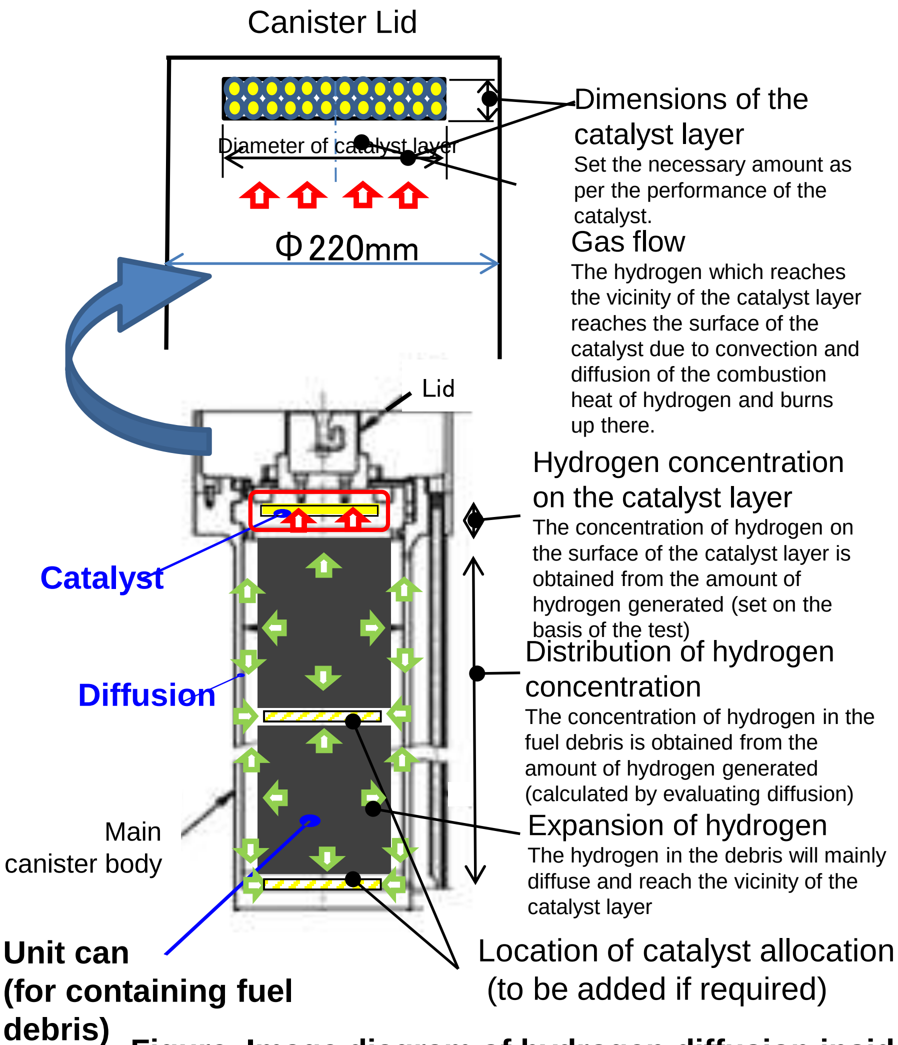
- In case of the TMI-2 fuel debris canisters, the catalyst believed to be effective at that point in time was adopted, but water-repellency was not considered.
- Various catalysts have been developed in Japan, and last year, operation tests were conducted under humid and room temperature environments for catalysts available in Japan, a catalyst with a powerful water-repellent treatment was selected, and radiation resistance of 7 days or more, which is the transfer period, was confirmed.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Implementation items and results (Estimated and actual)



Dimensions of the catalyst layer
Set the necessary amount as per the performance of the catalyst.

Gas flow
The hydrogen which reaches the vicinity of the catalyst layer reaches the surface of the catalyst due to convection and diffusion of the combustion heat of hydrogen and burns up there.

Hydrogen concentration on the catalyst layer
The concentration of hydrogen on the surface of the catalyst layer is obtained from the amount of hydrogen generated (set on the basis of the test)

Distribution of hydrogen concentration
The concentration of hydrogen in the fuel debris is obtained from the amount of hydrogen generated (calculated by evaluating diffusion)

Expansion of hydrogen
The hydrogen in the debris will mainly diffuse and reach the vicinity of the catalyst layer

Location of catalyst allocation (to be added if required)

Figure. Image diagram of hydrogen diffusion inside the canister

Basic approach

The performance of the catalyst (reaction rate coefficient) depends on the parameters such as the flow velocity. Hence evaluate the effectiveness of the catalyst by understanding about it from the flow-type reaction rate evaluation test.

Study methodology

a. Study of Catalyst
: Study on catalyst performance under environmental conditions such as the flow velocity conditions, etc. by conducting tests.

b. Detailed study of flow characteristics inside the canister
: Based on restrictions in a storage area, design of the canister, and other conditions including those related to hydrogen generation, the distribution of hydrogen concentration in the canister is estimated with respect to flow and diffusion, and a dominant part is identified with respect to hydrogen concentration. (In reality, only diffusion was taken into consideration since it was known to be dominant.)

c. Study on catalyst allocation
: An effective position of the catalyst is determined with respect to hydrogen concentration based on the position and amount of the catalyst suggested by the actions described in Paragraphs a. and b. above.

6. Implementation Details

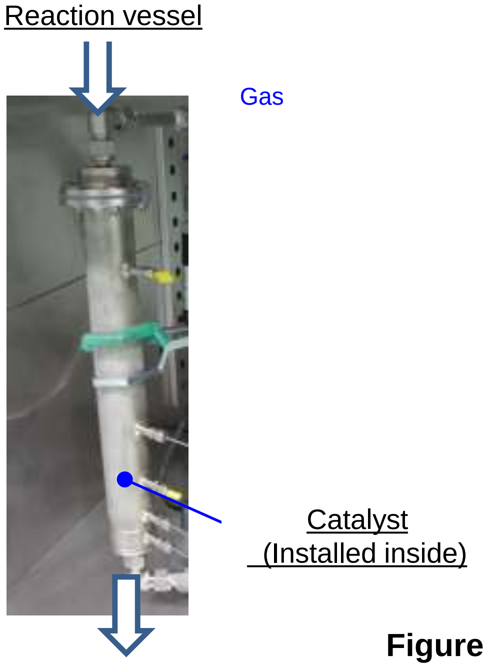
6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Implementation items and results (Estimated and actual)

a. Study of catalyst (1/3)

A test to evaluate the effect of the following gas conditions on the overall reaction rate constant of catalytic hydrogen and oxygen recombination reaction is performed using a hollow tube filled with a catalyst and test gas flowing through it with different conditions (gas flow-type reaction rate measurement test) to derive a formula to estimate the overall reaction rate constant of the said reaction in an atmosphere defined by the environmental conditions: flow rate (superficial velocity), gas temperature, hydrogen concentration, and the concentration of catalyst poisoning materials.



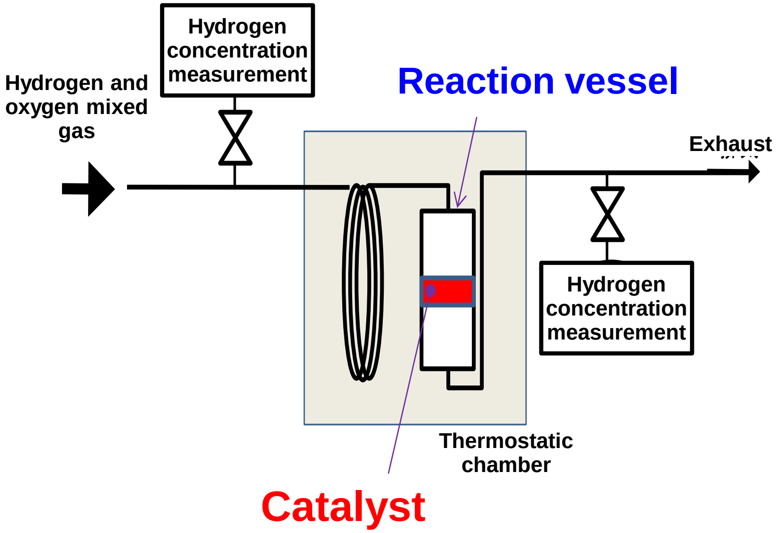


Figure. Concept of flow-type reaction rate evaluation test

Refer the following slides (Supplements) on the detailed procedure for calculating the overall reaction rate coefficient from the reaction rate obtained by the flow-type reaction rate evaluation test.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

(Supplement) Method for calculating the reaction rate formula and overall reaction rate coefficient

The formula for calculating the overall reaction rate coefficient K from the reaction rate (concentration change amount per unit time) and reaction efficiency rate η is shown below:

Reaction equation : $H_2 + 1/2O_2 \rightarrow H_2O$

$reaction\ rate\ when\ expressed\ as\ primary^{Note\ 1}$: $-r = KC_{H2}$ $\Rightarrow K = SV ln\left(\frac{1}{1-\eta}\right)$

$-r$: reaction rate K: Overall reaction rate coefficient C_{H2}: Hydrogen concentration

C_{O2}: Oxygen concentration $C_{H2}{}^0$: Inlet hydrogen concentration η: Reaction efficiency rate

SV: Space velocity (=$Q/Vcat$) Q: Gas flow rate $Vcat$: Volume of catalyst layer

As space velocity (*SV*) is the ratio of gas flow rate (*Q*) and amount of catalyst (*Vcat*: volume of catalyst layer), the effectiveness of hydrogen measures can be evaluated or confirmed by setting the amount of catalyst and its placement according to the following procedure.

- Testing stage: As reaction rate coefficient depends on environmental conditions such as temperature and flow velocity, the estimation formula of the overall reaction rate coefficient is constructed by calculating the overall reaction rate coefficient from the reaction rate corresponding to the space velocity and these conditions.
- Amount of catalyst in canister / placement study stage: The required reaction rate is set based on the hydrogen gas concentration and hydrogen generation amount inside the canister, and the amount of catalyst is set based on the estimation method of the reaction rate coefficient.

注1：Y.IWAI et.al, Journal of NUCLEAR SCIENCE and TECHNOLOGY, vol.48, No.8, P.1184-1192

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Action items and results (estimated and actual)

a. Study of catalyst (2/3)

- Outlines of the results of overall reaction rate constant estimation with different parameter settings
  An environmental condition with a temperature of 10°C, humidification, and a hydrogen concentration of 100 ppm, which could be assumed to occur in the canisters designed in this project, was adopted to estimate the overall reaction rate constant of the catalytic recombination reaction because the test results suggested that it would provide the most conservative estimate. At present, the inside of the canister is planned to be purged by nitrogen gas after putting fuel debris in it. Therefore, it is assumed that the inside of the canister is filled with an oxygen and hydrogen mixed gas at a ratio of 0.5 due to the radiolysis of water. Based on this assumption, the estimate of the reaction rate constant with the said ratio being 0.5 was adopted to study the position of a catalyst in the canister as it would be the most conservative estimate.

Table: Oxygen and hydrogen recombination tests with catalyst: Test conditions and results

Parameters	Values of the parameter used in the test	Outlines of results
Temperature (°C)	10, 30, 50	• The reaction rate constant K increased with the increase of temperature. The shown temperature dependency accords with the Arrhenius equation, which suggests that catalytic reaction is the rate-limiting factor rather than mass transfer. ⇒ **Using a lower temperature will result in a conservative estimation of the overall reaction rate constant.**
Superficial velocity LV (m/s)	0.03, 0.07, 0.14, 0.28, 0.42	• The effect of the gas flow rate on the reaction rate constant K was small in a temperature range below 10°C. ⇒ **LV-dependency is small.**
Hydrogen concentration (ppm)	100, 200, 500, 1000, 10000	• Without humidification, the reaction rate constant K decreased with the increase of hydrogen concentration within a range of 100–1,000 ppm, but increased at 10,000 ppm. Temperature rise due to reaction heat is the cause. • With humidification, the minimum reaction rate constant was observed at 100 ppm. ⇒ **Using humidification and a hydrogen concentration of 100 ppm will result in a conservative estimation of the overall reaction rate constant.**
Ratio of oxygen/hydrogen concentrations (–)	0.25, 0.50, 1.5, 1900	• The reaction rate constant K increased with the increase of the ratio of oxygen/hydrogen concentrations and showed the peak value at the ratio of 1.5. • However, the reaction rate constant K decreased under excessive oxygen. ⇒ An oxygen/hydrogen ratio of 0.5 was adopted for the estimation of the reaction rate constant based on the radiolysis of water ($H_2O \rightarrow H_2 + 0.5O_2$).
Humidification	No, Yes	• The reaction rate constant K decreased with humidified gas (almost 100% RH). ⇒ **Using humidified gas will provide the most conservative estimate.**

Environmental conditions with rectangular frames are those considered conservative for catalyst position study.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

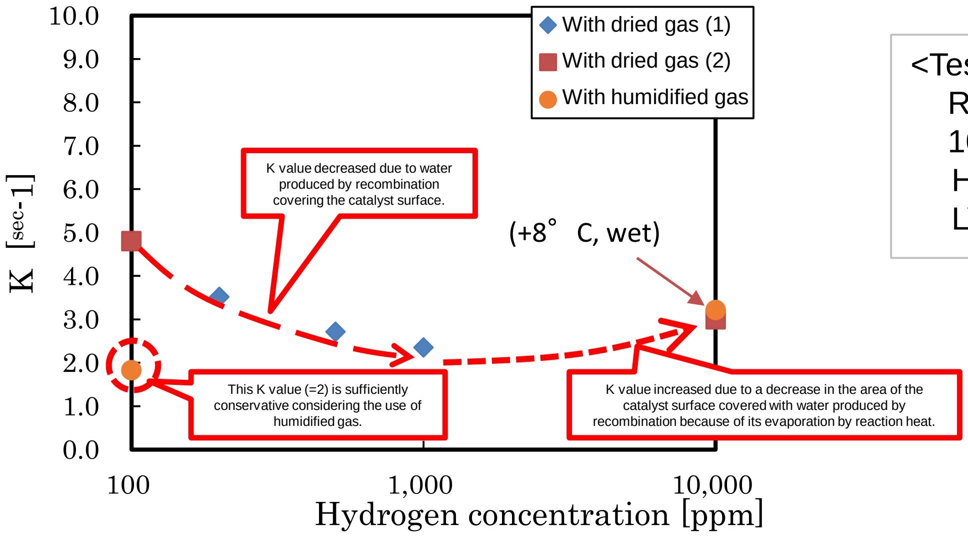
③ Action items and results (estimated and actual)

a. Study of catalyst (3/3)

The effect of humidity is shown below as one of the results of the representative test cases.

- The reaction rate constant K decreased with the increase of the hydrogen concentration when dried gas was used.
  The reaction rate turned to an increasing trend at a hydrogen concentration of 10,000 ppm and more.
  It can be inferred that the effect of temperature rise due to reaction heat cancelled or even surpassed the effect of water produced by recombination reaction.
- Similarly, the reaction rate turned to an increasing trend at a hydrogen concentration of 10,000 ppm when humidified gas (almost 100% RH) was used.

  ⇒ A reaction rate constant K measured in the condition with a hydrogen concentration of 100 ppm and humidified gas, which was equal to 2, was adopted as the most conservative condition for the study of the catalyst position with respect to hydrogen concentration and humidity.



K value decreased due to water produced by recombination covering the catalyst surface.

This K value (=2) is sufficiently conservative considering the use of humidified gas.

K value increased due to a decrease in the area of the catalyst surface covered with water produced by recombination because of its evaporation by reaction heat.

Figure: Effect of hydrogen concentration

<Test condition>
Reaction vessel: gas flow-type, catalyst: TKK-H1P, temperature: 10°C, H2 concentration: 100–10,000 ppm, ratio of O2/H2: 0.5
Humidification: No/Yes
LV: 0.14 m/s, SV: 50,000/h, thickness of catalyst bed: 10 mm

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Action items and results (estimated and actual)

b. Concentrate distribution in canister (1/3)

- **Concentration at the entrance of the catalyst bed**

A hydrogen concentration at the entrance of the catalyst bed was estimated using the value of $R_{H2(PHITS)powder}$ derived based on the assumption that 100% UO2 fuel debris is placed in the unit can at a filling rate to its capacity of 30 vol% and then the unit cans are placed in the canister, and based also on the assumption that all the fuel debris is in a powder form that was suggested by the outcomes of actions described in the section, “(1) Study of methods to predict hydrogen generation,” and shown in the graph below.

The results of the estimation showed that the hydrogen concentration at the entrance of the catalyst bed would be 0.02 vol% at a maximum and sufficiently lower than its lower explosive limit (4 vol%). Thus, it can be concluded that the capacity of the catalyst is sufficient.

Figure: Hydrogen concentration at the entrance of the catalyst layer

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Action items and results (estimated and actual)

b. Concentrate distribution in canister (2/3)

As described in the previous slide, the hydrogen concentration at the entrance of the catalyst bed would be sufficiently lower than its lower explosive limit (4 vol%). Based on this result, a hydrogen concentration in the canister was reestimated with the same conditions as those in the previous slide and assumption that the hydrogen concentration at the entrance of the catalyst bed was zero to simplify the estimation. The result of the reestimation showed that the hydrogen concentration in fuel debris would be less than 1 vol% and sufficiently lower than its lower explosive limit. Thus, a result that supported the feasibility of the canister design with a sufficient margin was obtained even taking into account hydrogen concentration at the entrance of the catalyst.

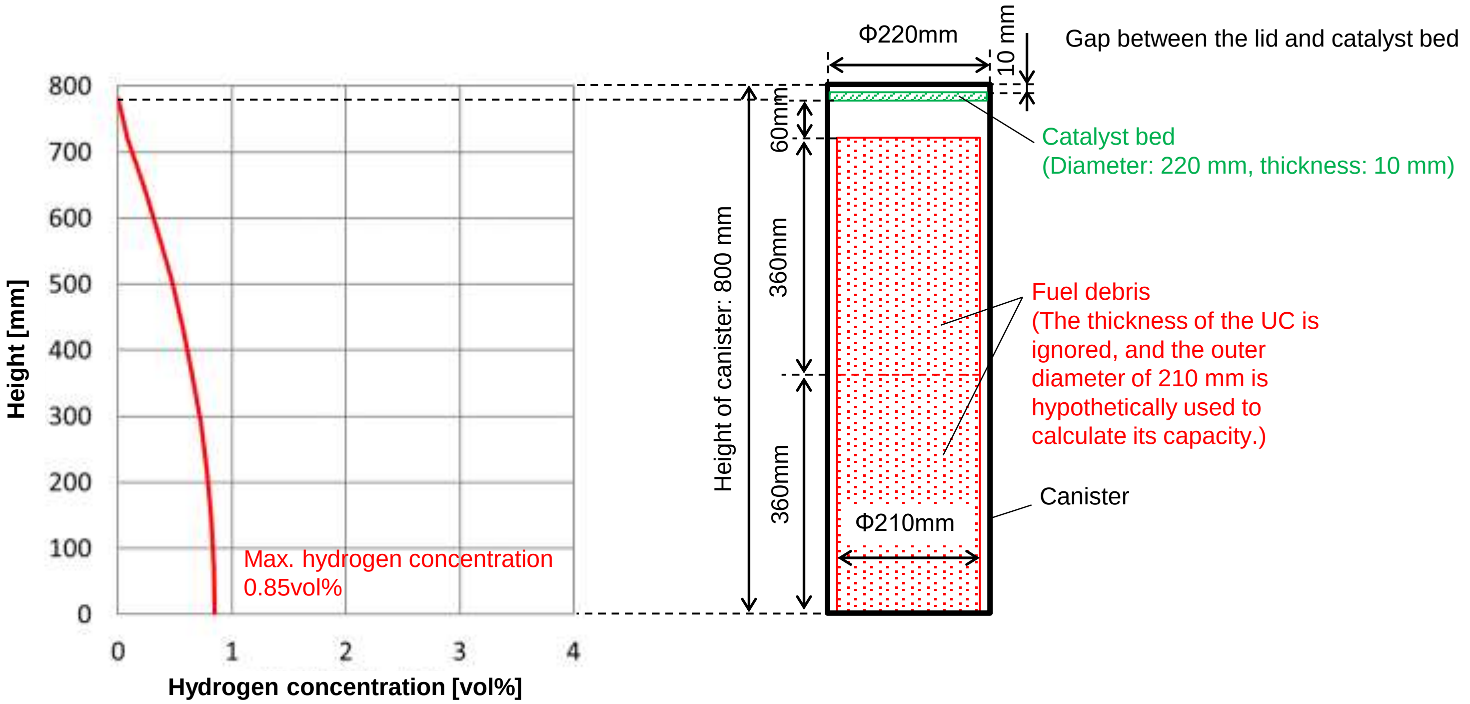


Figure: Hydrogen concentrate distribution in canister

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Action items and results (estimated and actual)

b. Concentrate distribution in canister (3/3)

(Supplement) Methodology to calculate the effective diffusion coefficient of hydrogen gas in the catalyst bed and fuel debris layer

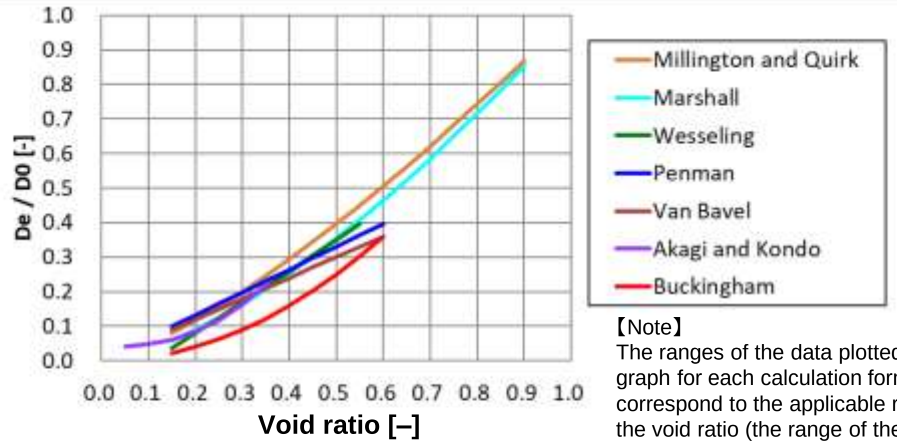
By reference to a case study on gas diffusion in soil, the Marshall's equation was applied because of its wide applicability. (See the Figure below.)

Effective diffusion coefficients of hydrogen gas were calculated for the catalyst bed and fuel debris layer by the method described below.

- **Catalyst bed**: The dimensions of the bed were set to be ø 220 mm × 10 mm corresponding to an inner diameter of 220 mm of the canister. An effective diffusion coefficient De was estimated for the catalyst layer by using a void ratio of 0.36 based on the packed condition in the catalyst performance test.
- **Fuel debris layer**: A void ratio of 0.70 was used for the fuel debris layer based on a packing efficiency of 30 vol% of the canister. An average diffusion coefficient weighted by the flow passage area D_m was calculated using the values of De in each layer and a hydrogen diffusion coefficient in gas phase D_0 in the gap around fuel debris (annulus).

Author of literature	Effective diffusion coefficient calculation formula
Millington and Quirk[1]	$D_e/D_0 = \varepsilon^{4/3}$
Marshall[2]	$D_e/D_0 = \varepsilon^{3/2}$
Wesseling[3]	$D_e/D_0 = 0.9\varepsilon - 0.1$
Penman[4]	$D_e/D_0 = 0.66\varepsilon$
Van Bavel[5]	$D_e/D_0 = 0.6\varepsilon$
Akagi and Kondo[6]	$D_e/D_0 = 2.5\varepsilon^{2.5} + 0.04$
Buckingham[7]	$D_e/D_0 = \varepsilon^2$

D_0: Hydrogen diffusion coefficient in an ordinary gas phase [m^2/s]
D_e: Effective diffusion coefficient that takes into account the void ratio of the packed layer and the curvature of the flow passage [m^2/s]
ε: Void ratio [–]



【Note】
The ranges of the data plotted in the graph for each calculation formula correspond to the applicable range of the void ratio (the range of the experimental database).

Figure: Examples of formulas to calculate an effective diffusion coefficient in a packed layer

【Source】
(1) R. J. Millington, J. P. Quirk, Transport in porous media, Transactions of 7th International Congr. Soil Sci. 1 (1960) 97-106.
(2) Marshall, T. J., The diffusion of gases through porous media, J. Soil Sci. 10 (1959) 79-82.
(3) J. Wesseling, Some solutions of the steady state diffusion of carbon dioxide through soils, Neth. J. Agr. Sci. 10 (1962) 109-117.
(4) H. L. Penman, Gas and vapor movements in soil: The diffusion of vapours through porous solids, J. Agric. Sci. 30 (1940) 437-462.
(5) Van Bavel, Gaseous diffusion and porosity in porous media, Soil Sci. 73 (1952) 91-104.
(6) Hirokazu Akagi, Satoshi Kondo, Diffusion properties of hydrogen gas in soil and method to measure it, 44th Conference of Japan Geotechnical Society (2009): 919–920
(7) E. Buckingham, Contributions to our knowledge of the aeration of soils, USDA Bur. Soil Bul. 25 (1904) 7-52.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

④ Contribution of outcomes to relevant study areas

The study aims to propose a method to suppress hydrogen gas generation during the transport of fuel debris in the canister.
(Especially, proposing a method (mitigation method) to support a measure to avoid the occurrence of a high hydrogen concentration by limiting time allowed for transport in case of fuel debris being put in the canister without dewatering)

⑤ Analysis with respect to the on-site applicability

The study aims to reduce technical burden that may arise in connection with the application of the design of the catalyst bed to the design of canisters used in operations at the 1F by taking into consideration the conditions assumed in the study of the catalyst performance in designing a catalyst bed.

⑥ Goal achievement level

Based on the following results, it can be considered that the goal set at the beginning of the study has been achieved.

- The catalyst evaluation tests were performed using a gas flow-type reaction rate measurement system, and the influence of temperature, vapor, hydrogen concentration, and poisoning materials on catalytic performance was evaluated.
- The results of the tests demonstrated that the performance of the catalyst was high enough to maintain the hydrogen concentration in the canister far below the lower explosive limit of hydrogen (4 vol%) even in the condition that would occur in the canister, including temperature, presence of vapor, and high hydrogen generation rate. It was also demonstrated that the performance of the catalyst was maintained with a sufficient margin in the presence of iodine at a predetermined concentration. Consequently, the effectiveness of the measures against hydrogen gas was demonstrated.
- It became possible to design the catalyst bed installation layout depending on the hydrogen generation rate by estimating a hydrogen concentration distribution in the canister.

6. Implementation details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

⑦ Issues to be addressed

- A suitable layout of the catalyst bed heavily depends on the hydrogen generation rate and filling rate of the fuel debris layer. Therefore, it is necessary to consider further actions, such as reexamining the source intensity, incorporating the method to estimate a hydrogen generation rate that is being studied separately, and studying a filling rate.
- · The condition of catalyst poisoning considered in this study is just an example case. The catalyst performance depends on the concentration of poisoning materials and their chemical form. Therefore, the types and concentration of poisoning materials contained in fuel debris need to be investigated when fuel debris removal operations begin at the 1F, and the influence of poisoning materials needs to be reevaluated based on such data. Since the behavior of poisoning materials over time is unclear, it is necessary to verify the behavior through tests that simulate the actual canister system.

Summary

- The catalyst evaluation tests were performed using a gas flow-type reaction rate measurement system, and the influence of temperature and poisoning materials on catalytic performance was evaluated.
- The effectiveness of the design of the catalyst bed was confirmed by estimating the hydrogen concentration distribution in the canister based on the catalyst performance data obtained in the tests.
- It is necessary to improve the knowledge of the amount and chemical form of catalyst poisoning components in fuel debris and to understand the effect on catalyst performance, including the behavior of poisoning materials.
- The method developed in this study is considered to be effective for other catalysts than the one used in this study, for example, for a case where a new catalyst with higher performances, such as resistance to poisoning materials, is developed.

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

① Purposes and goals

- A container that is transported to a fuel debris storage facility with fuel debris in it must be completely sealed during the transportation between the buildings. Then, how to maintain the concentration of hydrogen generated from water contained in fuel debris below its lower explosive limit during the transportation is one of the challenges. The dewatering of fuel debris by drying is expected to be effective to reduce hydrogen generation.
- This technical study is conducted to meet this need and contribute to the safe transportation of fuel debris. Specifically, the study hypothetically uses parameter conditions that can achieve an effective drying operation by focusing on the drying behavior of porous solid, in which fuel debris is inferred to have as its existing form, and verifies them. Based on the result, the basic specifications of drying apparatus that can process fuel debris from the 1F will be proposed. The maintenance and handling of the equipment in a contaminated area will also be considered.
- The outcomes of this study are expected to be used in the verification test with actual fuel debris from the 1F that is performed in the phase of engineering work toward the commencement of operations at the 1F and as the basis of the design of fuel debris drying apparatus used in operations at the 1F based on the result of the said verification test.

② Comparison with existing technology

- The purpose of TMI-2 fuel debris drying was to remove free water to maintain sub-criticality. It did not aim to achieve high performance drying. At the 1F, a high-performance drying must be achieved to reduce the moisture content of fuel debris to a considerably low level to reduce hydrogen generation. Knowledge on heating and vacuum drying that was used at TMI-2, such as contamination prevention measures, are thought to be useful information.
- A variety of drying methods are used in the general industry. There should be effective drying methods suitable for fuel debris from the 1F in addition to the method used at TMI-2. Of course, the methods used in the general industry cannot be used for drying fuel debris without modification because they will be used and maintained in a contaminated area.

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

Study method

a. Study of basic conditions

(i) Study of performance requirements (materials to be dried, process time, and target moisture content)

- Determination of target materials to be dried, target process time, and target moisture content and identification of performance requirements for drying apparatus necessary to meet those targets

(ii) Conceptual study of apparatus

- Clarification of safety requirements and identification of functional requirements for drying apparatus necessary to meet those requirements【Supplement-7】
- Study of the drying method used at TMI-2 and drying methods used in the general industry, and examination of the applicability of those methods to fuel debris drying【Supplement-8, 9】
- Study of the concept of drying apparatus (including maintenance plan, operating system, and apparatus configuration)

b. Collection of drying behavior data

(i) Performing element tests

- Identification of effective drying conditions and collection of drying behavior data

(ii) Preparation of full-scale test system

- Identification of data to be collected and items to be verified in full-scale tests (tests with canister and/or unit can), and formulation of a test plan

(iii) Collection of drying behavior data (including maintainability)

- Data collection and the verification of items including operability and maintainability necessary for actions described in Paragraph c. (i) using the full-scale test system

c. Basic design of drying system

(i) Study of maintenance plan, operating system, and apparatus configuration

- Identification of specific functional requirements, study of the concept of the system, and identification of data to be collected and items to be verified, and use of the results of these actions in actions described in Paragraph b.

(ii) Determination of the basic specifications of apparatus based on data collected in actions described in the preceding paragraphs

- Proposal of the basic specifications of apparatus (draft) based on the test results

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

a. Study of basic conditions (1/2)

(i) Clarification of performance requirements

Materials to be dried and target process time and moisture content were set as described below as performance requirements for the dying apparatus.

Materials to be dried:	Porous solid, based on the fact that collected materials at TMI-2 were porous solids. Zeolites, known as representative porous solids, were used for tests.
Target process time:	24 h from loading to the apparatus to unloading
Target moisture content:	0.1 wt.%[*1]

Note 1: Target moisture content that takes into account the density of fuel debris
It will be reconsidered based on the density of the zeolite sample used for the test.

Table: Performance requirements

Description of requirement		Description of target
Target items	**Can deal with the properties of fuel debris collected at the retrieval side**	**The target is porous material having small pores. Although slurry might be subject to drying, considering the fact that their current properties are unknown, the applicability of drying technologies that are under study as the main targets will be studied using element tests, etc.**
	Can be handled by a method allocated from the retrieval side	**Considering their handling in unit cans or canisters**
Target time	**Can dry within the time corresponding to the throughput of debris retrieval**	**The assumed target time from receiving to allocation is 24 h.**
Target moisture content	**Reduces the amount of water remaining after drying as much as possible**	**The target moisture content is set to 0.1 wt.% estimating a margin on the moisture content (1.5 wt.%) where the hydrogen concentration in the canister reaches the lower explosion limit (4 vol%) during the transfer period of 7 days.**

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

a. Study of basic conditions (2/2)

(ii) Conceptual study of apparatus

A method to dry fuel debris in a container was selected as the basis for the conceptual study based on the conformity with safety requirements and the results of research on drying equipment used in general industry and in consideration of the dispersion fuel debris during processing.

(See【Supplement-7, 8】for detail)

- ◆ Sub-criticality is maintained by handling fuel debris as it is held in the unit can.
- ◆ The unit can is made of mesh material to allow water and air to go through.
  ⇒ The facilitation of fuel debris dewatering and drying is expected.
- ◆ Evaporation facilitation: Direct heating (by hot air) and vacuuming is adopted to have water reach the boiling point quickly.
- ◆ Moisture transport facilitation: A concentration gradient is generated by suction exhaustion in principle.
- ◆ Increase of the surface area: The layout of unit cans is optimized, such as providing a certain distance between unit cans when stacking them, to maximize the surface area.
  An external heat source (heater) is added to the vacuum method to supply heat consumed for evaporation by reduced pressure.
- ◆ Design parameters
  - Heating temperature, inner pressure, hot air flow rate, and chamber capacity
- ◆ Restrictions
  - Heating temperature: The capacity of the heat source is determined so that temperature in the chamber or canister can go up to 200° C.
  - Shape of container: To maintain sub-criticality, the maximum inner diameter of a container for fuel debris is 220 mm.
  - Hot air flow rate: The upper limit of the flow rate is set taking into account the dispersion of fuel debris during processing.
  - Chamber: The inner pressure of the chamber or canister is maintained below atmospheric pressure for safety.

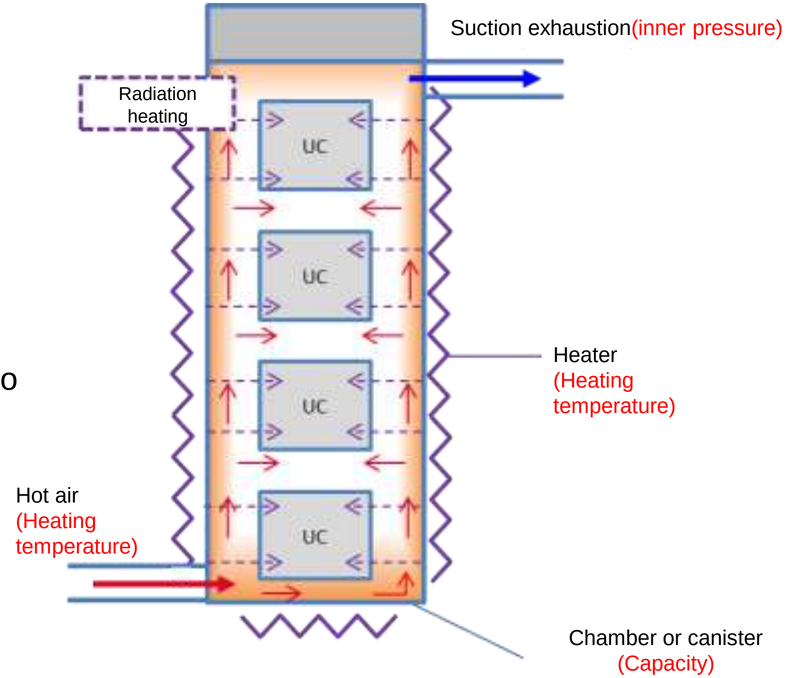


Figure: Basic concept of the drying apparatus

6. Implementation details

6.4 Development of drying technology and systems

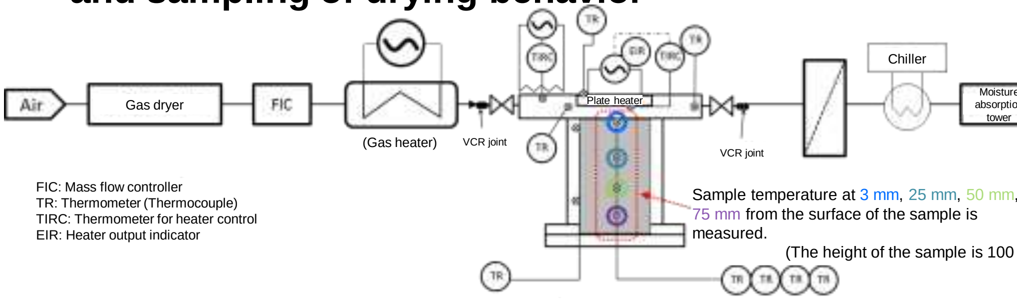
(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

b. Collection of drying behavior data (1/6)

(i) Element test

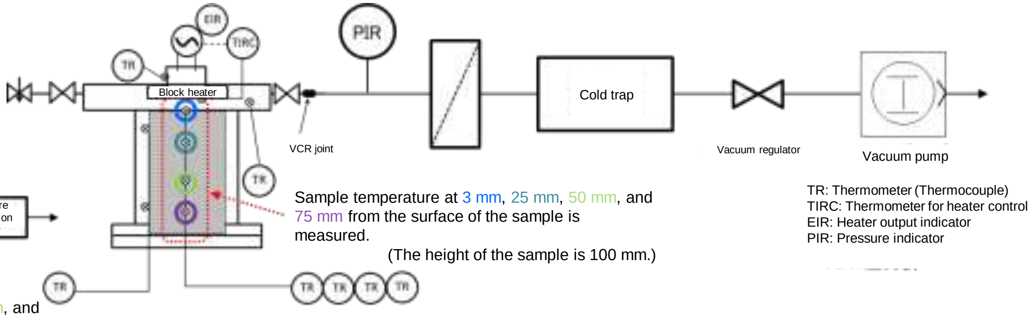
Purpose: Identification of effective drying conditions and sampling of drying behavior



FIC: Mass flow controller
TR: Thermometer (Thermocouple)
TIRC: Thermometer for heater control
EIR: Heater output indicator

Sample temperature at 3 mm, 25 mm, 50 mm, and 75 mm from the surface of the sample is measured.
(The height of the sample is 100 mm.)

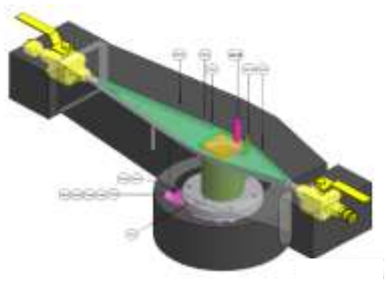
Figure: Schematic of the system for hot air drying element tests



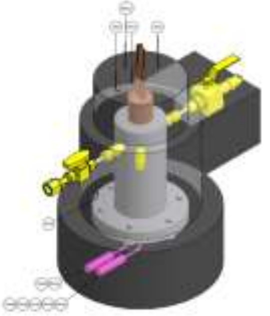
Sample temperature at 3 mm, 25 mm, 50 mm, and 75 mm from the surface of the sample is measured.
(The height of the sample is 100 mm.)

TR: Thermometer (Thermocouple)
TIRC: Thermometer for heater control
EIR: Heater output indicator
PIR: Pressure indicator

Figure: Schematic of the vacuum drying element test system



3D CAD drawing of hot air drying element test system and test container



3D CAD drawing of vacuum drying element test system and test container

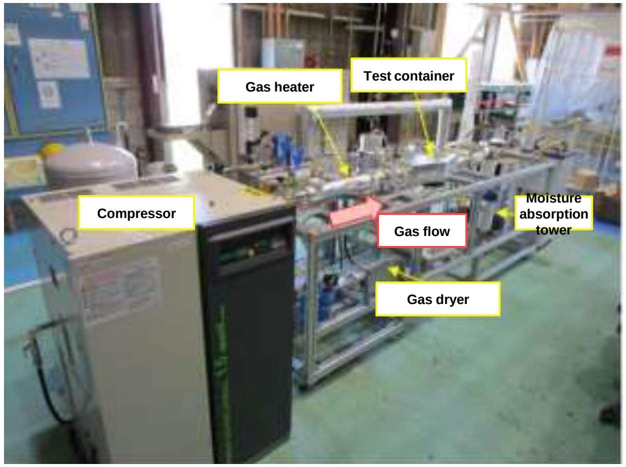


Figure: External appearance of the system for hot air drying element tests

Figure: External appearance of a test container filled with water containing particle samples

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual) b. Collection of drying behavior data (2/6)

(i) Element test

【Test results】
- Investigating the sensitivity of the operation parameters of the vacuum drying method ➡ Temperature, pressure, and gas flow rates were found to affect the drying performance significantly.
- The moisture content saturated in approximately 13 h for both methods ➡ There is a possibility of achieving the target moisture content 0.3 wt.% with a hot air drying method

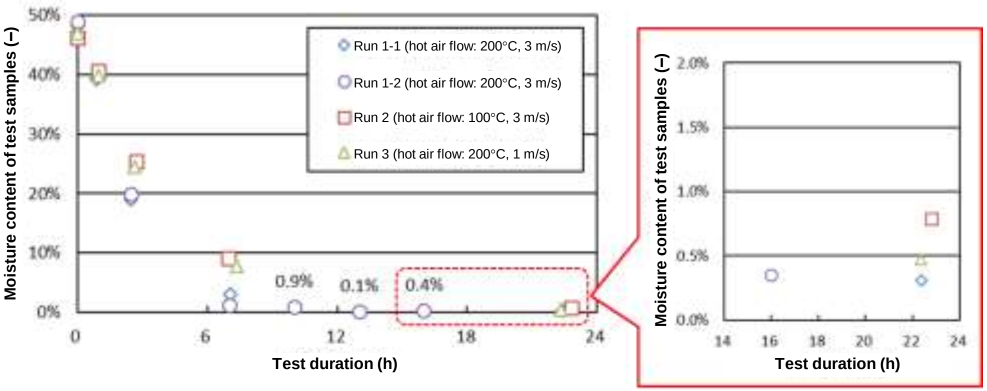


Figure: Vacuum drying element test—Moisture content change over time

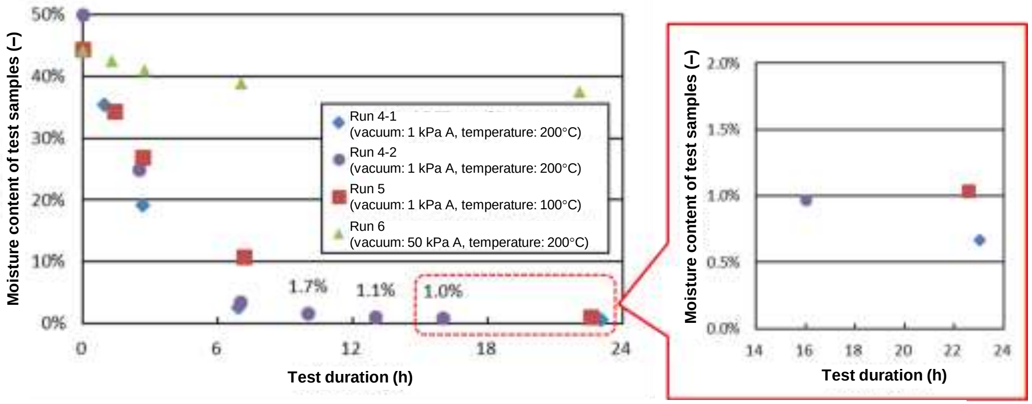


Figure: Vacuum drying element test—Moisture content change over time

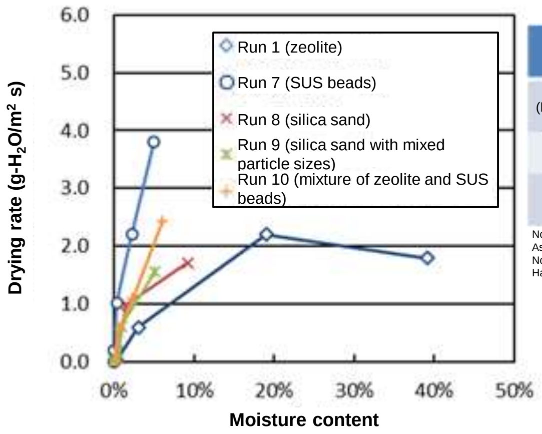


Figure: Drying curves of different materials (target materials for drying methods in discussion)

Table: Properties of materials to be dried

Materials to be dried	Density [g/cm³]	Thermal conductivity [W/mK]	Filling rate [%]
Zeolite[*1] (Degree of porosity: 38%)	1.17	0.09	55
SUS beads[*2]	7.93	16	62
Silica sand	2.7[*3]	1.0[*4]	47 (same particle size) 52 (mixed particle sizes)

Note 1: Actual measurements; Note 2: Cited from the website of Japan Stainless Steel Association (http://www.jssa.gr.jp/contents/)
Note 3: As per JIS Z 8901; Note 4: Data of soda lime glass cited from the Chemical Handbook, Revised 5th Edition, published Maruzen Publishing Co., Ltd.

【Test results】

- Thermal conductivity and the presence of fine pores affect drying behavior significantly.
- Characterization of fuel debris: Thermal conductivity, diameter of fine pores, particle size, etc.

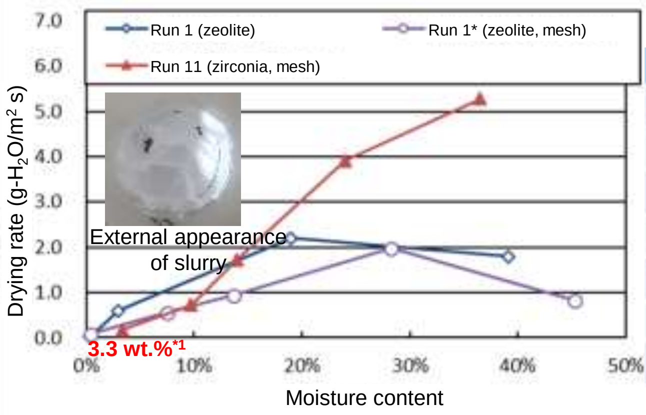


Figure: Slurry drying curves obtained by hot air drying tests

Table: Properties of slurry (zirconia)

Item	Value
Material	ZrO_2
Particle size	0.04 µm
Density	6.0 g/cm^3[*1]
Thermal conductivity	3 W/m・K[*1]
Specific surface area	14±3m^2/g
SS concentration	70wt%
Filling rate	27%

Note 1: moisture content of zirconia, mesh at 24 h from the start of the test

【Test results】Air layers were formed in low filling rate slurry between particles after drying.
➡ The drying rate decreased due to decrease in the thermal conductivity of the surface of the test sample.

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)   b. Collection of drying behavior data (3/6)

(i) Element

【Evaluation method】

(1) Reverse calculation of effective diffusion coefficients from test data using a drying process evaluation model (De′)

(2) Comparison of obtained De′ with the theoretical values of the steam diffusion coefficient in the layers concerned

○ Evaluation results (1/2)

(1) In the first half of drying period: De′/De >1

- Drying rate was greater than vapor diffusion rate.
- It was inferred that water in the liquid state diffused toward the surface and facilitated the drying process. (A diffusion coefficient was estimated greater in the model.)

(2) In the second half of drying period: De′/De <1

- Slow drying in fine pores was inferred to be a cause (based on the results of tests with SUS beads having no fine pores not indicating this tendency).
- This tendency was remarkable in vacuum drying.

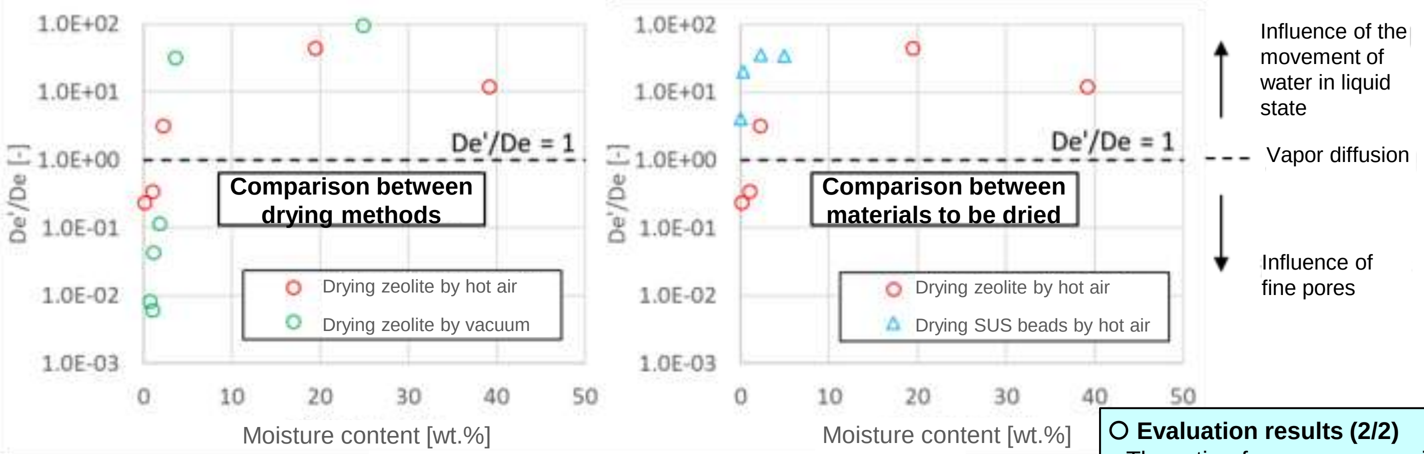


Figure: Results of the estimation of effective diffusion coefficient based on element tests

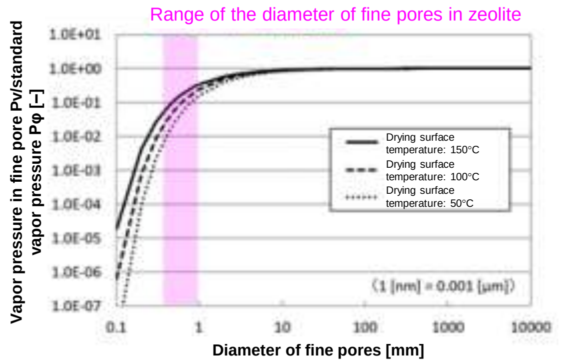


Figure: Relationship between fine pore diameter and vapor pressure

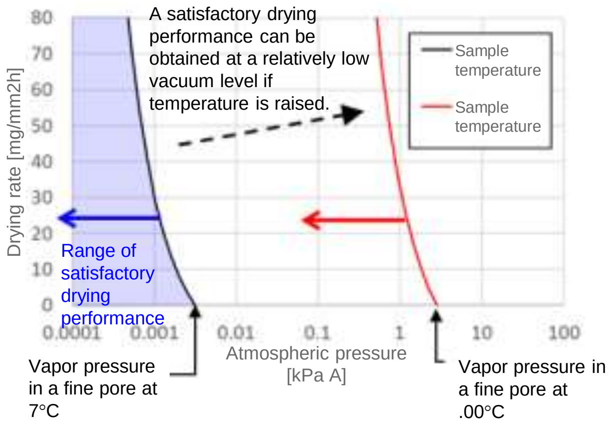


Figure: Relationship between atmospheric pressure and drying rate in vacuum drying

○ Evaluation results (2/2)

- The ratio of vapor pressure in fine pore to standard vapor pressure is 1/100–1/10 in a fine pore diameter of 0.4–1 nm.
- Moisture in fine pores cannot be dried by a method with low atmospheric temperature (7°C at drying surface) and an atmospheric pressure of 1 kPa A.
- A method to heat materials to be dried and reduce the inner pressure of the drying chamber is effective.

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

b. Collection of drying behavior data (4/6)

(ii) Preparation of test system

Identification of data to be collected and items to be verified in full-scale tests (tests with canister and/or unit can)

Table: Full-scale drying test item

Test item	Purpose
Remote operability evaluation test	The operation and maintenance of the drying apparatus will be conducted remotely from a safety view point. Accordingly, the use of manipulators will be needed. It is the purpose to demonstrate the feasibility of the maintenance of the apparatus by remote control through the test to evaluate the maintainability and visibility by remote control using a test system that has the same spatial dimensions as those of the apparatus used in operations at the 1F. <Items to be checked> ① Ability to remove residue in the dryer chamber ② Ability to decontaminate the inside of the dryer by wiping operation
Full-scale drying test	The applicability of the design method that was developed based on element tests is to be demonstrated from multiple viewpoints. <Items to be checked> ① Drying time (from residual heat, drying, to cooldown) ② Final moisture content ③ Indication used to judge the end of drying

(iii) Collection of drying behavior data

Drying tests are to be performed using a full-scale test system to collect data needed to develop and design a drying system used in operations at the 1F including data on maintainability and operability needed in actions described in Paragraph c.

6. Implementation details

6.4 Development of drying technology and systems

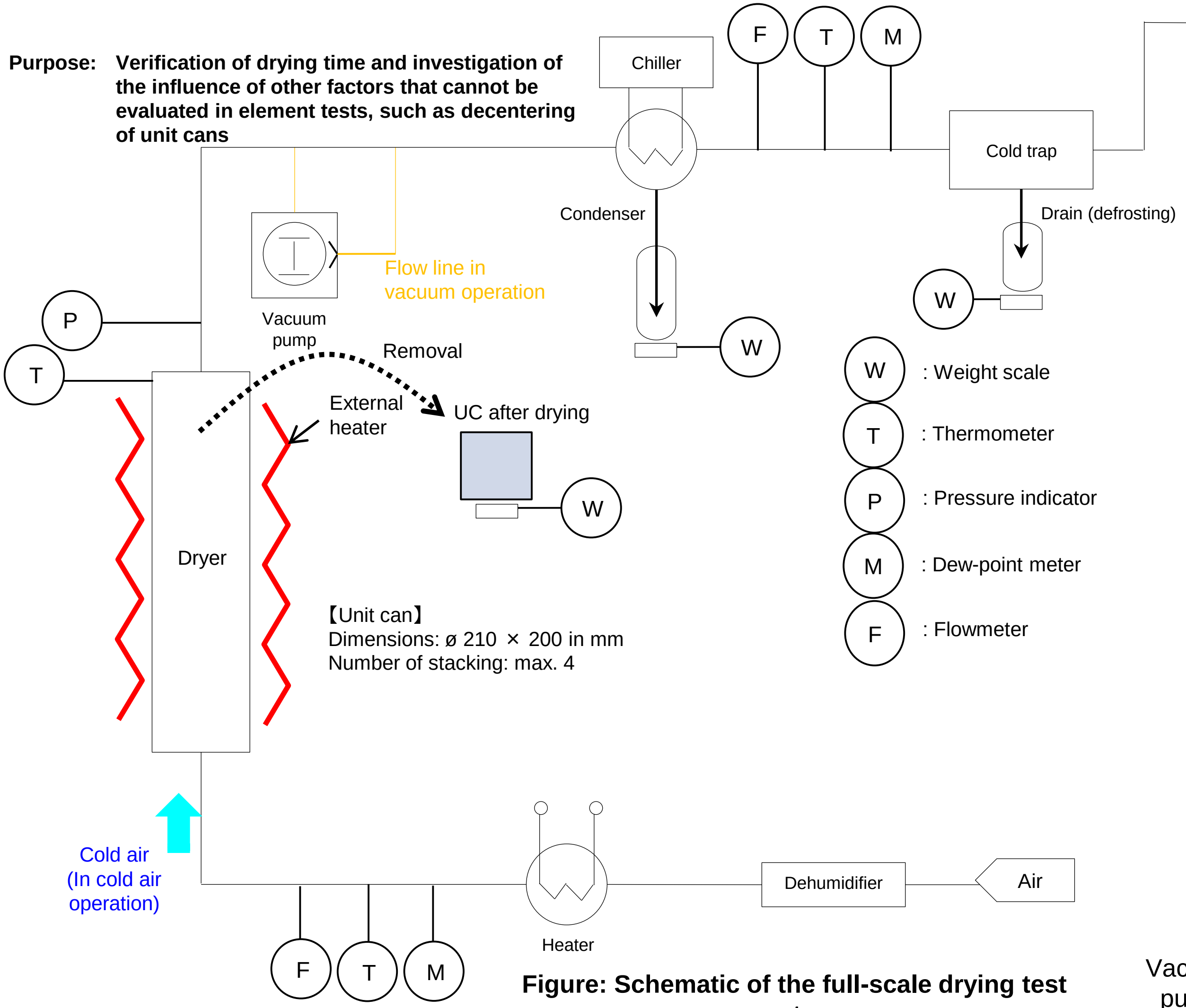
(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

b. Collection of drying behavior data (5/6)

(iii) Evaluation of handleability and collection of drying behavior data

Purpose: **Verification of drying time and investigation of the influence of other factors that cannot be evaluated in element tests, such as decentering of unit cans**



【Unit can】
Dimensions: ø 210 × 200 in mm
Number of stacking: max. 4

W : Weight scale
T : Thermometer
P : Pressure indicator
M : Dew-point meter
F : Flowmeter

Figure: Schematic of the full-scale drying test system

【Outlines of test system】

- Hot air as a drying medium, and a dehumidifier is used for dehumidification.
- Three operation modes are available: vacuum drying, hot air drying, and hot air and vacuum simultaneously.
- Automatic control for drying temperature and pressure
- The temperature of the surface of the drying apparatus main body is used for temperature control.
- The external heater is turned on at all times at 200°C.
- The amount of drain from the condenser is recorded over time
- Batch measurement of water collected by the cold trap by defrosting it by a defrosting heater and collecting in a measuring cup
- On-line measurement for temperature, pressure, flow rate, and dew point
- The UC is weighed after the drying process is finished and it is removed from the apparatus.

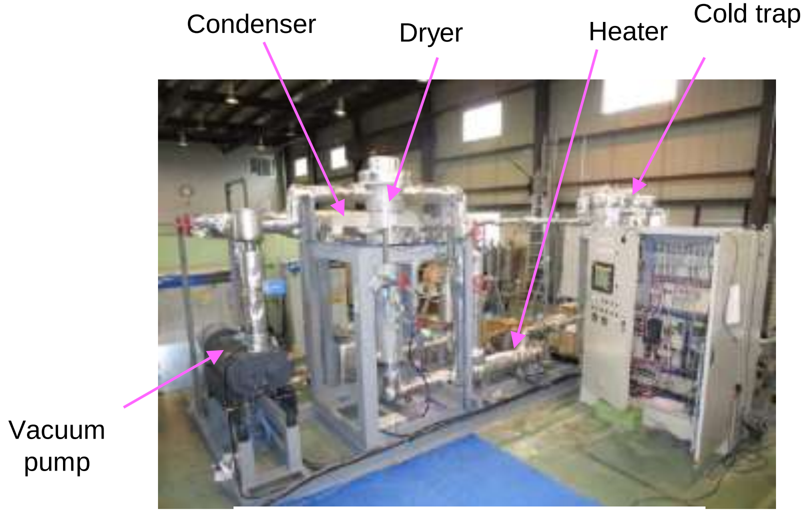


Figure: External appearance of the full-scale drying test system

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

Table: Results of full-scale test

No.	Test conditions	Drying time	Moisture content (wt.%)[*1]
#0	Hot air	14:00	0.31
#1	Periodic switching between heating and vacuum	16:00	<0.12
#2	Hot air with unit cans decentered	16:00	<0.13
#3-1	Periodic switching, a filling rate of 85%	14:00	<0.15
#3-2	Hot air, a filling rate of 85%	12:00	0.21
#5	Vacuum	16:00	2.54

Note 1: Moisture content = Moisture content (g)/Absolute dry weight (g)
The absolute dry weight in the test was approximately 16 kg as the total of four UCs with 100% filling rate.

- The target moisture content of 0.3 wt.% or less was achieved in approximately 14 h with 100% filling rate.
- As to comparison of drying methods, about the same performance was obtained in hot air and periodic switching drying, whereas longer drying time was needed in reduced drying.
- About the same result was obtained even when the UCs were placed decentered, which suggests that the influence of flow rate distribution in the dryer chamber is small.
- Drying time decreased with a decrease in filling rate. It can be explained by less initial water content.[*2]

Note 2: The drying time decreased to 85% when the filling height was reduced to 85%.

b. Collection of drying behavior data (6/6)

(iii) Evaluation of handleability and collection of drying behavior data

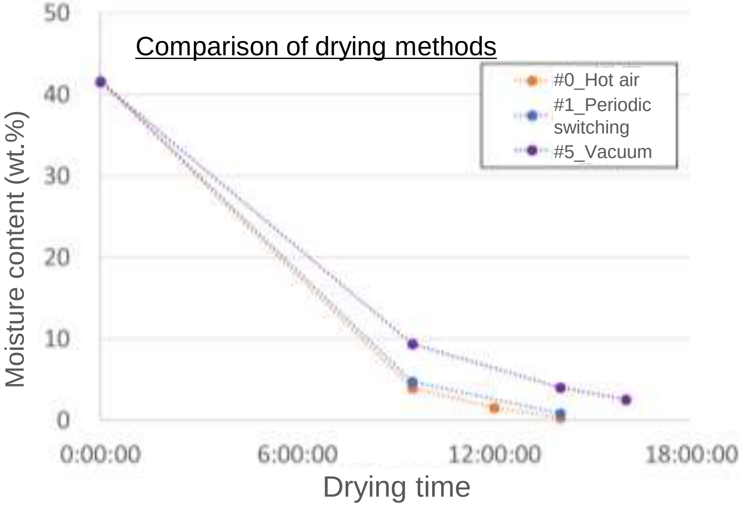


Figure: Comparison of drying methods with respect to moisture content change over time

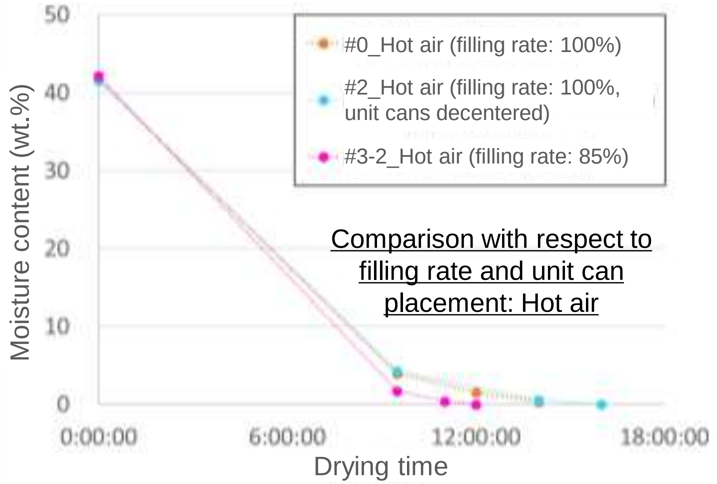


Figure: Comparison of change in moisture content over time in hot air drying with respect to filling rate and unit can placement

6. Implementation details

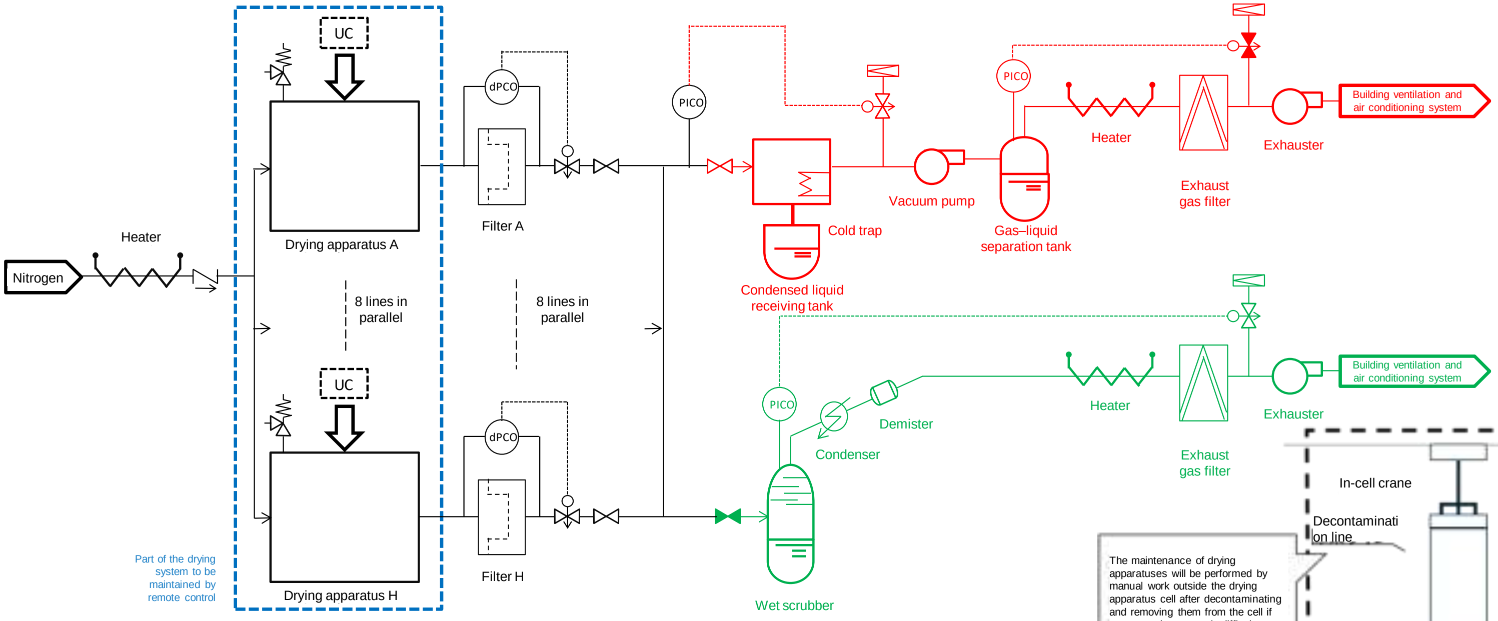
6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus c. Basic design of drying system (1/2)

③ Action items and results (estimated and actual)

(i) Study of maintenance plan, operating system, and apparatus configuration

The system design of the drying system was conducted, and the system concept (draft) was developed. Policies for remote maintenance (draft) were also formulated.



Red line: Used for vacuum drying

Green line: Used for hot air drying

Figure: Exemplary schematic of the drying system

【System design policy】

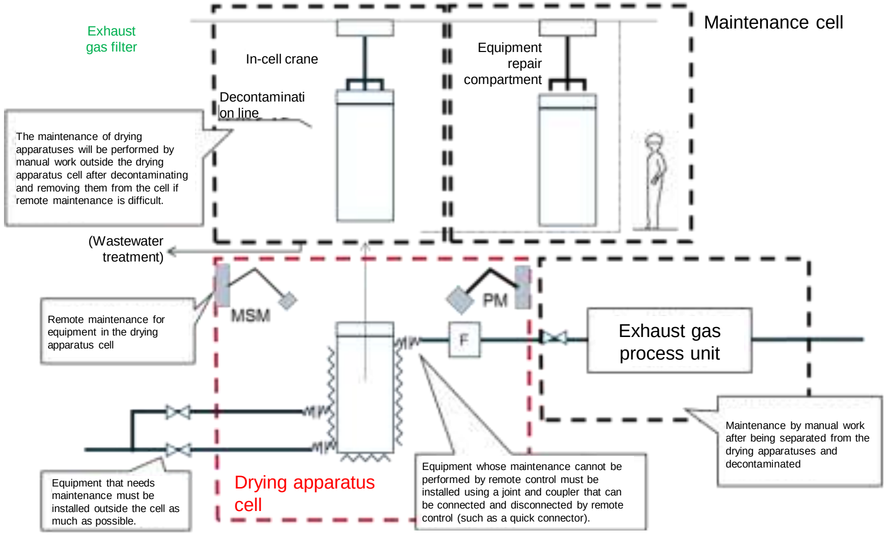
(1) It must be possible to switch between hot air drying and vacuum drying including using the both together.

(2) A filter must be installed at the downstream of the drying apparatus to minimize contamination spread.

(3) Vapor contained in the air used for drying must be collected by a cold trap and gas–liquid separation tank or a wet scrubber.

(4) An exhaust gas filter must be installed in each exhaust gas process line.

(5) A reduced pressure must be maintained using a pressure adjusting valve with a relief valve for safety.



The maintenance of drying apparatuses will be performed by manual work outside the drying apparatus cell after decontaminating and removing them from the cell if remote maintenance is difficult.

Remote maintenance for equipment in the drying apparatus cell

Equipment that needs maintenance must be installed outside the cell as much as possible.

Equipment whose maintenance cannot be performed by remote control must be installed using a joint and coupler that can be connected and disconnected by remote control (such as a quick connector).

Maintenance by manual work after being separated from the drying apparatuses and decontaminated

Figure: Maintenance plan

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

③ Action items and results (estimated and actual)

c. Basic design of the drying system (2/2)

(ii) Study of the basic specifications of the drying apparatus

Table: Operation conditions of the drying system

Temperature	200°C (hot air and heater)
Velocity of flow	3 m/s in the chamber 10 m/s around the cooling jacket
Pressure	Atmospheric to 1 kPa A
Drying methods	Hot air or vacuum (periodic switching)
Operation time	16 h/batch
Materials to be dried	Solid particles with a size of 0.1 mm or more (fine pores can be contained.[*1, 2])

Note 1: Except slurry and sludge

Note 2: Further consideration is needed for materials that contain a lot of hydrates and crystallization water, such as concrete.

Table: Structural dimensions of the drying chamber

Dimensions	Inner diameter of the lower section: 220 mm Inner diameter of the upper section: 350 mm Height of the lower section: 1,050 mm Height of the upper section: 700 mm
UC holding capacity	A stack of max. four UCs with dimensions of ø 210 mm (outer diameter) × 200 mm

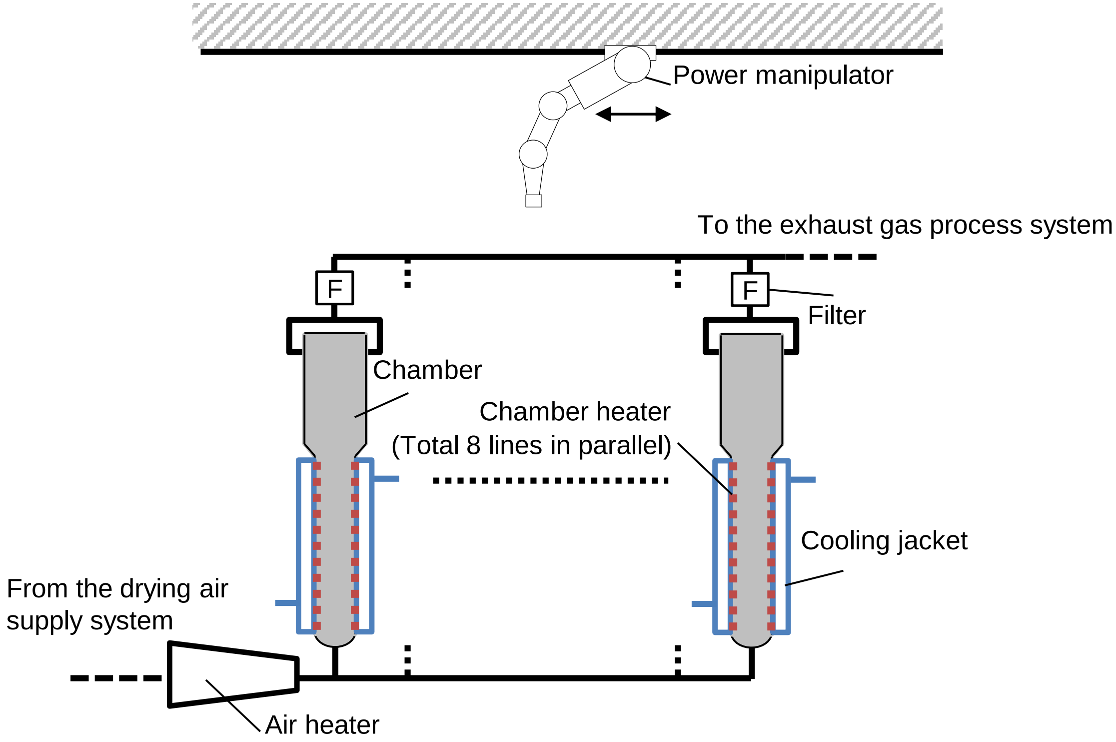


Figure: Equipment configuration (chambers and around them)

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

④ Contribution of outcomes to relevant study areas

Contribution to the development of measures to suppress hydrogen generation during fuel debris transport in a container by proposing the conceptual design of the fuel debris drying system

⑤ Analysis with respect to the on-site applicability

Study items were planned taking into account the possibility of the use and maintenance of the apparatus in high radiation areas.

The applicability of the proposed design in operations at the 1F will be examined as the design is elaborated toward a final design.

⑥ Goal achievement level

Items needed for the proposal of the basic specifications of the fuel debris drying system (draft) were studied in accordance with the plan, and intended outcomes were achieved.

⑦ Issues to be addressed

Details are described in the next page.

Summary

The basic specifications (draft) of the fuel debris drying apparatus that will be used in fuel debris removal operations at the 1F were proposed based on the drying behavior of porous solid particles obtained from the element tests designed by reference to the fuel debris drying method used at TMI-2, the results of full-scale verification tests, and the results of study on maintenance and handling in high contamination areas.

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of the basic specifications of the drying apparatus

Table: Issues to be addressed toward the use of the designed canisters in operations at the 1F

No.	Issues	When to work on*1	Concrete actions	Remarks
1	Study of fuel debris drying as it is contained in the canister because of its easiness in contamination control	Development	In comparison with the method to dry it in a drying chamber as it is held in the unit can, this method poses a concern that much longer drying time will be needed because the inside of the canister is so narrow that the gas flow rate distribution will not be even. To address this concern, the full-scale test system is to be modified to perform the test to examine whether this method can achieve the same drying performance as that of the chamber method (0.3 wt.% moisture content with zeolite).	Suggested to be studied in a succeeding subsidized project
2	Judgment of timing to terminate a drying cycle when foreign materials are mixed in such as concrete	Development	When concrete is mixed in fuel debris, a longer drying time will be needed as crystallization water contained in the concrete will be continuously emitted from it. In this study, the applicability of the method to judge the timing to terminate a drying cycle is evaluated using the full-scale drying test system with concrete. It is also necessary to investigate what types of materials will be mixed in fuel debris and how they affect the drying time in operations at the 1F.*2 For example, there is a possibility of waste from inside and outside the reactor core area being mixed in.	Suggested to be studied in a succeeding subsidized project
3	Drying of difficult-to-dry materials	Development	It is necessary to accumulate data needed for the assessment of the applicability of the drying method to difficult-to-dry materials, such as sludge and slurry.	Suggested to be studied in a succeeding subsidized project
4	Verification of time needed for remote controls	Final design	A standard process time is hypothetically set for each of the remote controls including the operation of the system and the maintenance and replacement of the components taking account of the building layout and other things. Then, the adequacy of the remote control methods and the processing capacity of related equipment are examined based on them and the results of mockup tests, including the necessity of expanding the facility.	
5	Measurement and estimation of fuel debris properties	Final design, operation	It is not known how accurately the materials used in the drying tests simulate the properties of fuel debris in the 1F because little information is available about them. Therefore, the design of the drying system will need to be reexamined and changed, if necessary, when fuel debris is sampled at the 1F and its properties become available, such as thermal conductivity.	

Note 1: Development for technical development phase, final design for final design engineering phase, and operation for after actual use of the canisters at the 1F
Note 2: This investigation will be conducted in the phase of final design engineering or after actual use of the system.

6. Implementation Details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

① Purpose and Goal

To prevent hydrogen combustion or explosion during transfer inside 1F premises, measure the hydrogen concentration in the canister and (or) transfer cask, and confirm that the hydrogen concentration in the cask stays below the lower explosion limit (4 vol.%) for 7 days Note 1, before delivering the canister to the storage building.

Therefore, investigate hydrogen concentration measurement technologies, and select and propose applicable candidate technologies.

Note 1： Set in consideration of the actual transfer time of removed spent nuclear fuel, and the time required for the expected recovery from a failure occurring during transfer in Unit 4 of 1F.

② Comparison with existing technology

Existing technologies can be used for hydrogen concentration measurement. However, there is little knowledge about hydrogen concentration measurement in a high-dose environment. It is necessary to study the applicability, etc., of the technologies in consideration of the storage and transfer process of fuel debris, the interaction with the canister and transfer cask, and the environmental conditions in 1F, etc.

6. Implementation Details

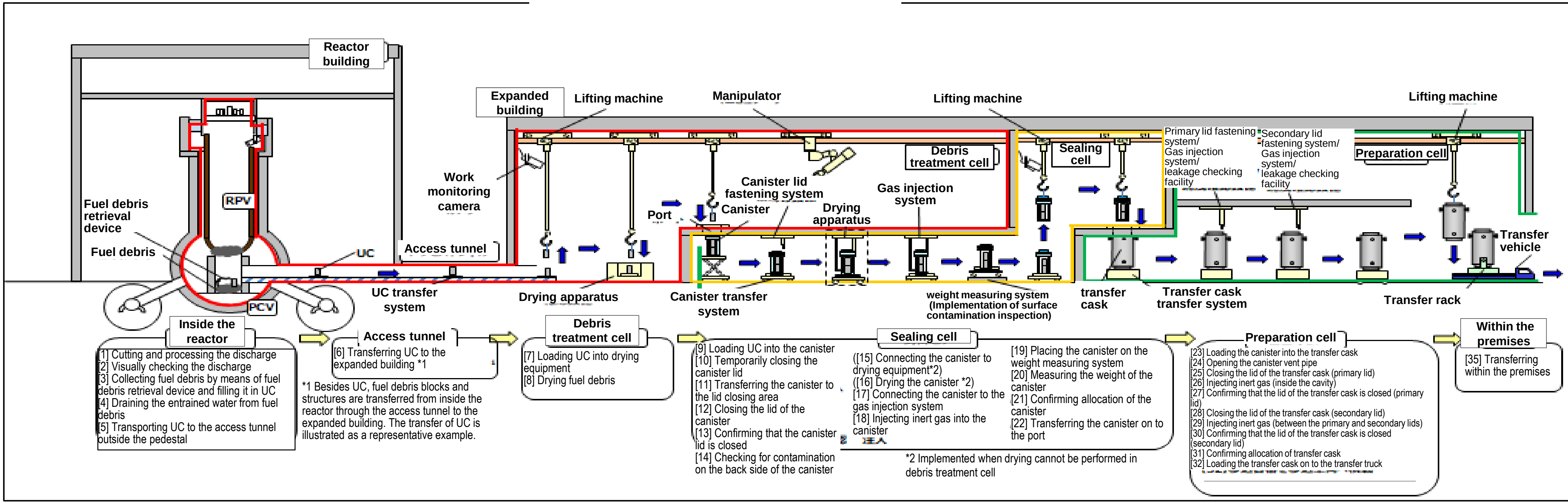
6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

③ Implementation items and results (Estimated and actual)

a. Study on required technical specifications and applicability criteria (FY 2019) (1/12)

- ✓ Study on the points for hydrogen concentration measurement from the perspective of “**continuous monitoring**” and “sequential monitoring”.
- ✓ “Sequential monitoring” helps in identifying the **work processes with which hydrogen concentration can be measured with minimum equipment support**, in the work processes from fuel debris retrieval to transfer cask allocation ([1] to [32] in the below figure)



Inside the reactor

[1] Cutting and processing the discharge
[2] Visually checking the discharge
[3] Collecting fuel debris by means of fuel debris retrieval device and filling it in UC
[4] Draining the entrained water from fuel debris
[5] Transporting UC to the access tunnel outside the pedestal

Access tunnel

[6] Transferring UC to the expanded building *1

*1 Besides UC, fuel debris blocks and structures are transferred from inside the reactor through the access tunnel to the expanded building. The transfer of UC is illustrated as a representative example.

Debris treatment cell

[7] Loading UC into drying equipment
[8] Drying fuel debris

Sealing cell

[9] Loading UC into the canister
[10] Temporarily closing the canister lid
[11] Transferring the canister to the lid closing area
[12] Closing the lid of the canister
[13] Confirming that the canister lid is closed
[14] Checking for contamination on the back side of the canister
([15] Connecting the canister to drying equipment*2)
([16] Drying the canister *2)
[17] Connecting the canister to the gas injection system
[18] Injecting inert gas into the canister
[19] Placing the canister on the weight measuring system
[20] Measuring the weight of the canister
[21] Confirming allocation of the canister
[22] Transferring the canister on to the port

*2 Implemented when drying cannot be performed in debris treatment cell

Preparation cell

[23] Loading the canister into the transfer cask
[24] Opening the canister vent pipe
[25] Closing the lid of the transfer cask (primary lid)
[26] Injecting inert gas (inside the cavity)
[27] Confirming that the lid of the transfer cask is closed (primary lid)
[28] Closing the lid of the transfer cask (secondary lid)
[29] Injecting inert gas (between the primary and secondary lids)
[30] Confirming that the lid of the transfer cask is closed (secondary lid)
[31] Confirming allocation of transfer cask
[32] Loading the transfer cask on to the transfer truck

Within the premises

[35] Transferring within the premises

Figure. Example of expanding the fuel debris retrieval process flow to the handling flow of the side-access retrieval method

6. Implementation Details

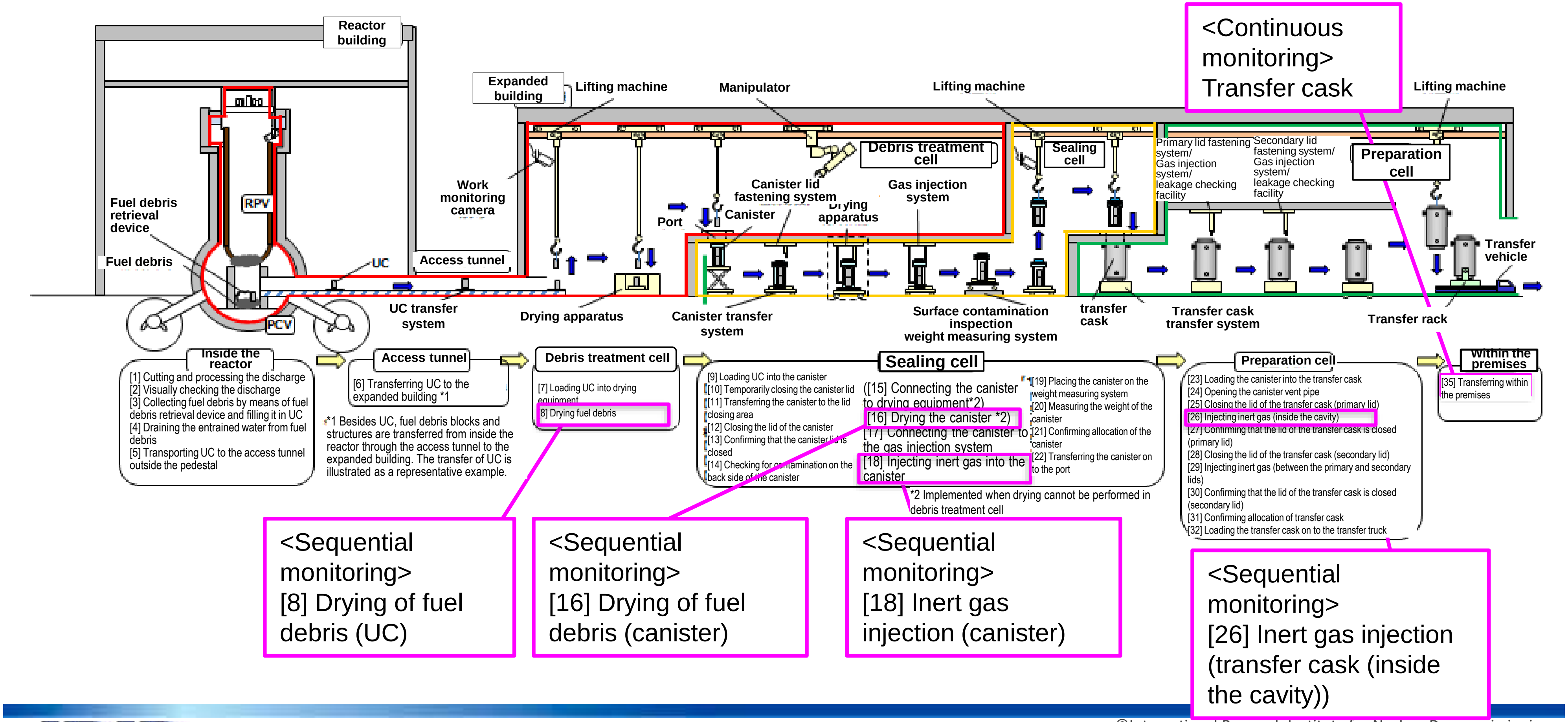
6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

③ Implementation items and results (Estimated and actual)

a. Study on required technical specifications and applicability criteria (FY 2019) (5/12)

Result of selection of candidate hydrogen concentration measurement points (process) for "continuous monitoring" and "sequential monitoring" (Summary)



<Continuous monitoring>
Transfer cask

Inside the reactor

[1] Cutting and processing the discharge
[2] Visually checking the discharge
[3] Collecting fuel debris by means of fuel debris retrieval device and filling it in UC
[4] Draining the entrained water from fuel debris
[5] Transporting UC to the access tunnel outside the pedestal

Access tunnel

[6] Transferring UC to the expanded building *1

*1 Besides UC, fuel debris blocks and structures are transferred from inside the reactor through the access tunnel to the expanded building. The transfer of UC is illustrated as a representative example.

Debris treatment cell

[7] Loading UC into drying equipment
[8] Drying fuel debris

Sealing cell

[9] Loading UC into the canister
[10] Temporarily closing the canister lid
[11] Transferring the canister to the lid closing area
[12] Closing the lid of the canister
[13] Confirming that the canister lid is closed
[14] Checking for contamination on the back side of the canister
([15] Connecting the canister to drying equipment*2)
[16] Drying the canister *2)
[17] Connecting the canister to the gas injection system
[18] Injecting inert gas into the canister
[19] Placing the canister on the weight measuring system
[20] Measuring the weight of the canister
[21] Confirming allocation of the canister
[22] Transferring the canister on to the port

*2 Implemented when drying cannot be performed in debris treatment cell

Preparation cell

[23] Loading the canister into the transfer cask
[24] Opening the canister vent pipe
[25] Closing the lid of the transfer cask (primary lid)
[26] Injecting inert gas (inside the cavity)
[27] Confirming that the lid of the transfer cask is closed (primary lid)
[28] Closing the lid of the transfer cask (secondary lid)
[29] Injecting inert gas (between the primary and secondary lids)
[30] Confirming that the lid of the transfer cask is closed (secondary lid)
[31] Confirming allocation of transfer cask
[32] Loading the transfer cask on to the transfer truck

Within the premises

[35] Transferring within the premises

<Sequential monitoring>
[8] Drying of fuel debris (UC)

<Sequential monitoring>
[16] Drying of fuel debris (canister)

<Sequential monitoring>
[18] Inert gas injection (canister)

<Sequential monitoring>
[26] Inert gas injection (transfer cask (inside the cavity))

6. Implementation details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

③ Action items and results (estimated and actual)

b. Investigation of hydrogen concentration measurement technologies (3/3)

Based on the result of the investigation of hydrogen concentration measurement technologies, technologies applicable to the monitoring schemes A, B, and C were identified and evaluated, and the following methods were selected as candidates.

A: Continuous monitoring: Heat conduction type hydrogen meter

B: Sequential monitoring during drying process: Gas chromatographic method or proton conductor hydrogen meter

C: Sequential monitoring during inert gas injection: Gas chromatographic method or proton conductor hydrogen meter

6. Implementation details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

③ Action items and results (estimated and actual)

c. Utilization of outcomes from related technology development

It was confirmed that there was no specific need of change based on the results of reexamining the progress and outcomes of the "study on drying system" in two studies conducted in this project in parallel, "Development of transfer technology for fuel debris" and "Development of drying technology and systems," as well as the results of the review on the outcomes of the project in FY2019 in reference to those results.

④ Contribution of outcomes to relevant study areas

The developed hydrogen concentration measurement methods will contribute to the safety assurance of the canister transfer.

It is also expected to contribute to the estimation of the water content of fuel debris during drying.

⑤ Analysis with respect to the on-site applicability

The developed hydrogen concentration measurement methods can be considered to be applicable since the currently estimated conditions of the hydrogen measuring points at the 1F were taken into account and measurement technologies were selected so as to fit those conditions, provided that the issues described in the next page need to be addressed.

6. Implementation details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

⑥ Goal achievement level

The candidates of hydrogen concentration measurement technologies applicable to the canister were selected in accordance with the original plan.

⑦ Issues to be addressed

The hydrogen concentration measurement technologies selected by this study still have the following issues before applying them in operations at the 1F:

A: Continuous monitoring in the transfer cask

- There is no issue as far as the measurement technology is concerned. The influence of the installation of the sensor on the structural strength of the transfer cask needs to be examined.

B: Sequential monitoring during drying process

- Gas sampling is needed when a gas chromatographic method is used.
  ⇒ A gas sampling port and piping needs to be installed in the exhaust gas process line of the drying system (after the filter). (Additional work is needed on the system.)
  A gas chromatography instrument must be installed in a shielded and contamination-free room so that workers can operate it directly.
  The sensitivity of the gas chromatography instrument needs to be improved.
- The sensitivity at a low concentration needs to be examined when a proton conductor hydrogen meter is used.

C: Sequential monitoring during inert gas injection

- Gas sampling is needed when a gas chromatographic method is used.
  ⇒ A gas sampling port and piping needs to be installed in the exhaust side of the inert gas injection line. (Additional work is needed on the system.)
  A gas chromatography instrument must be installed in a shielded and contamination-free room so that workers can operate it directly.
- There is no issue as far as the use of a proton conductor hydrogen meter.

In addition to the above-mentioned issues, the applicability of the selected hydrogen concentration measurement technologies will need to be examined whenever the conditions where they will be used at the 1F come into clear view, since the specifications of the drying system used at the 1F, such as structure, gas flow rate, and operating pressure, have not been determined much at present.

6. Implementation details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

Summary

The planned fuel debris transfer work flow was examined from its collection to bringing it out in the transfer cask to find processes in which hydrogen concentration measurement can be performed along with measurement technologies applicable in those steps. As the result, the feasibility of the use of a thermal conductivity-based hydrogen meter was confirmed for the continuous monitoring of hydrogen concentration in the transfer cask.

In addition, the feasibility of the use of a gas chromatography instrument and proton conductor hydrogen meter was confirmed when a sequential monitoring in each process is selected and the drying process and inert gas injection process are selected as those when the monitoring is performed.

6. Implementation details

6.5 Summary of evaluation

① Purposes and goals

The implementation items of related projects are to be reviewed, and the outcomes of studies described in Sections 6.1–6.4 are to be reviewed with respect to their utilization. It is also aimed to join and support, if requested, the research of technologies to sort materials collected in the primary containment vessel (PCV) into fuel debris and radioactive waste that is one of the related technology developments and conducted in the project “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures.”

6. Implementation details

6.5 Summary of evaluation

② Action items and results (estimated and actual)

a. Investigation of sorting technologies (conducted on an as needed basis based on a request from the project “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures”)

(Example of the investigation)

Table: Relaxation of restrictions applied to the canister when the mass of nuclear fuel in the canister can be identified

Destination of sorting	No sorting Designed based on the maximum enrichment level of the loaded fuel (reactivity equivalent to a U-235 enrichment level of 5 wt.%)	When materials whose reactivity is equal to or less than that equivalent to a U-235 enrichment level of 1.5 wt.% can be sorted	When uranium with a weight of 3–4 (kg)[*1] or less in the container can be sorted
Canister (inner diameter: 220 mm)	○	-	-
Canister with a lower safety requirement (Inner diameter: 400 mm)	-	○	-
Criticality control not needed	-	-	○

Note 1: This weight range is derived based on the assumption that rectangular containers are stacked up and UO2 with an enrichment level of 5 wt.% lies at the corner and dividing the minimum estimate of the criticality lower limit (31.1 kg) by eight.

6. Implementation details

6.5 Summary of evaluation

b. Summary of outcomes

The outcomes of this subsidized project are summarized as follows:

- As to the development of containment methods, it was confirmed that the developed specifications and design of the canister were robust enough to maintain the safety functions (such as confinement and criticality prevention) with respect to its structural integrity based on the results of the structural verification tests and structural analysis. The final plan of the specifications and design of the canister was proposed based on the results of the structural verification tests and structural analysis.
- Regarding the study of hydrogen generation estimation methods conducted as part of the development of transferring technologies, the validity of the method to estimate an energy absorption rate from the results of tests with spent fuel was confirmed, hydrogen generation rates were estimated using the estimated energy absorption rates, and the conditions for the design of the fuel debris transfer system (draft) were proposed. In the study of measures to maintain a low hydrogen concentration, the performance of the catalyst was derived based on the results of tests, including those with poisoning materials, the influence of the position of the catalyst bed on the hydrogen concentration distribution in the canister was examined, and the effectiveness of the measure with the catalyst was confirmed.
- With regard to the study of the basic specifications of the drying apparatus conducted as part of the development of drying technology and systems, element tests and full-scale tests were performed, and the conceptual design of the drying apparatus was conducted based on the knowledge obtained from the tests. Further, in the study of hydrogen concentration measurement technologies, usable technologies were listed and screened by setting technical requirements for the concentration measurement and criteria for applicability judgment.
- As to the sorting of materials collected in the PCV of the 1F into fuel debris and radioactive waste, the conditions that work to the advantage of fuel debris transfer and storage with respect to operation efficiency were proposed.

6. Implementation details

6.5 Summary of evaluation

③ Contribution of outcomes to relevant study areas

The developed methods and technologies will be evaluated individually, which are not mentioned in this section.

④ Analysis with respect to the on-site applicability

The developed methods and technologies will be evaluated individually, which are not mentioned in this section.

⑤ Goal achievement level

Support was provided to the investigation of sorting technologies through the joint meetings with the related project team. The developed methods and technologies will be evaluated individually, which will not be mentioned in this section.

⑥ Issues to be addressed

The developed methods and technologies will be evaluated individually, and this section will not mention the evaluations.

【Supplement-1】
Basic conditions of development of the canister (1/8)

The specifications of the canister used in this study were derived based on the properties of fuel debris known at present, requirements from fuel debris removal methods, and information provided by the project “Characterization of Fuel Debris,” and from the view point of safety assessment. The information and data used for the study of the specifications include those that were hypothetically set. Therefore, the proposed specifications will need to be examined and changed, if necessary, based on the progress and outcomes of the projects “Characterization of Fuel Debris” and “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures.” In addition, it was decided that specific methods and procedures, such as a frequency, would be studied after operations at the 1F are started.

【Properties of fuel debris】

- Composition of fuel debris (MCCI products are not included):

  Materials that are currently estimated to be present in the RPV and PCV (uranium dioxide, including FP by irradiation, zirconium alloys, stainless steel, low-alloy net, nickel-based alloys, concrete, and B_4C)

- Salinity: max. approximately 100 ppm

  This value is conservatively set based on the chlorine concentration of 10–20 ppm of the stagnant water. Note that a salinity of 3 ppm is used for the practical evaluation of corrosion resistance based on the measurement of water in the reactor.

  ⇒ This setting assumes continuous review as the fuel debris removal operation at the 1F proceeds. Note that visual inspection in maintenance or in other occasions is also an effective method to check corrosion.

- Zirconium: A minute amount of zirconium residue in a metallic state

  This is to take into consideration the risk of fire.

  ⇒ The risk of metal fire was taken into consideration in this study to prepare for harder conditions. Specifications developed based on this condition may be relaxed by continuously measuring the properties of fuel debris and accumulating data.

- Properties of MCCI products: The above-said fuel debris with concrete mixing in it

  It was estimated that the crystallized water had been lost due to the heat of fuel debris and some sort of reaction had occurred, such as gas generation. In this study, concrete is considered to have mixed in fuel debris simply physically.

【Supplement-1】
Basic conditions of development of the canister (2/8)

【Properties of fuel debris (continued from the previous page)】

- Stability of fuel debris: Stable in the temperature range of −20° C–300° C (nitrogen atmosphere)

  The behavior of fuel debris that makes a significant impact on the safety, such as significant variation in its volume due to the vaporization of components contained in it and the emission of a large amount of corrosive materials and radioactive gas, is not taken into consideration.

  ⇒ Safety must be ensured by the continuous investigation of the fuel debris stability due to limited knowledge of the stability of real fuel debris at present. This temperature condition may be relaxed based on the result of the investigation.

- Form: Solid in the form of lump, particle, or powder
- Rust inhibitor/neutron absorber: Sodium pentaborate

  The material that is currently planned to be used is selected. Note that the neutron absorption material is assumed to be studied when the specific details are determined.

  ⇒ Especially, the outcomes of other projects need to be watched continuously to select an insoluble neutron absorber, and the selected material may need to be reexamined.

【Supplement-1】

Basic conditions of development of the canister (3/8)

【Method to collect fuel debris in the canister】

The following conditions are hypothesized to design the shape of the canister based on the outcomes of the project “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures” and experts' advice.

- Method to collect fuel debris in the form of lump and particle: Picking up or scooping
- Canister dimensions: 220 and 400 mm for inner diameter, and 1,000 mm for total length

  The inner diameters of 220 and 400 mm were selected based the results of study until FY2018. The total length of 1,000 mm was determined based on “approximately 1 m,” which was hypothetically used in the project “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures.”

  ⇒ When the total length of the canister needs to be changed, the adequacy of the new length may need to be examined.
- Method to collect fuel debris in the form of powder: Collecting it in the unit can with a dewatering function, such as one made of mesh, and placing it in the canister as it is held in the unit can

  Metal strainers are popularly used as a filter for general water processing systems. The unit can with a similar design to those strainers is assumed to be used in the powder fuel debris suction system. The unit can is assumed to have dimensions so that it can fit into the canister and be made of thermally stable materials, such as stainless steel or sintered stainless steel mesh. The design of the unit can is being studied in the project “Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures” with the aim of achieving the collection of fuel debris with a particle size of 0.1 mm and more. Therefore, the unit can made of mesh with a size of 0.1 mm is used in this study.

  ⇒ The design of the unit can may be changed when there are changes in the size of fuel debris to be collected and dewatering conditions. In such a case, the design conditions for the canister used in this study may need to be reviewed.
- Site and conditions of fuel debris collection: Above water, area surrounded by boundary such as in the hot cell

  ⇒ When the collection method is changed in the future, the design conditions for the canister used in this study will need to be reviewed.
- Fuel debris removal operation from its collection to sending out to the preparation cell: It is assumed that it takes half a day to cut fuel debris and another half a day to collect it in a unit, place in the canister, and send out to the preparation cell.

  ⇒ When the operation is changed, the design conditions for the canister used in this study may need to be reviewed.

【Supplement-1】
Basic conditions of development of the canister (4/8)

【Method to transfer fuel debris】

- Transferring method: Use of transfer cask

Because there are proven track records at TMI-2 and in the transfer of spent fuel
⇒ When the transferring method is changed after operations at the 1F are started, the design conditions for the canister used in this study may need to be reviewed.

- Position of the transfer cask during transfer: Standing

It is to suppress the dispersion of fuel debris and guide hydrogen gas and residual water to specific areas in the cask so that they can be monitored better.

⇒ When the transferring method is changed after operations at the 1F are started, the design conditions for the canister used in this study may need to be reviewed.

- Capacity of the transfer cask: An inner diameter of 1,700 mm and inner height of 1,200 mm to accommodate 12 canisters
  Atmosphere in the cask: Inert gas atmosphere

All of the above-described conditions are hypothetically set based on the specifications of the spent fuel dry cask, except for the inner height, which is reduced to fit the dimensions of the canister.
⇒ The final dimensions need to be determined based on the final design of the unit can and canister.

【Storage of fuel debris】

The following conditions are hypothetically set based on the discussion with experts:

- Storage method

Wet storage: Considered to be an alternative at present

It is because the wet storage that makes use of the existing pool at the 1F will not provide many advantages and does not appear to be rational, considering modification costs and time and the degree of technical difficulty.
⇒ The studies that have been conducted until now are based on storage and transfer in a dry condition. Therefore, additional study will be necessary if wet transfer and storage is used.

【Supplement-1】
Basic conditions of development of the canister (5/8)

【Storage of fuel debris (continued from the previous page)】

- Dry storage: Primary storage method

  It is because dry storage is considered to be a safe and rational spent fuel storage method with respect to operation and management, such as maintenance. These advantages are expected to hold true for fuel debris. A concrete cask is also used for the dry storage of spent fuel in overseas countries. In this study, a metal cask is used as a representative type of the cask because it has track records in Japan and the requirements for the cask from materials to be contained are about the same between a concrete cask and metal cask.

  ⇒ The studies that have been conducted until now are based on storage and transfer in a dry condition. Therefore, additional study will be necessary if wet transfer and storage is used.

- Water content of fuel debris: A minute amount of residual moisture

  It is assumed that a minute amount of moisture remains in fuel debris even after undergoing drying process in the study of transfer and storage methods to stay on a safe side.

  ⇒ A minute amount of residual moisture was taken into consideration in this study to prepare for harder conditions. Measures developed based on this assumption and incorporated in the design of the canister and cask may be relaxed by continuously measuring the properties of fuel debris and accumulating data.

- Storage period of fuel debris in the canister: 50 years

  This period is set to cover a period of 30 years that is set in the roadmap as the period necessary to determine the final disposal method of fuel debris. The spent fuel dry storage facility maintains a database on the long-term integrity of storage containers with spent fuel in them, which assumes approximately 50 years of storage plus 10 years for preprocessing period. This database provides useful information.

  ⇒ A long period was used as the storage target in this study to prepare for harder conditions. As mentioned before, the properties of real fuel debris, such as stability, are not well known at present. The behavior of fuel debris with time needs to be investigated continuously, and effective data be accumulated. Meanwhile, the results of such investigation may lead to the relaxation of the measures developed and applied in this study.

[Supplement-1] Basic conditions of development of the canister (6/8)

During the development of the canister, the handling flow on the next slide was assumed and division of functions was set tentatively to ensure reasonable safety.

Safety functions		Design goals	Roles of safety functions		Concepts
			Canister	Other equipment	
Subcriticality		To maintain subcriticality	O	O	・The subcriticality of a single canister is maintained by the geometrical shape (inner diameter) of the canister. (Refilling of fuel debris is a large-scale process and is unreasonable) ・The subcriticality of an array of canisters is maintained by using other equipment (e.g. ensuring an appropriate distance between the canisters in the temporary storage rack).
Cooling	Heat removal	To prevent the impact on physical properties of canisters, fuel debris, etc.	-	O	・Since the calorific value is less than that of the same level of spent nuclear fuel and the canister can be cooled by static natural cooling, no special heat removal device is installed in the canister or transfer cask. ・ The fuel debris is handled at a temperature that is lower than the upper limit for the fuel debris temperature that does not inhibit safety (such as generation of toxic gases), including during the drying process of fuel debris.
Confinement	Confinement	To prevent exposure of workers and public	O	O	・Since the canister is provided with an outlet to prevent hydrogen retention, a filter is installed in the outlet in order to prevent the spread of contamination during actual operations. The canister and other facilities (storage facilities, transfer casks) should be able to carry out the confinement function (or control the release of gases).
	Shielding	To prevent exposure of workers and public	-	O	・Adding a shielding function to the canister increases the weight, which leads to an increase in the size of the handling equipment and a decrease in storage efficiency. Since there is a proven record of the same idea in TMI-2 and no major disadvantages were found in the assumed handling flow, the shielding function is not added to the canister and it is secured using other equipment (transfer cask, building).
Other (Maintaining the shutdown, cooling and confinement functions)	Structure	To achieve the structural strength for maintaining the safety functions	O	O	・The canister should have the necessary strength against postulated abnormal events while taking into account streamlining of canister handling equipment, etc. ・Other equipment is used to ease the load conditions and corrosion conditions on the canister.
	Material integrity	To maintain the structural strength	O	O	
	Hydrogen	To prevent the explosion of hydrogen generated by the radiolysis of water	O (Catalyst)	O	・During transfer between buildings (transport at the site), hydrogen countermeasures (catalyst, operation management, etc.) should be undertaken assuming that hydrogen cannot be released outside the transfer cask. ・Since the space inside the canister is small and the hydrogen concentration rises, scavenging, etc., is performed using another equipment as a structure that can release hydrogen outside the canister (outlet to prevent hydrogen retention).
	Fire prevention	To prevent fire caused by residual zirconium	-	O	・The inside of the canister or cell has an inert gas atmosphere to prevent ignition.

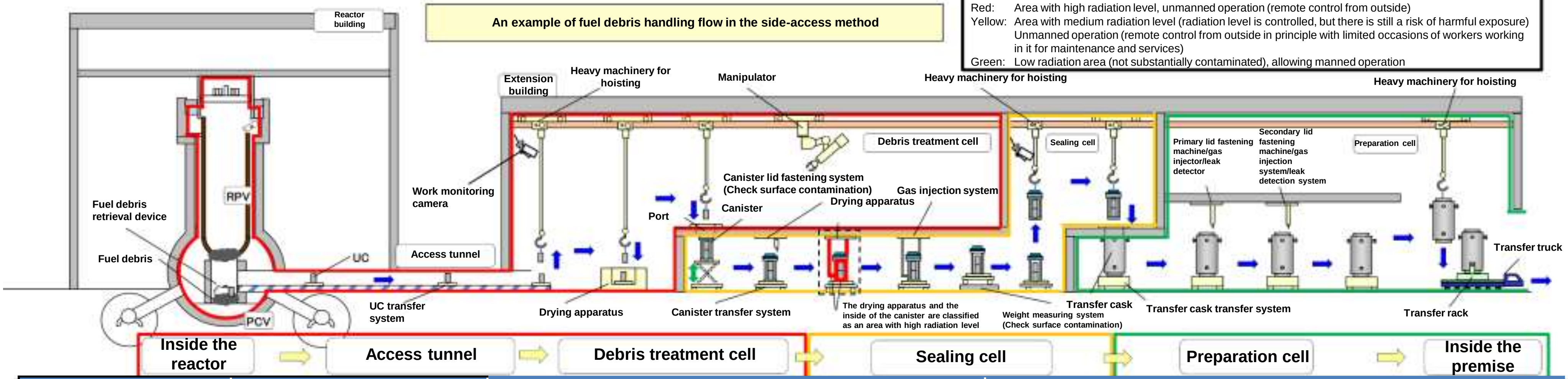
#: The roles of safety functions may be reviewed because it is affected by the fuel debris properties and canister handling procedures.

【Supplement-1】

Basic conditions of development of the canister (7/8)

The process of collecting, transferring, and storing fuel debris and safety functions

<Area classification>
Red: Area with high radiation level, unmanned operation (remote control from outside)
Yellow: Area with medium radiation level (radiation level is controlled, but there is still a risk of harmful exposure) Unmanned operation (remote control from outside in principle with limited occasions of workers working in it for maintenance and services)
Green: Low radiation area (not substantially contaminated), allowing manned operation



Safety functions		Design goals	Sealing cell		Preparation cell (in the transfer cask)	
			Canister	Sealing cell	Canister	Transfer cask
Sub-criticality		Maintaining sub-criticality	○ Sub-criticality in the case of an isolated container	- (Isolation is maintained.)	○	○ (Sub-criticality in the case of an array of containers)
Cooling	Heat removal	Elimination of the impact of heat on the properties of the canister, fuel debris, and other devices	—	○ Keeping inside temperature at the environment temperature	—	○ Keeping inside temperature at the environment temperature
Confinement	Confinement	Prevention of the exposure of workers and general public	○ Prevention of contamination spread	○	○ Prevention of contamination spread	○
	Shield	Prevention of the exposure of workers and general public	—	○	—	○
Others (Integrity of holding, cooling, and sealing functions)	Structure	Structural strength to hold fuel debris safely	○ Strength of the canister	○ Limiting a lifting height, shock-absorbing floor, etc.	○ Strength of the canister	○ Shock-absorbing performance of the transfer cask, etc.
	Integrity of materials	Strength of the materials to withstand mechanical stresses that may occur	○ Adoption of stainless steel	○ Drying at an early stage and maintaining dry condition	○ Adoption of stainless steel	○ Drying at an early stage and maintaining dry condition
	Hydrogen	Prevention of the explosion of hydrogen generated by the radiolysis of water	○ Vent/catalyst/(drying)	○ Purging the inside of the cell	○ Vent/catalyst/(drying)	○ Limiting transfer time
	Fire prevention	Prevention of fire caused by residual zirconium	—	○ Nitrogen atmosphere	—	○ Nitrogen atmosphere

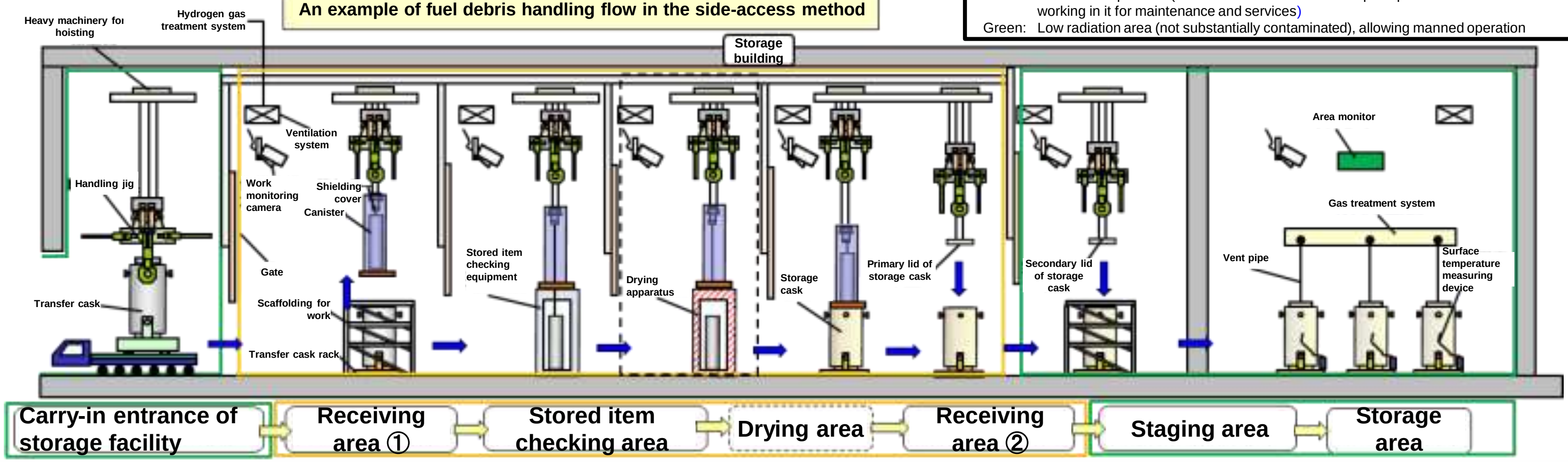
【Supplement-1】

Basic conditions of development of the canister (8/8)

The process of collecting, transferring, and storing fuel debris, as well as issues are shown as below.

<Area classification>
Yellow: Area with medium radiation level (radiation level is controlled, but there is still a risk of harmful exposure)
Unmanned operation (remote control from outside in principle with limited occasions of workers working in it for maintenance and services)
Green: Low radiation area (not substantially contaminated), allowing manned operation

An example of fuel debris handling flow in the side-access method



Safety functions		Design goals	Receiving area ①–Receiving area ②		Staging area to storage area	
			Canister	Area/fuel debris process equipment	Canister	Storage cask
Sub-criticality		Maintaining sub-criticality	○ Sub-criticality in the case of an isolated container	○ In the case of an array of canisters, other equipment is used	○	○ Sub-criticality in the case of an array of containers
Cooling	Heat removal	Elimination of the impact of heat on the properties of the canister, fuel debris, and other devices	—	○ Keeping inside temperature at the environment temperature	—	○ Keeping inside temperature at the environment temperature
Confinement	Confinement	Prevention of the exposure of workers and general public	○ Prevention of contamination spread	○ Area (anti-contamination measures required also in process equipment)	○ Prevention of contamination spread	○
	Shield	Prevention of the exposure of workers and general public	—	○	—	○
Others (Integrity of holding, cooling, and sealing functions)	Structure	Structural strength to hold fuel debris safely	○ Strength of the canister	○ Limiting a lifting height, shock-absorbing floor, etc.	○ Strength of the canister	○ Shock-absorbing performance of the transfer cask, etc.
	Integrity of materials	Strength of the materials to withstand mechanical stresses that may occur	○ Adoption of stainless steel	○ Drying at an early stage and maintaining dry condition	○ Adoption of stainless steel	○ Keeping inside dry
	Hydrogen	Prevention of the explosion of hydrogen generated by the radiolysis of water	○ Vent/catalyst/(drying)	○ Purging process equipment or limiting process time	○ Vent/catalyst/(drying)	○ Connecting vent pipe within predetermined time and venting
	Fire prevention	Prevention of fire caused by residual zirconium	—	○ Filling the area with nitrogen gas	—	○ Nitrogen atmosphere

[Supplement-2] Design conditions of the canister for safety requirements (1/3)

Table. Setting up design conditions of the canister for safety requirements (1/3)

Safety functions	Safety function requirements	Canister requirements	Canister design conditions	
			Lid	Main Body
Confinement	Confinement of radioactive materials	Prevention of leakage of radioactive materials from inside the canister except via the vent mechanism.	① As a measure to prevent the spread of contamination, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or a transfer cask and not by the canister.	② The main body of the canister should have a structure whereby the airtightness is maintained by a welded structure, etc.
			③ The integrity of the seal should be maintained against aging due to the corrosion and radiation expected during the transfer period.	-
			④ The integrity of the strength members should be maintained against aging due to the corrosion and radiation expected during the transfer and storage periods.	
		Appropriate reduction in leakage of radioactive materials associated with the release of hydrogen gas from the vent mechanism.	⑤ As a measure to prevent the spread of contamination, the structure should be such that the release of fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the vent mechanism is suppressed.	-
		Appropriate reduction in leakage of radioactive materials even in the event of occurrence of dropping events that must be expected	⑥ The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or transfer cask and not by the canister.	⑦ The main body of the canister should have a structure that does not incur serious damage such as breakage even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$, liquids, and gases are not released.

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-2] Design conditions of the canister for safety requirements (2/3)

Table. Setting up design conditions of the canister for safety requirements (2/3)

Safety functions	Safety function requirements	Canister requirements	Canister design conditions	
			Lid	Main Body
Criticality prevention	Prevention of additional nuclear fission reaction	The shape should be able to prevent criticality.	-	⑧ The structure should be such that the subcriticality of fuel debris is maintained by the geometric shape of the inner diameter of the canister.
			-	⑨ In the case of an array of canisters, the subcriticality should be maintained by retaining the array dimensions using other equipment (metal cask basket, etc.).
			⑩ The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or a transfer cask and not by the canister.	⑪ The structure should be such that the inner diameter of the canister can maintain the geometric shape that can maintain subcriticality even if it receives an impact load from dropping or tumbling. The structure of the main body of the canister should be such that it does not incur serious damage such as breakage, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$, liquids, and gases are not released.
Heat removal	Prevention of abnormal overheating	The canister should be able to maintain the temperature of the fuel debris at the appropriate level.	⑫ The structure should be such that integrity is maintained using the natural heat dissipation of the canister.	
		The design should be such that the internal temperature of the canister does not exceed the permissible temperature even if there is an expected rise in the building temperature.	⑬ The internal temperature of the canister should not exceed the permissible temperature even in the event of loss of external power or other events that must be expected.	

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-2] Design conditions of the canister for safety requirements (3/3)

Table. Setting up design conditions of the canister for safety requirements (3/3)

Safety functions	Safety function requirements	Canister requirements	Canister design conditions	
			Lid	Main Body
Shielding	Prevention of excessive exposure or internal exposure due to radiation	(No requirements)	⑭ The shielding function should be ensured by the building or transfer cask, etc., and not by the canister.	
Prevention of hydrogen explosion	Response to fires and explosions caused by flammable gas generated due to radiolysis of water (response to hazards)	The design should be such that the concentration of hydrogen inside the canister can be maintained below the design value.	⑮ The structure should be such that hydrogen generated by radiolysis of water due to fuel debris is appropriately discharged outside the canister.	
			⑯ The structure should be such that the hydrogen generation by the radiolysis of water due to fuel debris is suppressed.	
Prevention of dust fires	Response to fires caused by the reaction of oxygen and metal dust generated during fuel debris retrieval and cutting (response to hazards)	Conduct studies on measures to prevent ignition due to the fine zirconium powder expected in fuel debris.	⑰ The inside of the canister or cell should have an inert gas atmosphere to prevent ignition.	

[Supplement-3] Design conditions of the canister for handling requirements

Table. Setting up design conditions of the canister for handling requirements

Handling function requirements	Canister requirements	Canister design conditions	
		Lid	Main body
Handleability	The lid can be fastened and opened by remote operation.	(a) The lid structure should allow lid fastening and opening by remote operation.	—
	From the perspective of workability, the lid can be fastened and opened by a simple operation.	(b) The lid structure should allow lid fastening and opening by simple operations, such as turning the lid.	—
	The handling related to other operations such as fuel debris containing, transfer, and storage should be possible.	(c) The canister should have a liftable structure.	
		(d) The structure should enable connection with the (drying facility and) inert gas injection facility, etc.	
		(e) The structure should allow alignment of the lid and the bottom structure of the canister so that stacking is possible during transfer and storage.	
		(f) The size and structure should take into account the workability in the handling flow of canisters.	

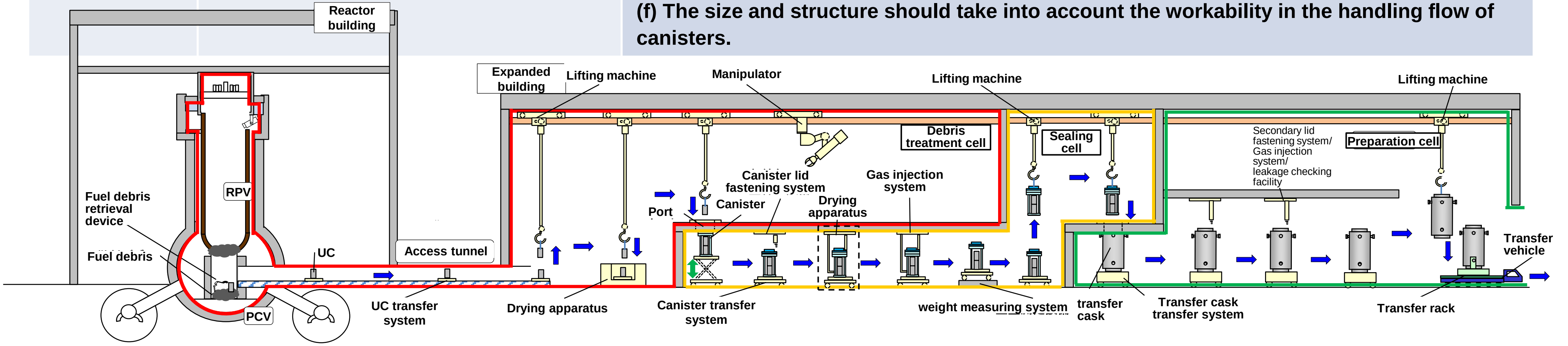


Figure. Canister handling flow plan (Example of side access)

[Supplement-4] Specification plan for the canister (1/15)

Table. Design conditions and specifications for the canister (plan) (1/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Lid	Confinement	⑥	The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)Note 1 passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or transfer cask and not by the canister.	Simple installation structure ・ Integral method-based lid fastening structure (equipped with a stopping mechanism) ・ Lid outer diameter 300 mm (for a canister with inner diameter 220 mm), 500 mm (for a canister with inner diameter 400 mm) Bolt structure ・ Bolt-based lid fastening structure (equipped with a guide pin) ・ Lid outer diameter φ300 mm (for a canister with inner diameter 220 mm), φ500 mm (for a canister with inner diameter 400 mm) [Concepts of specification selection] ・ The structure has a structural strength that does not cause detachment of the lid or serious damage leading to a large amount of leakage and does not create a continuous gap in the seal even when it receives an impact load such as a drop in the vertical position. ・ Two types of remotely-operable structures were selected: a bolt structure that has a proven track record in remote operation of a similar lid, and a simple installation structure that allows the lid to be opened and closed by simple operation (turning of the lid). ・ Considering workability and containing efficiency, the outer diameter of the lid was kept as small as possible, and the size used was such that a canister with inner diameter 220 mm could be contained in a basket with a 310 mm square opening, and a canister with inner diameter 400 mm could be contained in a basket with a 510 mm square opening. ・ The installation of a buffer structure prevents the stored items from shooting up and colliding with the inner surface of the lid, so the lifting of the lid due to the collision need not be considered and the processing time (processing amount) is reduced by using a structure where the amount of fitting required to attach the lid to the body is as small as possible. ・ In the unlikely event such as bolt galling, it will be cut from the side of the lid with a special tool (assuming a disk-shaped cutter), and to reduce the amount of cutting of the lid, it was decided to place the bolt as farther outside as possible.
	Criticality prevention	⑩	The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)Note 1 passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or transfer cask and not by the canister.	
	Handleability	(a)	The lid structure should allow lid fastening and opening by remote operation.	
		(b)	The lid structure should allow lid fastening and opening by simple operations, such as turning the lid.	
		(f)	The size and structure should take into account the workability in the handling flow of canisters.	

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-4] Specification plan for the canister (2/15)

Table. Design conditions and specifications for the canister (plan) (2/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Vent mechanism	Confinement	⑤	As a measure for preventing the spread of contamination, the structure should be such that the release of fuel debris pieces (solid)[Note 1] passing through the vent mechanism is suppressed.	・ Opening/ closing method: Coupler method (normally-open coupler) ・ Coupler size: 1 inch type (Minimum cross-sectional area: Approx. 490 mm^2) [Concepts of specification selection] ・ The structure is such that the release of fuel debris pieces (particle size 0.1 mm or more) is suppressed by a filter installed in the vent mechanism. ・ A specification (coupler size) that keeps the hydrogen concentration inside the canister below the lower explosion limit of 4 vol.% was selected, based on the release of hydrogen evaluated using the diffusion evaluation formula considering the effect of the filter and coupler on the vent flow path, for the amount of hydrogen generated based on actual measurements in the presence of water. ・ Based on the evaluation of the risk of increase in hydrogen concentration during the vent opening and closing operation when handling canisters, a coupler with a normally-open vent was selected to reduce the risk. ・ The inert gas injection facility was connected with one vent mechanism coupler creating a structure that allows gas replacement inside the canister by alternately performing air supply and exhaust.
	Prevention of hydrogen explosion	⑮	The structure should be such that hydrogen generated by radiolysis of water due to fuel debris is appropriately discharged outside the canister.	
	Handleability	(d)	The structure should enable connection with the (drying facility and) inert gas injection facility, etc.	
Air supply mechanism	Handleability	(d)	The structure should enable connection with the (drying facility and) inert gas injection facility, etc.	・ Drying fuel debris in a unit can: Air supply mechanism absent ・ Drying fuel debris in a canister: Air supply mechanism present (Two connection ports for air supply and exhaust) [Concepts of specification selection] ・ The heated vacuum drying method and the warm air heated drying method are being studied as the methods of drying fuel debris, and the unit-can-state and canister-state are being studied as the drying states, but the method has not been selected. Therefore, structures with and without air supply mechanism, which can handle either of the methods or states, were studied. ・ When drying the fuel debris in the unit can, the unit can is placed in a drying chamber to implement the drying process, so the air supply mechanism need not be installed. In the case of canister drying (heated vacuum drying), by alternating the air supply and exhaust operations with the vent mechanism (one connection port), it may be possible to eliminate the need to install an air supply mechanism. ・ In the case of canister drying (warm air heated drying), since the vent mechanism (one connection port) cannot be used, it is necessary to install an air supply mechanism in the canister.

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-4] Specification plan for the canister (3/15)

Table. Design conditions and specifications for the canister (plan) (3/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Body	Confinement	②	The main body of the canister should have a structure whereby the airtightness is maintained by a welded structure, etc.	・ Inner diameter: 220 mm, 400 mm ・ Plate thickness: 10 mm ・ Internal height: 840 mm (for a canister with inner diameter 220 mm), 845 mm (for a canister with inner diameter 400 mm) ・Welded structure: Butt-joint full penetration weld [Concepts of specification selection] ・Temporarily considered equivalent to a Class 3 vessel, the structure of the welded part was adopted in accordance with JSME “Design and Construction Standard PVD-4000 Manufacturing of vessels". ・ Since the wall thickness of TMI-2 canisters was ¼ inch (6.35 mm), the canister wall thickness was taken as 10 mm to be on the safe side. The structure is strong enough not to cause serious damage leading to a large amount of leakage even if it receives an impact load such as a drop in the vertical position. In addition, a hub (tapered part) was installed at the joint between the body and flange to ease stress in the event of a lid collision. The shape of the hub (tapered part) conformed to JSME “Design and Construction Standards PVD-3000 Class 3 Vessel Design”. ・ The inner diameter was set to 220 mm, which has been confirmed by subcriticality evaluation to be able to maintain subcriticality regardless of the fuel debris particle size and moisture content, and to 400 mm temporarily set in consideration of expansion of the inner diameter to improve workability. ・ The array size was temporarily set to 330 mm or more, which has been confirmed to be capable of maintaining subcriticality based on the results of criticality evaluation for canister inner diameter of 220 mm with uranium enrichment 4.9 wt%, water volume 20%, and finite array (10 x 10). ・ The structure is such that even if it receives an impact load of a drop in the vertical position, a canister of inner diameter 220 mm is deformed within the range that can maintain subcriticality due to the installation of a buffer structure. ・ The internal height of the canister was set to 840 mm (for a canister with inner diameter 220 mm) and 845 mm (for a canister with inner diameter 400 mm), allowing space above the unit cans, taking into account the catalyst case thickness (20 mm (temporarily set)) and height of two unit cans it will store (400 mm per can), in addition to considering a margin on the thermal expansion of the unit cans, the manufacturing tolerance, and the height when the unit cans are stored at an angle.
		⑦	The structure of the main body of the canister should be such that serious damage such as breakage does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)Note 1, liquids, and gases are not released.	
	Criticality prevention	⑧	The structure should be such that the subcriticality of fuel debris is maintained by the geometric shape of the inner diameter of the canister.	
		⑨	In the case of an array of canisters, the subcriticality should be maintained by retaining the array dimensions using other equipment (metal cask basket, etc.).	
		⑪	The structure should be such that the inner diameter of the canister can maintain the geometric shape that can maintain subcriticality even if it receives an impact load from dropping or tumbling. The structure of the main body of the canister should be such that serious damage such as breakage does not occur, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)Note 1, liquids, and gases are not released.	
	Handleability	(f)	The size and structure should take into account the workability in the handling flow of canisters.	

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-4] Specification plan for the canister (4/15)

Table. Design conditions and specifications for the canister (plan) (4/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Heat removal structure	**Heat removal**	⑫	The structure should be able to maintain integrity using the natural heat dissipation of the canister.	・ No heat removal structure (cooling fin, etc.) [Concepts of specification selection] ・ As a result of an evaluation conducted in a heat removal study in FY2014, assuming the handling of heat removal in the air, it was confirmed that when the block-like fuel debris with the highest burnup was placed at a filling rate of 50%, the fuel debris limit temperature of 300ºC, set with reference to TMI-2, was not exceeded, so it was decided not to provide a special heat removal structure (fins, etc. to improve heat removal). ・ The temperature environment around the canister would be ensured through heat removal by other equipment (transfer cask/ storage cask basket, cooling fins, etc.) and air conditioning in the facility, and it was decided that the canister would not be provided with a special heat removal structure (fins, etc. to improve heat removal).
		⑬	The internal temperature of the canister should not exceed the permissible temperature even in the event of loss of external power or other events that must be expected.	
Shielding structure	**Shielding**	⑭	The shielding function should be ensured by the building or transfer cask and not by the canister.	・ No shielding structure [Concepts of specification selection] ・ In order to avoid a decrease in workability due to an increase in the weight of the canister and a decrease in handleability due to the installation of a shielding structure, no shielding structure was installed on the canister.
Inert atmosphere	**Prevention of dust fires**	⑰	The inside of the canister or cell should have an inert gas atmosphere to prevent ignition.	・ Installation of a coupler (shared with the coupler of the vent mechanism) that can be connected to the inert gas injection facility [Concepts of specification selection] ・ The measures to prevent ignition by fine zirconium powder have not been decided, but assuming that the inside of the canister has an inert gas atmosphere to prevent ignition, a coupler (shared with the coupler of the vent mechanism) is provided for the canister so that it can be connected to the gas injection facility.

[Supplement-4] Specification plan for the canister (5/15)

Table. Design conditions and specifications for the canister (plan) (5/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Suspending part	Handleability	(c)	The structure of the canister should be such that it can be lifted.	・Structure to lift the canister by gripping the lifting groove provided inside the lid (Note that if the storage space is a square prism (or unrestricted), the canister can also be lifted by gripping the body flange) [Concepts of specification selection] ・ By providing a lifting groove inside the lid and making the hanging jig of the canister suspending device smaller than the outer diameter of the canister lid, the structure allows lifting without being affected by the shape of the storage space (square prism, cylinder, plate (drilled hole)). ・ The structure is such that by not installing the suspending part that was installed in the center of the upper end plane of the lid, the event of entry of the buffer structure into the suspending part, which was seen in the FY 2018 feasibility verification test for canister lid structure, does not occur.
Sealing method for canisters and the port between cells	Handleability	(f)	The size and structure should take into account the workability in the handling flow of canisters.	・ Structure that can be sealed by pressing against the seal installed in the port between cells by using a planar structure for the upper end of the canister body ・ Structure in which the inner lid (with filter) is installed on the canister body [Concepts of specification selection] ・ As a method of preventing contamination as much as possible at the area boundary between cells in the handling flow of canisters, the structure is such that the upper end plane of the canister body can be pressed against the seal of the port between cells to seal it. ・ As a method of preventing contamination as much as possible during the handling of canisters from the port between cells to lid fastening, the canister body was installed with an inner lid. Note that the inner lid was provided with a filter on par with the vent mechanism for hydrogen venting.

[Supplement-4] Specification plan for the canister (6/15)

Table. Design conditions and specifications for the canister (plan) (6/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Filter	Confinement	⑤	As a measure for preventing the spread of contamination, the structure should be able to prevent the release of fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the vent mechanism.	・ Mesh diameter: 0.3 μm (suitable for HEPA) ・ Type: Wire mesh type ・ Material : SUS316 [Concepts of specification] ・ While selecting the filter specifications, the requirements for safety functions were organized and set as a design policy plan for the filter. (1) The particle size of the fuel debris to be handled in a canister has been specified as 0.1 mm or more, so the mesh diameter was set to less than 0.1 mm. (2) The mesh diameter should be such that the hydrogen generated inside the canister can be released appropriately. (3) From the viewpoint of fire resistance, heat resistance, and aging of material, the filter material shall be the same material as the canister. ・ From the above design policy plan, release of hydrogen was evaluated based on the hydrogen diffusion evaluation formula with the minimum mesh diameter assumed currently (0.3μm (suitable), and it was confirmed that the concentration of hydrogen inside the canister could be kept at the lower explosion limit of 4vol.% or less, so 0.3 μm was selected as the mesh diameter for the filter. ・ The wire mesh type and the sintered metal powder type were the two types of filters considered, but the wire mesh type was selected in consideration of the results of BWR filter vents, etc. ・ The material used for the filter was SUS316, which is the same material as that of the canister. ・ As measures against clogging of the filter, the surface area of the filter was increased by making the diameter of the filter as large as possible, and the structure was made less susceptible to clogging. In the unlikely event that the filter becomes clogged, it is assumed that the filter will be replaced by replacing the lid.

[Supplement-4] Specification plan for the canister (7/15)

Table. Design conditions and specifications for the canister (plan) (7/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Seal	Confinement	③	The integrity of the seal should be maintained against aging due to the corrosion and radiation expected during the transfer period.	・ Elastomer gasket (EPDM: Ethylene Propylene Diene monomer) [Concepts of specification selection] ・ Since the storage facility ensures the confinement function during storage, the confinement function during storage is not expected for canisters, for which it is difficult to maintain and confirm sealing during storage (regular leak inspection, etc.). Therefore, elastomer gasket (EPDM) was adopted prioritizing storage efficiency (minimization of outer diameter of lid), lid fastening workability, and applicability to a simple installation structure. ・ The radiation resistance is approx. two years as per a rough evaluation when all the fuel debris in the canister was temporarily set to UO_2 with fuel debris burnup 41 (GWd/t), and there was no problem with durability during transfer and handling (assumed to be about 7 days). ・ During storage, which is estimated to be about 50 years, the confinement function may be lost due to aging, but even if the confinement function is lost, it is unlikely that a large amount of fuel debris pieces will be released from the seal during stationary storage, and even if they are released, they will remain in the storage cask (in the case of the metal cask method) that ensures the confinement function, so it will not impair the confinement function as a storage facility. ・ As a means for ensuring the confinement function during storage (and after storage), adoption of a metal gasket may be considered, but it has the following issues and was not adopted in the current design: (i) Cannot be applied to the simple installation lid structure. (ii) Can be applied to a bolt lid structure, but since a large fastening force is required, the lid outer diameter/ bolt diameter becomes large, which increases the weight of the canister and reduces the storage efficiency. (iii) Compared to the elastomer gasket, careful consideration is required for cleaning of the sealing surface (prevention of scratches and management of foreign material intrusion) and management of bolt fastening work.

[Supplement-4] Specification plan for the canister (8/15)

Table. Design conditions and specifications for the canister (plan) (8/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Seal (continued)	Confinement	①	As a measure to prevent the spread of contamination, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or a transfer cask and not by the canister.	<u>Simple installation structure</u> ・ Outer cylindrical surface: Elastomer (EPDM) O ring ・ Upper end plane (O ring is installed on the lid): Elastomer (EPDM) O ring [Concepts of specification selection] ・ From the lid structure, the position for installing the O-ring as a confinement boundary can be considered to be the upper end plane and the outer cylindrical surface of the canister, but if the O ring is installed on the upper end plane, it is difficult to manage the O-ring squeeze rate due to the structure of the lid, so the O ring was installed on the outer cylindrical surface setting it as the confinement boundary. ・ Due to the structure of the lid, the simple installation structure has a relatively large gap between the mating parts of the lid and the body, and when there is an impact load such as that caused by tumbling, there may be a momentary gap in the outer cylindrical surface seal, so an O ring is also installed on the upper end plane to suppress momentary leakage. ・ The O ring on the upper end plane was installed on the lid side so that the O ring could be replaced in light of the measures to be taken when the seal can no longer function due to the effects of aging, etc. <u>Bolt structure</u> ・Upper end plane (O ring is installed on the lid): Elastomer (EPDM) O ring [Concepts of specification selection] ・ Since the squeeze rate can be controlled by fastening bolts and the target size of the outer diameter of the lid is restricted, the O-ring on the upper end plane of the canister body was set as the confinement boundary. ・ The O ring on the upper end plane was installed on the lid side so that the O ring could be replaced in light of the measures to be taken when the seal can no longer function due to the effects of aging, etc.
		⑥	The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or a transfer cask and not by the canister.	
	Criticality prevention	⑩	The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)$^{\text{Note 1}}$ passing through the gaps between the canister body and lid is not released. Note that liquid and gas confinement should be ensured by a cell or a transfer cask and not by the canister.	

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-4] Specification plan for the canister (9/15)

Table. Design conditions and specifications for the canister (plan) (9/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Buffer structure	**Confinement**	⑥	The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)[Note 1] passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or transfer cask and not by the canister.	・DOE (skirt) type [Concepts of specification selection] ・ A buffer structure was installed to deal with events such as the event that occurred in the FY 2018 feasibility verification test for canister lid structure in which the simple installation structure lid could not be opened due to the stored items shooting up and colliding with the inner surface of the lid when the canister fell, and in order to reduce the deformation of the body of the lower canister in the event of a canister dropping on top of another canister. ・ The buffer structures being considered included the existing TMI (concave) type, Paks (doughnut) type, and DOE (skirt) type. The DOE (skirt) type was selected in consideration of its simple structure, good manufacturability, ease of canister stacking and ease in provision of holes for preventing retention of hydrogen gas. ・ Although there are difficulties in decontamination work by wiping and surface contamination density measurement by smearing, it is assumed that structural measures (such as not having an uneven shape on the inner surface) and measures to prevent contamination during handling (such as placing the lid on openings and covering) can be used to deal with these issues. ・ In order to have a structure that prevents deformation of the buffer structure when handling the canister, the lower end ring is installed as reinforcement.
		⑦	The structure of the main body of the canister should be such that serious damage such as breakage does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of preventing the spread of contamination, the structure should be such that fuel debris pieces (solid)[Note 1], liquids, and gases are not released.	
	Criticality prevention	⑩	The structure should be such that serious damage such as detachment or breakage of the canister lid does not occur even if it receives an impact load from dropping or tumbling, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)[Note 1] passing through the gaps between the canister body and lid are not released. Note that liquid and gas confinement should be ensured by a cell or transfer cask and not by the canister.	
		⑪	The structure should be such that the inner diameter of the canister can maintain the geometric shape that can maintain subcriticality even if it receives an impact load from dropping or tumbling. The structure of the main body of the canister should be such that serious damage such as breakage does not occur, and from the perspective of maintaining subcriticality, the structure should be such that fuel debris pieces (solid)[Note 1], liquids, and gases are not released.	
	Handleability	(e)	The structure should allow alignment of the lid and the bottom structure of the canister so that stacking is possible during transfer and storage.	
		(f)	The size and structure should take into account the workability in the handling flow of canisters.	

Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected through the liquid phase system, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

[Supplement-4] Specification plan for the canister (10/15)

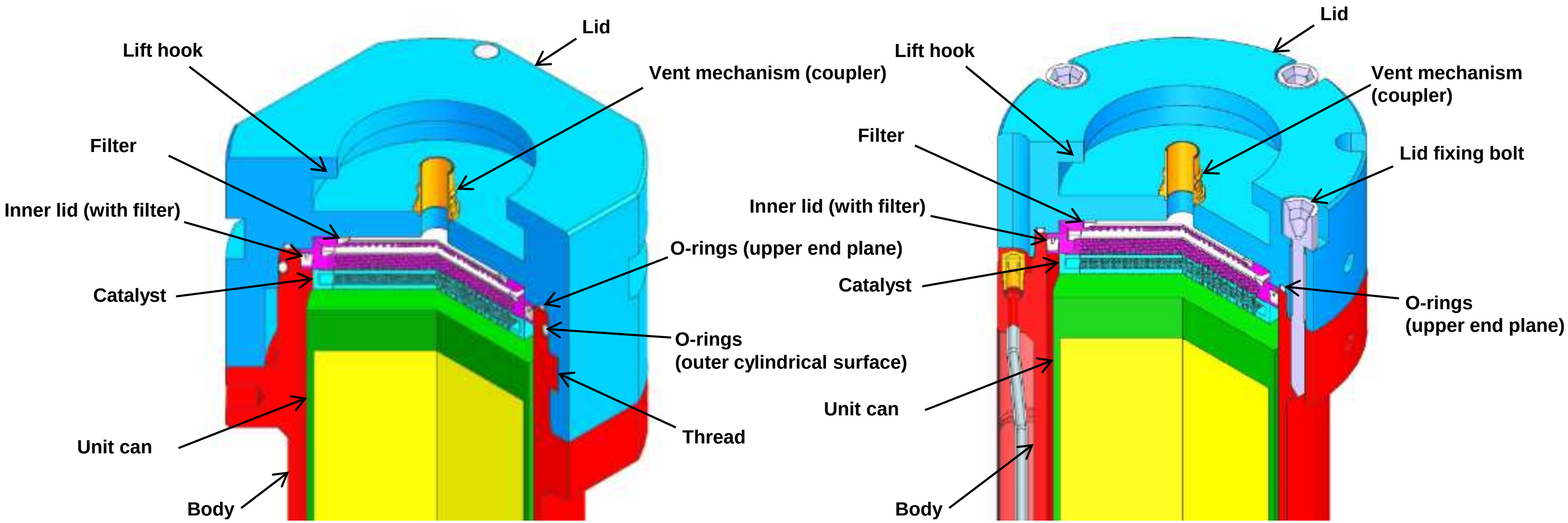
Table. Design conditions and specifications for the canister (plan) (10/10)

Part	Safety functions and functional requirements	Design conditions		Canister specifications (plan)
Catalyst	Prevention of hydrogen explosion	⑯	The structure should be able to prevent the hydrogen generation by the radiolysis of water due to fuel debris.	・ Catalyst case (disk-shaped, 20 mm thick) is installed on the bottom of the inner lid [Approach to selection of specifications] ・ As a measure to prevent hydrogen generation, the effectiveness, required amount, installation position, etc. of the catalyst is being studied separately, but as a provisional specification, a catalyst case (disk-shaped, 20 mm thick) is installed on the bottom of the inner lid.
Material	Confinement	④	The integrity of the strength members should be maintained against aging due to the corrosion and radiation expected during the transfer and storage periods.	・ SUS316L [Concepts of specification selection] ・ At present, it is difficult to predict the environment inside the canister, but in general, austenite stainless steel was selected as a material that has excellent corrosion resistance and is relatively easy to procure and process. Of this, SUS316L was selected in consideration of its superiority in SCC resistance control (chloride ion concentration, humidity control) over SUS304L. In order to avoid SCC sensitization due to welding, low carbon steel material (L material) was used. ・ Scenarios were created taking into account the viewpoints of operation and design, and based on the evaluation of crevice corrosion and stress corrosion cracking on the presumption of operation in dry conditions, it is projected that the material can be adopted.

【Supplement-4】Specification plan for the canister (11/15)

1) Lid

- The following two types of lids were designed to make its opening and closing possible by remote control: one with thread provided on the lid so that its opening and closing can be done by turning, called the “simple installation structure” in this report; and the other that uses bolts to fix the lid, which has a lot of track records in its opening and closing operation by remote control, such as the one used at TMI-2, called “bolt structure” in this report.
- The lid was designed with a structure strong enough to withstand an impact load in the event of falling and crashing onto the floor, by any possibility, maintain its sealing performance by protecting the lid and sealing structure, and prevent continuous leakage through the sealing part.



Simple mounting structure
(Inner diameter of 220 mm and without air supply mechanism)

Bolt structure
(Inner diameter of 220 mm and with air supply mechanism)

Figure: Schematic drawing of proposed lid structures*1

Note 1: In the cross-sectional view, the lid, body, vent mechanism, filter, catalyst, O-ring, etc. are color coded for identification of the components.

【Supplement-4】Specification plan for the canister (12/15)

2) Body

- The following two types of canisters were designed depending on what to be prioritized: one with its body inner diameter being 220 mm to achieve a geometric shape capable to maintain sub-criticality regardless of the size and moisture content of fuel debris, and the other that has the body with an inner diameter of 400 mm to increase the capacity for better operation productivity.
- The thickness of the body was determined to be 10 mm by reference to the canister used at TMI-2, whose thickness was 1/4 in. (6.35), and by imposing additional strength requirement that the canister must withstand an impact load in the event of falling and crashing onto the floor, by any possibility, maintain its sealing performance and prevent a large amount of leak by protecting the lid and sealing structure, and protect its body (inner diameter of 220 mm) from deformation at a level where its ability to maintain sub-criticality is lost.
- The inner space of the body was designed so that it could hold two unit cans (outer diameter: 210 mm, height: 400 mm) in a vertically stacked arrangement.
- The joints between the body and the flange and between the body and the bottom plate were designed with a tapered shape so that they can reduce stress caused by the impact load in the event of falling and crashing onto the floor by any possibility.

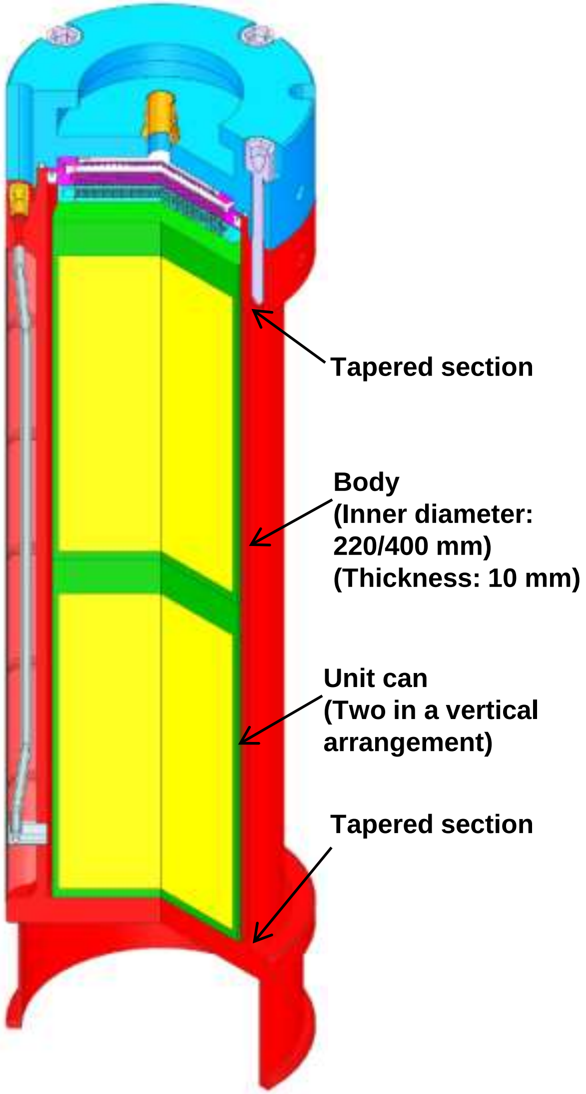


Figure: Schematic drawing of proposed canister structure[*1]

(Design with the bolt structure, an inner diameter of 220 mm, and air supply mechanism)

Note 1: In the cross-sectional view, the components are color coded for identification.

【Supplement-4】Specification plan for the canister (13/15)

3) Sealing (1/2)

- The canister needs to maintain its confinement performance during its transfer and handling period (assumed to be approximately 7 days). On the other hand, there is no requirement in its confinement performance for the period of storage (assumed to be approximately 50 years). (The storage facility is responsible for the confinement function.)
- Based on this requirement, an elastomer gasket (EPDM) was adopted among the sealing devices that provide a performance and durability to ensure reliable sealing during the transfer and handling period (assumed to be approximately 7 days), focusing on the storing efficiency (the outer diameter of the lid can be minimized), easiness of lid fastening operation, and applicability to the simple installation structure.
- There is a risk of the canister losing its confinement performance due to the degradation of the sealing device with time. (The storage period is assumed to be approximately 50 years.) However, the spread of a large amount of fuel debris from the stationary stored canister into air through its sealing part is not likely to occur. Even if the spread of fuel debris from the canister occurs, it will remain in the storage cask (when it is made of metal) and will not cause a problem in the confinement function of the storage facility.
- A metal gasket would be an option to improve the confinement performance of the canister during storage period (and after storage). However, it was not adopted as a sealing device for the canister used in the structure verification test for the following reasons. Meanwhile, a metal gasket will remain one of options (for the bolt structure) in the future.

  (i) It is not applicable to the simple installation structure.

  (ii) It is applicable to the bold structure if a larger fastening force can be applied to the lid compared to an elastomer gasket. However, it will require larger dimensions of the lid (outer diameter) and bolts and result in an increase in the canister weight and a decrease in the storing efficiency.

  (iii) The sealing surface needs to be much cleaner than that for an elastomers gasket (i.e., stricter control is required on scratches and foreign materials), and bolt tightening torque must be precisely controlled.

【Supplement-4】Specification plan for the canister (14/15)

3) Sealing (2/2)

Elastomer gasket was adopted.
It was selected from the sealing devices that met the criteria of the confinement performance and durability and adopted by focusing on the storing efficiency (the outer diameter of the lid can be minimized), easiness of lid fastening operation, and applicability to the simple installation structure.

Table: Comparison of sealing

	Elastomer gasket	Metal gasket	Metal touch seal	Welding
Confinement performance	· Good for short-term confinement	· Good for long-term confinement	· Difficult to ensure confinement performance for both short- and long-term confinement	· Good for long-term confinement
Long-term integrity of the sealing material/surface	· Good for transfer period but difficult to ensure for storage period	· Good for both transfer and storage periods	· No problem because of metal sealing surface	· Good for both transfer and storage periods
Radiation resistance	· Good for about 2 years*1 with the maximum radiation dose rate of 30 Gy/h, which is estimated at the sealing part of the canister during transport and storage	· No degradation will occur with the maximum radiation dose rate of 30 Gy/h, which is estimated at the sealing part of the canister during transport and storage.	· No degradation will occur with the maximum radiation dose rate of 30 Gy/h, which is estimated at the sealing part of the canister during transport and storage.	· No degradation will occur with the maximum radiation dose rate of 30 Gy/h, which is estimated at the sealing part of the canister during transport and storage.
Thermal resistance	· No degradation will occur in the temperature range that is estimated at the sealing part of the canister during transport and storage (max. 200°C*2).	· No degradation will occur in the temperature range that is estimated at the sealing part of the canister during transport and storage (max. 200°C*2).	· No degradation will occur in the temperature range that is estimated at the sealing part of the canister during transport and storage (max. 200°C*2).	· No degradation will occur in the temperature range that is estimated at the sealing part of the canister during transport and storage (max. 200°C*2).
Handling easiness	· Fairly good · A certain compressive force (less than metal gasket) needs to be provided.	· More careful tightening is required than elastomer gasket. · A certain compressive force (larger than elastomer gasket) needs to be provided.	· Fairly good	· Difficult to perform welding in the reactor building and expanded building
Possibility of opening and closing the canister after it has been sealed	· Possible; the gasket may need to be replaced depending on its condition.	· Possible; the metal gasket needs to be replaced.	· Possible, but difficult to obtain the same confinement performance as that before opening	· Possible, but the canister cannot be used again.
Impact on the lid design	· Applicable to the simple installation structure; attention must be paid to the shear strength of the gasket if the opening/closing of the lid involves a sliding action.	· Not applicable to the simple installation structure · The lid needs to have a larger outer diameter (than that with an elastomer gasket).	· Not applicable to the simple installation structure	· There will not be many restrictions in the lid design if overpack welding is used.

Note 1: The maximum radiation dose rate was derived based on a burnup of 41 GWd/t, which was cited from the report of the Japan Atomic Energy Agency, JAEA-Data/Code. 2012-18 (September 2012), "The Estimation of the Burnup of Fuel Debris Based on the Burnup of the Irradiated 6th Batch Fuel and in Consideration of Its Irradiation History as Part of the Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant" (Nishihara, K., Iwamoto, H. and Suyama), and on the assumption that a cooling period would be 10 years and fuel debris in the canister be all UO_2. If a burnup of 26 GWd/t, the average burnup of fuel in the reactor, and a cooling period of 10 years are used to set the maximum radiation dose rate, the life of the elastomer gasket is estimated to be approximately 5 years.

Note 2: The maximum temperature of 200° C was set based on the result of the heat removal analysis in FY2014. The analysis estimated that the center of fuel debris would reach 209° C and approximately 90° C on the body when the fuel debris in the canister has the maximum burnup of 41 GWd/t and the fuel debris filling rate of the canister is 30%.

【Supplement-4】Specification plan for the canister (15/15)

4) Vent mechanism

- A coupler with a size of 1 in. was selected to achieve the estimated hydrogen concentration in the canister below its lower explosive limit of 4 vol%.[*1] The hydrogen concentration in the canister was estimated using the same diffusion equation as the one used at TMI-2 and taking account of components in the vent pipe system, such as a coupler and filter.
- The following three types of estimates and measurements could be used as a hydrogen generation rate for the estimation of hydrogen concentration in the canister, and it was decided to use the second one ② based on the plan to dry fuel debris (to a water content of 0.1 wt.% as a target), which allows the assumption that the hydrogen generation rate could be reduced to below the actual measurement in the test with spent fuel submerged in water.

Condition ①: Estimate by the diffusion equation used at TMI-2 in 2018 (particle transport calculation); 1.3×10^{-16} (L/h/Bq)

Condition ②: Measurements in the hydrogen generation tests with spent fuel in FY2018 with margins taking into consideration measurement error and fluctuation：1.2×10^{-17}［L/h/Bq］

Condition ③: Measurements in the hydrogen generation tests with spent fuel in FY2018; 5.1×10^{-18} (L/h/Bq)

- The size of the coupler of the ø 220 mm canister, which is expected to be primarily used in the initial phase of the fuel debris removal operation at the 1F, was determined taking into consideration uncertainties, such as filter clogging, so that it can keep the hydrogen concentration in the canister sufficiently lower than its lower explosive limit of 4 vol%.

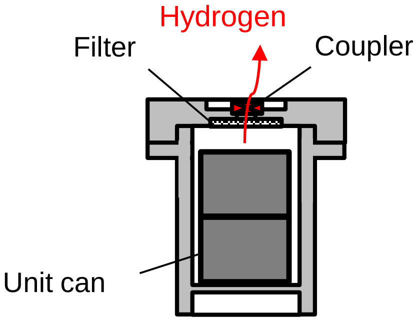
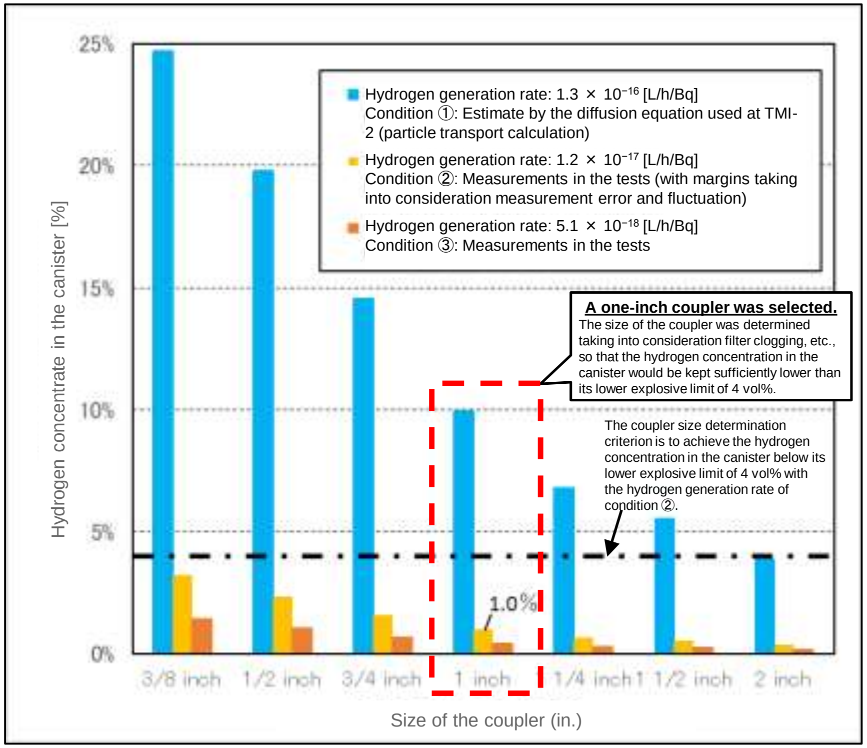


Figure: Diffusion evaluation model



A one-inch coupler was selected. The size of the coupler was determined taking into consideration filter clogging, etc., so that the hydrogen concentration in the canister would be kept sufficiently lower than its lower explosive limit of 4 vol%.

The coupler size determination criterion is to achieve the hydrogen concentration in the canister below its lower explosive limit of 4 vol% with the hydrogen generation rate of condition ②.

Figure: Estimate of hydrogen concentration in the ø 220 mm canister by the diffusion equation

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Note 1: **The current coupler size of 1 in. is considered to be the maximum based on the current lid design and taking into consideration the connection and disconnection of the sealing cap by remote control. However, the size can be enlarged to approximately 2 in. when the design is changed in the future.**

【Supplement-5】Methodology used for the collection of catalyst performance data (1/2)

(Supplement) Mass transfer coefficient of gas film and how it affects the overall reaction rate constant

Steps of the transfer and reaction of hydrogen near the catalyst

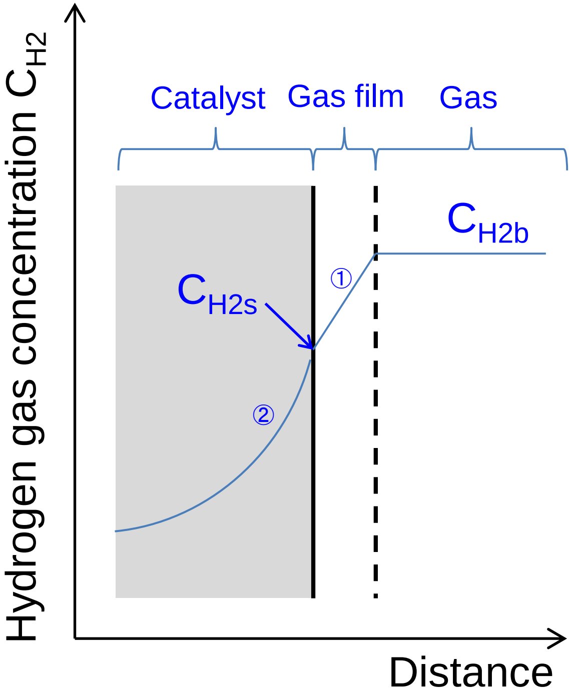


Figure: Model of the transfer and reaction of hydrogen near the catalyst[*1]

- ○ The reaction rate of a catalytic hydrogen recombination is determined by the following two steps:
  ① Mass transfer from the fluid to the surface of the catalyst
  ② Reaction on the catalyst
- ○ How those two steps ① and ② affect the overall reaction rate depends on the conditions of the reaction, and one with a slower rate will limit it.
- ○ The mass transfer rate from the fluid to the surface of the catalyst is expressed by the mass transfer rate of film (mass transfer rate of gas film).
  $r_G = k_G(C_{H2b}-C_{H2s})$
- ○ The reaction rate on the surface of the catalyst is expressed by the following equation:
  $r_R = k_R C_{H2s}$
- ○ Accordingly, the overall reaction rate constant K is expressed by the following equation:

$$\frac{1}{K} = \frac{1}{k_R} + \frac{1}{k_G}$$

K: Overall reaction rate constant
k_R: Catalyst reaction rate constant
k_G: Mass transfer coefficient of gas film

Note 1: The illustration of the model was created by reference to the figure in the page 183 of Kenji Hashimoto, “Hannou Kougaku” (Chemical Reaction Engineering) published by Baifukan Co., Ltd.

【Supplement-5】Methodology used for the collection of catalyst performance data (2/2)

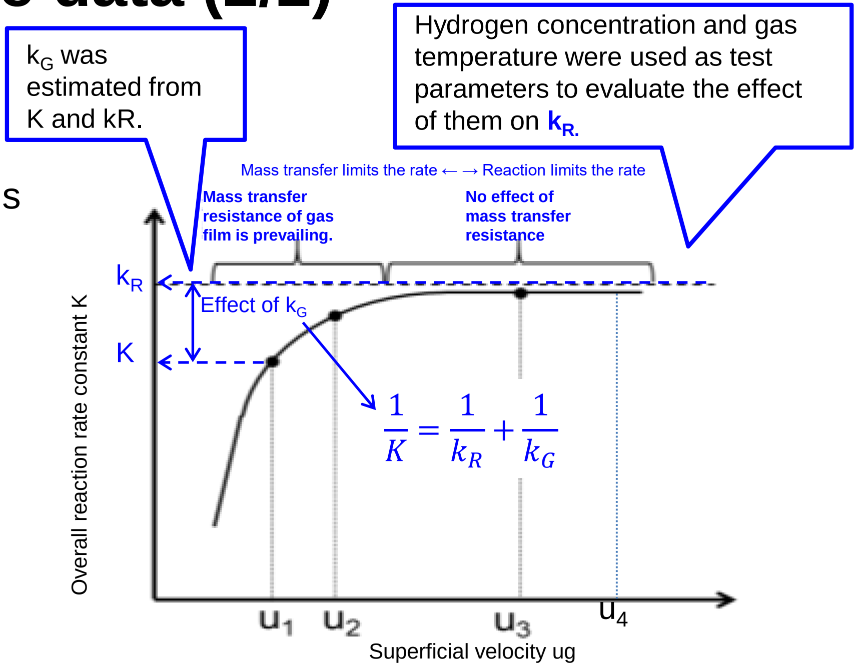
(Supplement) Methodology used for the collection of catalyst performance data

As described above, the reaction rate of the hydrogen recombination is expressed by the equation below:

Reaction rate equation

For the first order reaction: $-r = KC_{H2}$

r: reaction rate, C_{H2}: hydrogen concentration, and
C_{O2}: oxygen concentration
K: Overall reaction rate constant



k_G was estimated from K and kR.

Hydrogen concentration and gas temperature were used as test parameters to evaluate the effect of them on k_R.

(k_R: catalytic reaction rate constant, k_G: mass transfer coefficient of gas film)

Figure: Methodology for reaction rate constant estimate

- ✓ The equation above can be used when other reaction conditions are the same, such as temperature and gas flow rate. An overall reaction rate constant (K) depends on the reaction conditions. Therefore, K must be measured with different conditions that cover those that actually occur in the reaction under discussion. Especially, the gas flow rate is also important with respect to gas film formed on the surface of the catalyst.
- ✓ Thus, it was necessary to estimate the value of K at different gas flow rates. For this purpose, gas flow-type reaction rate measurement tests were conducted in which the effect of the reaction rate constant of the catalytic reaction (k_R: catalytic reaction rate constant) and the mass transfer (k_G: mass transfer coefficient of gas film) on K were able to be evaluated independently.

$$\frac{1}{K} = \frac{1}{k_R} + \frac{1}{k_G}$$

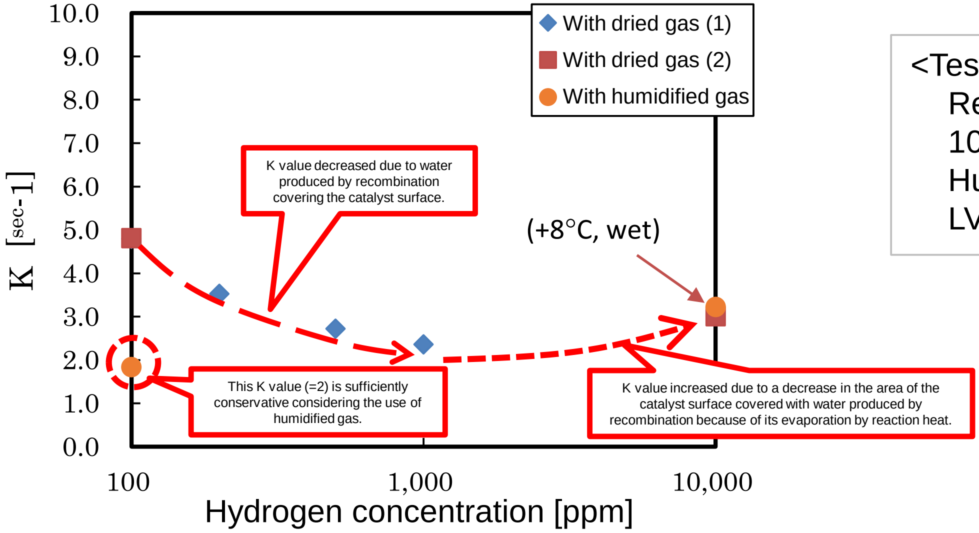
(K: overall reaction rate constant, k_R: catalytic reaction rate constant, k_G: mass transfer coefficient of gas film)

【Supplement-6】 Organized results of catalyst performance evaluation tests (1/7)

①Influence of humidity

- The reaction rate constant K decreased with the increase of the hydrogen concentration when dried gas was used. The reaction rate turned to an increasing trend at a hydrogen concentration of 10,000 ppm and more.
  It can be inferred that the effect of temperature rise due to reaction heat cancelled or even surpassed the effect of water produced by recombination reaction.
- Similarly, the reaction rate turned to an increasing trend at a hydrogen concentration of 10,000 ppm when humidified gas (almost 100% RH) was used.

⇒ A reaction rate constant K measured in the condition with a hydrogen concentration of 100 ppm and humidified gas, which was equal to 2, was adopted as the most conservative condition for the study of the catalyst position with respect to hydrogen concentration and humidity.



K value decreased due to water produced by recombination covering the catalyst surface.

This K value (=2) is sufficiently conservative considering the use of humidified gas.

K value increased due to a decrease in the area of the catalyst surface covered with water produced by recombination because of its evaporation by reaction heat.

Figure: Effect of hydrogen concentration

<Test condition>
Reaction vessel: gas flow-type, catalyst: TKK-H1P, temperature: 10°C, H2 concentration: 100–10,000 ppm, ratio of O2/H2: 0.5
Humidification: No/Yes
LV: 0.14 m/s, SV: 50,000/h, thickness of catalyst bed: 10 mm

【Supplement-6】 Organized results of catalyst performance evaluation tests (2/7)

② Influence of temperature

- The overall reaction rate constant increased with the increase of temperature T.
  lnK shows a linear relation with 1000/T, which means that K follows the Arrhenius equation and thus the activation energy is constant.
  The temperature dependency of K in the range of 10° C–50° C is the temperature dependency of the catalytic reaction, which suggests that the effect of other factors on K, such as mass transfer and parameters that affect them, is relative.
- Based on this result, it was decided to use 10° C as the temperature in the canister to study the suitable position of the catalyst bed in it as it was the lowest possible temperature and the most conservative temperature with respect to the catalyst performance.

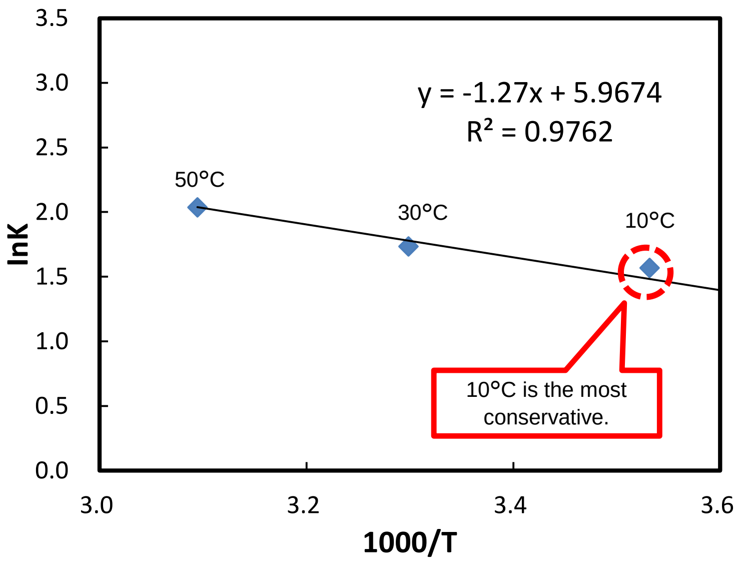


Figure: Influence of temperature

<Test condition>

Reaction vessel: gas flow-type, catalyst: TKK-H1P, temperature: 10°C–50°C, H_2 concentration: 100 ppm, O_2 concentration: 50 ppm, no humidification

LV: 0.14 m/s, SV: 50,000/h, thickness of catalyst bed: 10 mm

Arrhenius equation

$$k = Ae^{\left(-\frac{Ea}{RT}\right)}$$

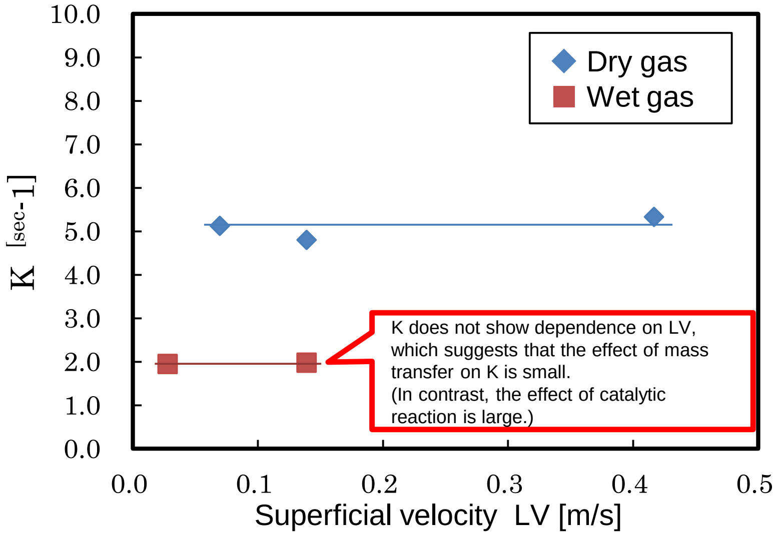
$$lnk = lnA - \frac{Ea}{RT}$$

(A: frequency factor (s^{-1}), Ea: activation energy (J mol^{-1}),
R: gas constant=8.314 (J K−1 mol−1), and T: temperature (in K))
* Activation energy Ea = 1.27 × 8.314 × 1,000 = 10,600 J mol^{-1}

【Supplement-6】 Organized results of catalyst performance evaluation tests (3/7)

③ Influence of superficial velocity LV (1/2)

- The influence of LV on the overall reaction rate constant K is small, which suggests that the effect of mass transfer is relatively small and chemical reaction is the rate-limiting step.
- K can be estimated using a mass transfer coefficient with an LV of 0 m/s in the canister. (K is 1.96 s^{-1} with an LV of 0.03–0.14 m/s and is 1.91 s^{-1} with an LV of 0 m/s)



K does not show dependence on LV, which suggests that the effect of mass transfer on K is small. (In contrast, the effect of catalytic reaction is large.)

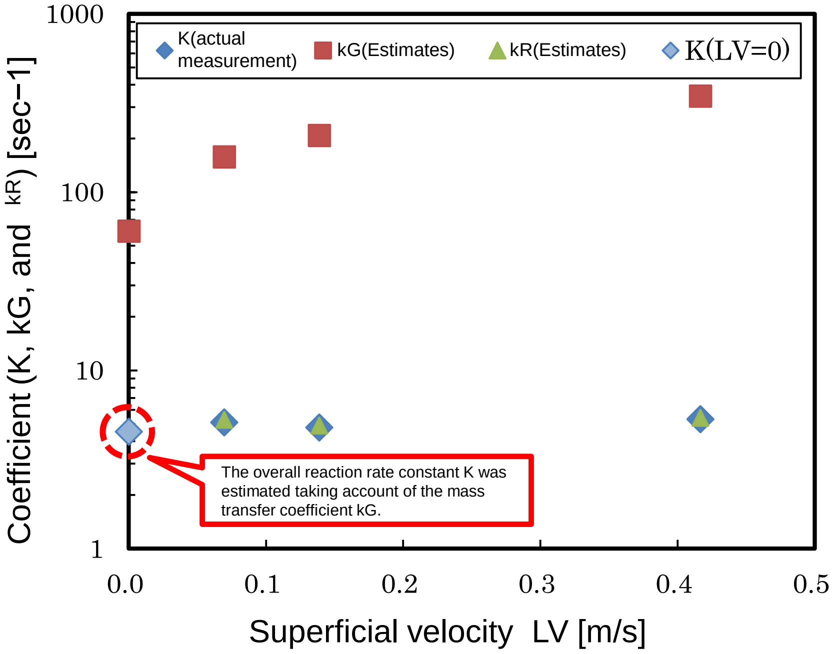
Figure: Influence of superficial velocity LV

<Test condition>
Reaction vessel: gas flow-type, catalyst: TKK-H1P, temperature: 10°C, H_2 concentration: 100 ppm, O_2 concentrations: 50 ppm, with and without humidification
LV: 0.03–0.42 m/s, thickness of catalyst bed: 10 mm

【Supplement-6】 Organized results of catalyst performance evaluation tests (4/7)

③ Influence of superficial velocity LV (2/2)

- The value of the mass transfer coefficient k_G is greater by one to two orders of magnitude than the overall reaction rate constant K, which suggests that mass transfer is not rate-limiting.
  Hydrogen molecules reach the surface of the catalyst quickly, but their recombination with oxygen on the catalyst proceeds slowly. Thus, the catalytic reaction rate constant (k_R) determines the overall reaction rate constant (K).
  This is the reason of the minute dependence of K on LV shown in the conditions of this test.



The overall reaction rate constant K was estimated taking account of the mass transfer coefficient kG.

Figure: Estimation of reaction rate constant

<Test condition>
Reaction vessel: gas flow-type, catalyst: TKK-H1P,
temperature: 10°C, H_2 concentration: 100 ppm,
O_2 concentration: 50 ppm, no humidification
LV: 0.07–0.42 m/s, thickness of catalyst bed: 10 mm

Mass transfer coefficient kG

$$sh = \frac{k_G d_p}{D} \qquad Sc = \frac{\mu}{\rho D} \qquad Re = \frac{d_p u \rho}{\mu}$$

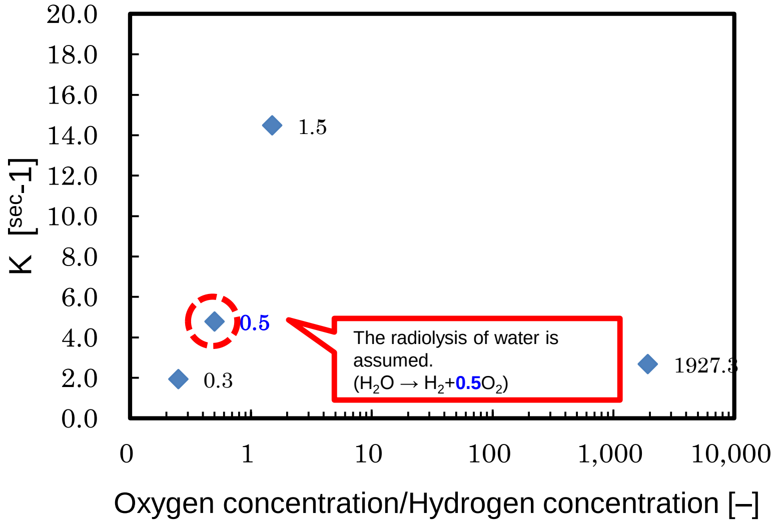
$$sh = 2.0 + 1.1 Sc^{1/3} Re^{0.6}$$

kG: Mass transfer coefficient [m/s^{-1}], u: Superficial velocity (LV) [m/s^{-1}]
dp: particle size [m], μ: viscosity of fluid [$kg\ m^{-1}\ s^{-1}$],
ρ: density of fluid [$kg\ m^{-3}$], D: effective diffusion coefficient [$m^2\ s^{-1}$]
(Cited from Kenji Hashimoto, “Hannou Kougaku”
(Chemical Reaction Engineering))

【Supplement-6】 Organized results of catalyst performance evaluation tests (5/7)

④ Influence of the ratio of oxygen/hydrogen concentrations

- The overall reaction rate constant K increases with the increase of the ratio of oxygen/hydrogen in a range of 0.25–1.5.
- The value of K decreases in the presence of excessive oxygen. According to the literature,[*1] this phenomenon can be explained by the competitive adsorption of oxygen and hydrogen on the catalyst. Excessive oxygen blocks hydrogen from adsorbing onto the adsorption site of the catalyst.
- The mixture of oxygen gas:hydrogen gas at a ratio 0.5:1 was used in this study as the inside of the canister would be purged by nitrogen gas before putting fuel debris in it and oxygen and hydrogen in it would originate from the radiolysis of water.
  (When the ratio of oxygen to hydrogen in the canister changes by some reasons, the effect of the ratio on the catalyst performance needs to be investigated)



The radiolysis of water is assumed.
($H_2O \rightarrow H_2+0.5O_2$)

Figure: Influence of oxygen/hydrogen ratio

<Test condition>
Reaction vessel: gas flow-type, catalyst: TKK-H1P,
temperature: 10°C, H_2 concentration: 100 ppm, ratio of O_2 /H_2: 0.5–1,927, no humidification
LV: 0.14 m/s, SV: 50,000/h, thickness of catalyst bed: 10 mm

Note 1: Murata et al., “Development of Catalytic Recombiner for Boiling Water Reactor,” Hitachi Hyoron 50-12 (1968): 1072

【Supplement-6】 Organized results of catalyst performance evaluation tests (6/7)

⑤ Influence of poisoning materials (Iodine)

- Since there is no information on the catalyst poisoning materials, such as halogens, that will be contained in fuel debris to be collected and placed into the canister, and their contents and chemical form at present, iodine (I_2)*1 was used for the test.
- The overall reaction rate constant decreased by adding iodine. It is considered to be due to the poisoning of the catalyst by iodine.
  The overall reaction rate constant decreased to approximately 1/3 at an iodine/catalyst ratio of 0.05 mg-I_2/mL-catalyst.
  When the amount of iodine is small, the reaction rate does not become zero, and the catalyst’s ability to promote hydrogen–oxygen recombination is retained.

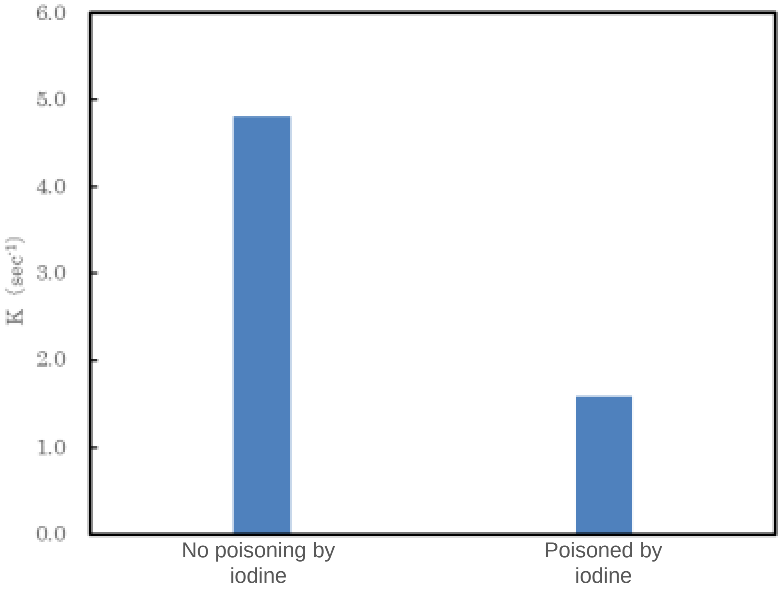


Figure: Influence of oxygen/hydrogen ratio

<Test condition>
Reaction vessel: gas flow-type, catalyst: TKK-H1P,
temperature: 10°C, H_2 concentration: 100 ppm,
ratio of O_2/H_2: 0.5, no humidification
LV: 0.14 m/s, SV: 50,000/h, thickness of catalyst bed: 10 mm
Amount of iodine: 0 and 0.05 mg-I_2/mL-catalyst

Note 1: According to the literature, the content of chloride ion in the reactor water is less than 1 ppm. Therefore, iodine (produced as a fission product) was used for the test. (Literature: Fukaya et al. in the 63rd Japan Conference on Materials and Environments at the Osaka International Convention Center on October 17 to 19, 2016, “The current status and issues of the efforts to slow down the progress of the rust of the pressurized containment vessel and piping in Fukushima Daiichi Power Plant)

【Supplement-6】Organized results of catalyst performance evaluation tests (7/7)

⑥ Test to simulate the inside condition of the canister (Batch test)

- While the catalyst performance evaluation tests in this study are performed with a tube filled with the catalyst and by flowing gas through it, the catalyst in the canister will need to process static gas mixture of hydrogen and oxygen.
- To investigate the influence of the flow of oxygen–hydrogen mixed gas, the catalyst was subjected to the amount of hydrogen more than that which would be generated in the canister during 7 days transfer period in the test tube first. Then, it was placed in a reactor filled with the oxygen–hydrogen mixed gas 100% saturated with water vapor (hydrogen concentration: 10,000 ppm), and change in the hydrogen concentration with time was measured.
- The test result showed that sufficient hydrogen recombination had occurred (reduction of hydrogen concentration below 10 ppm) even in static gas mixture, which demonstrated the performance of the catalyst in static gas.

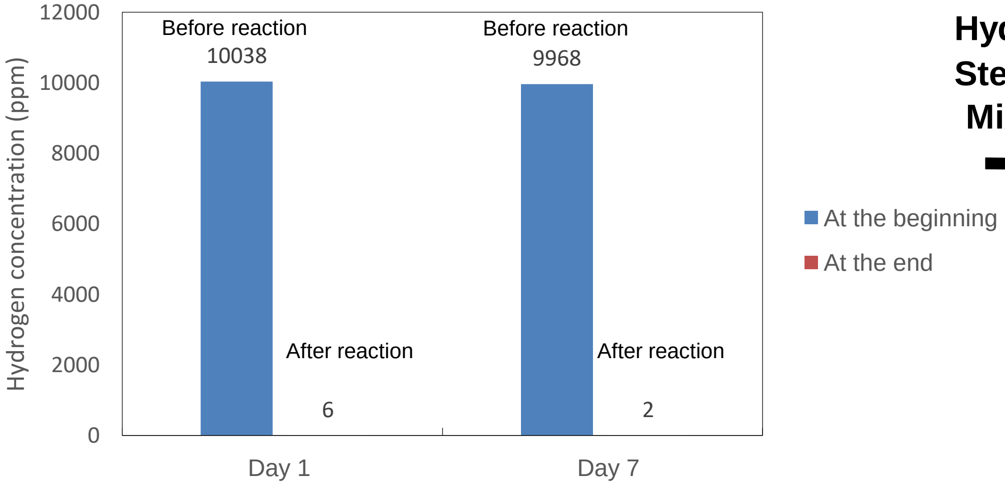


Figure: Result of recombination reaction tests by the batch method

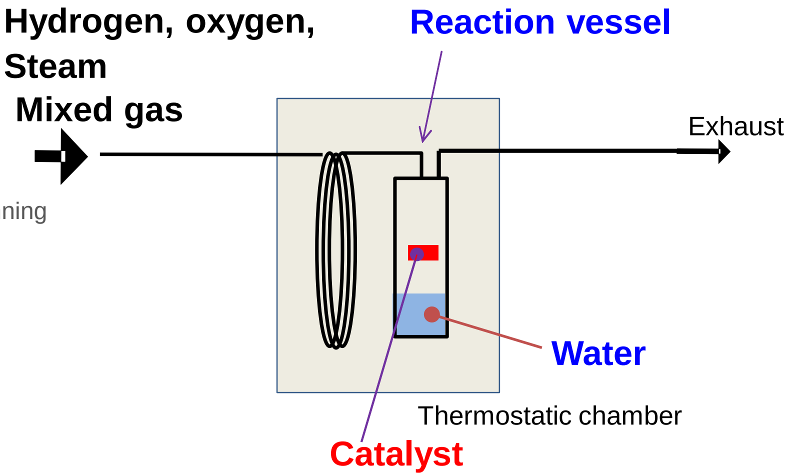


Figure: Conceptual diagram of batch-type catalytic reactor

<Test condition>

Catalyst: TKK-H1P, Φ 3 mm (after saturated with recombined water)
Gas: mixture of H_2 (10,000 ppm), O_2 (5,000 ppm), and saturated water vapor
Reactor: batch type, filled with water at its bottom and catalyst placed at its center
Temperature: cooled at 10°C, reaction time: 14 h on the first day and 15 h on the second day
Measurement: two times, first at the end of 14 h on the first day and second at the end on the 7th day after having been placed above water in the reactor

【Supplement-7】 Safety function sharing and required functions for the fuel debris drying apparatus

The requirements for the drying apparatus are to be the same as those for the canister with respect to the safety functions this technical development project aims to achieve.

Table: Functional requirements for the drying apparatus with respect to safety functions

Safety functions		Design goals	Safety function sharing	
			Canister	Other equipment
Sub-criticality		Maintaining sub-criticality	○	○
Cooling	Heat removal	Elimination of the impact of heat on the properties of the canister, fuel debris, and other devices	—	○
Confinement	Confinement	Prevention of the exposure of workers and general public	○	○
	Shield	Prevention of the exposure of workers and general public	—	○
Others (Integrity of holding, cooling, and sealing functions)	Structure	Structural strength to achieve and maintain the safety functions	○	○
	Integrity of materials	Strength of the materials to withstand mechanical stresses that may occur	○	○
	Hydrogen	Prevention of the explosion of hydrogen generated by the radiolysis of water	○ (Catalyst)	○
	Fire prevention	Prevention of fire caused by residual zirconium	—	○

➡

Required functions	
Drying apparatus	Remarks
○	
○ (Added)	Heat generation during drying (Overheating prevention)
○	Prevention of contamination spread
-	Installed in the cell
○	
○	
○ (Drying)	
-	

【Supplement-8】 Results of the study of drying technologies used in general industries

The drying methods used in the general industry were investigated, and those applicable to fuel debris drying were selected.

Table: Results of the investigation and analysis of drying devices used in the general industry

Drying method	Level of difficulty to meet safety requirements				Remarks
	Maintaining sub-criticality	Confinement performance	Prevention of contamination spread	Overheating prevention	
Hot air (carrier gas)	○	○	○	○	
Heat conductor	○	○	△	○	The heating part of the drying device that requires maintenance is directly contaminated because it directly touches fuel debris to transfer drying heat.
Radiation	○	○	○	○	
Microwave	○	△ (A large cell is required)	× (Waveguide sealing)	○	The microwave generator is also contaminated because the waveguide cannot be sealed during drying.
Induction heating (IH)	○	○	○	○	
Superheated steam	(Not applicable because of the use of water)				
Vacuum	○	○	○	○	
Agitation	× (Fuel debris needs to be taken out from the unit can)	○	× (Risk of contamination spread)	○	The dust of fuel debris gets airborne by taking it out from the unit can and agitating/flowing it in a chamber.
Floating and flowing	× (Fuel debris needs to be taken out from the unit can)	△ (A large cell is required)	× (Risk of contamination spread)	○	

Legends: ○…Applicable △…Conditional ×…Not applicable

Criteria for screening

- Drying will be performed as fuel debris is held in the unit can (UC) in principle.
- The safety (maintaining sub-criticality) is achieved by handling fuel debris as it is held in the unit can.
- With regard to the agitation and floating and flowing methods, additional studies are necessary on anti-contamination measures and safe criticality control since fuel debris needs to be taken out from the unit can to carry out them.
- The use of microwave will require additional anti-contamination measures taking account of the maintainability of the entire drying system because the microwave generator as well as the waveguide are exposed to fuel debris.

⇩

【Applicable drying methods】Hot air, heat conductor, radiation, induction heating (IH), and vacuum

【Supplement-9】 Proven TMI-2 fuel debris drying and its applicability to this technical development

Proven TMI-2 fuel debris drying was examined, and its applicability to this technical development was studied.

Table: Study of the applicability of TMI-2 fuel debris drying to this technical development

Relevant area	Items to be investigated and studied	Proven TMI-2 fuel debris drying	Applicability to this technical development
Design	Purposes and target	Purpose: Maintaining sub-criticality Target: Water removal between particles, and the allowable water content is set to 8ℓ/can (42 $cm^3/ℓ$ per canister internal volume)	The purpose of this development is to control the hydrogen generation gas, and the drying target is strictly set to 1/20 or less (2 cm3/ℓ or less) of TMI-2.
	Material under test for preliminary study	Sand and pumice (porous solid)	Policy of using porous materials that are more difficult to dry than that in TMI-2
	Drying method	Heating with reduced pressure (Maximum permissible temperature of the sealing materials is 150°C) Heated gas (testing only)	· It is expected that the method used in TMI-2 can be applied to the drying of free water between particles. · It is necessary to consider the optimum drying conditions, and decide on them by conducting surveys on heating, depressurization, air speed, etc.
Safety measures	Sub-criticality	There is no information on the conditions of the drying chamber evaluation.	To be studied
	Cooling	There is no information on design policy.	To be studied
	Anti-contaminations measures of the drying system	Installation of a metal filter in the canister	**There is useful information that** installing a metal filter in the canister is an effective method to reduce the contamination of the drying system.

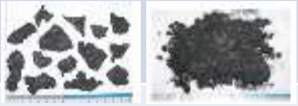
【Conclusion】

- **The track record at TMI-2 is useful for the removal of free water between particles.**
- **The target of drying of this development is much more challenging that the method used at TMI-2 cannot be used as it is.**
- **It is useful information that installing a filter in the canister is an effective method to reduce the contamination of the drying system.**

【Supplement-10】 Processes of fuel debris removal operation and materials that are assumed to be collected in the processes in addition to fuel debris

The materials listed in the table below are assumed to be collected. In addition, porous solids with fine pores and fine particles that contain moisture in them (slurry) are known to affect drying behavior, and porous solids are estimated to account for a large part of collected materials. Based on the above consideration, zeolites were selected as drying test samples.

Table: Materials that are assumed to be collected

Process	Materials	Outlines	Photo image	Properties
Removal process	Piece of broken fuel rod	Pieces of broken fuel assemblies left unmelted		• Fuel debris collected in the removal process is **the main material to be dried**. • The project “Characterization of Fuel Debris” concluded that fuel debris consisting of oxides was **likely to be porous.**
	Fuel debris in the form of lump, MCCI	Molten materials slowly cooled down into the form of lump		
	Fuel debris in the form of pebble and powder	Molten reactor core materials quickly cooled down into small pieces		
	Pieces of broken structures with nuclear fuel adhering to them	Pieces of broken structures left unmelted with fuel debris adhering to them		
Water treatment system	Slurry	Fuel debris in the form of powder and fine particle		• The drying system may need to deal with fuel debris in the form of fine particles**.** • However, details are **not known about its properties**. (For this reason, the applicability of the drying method developed for porous solids to fine particle fuel debris is to be studied.)
Others	Filters	Filters used in the water treatment system and gas treatment process		

【Supplement-11】TG-DTA measurement results with fuel debris drying test samples (zeolites)

Measurement of drying characteristics (study in FY2019 and FY2020)

- A synthesized zeolite was selected as a representative material of porous solids and its drying characteristics were measured
- The moisture content reached 0.22 wt.% in 10 h with 200゜ C
- Element tests are planned to collect basic drying characteristic data including the effects of the drying system operation conditions and the influence of the properties of the drying sample

Table: Conditions of TG-DTA measurement

Equipment name	RIGAKU TG TG-DTA8122 (OT6800049)
Measurement items	Time, mass, and temperature
Temperature	Held at 200°C for 10 h (Then raised to 300°C and held for 1 h to reach a fully dried condition)
Pressure	Atmospheric pressure
Used gas	Dry-N_2 100mL/min
Shape of the test chamber	Rectangle with a dimension of 15 × 10 in mm
Sample container	Platinum crucible
Sample material	Synthesized zeolite (HiSivTM-3000 1.6)
Sample amount	Approx. 16 mg

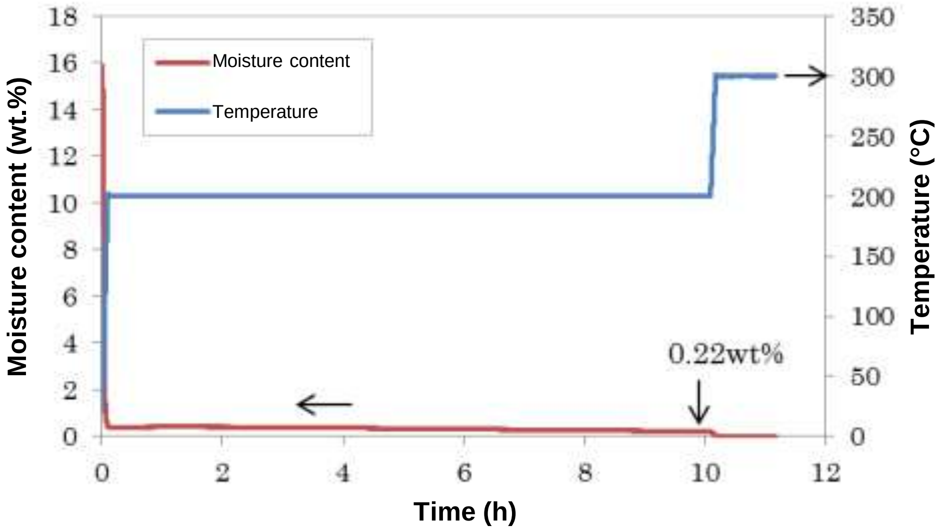


Figure: Test result (Change in moisture content)

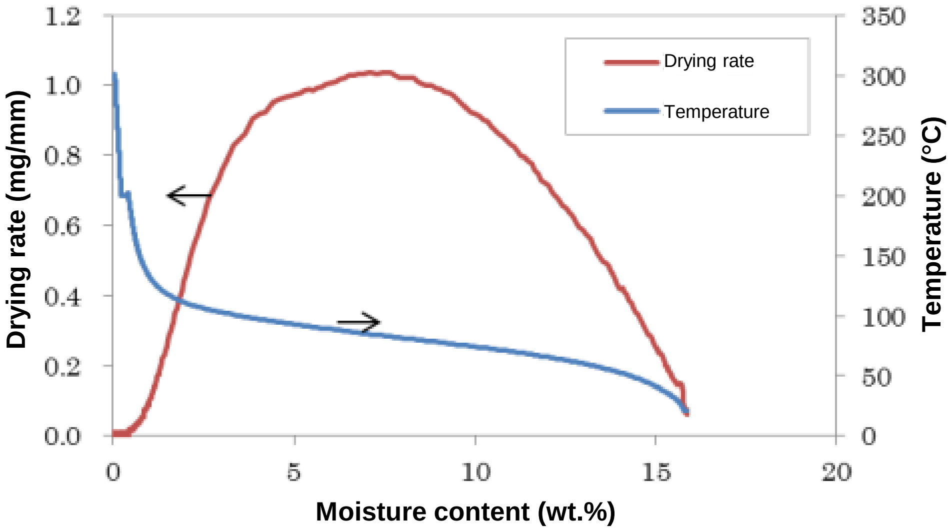


Figure: Test result (Drying curve)

【Supplement-12】Test cases for drying element tests

○ Purpose

- Collection of basic data focusing on change in drying characteristics with the drying method and materials to be dried through beaker scale element tests
- The test parameters are gas temperature, heater temperature, and gas flow rate for the hot air method, and heater temperature and vacuum level for the vacuum method.
- · Evaluation of the influence of the properties (such as the presence of fine pores and thermal conductivity) of materials to be dried

Table: Element test conditions

Run	Materials to be dried	Particle size [mm]	Filling rate [vol%]	Filling height [mm]	Gas flow rate [m/s]	Gas temperature [°C]	Heater temperature [°C]	Pressure [kPa-A]	Evaluation item
1	Zeolite	1.3	60	100	3	200	200	100	Heat supply conditions (Hot air)
2	↑	↑	↑	↑	↑	100	100	100	
3	↑	↑	↑	↑	1	200	200	100	Influence of gas flow rate
4	↑	↑	↑	↑	—	—	200	1	Heat supply conditions (Vacuum)
5	↑	↑	↑	↑	↑	↑	100	↑	
6	↑	↑	↑	↑	↑	↑	200	50	Influence of pressure
7	Metal ball	Approx. 1	Approx. 60	100	Conditions of Run 1				Influence of materials to be dried
8	Silica sand	↑	↑	↑	↑				
9	Silica sand	1, 3	Whatever available	↑	↑				Influence of mixed particle sizes
10	Zeolite Metal ball	1.3 1	↑	↑	↑				Influence of mixed materials (Mixed at a volume ratio of 1:1)
11	ZrO2	Whatever available	↑	↑	↑				Drying behavior of slurry

【Supplement-13】Test cases for full-scale drying tests

Table: Test cases

Type of test	Purpose	Test parameters								Remarks
		UC (Units)	Distance between UCs (mm)	Method	Pressure (kPa)	Temperature (°C)	Flow rate*1 (m/s)	Run (Units)	Time*2 (hr)	
0. Hot air drying	To demonstrate the feasibility to achieve the performance target by the standard conditions of the hot air drying	4	50 (No gap)	Hot air	100	200	3	1	14	
1. Periodic switching drying	To demonstrate the feasibility to achieve the performance target by the standard conditions of the periodic switching drying	4	50 (No gap)	Periodic switching*3	1	200	3	1	14	
2. Test with UCs placed decentered	To investigate the influence of the position of UCs in the chamber; for this purpose, a drying test is performed with UCs being placed off the center of the drying chamber toward its side wall.	4	50 (No gap)	Hot air*4	100	200	3	1	14	Evaluation of the influence of UCs' position and gas flow rate distribution in the chamber
3.-1 Filling height test	The influence of filling height was checked by changing the zeolite filling height in No. 1	4	50 (No gap)	Periodic switching*3	1	200	3	1	14	The UC filling height is 85% of that in No. 1
3.-2 Filling height test	The influence of filling height was checked by changing the zeolite filling height in No. 0	4	50 (No gap)	Hot air	100	200	3	1	14	The UC filling height is 85% of that in No. 0
4. Vacuum drying	To accumulate more data; for this purpose, the performance of the vacuum drying method is investigated by a test. The test is approximately 2 days long because this method requires a longer drying time.	4	50 (No gap)	Vacuum	1	200	-	1	14	

Note 1: At annulus (space between the UC and the inner wall of the chamber)
Note 2: Approximate hours
Note 3: "Periodic switching" means that heating and vacuuming are applied alternately at an interval of 30 min. (See the figure on the right.)
Note 4: If UCs' position is found to affect the drying time, the same test needs to be performed with the periodic switching method.

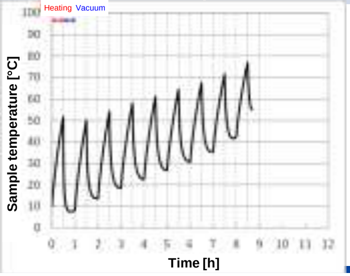


Figure: Operation pattern of the periodic switching method

【Supplement-14】 Details of the fuel debris drying behavior model

Purpose: Analysis of the drying behavior obtained in the element tests and analysis

The drying test data is considered from the evaluation model of reduced rate drying rate (second falling) period, which is the a for the completion of drying.

	Drying behavior	Drying rate
Constant drying rate period 【Period A-B in the figure on the right】	• Liquid water diffusion • Water evaporating on the surface of the sample	Constant
Reduced rate drying rate (first falling) period 【B-C】	• Simultaneous diffusion of liquid water and steam • Water evaporating inside the sample	Proportional to the moisture content
Reduced rate drying rate (second falling) period 【C-D】	• Steam diffusion • Water evaporating inside the sample	Deduction rate is less than that in the first step.

Model to estimate a drying rate in the reduced drying rate period (second step)

$$W = \frac{A}{\dfrac{1}{h_D} + \dfrac{\delta}{\beta \phi_V D_0}} \left(\frac{p_\phi}{R_w T_\phi} - \frac{p_1}{R_w T_1} \right)$$

De (See the next page)

(Denominator: Diffusion resistance)

(Drive force for diffusion)

Source: Toei et al., “The Mechanism of Drying of a Bed of Granular and Powdered Materials during the Second Falling Rate Period,” 1964 Volume 28 Issue 6 Pages 458-467, Chemical engineering of Japan

A: Surface area of the sample [m2]
D_0: Diffusion coefficient of steam [m2/s]
h_D: Mass transfer coefficient of gas film [m/s]
p_1: Partial pressure of steam in the atmosphere [Pa]
p_Φ: Saturated water vapor pressure at temperature TΦ [Pa]
R_w: Gas constant of steam [J/(kg-K)]
T_1: Ambient temperature [K]
T_Φ: Temperature of the dry zone [K]
W: Drying rate [kg/s]
β: Correction coefficient to take into account the curvature of diffusion path [–]
δ: Depth of the dry zone [m]
Φ_V: Void ratio between sample particles [–]

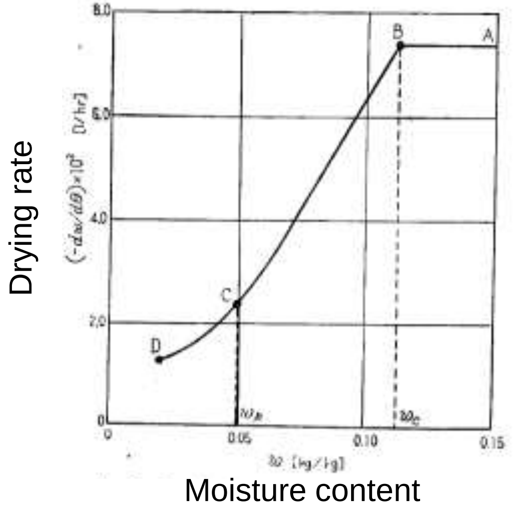


Figure: Drying curves (relationship between moisture content and drying rate)

Source: Toei et al., “The Mechanism of Drying of a Bed of Granular and Powdered Materials during the Second Falling Rate Period,” 1964 Volume 28 Issue 6 Pages 458-467, Chemical engineering of Japan

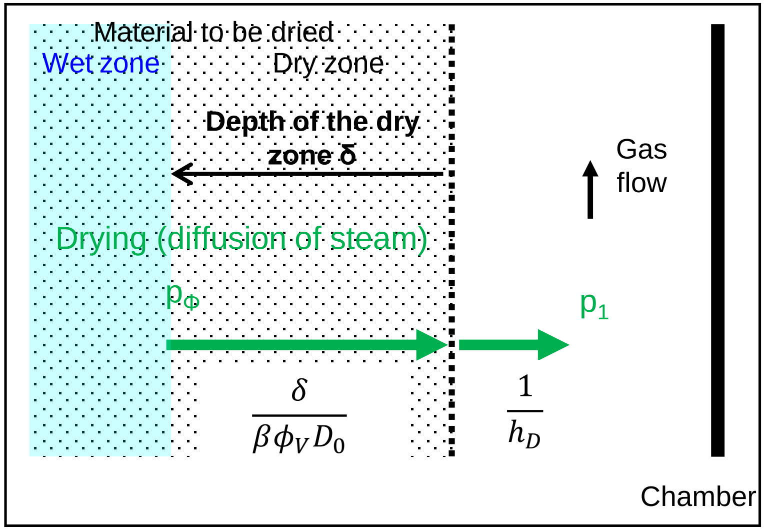


Figure: Illustration of the drying rate estimation model

【Supplement-15】 Evaluation test of decontamination for the conceptual design of the fuel debris drying apparatus (1/2)


Manipulator operation test facility

○ Purpose of the test

- ✔ Evaluation of remote visibility and operability ⇒
  Evaluation of the feasibility of remote operation by full-scale tests
- ✔ Evaluation of the feasibility of maintenance by workers after decontamination ⇒
  Evaluation of the level of decontamination after wiping

○ Test method


Note 1: Sandblasting sand

(1) Make a drying chamber with stainless steel.

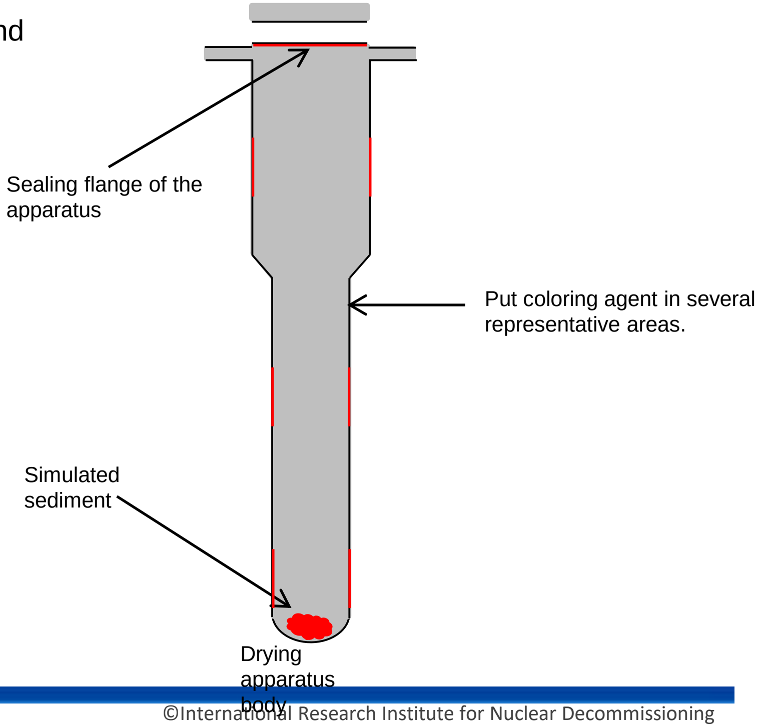
(2) Put coloring agent (such as water pigment) on the inner wall in areas that are subjected to the wiping test by a marking tool and place deposit simulant (such as sandblasting sand*1) at the bottom.

(3) Perform vacuuming and wiping by remote control using a manipulator and **camera image** *2
【Areas to be vacuumed and wiped】
  a. Inner wall of the body (Several representative areas, such as upper part, lower part, and bottom)
  b. Seal flange area

(4) Check the vacuumed and wiped areas by a microscope^{*3} and glossmeter^{*4} to evaluate the degree of coloration after the removal of the **coloring agent**

Note 1: The possibility of residue of waste such as dust from the exhaust piping backwash lying at the bottom is assumed.
Note 2: All operations are performed based on camera images in principle.


*3: Glossmeter



○ Check items

- Whether there is the influence of reflected light, etc., in the microscope field
- Whether the deposit simulant remains (at the bottom)
- Whether the vacuumed and wiped areas show the same level of cleanliness as that which can be achieved by manual wiping

○ Result

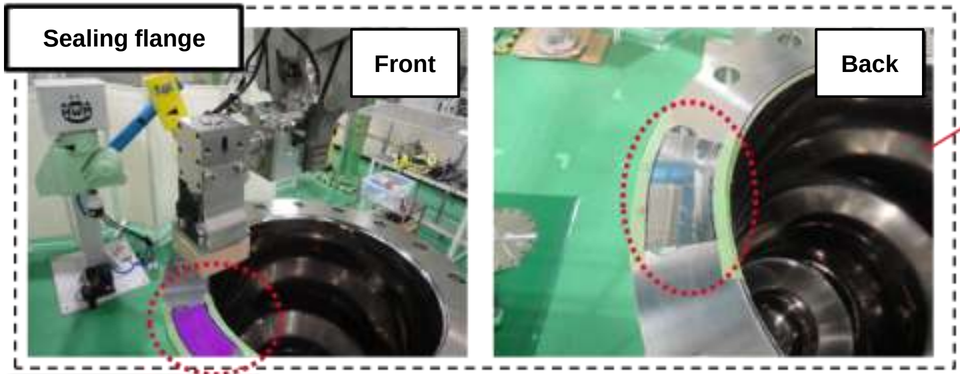
- Satisfactory vacuuming and wiping performance was demonstrated

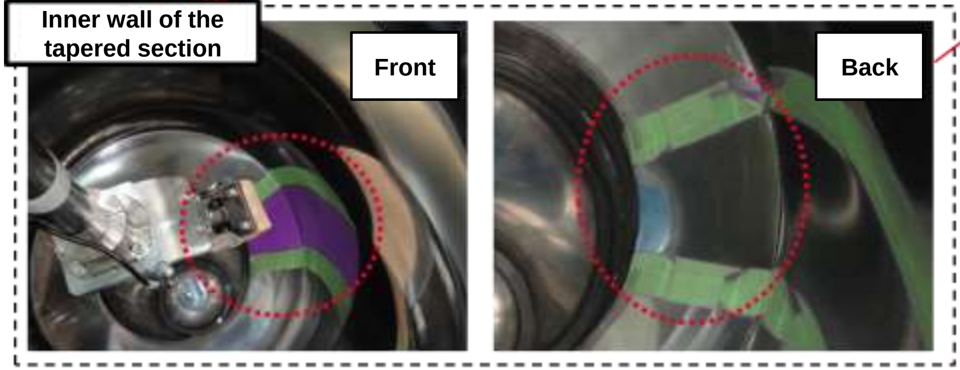

Note 4: Microscope with LED

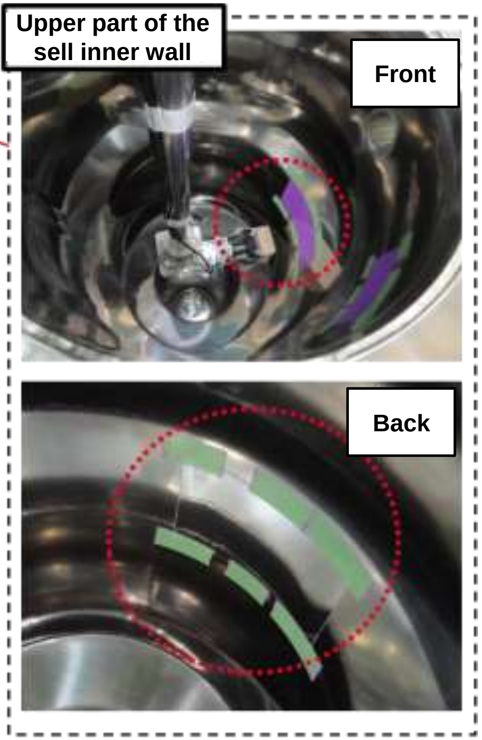
【Supplement-15】 Evaluation test of decontamination for the conceptual design of the fuel debris drying apparatus (2/2)

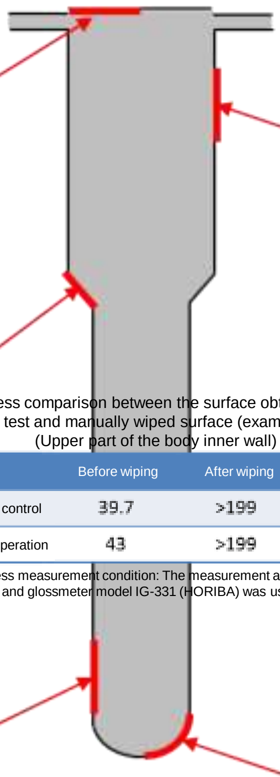
○ Details of the results

Left (top): Before wiping, right (bottom): after wiping





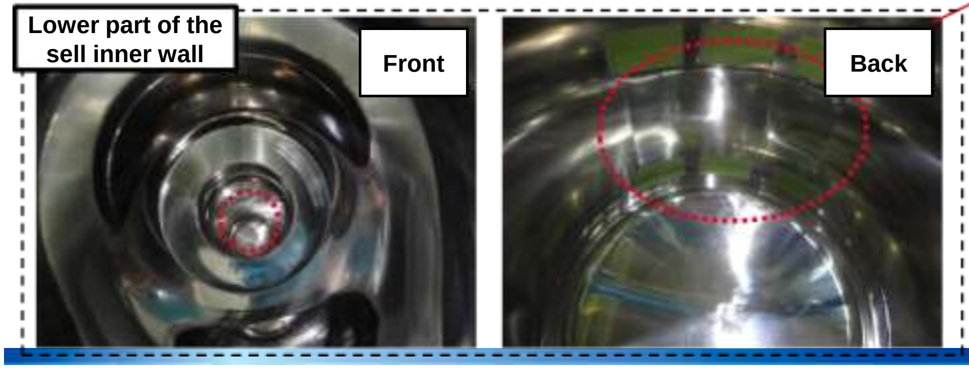


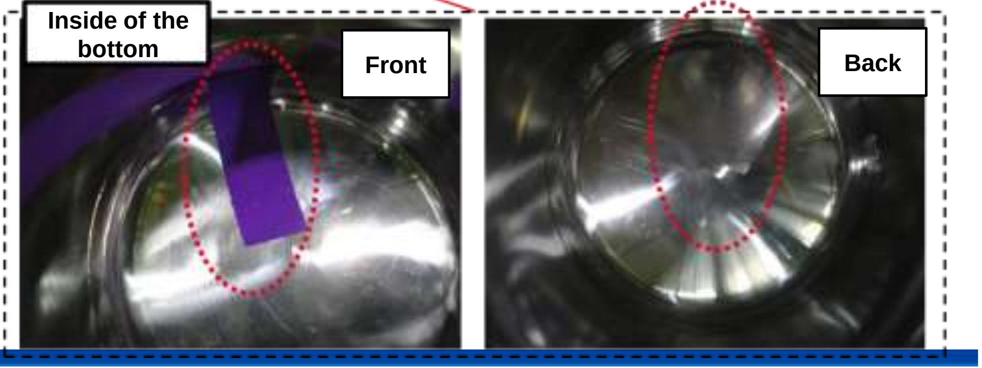


Glossiness comparison between the surface obtained by the test and manually wiped surface (example)
(Upper part of the body inner wall)

	Before wiping	After wiping	Judgment
Remote control	39.7	>199	○
Manual operation	43	>199	—

(Glossiness measurement condition: The measurement angle was 60°, and glossmeter model IG-331 (HORIBA) was used)

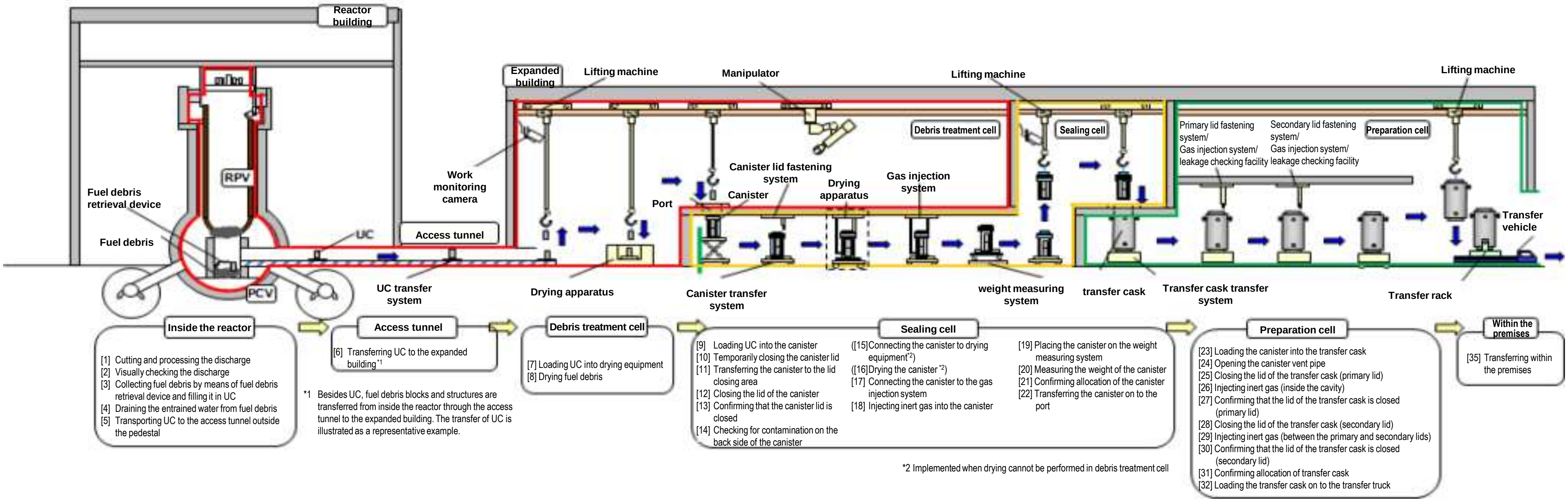




【Supplement-16】 Details of hydrogen measurement technology (1/18)

a. Study of required technical specifications and the criteria of applicability judgment (1/12)

- ✓ Two types of methods were studied for hydrogen concentration monitoring: **continuous monitoring** and **sequential monitoring**.
- ✓ As to sequential monitoring, **processes in which the monitoring of hydrogen can be performed by the simplest system and device were identified** in the planned operation flow from the process of fuel debris collection to the process to bring it out in the transfer cask (Figures【1】 to 【32】 below).



Inside the reactor

[1] Cutting and processing the discharge
[2] Visually checking the discharge
[3] Collecting fuel debris by means of fuel debris retrieval device and filling it in UC
[4] Draining the entrained water from fuel debris
[5] Transporting UC to the access tunnel outside the pedestal

Access tunnel

[6] Transferring UC to the expanded building*1

*1 Besides UC, fuel debris blocks and structures are transferred from inside the reactor through the access tunnel to the expanded building. The transfer of UC is illustrated as a representative example.

Debris treatment cell

[7] Loading UC into drying equipment
[8] Drying fuel debris

Sealing cell

[9] Loading UC into the canister
[10] Temporarily closing the canister lid
[11] Transferring the canister to the lid closing area
[12] Closing the lid of the canister
[13] Confirming that the canister lid is closed
[14] Checking for contamination on the back side of the canister
([15]Connecting the canister to drying equipment*2)
([16]Drying the canister *2)
[17] Connecting the canister to the gas injection system
[18] Injecting inert gas into the canister
[19] Placing the canister on the weight measuring system
[20] Measuring the weight of the canister
[21] Confirming allocation of the canister
[22] Transferring the canister on to the port

*2 Implemented when drying cannot be performed in debris treatment cell

Preparation cell

[23] Loading the canister into the transfer cask
[24] Opening the canister vent pipe
[25] Closing the lid of the transfer cask (primary lid)
[26] Injecting inert gas (inside the cavity)
[27] Confirming that the lid of the transfer cask is closed (primary lid)
[28] Closing the lid of the transfer cask (secondary lid)
[29] Injecting inert gas (between the primary and secondary lids)
[30] Confirming that the lid of the transfer cask is closed (secondary lid)
[31] Confirming allocation of transfer cask
[32] Loading the transfer cask on to the transfer truck

Within the premises

[35] Transferring within the premises

Figure: Example of applying the fuel debris retrieval process flow to the handling flow of the side-access retrieval method

【Supplement-16】 Details of hydrogen measurement technology (2/18)

a. Study of required technical specifications and the criteria of applicability judgment (2/12)

(i) Study of where and how to carry out the continuous hydrogen concentration monitoring

The feasibility of the application (installation) of hydrogen concentration meters to the unit can (UC), container, and transfer cask was examined.

⇒ Based on the results shown in the table below, **the transfer cask was determined to be feasible for the application (installation) of them**.

It is possible to use conventional hydrogen concentration meters **for continuous monitoring because they must only be capable to indicate if the hydrogen concentration is below its lower explosive limit.**

It must be noted the impact of the installation of a hydrogen meter in the transfer cask on its strength needs to be examined separately.

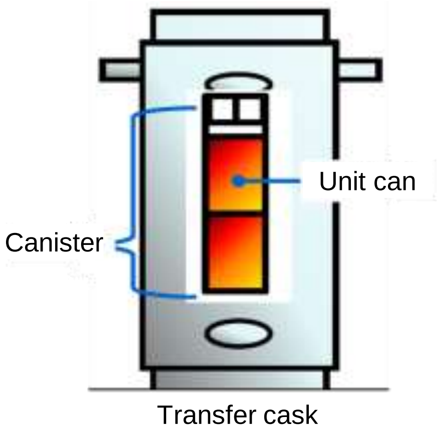


Figure: Illustration of the transfer cask ready to be carried out

Table: Comparison of the feasibility of hydrogen concentration monitoring among fuel debris containers

	Structure	Frequency of use	Signal transmission	Continuous monitoring
Unit can (UC)	Made of mesh sheet metal	High	×	× Structurally impossible
Canister	A vent pipe is attached	Medium	×	× Due to frequency and difficulty of signal transmission
Transfer cask	Sealed	Low	○	○

【Supplement-16】 Details of hydrogen measurement technology (3/18)

a. Study of required technical specifications and the criteria of applicability judgment (3/12)

(ii) Study on when (in which process) to carry out the sequential hydrogen concentration monitoring (1/2)

The following requirements need to be met by the hydrogen concentration measuring method that will be used for the sequential monitoring:

- ✓ The method must be accurate so that the hydrogen concentration around fuel debris in the canister after the fuel debris is kept in it for 7 days with a hydrogen generation rate that is estimated based on the hydrogen concentration measured by the method in the sequential monitoring in a certain process and the gas flow rate of the process is below the lower explosive limit of hydrogen 4 vol%.
- ✓ The method should not affect the throughput of the fuel debris removal operation. (In other words, there should be no additional requirements in the operation flow, such as requiring new process for measurement and analysis)

After screening the methods base on the above-mentioned requirements, the following processes were found to be feasible for sequential monitoring:

Process to replace the gas in the canister or transfer cask
Processes where there is no work that entails a risk of gas leakage

【Supplement-16】 Details of hydrogen measurement technology (4/18)

a. Study of required technical specifications and the criteria of applicability judgment (4/12)

(ii) Study on when (in which process) to carry out the sequential hydrogen concentration monitoring (2/2)

- **Fuel debris drying process**
- **Inert gas injection process (canister)**
- **Inert gas injection process (transfer cask)**
- **Process that combines above three processes**

✓ **The range of hydrogen concentration that needs to be covered by the measuring method applied to each selected process is estimated based on a hydrogen generation (rate) estimated for the process.**

✓ **Whether the estimated hydrogen concentration is practical or not is assessed using the lowest measuring limit of a conventional hydrogen concentration meter as a criterion.**

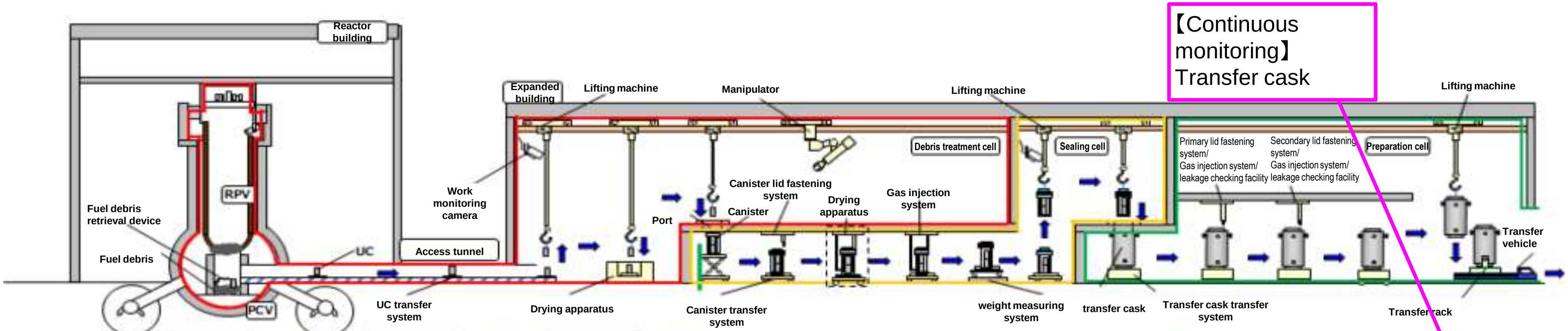
Table: Result of the study on when to carry out the sequential monitoring

No.	Process	Measuring point	Feasibility	Points of assessment
【8】	Fuel debris drying	Unit can/drying chamber	○	Gas in the drying chamber is discharged out of it during drying, and a hydrogen concentration can be measured by sampling the discharged gas.
【16】	Fuel debris drying	Canister	○	Gas in the canister is discharged out of it during drying, and a hydrogen concentration can be measured by sampling the discharged gas.
【18】	Inert gas injection	Canister	○	Gas in the canister is discharged out of it by inert gas injection, and a hydrogen concentration can be measured by sampling the discharged gas.
【24】	Releasing the canister vent pipe	Canister	×	Releasing the canister vent pipe will cause part of gas in the canister to flow out of it, but the amount of the gas coming out through the vent pipe is too little to represent the hydrogen concentration in the canister.
【26】	Inert gas injection	Transfer cask (Inside the cavity)	○	Gas in the transfer cask is discharged out of it by inert gas injection into it, and a hydrogen concentration can be measured by sampling the discharged gas.

【Supplement-16】 Details of hydrogen measurement technology (5/18)

a. Study of required technical specifications and the criteria of applicability judgment (5/12)

(iii) Summary of the results of study on when and how to carry out continuous and sequential hydrogen concentration monitoring



【Continuous monitoring】
Transfer cask

Inside the reactor

[1] Cutting and processing the discharge
[2] Visually checking the discharge
[3] Collecting fuel debris by means of fuel debris retrieval device and filling it in UC
[4] Draining the entrained water from fuel debris
[5] Transporting UC to the access tunnel outside the pedestal

Access tunnel

[6] Transferring UC to the expanded building [*1]

Debris treatment cell

[7] Loading UC into drying equipment
[8] Drying fuel debris

Sealing cell

[9] Loading UC into the canister
[10] Temporarily closing the canister lid
[11] Transferring the canister to the lid closing area
[12] Closing the lid of the canister
[13] Confirming that the canister lid is closed
[14] Checking for contamination on the back side of the canister
([15] Connecting the canister to drying equipment[*2])
([16] Drying the canister [*2])
[17] Connecting the canister to the gas injection system
[18] Injecting inert gas into the canister
[19] Placing the canister on the weight measuring system
[20] Measuring the weight of the canister
[21] Confirming allocation of the canister
[22] Transferring the canister on to the port

Preparation cell

[23] Loading the canister into the transfer cask
[24] Opening the canister vent pipe
[25] Closing the lid of the transfer cask (primary lid)
[26] Injecting inert gas (inside the cavity)
[27] Confirming that the lid of the transfer cask is closed (primary lid)
[28] Closing the lid of the transfer cask (secondary lid)
[29] Injecting inert gas (between the primary and secondary lids)
[30] Confirming that the lid of the transfer cask is closed (secondary lid)
[31] Confirming allocation of transfer cask
[32] Loading the transfer cask on to the transfer truck

Within the premises

[35] Transferring within the premises

【Sequential monitoring】
(8) Fuel debris drying (UC)

【Sequential monitoring】
(16) Fuel debris drying (Canister)

【Sequential monitoring】
(18) Inert gas injection (canister)

【Sequential monitoring】
(26) Inert gas injection (transfer cask (inside the cavity))

[*1] Besides UC, fuel debris blocks and structures are transferred from inside the reactor through the access tunnel to the expanded building. The transfer of UC is illustrated as a representative example.

[*2] Implemented when drying cannot be performed in debris treatment cell

【Supplement-16】 Details of hydrogen measurement technology (6/18)

a. Study of required technical specifications and the criteria of applicability judgment (6/12)

(iv) Estimation of a hydrogen generation (rate) in the containers that were selected to measure hydrogen concentration in for sequential hydrogen concentration monitoring (1/3)
As to the hydrogen generation (rate), the estimates in the previous studies shown in the table below are used as reference, and the maximum (case I) and minimum (case IV) values are used for the estimation.

Table: Estimates of hydrogen generation rate

Case	Canister inner diameter (mm)	UO_2 content in fuel debris (wt%)	Hydrogen generation model used for hydrogen generation rate estimation	Energy absorption rate	Hydrogen generation rate in the canister (m3/h/canister)
I	220	26	TMI model	Total absorption	2.15×10^{-4}
II	220	26	TMI model	Transport calculation	3.83×10^{-5}
III	220	26	TMI model	Test results	1.50×10^{-6}
IV	220	26	Radiolysis model	Total absorption	1.09×10^{-4}
V	220	26	Radiolysis model	Transport calculation	1.30×10^{-5}
VI	220	26	Radiolysis model	Test results	7.36×10^{-7}

Cited from the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris

【Supplement-16】 Details of hydrogen measurement technology (7/18)

a. Study of required technical specifications and the criteria of applicability judgment (7/12)

(iv) Estimation of a hydrogen generation (rate) in the containers that were selected to measure hydrogen concentration in for sequential hydrogen concentration monitoring (2/3)
A maximum permissible hydrogen generation rate that can keep the hydrogen concentration in the container in discussion below the lower explosive limit (4 vol%) after 7 days of fuel debris containment in it was estimated for each of the containers (drying chamber, canister, and transfer cask) that were selected to measure hydrogen concentration in for hydrogen concentration monitoring based on their volumes (See the next page).

Table: Estimation of maximum permissible hydrogen generation rate

Process No.	Container to measure hydrogen concentration in	Process that the container undergoes	Number of canisters (units)	Gas phase volume (m^3)	Maximum permissible hydrogen generation rate[*4] (m^3/h)
【8】	Drying chamber (Unit can)	(Drying process) (Vacuum and hot air)	5	0.356[*1]	8.4×10^{-5}
【16】	Canister	(Drying process) (Vacuum and hot air)	1	0.02[*2]	4.7×10^{-6}
【18】	Canister	Inert gas injection process	1	0.02[*2]	4.7×10^{-6}
【26】	Cavity of the transfer cask	Inert gas injection process	12	1.78[*3]	4.2×10^{-4}

Note 1: The dimensions of the drying chamber are hypothetically determined by reference to the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris

Note 2: Cited from the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris

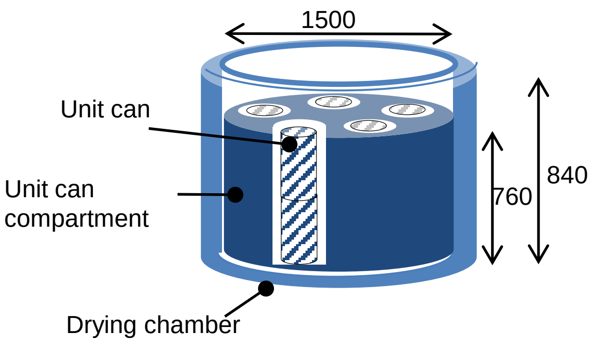
Note 3: The dimensions of the transfer cask are hypothetically determined by reference to the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris

Note 4: Maximum permissible hydrogen generation rate v_a = Volume of the container in which hydrogen concentration is measured V_g × Lower explosive limit 4 vol% /Containment period 168 h

【Supplement-16】 Details of hydrogen measurement technology (8/18)

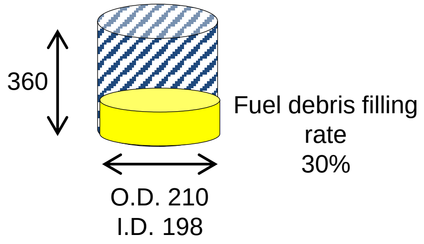
a. Study of required technical specifications and the criteria of applicability judgment (8/12)

(iv) Estimation of a hydrogen generation (rate) in the containers that were selected to measure hydrogen concentration in for sequential hydrogen concentration monitoring (3/3)
The assumed volumes of the drying chamber, canister, and the cavity of the transfer cask are shown below.



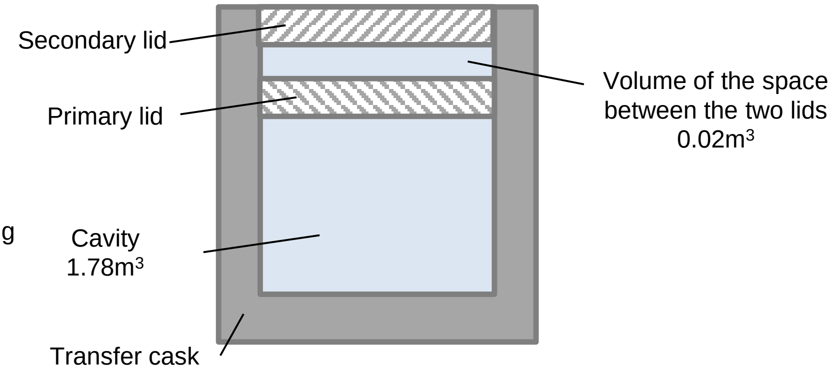
Total volume	1480L
Gas phase volume	356L

(a) Unit can drying chamber



Inner volume	11.1L
Fuel debris volume	3.33L
Gas phase volume	7.77L

(b) Unit can



Total inner volume	1.80m^3
Cavity volume	1.78 m^3
Volume of the space between the two lids	0.02m^3

(c) Transfer cask

Figure: Outlines of unit can drying chamber, unit can, and transfer cask

- The gas phase volume of the unit can drying chamber is estimated by reference to the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris. In the said report, the height of the unit can compartment was not specified. In the estimation, it is hypothetically set to be equal to twice of the unit can height. It is also hypothesized that the inner diameter of the drying chamber is equal to the outer diameter of the unit can compartment and its height is 10% higher than that of the unit can compartment.
- The gas phase volume of the transfer cask is assumed to be 1.80 m^3 by reference to the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris, and the volume of the space between the primary and secondary lids is assumed by reference to the ratio of the same space to the cavity of the cask that can be used for both the transfer and storage of fuel debris.

【Supplement-16】 Details of hydrogen measurement technology (9/18)

a. Study of required technical specifications and the criteria of applicability judgment (9/12)

(v) Estimation of the range of a hydrogen concentration to be measured for sequential monitoring and the assessment of the applicability of a conventional hydrogen concentration meter (1/4)

A hydrogen concentration in the container in discussion after 7 days of fuel debris containment in it was estimated for each of the containers (drying chamber, canister, and transfer cask) that were selected to measure hydrogen concentration in for hydrogen concentration monitoring. In this estimation, fuel debris was assumed to generate hydrogen at the following three rates: the rate of case I, rate of case Vi, and maximum permissible rate (See the next page).

The judgment of the applicability of a conventional hydrogen concentration meter is made by using the estimate with the maximum permissible hydrogen concentration rate and based on the criteria for applicability judgment below.

【Assessment criteria】

Estimated hydrogen concentration with the maximum permissible hydrogen generation rate ≧ 100 ppm: Applicable (A conventional hydrogen concentration meter can be used)

Estimated hydrogen concentration with the maximum permissible hydrogen generation rate = 1–100 ppm: Conditional (A hydrogen concentration meter with a higher sensitivity is needed)

Estimated hydrogen concentration with the maximum permissible hydrogen generation rate < 1 ppm: Not applicable (It is difficult to detect this concentration by any of conventional hydrogen concentration meters)

【Assessment result】

- Drying process
  - ✓ Hot air drying: The estimated hydrogen concentration is below 1 ppm, and it is difficult to detect this concentration by any of conventional hydrogen concentration meters.
  - ✓ Pressurizing and vacuuming: The estimated hydrogen concentration is in a range of 1–100 ppm, and a hydrogen concentration meter with a higher sensitivity is needed.
- Inert gas injection process
  - ✓ **<u>The estimated hydrogen concentration with the maximum permissible hydrogen generation rate is higher than 100 ppm for the canister and transfer cask, and a conventional hydrogen concentration meter can be used.</u>**

【Supplement-16】 Details of hydrogen measurement technology (10/18)

a. Study of required technical specifications and the criteria of applicability judgment (10/12)

(v) Estimation of the range of a hydrogen concentration to be measured for sequential monitoring and the assessment of the applicability of a conventional hydrogen concentration meter (2/4)

Table: Estimation of hydrogen concentration

Process	Container to measure hydrogen concentration in	Gas replacement rate (m^3/h) @0° C, 100 kPa	Amount of hydrogen generation per unit time (m^3/h)			Hydrogen concentration (ppm)[*5]			Assessment result
			Case I	Case VI	Permissible maximum hydrogen generation rate	Case I	Case VI	Permissible maximum hydrogen generation rate	
Fuel debris drying (Heating with reduced pressure)	Drying chamber	2.95E+00[*1]	1.07E-03	3.68E-06	8.48E-05	3.6E+02	1.2E+00	2.9E+01	△
Fuel debris drying (Heating with reduced pressure)	Canister	5.90E-01[*2]	2.15E-04	7.36E-07	4.76E-06	3.6E+02	1.2E+00	8.1E+00	△
Fuel debris drying (Hot air drying)	Drying chamber	1.22E+03[*3]	1.07E-03	3.68E-06	8.48E-05	8.8E-01	3.0E-03	7.0E-02	×
Fuel debris drying (Hot air drying)	Canister	2.43E+02[*2, 3]	2.15E-04	7.36E-07	4.76E-06	8.8E-01	3.0E-03	2.0E-02	×
Inert gas injection	Canister	1.98E-02[*4]	2.15E-04	7.36E-07	4.76E-06	1.1E+04	3.7E+01	2.4E+02	○
Inert gas injection (Inside the cavity)	Transfer cask	1.76E+00[*4]	2.58E-03	8.84E-06	4.24E-04	1.5E+03	5.0E+00	2.4E+02	○

Note 1: A gas replacement rate at 0°C and a pressure of 100 kPa was estimated by reference to the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris.

Note 2: This is the quotient of the gas replacement rate estimate of Note 1 by the number of the unit can compartments in the drying chamber based on the assumption that the gas replacement rate of the single canister is equal to that of the single unit can compartment.

Note 3: A gas replacement rate at 0° C and a pressure of 100 kPa was estimated by reference to the FY2018 Final Research Report of the Development of Technology for Containing, Transfer and Storage of Fuel Debris and based on the assumption that a vacuum pump with the same specifications as those of the vacuum pump used for the hot air and vacuum drying is used for the hot air drying

Note 4: This is the gas suction rate from the canister during an hour of vacuuming that is performed once before injecting inert gas into it.

Note 5: Hydrogen concentration (ppm) ＝ Amount of hydrogen generation per unit time (m^3/h) /Gas replacement rate (m^3/h) × 10^6

【Supplement-16】 Details of hydrogen measurement technology (11/18)

a. Study of required technical specifications and the criteria of applicability judgment (11/12)

(v) Estimation of the range of a hydrogen concentration to be measured for sequential monitoring and the assessment of the applicability of a conventional hydrogen concentration meter (3/4)

The two processes in the table below were selected as primary candidates for sequential hydrogen concentration monitoring based on the estimated range of a hydrogen concentration to be measured and the applicability of a conventional hydrogen concentration meter to the estimated range.
Hot wire semiconductor sensors, which do not require the presence of oxygen, will be mainly studied as candidate measurement devices since the atmosphere to be measured contains little oxygen due to inert gas injection.

Table: Result of the evaluation of inert gas injection processes

Process	Assumed atmosphere condition		Criteria for applicability judgment
【18】Inert gas injection (Canister)	Where to monitor hydrogen concentration[*1]	Discharged gas by replacing operation/pump exhaust gas	The meter must be able to measure the hydrogen concentration of flowing gas
	Atmosphere	Room temperature[*2] and atmospheric pressure	The meter must be able to be used in 10°C–40°C temperature range and in an atmospheric pressure
	Gas composition	Mixture of nitrogen, steam, and hydrogen	The meter must be able to detect a hydrogen concentration of 240 ppm in the relevant atmosphere
【26】Inert gas injection (Inside the cavity of the transfer cask)	Where to monitor hydrogen concentration[*1]	Discharged gas by replacing operation/pump exhaust gas	The meter must be able to measure the hydrogen concentration of flowing gas
	Atmosphere	Room temperature[*2] and atmospheric pressure	The meter must be able to be used in 10°C–40°C temperature range and in an atmospheric pressure
	Gas composition	Mixture of nitrogen, steam, and hydrogen	The meter must be able to detect a hydrogen concentration of 240 ppm in the relevant atmosphere

Note 1: The two assumed methods are listed as the details of the inert gas injection method are not known.
Note 2: approximately 10–40°C

【Supplement-16】 Details of hydrogen measurement technology (12/18)

a. Study of required technical specifications and the criteria of applicability judgment (12/12)

(v) Estimation of the range of a hydrogen concentration to be measured for sequential monitoring and the assessment of the applicability of a conventional hydrogen concentration meter (4/4)

The two processes in the table below were selected as secondary candidates for sequential hydrogen concentration monitoring based on the estimated range of a hydrogen concentration to be measured and the availability of a highly sensitive hydrogen concentration meter that can cover the estimated range.

The availability of a highly sensitive hydrogen concentration meter that can be used in the assumed atmosphere and cover the estimated range is investigated.

Table: Result of the evaluation of fuel debris drying processes

Process	Assumed atmosphere condition		Criteria for applicability judgment
【8】 Fuel debris drying (Hot air with vacuum, drying chamber)	Where to monitor hydrogen concentration	Pump exhaust gas	The meter must be able to measure the hydrogen concentration of flowing gas
	Atmosphere	Room temperature^{*1} and negative pressure	The meter must be able to be used in 10–40°C temperature range and in a negative pressure.
	Gas composition	Mixture of nitrogen, steam, and hydrogen	The meter must be able to detect a hydrogen concentration of 28 ppm in the relevant atmosphere The meter must be able to measure a hydrogen concentration at around the dew point
【16】 Fuel debris drying (Heating with vacuum, canister)	Where to monitor hydrogen concentration	Pump exhaust gas	The meter must be able to measure the hydrogen concentration of flowing gas
	Atmosphere	Room temperature^{*1} and negative pressure	The meter must be able to be used in 10–40°C temperature range and in a negative pressure.
	Gas composition	Mixture of nitrogen, steam, and hydrogen	The meter must be able to detect a hydrogen concentration of 8.1 ppm in the relevant atmosphere The meter must be able to measure a hydrogen concentration at around the dew point

Note 1: approximately 10° C–40° C

【Supplement-16】 Details of hydrogen measurement technology (13/18)

b. Investigation of hydrogen concentration measurement technologies (1/4)

Based on the results organized in section a., the technologies to measure hydrogen concentration were investigated extensively with the focus on the existing technologies.

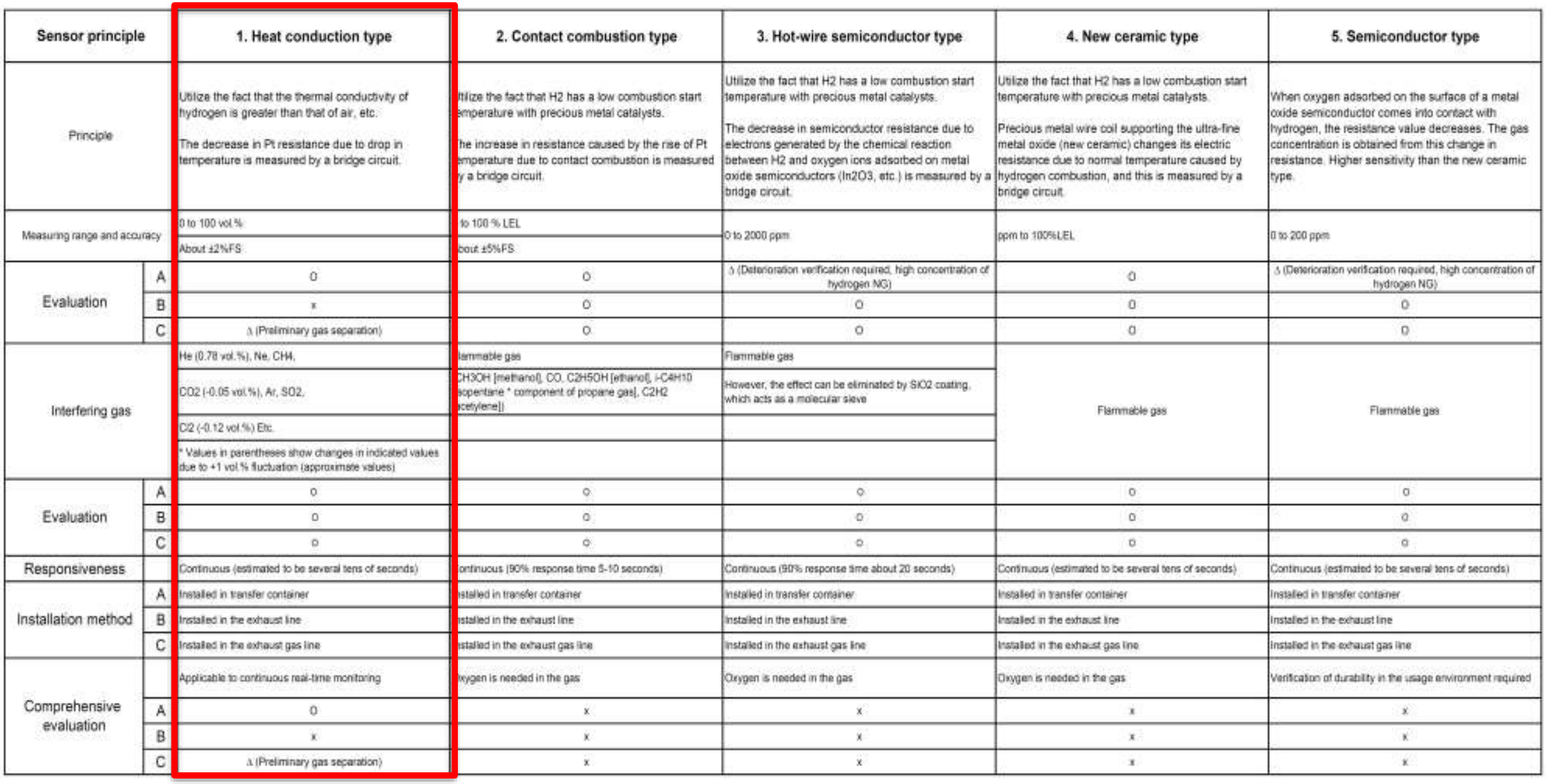
In addition, the three monitoring scenarios A, B, and C were formulated based on the processes and/or container selected as a candidate for the hydrogen concentration monitoring, conditions and components of gas in them, and the assumed hydrogen concentration in them, as shown in the table below, and technologies applicable to those scenarios were selected.

Table: Hydrogen concentration monitoring scenarios and assumed concentration measurement conditions in them

Monitoring scenarios	Monitoring method	Processes and/or container selected as a candidate which the hydrogen concentration monitoring can be carried out in	Assumed atmosphere	Assumed hydrogen concentration range	Measurement method
A	Continuous monitoring	Transfer cask	Room temperature and atmospheric pressure Mixture of nitrogen, steam, and hydrogen	0–4 vol%	Install a sensor in the transfer cask.
B	Sequential monitoring	(Drying process) C-1: Drying chamber C-2: Canister	Room temperature and negative pressure Mixture of nitrogen, steam, and hydrogen	0–100 ppm	Sample gas from the selected container using a pump, or install a sensor in the pipe.
C	Sequential monitoring	Inert gas injection process B-1: Canister B-2: Cavity of the transfer cask	Room temperature and atmospheric pressure Mixture of nitrogen, steam, and hydrogen	100ppm Or higher	Sample gas from the selected container using a pump, or install a sensor in the pipe.

A: Continuous monitoring in the transfer cask, B: Sequential monitoring during drying, and C: Sequential monitoring during inert gas injection

[Supplement-16] Details of hydrogen measurement technology (14/18)
Investigation results of hydrogen concentration measurement technology (2/4)



Sensor principle		1. Heat conduction type	2. Contact combustion type	3. Hot-wire semiconductor type	4. New ceramic type	5. Semiconductor type
Principle		Utilize the fact that the thermal conductivity of hydrogen is greater than that of air, etc. The decrease in Pt resistance due to drop in temperature is measured by a bridge circuit.	tilize the fact that H_2 has a low combustion start emperature with precious metal catalysts. he increase in resistance caused by the rise of Pt emperature due to contact combustion is measured y a bridge circuit.	Utilize the fact that H_2 has a low combustion start temperature with precious metal catalysts. The decrease in semiconductor resistance due to electrons generated by the chemical reaction between H_2 and oxygen ions adsorbed on metal oxide semiconductors (In_2O_3, etc.) is measured by a bridge circuit.	Utilize the fact that H_2 has a low combustion start temperature with precious metal catalysts. Precious metal wire coil supporting the ultra-fine metal oxide (new ceramic) changes its electric resistance due to normal temperature caused by hydrogen combustion, and this is measured by a bridge circuit.	When oxygen adsorbed on the surface of a metal oxide semiconductor comes into contact with hydrogen, the resistance value decreases. The gas concentration is obtained from this change in resistance. Higher sensitivity than the new ceramic type.
Measuring range and accuracy		0 to 100 vol.%	to 100 % LEL	0 to 2000 ppm	ppm to 100%LEL	0 to 200 ppm
		About ±2%FS	bout ±5%FS			
Evaluation	A	○	○	△ (Deterioration verification required, high concentration of hydrogen NG)	○	△ (Deterioration verification required, high concentration of hydrogen NG)
	B	×	○	○	○	○
	C	△ (Preliminary gas separation)	○	○	○	○
Interfering gas		He (0.78 vol.%), Ne, CH_4,	lammable gas	Flammable gas	Flammable gas	Flammable gas
		CO_2 (-0.05 vol.%), Ar, SO_2,	CH_3OH [methanol], CO, C_2H_5OH [ethanol], i-C_4H_{10} sopentane * component of propane gas], C_2H_2 cetylene])	However, the effect can be eliminated by SiO_2 coating, which acts as a molecular sieve		
		Cl_2 (-0.12 vol.%) Etc.				
		* Values in parentheses show changes in indicated values due to +1 vol.% fluctuation (approximate values)				
Evaluation	A	○	○	○	○	○
	B	○	○	○	○	○
	C	○	○	○	○	○
Responsiveness		Continuous (estimated to be several tens of seconds)	ontinuous (90% response time 5-10 seconds)	Continuous (90% response time about 20 seconds)	Continuous (estimated to be several tens of seconds)	Continuous (estimated to be several tens of seconds)
Installation method	A	Installed in transfer container	stalled in transfer container	Installed in transfer container	Installed in transfer container	Installed in transfer container
	B	Installed in the exhaust line	stalled in the exhaust line	Installed in the exhaust line	Installed in the exhaust line	Installed in the exhaust line
	C	Installed in the exhaust gas line	stalled in the exhaust gas line	Installed in the exhaust gas line	Installed in the exhaust gas line	Installed in the exhaust gas line
Comprehensive evaluation		Applicable to continuous real-time monitoring	xygen is needed in the gas	Oxygen is needed in the gas	Oxygen is needed in the gas	Verification of durability in the usage environment required
	A	○	×	×	×	×
	B	×	×	×	×	×
	C	△ (Preliminary gas separation)	×	×	×	×

A: Continuous monitoring in the transfer cask

[Supplement-16] Details of hydrogen measurement technology (15/18)

Investigation results of hydrogen concentration measurement technology (details) (3/4)

Sensor Principle		6. Light wave interference type	7. Non-dispersed infrared ray type	8. Difference absorption spectroscopy (DOAS)	9. Gas chromatography type	10. Proton conductor (proton conductive solid electrolyte)
Principle		Utilize the fact that the refractive index of H2 is smaller than that of air, etc. The LED light is split into two, and after passing through the sample gas and standard gas, they are combined and the position of the interference fringes is measured by CCD.	The target gas is passed through the measurement cell, infrared rays are irradiated, and the concentration is obtained from the amount of change in infrared rays due to absorption.	Gas concentration is measured by utilizing the fact that light of the wavelength determined for each gas type is absorbed. Measure the concentration of gas present between the light source and the detector.	Utilizes the separation of H2 from other flammable gases by gas chromatography. H2 is separated by gas chromatography and then detected by a metal oxide semiconductor.	Measurement method using an inorganic proton conductor. Using the Nernst equation, the potential difference is converted to hydrogen partial pressure ratio between the reference gas and the measurement gas.
Measuring range and accuracy		0 to 100 vol.% About ±1%FS to ±4%FS	Hundreds of ppm to tens of vol.%	1000 ppm to several vol.%	0 to 100 vol.% About ±10%FS	0 to 100 vol.% 1%±0.1%; 10%±1%; 100%±3%
Evaluation	A	O	O	O	O	O
	B	x	Δ (Preliminary gas separation)	Δ (Adjustment of optical path length required)	Δ (Additional sensor required)	Δ (Verification required)
	C	Δ	O	O	O	O
Interfering gas		O2 (0.16vol.%), CO2 (−0.96vol.%), Cl2, etc. * Values in parentheses show changes in indicated values due to +1 vol.% fluctuation (approximate values)	Gas that absorbs large amount of infrared rays (H_2O, Co_2, etc.)	Dust, fume, mist, etc. that cause light scattering and absorption	None	Oxygen gas (combustion)
Evaluation	A	O	O	O	O	O
	B	O	Δ (Preliminary gas separation)	Δ (Preliminary gas separation)	O	O
	C	O	Δ (Preliminary gas separation)	Δ (Preliminary gas separation)	O	O
Responsiveness		Scattered (also continuous)	Continuous (Filter regeneration required)	Continuous	Scattered (1 data/ 10 mins)	Continuous – Response time 1s or less
Installation method	A	Installed near the cask to collect gas	Installed near the cask to collect and analyze gas	Transfer cask installation (light source and detector)	Installed near the cask to collect and analyze gas	Installation of transfer cask
	B	Installed near the exhaust line to collect gas	Installed near the exhaust line to collect gas	Exhaust line installation	Installed near the exhaust line to collect gas	Exhaust line installation
	C	Installed near the exhaust line to collect gas	Installed near the exhaust line to collect gas	Exhaust line installation	Installed near the exhaust line to collect gas	Exhaust line installation
Comprehensive evaluation		Low concentration and depends on CCD resolution: Difficult	Interference gas filter regeneration required	Adjustment of optical path length and filter for dust, etc.	Multiplexing for continuous monitoring	The temperature of part to be measured is high. Heat shock countermeasures required
	A	x	x	Δ	Δ (Suction pump required)	Δ (Damage countermeasures required)
	B	x	x	Δ	Δ (Additional sensor required)	Δ (Concentration measurement required)
	C	Δ	Δ	Δ	O	O

B: Sequential monitoring in the drying process (decompression heating)
C: Sequential monitoring in the inert gas injection process

【Supplement-16】 Details of hydrogen measurement technology (16/18)

b. Investigation of hydrogen concentration measurement technologies (4/4)

Based on the result of the investigation of hydrogen concentration measurement technologies, technologies applicable to the monitoring schemes A, B, and C were identified and evaluated, and the following methods were selected as candidates.

A: Continuous monitoring: Heat conduction type hydrogen meter

B: Sequential monitoring during drying process: Gas chromatographic method or proton conductor hydrogen meter

C: Sequential monitoring during inert gas injection with a gas chromatographic method or **proton conductor hydrogen meter**

[Supplement-16] Details of hydrogen measurement technology (17/18)

Principles of hydrogen concentration measurement technology (heat conduction type)

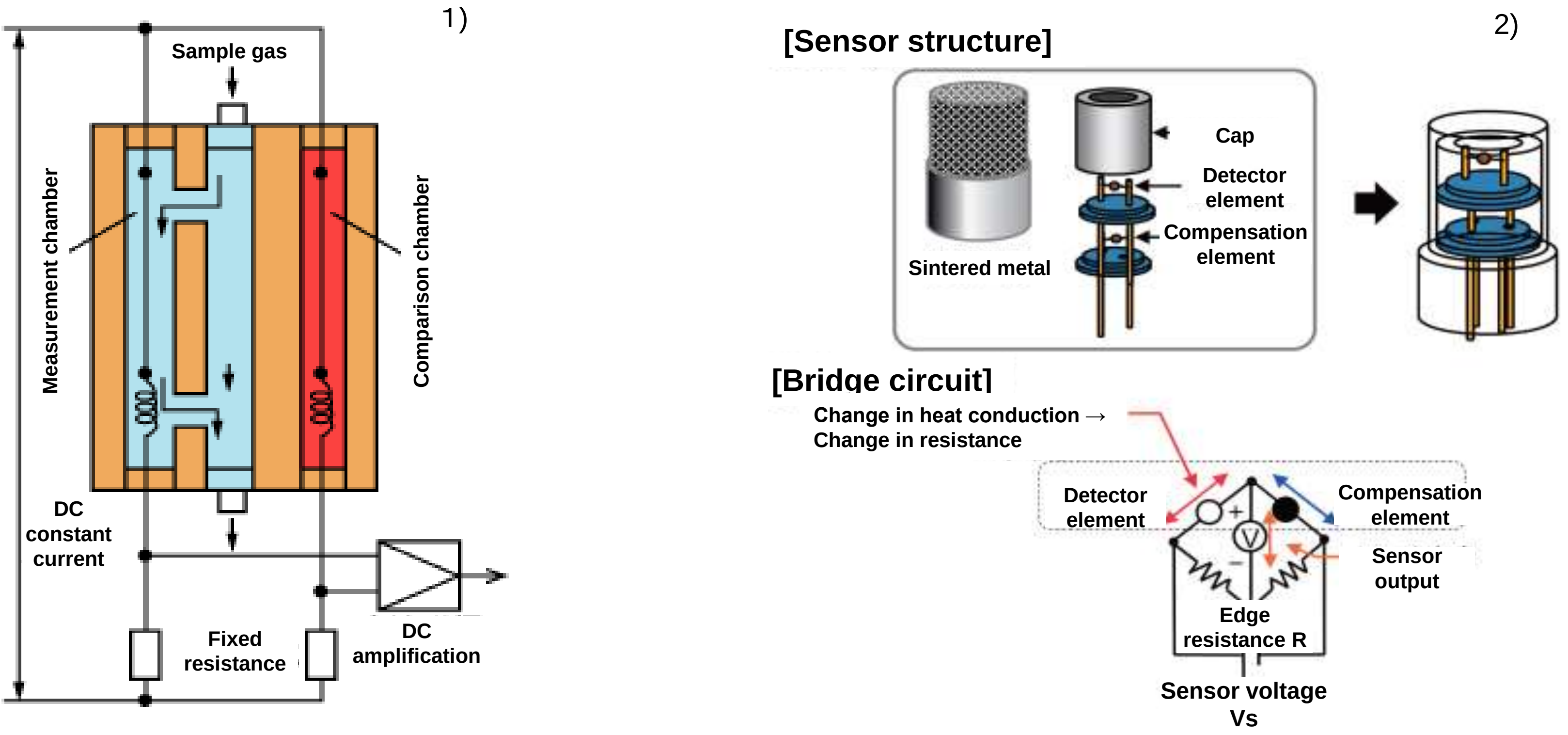


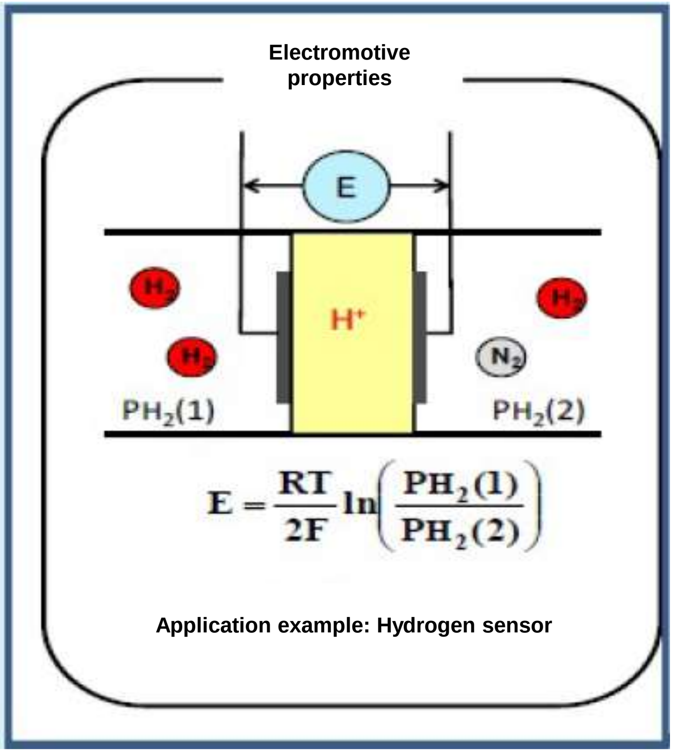
Figure. Diagram showing the principle of the heat conduction type analysis device

Uses the fact that the heat transfer coefficient differs depending on the gas type.
The difference in temperature of platinum wire heated with a constant current in the reference gas atmosphere and the gas atmosphere to be measured, is measured as the difference in electric resistance.

Source:
1) Fuji Electric Co., Ltd. HP “Thermal Conductivity Gas Analyzer - Optimum for concentration measurement for H2, Ar, and He; Type: ZAF”
https://www.fujielectric.co.jp/products/instruments/products/anlz_gas/ZAF.html
2) RIKEN KEIKI Co., Ltd. Document “Riken Sensors - Introduction to Technology”
https://www.rikenkeiki.co.jp/cms/riken/pdf/support/PC9-0314-180610S.pdf

[Supplement-16] Details of hydrogen measurement technology (18/18)

Principles of hydrogen concentration measurement technology (proton conductor)



$$E = \frac{RT}{2F} \ln\left(\frac{PH_2(1)}{PH_2(2)}\right)$$

Figure. Diagram showing the principle of a proton conduction-type hydrogen sensor

A solid that selectively permeates hydrogen ions (protons) is called a proton conductive solid electrolyte, and when the hydrogen gas concentration at both ends of the proton conductive solid electrolyte is different, an electromotive force is generated according to the partial pressure.

The generated electromotive force can be converted to concentration by the formula in the figure.

Source: TYK Corporation; HP “Hydrogen Sensor for Gas – NOTORP-G”
http://www.tyk.co.jp/02ProductInfo/product02-04/details01.html