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 2019 Research Report

August 2020

International Research Institute for Nuclear Decommissioning (IRID)

Contents

1. Research background and purpose

1.1. Background

For decommissioning of the 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.

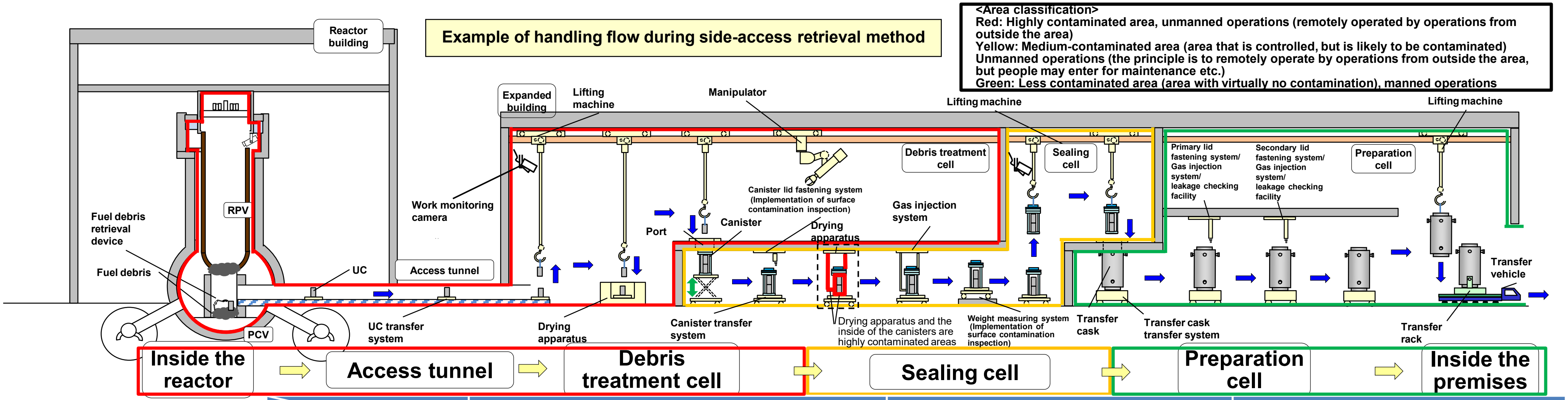
•1.2. Purpose

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

Black text: Indicates that technological development is not required based on past results, etc.
Blue text: Indicates study has been completed
Red text: Indicates that issues remain ⇒ under study in this PJ

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)

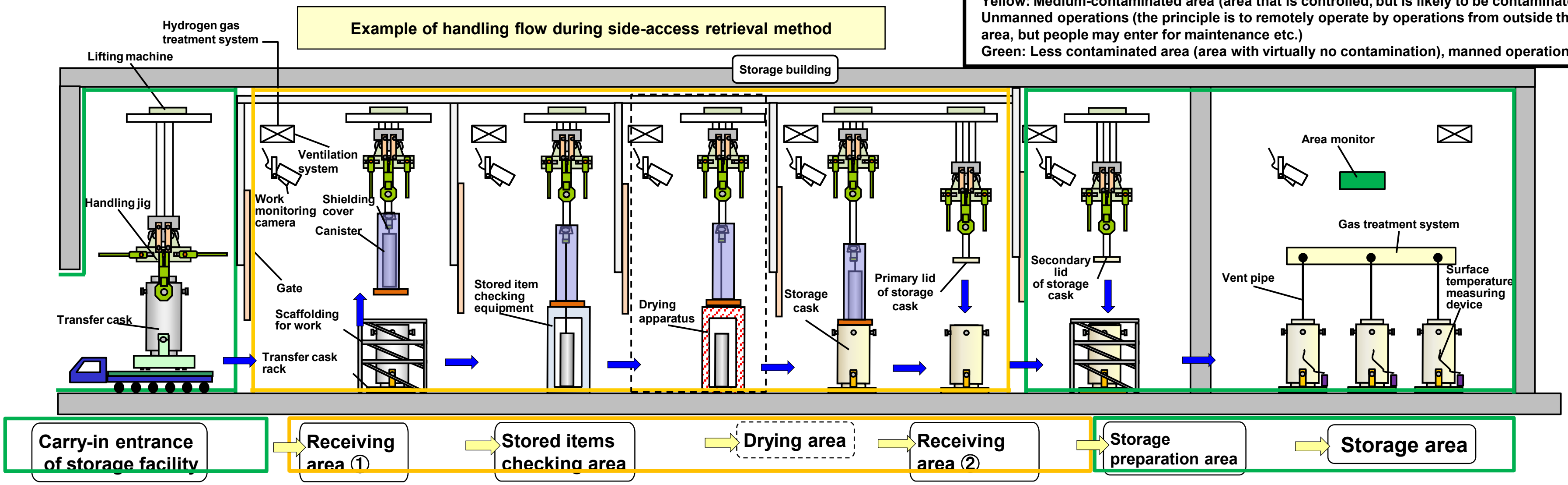
Area Canister		Sealing cell	Preparation cell (excluding drying apparatus)	Inside the premises
Safety design	Subcriticality	Subcriticality can be maintained by the geometrical shape of canister	Subcriticality can be maintained by the geometrical shape of the canister and the arrangement inside the transfer 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, study of filter and sealing cell. (Gas is released in a controlled manner)	Confinement using the sealing material of canister, study of filter and preparation cell. (Gas is released in a controlled manner)	Confinement using the sealing material of canister, study of filter 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		Can withstand accidents during transfers (Designed to be encapsulated during fall)
	Material	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/ 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) · Study of hydrogen concentration measurement inside transfer cask to ensure that the hydrogen concentration is 4 vol.% or less at the time of transfer		· Study for sealing the canister/ transfer cask for up to 7 days · Study of method to predict hydrogen generation at the time of transfer (by evaluation formula) · Study on recombination catalyst
	Fire prevention	Can maintain the inside of sealing cell/ preparation cell/ transfer cask at an inert atmosphere		
Handleability		Can be remotely transported and closed with a lid	Can be remotely transported	Can be stored in transfer cask
Improvement in storage workability		The storage work efficiency can be improved by expanding the inner diameter of the canister	None	

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



Black text: Indicates that technological development is not required based on past results, etc.
Blue text: Indicates study has been completed
Red text: Indicates that issues remain ⇒ under study in this PJ

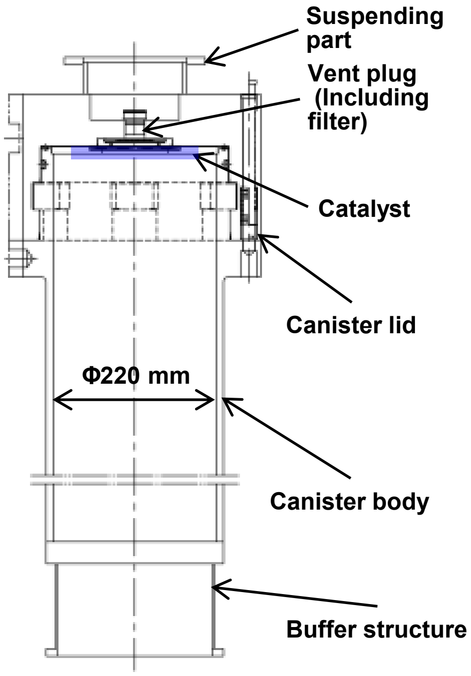
Note: Drying area shall be set up when drying apparatus cannot be installed inside the debris treatment cell

Canister \ Area		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, study of filter 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		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/ Can be scavenged inside the building		Can be vented/ scavenged inside the storage cask
	Fire prevention	Can maintain the building/ inside of transfer cask at an inert atmosphere		
Handleability		Can be remotely transported		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 set (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 as “development of storage technology”)
	Shielding	・No problem.	–
Other (Maintaining the shutdown, cooling and confinement functions)	Structure	・The integrity was checked 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 as “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 as “development of transfer technology”) ・Study on vent diameter (Studied as “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 as “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 FY2 020)
・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 technology for containing of fuel debris	
① Study of canister specifications and structure	• The structural integrity of the canister as per the provisionally 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 technology for transfer of 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)
② Study 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)

IRID

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

3.1 Implementation Items

This subsidy project plans to work 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 real-size canister.

(3) Development of technology for transfer of fuel debris

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.

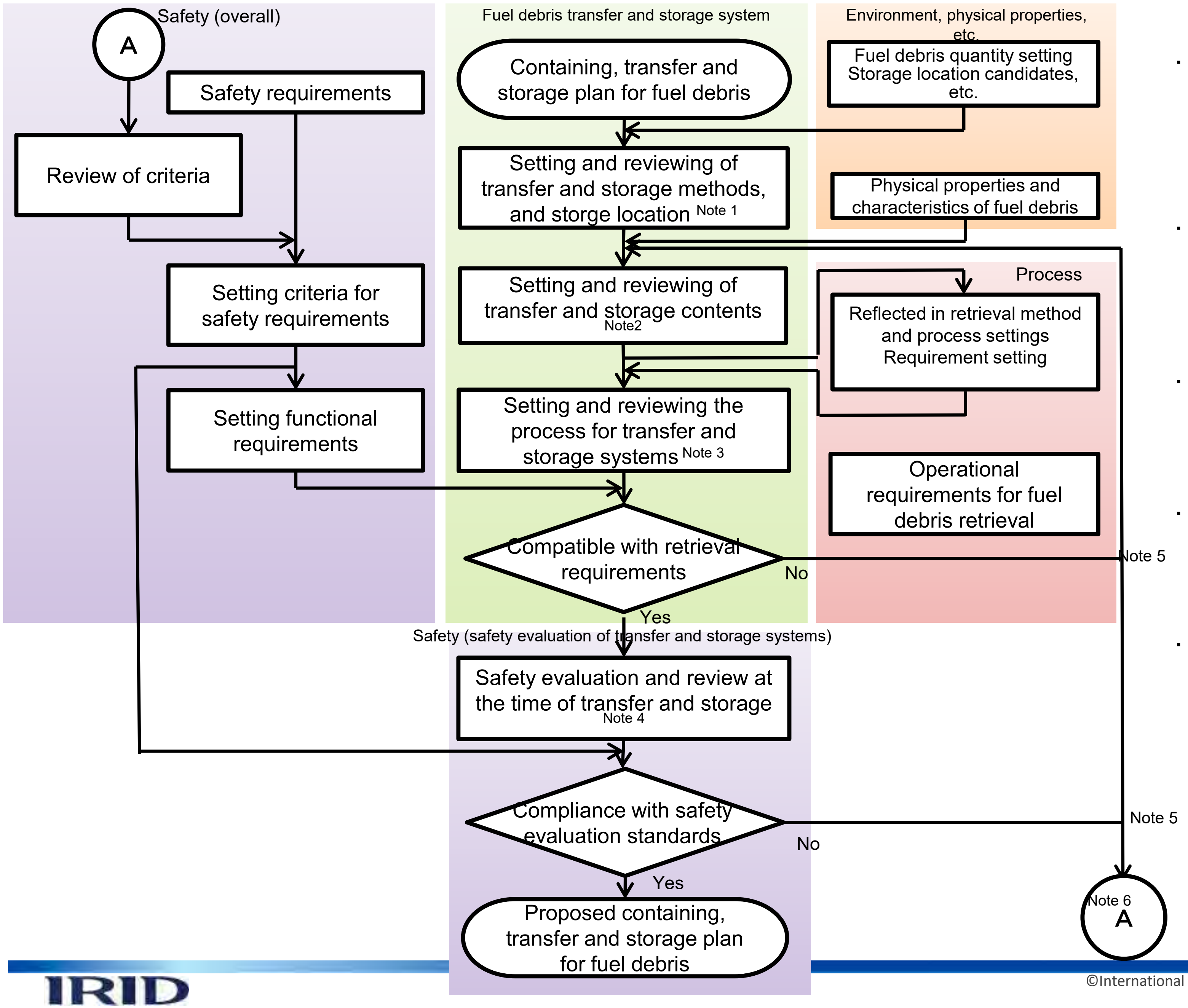
As catalyst-based hydrogen measures, acquire performance data for the candidate catalyst in consideration of the canister environment and confirm the effectiveness considering the diffusion of hydrogen inside the canister.

(4) Development of drying technology and systems

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 real-size test device.

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

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

Note 5

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

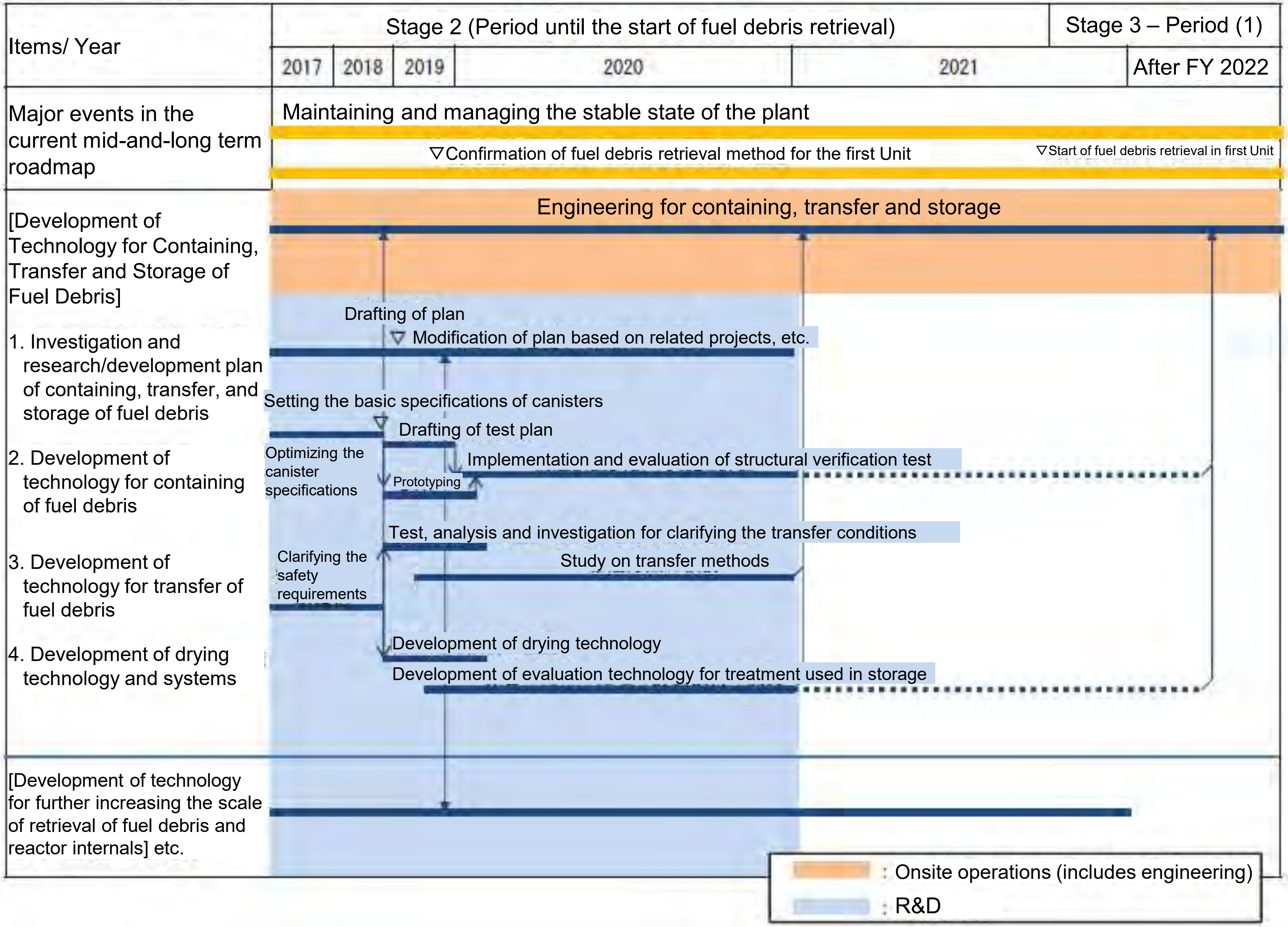
A

- 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

Prototyping

Implementation and evaluation of structural verification test

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

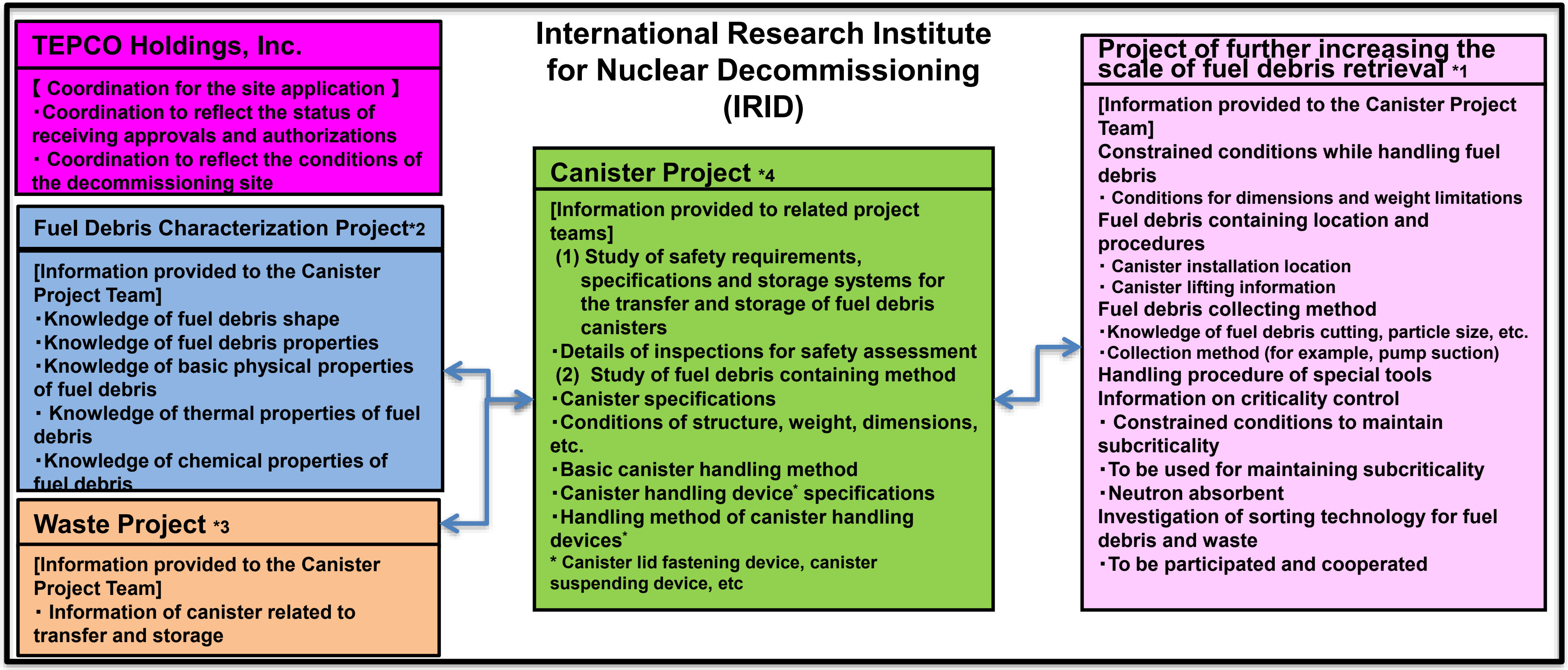
[Development of technology for further increasing the scale of retrieval of fuel debris and reactor internals] etc.

🟧 : 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)

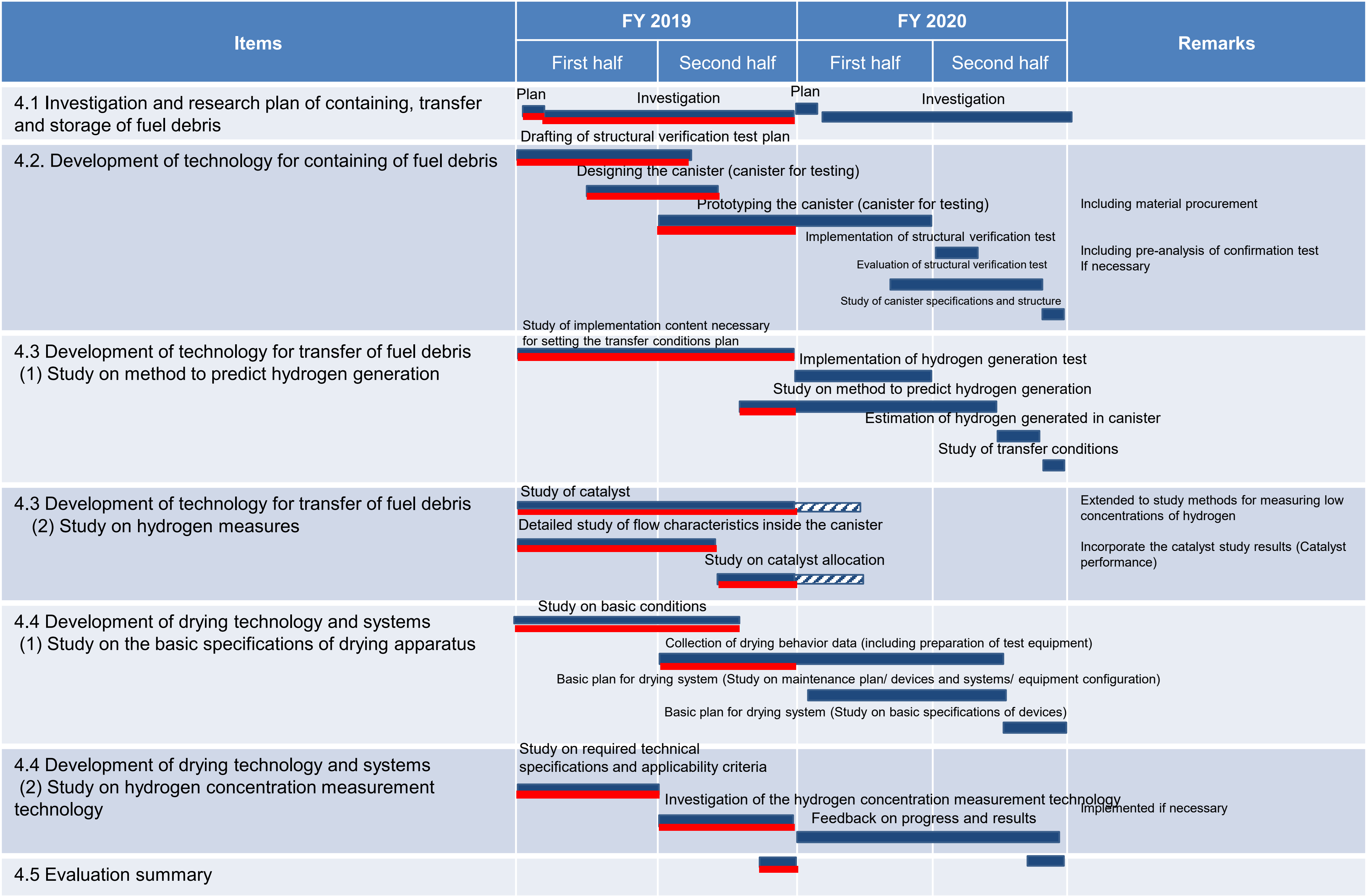
1: Project of further increasing the scale of fuel debris retrieval: Development of technology for further increasing the scale of retrieval of fuel debris and reactor internal structures
*2: Fuel debris characterization project: Development of technology for analysis and estimation of fuel debris characterization
*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

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.

*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*.

4. Implementation schedule

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

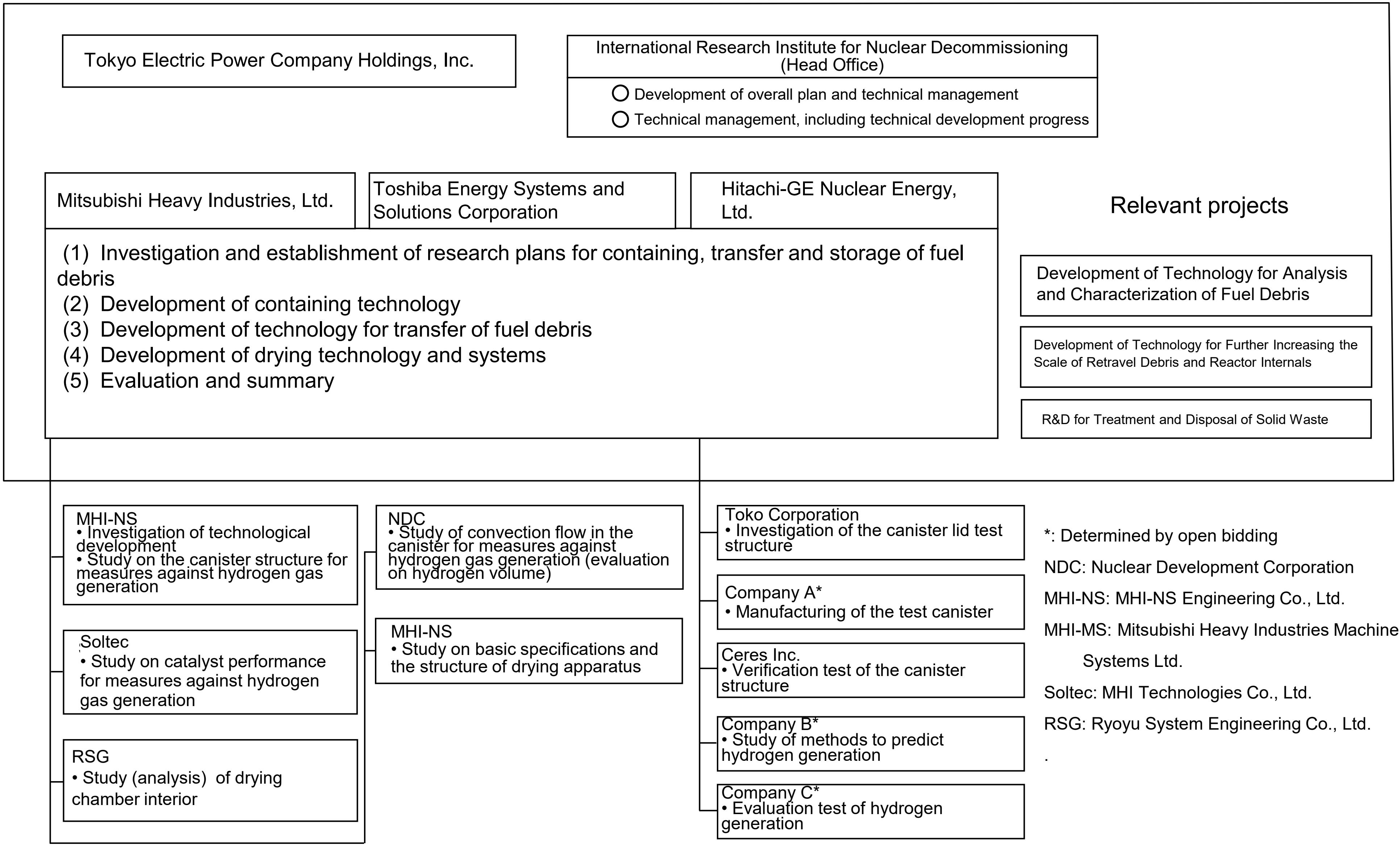


Items	FY 2019 First half	FY 2019 Second half	FY 2020 First half	FY 2020 Second half	Remarks
4.1 Investigation and research plan of containing, transfer and storage of fuel debris	Plan Investigation		Plan Investigation		
4.2. Development of technology for containing of fuel debris	Drafting of structural verification test plan Designing the canister (canister for testing)	Prototyping the canister (canister for testing)	Evaluation of structural verification test	Implementation of structural verification test Study of canister specifications and structure	Including material procurement Including pre-analysis of confirmation test If necessary
4.3 Development of technology for transfer of fuel debris (1) Study on method to predict hydrogen generation	Study of implementation content necessary for setting the transfer conditions plan	Study on method to predict hydrogen generation	Implementation of hydrogen generation test	Estimation of hydrogen generated in canister Study of transfer conditions	
4.3 Development of technology for transfer of fuel debris (2) Study on hydrogen measures	Study of catalyst Detailed study of flow characteristics inside the canister	Study on catalyst allocation			Extended to study methods for measuring low concentrations of hydrogen Incorporate the catalyst study results (Catalyst performance)
4.4 Development of drying technology and systems (1) Study on the basic specifications of drying apparatus	Study on basic conditions	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		Implemented if necessary
4.5 Evaluation summary					

▬ : Plan 🟥 : Actual ▨ : Reviewed plan

5. Project Organization Chart

(as of the end of March 2020)



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 Scale of Retravel Debris and Reactor Internals

R&D for Treatment and Disposal of Solid Waste

MHI-NS
- Investigation of technological development
- Study on the canister structure for measures against hydrogen gas generation

Soltec
- Study on catalyst performance for measures against hydrogen gas generation

RSG
- Study (analysis) of drying chamber interior

NDC
- Study of convection flow in the canister for measures against hydrogen gas generation (evaluation on hydrogen volume)

MHI-NS
- Study on basic specifications and the structure of drying apparatus

Toko Corporation
- Investigation of the canister lid test structure

Company A*
- Manufacturing of the test canister

Ceres Inc.
- Verification test of the canister structure

Company B*
- Study of methods to predict hydrogen generation

Company C*
- Evaluation test of hydrogen generation

*: Determined by open bidding

NDC: Nuclear Development Corporation

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

MHI-MS: Mitsubishi Heavy Industries Machinery Systems Ltd.

Soltec: MHI Technologies Co., Ltd.

RSG: Ryoyu System Engineering Co., Ltd.

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Contents

6. Implementation Details

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

① Purpose and Goal

To obtain the latest trends of related PJs and the latest trends of on-site operations and work together to make technology development useful, and in addition, to improve the efficiency of technological development by collecting information from overseas.

② Implementation items and results (Estimated and actual)

a. Reflection of latest trends in research plan (FY 2019, FY 2020)

In order to make the technological development useful from the viewpoint of consistency with related PJs and site application, the latest knowledge and study status of the project of further increasing the scale of fuel debris retrieval, fuel debris characterization project, waste project, etc., were obtained through joint meetings, and the status of coordination related to on-site work at TEPCO Holdings and latest trend/ information such as the status of coordination related to licensing were obtained, and incorporated in the research plan.

For example, the plan for the current unit can shape was obtained from the project of further increasing the scale of fuel debris retrieval and reflected in the drying test plan.

b. Investigation of overseas information (FY2019, FY2020)

The already obtained literature on the drying of TMI-2 fuel debris was re-evaluated for an efficient development plan. (Described in 6.4 Development of drying technology and systems (1) Study on the basic specifications of drying apparatus)

6. Implementation Details

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

③ Contribution of the results to the areas where they can be reflected

The implementation results will be reflected in the study items of this subsidy project.

④ Analysis from the perspective of site application

The latest on-site trends are reflected in the study items of this subsidy project, which is useful.

⑤ Issues

There are no issues in executing the current plan.

⑥ Level of achievement

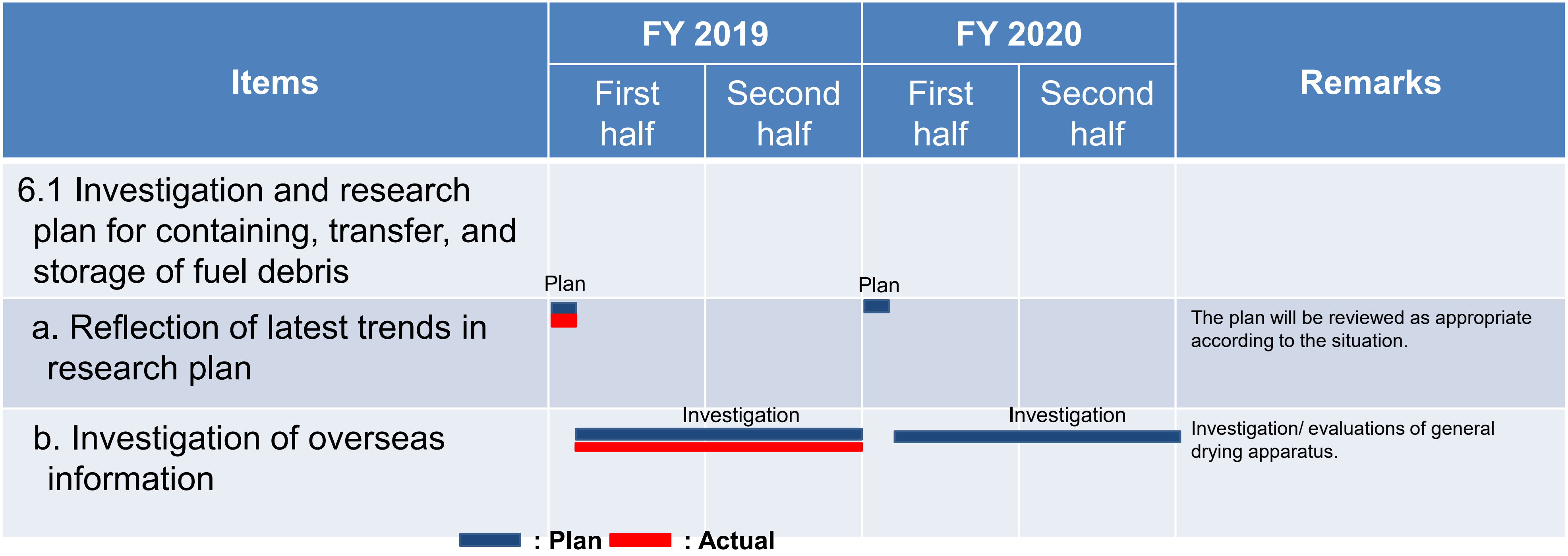
The latest study status and findings of other projects and actual projects were collected and overseas safety-related technical requirements, etc., were additionally analyzed and organized based on already obtained information. In the future, it is expected that the specified results will be obtained by reflecting these along with the experts' opinions in the respective research plans.

6. Implementation Details

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

⑦ Future plans

Table　　Study schedule for the investigation and research plan for containing, transfer, and storage



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
6.1 Investigation and research plan for containing, transfer, and storage of fuel debris					
a. Reflection of latest trends in research plan	Plan		Plan		The plan will be reviewed as appropriate according to the situation.
b. Investigation of overseas information	Investigation		Investigation		Investigation/ evaluations of general drying apparatus.

🟦 **: Plan** 🟥 **: Actual**

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

① Purpose and Goal

To propose the specification and structural plan of the canister.

To review the specification and structural plans of the canister that were provisionally set in FY 2018, and to make a prototype of the real-size canister, for that purpose. Also, to conduct a structural verification test using the prototype canister to confirm the maintenance of the safety functions (criticality prevention and confinement) during evaluation events.

In addition, to confirm the applicability of the analysis methods that can simulate the structural integrity of the canister in various events, by comparing and evaluating with the results of the structural verification test.

② Comparison with existing technology

Among the lid structures studied in FY2018, the bolt structure is a method of fastening the lid by tightening the bolts, and it is considered possible to be designed within the application range of the existing technology.

Meanwhile, the simple mounting 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 or tumbling, etc. Hence 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

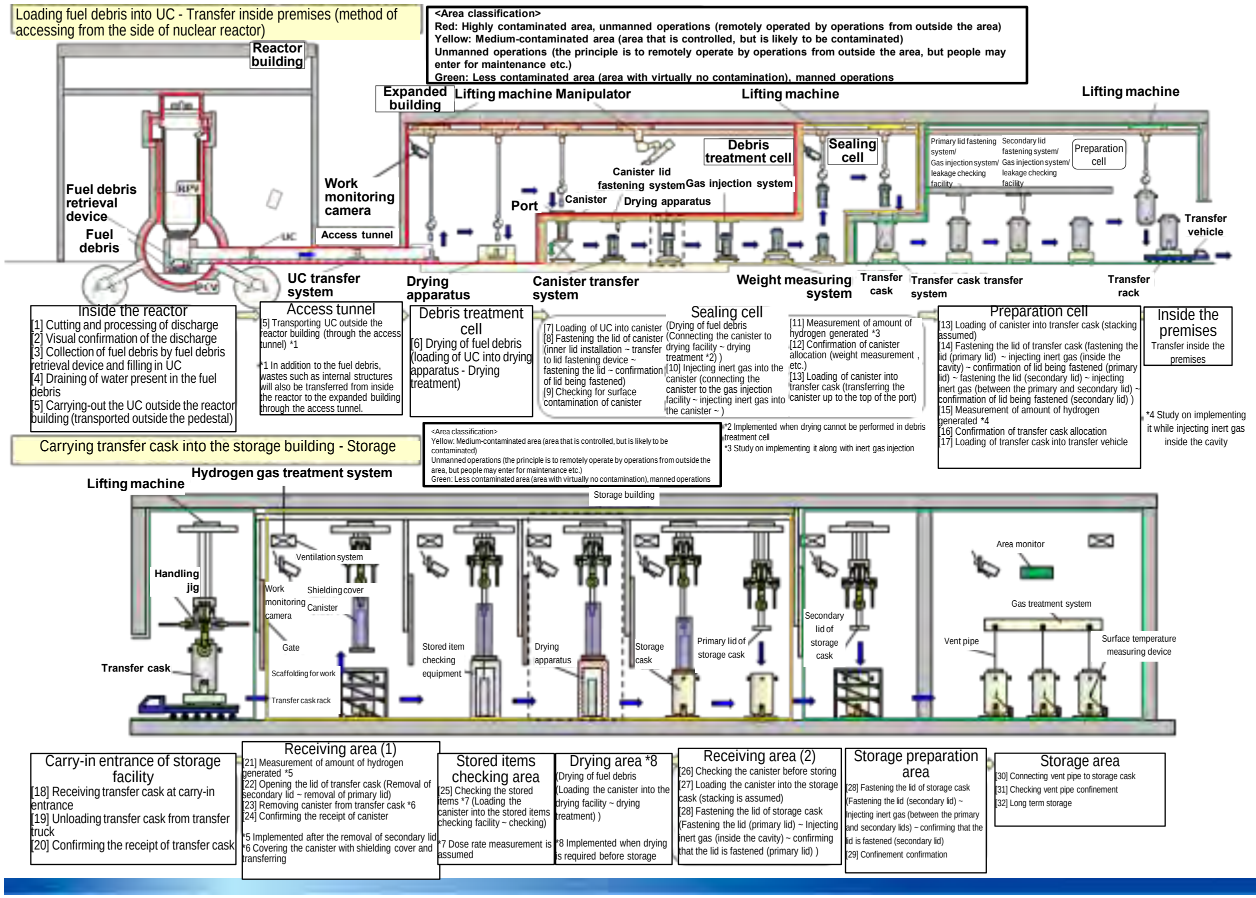
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY 2019) (1/10)

(i) Selection of events to be tested (1/4)

Events from each operation of the latest handling flow of canister (side-access retrieval method, dry storage, metal cask storage) were identified as the targets for event selection.



Loading fuel debris into UC - Transfer inside premises (method of accessing from the side of nuclear reactor)

<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

Inside the reactor
[1] Cutting and processing of discharge
[2] Visual confirmation of the discharge
[3] Collection of fuel debris by fuel debris retrieval device and filling in UC
[4] Draining of water present in the fuel debris
[5] Carrying-out the UC outside the reactor building (transported outside the pedestal)

Access tunnel
[5] Transporting UC outside the reactor building (through the access tunnel) *1

*1 In addition to the fuel debris, wastes such as internal structures will also be transferred from inside the reactor to the expanded building through the access tunnel.

Debris treatment cell
[6] Drying of fuel debris (loading of UC into drying apparatus - Drying treatment)

Sealing cell
[7] Loading of UC into canister
[8] Fastening the lid of canister (inner lid installation ~ transfer to lid fastening device ~ fastening the lid ~ confirmation of lid being fastened)
[9] Checking for surface contamination of canister
(Drying of fuel debris (Connecting the canister to drying facility ~ drying treatment *2))
[10] Injecting inert gas into the canister (connecting the canister to the gas injection facility ~ injecting inert gas into the canister ~)
[11] Measurement of amount of hydrogen generated *3
[12] Confirmation of canister allocation (weight measurement , etc.)
[13] Loading of canister into transfer cask (transferring the canister up to the top of the port)

*2 Implemented when drying cannot be performed in debris treatment cell
*3 Study on implementing it along with inert gas injection

Preparation cell
[13] Loading of canister into transfer cask (stacking assumed)
[14] Fastening the lid of transfer cask (fastening the lid (primary lid) ~ injecting inert gas (inside the cavity) ~ confirmation of lid being fastened (primary lid) ~ fastening the lid (secondary lid) ~ injecting inert gas (between the primary and secondary lid) ~ confirmation of lid being fastened (secondary lid))
[15] Measurement of amount of hydrogen generated *4
[16] Confirmation of transfer cask allocation
[17] Loading of transfer cask into transfer vehicle

Inside the premises
Transfer inside the premises

*4 Study on implementing it while injecting inert gas inside the cavity

Carrying transfer cask into the storage building - Storage

<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

Carry-in entrance of storage facility
[18] Receiving transfer cask at carry-in entrance
[19] Unloading transfer cask from transfer truck
[20] Confirming the receipt of transfer cask

Receiving area (1)
[21] Measurement of amount of hydrogen generated *5
[22] Opening the lid of transfer cask (Removal of secondary lid ~ removal of primary lid)
[23] Removing canister from transfer cask *6
[24] Confirming the receipt of canister

*5 Implemented after the removal of secondary lid
*6 Covering the canister with shielding cover and transferring

Stored items checking area
[25] Checking the stored items *7 (Loading the canister into the stored items checking facility ~ checking)

*7 Dose rate measurement is assumed

Drying area *8
(Drying of fuel debris (Loading the canister into the drying facility ~ drying treatment))

*8 Implemented when drying is required before storage

Receiving area (2)
[26] Checking the canister before storing
[27] Loading the canister into the storage cask (stacking is assumed)
[28] Fastening the lid of storage cask (Fastening the lid (primary lid) ~ Injecting inert gas (inside the cavity) ~ confirming that the lid is fastened (primary lid))

Storage preparation area
[28] Fastening the lid of storage cask (Fastening the lid (secondary lid) ~ Injecting inert gas (between the primary and secondary lids) ~ confirming that the lid is fastened (secondary lid)
[29] Confinement confirmation

Storage area
[30] Connecting vent pipe to storage cask
[31] Checking vent pipe confinement
[32] Long term storage

Figure. Handling flow of canister

<Definition of events>

① Abnormal events

Refers to the events caused by a single failure or malfunction of the equipment handled or by a single incorrect operation by the operator, in each operation in the handling flow of canister

② Accident events

Refers to events that exceed the abnormal events in each operation in the handling flow of canister. It is an event that is technically expected to occur, and when it does occur, it may release radioactive materials, and is important from the perspective of radiation exposure of the general public.

③ Design events

Of the above abnormal events/ accident events, design event refers to events, the occurrence and spread of which should be prevented by the design of the facilities/ equipment, and which should be considered in the design.

④ Evaluation event

Refers to events that are not expected to occur as they can be dealt with by equipment or operations, however, the impact of these events needs to be evaluated from a safety viewpoint.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

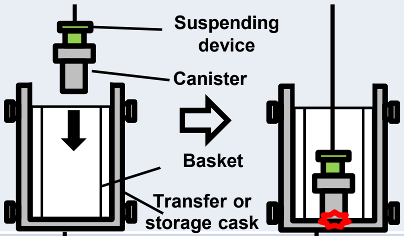
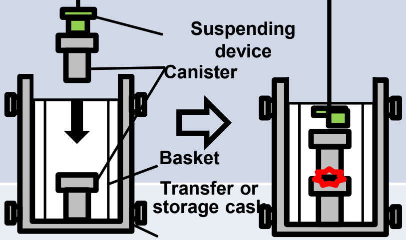
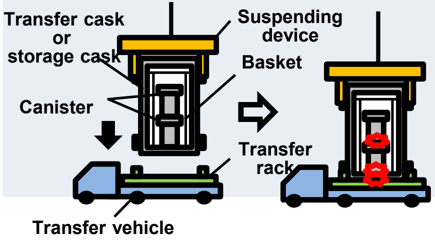
③Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY 2019) (2/10)

(i) Selection of events to be tested (2/4)

Design events were identified from each operation based on the latest handling flow of a canister.

Table Results of identification of design events (typical example)

No.	Design events		Diagram showing the events	Possibility of event occurrence Note1	Impact on basic safety functions and structural strength Note2	Events for which structural verification test is implemented	
						Accepted/ Rejected	Approach to selection
1	Abnormal landing of canister inside the transfer or storage cask, etc.	An event where the canister being loaded inside the transfer or storage cask, etc., collides with the bottom of the transfer or storage cask at a lowering velocity due to an incorrect operation by the worker.		○	△	x	As the collision velocity in the evaluation event "No. 5 drop of canister" is faster than the lowering velocity at the time of collision (assuming about 0.025 m/s), it is assumed to be covered under that event, and not considered as an event to be tested.
2	Abnormal landing of canister on top of another canister	An event where the canister being loaded inside the transfer or storage cask, collides with the top of an already loaded canister inside the transfer or storage cask at a lowering velocity due to an incorrect operation by the worker.		○	△	x	As the collision velocity in the evaluation event "No. 6 drop of canister on top of another canister" is faster than the lowering velocity at the time of collision (assuming about 0.025 m/s), it is assumed to be covered under that event, and not considered as an event to be tested.
3	Abnormal landing of transfer or storage cask on transfer rack	An event where the transfer or storage cask to be placed on the transfer rack, collides with the transfer rack at the lowering velocity due to the incorrect operation by the worker.		○	△	x	As the collision velocity in the evaluation event "No. 5 drop of canister" is faster than the lowering velocity at the time of collision (assuming about 0.025 m/s), it is assumed to be covered under that event, and not considered as an event to be tested.

Note 1: Possibility of event occurrence

x: The occurrence of event can be avoided by handling it with equipment or operations. ○: Occurrence of event cannot be avoided

Note 2: Impact on basic safety functions and structural strength

x: Events that do not have an impact △: Events that have an impact, but are not expected to lead to criticality or the release of radioactive materials ○: Events that have an impact and are expected to lead to criticality or the release of radioactive materials

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

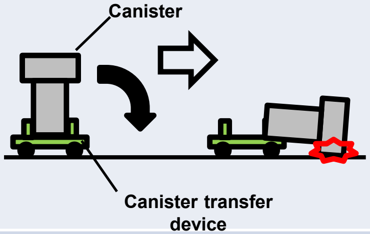
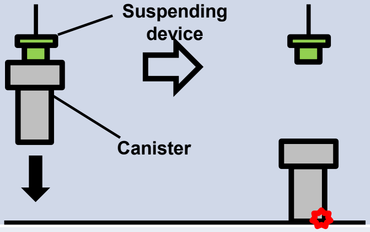
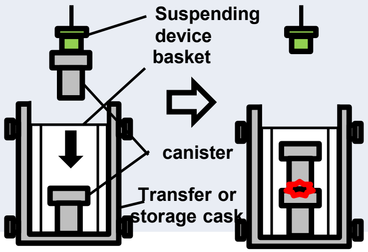
③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY2019) (3/10)

(i) Selection of events to be tested (3/4)

Evaluation events were identified from each operation based on the latest handling flow of a canister.

Table Results of identification of evaluation events (typical example)

No.	Evaluation events		Diagram showing the events	Possibility of event occurrence Note1	Impact on basic safety functions and structural strength Note2	Events for which structural verification test is implemented	
						Accepted/ Rejected	Approach to selection
4	Tumbling of canister	An event where the canister being moved tumbles due to damaged fixing mechanism of the canister transfer device, etc.		x	○	x	The result of preliminary analysis showed that the collision velocity from the side when a canister falls in the oblique orientation in the evaluation event "No. 5 drop of canister" was faster than tumbling (tumbling: about 7 m/s, dropping in the oblique orientation: 18 m/s). So, it is assumed to be covered under that event, and not considered as an event to be tested.
5	Dropping of canister	An event where the canister being lifted falls due to the damage in the suspending device, etc.		x	○	○	① Canister dropping in the vertical orientation: Compared to other events, the impact load received at the bottom of the canister is supposed to be the largest, so it is considered as an event to be tested. ② Canister dropping in the oblique orientation : Compared to other events, the impact load received from the sides of the canister is supposed to be the largest, so it is considered as an event to be tested.
6	Fall of canister on top of another canister	An event where the canister being loaded inside the transfer or storage cask, falls on top of an already loaded canister due to damage in the suspending device, etc.		x	○	○	Compared to other events, the impact load received at the top of the canister is supposed to be the largest, so it is considered as an event to be tested.

Note 1 : Possibility of event occurrence
x : The occurrence of event can be avoided by handling it with equipment or operations. ○ : Occurrence of event cannot be avoided
Note 2 : Impact on basic safety functions and structural strength
x : Events that do not have an impact △ : Events that have an impact, but are not expected to lead to criticality or the release of radioactive materials ○ : Events that have an impact and are expected to lead to criticality or the release of radioactive materials

6. Implementation Details

6.2 Development of technology for containing of fuel debris
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY 2019) (4/10)

(i) Selection of events to be tested (4/4)

Among the identified design events and evaluation events, the events of the canister dropping in the vertical orientation, the canister dropping in the oblique orientation, and the canister dropping on top of another canister in the vertical orientation, 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 provisionally set to 60º, which has a large impact based on the preliminary analysis.

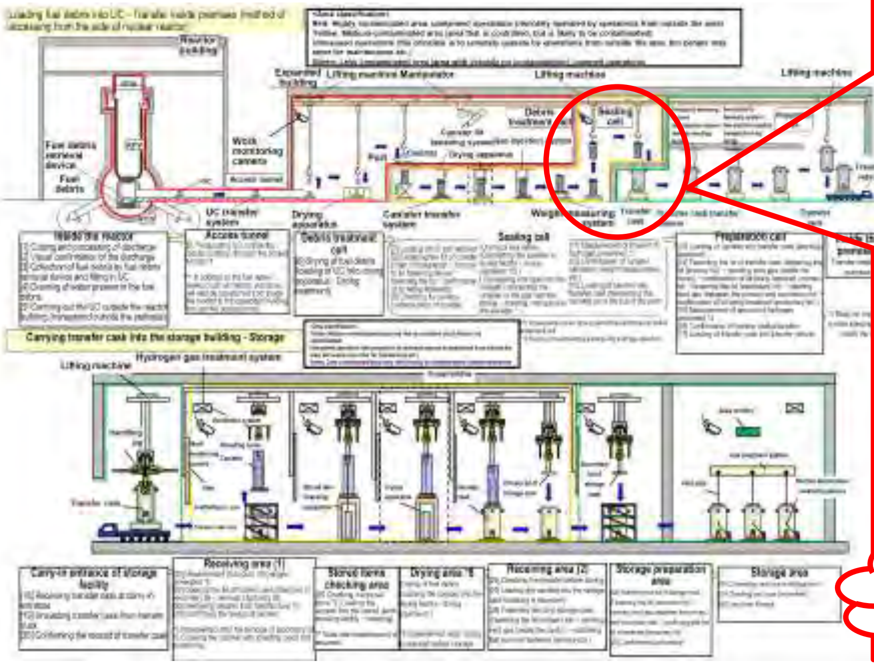


Figure. Canister handling flow plan

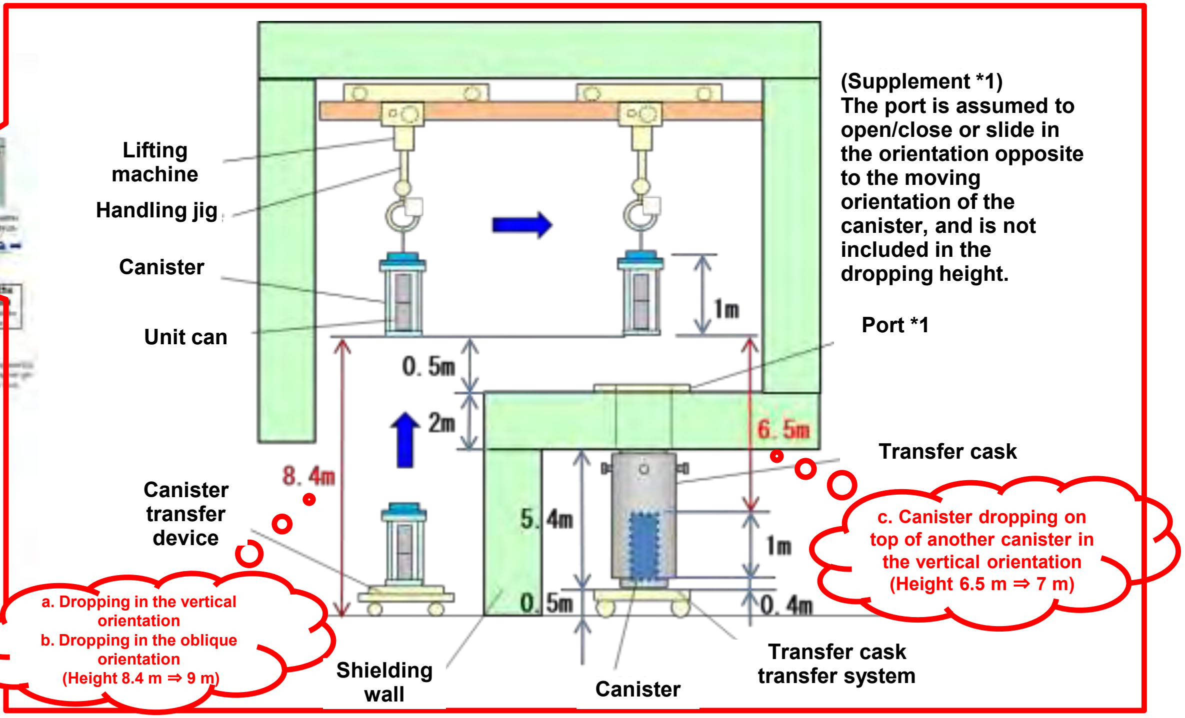


Figure. Approach to setting of the dropping height

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY 2019) (5/10)

(ii) Test cases

For each event, a test was planned with a combination of test conditions and a real-size canister (canister for testing) structure.

Table Test cases (Plan)

No.	Events	Testing conditions			Structure of real-size canister (Canister for testing)				Main goal of the test	Approach to selection of combination for real-size canister (canister for testing) structure
		Drop height	Drop angle	No. of tests	Lid structure	Inner diameter of the body	Air supply mechanism	No. of units		
1	Canister dropping in the vertical orientation	9 m	0º	Once	Simple mounting structure	400 mm	No	1	・The main purpose is to confirm the effect of vertical drop on the body of canister (confirming the amount of deformation of the inner diameter of the body) and to confirm the effectiveness of buffer structure (includes confirming the effect of preventing the collision of stored items with the inner surface of the lid).	・Two types of lid structures, simple mounting structure and bolt structure, are chosen, to check the effect on each lid structure (including confirming the validity of analysis). ・Two types of inner diameter of body, 220 mm and 400 mm [Note 1], are chosen as the condition for different weight/ buffer structure, to confirm the effect of vertical drop on the body of canister (confirming the amount of deformation of the inner diameter of the body) and to confirm the effectiveness of the buffer structure (includes confirming the effect of preventing the collision of stored items with the inner surface of the lid). ・As there is no air supply mechanism in the main plan (the main process involves drying the fuel debris in the unit can, so the air supply mechanism is absent), air supply mechanism is considered absent (if there is an air supply mechanism, it will be evaluated by analysis).
2					Bolt structure	220 mm				
3	Canister dropping in the oblique orientation	9 m	60º (Tentative)	Once	Simple mounting structure	400 mm	Yes	1	・The main purpose is to confirm the effect of dropping in the oblique orientation (including collision of canister on the floor surface after dropping in the oblique orientation) on the lid, bottom plate and air supply mechanism of canister (confirmation of sealability of lid, integrity of air supply mechanism).	・Two types of lid structures, simple mounting structure and bolt structure, are chosen, to check the effect on each lid structure (including confirming the validity of analysis). ・Two types of inner diameter of body, 220 mm and 400 mm [Note 2], are chosen as the condition for different weight/ bottom plate structure/ air supply mechanism structure, to confirm the effect of dropping in the oblique orientation (including collision of the canister on the floor surface after dropping in the oblique orientation) on lid, bottom plate and air supply mechanism of the canister (confirmation on the sealability of the lid, confirmation on the integrity of the bottom plate and air supply mechanism). ・Though there is no air supply mechanism in the main plan (the main process involves drying the fuel debris in the unit can, so the air supply mechanism is absent), air supply mechanism is considered present to confirm the impact of collision with the floor surface.
4					Bolt structure	220 mm				
5	Canister dropping on top of another canister in the vertical orientation	7 m	0º	Once	Simple mounting structure	220 mm	No	2	・The purpose is to confirm the effect of a canister dropping on top of another canister in the vertical orientation, on the body of the canister (confirmation of deformation of inner diameter of body) and to confirm the effectiveness of buffer structure (including deformation of suspending part and confirmation on effectiveness of countermeasures for the event where the buffer structure enters suspending part).	・Two types of lid structures, simple mounting structure and bolt structure, are chosen, to check the effect on each lid structure (including confirming the validity of analysis) ・Two types of inner diameter of body, 220 mm and 400 mm [Note 2], are chosen as the condition for different weight/ buffer structure, to confirm the effect on the body (confirmation on the amount of deformation of the inner diameter of body) and to confirm the effectiveness of the buffer structure (including the deformation of the suspending part and the effectiveness of countermeasures for the event where the buffer structure enters the suspending part) ・As there is no air supply mechanism in the main plan (the main process involves drying the fuel debris in the unit can, so the air supply mechanism is absent), air supply mechanism is considered absent (if there is an air supply mechanism, it will be evaluated by analysis).
6					Bolt structure	400 mm				

Note 1: For simple mounting structure, the inner diameter is set to 400 mm (and for bolt structure, it is set to 220 mm), since the feasibility verification test of the canister lid structure in FY 2018 confirmed that the lid cannot be opened in a simple mounting structure of inner diameter φ400 mm.

Note 2: When the inner diameter of body is 400 mm, the lid should be a simple mounting structure for conditions of heavy weight and heavy impact load (for body with inner diameter of 220 mm, the lid should have a bolt structure).

Note 3: As a test for an impact load in the vertical orientation, consider a combination opposite to that of the test for canister dropping in the vertical orientation, that is, inner diameter of simple mounting structure is set to 220 mm and for bolt structure, it is set to 400 mm.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

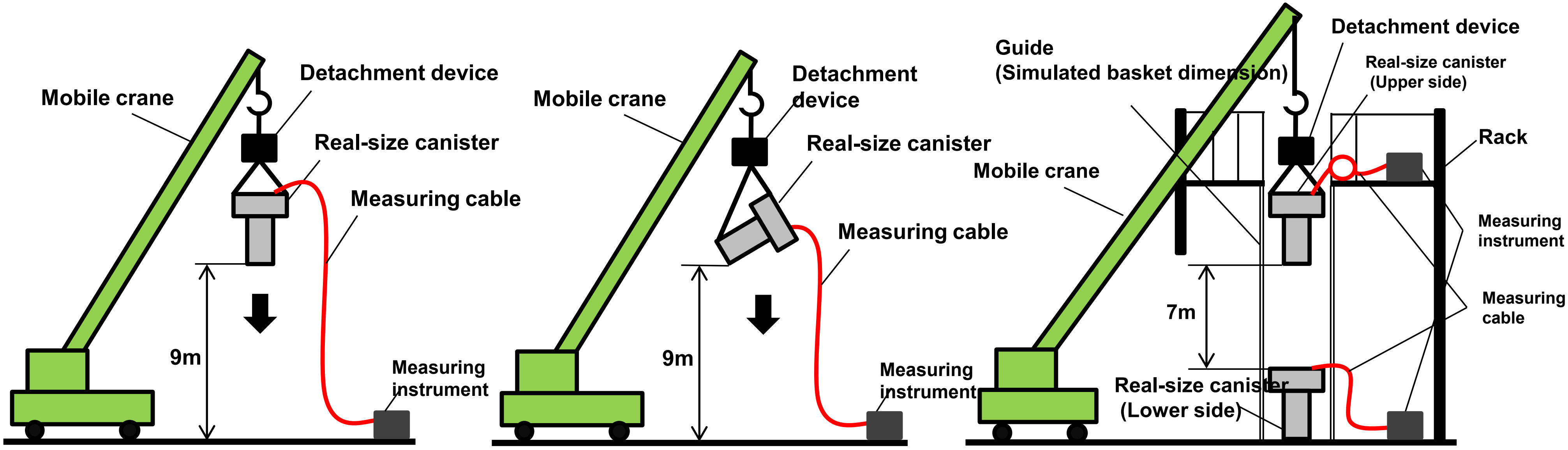
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY2019) (6/10)

(iii) Test system

The structural verification test was planned to be carried out by preparing the test equipment shown in the image below to reproduce the events that occur in actual operations.



(a) Canister dropping in the vertical orientation (b) Canister dropping in the oblique orientation (c) Canister dropping on top of another canister in the vertical orientation

Figure. Image of structural verification test of a real-size canister

6. Implementation Details

6.2 Development of technology for containing of fuel debris
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY2019) (7/10)

(iv) Safety function requirement related items to be confirmed during tests (1/3)

The items to be confirmed by the structural verification test were set based on the safety function requirements of canisters.

Table Safety requirements and items to be confirmed during testing (plan) (1/3)

Safety functions	Safety function requirements	Canister requirements	Items to be confirmed during the test			Approach to selection of confirmation items
			Details	Period	Evaluation criteria	
Confinement	Confinement of radioactive materials	Prevention of leakage of radioactive materials from inside the canister except via the vent mechanism.	Leakage test	Before the test	･Leakage rate: Impact evaluation by actual measurement (Target：3 x 10^{-2} (ref cm^3/s) or less $^{\text{Note1}}$)	･ Confinement in the normal state (pre-test state) is confirmed through leakage test
		Appropriate reduction in leakage of radioactive materials associated with the release of hydrogen gas from the vent mechanism.	Appearance check	After the test	･Filter, coupler: Check the degree of damage and evaluate the impact	･ Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, the extent of damage to the filter and coupler after receiving the impact load of the evaluation event are checked from a safety point of view, to evaluate the impact on the confinement of radioactive materials when the event occurs.
		Appropriate reduction in leakage of radioactive materials even in the event of occurrence of dropping events that must be expected.	Leakage test	After the test	･Leakage rate：Impact evaluation by actual measurement (Target: 3 x 10^{-2} (ref cm^3/s) or less $^{\text{Note1}}$)	･ Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, the leakage rate after receiving the impact load of the evaluation event, and the dimensional difference/ presence or absence of plastic deformation/ relative displacement of the O ring seal before and after the test are checked from a safety point of view, to evaluate the impact on the confinement of radioactive materials when the event occurs. ･ Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, lid detachment and serious damage (cracks that penetrate inside and outside) leading to leakage of large amounts of radioactive materials shall not be allowed from a safety point of view.
			Appearance check	After the test	･Lid: Lid does not come off ･Lid, main body (body, bottom plate), air supply mechanism (piping)：Absence of serious damages leading to large leaks (such as cracks penetrating inside and outside) ･ Others (hook , bolt, stopping pin, O ring, coupler, air supply mechanism (cover)): The extent of damage is checked and impact is evaluated	
			Dimension check (Checking the dimensional difference of O ring seal part before and after the test)	Before the test After the test	･Difference in dimension before and after the test: Impact evaluation by actual measurement (Target: ±0.5 mm $^{\text{Note2}}$)	
			Distortion time history measurement (Checking the presence or absence of plastic deformation near the O ring seal surface)	During the test	･Distortion: Impact evaluation by actual measurement (Target: 9 x 10^{-4} or less $^{\text{Note 3}}$)	
			Momentary opening of the openings (measurement of relative displacement of the O ring seal before and after the test)	During the test	･Relative displacement measurement (or pressure change measurement) of lid and body ：Impact evaluation by actual measurement	

Note 1：Set with reference to the maximum allowable air leakage rate of the NFT-22B type spent nuclear fuel transport cask
Note 2：Set with reference to the O ring squeeze rate (0.6 mm)
Note 3：From the ratio of the yield stress σ to the longitudinal elastic modulus E of SUS316L, ε is set as $\varepsilon = \sigma / E = 175/195000 \fallingdotseq 9 \times 10^{-4}$

6. Implementation Details

6.2 Development of technology for containing of fuel debris
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)
a. Drafting of structural verification test plan (FY2019) (8/10)
(iv) Safety function requirement related items to be confirmed during tests (2/3)

The items to be confirmed by the structural verification test were set based on the safety function requirements of canisters.

Table Safety requirements and items to be confirmed during testing (plan) (2/3)

Safety functions	Safety function requirements	Canister requirements	Items to be confirmed during the test			Approach to selection of confirmation items
			Details	Period	Evaluation criteria	
Criticality prevention	Prevention of additional nuclear fission reaction	The shape should be able to prevent criticality.	Appearance check	After the test	・Lid: Lid does not come off ・Lid, main body (body, bottom plate), air supply mechanism (piping): Absence of serious damages leading to large leaks (such as cracks penetrating inside and outside) ・Other (hook , bolt, stopping pin, O ring, coupler, air supply mechanism (cover)): The extent of damage is checked and impact is evaluated.	・Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, large deformations that makes subcriticality maintenance impossible, lid detachment and serious damages (such as cracks penetrating inside and outside) that lead to leakage of large amounts of radioactive materials shall not be allowed from a safety point of view.
			Dimension check (dimensional check of inner diameter of body)	After the test	・Dimension of inner diameter of body (220 mm): 245 mm or less [Note1] (Target: 232.5 mm or less [Note2]) ・Dimension of inner diameter of body (400 mm) : Impact evaluation by actual measurement	
Heat removal	Prevention of abnormal overheating	The canister should be able to maintain the temperature of the fuel debris at the appropriate level.	Appearance check	After the test	・Lid, main body (body, bottom plate): Check the degree of damage and evaluate the impact	・Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, the extent of damage to the lid and main body after receiving the impact load of the evaluation event are checked from the viewpoint of safety, to evaluate the effect on natural heat dissipation when the event occurs.
		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.	No items to be tested	―	―	・There are no items to be confirmed in the test as other equipment and building air conditioning are designed not to let the canister exceed the permissible temperature even in the event of loss of external power or other expected events.

Note 1：In the criticality evaluation in FY 2016, when SUS material was considered, the inner diameter equivalent to Keff = 0.925 was evaluated as 245 mm. So, that value was set.

Note 2：In the criticality evaluation in FY 2016, when SUS material was not considered, the inner diameter for Keff = 0.925 was evaluated as 220 mm, and it was confirmed that increasing the inner diameter by 10 mm increases Keff by 0.02. Therefore, the inner diameter when Keff = 0.95, which is the upper limit of the criticality safety design evaluation standard, can be calculated as 232.5 mm. The 232.5 mm, which was the value when not considering SUS material, was conservatively set as the target value with respect to design.

6. Implementation Details

6.2 Development of technology for containing of fuel debris
- Prototyping of real-size canister and structural verification test -

③Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY2019) (9/10)

(iv) Safety function requirement related items to be confirmed during tests (3/3)

The items to be confirmed by the structural verification test were set based on the safety function requirements of canisters.

Table Safety requirements and items to be confirmed during testing (plan) (3/3)

Safety functions	Safety function requirements	Canister requirements	Items to be confirmed during the test			Approach to selection of confirmation items
			Details	Period	Evaluation criteria	
Shielding	Prevention of excessive exposure and internal exposure due to radiation	(No requirements)	No items to be tested	—	—	・As there are no requirements related to shielding function of the canister, there are no items to be confirmed in the test.
Prevention of hydrogen explosion	Response to fires and explosions caused by flammable gas 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.	No items to be tested	—	—	・As the design allows the release of hydrogen generated inside the canister through the vent mechanism, there are no items to be confirmed in the test. ・As reduction of hydrogen concentration by catalyst is evaluated separately as part of the "Study on hydrogen measures", there are no items to be confirmed in the test.
		The design should be such that the hydrogen concentration does not exceed the specified value even in the event of occurrence of an expected event.	Appearance check	After the test	・Filter, coupler: Check the extent of damage and evaluate the impact	・Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, the extent of damage to the filter and coupler after receiving the impact load of the evaluation event is checked from a safety point of view, to evaluate the effect on hydrogen release when the event occurs.
Prevention of dust fires	Response to fires caused by the reaction of oxygen and metal dust generated during debris retrieval and cutting (response to hazards)	To prevent ignition by creating an inert gas atmosphere inside.	Leakage test	Before the test	・Leakage rate: Impact evaluation by actual measurement (Target: $3x10^{-2}$ (ref cm^3/s) or less [Note 1])	・Assuming that the inside of the canister is replaced with an inert gas atmosphere, the confinement property under the normal state (pre-test state) is confirmed by the leakage test.
-	≪Handling function requirements≫	The lid can be fastened and opened by remote operations.	Confirmation of lid fastening/ lid opening (Including the confirmation of lid rotation during lid fastening and lid opening, and bolt fastening/ rotation torque)	Before the test After the test	・Lid fastening/ lid opening (Before the test): Must be possible ・Opening the lid (After the test): Check if it is possible or not, and evaluate the impact	・Use manual tools to confirm that the lid can be fastened and opened under normal conditions (pre-test state). ・Though evaluation events (canister dropping in the vertical orientation, etc.) are events that are not expected to occur, the possibility of opening the lid after receiving the impact load of the evaluation event is confirmed using manual tools to serve as information for studying the treatment method after the occurrence of the event.

Note 1: Set with reference to the maximum allowable air leakage rate of the NFT-22B type spent nuclear fuel transport cask

6. Implementation Details

6.2 Development of technology for containing of fuel debris
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

a. Drafting of structural verification test plan (FY 2019) (10/10)

(v) Items to be confirmed during test to check the applicability of analysis method

Items to be confirmed by the structural verification test were set to obtain the data necessary to confirm the applicability of the analysis method by comparing with the test results.

Table Items to be confirmed during test to check the applicability of analysis method (plan)

Data items related to confirming the applicability of analysis method	Items to be confirmed during the test			Approach to selection of confirmation items
	Details	Period	Acquired data	
External appearance	Appearance check	Before the test After the test	· Key external appearances of the lid (including hook), main body (including flange, body, bottom plate, hook), bolt, buffer structure and air supply mechanism (piping) (focus on observation of parts where deformation was confirmed in preliminary analysis)	· To confirm the accuracy of the analysis, the changes during the test are measured and a comparative evaluation is performed between the deformation state obtained from the analysis and the test results.
Dimension	Dimensional check	Before the test After the test	· Key dimensions of the lid (including hook), main body (including flange, body, bottom plate, hook), bolt, buffer structure and air supply mechanism (piping) (focus on measuring the parts where deformation was confirmed in preliminary analysis)	·To confirm the accuracy of the analysis, the amount of change (dimensions) during the test is measured and a comparative evaluation is performed between the amount of deformation obtained from the analysis and the test results.
Distortion	Distortion time history measurement	During the test	·Distortions in the key parts of the lid (including hooks), main body (including flanges, body, bottom plate, hooks), bolts, buffer structure, and air supply mechanism (piping) (focus on measuring the parts where a large (characteristic) distortion was confirmed in the preliminary analysis)	·To confirm the accuracy of the analysis, the distortion during the test is measured and a comparative evaluation is performed between the distortion obtained from the analysis and the test results.
Acceleration	Acceleration time history measurement	During the test	·Acceleration of lid, main body, buffer structure	·To confirm the accuracy of the analysis, the acceleration during the test is measured and a comparative evaluation is performed between the acceleration obtained from the analysis and the test results.
Velocity	Velocity measurement	During the test	· Velocity of canister just before the collision	·To confirm the accuracy of the analysis, the velocity during the test is measured and a comparative evaluation is performed between the velocity used as input conditions for analysis and the test results.
Relative displacement of lid and body	Displacement time history measurement	During the test	·Relative displacement of lid and main body during collision	·To confirm the accuracy of the analysis, the relative displacement of the lid and the main body during the test is measured and a comparative evaluation is performed between the relative displacement obtained from the analysis and the test results.
Video (high-speed camera video)	High-speed camera video shooting	During the test	·High-speed camera video at the time of collision (near the colliding part)	·To confirm the accuracy of the analysis, a picture of the deformation behavior during the test is taken and a comparative evaluation is performed between the deformation behavior obtained from the analysis and the test results.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

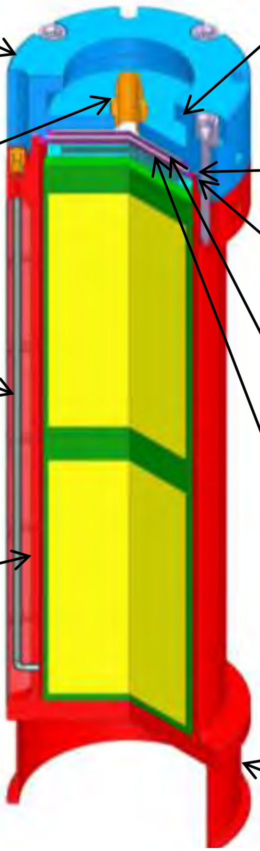
- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY 2019) (1/7)

(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 mounting 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 orientation.

Vent mechanism

The inner diameter of the coupler was set to 1 inch by conducting diffusion evaluation considering the coupler and filter for the amount of hydrogen generated based on actual measurements in the presence of water (since it dries, the amount of hydrogen generated is assumed to reduce to a value lower than that based on actual measurements in the presence of water). Also, a coupler was installed in normally-open state based on the risk evaluation conducted for vent opening and closing operations when handling canisters.

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, 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 body, the flange, 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.

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 mounting structure.

Method of sealing the port between cells and the canister

・A structure where the upper end plane of the canister body is pressed and sealed against the seal part of the port between cells, as a method to prevent contamination as much as possible at the area boundary between cells.
・A structure with an inner lid (with a filter for hydrogen venting) is installed on the canister body to prevent contamination as much as possible during handling of the canister from the port between cells to the fastening of the lid.

Filter

・The release of hydrogen was evaluated by the hydrogen diffusion evaluation formula, 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 (suitable for HEPA). So, it is a structure which is less susceptible to clogging by increasing the filter diameter and increasing the surface area of the flow path.

Catalyst

・Assuming that catalyst will be installed, it was temporarily installed under 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.

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

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

6. Implementation Details

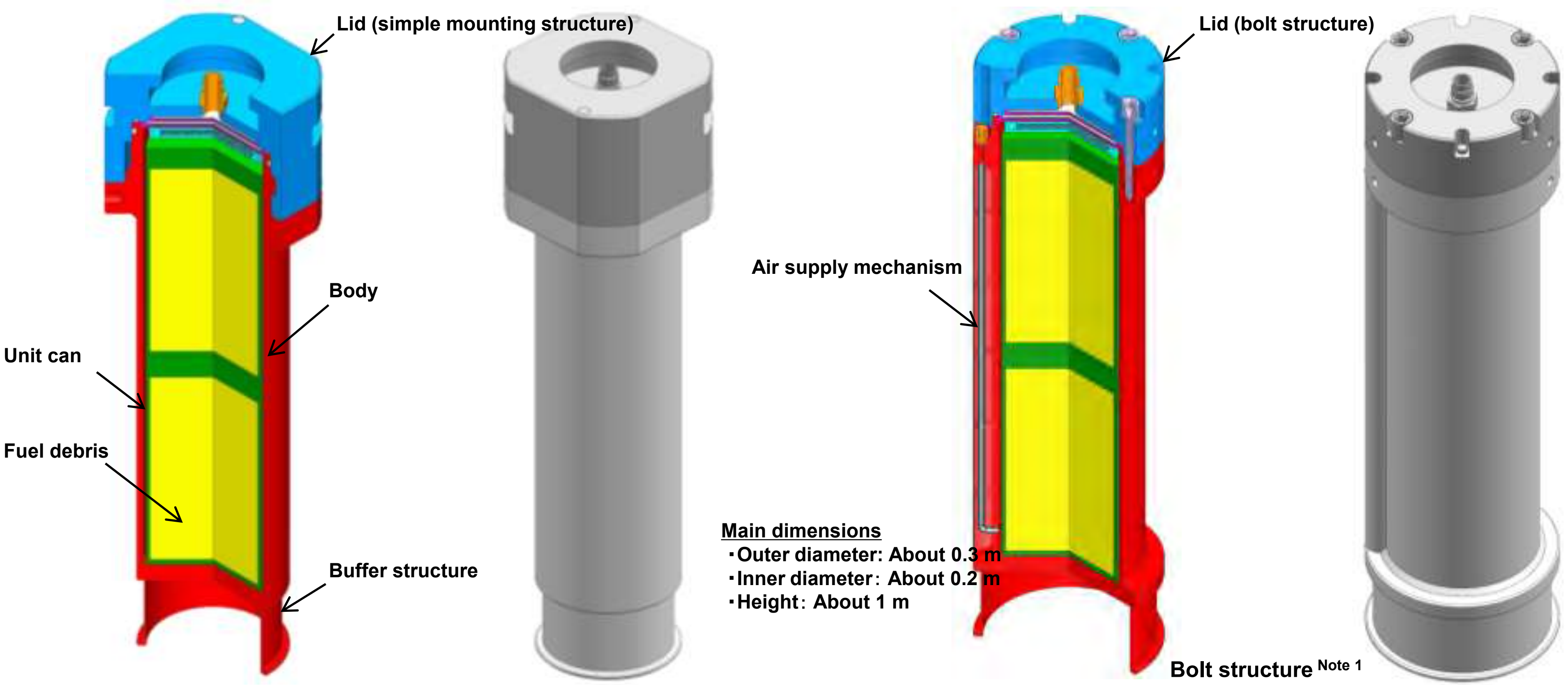
6.2 Development of technology for containing of fuel debris

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY 2019) (2/7)

(ii) Canister structural plan

Eight types of structural plans were selected for the canister: two types of lid structures (simple mounting 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
(Case where 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 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

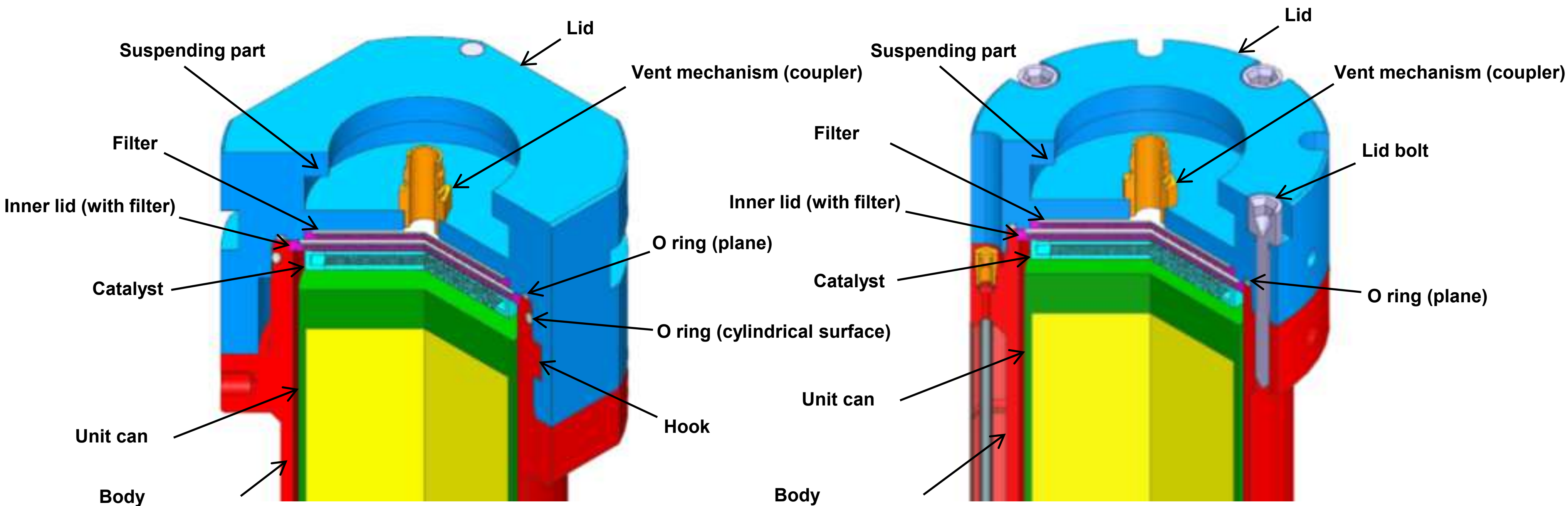
③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY—2019) (3/7)

(iii) Main specification plan (1/5)

1) Lid

- Two types of lids were designed as remotely operable structures: a simple mounting 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 orientation.



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

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

Figure. Structural plan of the lid Note 1

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

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY 2019) (4/7)

(iii) Main specification plan (2/5)

2) Body

- Two types of bodies were designed, 220 mm, with a geometrical shape, which can maintain subcriticality irrespective of the particle size and moisture content of the fuel debris, and 400 mm, which has an expanded inner diameter for improved workability.
- Referencing the ¼ inch (6.35 mm) shell thickness of the TMI-2 canisters, the shell thickness was designed to be 10 mm for a canister with an inner diameter of 220 mm, which had a structure 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 orientation, and which deforms within the range in which it can maintain subcriticality.
- The inner space of the canister body was designed to have a structure ,which can contain two unit cans (outer diameter 210 mm and height 400 mm) stacked one on top of the other.
- A tapered portion is provided at the joint between the body, the flange, and the bottom plate to relieve stress when an impact load, such as drop in the vertical orientation, is applied.

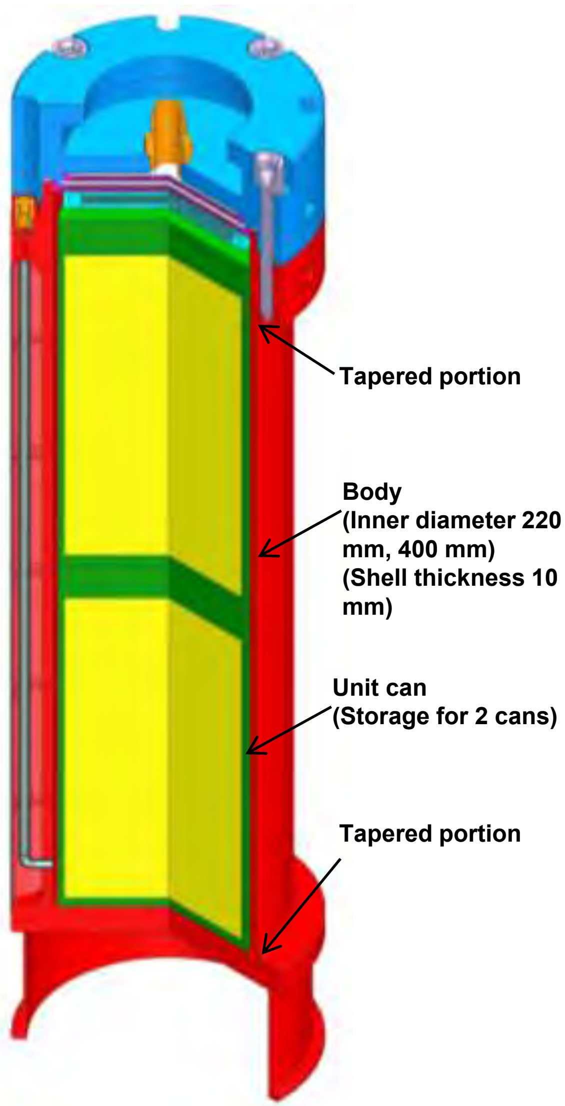


Figure. Structural plan for body Note 1

(For a bolt structure, inner diameter of body 220 mm, and with air supply mechanism)

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

- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY 2019) (5/7)

(iii) Main specification plan (3/5)

3) Seal (1/2)

- The canister seal is required to provide the confinement function during transfer and handling (assuming a period of about 7 days) while the confinement function is not required during storage (assuming a period of about 50 years) (during storage, the confinement function will be ensured in the storage facility).

- For this purpose, the elastomer gasket (EPDM) was adopted from among the candidates to fulfill the requirement of confinement and durability during transfer and handling (assuming a period of about 7 days) along with prioritizing storage efficiency (minimization of outer diameter of lid), lid fastening workability, and applicability to a simple mounting structure.

- During storage (assuming a period of about 50 years), the confinement function may be lost due to aging of the seal, but it is unlikely that a large amount of fuel debris will be released from the seal of the canister during stationary storage. Even if the fuel debris is released, it will remain in the storage cask (in the case of the metal cask method), so it will not impair the confinement function as a storage facility.

- As a means for improving the confinement function during storage (and after storage), adoption of a metal gasket could have been considered, but it has the following issues and was not adopted for the canister (canister for testing) used in the structural verification test. However, with a view to considering its adoption in the future, the metal gasket (bolt structure) has been retained as an alternative idea.
  - (i) Cannot be applied to the simple mounting lid structure.
  - (ii) Can be applied to a bolt lid structure, but since a large fastening force is required compared to the elastomer gasket, 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.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY 2019) (6/7)

(iii) Main specification plan (4/5)

3) Seal (2/2)

Table Comparison of various types of seals for the canister lid

	Elastomer gasket	Metal gasket	Metal touch	Welded type
Confinement	･Can ensure short-term confinement.	･Can ensure long-term confinement.	･Difficult to guarantee both short-term or long-term confinement.	･Can ensure long-term confinement.
Long term integrity of sealing material/ surface	･Although there is no issue during transfer, difficult to guarantee the same during storage.	･No issues during both transfer and storage.	･Since the sealing surface is metallic, there is no issue.	･No issues during both transfer and storage.
Radiation resistance	･About two years Note 1 for the irradiation (up to 30 Gy/h) assumed for the seal during transfer or storage.	･There is no issue at the irradiation (up to 30 Gy/h) assumed for the seal during transfer or storage.	･There is no issue at the irradiation (up to 30 Gy/h) assumed for the seal during transfer or storage.	･There is no issue at the irradiation (up to 30 Gy/h) assumed for the seal during transfer or storage.
Heat resistance	･There is no issue in the temperature range (up to 200°C Note 2) assumed for the seal during transfer or storage.	･There is no issue in the temperature range (up to 200°C Note 2) assumed for the seal during transfer or storage.	･There is no issue in the temperature range (up to 200°C Note 2) assumed for the seal during transfer or storage.	･There is no issue in the temperature range (up to 200°C Note 2) assumed for the seal during transfer or storage.
Workability	･It is comparatively easy. ･Constant fastening force is necessary (less than that for the metal gasket).	･As compared to the elastomer gasket, precaution is necessary during fastening. ･Constant fastening force is necessary (larger than the one required for the elastomer gasket).	･It is easy.	･Welding work at the Reactor Building (including the Expanded Building) is difficult.
Ease of removal	･Removal is possible ･Gasket must be replaced depending on its condition.	･Removal is possible ･Metal gasket must be replaced.	･Removal is possible ･Ensuring the same confinement capability all the time is difficult.	･Removal is possible ･It cannot be re-used.
Effect on lid design	･It can be adopted for a simple mounting structure, but precaution is necessary if there are lapping sections.	･It cannot be adopted for a simple mounting structure. ･The outer diameter of the lid becomes larger (larger than that for the elastomer gasket).	･It cannot be adopted for a simple mounting structure.	･Wider extent of freedom for overpack welds.

Note 1: When it is assumed that all the fuel debris in the unit cans is UO2, and the burn-up of 41 GWd/t and the cooldown period of 10 years has been set from the burn-up of the sixth batch irradiation fuel considering the irradiation history of burn-up of fuel debris (from September 2012 Fukushima Daiichi Fuel Composition Evaluation by Japan Atomic Energy Agency JAEA-Data/Code2012-18 by Nishihara Kenji, Hiroki Iwamoto, Kenya Suyama). Note that it has been evaluated to be around 5 years when the average burn-up inside the reactor of 26 GWd/t and the cooldown period of 10 years was used for evaluation.

Note 2: As a result of heat removal analysis FY 2014, the temperature of the seal is assumed to be up to 200℃ under the conditions when there is the highest burn-up (41 GWd/t) in a canister and the filling rate of fuel debris is 30% and when the centre of the fuel debris is 209℃ and the canister body heats up to about 90℃.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

b. Designing the canister (canister for testing) (FY 2019) (7/7)

(iii) Main specification plan (5/5)

4) Vent mechanism

- By using an evaluation formula that is similar to the diffusion evaluation formula used for evaluation at TMI-2, the hydrogen concentration inside the canister was calculated considering the coupler and filter, etc., on the vent flow path, and a one inch coupler was selected as a specification so that the lower explosion limit is 4 vol.% or less.
- The following three conditions were considered for the hydrogen generation rate. Since there is a plan to dry the fuel debris (target value of dryness 0.1 wt.%), condition ② was selected as the evaluation condition assuming that the hydrogen generation rate can be reduced to less than the actual measurements from the test of immersing spent nuclear fuel in water.

Condition ①: Estimated on the basis of the TMI-2 evaluation formula of FY 2018 (particulate transport calculation)

:1.3×10^{-16}[L/h/Bq]

Condition ②: Value that considers any measurement error or variation in the actual measurements in the FY 2018 hydrogen generation test using spent nuclear fuel

:1.2×10^{-17} [L/h/Bq]

Condition ③: Actual measurements in the FY 2018 hydrogen generation test using spent nuclear fuel

:5.1×10^{-18} [L/h/Bq]

- For canisters with inner diameter φ 220 mm which are supposed to be used during the initial period of retrieval, a coupler with a size, which has tolerance for the lower explosion limit of 4 vol.%, was selected considering the uncertain factors such as the clogging of the filter, etc.

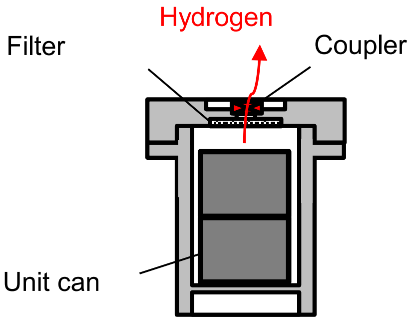
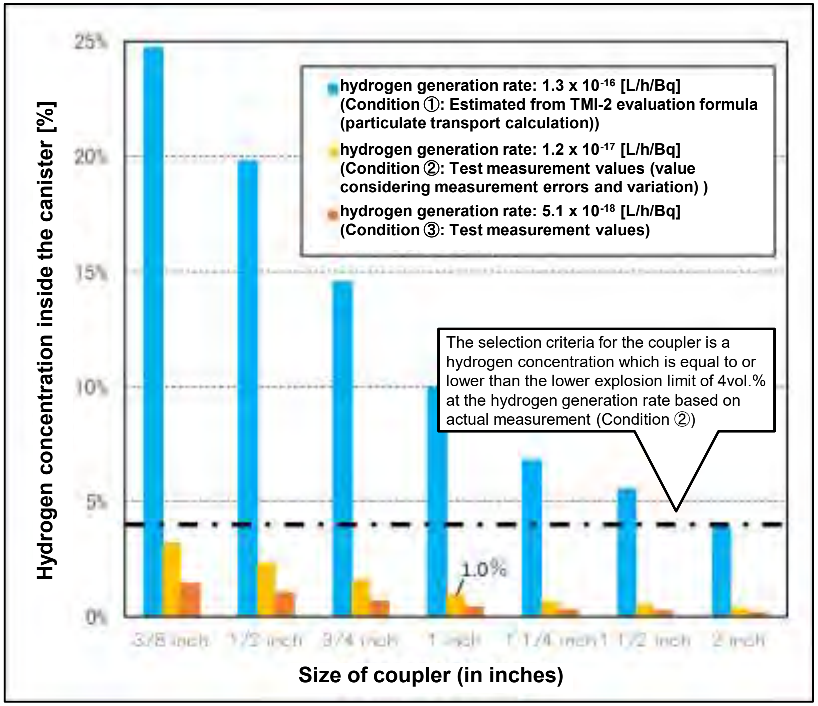


Figure. Diffusion Evaluation Model



The selection criteria for the coupler is a hydrogen concentration which is equal to or lower than the lower explosion limit of 4vol.% at the hydrogen generation rate based on actual measurement (Condition ②)

Figure. Results of evaluating the hydrogen concentration in the canister by means of the diffusion evaluation formula (inner diameter 220 mm)

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

③ Implementation items and results (Estimated and actual)

c. Prototyping the canister (canister for testing) (FY 2019, FY 2020)

Based on the canister (canister for testing) design implemented in point b., preparations such as material procurement, etc. for the prototyping of real-size canister (canister for testing) are underway. The prototyping will start in FY 2020.

d. Implementation of structural verification test (FY 2020) [Scheduled]

The structural verification test will be carried out on the basis of the structural verification test plan studied in point a. using the canister (canister for testing) prototyped in point c. Note that at the time of executing the structural verification test, data that can help in the verification of the structural integrity concerning the maintenance of safety functions, etc., will be acquired.

e. Evaluation of structural verification test (FY 2020) [Scheduled]

From the results of the structural verification test executed as per point d., evaluation will be conducted from the view point of maintenance of safety functions of the canister (subcriticality maintenance, fuel debris confinement). Moreover, based on the structural analysis methods studied till FY 2018, the structural analysis will be conducted by simulating the structural verification tests, and by comparing and evaluating the results of the structural verification tests, the feasibility of the canister specifications and structure will be verified along with verifying the applicability of the analysis methods.

f. Study of canister specifications and structure (FY 2020) [Scheduled]

Incorporating the evaluation results of the structural verification tests conducted as per point e., the canister specifications and structure will be reviewed and studied as necessary.

Based on the above-mentioned study, the specification and structural plan (structural drawing) of the canister will be proposed at the end of FY 2020.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

④ Contribution of the results to the areas where they can be reflected

On the basis of the proposed specification and structural plan for canisters, it is believed that it should be possible to contribute to the designing or manufacturing of the real-size canister. Moreover, it should also be possible to contribute to the study of the related facilities for the canister (expanded building, storage facilities, handling devices etc.).

⑤ Analysis from the perspective of site application

The specifications and structure of the canisters are being studied in consideration of the handling right from containing to storage of the canisters in 1F and the evaluation events assumed during handling, and it is believed that there are no issues in the applicability to the site.

⑥ Issues

There are no issues in the execution of the present plan.

⑦ Level of achievement in light of the goal

The processes up to the drafting of structural verification test plan are complete, and the prototyping of the canister (canister for testing) is underway. The progress is almost as planned, and it is expected that the target results can be achieved by the end of FY2020.

6. Implementation Details

6.2 Development of technology for containing of fuel debris

- Prototyping of real-size canister and structural verification test -

Summary

In FY 2019, in view of developing containment technology, a plan was drafted for the test items to be implemented during the structural verification test of the canister, and the canister (canister for testing) was designed based on the safety requirements of the canister. Moreover, material procurement, etc. was carried out for the prototyping of the canister (canister for testing).

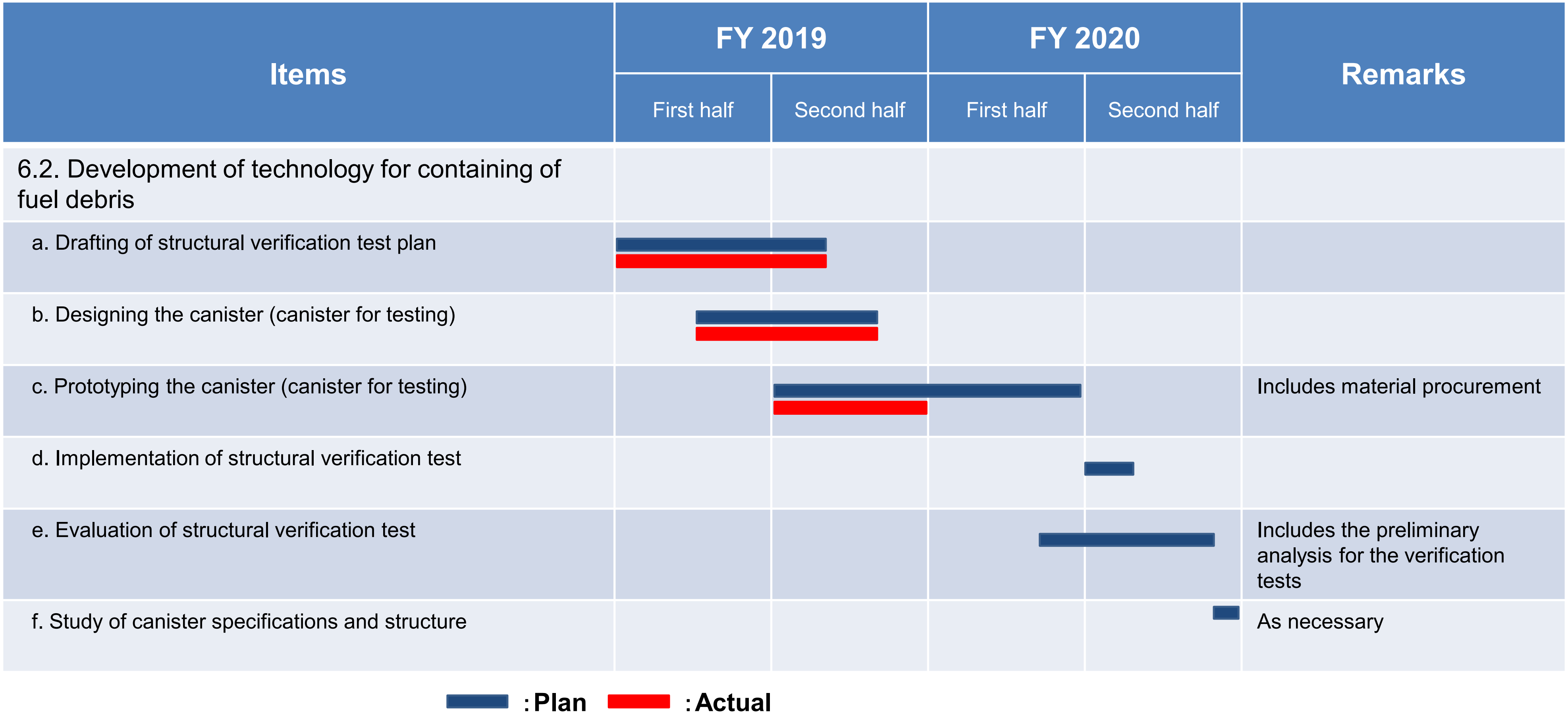
In FY 2020, real-size canister (canister for testing) to be used in the structural verification test will be prototyped, and the structural verification test will be carried out to verify the maintenance of the safety functions (criticality prevention, confinement). Moreover, the structural analysis will be compared and evaluated with the results of the structural verification test, and the applicability of the analysis methods will be verified. Note that the canister specifications and structure will be reviewed or studied as necessary.

6. Implementation Details

6.2 Development of technology for containing of fuel debris - Prototyping of real-size canister and structural verification test -

⑧ Future Schedule

Table. Schedule for the development of containment technology



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
6.2. Development of technology for containing of fuel debris					
a. Drafting of structural verification test plan	▬ 🟥	▬ 🟥			
b. Designing the canister (canister for testing)	▬ 🟥	▬ 🟥			
c. Prototyping the canister (canister for testing)		▬ 🟥	▬		Includes material procurement
d. Implementation of structural verification test				▬	
e. Evaluation of structural verification test			▬	▬	Includes the preliminary analysis for the verification tests
f. Study of canister specifications and structure				▬	As necessary

▬ : Plan 🟥 : Actual

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 means of testing.

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 Implementation items and results (Estimated and actual)

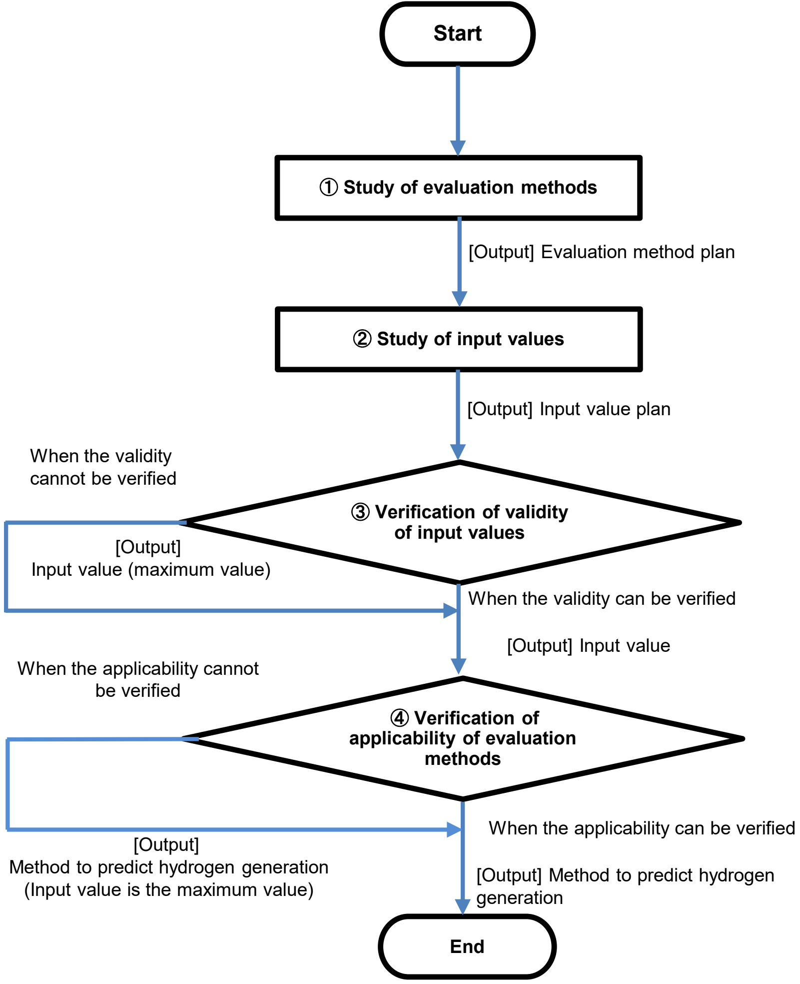
a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (1/14)

(i) Establishing the evaluation method study flow

The study of various implementation items was conducted by establishing a study flow for the evaluation methods.

Table. Implementation details of the study of methods to predict hydrogen generation (plan)

Study items		Implementation details (plan)
Major items	Minor items	
①Study of evaluation methods	Investigation of evaluation methods	Investigation of other domestic and overseas evaluation methods (evaluation methods for waste etc.) (Refer to 6.3 (1) ③ a. (ii) a.)
	Study of evaluation methods	Deciding the evaluation methods based on the investigation results of the evaluation methods and the availability of data etc. (Refer to 6.3 (1) ③ a. (ii) b.)
②Study of input values	Study of methods for evaluating the input values	Evaluation of the energy absorption rate using the particulate transport calculation results (Refer to 6.3 (1) ③ a. (iii))
	Evaluation of input values	
③Verification of validity of input values	Study of methods to verify the validity of input values	Confirming that the evaluation of the amount of energy absorption using the particulate transport calculation for the energy absorption rate is moderately conservative with respect to the results of the test using single radiation source or test using spent nuclear fuel (Refer to 6.3 (1) ③ a. (iv))
	Verification of validity of input values	
④Verification of applicability of evaluation methods	Study of methods to verify the applicability of the evaluation methods	Confirming that the hydrogen generation rate as per the linear model is moderately conservative with respect to the results of the test using spent nuclear fuel (Refer to 6.3 (1) ③ a. (v))
	Verification of applicability of evaluation methods	



Start

① Study of evaluation methods

[Output] Evaluation method plan

② Study of input values

[Output] Input value plan

When the validity cannot be verified

③ Verification of validity of input values

[Output] Input value (maximum value)

When the validity can be verified

[Output] Input value

When the applicability cannot be verified

④ Verification of applicability of evaluation methods

[Output] Method to predict hydrogen generation (Input value is the maximum value)

When the applicability can be verified

[Output] Method to predict hydrogen generation

End

Figure. Study flow of the evaluation methods

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (2/14)

(ii) Study of evaluation methods (1/2)

a. Investigation of evaluation methods

Domestic and overseas evaluation methods were investigated in order to select the evaluation methods that could be applied to the methods of estimating the hydrogen generation at 1F.

[Investigation Results]

Evaluation method A: Evaluation method in which the hydrogen generation rate does not depend on the time period (Linear model)

- Concise evaluation formula of "Amount of energy absorbed per unit time" x "G-value of hydrogen generation"
- There are two types of "Amount of energy absorbed per unit time”

A-1: **"Released energy" x “Energy absorption rate "**

Actual evaluation results are available for the amount of hydrogen generated at the TMI-2 (fuel debris), at the Savannah River National Laboratory (radioactive sludge and slurry), and at the U.S. Nuclear Regulatory Commission (TRU waste)

A-2: **"Absorbed dose rate" x "Weight of absorption medium"**

Actual evaluation results are available for the amount of hydrogen generation at the TMI-2 (Filling for the low-level radioactive material removal device)

Evaluation method B: Evaluation method using the radiolysis model (Radiolysis model)

- It is possible to consider a change in various chemicals due to the passage of time, and in particular, the hydrogen generation rate can be reduced by considering the recombination reaction.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (3/14)

(ii) Study of evaluation methods (2/2)

b. Study of evaluation methods

Based on the investigation results of the evaluation methods, the “Evaluation method A: Linear model", which enables conservative evaluation because the recombination reaction is not considered, and in this, "A-1: "Released energy" x "Energy absorption rate"", which has a proven track record in TMI-2 (fuel debris), were adopted.

Note that only the beta rays and gamma rays are considered at TMI-2 (fuel debris), so the amount of energy absorbed per unit time is multiplied with the G-values of hydrogen generation of the beta rays and gamma rays. Meanwhile, since there is the possibility of impact of alpha rays at 1F, the hydrogen generation rate was calculated from the amounts of energy absorbed per unit time and the G-values of hydrogen generation of the alpha, beta and gamma rays respectively, and these hydrogen generation rates were added up.

[Evaluation method: Linear model]

$$R_{H2} = \underbrace{\underbrace{E \text{ x } P \text{ x } M \text{ x } C}_{\textbf{Released energy}} \text{ x } \underbrace{F}_{\textbf{Energy absorption rate}}}_{\textbf{Amount of energy absorbed per unit time}} \text{ x } \underbrace{G}_{\textbf{G-value of hydrogen generation}}$$

R_{H2} : Hydrogen generation rate, E : Decay heat,
P : Peaking factor, M : Weight of fuel debris
C : Fuel content ratio, F : Energy absorption rate,
G : G-value of hydrogen generation

Since it was not possible to verify the actual results which would confirm the applicability of the evaluation method (Linear model) to a coexisting system of alpha, beta and gamma rays, the applicability must be confirmed considering the individual input values.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (4/14)

(iii) Study of input values (1/4)

a. Overview of input value settings

Each input value for the evaluation method (Linear model) was set on the basis of the following policy.

Table. Policy for input value settings

Symbol	Input value	Setting policy
E	Decay heat	Set for each type of ray after adding up the decay heat of the nuclides based on the literature Note 1.
P	Peaking factor	Set the ratio of maximum decay heat and average decay heat OR set the ratio of maximum burn-up and average burn-up based on the literature Note 1.
M	Weight of fuel debris	Set the design value.
C	Fuel content ratio	Assume that the entire fuel debris is made up of spent nuclear fuel.
F	Energy absorption rate	Set the ratio of the amount of energy absorbed by water and the energy amount contained in the fuel debris. With an aim to ease the transfer conditions, the policy is to evaluate the amount of energy absorbed by water by means of the particulate transport calculation so as to get closer to the real state. (Refer to 6.3 (1) ③ a. (iii) b. for details)
G	G-value of hydrogen generation	Set the initial G-value of hydrogen generation for each type of ray based on the literature Note 2.

Note 1: Fukushima Daiichi NPS Fuel Composition Evaluation, September 2012, Tables 5, 8, 11, 43, 45, 47 by the Japan Atomic Energy Agency, JAEA-Data/Code2012-18 by Nishihara Kenji, Hiroki Iwamoto, Kenya Suyama.

Note 2: Hilbert Christensen and Erling Bjergbakke, NUCLEAR AND CHEMICAL WASTE MANAGEMENT, Vol.6, pp.265-270, TABLE 2, APPRICATION OF CHEMISIMUL FOR GROUNDWATER RADIOLYSIS, 1986

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (5/14)

(iii) Study of input values (2/4)

b. Energy absorption rate (1/3)

The evaluation of the hydrogen generation amount using the energy absorption rate (F_{max}) for the instance when all the energy contributes to the radiolysis of water, can explain the situation well, but is excessively conservative, so the fuel debris transfer conditions become very severe (Refer to 6.3(1)③a.(iii)b.(2/3)).

Therefore, in order to ease the transfer conditions, the energy absorption rate ($F_{(calc.)d}$) that is close to the real state was evaluated on the basis of the results of the particulate transport calculation, wherein self-shielding can be considered, thereby, easing the transfer conditions.

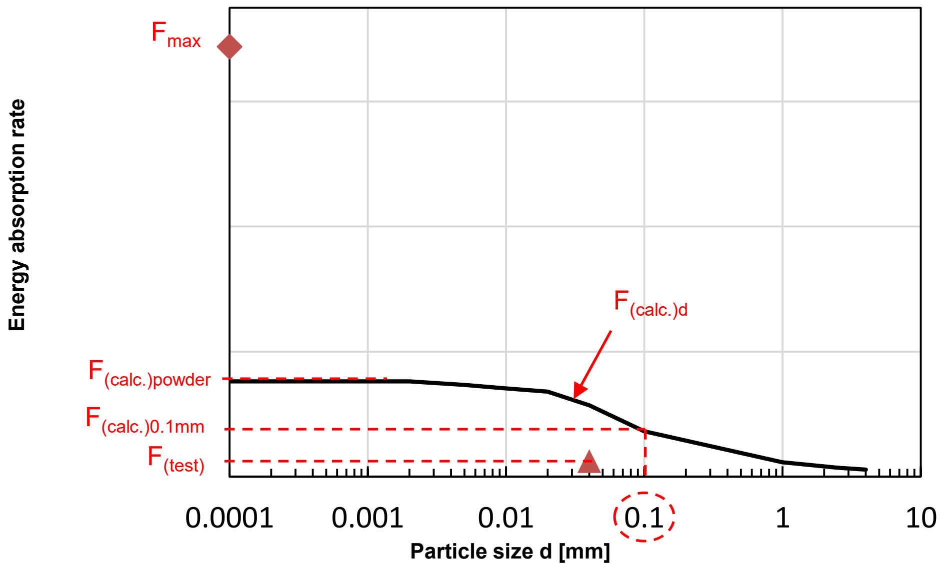


Figure. Relation between the particle size and the energy absorption rate (Image diagram)

◆	Energy absorption rate when all the energy contributes to the radiolysis of water (F_{max})
▬	Energy absorption rate evaluated from the particulate transport calculation result (amount of moisture is the extent of drainage) ($F_{(calc.)d}$)
▲	Energy absorption rate evaluated from the measurement results of the FY 2018 hydrogen generation test using the spent nuclear fuel ($F_{(test)}$)

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (6/14)

(iii) Study of input values (3/4)

b. Energy absorption rate (2/3)

The aim is to ease the transfer conditions to be evaluated on the basis of the energy absorption rate using the particulate transport calculation, solely with the method for predicting hydrogen generation, without relying on other hydrogen measures (drying, measurement of hydrogen concentration, and catalyst).

Table. Energy absorption rate and transfer conditions Note 1 studied in FY 2018

Evaluation methods	Energy absorption rate	Calculation results		Transfer conditions (Evaluation conditions: Hydrogen concentration is less than 4vol.% and the transfer period is 7 days)
		Time required for the concentration of hydrogen inside the canister to reach 4 vol.%	Time required for the concentration of hydrogen inside the transfer cask to reach 4 vol.%	
TMI-2 Evaluation Model	Total absorption (F_{max} equivalent)	Approx. 0.04 day (Approx. 1.0 hour)	Approx. 0.3 day (Approx. 7.1 hours)	Sealed transfer of the canister is not possible. In case of a sealed transfer via a transfer cask, it is necessary to decrease the number of canisters to one Note 2 along with decreasing the amount of fuel debris contained to about 50 percent.
	Transfer calculation ($F_{(calc.)0.1mm}$ equivalent)	Approx. 0.2 day (Approx. 5.5 hours)	Approx. 1.7 days (Approx. 41 hours)	Sealed transfer of the canister is not possible. In case of a sealed transfer via a transfer cask, it is necessary to decrease the number of canisters to two Note 2.
	Test results ($F_{(test)}$ equivalent)	Approx. 5.8 days (Approx.139 hours)	Approx. 43 days (Approx. 1029 hours)	The sealed transfer of canisters is possible if the amount of fuel debris contained is reduced to about 80 percent when there are still 12 canisters Note 2. Sealed transfer of the transfer cask is possible.

Note 1: International Research Institute for Nuclear Decommissioning (IRID), FY2016 Supplementary Budget "Subsidy Project of Decommissioning and Contaminated Water Management (Development of Technology for Containing, Transfer and Storage of Fuel Debris)" FY 2018 Final report, June 2019

Note 2: It is assumed that the number of canisters stored in the transfer cask is 12

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (7/14)

(iii) Study of input values (4/4)

b. Energy absorption rate (3/3)

Although fuel debris of size 0.1 mm or more (standard) is to be stored in the canister, considering that fuel debris less than 0.1 mm could unintentionally be stored with the other fuel debris during actual operations, the hydrogen generation rate is calculated from the energy absorption rate based on the transport calculation result taking the particle size into account. Therefore, it is necessary to verify the validity of the energy absorption rate corresponding to the particle size that is evaluated on the basis of the particulate transport calculation result.

- When the entire fuel debris has a particle size of 0.1 mm or more

$$R_{H2} = E \text{ x } P \text{ x } M \text{ x } C \text{ x } F_{(calc.)0.1mm} \text{x } G$$

- When a% of the fuel debris has a particle size of 0.1 mm or more AND b% of the fuel debris has a particle size of less than 0.1 mm

$$R_{H2} = E \text{ x } P \text{ x } M \text{ x } C \text{ x } (F_{(calc.)0.1mm} \text{x} \frac{a}{100} + F_{(calc.)powder} \text{x} \frac{b}{100}) \text{x} G$$

R_{H2} : Hydrogen generation rate, E : Decay heat, P : Peaking factor, M : Weight of fuel debris
C : Fuel content ratio, F : Energy absorption rate, G : G-value of hydrogen generation
a: Ratio of particles whose size is 0.1 mm or more, b: Ratio of particles whose size is less than 0.1 mm

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (8/14)

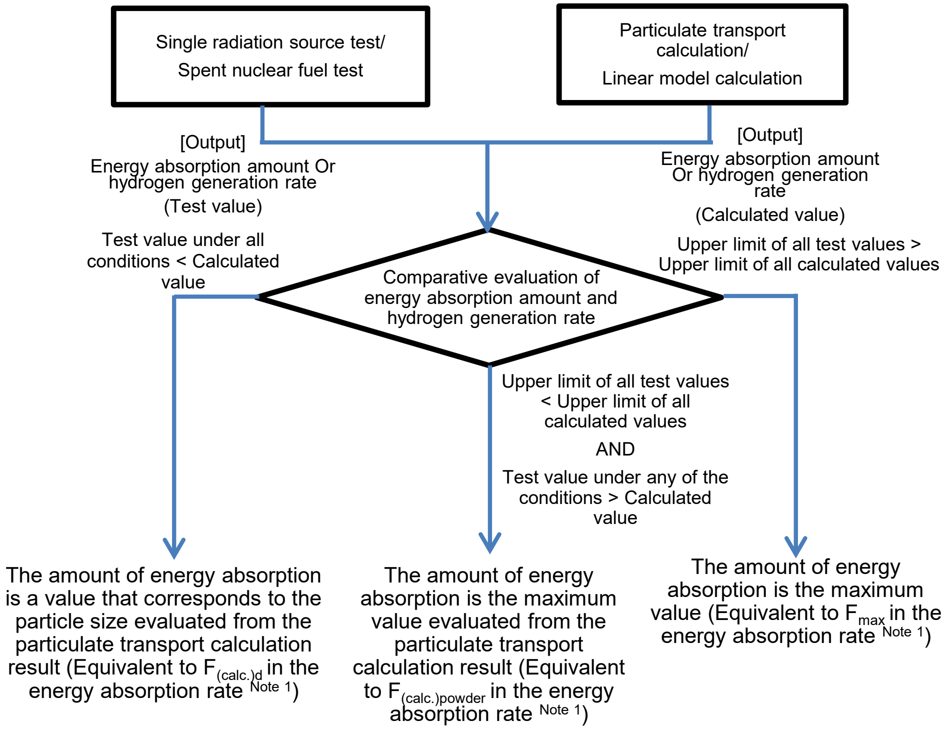
(iv) Verification of validity of input values (1/5)

a. Verification of validity of the energy absorption rate (1/2)

The particulate transport calculation code, "PHITS Note 1", which is used for the evaluation of the energy absorption amount, is the Monte Carlo calculation code that simulates various radiation behavior in matter using the nuclear reaction model and nuclear data, but it could not verify the results of evaluation of amount of energy absorbed by water for the alpha, beta and gamma rays in a complex system in which solids and liquids are mixed.

Note that, if the validity of the energy absorption amount evaluated based on the calculation result of PHITS cannot be verified, then the transfer conditions become severe due to the use of energy absorption rate F_{max} Note 2, which is excessively conservative, hence the verification of validity of PHITS is necessary in order to ease the transfer conditions.

Therefore, the policy of verifying the validity of PHITS by a comparative evaluation of the energy absorption amount obtained from the test and the calculation results of PHITS, and by checking the extent of maintainability of the calculation result of PHITS with respect to the actual phenomenon, was adopted.



Single radiation source test/
Spent nuclear fuel test

Particulate transport calculation/
Linear model calculation

[Output]
Energy absorption amount Or hydrogen generation rate
(Test value)

[Output]
Energy absorption amount Or hydrogen generation rate
(Calculated value)

Comparative evaluation of energy absorption amount and hydrogen generation rate

Test value under all conditions < Calculated value

Upper limit of all test values < Upper limit of all calculated values
AND
Test value under any of the conditions > Calculated value

Upper limit of all test values > Upper limit of all calculated values

The amount of energy absorption is a value that corresponds to the particle size evaluated from the particulate transport calculation result (Equivalent to $F_{(calc.)d}$ in the energy absorption rate Note 1)

The amount of energy absorption is the maximum value evaluated from the particulate transport calculation result (Equivalent to $F_{(calc.)powder}$ in the energy absorption rate Note 1)

The amount of energy absorption is the maximum value (Equivalent to F_{max} in the energy absorption rate Note 1)

Figure. Study flow (plan) for the verification of validity of input values (Energy absorption rate)

Note 1: Particle and Heavy Ion Transport code System, the Monte Carlo calculation code which simulates various radiation behavior in matter using the nuclear reaction model and nuclear data, etc.

Note 2: $F_{(calc.)d}$, $F_{(calc.)powder}$, and F_{max} are the energy absorption rates described in the graph in 6.3 ③ (1) a. (iii) b.(1/3)

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (9/14)

(iv) Verification of validity of input values (2/5)

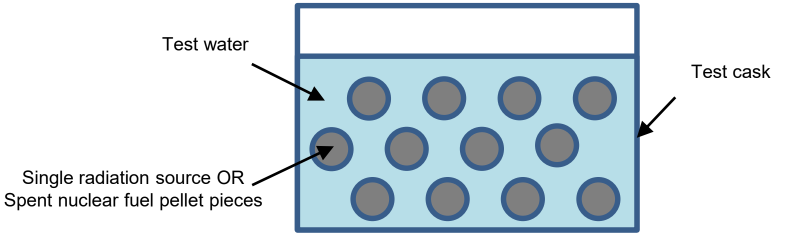
a. Verification of validity of the energy absorption rate (2/2)

The test results of the hydrogen generation test conducted using spent nuclear fuel in FY 2018, were considered as the existing test results, which could be used for the verification of validity, but upon re-evaluation (refer to 6.3③(1)a.(iv)b.), it was found that the test results also included the effect of contact between particles and the effect of air bubbles in the pellet pieces-test water layer, and that the test results of FY 2018, which might have been less conservative, were not suitable for verifying the validity of the evaluation of energy absorption amount.

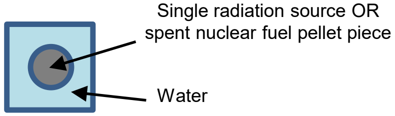
When verifying the validity through tests, the following tests (Test plan 1 Or Test plan 2) are believed to be necessary wherein, by using a particle size or a radiation source whose radioactivity is already known, the test water is stirred in order to eliminate the effect of contact between particles or the effect of air bubbles in the particles-test water layer, thereby suspending the particles.

Test plan 1: Conduct a test using a single radiation source (Single radiation source test) where it is comparatively easy to make the particle size uniform and it is easy to evaluate the radioactivity, and confirm that the evaluation of energy absorption amount using the particulate transport calculation is moderately conservative with respect to the test results.

Test plan 2: By means of test using spent nuclear fuel pellet pieces (Spent nuclear fuel test (The same test as the spent nuclear fuel test used for verifying the applicability of the evaluation methods (Refer to 6.3 ③ (1) a.(v))), confirm that the particulate transport calculation results are moderately conservative even in case of a coexisting system of alpha, beta and gamma rays.



(a) Single radiation source test OR spent nuclear fuel test



(b) Particulate transport calculation model

Figure. Image of the test system

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (10/14)

(iv) Verification of validity of input values (3/5)

b. Re-evaluation of hydrogen generation test (Summary of re-evaluation results)

The results of the hydrogen generation test (conducted in FY 2018) using spent nuclear fuel were re-evaluated and it was presumed that the main causes for the difference between the calculated results and the test results are the air bubbles inside the pellet pieces layer and the contact between the pellet pieces.

Table. Results of re-evaluation of differences between the calculated results (evaluation result by means of the particulate transport calculation) and the test results

Causes of difference studied		Extent of impact	
		Small diameter (average particle size 0.04 mm)	Large diameter (average particle size 2.5 mm)
Test results	① Release of nuclides due to the washing of pellet pieces	Maximum about 10%	
	② Burn-up distribution of pellet pieces	Almost none	
	③ Uneven distribution of elements in the gas during the gaseous phase	Almost none	
	④ Residue of generated gas in the pellet pieces - test water layer	Almost none	
	⑤ Error by measurement devices	Maximum about 10%	
Particulate transport calculation	① Overestimation of radioactivity of the pellet pieces	Maximum about 5%	
	② Effect of dissipation of the alpha, beta and gamma rays	About 10%	About 30%
	③ G-value of hydrogen generation considering the LET [Note 1] of alpha rays	About 10%	About 3%
	④ Particle size distribution of pellet pieces	About 10%	Almost none
	⑤ Collection of air bubbles on pellet pieces - test water layer (Refer to 6.3 (1) ③ a. (iv) c. for details)	With a rise in the air bubble content percentage, the extent of impact increases [Note 2] up to several tens of percent points	
	⑥ Contact between the pellet pieces (Refer to 6.3 (1) ③ a. (iv) d. for details)	As the contact increases, the extent of impact increases [Note 3] up to several tens of percent points	Not evaluated

Note 1: Linear Energy Transfer. Energy lost on average per unit length of range as radiation passes through matter

Note 2: The extent of impact is about 20% when the air bubble content ratio is 0.3 with respect to the hydrogen generation rate considering the impact of particulate transport calculation ②

Note 3: The extent of impact is about 70% when the void size generated due to the contact between pellet pieces is 0.3 mm with respect to the hydrogen generation rate considering the impact of particulate transport calculation ②

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

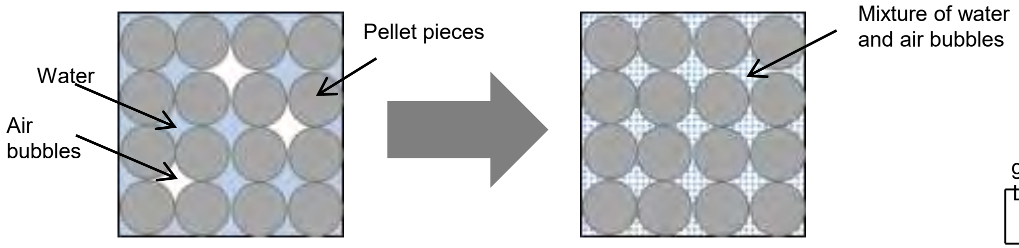
③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (11/14)

(iv) Verification of validity of input values (4/5)

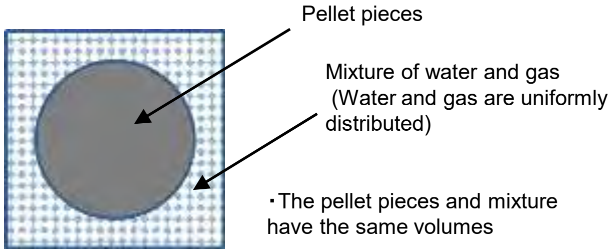
c. Example 1 of re-evaluation of the hydrogen generation test (Impact verification of collection of air bubbles on pellet pieces - test water layer)

When the particulate transport calculation was used to verify the impact of the collection of air bubbles due to the gas (oxygen and hydrogen) generated as a result of water radiolysis, and due to the residual gas after the injection of test water, it was confirmed that the hydrogen generation rate decreased as the air bubble content percentage increased (For instance, at an air bubble content ratio of 0.3, the hydrogen generation rate decreased by about 20%).



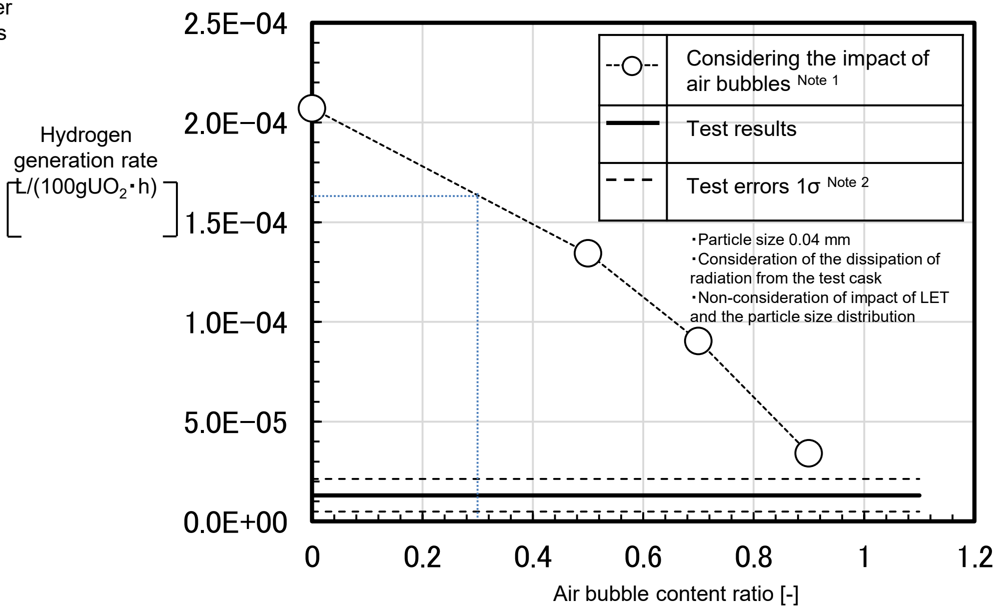
(a) Collection of air bubbles during test **(b) Collection of air bubbles in re-evaluation**

Figure. Image of collection of air bubbles



・The pellet pieces and mixture have the same volumes

Figure. Image of single particle system for particulate transport calculation



・Particle size 0.04 mm
・Consideration of the dissipation of radiation from the test cask
・Non-consideration of impact of LET and the particle size distribution

Figure. Evaluation results from the particulate transport calculation: Air bubble content ratio and hydrogen generation rate

Note 1: The hydrogen generation rate is calculated by multiplying the G-value of hydrogen generation with the amount of energy absorbed by water calculated using particulate transport calculation. (The peaking factor is not considered for the calorific value in the TMI-2 evaluation formula)
Note 2: Variation in the test results of four cases using pellet pieces with small particle size

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

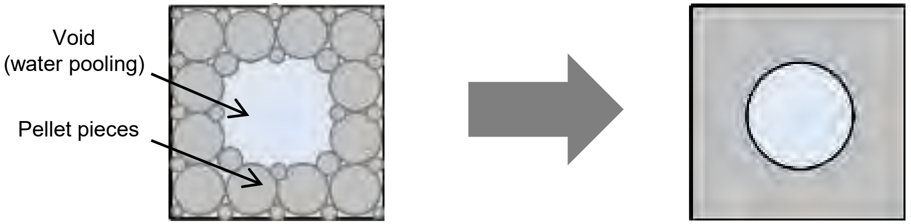
③ Implementation items and results (Estimated and actual)

a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (12/14)

(iv) Verification of validity of input values (5/5)

d. Example 2 of re-evaluation of the hydrogen generation test (Impact verification of the impact of contact between the pellet pieces)

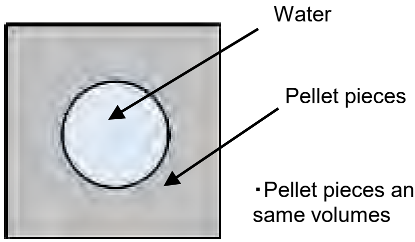
The variation in particle size distribution of small particle sizes (0.02 to 0.3 mm) is large and the particles differ in shape and dimensions, so the pellet pieces tend to come in close contact with each other, and when the impact of this contact was verified by means of the particulate transport calculation, it was confirmed that the hydrogen generation rate decreased with the decrease in the contact area (For instance, when the void diameter (water pooling) was 0.3 mm, the hydrogen generation rate decreased by about 70%).



(a) Contact between the pellet pieces during test

(b) Contact between the pellet pieces in re-evaluation

Figure. Image of contact between particles



・Pellet pieces and water have the same volumes

Figure. Image of single particle system for particulate transport calculation

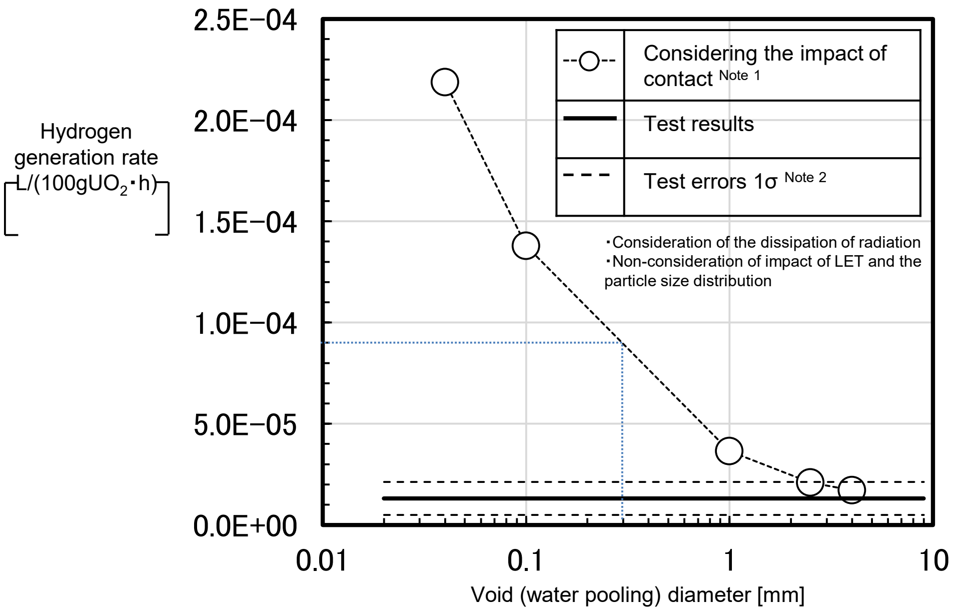


Figure. Evaluation results from particulate transport calculation: Void (water pooling) diameter and hydrogen generation rate

Note 1: The hydrogen generation rate is calculated by multiplying the G-value of hydrogen generation with the amount of energy absorbed by water calculated using particulate transport calculation. (The peaking factor is not considered for the calorific value in the TMI-2 evaluation formula)

Note 2: Variation in the test results of four cases using pellet pieces with small particle size

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

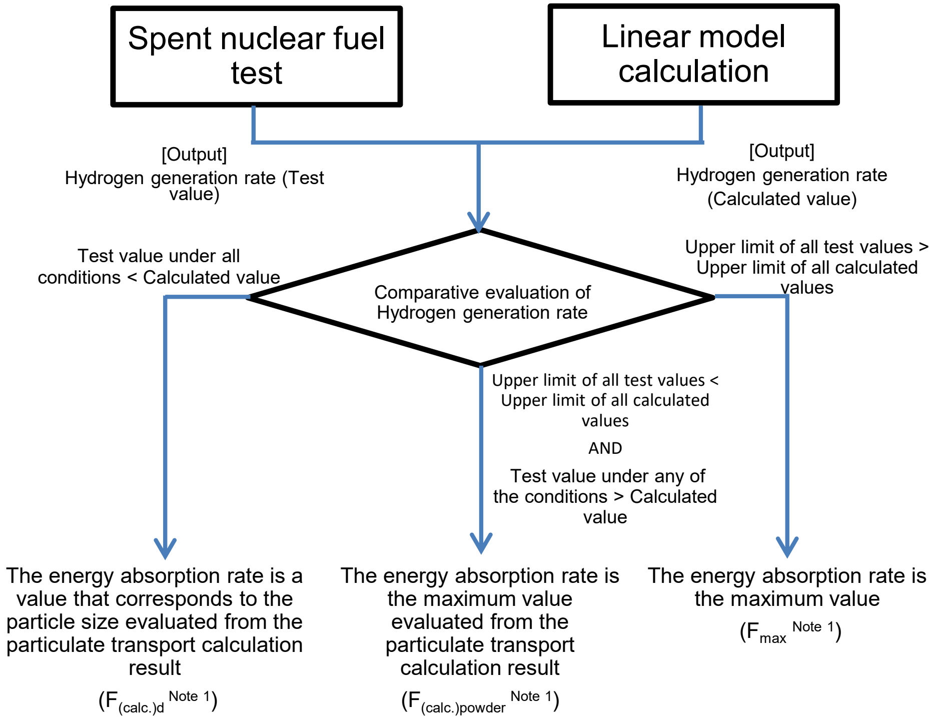
a. Study of implementation details necessary for setting the transfer conditions plan (FY 2019) (13/14)

(v) Verification of applicability of evaluation method~~s~~ (1/2)

The actual results verifying the applicability of the evaluation method (Linear model) to a system containing alpha, beta and gamma rays could not be verified, so it is necessary to verify the applicability after considering individual input values.

It is believed that the comparison with the hydrogen generation rate by means of the actual fuel debris is most appropriate to verify the applicability to the 1F conditions, but it is difficult at the present moment from the viewpoint of availability.

Therefore, the policy that was adopted to verify the applicability of the evaluation method (Linear model) by confirming that the hydrogen generation rate calculated by the Linear model, which uses the energy absorption rate evaluated from the particulate transport calculation result as the input value, was moderately conservative with respect to the test results in case of a coexisting system of alpha, beta and gamma rays simulating the fuel debris.



Spent nuclear fuel test

Linear model calculation

[Output]
Hydrogen generation rate (Test value)

[Output]
Hydrogen generation rate (Calculated value)

Comparative evaluation of Hydrogen generation rate

Test value under all conditions < Calculated value

Upper limit of all test values < Upper limit of all calculated values

AND

Test value under any of the conditions > Calculated value

Upper limit of all test values > Upper limit of all calculated values

The energy absorption rate is a value that corresponds to the particle size evaluated from the particulate transport calculation result

($F_{(calc.)d}$ Note 1)

The energy absorption rate is the maximum value evaluated from the particulate transport calculation result

($F_{(calc.)powder}$ Note 1)

The energy absorption rate is the maximum value

(F_{max} Note 1)

Figure. Study flow (plan) for the verification of applicability of evaluation methods (Linear model)

Note 1: $F_{(calc.)d}$, $F_{(calc.)powder}$, F_{max} are the energy absorption rates described in the graph in 6.3③(1)a.(iii)b.(1/3)

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

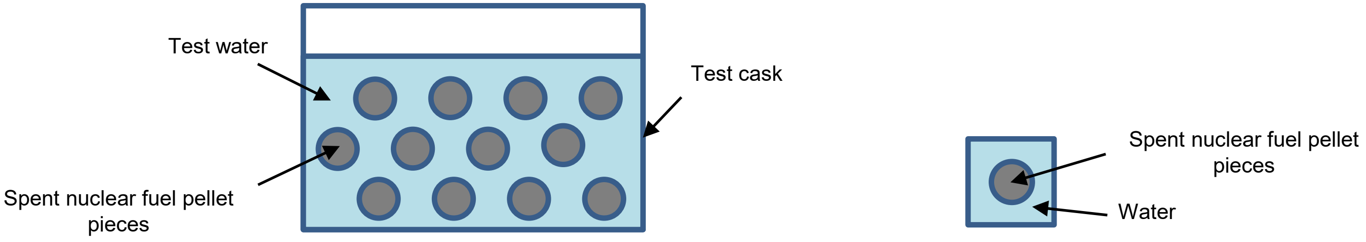
a. Study of implementation details necessary for setting the transfer conditions plan (FY2019) (14/14)

(v) Verification of applicability of evaluation method~~s~~ (2/2)

The test results of the hydrogen generation test conducted in FY2018 using spent nuclear fuel were considered as the existing test results that could be used for the verification of applicability of evaluation method, but upon re-evaluation (refer to 6.3③a.(iv)b.), it was found that the test results also included the effect of contact between particles and the effect of air bubbles in the pellet pieces-test water layer, and that the test results of FY 2018, which might have been less conservative, were not suitable for verifying the applicability of the evaluation method (Linear model).

When verifying the applicability through tests, the following test is believed to be necessary wherein, by using fuel debris simulants (radiation source) containing of alpha, beta and gamma rays, the test water is stirred in order to eliminate the effect of contact between simulants or the effect of air bubbles in the simulant-test water layer, thereby, suspending the particles.

Test plan: By means of the test using spent nuclear fuel pellet pieces (spent nuclear fuel test (the same test as the spent nuclear fuel test used for the verification of validity of the energy absorption rate (refer to 6.3③(1)a.(iv)a.))), confirm that the hydrogen generation rate calculated by the Linear model, which uses the energy absorption rate evaluated from the particulate transport calculation result as the input value, is moderately conservative with respect to the test results in case of a coexisting system of alpha, beta and gamma rays.



(a) Spent nuclear fuel test (b) Particulate transport calculation model

Figure. Image of the test system

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

③ Implementation items and results (Estimated and actual)

b. Implementation of hydrogen generation test (to be implemented if necessary) (FY 2020) [Scheduled]

Based on the results of the study in point a., a study will be conducted in view of executing the hydrogen generation test in FY 2020. The study results will be evaluated using the evaluation formula and analysis, etc., and the results will be compared. Moreover, even while evaluating the results of this test, expert opinions will be heard as appropriate.

c. Study of method to predict hydrogen generation (FY 2019, FY 2020)

The proposed methods to predict hydrogen generation are being studied on the basis of the test results in point a. During the study, the hydrogen generation test results (if the tests were conducted) from point b. will also be referenced. In addition, if necessary, evaluation will also be carried out by means of analysis.

d. Estimation of hydrogen generated in canister (FY 2020) [Scheduled]

The amount of the hydrogen generation under the 1F canister conditions will be presumed on the basis of the proposed methods to predict hydrogen generation studied in point c.

e. Study of transfer conditions (FY 2020) [Scheduled]

Based on the study results of point d., the hydrogen generation countermeasures (study of recombination catalyst) implemented separately and the study results of the drying technology, etc., transfer condition plans for canisters will be studied and proposed so that the canisters can be transferred safely from the viewpoint of hydrogen measures.

Based on the above-mentioned study, a method to predict hydrogen generation suitable in the 1F fuel debris conditions will be proposed along with proposing the conditions, restrictions, and additional countermeasures necessary for the transfer of fuel debris.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

④ Contribution of the results to the areas where they can be reflected

On the basis of the presumed amount of hydrogen generation and the proposed transfer condition plans, it is believed that it should be possible to contribute to the drafting of operation plans for transfer and storage of actual canisters, designing and manufacturing of the vent mechanism for the actual canisters, and the study of hydrogen gas treatment facility.

⑤ Analysis from the perspective of site application

For application to the site, in addition to the method to predict hydrogen generation, which will be the outcome of this project, it is necessary to conduct studies combining the drying treatment to reduce the amount of hydrogen generation, ensuring tolerance by means of a hydrogen catalyst, and checking if transfer is possible by means of actual measurement of hydrogen concentration prior to transfer, etc.

⑥ Issues

There are no issues in the execution of the present plan.

⑦ Level of achievement in light of the goal

As a study for the implementation details necessary for setting the transfer condition plans, the method of verifying the validity of the input values for the method to predict hydrogen generation and the method of verifying the applicability of evaluation methods, are being studied. The progress is almost as planned, and it is expected that the target results can be achieved by the end of FY2020.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

Summary

For the development of technology for transfer of fuel debris, in FY2019, the study items and implementation details required for setting the transfer condition plans were studied by investigating domestic and overseas findings and by hearing expert opinions on the methods to predict hydrogen generation.

In FY 2020, the study of methods to predict hydrogen generation will proceed, wherein the amount of hydrogen generated inside the canisters will be presumed on the basis of the results of hydrogen generation tests implemented as needed, and transfer condition plans to enable safe transfer will be studied.

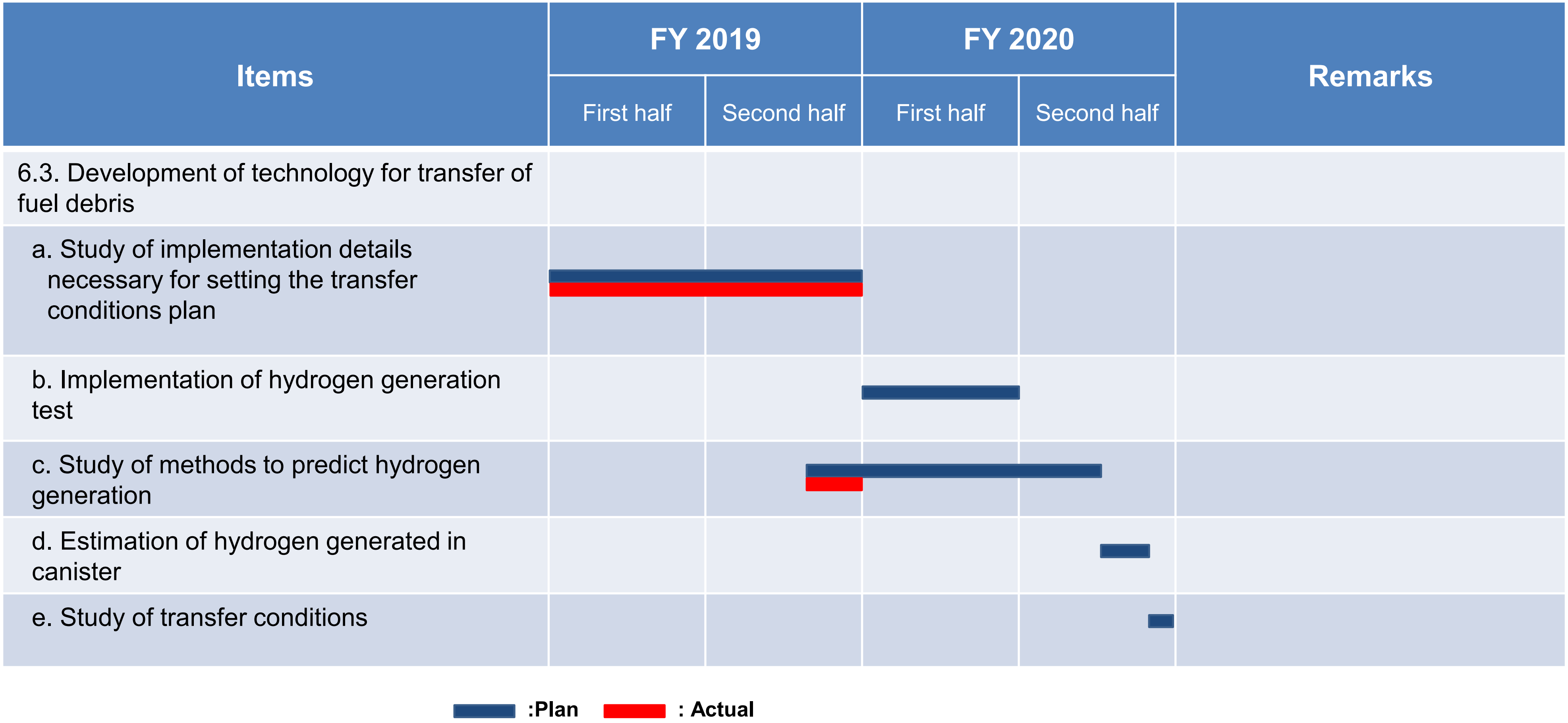
6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(1) Study of methods to predict hydrogen generation

⑧ Future plans

Figure. Schedule for development of technology for transfer of fuel debris/ study of methods to predict hydrogen generation



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
6.3. Development of technology for transfer of fuel debris					
a. Study of implementation details necessary for setting the transfer conditions plan	🟦 🟥	🟦 🟥			
b. Implementation of hydrogen generation test			🟦		
c. Study of methods to predict hydrogen generation		🟦 🟥	🟦	🟦	
d. Estimation of hydrogen generated in canister				🟦	
e. Study of transfer conditions				🟦	

🟦 :Plan 🟥 : Actual

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

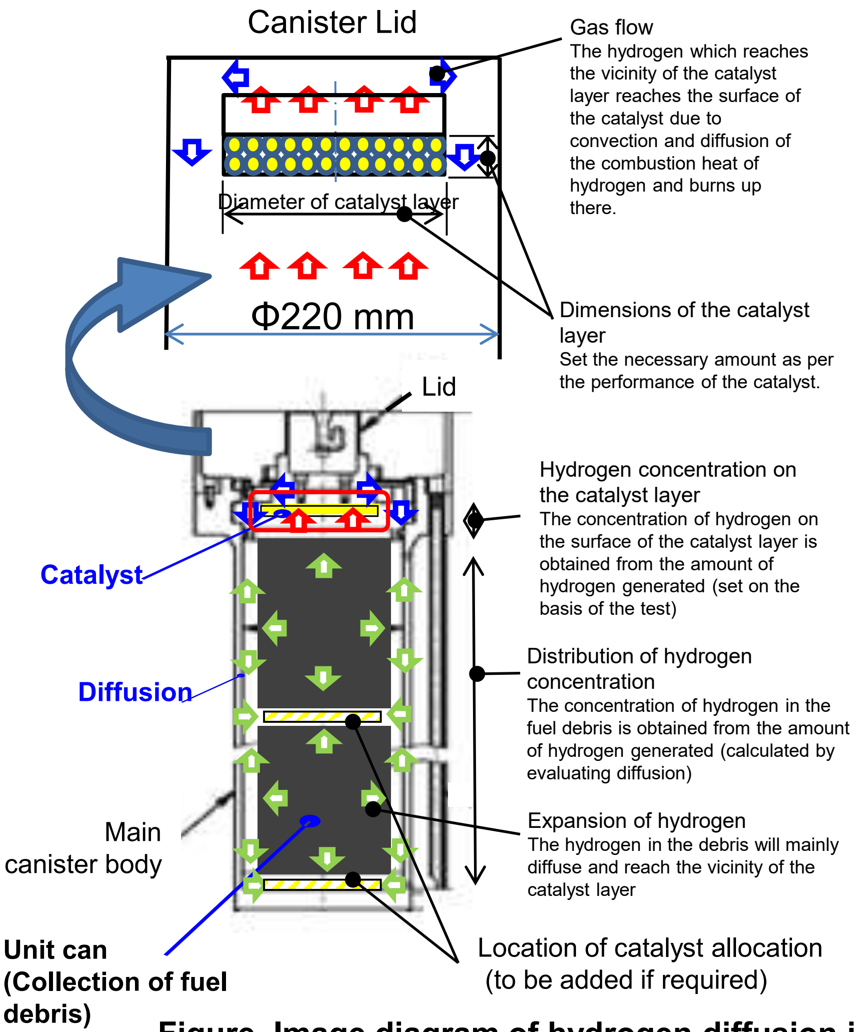
- In case of the TMI-2 fuel debris canisters, the catalyst believed to be effective at that point in time was adopted, but water-repellency was not considered.
- Various catalysts have been developed in Japan, and last year, operation tests were conducted under humid and room temperature environments 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)



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.

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

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 : Determine catalyst performance under environmental conditions such as the flow velocity conditions, etc. by means of tests.

⇩

b. Detailed study of flow characteristics inside the canister : Based on the restrictions of the placement location and conditions such as the canister shape and the amount of hydrogen generated, etc., evaluate the distribution of hydrogen concentration inside the canister from the viewpoint of flow/diffusion, and select the predominant location from the viewpoint of concentration.

⇩

c. Study on catalyst allocation : Based on the study of catalyst allocation and catalyst amount in points a. and b. above, set up an effective placement from the viewpoint of hydrogen concentration inside the canister.

6. Implementation Details

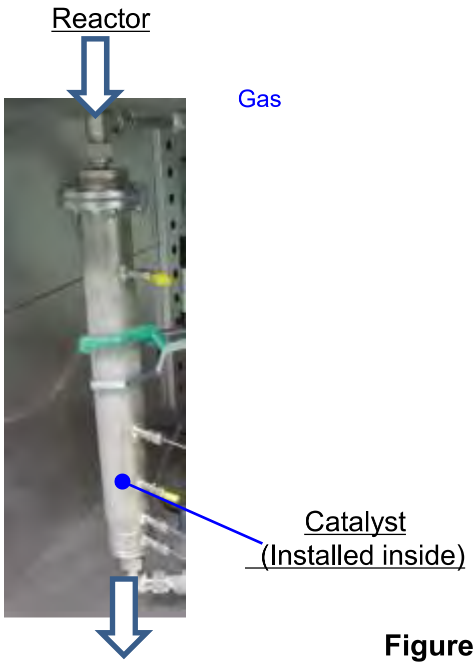
6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

③ Implementation items and results (Estimated and actual)

a. Study of catalyst (1/2)

In a test where a catalyst is filled in a void tower and gas is circulated (flow-type reaction rate evaluation test), obtain the overall reaction rate coefficient data by varying the conditions of the circulated gas (flow velocity (superficial velocity), gas temperature, hydrogen concentration, toxic components), and derive an estimation formula for the overall reaction rate coefficient of the catalyst for environmental conditions such as flow velocity.



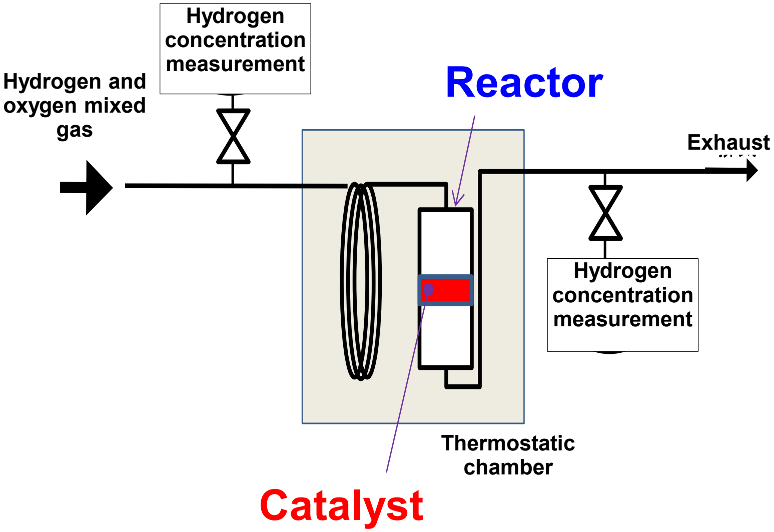


Figure. Concept of flow-type reaction rate evaluation test

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 temporarily set based on the estimation method of the reaction rate coefficient. As the environment inside the canister is also affected by the amount of catalyst and its arrangement, the effectiveness of hydrogen measures is confirmed by evaluating the hydrogen concentration in the canister under the set catalyst conditions. Also, the amount of catalyst and its placement are reviewed and re-evaluated or confirmed as necessary.

Note 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

(Supplement) Approach to laminar gas film mass transfer and overall reaction rate coefficient

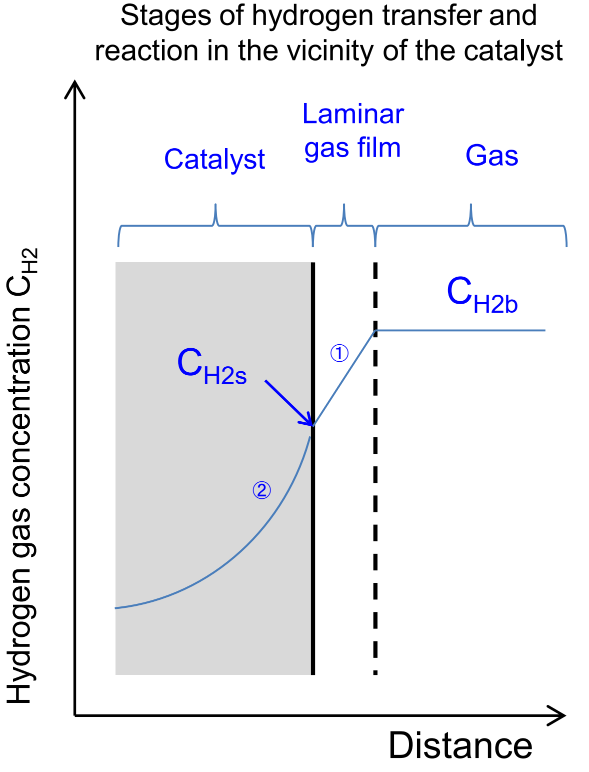


Figure. Concept of hydrogen transfer and reaction in the vicinity of the catalyst Note 1

○ The reaction of hydrogen by a catalyst can be explained in the following two stages:

① Mass transfer from fluid to catalyst surface
② Reaction on the catalyst surface

○ Depending on the conditions of use, the velocity of both ① and ② change, and the stage where the velocity is relatively low becomes the rate-determining step and this determines the overall velocity.

○ The mass transfer rate from the fluid to the catalyst surface is expressed by laminar film mass transfer (laminar gas film mass transfer).

$$r_G = k_G (C_{H2b} - C_{H2s})$$

○ The reaction rate on the catalyst surface is expressed by the following equation:

$$r_R = k_R C_{H2s}$$

○ Based on the above, the overall reaction rate coefficient K is expressed by the following equation:

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

K: Overall reaction rate coefficient
k_R: Catalyst reaction rate coefficient
k_G: Laminar gas film mass transfer coefficient

Note 1: Created from Pg. 183 of Reaction Engineering, Baifukan, by Kenji Hashimoto

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

(Supplement) Approach to collection of performance data of catalyst

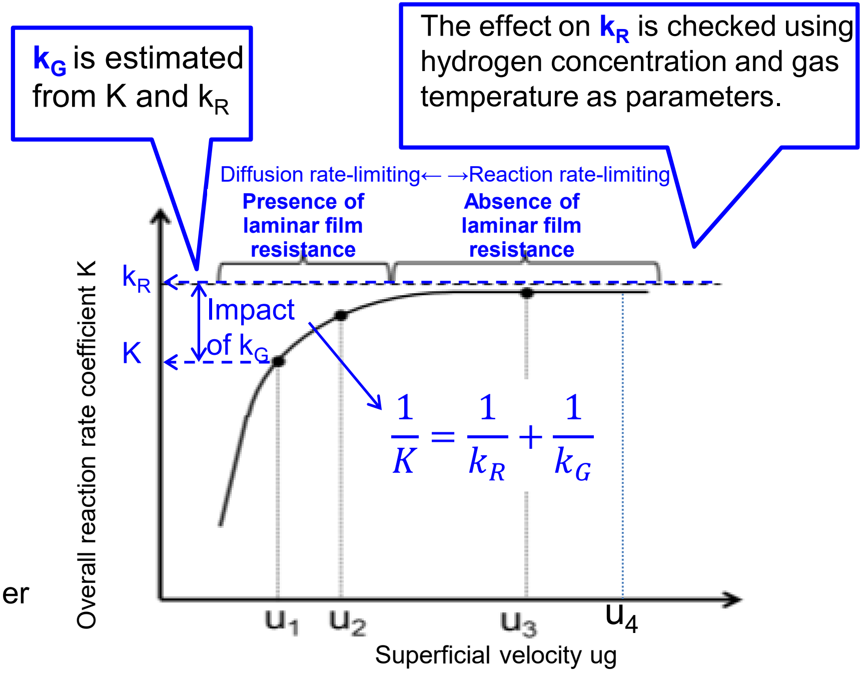
As described above, the reaction rate equation of the hydrogen recombination reaction is expressed by the following equation:

reaction rate equation

Reaction when expressed as primary : $-r = KC_{H2}$

r: reaction rate C_{H2}: Hydrogen concentration C_{O2}: Oxygen concentration
K: Overall reaction rate coefficient

- ✓ The prerequisite for the above relation is similar environment conditions such as temperature and gas flow velocity. As the overall reaction rate coefficient (K) depends on these environmental conditions, it is necessary to collect data so that these conditions can be dealt with. In particular, it is necessary to consider that the gas flow velocity forms a laminar gas film on the catalyst surface.
- ✓ Therefore, when setting K, it was decided to acquire data through flow-type reaction rate evaluation test so as to focus individually on the reaction velocity coefficient of the catalyst itself (k_R: catalyst reaction rate coefficient) and the effect of diffusion inside the laminar film (k_G: laminar gas film mass transfer coefficient), and estimate K for any flow velocity condition.



k_G is estimated from K and k_R

The effect on **k_R** is checked using hydrogen concentration and gas temperature as parameters.

(k_R: Catalyst reaction rate coefficient,
k_G: Laminar gas film mass transfer coefficient)

Figure. Approach to obtaining reaction rate coefficient

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

(K: Overall reaction rate coefficient, k_R: Catalyst reaction rate coefficient, k_G: Laminar gas film mass transfer coefficient)

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 (2/2)

The superficial velocity (flow velocity) dependence data of overall reaction rate coefficient is being collected through tests.

b. Detailed study of flow characteristics inside the canister

Based on the study in FY 2018, it was found that the flow inside the canister was very little and diffusion was dominant, so it was decided to carry out the evaluation focusing on diffusion.

c. Study on catalyst allocation

The hydrogen concentration in the sealed canister will be evaluated with respect to the catalyst allocation and amount of catalyst set based on the results of points a. and b., and the effectiveness of catalyst-based hydrogen measures will be confirmed.

6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

④ Contribution of the results to the areas where they can be reflected

Investigated as one of the candidate plans for hydrogen measures during canister transfer.
(It is a back-up for hydrogen measures by means of time management (mitigation measures) especially when drying before transfer is not possible)

⑤ Analysis from the perspective of site application

Ensure that it does not become a burden during actual application, by incorporating the environment assumed in the catalyst performance study related to catalyst installation.

⑥ Issues

As a result of preliminary tests while acquiring catalyst performance data, the hydrogen concentration after passing through catalyst was low, and a method for precisely measuring low-concentration hydrogen was required to understand catalyst performance. Therefore, it was decided to collect catalyst performance data in FY 2020 after determining the method.

⑦ Level of achievement in light of the goal

After doing the needed measures to collect more precise catalyst performance, we would like to proceed with a study that will collect the catalyst performance including the impact of iodine (as a toxic catalyst substance) and will obtain the desired results by evaluating the validity of catalyst-based hydrogen measures.

Summary

In FY 2019, the flow inside the canister was studied as catalyst-based hydrogen measures. The study on the method for obtaining catalyst performance is underway.

In FY 2020, the required amount of catalyst and its installation position will be studied, and the hydrogen concentration inside the canister will be evaluated to confirm the effectiveness of the catalyst, based on the catalyst performance data obtained through tests and the evaluation of flow inside the canister.

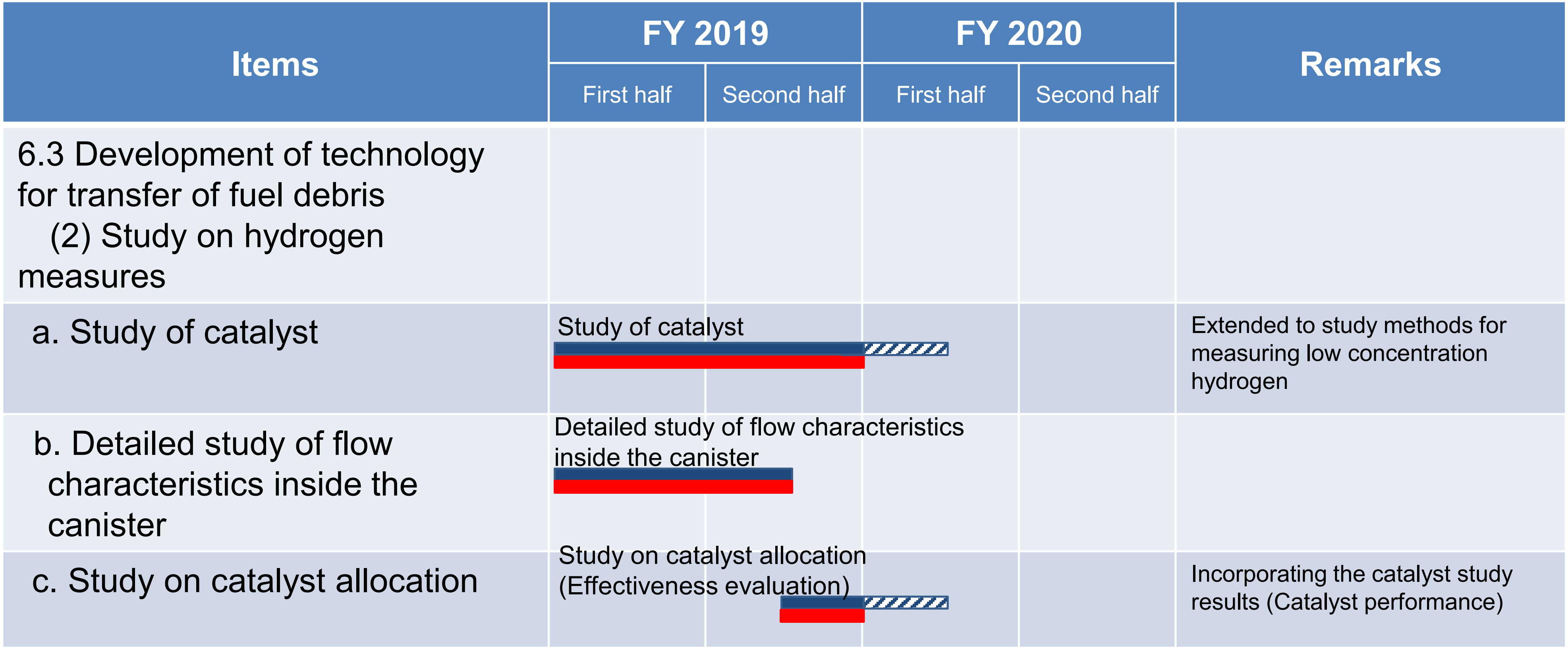
6. Implementation Details

6.3 Development of technology for transfer of fuel debris

(2) Study on hydrogen measures

⑧ Future plans

Table. Schedule for development of technology for transfer of fuel debris/ study on hydrogen measures



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
6.3 Development of technology for transfer of fuel debris (2) Study on hydrogen measures					
a. Study of catalyst	Study of catalyst				Extended to study methods for measuring low concentration hydrogen
b. Detailed study of flow characteristics inside the canister	Detailed study of flow characteristics inside the canister				
c. Study on catalyst allocation	Study on catalyst allocation (Effectiveness evaluation)				Incorporating the catalyst study results (Catalyst performance)

▬ : Plan ▬ : Actual ▨ : Reviewed plan

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

① Purpose and Goal

- During the inter-building transfer of fuel debris up to the storage facility, the sealing of fuel debris is essential as the accumulation of hydrogen due to the moisture content of the fuel debris is an issue. Hence, moisture removal by drying is considered to be effective in reducing the amount of hydrogen generation.
- Therefore, in this technological development, for the purpose of safer transfer, the goal is to propose a draft on the basic specifications of a drying apparatus for 1F fuel debris by setting the parameter conditions that are effective for drying with the focus on the drying behavior of the porous material, which may be a possible form of fuel debris, and also considering the maintenance and handling of even fuel debris substitutes in contaminated areas.
- It is expected that these results will be utilized as the base for the verification tests using actual fuel debris performed at the stage of engineering work for the actual equipment or for the design of actual equipment based on the test results.

② Comparison with existing technology

- The purpose of drying the fuel debris in TMI-2 is to remove free water to ensure subcriticality and it is not a treatment method aimed at advanced drying. Meanwhile, as the purpose in 1F is to reduce the hydrogen generation amount, it is necessary to determine concrete details of a treatment method that can achieve a low moisture content. Also, the findings (contamination measures, etc.) related to heated vacuum drying selected for TMI-2 are considered to be useful information.
- There are various methods used for drying in general industries, and it is believed that there are methods other than the methods used in TMI-2, which would be effective for 1F fuel debris. Meanwhile, there are problems in applying them to the drying of fuel debris as is, in terms of maintenance and handling, etc., in contaminated areas.

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

Study methodology

a. Study on basic conditions

(i) Study on performance requirements (target items, target time, target moisture content)

- Set the targets to be dried, the target time, and the target moisture content, and organize the requirements of drying apparatus performance.

(ii) Study on safety requirements

- Clarify the safety requirements and organize the functional requirements of drying apparatus.

(iii) Investigation and analysis of existing drying technology

- Investigate the drying technologies used in TMI-2, organize the drying technologies used in general industries, and study their applicability to debris drying.

(iv) Study on the device concept

- Study on the concept of drying apparatus (including maintenance plan, equipment systems, equipment configuration) based on (i)-(iii) and element tests Note 1.

b. Collection of drying behavior data

Note 1: Implemented as needed

(i) Preparation of test equipment

- Identify the items to be collected / verified on a real-size (canister or / and unit can) and formulate a test plan

(ii) Collection of drying behavior data (including maintainability, etc.)

Element tests are conducted as necessary.

- Perform data collection / verification including operability and maintainability required for b.(i) and c.(i) using a real-size test equipment.

c. Basic plan for drying system

(i) Study on maintenance plan / equipment systems / equipment configuration

- Specify the functional requirements and study the system concepts, identify the items that need to be collected / verified and reflect them in section b.

(ii) Formulation of basic specifications of the equipment (after reflecting the data)

- Reflect the test results and come up with the basic specifications (plan) of drying apparatus and the configuration (plan) of ancillary facilities

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a. Study on basic conditions (1/8)

(i) Organizing performance requirements (1/3)

As performance requirements of the drying system, the standard values of the target items, drying time, and moisture content were set as follows:

(Target items) Porous materials
(Target time) Receiving to allocation 24 hrs
(Target moisture content) 0.1 wt.% Note 1

Note 1: Moisture content based on the density of fuel debris. The target moisture content in the test should be reviewed based on the density of the test specimen.

Table. Evaluation for performance requirements

Performance requirements		Response policy plan
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 hours.
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 on the basic specifications of drying apparatus

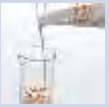
③ Implementation items and results (Estimated and actual)

a. Study on basic conditions (2/8)

(i) Organizing performance requirements (2/3)

Following are the main collections that were identified as drying targets during the study.

Table. Main collections to be studied

Generation source	Name	Overview	Image	Features
Retrieval process	Stump fuel debris	Part of the fuel assemblies that remained intact without melting		・Debris collected from the retrieval process is the **main target for drying**. ・ Oxide debris is **presumed to be porous material** in the study for the Characterization PJ.
	Block-like fuel debris, MCCI	Fuel debris that cooled slowly to become like a block		
	Pebble or powder-like fuel debris	Molten core material that cooled rapidly and fragmented		
	Structures with deposits of nuclear fuel material	Structures that remained without melting and on which fuel debris has deposited		
Water treatment system	Slurry	Powdery, fine particulate debris		・**Fine particulate debris may be a target for drying.** ・ However, the **detailed properties are unknown**. (Therefore, applicability of drying technologies studied using porous materials is considered)
Others	Filters	Filters present in water treatment system / gas treatment process		

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a. Study on basic conditions (3/8)

(i) Organizing performance requirements (3/3)

In the Fuel Debris Characterization Project, the following results were collected until FY 2016 by conducting the “Evaluation of moisture content and drying properties of fuel debris” :

- ✓ In the case of porous materials, the drying rate at the end of the drying process becomes slow when the impact of small pores is large.
- ✓ In the case of powdered granular material, when fine particles are moistened, they become clay-like and the drying rate decreases.

From the above, it is assumed that properties such as porous materials containing small pores and fine particles containing moisture (slurry) affect the drying behavior.

From the above, the development of the targets to be dried will be carried out as per the below policy, based on the organized results on the targets and their features for each retrieval process (previous slide).

- ✓ **The main target is porous material with** small **pores. (Typical porous material ⇒ Zeolite test specimen)**
- ✓ **Although slurry might be a target for drying, considering the fact that current properties of the slurry are not known, the applicability of drying technologies to be studied with porous materials as the main target, will be studied using element tests, etc.**

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a.Study on basic conditions (4/8)

(ii) Organizing safety requirements

The requirements of drying apparatus with respect to the safety functions being considered in this development are similar to those of the canisters, and are set as follows.

Table. Required functions of drying apparatus with respect to the safety functions

Safety functions		Design goals	Division of safety functions		Required functions	
			Canister	Other equipment	Drying apparatus	Remarks
Subcriticality		To maintain subcriticality	O	O	O	
Cooling	Heat removal	To prevent the impact on physical properties of canisters, fuel debris, etc.	-	O	O (Additional)	Heated by drying treatment (Prevention of abnormal heating)
Confinement	Confinement	To prevent exposure of workers and public	O	O	O	Preventing the spread of contamination
	Shielding	To prevent exposure of workers and public	-	O	-	Installed inside the cell
Other (Maintaining the shutdown, cooling and confinement functions)	Structure	To achieve the structural strength for maintaining the safety functions	O	O	O	
	Material integrity	To maintain the structural strength	O	O	O	
	Hydrogen	To prevent the explosion of hydrogen generated by the radiolysis of water	O (Catalyst)	O	O (Drying)	
	Fire prevention	To prevent fire caused by residual zirconium	-	O	-	

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a.Study on basic conditions (5/8)

(iii) Investigation and analysis of existing drying technologies (1/2)

The drying methods used in general industries were organized, and the drying methods applicable to the drying of fuel debris were selected.

Table. Investigation and analysis of drying apparatus in general industries

Drying method	Level of difficulty in responding to safety requirements				Remarks
	Maintaining subcriticality	Confinement function	Prevention of spread of contamination	Prevention of abnormal heating	
Warm air (carrier gas)	O	O	O	O	
Heat conduction medium	O	O	△	O	As heat is input by directly touching the heat transfer surface, the maintenance target becomes a direct contaminant.
Radiation	O	O	O	O	
Microwave	O	△ (Increase in size of cell)	x (Waveguide sealing)	O	As the waveguide cannot be sealed during drying, the microwave generating equipment is also subject to contamination.
Induction heating (IH)	O	O	O	O	
Superheated steam	(Not applicable as it will bring in moisture)				
Depressurization	O	O	O	O	
Stirring	x (UC retrieval)	O	x (Expansion of contaminated area)	O	The fuel debris is retrieved from the UC and stirring and suspension flow is carried out on it to whirl up the powder.
Suspension flow	x (UC retrieval)	△ (Increase in size of cell)	x (Expansion of contaminated area)	O	

Legend: O…Low level of difficulty △…Medium level of difficulty x… High level of difficulty

Approach to narrowing down the methods

- As a prerequisite fuel debris is handled in unit cans (UC).
- Ensures safety (maintaining subcriticality) by handling UC.
- **Stirring and suspension flow** requires retrieval from UC and necessitates further contamination measures and subcriticality evaluation.
- In the case of **microwaves**, as the waveguide and the inside of the drying apparatus have the same atmosphere, further contamination measures are required in consideration of maintainability.

[Drying methods] Warm air, Heat conduction medium, Radiation, Induction heating (IH), Depressurization

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a. Study on basic conditions (6/8)

(iii) Investigation and analysis of existing drying technologies (2/2)

The drying performance of TMI-2 fuel debris was evaluated and its applicability to the development of this technology was studied.

Table. Study on the applicability of TMI-2 fuel debris drying technology to this development

Items	Targets for investigation and study	Performance with TMI-2 fuel debris	Applicability to this development
Design	Purpose / Goal	Purpose: Maintaining subcriticality Target: Water removal between particles, and the allowable water content is set to 8 ℓ/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 cm^3/ℓ or less) of TMI-2.
	Material under test for preliminary study	Sand, pumice (porous materials)	Policy of using porous materials that are more difficult to dry than that in TMI-2
	Drying method	Heated vacuum (temperature limit of sealing material 150 ℃) Heated gas (used only in test)	・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	Subcriticality	No information available on the evaluation conditions for drying furnace	Requires study
	Cooling	No information available on design approach	Requires study
	Contamination measures for drying apparatus (system)	Installation of metal filter in canister	The lesson learned that **installing a metal filter in a canister** is effective in controlling equipment contamination is useful information.

[Summary] ・The results of TMI-2 can be used as a reference for removing free water between particles.
・As the goals set for drying in this development are strict, their direct application is difficult.
・The installation of a filter in the canister as a measure against system contamination in the device is useful information.

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a. Study on basic conditions (7/8)

(iv) Conceptual study of the device (1/2)

◆ Subcriticality is maintained by handling fuel debris in unit cans

◆ The unit can is a netted-caged structure made of a mesh that allows easy flow of water / air ⇒ Assuming that it facilitates the draining and drying of fuel debris

◆ Elements that facilitate drying are **evaporation facilitation, mass transfer facilitation, area improvement ⇒ Combined for maximum use**

◆ Evaporation facilitation: **Direct heating method (warm air) and depressurization method** are used to reach the boiling point efficiently

◆ Mass transfer facilitation: In principle, the concentration gradient is secured by **scavenging**

◆ Area improvement: Ensure as much surface area as possible by **providing gaps** between the unit cans when stacking, etc.

◆ As latent heat of vaporization needs to be input in the depressurization method, an **external heat source (heater)** is added

◆ Basically, the confinement property is secured in the chamber or canister (reduces the load in the later stage)

◆ Design parameters

- Heating temperature
- Internal pressure
- Flow velocity of warm air
- Chamber capacity

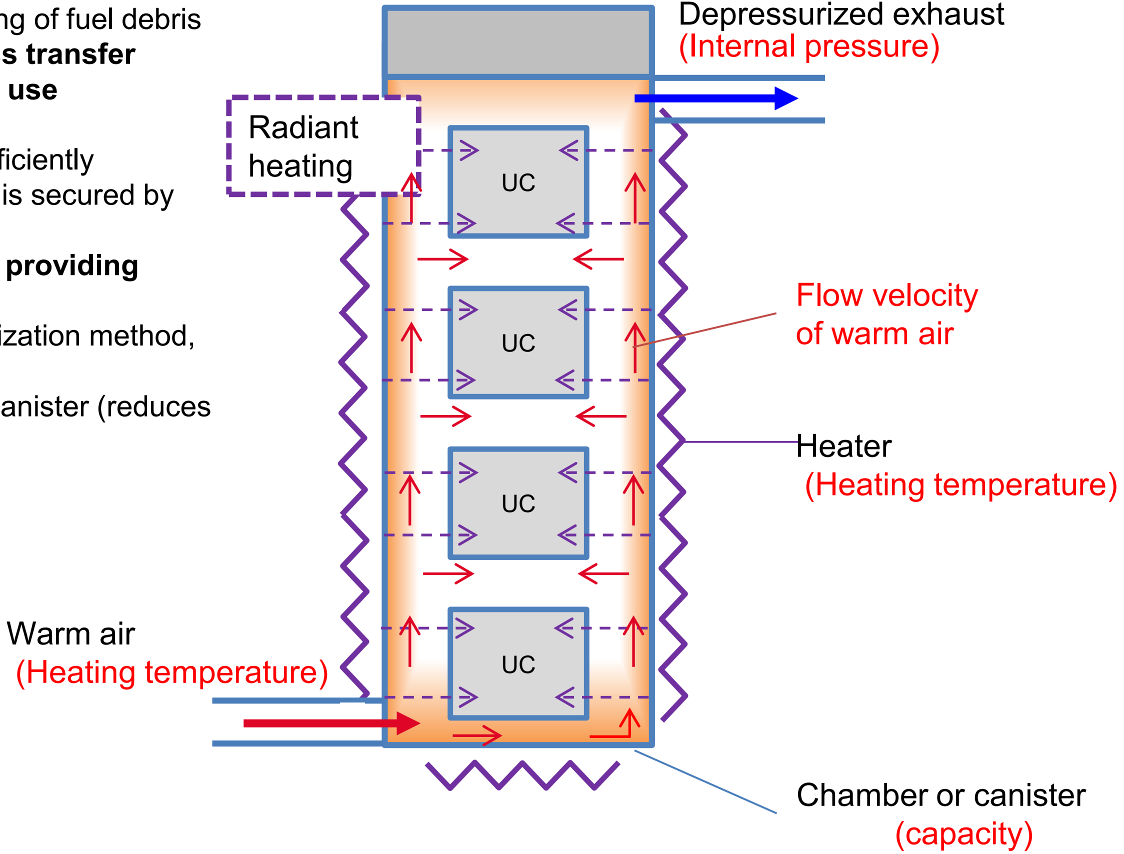


Figure. Basic concept of drying apparatus

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

a. Study on basic conditions (8/8)

(iv) Conceptual study of the device (2/2)

The basic specifications of the device are set as follows based on the safety requirements:

(1) Heating temperature

The equipment capacity of the heat source is selected so that the chamber or canister can be **heated up to 200 ℃**.

- ✓ Heat resistant temperature of canister sealing material for 1F ⇒ About 200 ℃
- ✓ Behavior of radionuclides ⇒ Released above 200 ℃

(2) Consideration for maintenance

The **number of parts** installed inside the cell and chamber, **which need to be maintained are minimized.**

(3) Shape

For maintaining subcriticality, the **maximum inner diameter** of the treatment device used for filling debris is **set to φ 220 mm**.

(4) Flow velocity

An upper limit for flow velocity is set in consideration of the scattering of debris particles. A negative pressure is maintained inside the chamber or canister to ensure safety.

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

b. Collection of drying behavior data (Study in FY 2019 and FY 2020) (1/2)

(i) Element tests

- Collect the data on drying properties of synthetic zeolite as a typical porous material
- The moisture content should be 0.22 wt% at 10 hours and 200 ℃

- In the future, basic data on the drying properties will be obtained, with the operating conditions and characteristics of the materials to be dried as parameters.

Table. TG-DTA test conditions

Equipment name	RIGAKU TG TG-DTA8122 (OT6800049)
Measurement items	Time, mass, temperature
Temperature	Retained at 200 ℃ for 10 hours (After that, hold at 300 ℃ for 1 hour to dry completely)
Pressure	Atmospheric pressure
Gas used	Dry-N_2　100 mL/min
Shape of chamber	Rectangular 15 mm x 10 mm
Sample cask	Platinum crucible
Name of sample	Synthetic zeolite (HiSivTM-3000 1.6)
Amount of sample	About 16 mg

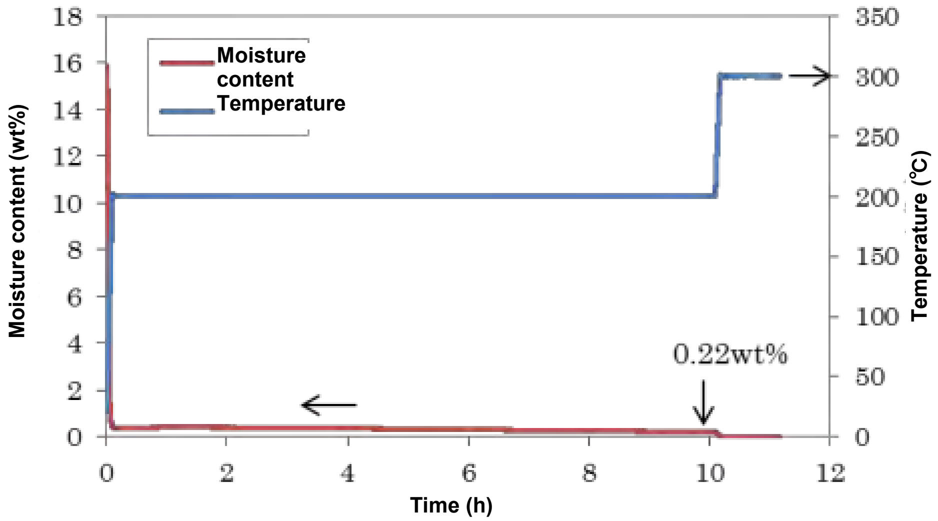


Figure. Test result (change in moisture content)

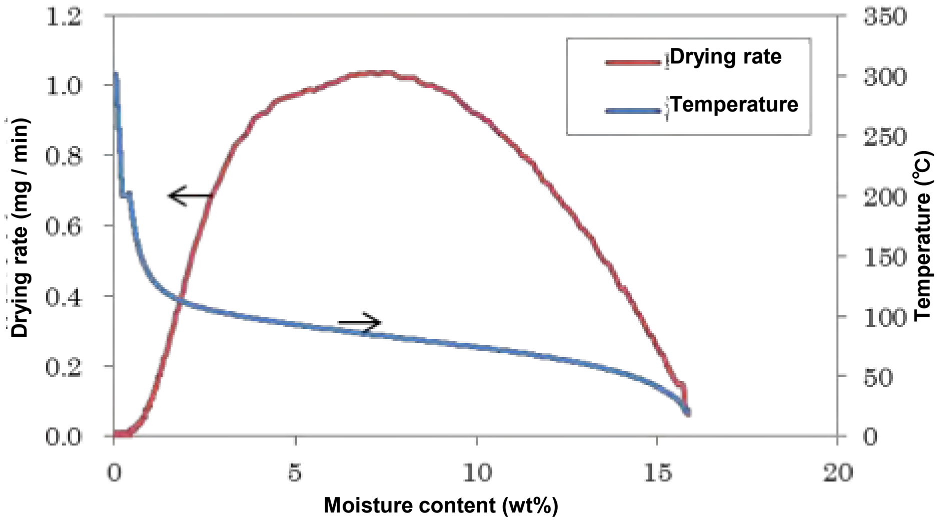


Figure. Test result (drying properties curve)

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

b. Collection of drying behavior data (Study in FY 2019 and FY 2020) (2/2)

(ii) Preparation of test equipment

Identification of items to be collected / verified in real size (canister / unit can). The specific details of the test plan will be determined in the future.

Table. Full-scale drying test items

Test items	Goal
Remote operation and operability test	As operations and maintenance are oriented toward remote operations from the viewpoint of safety, operations using a manipulator are required. For these operations, confirm that one-through operations and maintenance operations by remote control are possible by verifying the **operability and visibility** in the same space dimensions as the actual equipment. <Checklist> ① Possibility of removing foreign materials from inside the drying apparatus chamber ② Possibility of wiping decontamination inside the drying apparatus ③ Replacement of drying apparatus seal (under study)
Full-scale drying test	To **comprehensively confirm** the applicability of the design methods created on the basis of element tests. <Checklist> ① Drying time (residual heat ~ drying ~ cooling) ② Final moisture content ③ Decision criteria for completion of drying

(iii) Collection of drying behavior data

Collection of data that contributes to the actual drying system, including maintainability and operability required in point c., by conducting a drying test using real-size test equipment

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

③ Implementation items and results (Estimated and actual)

c. Basic plan of the drying system (Study in FY 2019 and FY 2020)

(i) Study on maintenance plan / equipment systems / equipment configuration

Study on the system concept (plan) by creating a system design for drying facilities. Also, study on the remote maintenance policy.

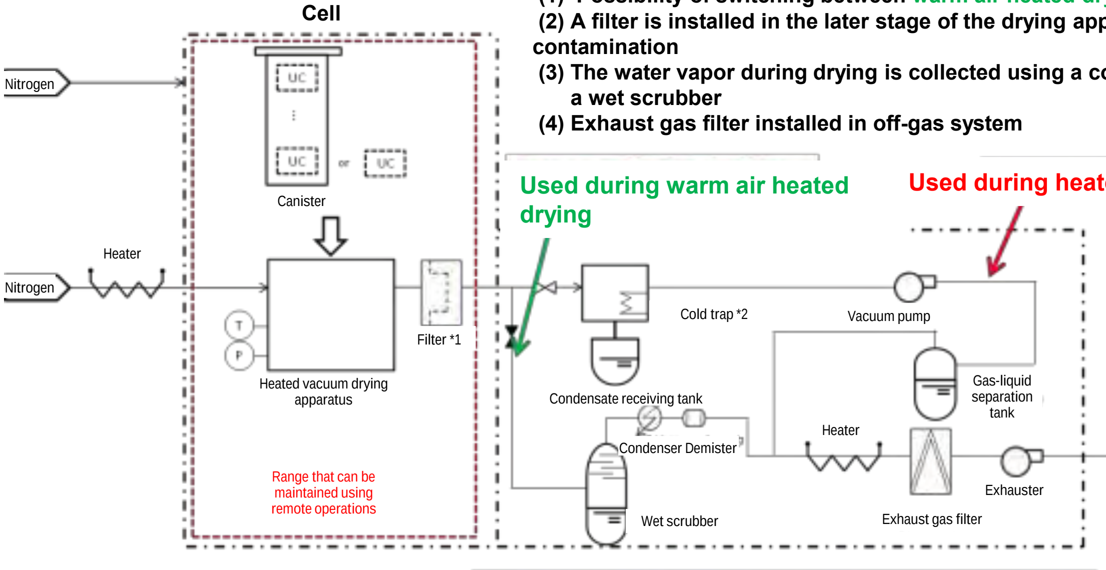
[Approach to system design]

(1) Possibility of switching between warm air heated drying / heated vacuum drying

(2) A filter is installed in the later stage of the drying apparatus to minimize the spread of contamination

(3) The water vapor during drying is collected using a cold trap / gas-liquid separation tank or a wet scrubber

(4) Exhaust gas filter installed in off-gas system



*1 Can be installed in canister or drying apparatus
*2 The necessity is decided based on the vacuum pump model

Figure. Drying apparatus - Conceptual example of system diagram (Example: During heated vacuum drying operation)

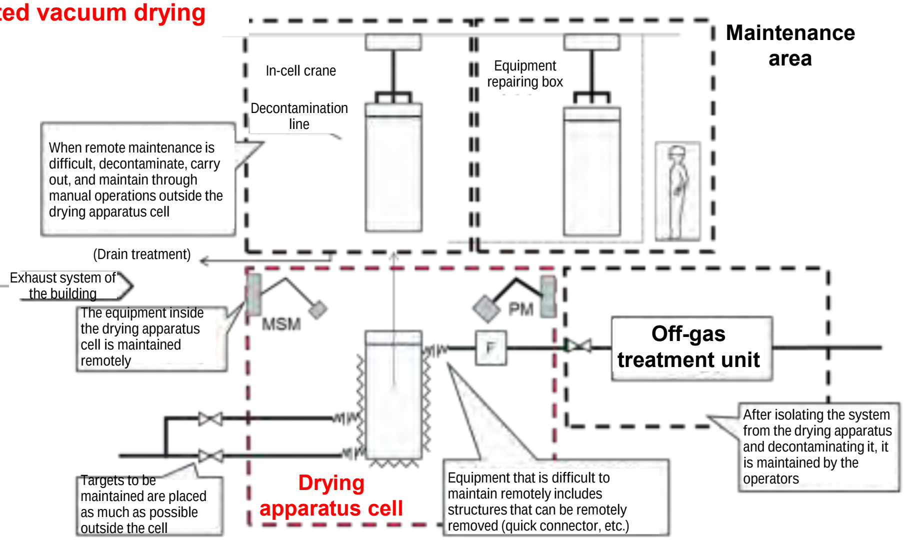


Figure. Concept of drying system

(ii) Study on basic specifications of the equipment

Reflect the test results, and come up with the basic specifications (plan) of drying apparatus and the configuration (plan) of ancillary facilities

6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

④ Contribution of the results to the areas where they can be reflected

A summarization of the concept of the fuel debris drying apparatus should contribute to hydrogen measures during transfer.

⑤ Analysis from the perspective of site application

Included in study items assuming hot handling and maintenance.
The plan is to decide on the applicability using the process to determine specific details in the future.

⑥ Issues

There are no issues in the execution of the present plan.

⑦ Level of achievement in light of the goal

A study is underway to present the basic specifications plan for the fuel debris drying system, and it is expected that the desired results will be obtained as per the plan.

Summary

In FY 2019, as the development of drying technology and system, the functional requirements of the drying apparatus, investigation on existing technologies, and planning for element tests required for the conceptual design of the drying apparatus were studied, and studies were conducted for the tests.

In FY 2020, the drying behavior data will be collected by planning a drying test with real-size test equipment based on the concept of drying apparatus, and in addition, the basic specifications plan of the drying apparatus for 1F fuel debris will be proposed by studying about maintenance and handling, etc., inside the contaminated areas.

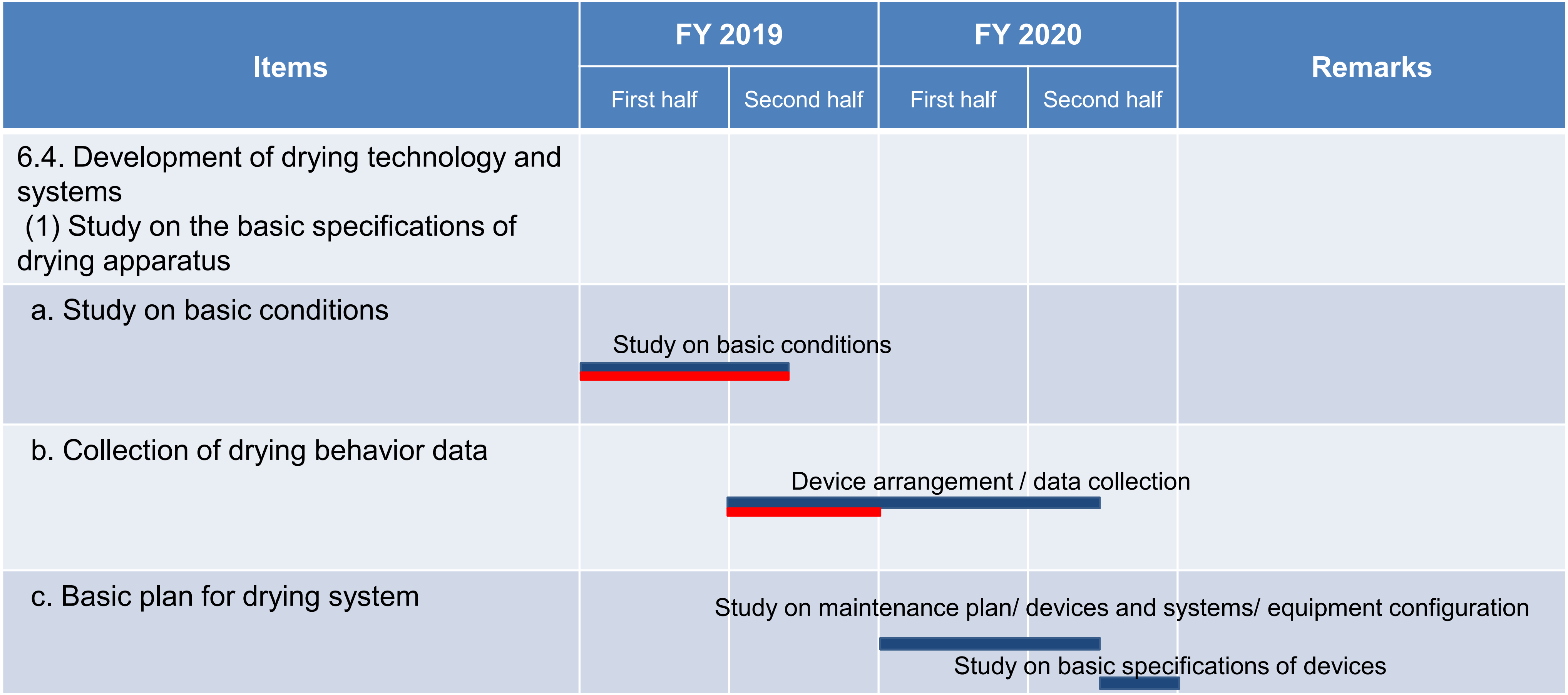
6. Implementation Details

6.4 Development of drying technology and systems

(1) Study on the basic specifications of drying apparatus

⑧ Future plans

Table. Schedule for the study on the basic specifications of drying apparatus



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
6.4. Development of drying technology and systems (1) Study on the basic specifications of drying apparatus					
a. Study on basic conditions	Study on basic conditions				
b. Collection of drying behavior data		Device arrangement / data collection			
c. Basic plan for drying system			Study on maintenance plan/ devices and systems/ equipment configuration	Study on basic specifications of devices	

🟦 : Plan 🟥 : Actual

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.

For this, 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

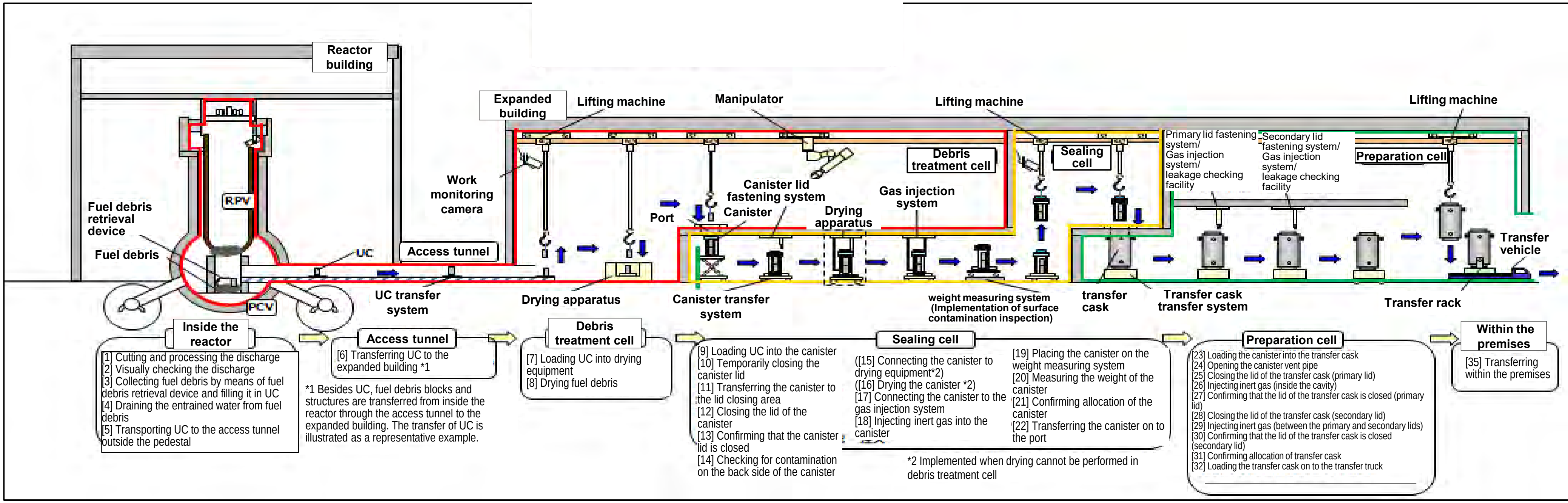
6.4 Development of drying technology and systems

(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) (2/12)

(i) Hydrogen measurement points for continuous monitoring

Study on the applicability (installation) of hydrogen densitometer to unit cans (UC), canisters, and transfer casks.

⇒ From the table below, **it was decided that** the densitometer **can be applied (installed) to the transfer cask**.

As it is only necessary to confirm that hydrogen is below the lower explosion limit, **the existing general-purpose hydrogen densitometer can be applied** in continuous monitoring. Note that it is necessary to separately evaluate the effect of installation of hydrogen densitometer on the strength of the transfer cask.

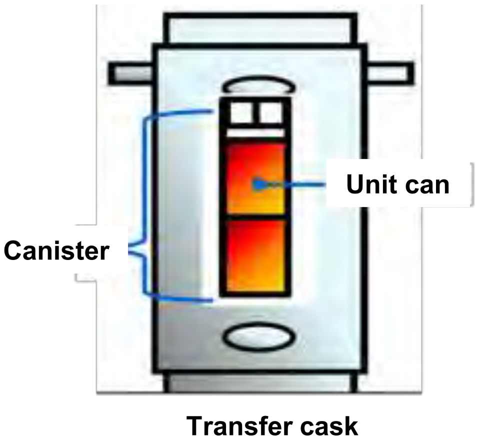


Figure. Image of transfer cask allocation

Table. Shape of each cask and amount generated

Target cask	Structure	Amount generated	Signal transmission	Continuous monitoring
Unit can (UC)	Mesh shape	Maximum	x	x Due to the structure of the cask, hydrogen escapes from the cask, making measurement impossible.
Canister	Sealed (presence of vent pipe with filter)	Many	x	x Signal transmission during storage in transfer cask is difficult. Also, as large number of canisters is expected, installation on all canisters will be expensive.
Transfer cask	Sealed	Less	O	O

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) (3/12)

(ii) Hydrogen measurement points for sequential monitoring (Process) (1/2)

The following were the necessary conditions used as the criteria for identifying hydrogen measurement technology in sequential monitoring:

✓ In a process where sequential monitoring is performed, the hydrogen concentration obtained from that process, and the hydrogen concentration in the cask near the fuel debris when the amount of hydrogen generated per hour (calculated from the gas flow rate of that process) continues for 7 days, should be 4 vol.% or less.

✓ It should not affect the throughput of fuel debris (Must be a hydrogen concentration measurement technology that can measure hydrogen concentration without involving any new processes or taking extra analysis time)

From the above,

Work processes that can replace the gas inside the canister or transfer cask, or processes where there are no dynamic operations that could cause gas leakage within the process, were selected as candidate processes.

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) (4/12)

(ii) Hydrogen measurement points for sequential monitoring (Process) (2/2)

Select from

- **Fuel debris drying process**
- **Inert gas injection process (canister)**
- **Inert gas injection process (transfer cask)**
- **Combination of the above.**

- ✓ **Evaluate the required measurement range from the expected hydrogen generation amount (rate) in each selected work process.**
- ✓ **Study whether or not the required measurement range can be met with the lower measurement limit of general-purpose hydrogen densitometer as the criteria.**

Table. Study results on work processes for sequential monitoring

No.	Work process	Handled item	Decision	Reason for decision
【8】	Drying of fuel debris	Unit can / Drying chamber	○	Since gas is replaced inside the drying chamber along with the drying treatment, it was decided that the hydrogen concentration can be measured at that time.
【16】	Drying of fuel debris	Canister	○	Since gas is replaced inside the canister along with the drying treatment, it was decided that the hydrogen concentration can be measured at that time.
【18】	Inert gas injection	Canister	○	Since gas is replaced inside the canister along with the injection of inert gas, it was decided that the hydrogen concentration can be measured at that time.
【24】	Opening of canister vent pipe	Canister	×	Since just opening the vent pipe does not completely replace the gas inside the canister, it was decided that the measurement of hydrogen concentration is difficult.
【26】	Inert gas injection	Transfer container (inside the cavity)	○	As gas is replaced inside the transfer container along with the injection of inert gas into the transfer container, it was decided that the hydrogen concentration can be measured at that time.

6. Implementation Details

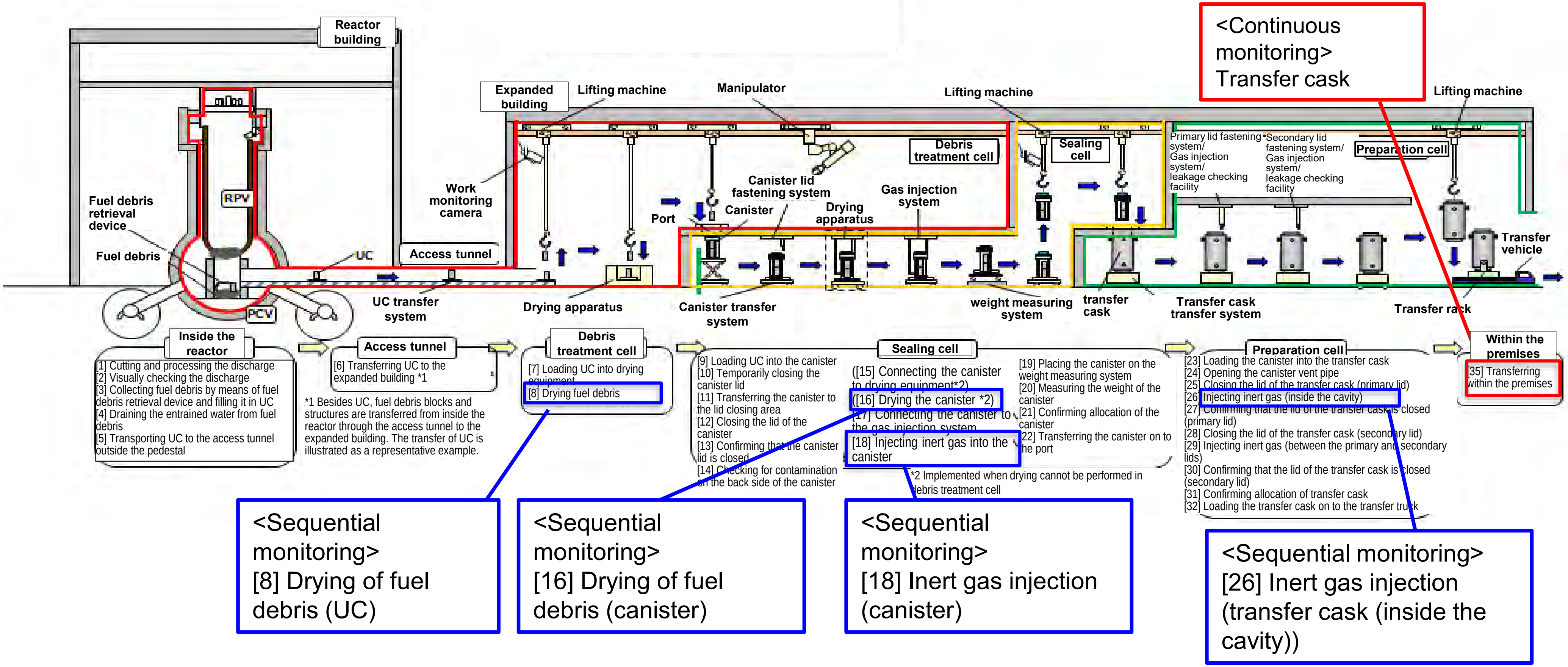
6.4 Development of drying technology and systems

(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)

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

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[8] Drying fuel debris

Sealing cell

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[10] Temporarily closing the canister lid
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[14] Checking for contamination on the back side of the canister
([15] Connecting the canister to drying equipment*2)
([16] Drying the canister *2)
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[22] Transferring the canister on to the port

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

Preparation cell

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[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 Implementation items and results (Estimated and actual)

a. Study on required technical specifications and applicability criteria (FY 2019) (6/12)

(iv) Hydrogen generation amount (rate) expected in the hydrogen measurement process selected by sequential monitoring (1/3)

The maximum value (Case I) and the minimum value (Case VI) of hydrogen generation amount (rate) from past evaluation results, which are indicated in the table below, are used.

Table. Evaluation result of hydrogen generated per hour Note 1

Case	Inner diameter of canister (mm)	UO2 rate in debris	Hydrogen generation model with defined hydrogen generation rate	Energy absorption rate	Amount of hydrogen generated per unit time per storage can (m3 / h / canister)
I	220	26	TMI evaluation model	Total absorption	2.15×10^{-4}
II	220	26	TMI evaluation model	Transfer calculation	3.83×10^{-5}
III	220	26	TMI evaluation model	Test results	1.50×10^{-6}
IV	220	26	Radiolysis model	Total absorption	1.09×10^{-4}
V	220	26	Radiolysis model	Transfer calculation	1.30×10^{-5}
VI	220	26	Radiolysis model	Test results	7.36×10^{-7}

Note 1: Referenced from the FY 2018 study results of the Canister Project. The hydrogen generation amount will be reviewed in FY 2020 based on the progress and outcome of the “Study of method to predict hydrogen generation”.

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) (7/12)

(iv) Hydrogen generation amount (rate) expected in the hydrogen measurement process selected by sequential monitoring (2/3)

Based on the cask volume (see next slide) in each work process for the selected hydrogen concentration measurement, evaluate the allowable hydrogen generation rate at which the inside of the target cask (drying chamber, canister, transfer cask) is less than the lower explosion limit concentration of 4 vol.% for 7 days.

Table. Evaluation results on the allowable hydrogen generation rate [Note 5]

Work process No.	【8】	【16】	【8】	【16】	【18】	【26】
Operations in the process	Drying process (heated vacuum drying)		Drying process (warm air heated drying)		Inert gas injection process	
Work target	Drying chamber (unit can)	Canister	Drying chamber (unit can)	Canister	Canister	Transport container cavity
Number of canisters inside the work target	5	1	5	1	1	12
Gas phase volume in work target (m3)	0.356 [Note 1]	0.02 [Note 2]	0.356 [Note 1]	0.02 [Note 2]	0.02 [Note 2]	1.78 [Note 3]
Allowable hydrogen generation rate [Note 4] (m^3/h)	8.4×10^{-5}	4.7×10^{-6}	8.4×10^{-5}	4.7×10^{-6}	4.7×10^{-6}	4.2×10^{-4}

Note 1: Set by assuming the dimensions of drying chamber referencing the FY 2018 study results of the Canister Project
Note 2: Referenced from the FY 2018 study results of the Canister Project
Note 3: Set by assuming the dimensions of transfer cask referencing the FY 2018 study results of the Canister Project
Note 4: Allowable hydrogen generation rate v_a = Volume of work target cask V_g x Lower explosion limit concentration 4 vol.% / storage duration168 h
Note 5: The drying chamber gas phase volume, etc., will be reviewed in FY 2020 based on the progress and results of the “Study on the basic specifications of drying apparatus”.

6. Implementation Details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

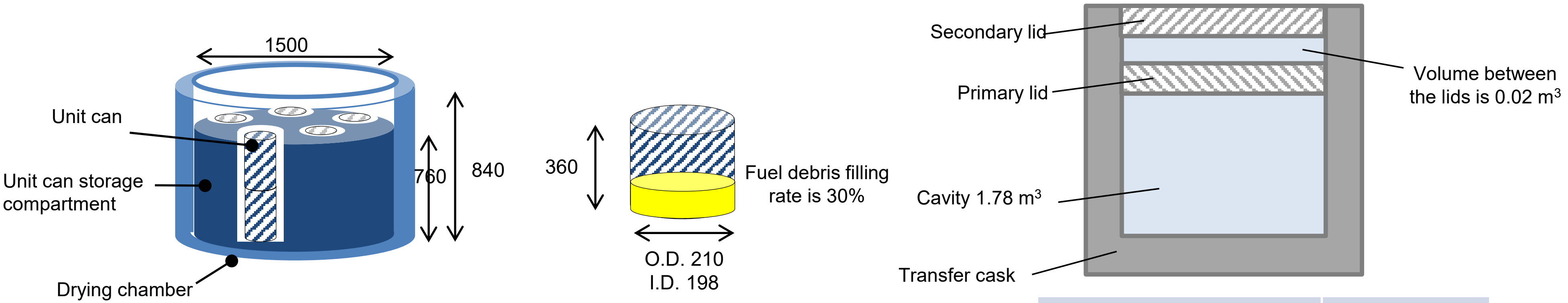
③ Implementation items and results (Estimated and actual)

a. Study on required technical specifications and applicability criteria (FY 2019) (8/12)

(iv) Hydrogen generation amount (rate) expected in the hydrogen measurement process selected by sequential monitoring (3/3）

The assumed volumes of the drying chamber, canister, and transfer cask cavity are shown below.

The shapes and dimensions will be reviewed in FY 2020 based on the progress and results of the "Study on the basic specifications of drying apparatus"



Entire volume	1480 L
Gas phase volume	356 L

Housing volume	11.1 L
Volume of fuel debris	3.33 L
Gas phase volume	7.77 L

cask volume	1.80 m^3
Cavity volume	1.78 m^3
Volume between the lids	0.02 m^3

(a) Unit can drying chamber (b) Unit can (c) Transfer cask

Figure. Overview of the unit can drying chamber, unit can, and transfer cask

- The gas phase volume in the unit can drying chamber has been calculated by referencing the FY 2018 study results of the Canister Project. For trial calculation, the height of the unit can storage compartment, which is not mentioned, is assumed to be equal to two unit cans with the external diameter of the unit can storage compartment being equal to the internal diameter of the drying chamber, and the trial calculation is carried out assuming that the height of the drying chamber is 10% the height of the compartment.
- Referencing the FY 2018 study results of the Canister Project, the gas phase volume of the transfer cask is 1.80 m^3, and the volume between the primary and the secondary lids is set by referring to the volume ratio of the cask capacity used for both transport and storage.

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) (9/12)

(v) Decision on the required measurement range and the applicability of general-purpose hydrogen densitometer in sequential monitoring (1/4)

Hydrogen concentration was calculated on a trial basis after 7 days inside the target (drying chamber, canister, transfer cask) by assuming the hydrogen generation rate cases I and VI, and that hydrogen is continuously generated at the allowable hydrogen generation rate (Refer to next slide).

The applicability of the existing hydrogen densitometers was determined from the concentration of hydrogen at the allowable hydrogen generation rate based on the following criteria.

[Criteria]

Concentration of hydrogen at the allowable hydrogen generation rate - 100 ppm or more:	○ (General-purpose hydrogen densitometer can be used)
Concentration of hydrogen at the allowable hydrogen generation rate - 1 to 100 ppm:	△ (High-sensitivity hydrogen densitometer is necessary)
Concentration of hydrogen at the allowable hydrogen generation rate - Less than 1 ppm:	× (Difficult to handle with the existing hydrogen densitometers)

[Results]

・Drying process

- ✓ Warm air heated drying: The hydrogen concentration is less than 1 ppm and is difficult to handle with the existing hydrogen densitometers.
- ✓ Heated vacuum drying: The hydrogen concentration is between 1 to 100 ppm and a high-sensitivity hydrogen densitometer is necessary.

・Inert gas injection process

- ✓ **The hydrogen concentration is 100 ppm or more at the allowable hydrogen generation rate in both canister and transfer cask and a general-purpose hydrogen densitometer can be used.**

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) (10/12)

(v) Decision on the required measurement range and the applicability of general-purpose hydrogen densitometer in sequential monitoring (2/4)

Table. Result of evaluation of hydrogen concentration Note 6

Process No.	Process	Work target	Gas replacement rate (m³/ h) @0℃ 100 kPa	Amount of hydrogen generation per unit time (m³/h)			Hydrogen concentration (ppm) Note 5			Decision
				Case I	Case VI	Allowable hydrogen generation rate	Case I	Case VI	Allowable hydrogen generation rate	
[8]	Drying of fuel debris (Heated vacuum drying)	Drying chamber	2.95E+00 Note 1	1.07E-03	3.68E-06	8.48E-05	3.6E+02	1.2E+00	2.9E+01	△
[16]	Drying of fuel debris (Heated vacuum drying)	Canister	5.90E-01 Note 2	2.15E-04	7.36E-07	4.76E-06	3.6E+02	1.2E+00	8.1E+00	△
[8]	Drying of fuel debris (Warm air heated drying)	Drying chamber	1.22E+03 Note 3	1.07E-03	3.68E-06	8.48E-05	8.8E-01	3.0E-03	7.0E-02	X
[16]	Drying of fuel debris (Warm air heated drying)	Canister	2.43E+02 Notes 2,3	2.15E-04	7.36E-07	4.76E-06	8.8E-01	3.0E-03	2.0E-02	X
[18]	Inert gas injection	Canister	1.98E-02 Note 4	2.15E-04	7.36E-07	4.76E-06	1.1E+04	3.7E+01	2.4E+02	O
[26]	Inert gas injection (Inside the cavity)	Transfer cask	1.76E+00 Note 4	2.58E-03	8.84E-06	4.24E-04	1.5E+03	5.0E+00	2.4E+02	O

Note 1: Referencing the FY 2018 study results of the Canister Project, the gas replacement rate is calculated on a trial basis for 0℃ 100 kPa.

Note 2: The gas replacement rate of the drying chamber in Note 1 is proportional to the number of unit can storage compartments, and the gas replacement rate of one compartment is equivalent to the gas replacement rate of a canister.

Note 3: Referencing the FY 2018 study results of the Canister Project, the gas replacement rate is calculated on a trial basis for 0℃ 100 kPa assuming that a vacuum pump with specifications similar to the one used for heated vacuum drying is also used for warm air heated drying.

Note 4: Flow rate when the inside of the cask is vacuumed once for an hour before injecting the inert gas.

Note 5: Hydrogen concentration (ppm) = Amount of hydrogen generation per unit time (m^3/h) / Gas replacement rate (m^3/h) x 10^6

Note 6: The gas replacement rate will be reviewed in FY 2020 based on the progress and results of the "Study on method to predict hydrogen generation" and "Study on the basic specifications of drying apparatus“.

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) (11/12)

(v) Decision on the required measurement range and the applicability of general-purpose hydrogen densitometer in sequential monitoring (3/4)

The following work processes were selected as the **first candidate** assuming that the application of a general-purpose hydrogen densitometer is possible from the viewpoint of the required concentration range. **As there is almost no oxygen in the measured atmosphere due to the injection of inert gas, the hot-wire semiconductor type, etc., which does not need oxygen, is considered as the main target for investigation.**

Table. Evaluation results of the inert gas injection process

Work processes	Assumed atmospheric conditions		Applicability criteria
[18] Inert gas injection (Canister)	Measurement target Note1	Gas discharged during replacement/ pump exhaust gas	Measurement in flow field is possible
	Atmosphere	Room temperature Note2, atmospheric pressure	Operating temperature 10 to 40℃ Operation at atmospheric pressure
	Gas element	Nitrogen/ Steam/ Hydrogen	240 ppm is detected in the said atmosphere
[26] Inert gas injection (Inside the transfer cask cavity)	Measurement target Note1	Gas discharged during replacement/ pump exhaust gas	Measurement in flow field is possible
	Atmosphere	Room temperature Note2, about atmospheric pressure	Operating temperature 10 to 40℃ Operation at atmospheric pressure
	Gas element	Nitrogen/ Steam/ Hydrogen	240 ppm is detected in the said atmosphere

Note 1: The method of injecting the inert gas is unclear, so the assumed method is also described.
Note 2: About 10 to 40℃

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) (12/12)

(v) Decision on the required measurement range and the applicability of general-purpose hydrogen densitometer in sequential monitoring (4/4)

The following work processes were selected as the **second candidate** assuming that the application of a high-sensitivity hydrogen densitometer is possible from the viewpoint of the required concentration range. **The presence of an applicable high-sensitivity hydrogen densitometer was investigated based on the atmospheric conditions presumed in the drying treatment (heated vacuum drying).**

Table. Evaluation results of the drying process (Heated vacuum drying)

Work processes	Assumed atmospheric conditions		Applicability criteria
[8] Drying of fuel debris (Heated vacuum drying - Drying chamber)	Measurement target	Pump exhaust gas	Measurement in flow field is possible
	Atmosphere	Room temperature Note 1, below the atmospheric pressure	Operating temperature 10 to 40℃ Operation below the atmospheric pressure
	Gas element	Steam/ Nitrogen/ Hydrogen	28 ppm is detected in the said atmosphere Measurement is possible around the dew point
[16] Drying of fuel debris (Heated vacuum drying - Canister)	Measurement target	Pump exhaust gas	Measurement in flow field is possible
	Atmosphere	Room temperature Note 1, below the atmospheric pressure	Operating temperature 10 to 40℃ Operation below the atmospheric pressure
	Gas element	Steam/ Nitrogen/ Hydrogen	8.1 ppm is detected in the said atmosphere Measurement is possible around the dew point

Note 1: 10 to 40℃ is assumed

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)

b. Investigation of the hydrogen concentration measurement technology (FY 2019) (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 selected targets (casks and work processes) for measuring the hydrogen concentration were classified into the following A, B, and C types from the viewpoint of assumed atmosphere and assumed range of hydrogen concentration, and the hydrogen concentration measurement technology applicable to each condition was selected.

Table. Classification and assumed environment for hydrogen concentration measurement points (processes)

Classification	Monitoring method	Selected hydrogen concentration measurement points (processes)	Assumed atmosphere	Assumed range of hydrogen concentration	Measurement methods
A	Continuous monitoring	Transfer cask	Room temperature and atmospheric pressure Nitrogen/ Steam/ Hydrogen	0 to 4 vol.%	By installing a sensor in the transfer cask
B	Sequential monitoring	Drying process (Heated vacuum drying) C－1 Drying chamber C－2 Canister	Room temperature and below the atmospheric pressure Nitrogen/ Steam/ Hydrogen	0 to 100 ppm	Gas sampling from the measurement target by means of a pump Or by installing a sensor in the piping
C	Sequential monitoring	Inert gas injection process B－1 Canister B－2 Transfer cask cavity	Room temperature and around the atmospheric pressure Nitrogen/ Steam/ Hydrogen	100 ppm or more	Gas sampling from the measurement target by means of a pump Or by installing a sensor in the piping

A: Continuous monitoring in the transfer cask, B: Sequential monitoring during the drying treatment,
C: Sequential monitoring during inert gas injection

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)

b. Investigation of the hydrogen concentration measurement technology (FY2019) (2/4)

Table. Investigation results of hydrogen concentration measurement technology (Overview) (1/2)

Sensor principle	1. Heat conduction type		2. Contact combustion type	3. Hot-wire semiconductor type	4. New ceramic type	5. Semiconductor type
Measuring range and accuracy	0 to 100 vol% About ± 2% FS		0 to 100 LEL About ± 5% FS	0 to 2000 ppm	ppm to 100% LEL	0 to 200 ppm
Installation method	A	Installed in transfer cask	Installed in transfer cask	Installed in transfer cask	Installed in transfer cask	Installed in transfer cask
	B	Installed in the exhaust gas line	Installed in the exhaust gas line	Installed in the exhaust gas line	Installed in the exhaust gas line	Installed in the exhaust gas line
	C	Installed in the exhaust gas line	Installed 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 monitoring	Oxygen 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	△ (Prior gas separation)	×	×	×	×

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)

b. Investigation of the hydrogen concentration measurement technology (FY2019) (3/4)

Table. Investigation results of hydrogen concentration measurement technology (Overview) (2/2)

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)
Measuring range and accuracy		0 to 100 vol% About ± 1% FS to ± 4% FS	Several hundred ppm to several 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%
Installation method	A	Installed near the cask to collect gas	Installed near the cask to collect and analyze gas	Installed in transfer cask (light source and detector)	Installed near the cask to collect and analyze gas	Installed in transfer cask
	B	Installed near the exhaust line to collect gas	Installed near the exhaust line to collect gas	Installed in the exhaust line	Installed near the exhaust line to collect gas	Installed in the exhaust line
	C	Installed near the exhaust line to collect gas	Installed near the exhaust line to collect gas	Installed in the exhaust line	Installed near the exhaust line to collect gas	Installed in the exhaust line
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 the part to be measured is high. Heat shock countermeasures required
	A	×	×	△	△ (Suction pump required)	△ (Damage countermeasures required)
	B	×	×	△	△ (Sensitization device required)	△(Concentration measurement required)
	C	△	△	△	○	○

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)

b. Investigation of the hydrogen concentration measurement technology (FY 2019) (4/4)

As a result of investigating the technologies to measure hydrogen concentration, the applicable hydrogen concentration measurement technologies were evaluated under the conditions A, B, and C and the following candidates were selected:

A Continuous monitoring: Heat conduction type

B Sequential monitoring during the drying process (heated vacuum drying): Gas chromatography type, Or Proton conductor

C Sequential monitoring during the inert gas injection process: Gas chromatography type, Or Proton conductor

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)

c. Feedback on progress and results of development of related technologies (FY 2020 [Scheduled])

In FY 2020, feedback on the progress and results of the "Development of technology for transfer of fuel debris" and the "Study of drying systems" conducted under the "Development of drying technology and systems“, which are being pursued in parallel under this Project, will be provided in the Annual Research Report 2019.

④ Contribution of the results to the areas where they can be reflected

The studied hydrogen concentration measurement technologies should contribute to ensuring the safety of a canister during transfer.

Moreover, the technologies might also be able to contribute to the presumptions about the fuel debris drying states.

⑤ Analysis from the perspective of site application

Based on the currently assumed atmospheric conditions at the hydrogen concentration measurement points in 1F, a hydrogen concentration measurement technology suitable to these atmospheric conditions has been selected, and although it is necessary to address the issues mentioned on the following slide, the technology is believed to be applicable.

6. Implementation Details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

⑥ Issues

The hydrogen concentration measurement technology selected at present has the following issues in actual application:

A Continuous monitoring inside the transfer cask

✓There is no issue specifically related to the measurement technology. It is, however, necessary to study the impact of the installation of a sensor on the structural strength of the transfer cask.

B Sequential monitoring during the drying process (heated vacuum drying)

✓Gas sampling is necessary for gas chromatography.

⇒A gas sampling line (for the facility) must be connected to the exhaust line of the drying facility (after the filter).
It must be installed in a shielded, uncontaminated area that can be directly operated by the workers.
Measures to improve the sensitivity of the measuring devices are necessary.

✓In the case of the proton conductor, the verification of sensitivity in low concentrations is essential.

C Sequential monitoring during the inert gas injection process

✓ Gas sampling is necessary for gas chromatography.

⇒ A gas sampling line (for the facility) must be connected to the exhaust side of the inert gas injection line.
It must be installed in a shielded, uncontaminated area that can be directly operated by the workers.

✓No specific requirements in the case of the proton conductor.

As several of the site conditions of the drying apparatus (shape, flow velocity, pressure etc.) are undetermined, it is necessary to verify and study the need to provide feedback to the selected hydrogen concentration measurement technology as and when the site conditions become clear.

6. Implementation Details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

⑦ Level of achievement in light of the goal

The selection of candidate hydrogen concentration measurement technology, applicable to canisters, was completed as per the goal.

Summary

In FY2019, the required technical specifications and applicability criteria for hydrogen concentration measurement were studied and set up. Furthermore, technical investigations were conducted based on these results, and the targets for continuous monitoring and sequential monitoring (casks and work processes) and the candidates for the applicable hydrogen concentration measurement technology were selected as follows:

[Continuous monitoring]
Target cask: Transfer cask
Candidate technology: Heat conduction type

[Sequential monitoring]
Target work processes: Inert gas injection process (first candidate), drying process (heated vacuum drying) (second candidate)
Candidate technology: Gas chromatography type or proton conductor

In FY 2020, based on the estimations about the amount of hydrogen generated and the progress and results of the study on the drying apparatus, the required technical specifications will be reviewed as appropriate, and if necessary, the candidate technologies will be re-selected.

6. Implementation Details

6.4 Development of drying technology and systems

(2) Study on hydrogen concentration measurement technology

⑧Future plans

Table. Schedule for study on hydrogen concentration measurement technology

Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
Study on hydrogen concentration measurement technology					
a. Study on required technical specifications and applicability criteria	🟦 🟥				
b. Investigation of the hydrogen concentration measurement technology		🟦 🟥			
c. Feedback on progress and results of development of related technologies			🟦	🟦	Implemented if necessary

🟦 : Plan 🟥 : Actual

6. Implementation Details

6.5 Evaluation Summary

① Purpose and Goals

To review the implementation items of the related projects and reflect the implementation items mentioned in Sections 6.1 to 6.4. The goal is to also participate and cooperate, based on requests, in the investigation of technologies for sorting the objects retrieved from inside the PCV into fuel debris and radioactive wastes, which will be implemented under the Project of Further Increasing the Scale of Fuel Debris Retrieval, as a part of the development of related technologies.

② Implementation items and results (Estimated and actual)

a. Investigation of sorting technology (Implemented as required on the basis of requests from the Project of Further Increasing the Scale of Fuel Debris Retrieval)

Based on the request from the Project of Further Increasing the Scale of Fuel Debris Retrieval, the requirement for sorting was presented from the viewpoint of fuel debris storage. The Project of Further Increasing the Scale of Fuel Debris Retrieval consolidated the required details as investigation results on the sorting requirements from other related projects.

b. Evaluation summary (Implemented at the end of FY 2019 and FY 2020)

The study of canister specifications and structures was conducted under the development of technology for containing of fuel debris; the study on method to predict amount of hydrogen generation and the study on hydrogen measures was conducted under the development of technology for transfer of fuel debris; and the study on the basic specifications of drying apparatus and the study on hydrogen concentration measurement technology was conducted under the development of drying technology and systems. In future, the latest findings will be incorporated to advance research and development, and studies will continue to be conducted in FY 2020 as well.

6. Implementation Details

6.5 Evaluation Summary

③ Contribution of the results to the areas where they can be reflected

The implementation results will be reflected in the study items of this subsidy project.

④ Analysis from the perspective of site application

The investigation of sorting technologies undertaken by the Project of Further Increasing the Scale of Fuel Debris Retrieval is conducted to reduce the amount of fuel debris, which is more difficult to handle as compared to radioactive wastes, from the viewpoint of criticality safety control, and the participation in and cooperation with the Canister Project is beneficial.

The summary of the evaluation clarifies the outcome of this subsidy project and is beneficial.

⑤ Issues

There are no issues in the execution of the present plan.

⑥ Level of achievement in light of the goal

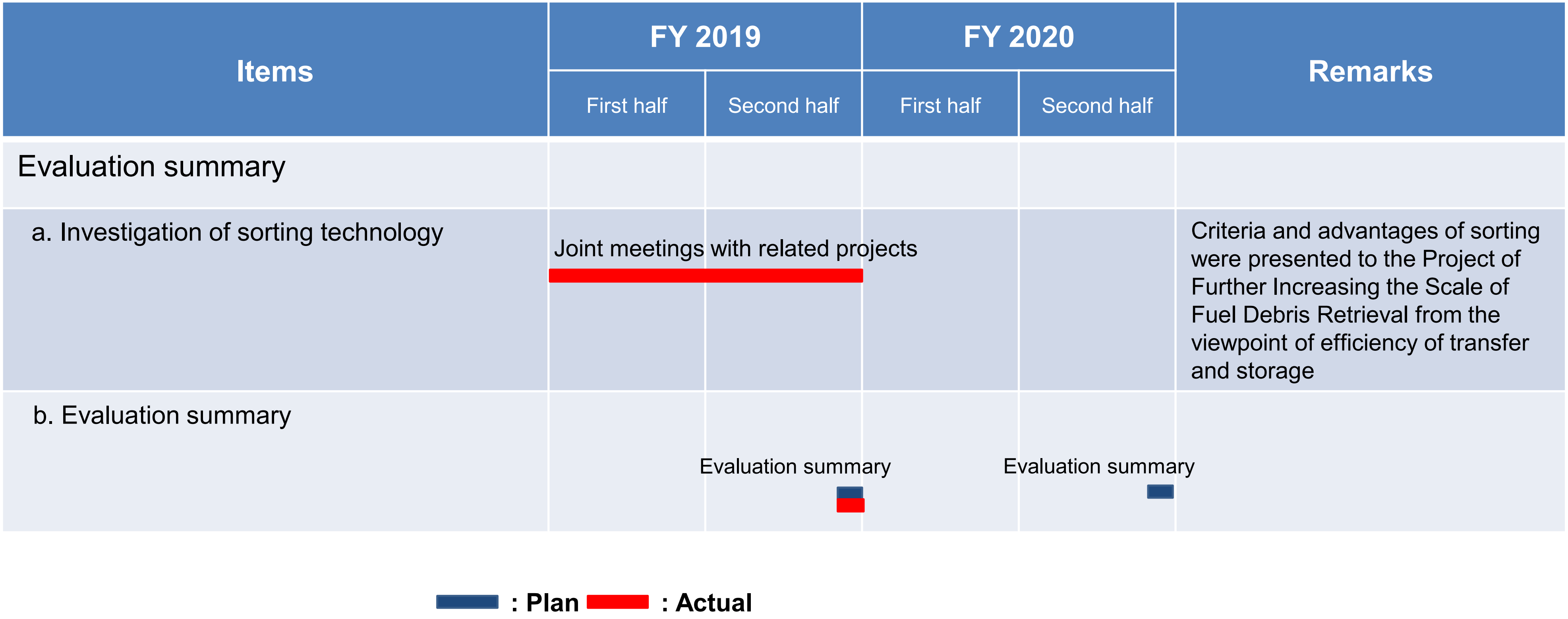
It is expected that the defined results will be obtained by conducting joint meetings with related projects, cooperating in the investigation of sorting technologies, and by summarizing the evaluation of individual implementation items at the end of each fiscal year.

6. Implementation Details

6.5 Evaluation Summary

⑦ Future plans

Table. Schedule of study on evaluation summary



Items	FY 2019		FY 2020		Remarks
	First half	Second half	First half	Second half	
Evaluation summary					
a. Investigation of sorting technology	Joint meetings with related projects 🟥	🟥			Criteria and advantages of sorting were presented to the Project of Further Increasing the Scale of Fuel Debris Retrieval from the viewpoint of efficiency of transfer and storage
b. Evaluation summary		Evaluation summary 🟦 🟥		Evaluation summary 🟦	

🟦 : Plan 🟥 : Actual

7. Overall Summary

<Outcomes in FY 2019>

- For the Development of Technology for Containing of Fuel Debris, a plan was drafted for the test items to be implemented during the structural verification test of the canister, and the canister (canister for testing) was designed based on the safety requirements of the canister. Moreover, material procurement etc. was carried out for the prototyping of the canister (canister for testing).
- For the Development of Technology for Transfer of Fuel Debris, the study items and implementation details required for setting the transfer condition plans were studied by investigating domestic and overseas findings and by hearing expert opinions on the methods to predict hydrogen generation. Moreover, the flow inside the canister was studied as a catalyst-based hydrogen measure. In addition, a study of methods to acquire the performance of a catalyst is underway.
- For the Development of Drying Technology and Systems, the functional requirements of the drying apparatus, investigation on existing technologies, and planning for element tests required for the conceptual design of the drying apparatus were studied, and studies for the tests are underway. Moreover, upon studying and specifying the required technical specifications and applicability criteria for hydrogen concentration measurements, a technical investigation was carried out and the candidate hydrogen concentration measurement technologies were selected.
- The advantages and conditions effective in improving the efficiency of transfer and storage with respect to the sorting of fuel debris and radioactive waste, were presented to the Project of Further Increasing the Scale of Fuel Debris Retrieval.
- As the subsidy project continues to make progress, the effective findings will be incorporated, and studies will continue to be conducted in FY 2020 as well.

7. Overall Summary

<Plan for FY 2020>

- The real-size canister (canister for testing) to be used in the structural verification test will be prototyped, and the structural verification test will be carried out to verify the maintenance of the safety functions (criticality prevention, confinement). Moreover, the structural analysis will be compared and evaluated with the results of the structural verification test, and the applicability of the analysis methods will be verified.
- The study of methods to predict hydrogen generation will proceed wherein the amount of hydrogen generated inside the canisters will be presumed on the basis of the results of hydrogen generation tests implemented as needed, and transfer condition plans to enable safe transfer will be studied. Moreover, the placement of the catalyst will be studied based on the evaluation of flow inside the canister by acquiring data on catalyst performance.
- The drying behavior data will be collected by planning a drying test with real-size test equipment based on the concept of drying apparatus, and in addition, the basic specifications plan of the drying apparatus for 1F fuel debris will be proposed by studying about maintenance and handling inside the contaminated areas.
  With reference to the hydrogen concentration measurement technology, based on the estimations about the amount of hydrogen generated and the progress and results of the study on the drying apparatus, the required technical specifications will be reviewed as appropriate, and if necessary, the candidate technologies will be re-selected.
- If there are any fresh requests, etc., from the Project of Further Increasing the Scale of Fuel Debris Retrieval, pertaining to the sorting of fuel debris and radioactive wastes, those requests will be dealt with.

[Supplement-1] Basic conditions of development of the canister (1/4)

The canister specifications have been set mainly from the viewpoint of safety evaluation based on the information on the fuel debris properties obtained so far, the requirements from the fuel debris retrieval methods, and the information offered by the Fuel Debris Characterization Project, etc. As these conditions also contain assumptions, it is necessary to verify and review them on the basis of the outcomes of the Fuel Debris Characterization Project and the Project of Further Increasing the Scale of Fuel Debris Retrieval.

[Fuel debris properties]

- Fuel debris composition (Excluding MCCI products):

  The components assumed to be currently present inside the RPV/ PCV (uranium dioxide (including FP associated with irradiation), zirconium alloy, stainless steel, low-alloy steel, nickel-based alloy, concrete, and B_4C)

- Salinity: About 100 ppm max.

  The salinity of stagnant water was set conservatively to 10 to 20 ppm. Note that in the corrosion evaluation, it was realistically set to about 3 ppm based on the actual results of the water inside the reactor.

- Zirconium: Small amounts of residue in metallic state

  To consider the possibility of fire.

- Physical properties of MCCI products: Concrete mixed with the above-mentioned fuel debris

  It is believed that the heat of fuel debris caused reactions such as loss of water of crystallization and generation of gas, but the concrete components were assumed to be physically turbid in the evaluation.

- Stability of fuel debris: Stable at -20 to 300℃ (nitrogen atmosphere)

  It was assumed that there is no occurrence of behaviors that would significantly affect safety, such as significant volume fluctuations due to vaporization of the elements contained in the fuel debris, etc., or the release of large amounts of corrosive substances and radioactive gases, etc.

- Shape: Block-like, particulate, and powdered solids

- Rust inhibitor/ neutron absorber: Sodium pentaborate

  It is assumed that adoption of sodium pentaborate is being studied at the present time. Note that it was assumed that the insoluble neutron shield material will be studied when the specific details are determined.

[Supplement-1] Basic conditions of development of the canister (2/4)

For setting the shape of the canister, the following conditions were assumed based on the Project of Further Increasing the Scale of Fuel Debris Retrieval and the opinions of experts.

[Fuel debris containment methods]

- Block-like and particulate fuel debris: To be collected and stored by gripping, scooping etc.
- Canister dimensions: Internal diameter is 220 mm and 400 mm and total length is 1000 mm

  The canister internal diameter of 220 mm and 400 mm was assumed on the basis of studies conducted until FY 2018. The total length of the canister was set based on the approx. 1 m assumed by the Project of Further Increasing the Scale of Fuel Debris Retrieval.
- Powdered fuel debris: Collected in a mesh-like drainable unit can and each unit can is stored in the fuel debris canister

  In the general water treatment, a metal strainer-shaped filter is used, and it is assumed that a unit can with the same structure is used for the collection of powdered fuel debris by a pump. The unit can is assumed to be of a size that can be stored inside a canister, and the unit can is made of thermally stable material such as stainless steel and sintered stainless steel net. Since the shape of the unit can is being studied under the Project of Further Increasing the Scale of Fuel Debris Retrieval, a unit can with a net structure having a mesh size of 0.1 mm has been assumed at present in light of the fact that the said project is targeting the collection of fuel debris up to size Φ0.1 mm.
- Storage location: Storage work is non-flooding. Work is carried out in a space with a boundary such as a hot cell.
- Procedures from containing to carrying out the fuel debris: The fuel debris retrieval-related work is bifurcated into half day for cutting work and half day for fuel debris collection, containment in canisters, and carrying out work.

[Fuel debris transfer methods]

- Transfer method: Casks

  As there are precedents in TMI-2 or proven track record with spent nuclear fuel.
- Requirement of filling water in the transfer cask: The restrictive conditions for the transfer casks have been assumed in this project on the basis of technical studies.

[Supplement-1] Basic conditions of development of the canister (3/4)

The following conditions were assumed based on discussions with experts:

[Storage of fuel debris]

- Storage method

  Wet storage: Optional as of now

  Wet storage utilizing the existing 1F pool is optional as of now because the expected profit is small and the method is not highly reasonable considering the converting cost, period, level of technical difficulty, and so on.

  Dry storage: Basic storage method

  The dry storage method is considered as the basic storage method because dry storage is considered to be a reasonable method for storage of spent nuclear fuel in terms of operation management, such as maintenance in addition to safety, and it is considered to be advantageous for fuel debris as well. Note that concrete casks, etc., are also used overseas for the dry storage of spent nuclear fuel, however, since the requirements for stored items are the same, storage in metal casks with a track record in Japan shall be used as a typical example.

- Drying of fuel debris: Minuscule amount of water content remains

  The studies on transfer and storage assumed that some water remained in the fuel debris even after conservative drying.

- Storage period of fuel debris using canisters: 50 years

  The storage period of fuel debris using canisters was set to 50 years to cover the 30-year period until the final treatment or disposal decision of fuel debris specified in the roadmap. Note that the spent nuclear fuel dry storage facility maintains data on long-term integrity assuming a 50-year storage period and 10 years for carrying in and out, and this data is available for reference.

[Supplement-1] Basic conditions of development of the canister (4/4)

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	Division of safety functions		Approach
			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 division of safety functions may be reviewed because it is affected by the fuel debris properties and canister handling procedures.

[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 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 by suction, 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)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 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)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 by suction, 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 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.	

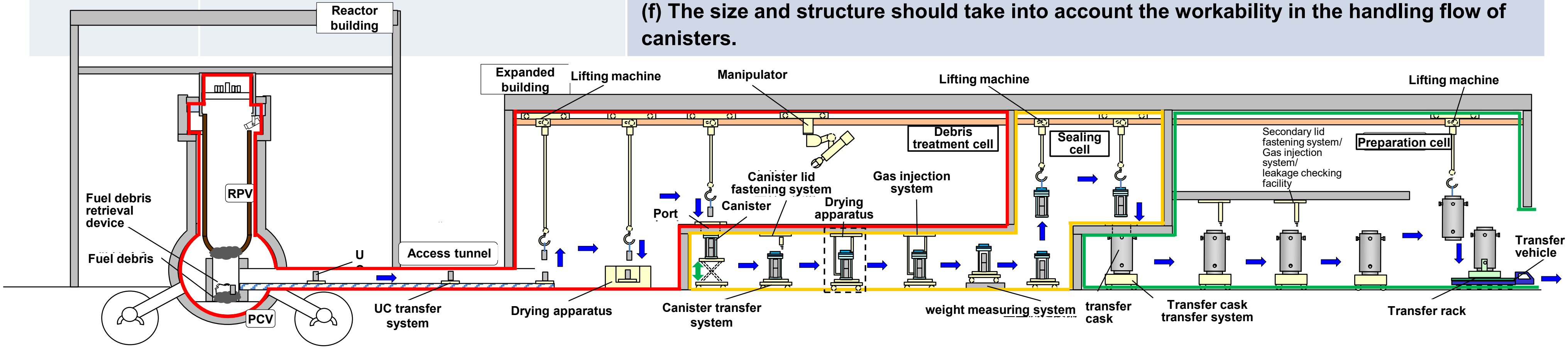


Figure. Canister handling flow plan (Example of side access)

[Supplement-4] Specification plan for the canister (1/10)

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.	<u>Simple mounting structure</u> ・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) <u>Bolt structure</u> ・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) [Approach to selection of specifications] ・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 orientation. ・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 mounting 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 opening, and a canister with inner diameter 400 mm could be contained in a basket with a 510 mm 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 cask is as small as possible. ・In the unlikely event that a bolt wears away, 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 by suction, 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 (2/10)

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. 452 mm^2) [Approach to selection of specifications] ・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) [Approach to selection of specifications] ・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 by suction, 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 (3/10)

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.	・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 [Approach to selection of specifications] ・Temporarily considered equivalent to a Class 3 cask, the structure of the welded part was adopted in accordance with JSME "Design and Construction Standard PVD-4000 Manufacturing of casks". ・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 orientation. 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 cask 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 percent 0.2, and finite array (10 x 10). ・The structure is such that even if it receives an impact load of a drop in the vertical orientation, 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) 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, as well as allowing space above the unit cans.
		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 by suction, 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 (4/10)

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.) [Approach to selection of specifications] ・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 300°C, 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 [Approach to selection of specifications] ・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 [Approach to selection of specifications] ・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 (5/10)

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) [Approach to selection of specifications] ･ 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 [Approach to selection of specifications] ･ 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 (6/10)

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 quality: SUS316 [Approach to selection of specifications] ・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 for HEPA)), 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 (7/10)

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) [Approach to selection of specifications] ・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 mounting 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 mounting 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 (8/10)

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)[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.	<u>Simple mounting structure</u> ・Outer cylindrical surface: Elastomer (EPDM) O ring ・Upper end plane (O ring is installed on the lid): Elastomer (EPDM) O ring [Approach to selection of specifications] ・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 mounting 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 [Approach to selection of specifications] ・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)[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.	
	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 is not released. Note that liquid and gas confinement should be ensured by a cell or 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 by suction, 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 (9/10)

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 [Approach to selection of specifications] ･ 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 mounting 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.	

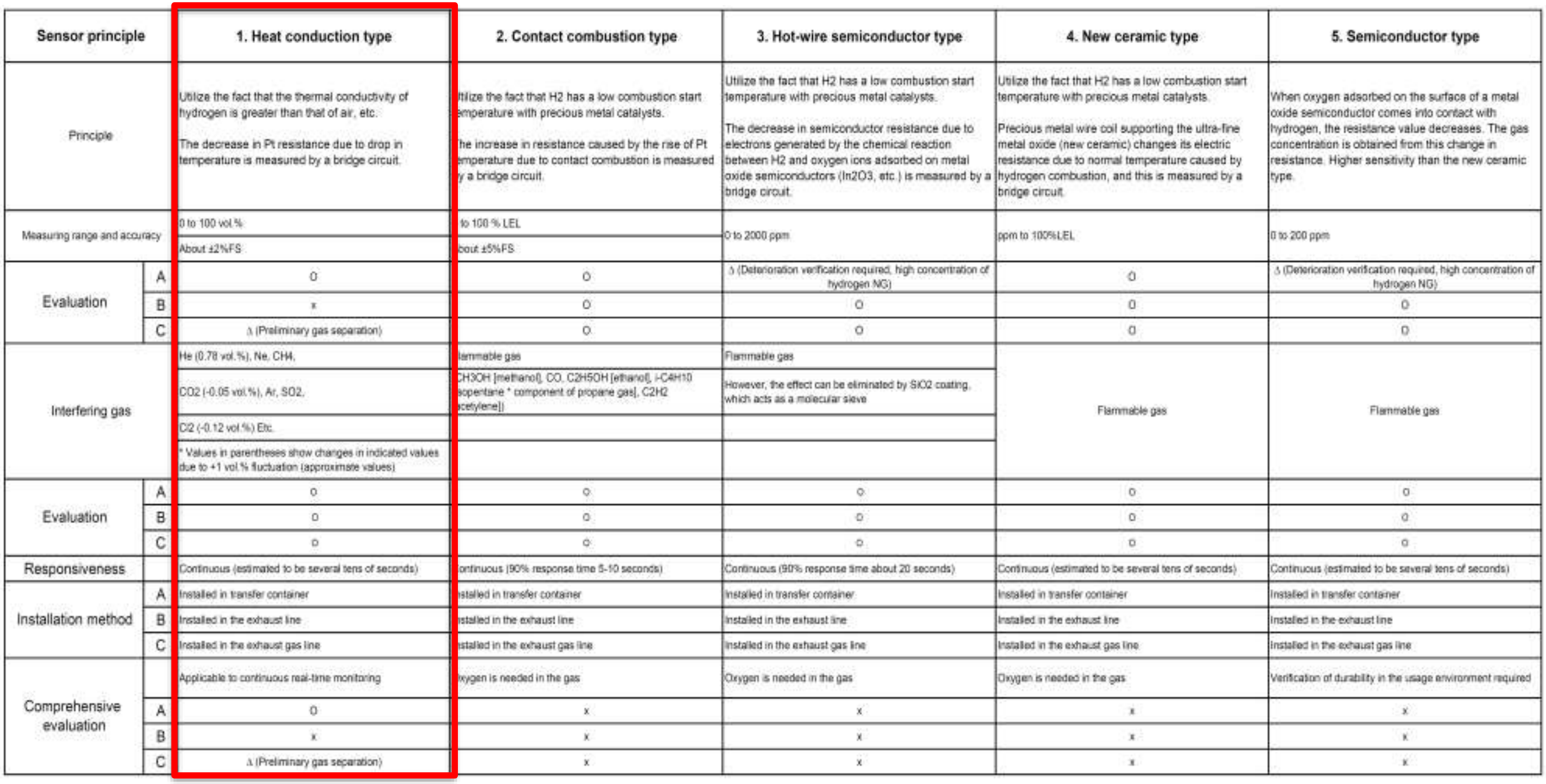
Note 1: The particle size of fuel debris pieces (solid) is set to 0.1 mm or more (Definition of debris: Powder debris (collected by suction, etc.): less than 0.1 mm, particulate debris (collected by suction, etc.): 0.1 mm to 10 mm, block debris (collected in unit cans): more than 10 mm)

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

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.
Quality of 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 [Approach to selection of specifications] ・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-5] Investigation results of hydrogen concentration measurement technology (details) (1/2)



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		
		O_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 real time monitoring in the transfer cask

[Supplement-5] Investigation results of hydrogen concentration measurement technology (details) (2/2)

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-6] Principles of hydrogen concentration measurement technology (heat conduction type)

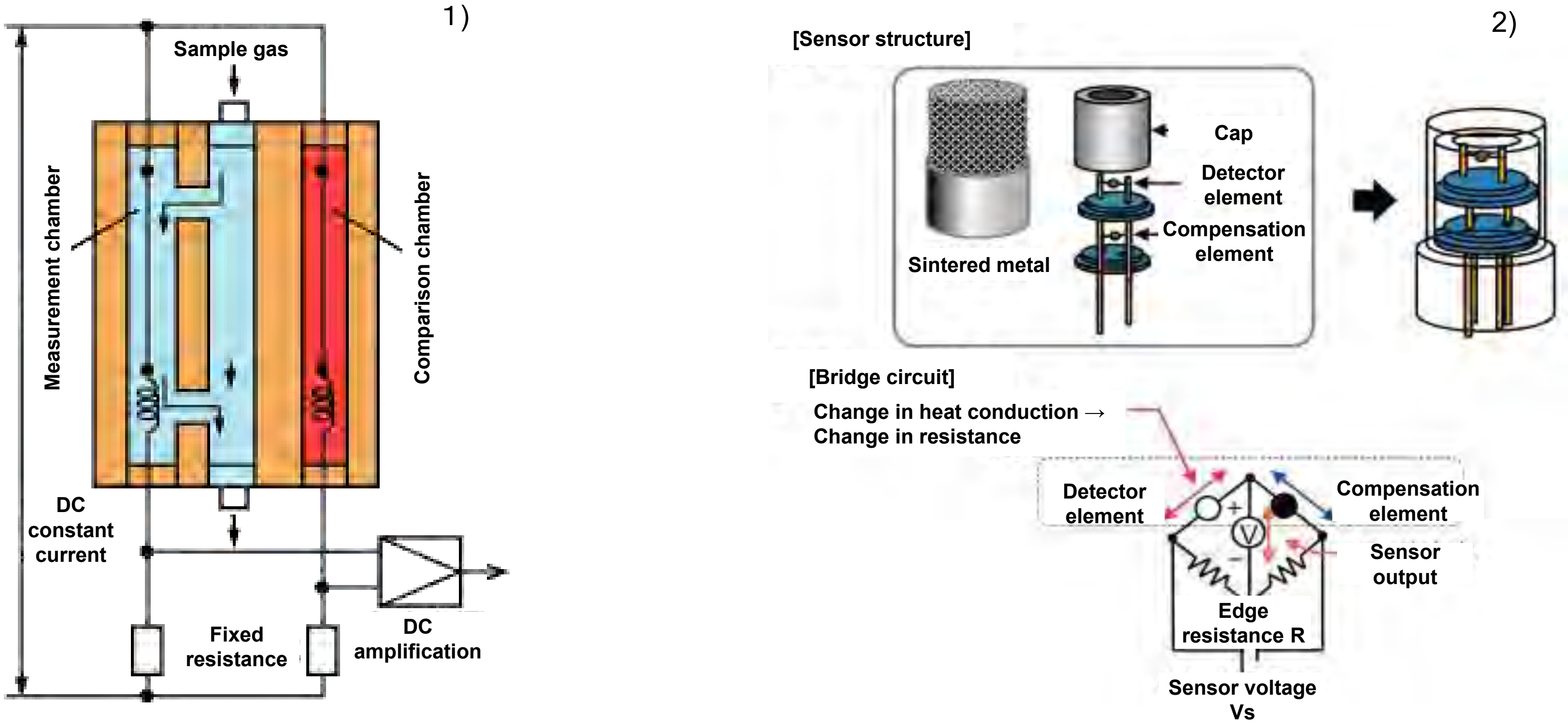
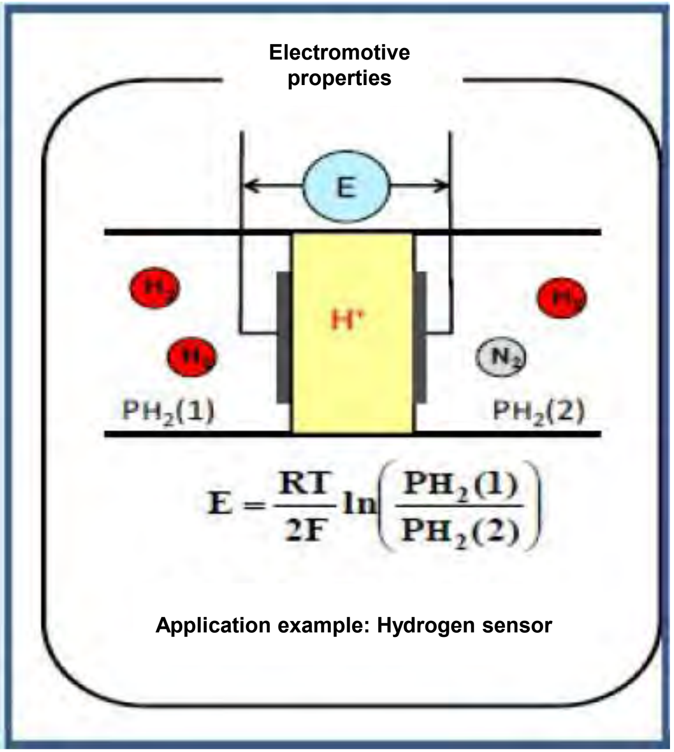


Figure. Diagram showing the principle of the heat conduction type analysis device

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-7] 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