Subsidy Project of Decommissioning and Contaminated Water Management
Started From FY2020

Development of Technologies for Containing, Transfer and Storage of Fuel Debris
(Treatment for Fuel Debris in Powder and Slurry/Sludge State)

Final Report for FY2021

August 2022

International Research Institute for Nuclear Decommissioning
(IRID)

Contents

1. Background and purpose of the project

1.1 Background

For the decommissioning of the Fukushima Daiichi Nuclear Power Station (Fukushima Daiichi), equipment and facilities (including collection containers) suitable for the conditions of fuel debris are required to safely and reliably collect, transfer, and store the retrieved fuel debris.

A contaminated water treatment (liquid system) is currently under review by the retrieval side (Subsidy Project of Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals) and fuel debris in slurry and sludge state is expected to be retrieved.

However, both collection containers and methods for transfer and storage of fuel debris in slurry or sludge state have not yet been studied.

1.2 Purpose

The purpose of this subsidy project is to conduct case studies in Japan and abroad involving containers for slurry or sludge, and transferring, collecting and storing of the containers for addressing one of technological issues. The technological issues are also clarified in case of that applying existing technologies such as technology for transferring and storing the collection containers (canisters) of powdery and lump-like fuel debris.

Fuel debris is expected to spread easily because water lost in the fuel debris due to drying treatment against suppressing hydrogen generation, therefore, the impact on the performance of filters (blockage, degradation, etc.) that are installed on the canister lid to prevent from dispersing dust outside the canister is studied.

1. Background and purpose of the project (Supplementary)

No.3

The collection of slurry or sludge from contaminated water is currently under review, but a review of collection containers, transfer methods, and storage methods has not yet been undertaken.

- Investigation of collection containers, and transfer and storage methods for slurry or sludge should be conducted in Japan and abroad to collect information including focusing points.
- Canisters can also be used as collection containers. Issues are identified in methods for transfer and storage of the canister that the same method using the canister for particulate and lump-like fuel debris is currently under review.
- The filters that are installed on the canister lid are studied since the handling of powdery fuel debris has issues.

Source: Extracted and processed from the results of the IRID HP FY2019 research and development project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals”

Target substance

Fuel debris in lump form
Particle diameter: 100 mm or more
Requires processing before collecting in a unit can

Fuel debris in pebble form
Particle diameter: 10 to 100 mm
Can be collected in a unit can without processing

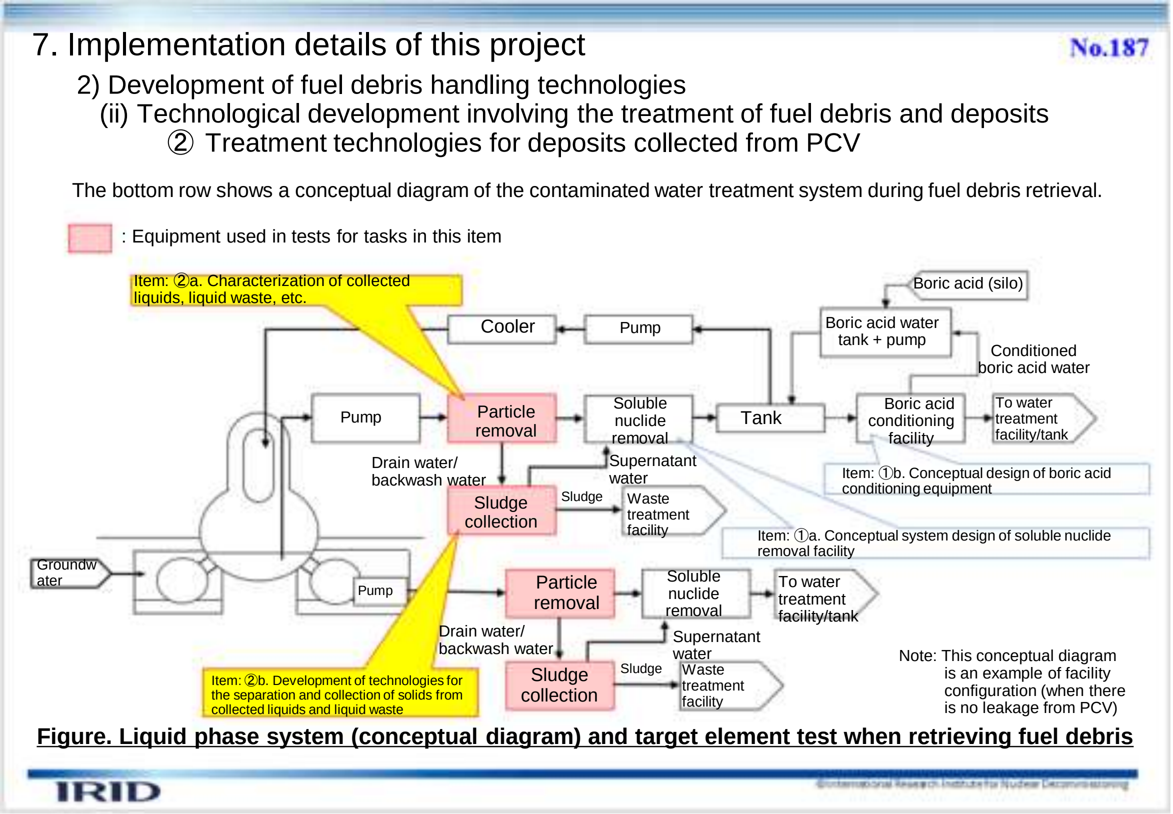
Fuel debris in particle form
Particle diameter: 0.1 to 10 mm
Collected by suction because it is difficult to handle with tools.

Powdery fuel debris
Particle diameter: 0.1 mm or less
Collected through the liquid phase system

Planned to collect by grabbing, scooping, etc.

Planned to develop a suction collection system

Planned to collect through the liquid phase system (particle size: 0.1 mm or less)



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7. Implementation details of this project

2) Development of fuel debris handling technologies

(ii) Technological development involving the treatment of fuel debris and deposits

② Treatment technologies for deposits collected from PCV

The bottom row shows a conceptual diagram of the contaminated water treatment system during fuel debris retrieval.

🟥 : Equipment used in tests for tasks in this item

Note: This conceptual diagram is an example of facility configuration (when there is no leakage from PCV)

Figure. Liquid phase system (conceptual diagram) and target element test when retrieving fuel debris

2. Goals

The indicators for determining target achievement for the end of FY2021 are as follows.

1. Case study of handling radioactive materials in powder, slurry, or sludge form

- Overseas case study of handling powdery, slurry or sludge radioactive materials must be analyzed. Specific precautions and a concept of ensuring the safety for radioactive materials in powder, slurry, or sludge form must be clarified.

(Not subject to TRL* evaluation)

2. Identify issues involving the storage of fuel debris in powder, slurry, or sludge form

- Issues involving safe, reliable, and rational storage manners when fuel debris is stored in the dry condition using the same canister for particulate or lump-like fuel debris must be identified.

(Target TRL* upon completion: Level 1)

3. Performance assessment of canister filters

- The environments and conditions that affect canister filter life must be understood and organized. Also, the test methods and conditions for any item that are required to be tested for evaluation of the filter life must be studied and any relevant existing knowledge must be organized.

(Target TRL* upon completion: Level 1)

*TRL: Technology readiness level

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

3.1 Implementation items

The following technological development issues were addressed for the engineering of transfer and storage of fuel debris in the Fukushima Daiichi under this subsidy project.

(1) Case study of handling radioactive materials in powder, slurry, or sludge form

It is useful to collect and analyze experience, knowledge, and information on the handling and storage of radioactive materials in powder, slurry, or sludge form when identifying issues involving the storage of powdery, slurry and sludge form fuel debris (implementation items in (2) below). Therefore, case studies of handling powdery nuclear and radioactive materials in Japan and overseas, the storage methods and the facility size were investigated. Experience, knowledge and information that are required to establish the system for containing, transfer and storage of the fuel debris including precautions in handling powdery, slurry or sludge type fuel debris, concepts for ensuring safety, and methods for reflecting these concepts in the design, etc. were analyzed and organized.

(2) Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

Based on the results of the analysis and organization of experience, knowledge, and information obtained from implementation items (1), issues involving safe, reliable, and rational storage conditions were identified when fuel debris that is mainly powder, slurry or sludge form is stored in drying conditions using the same canister for fuel debris in particle or lump form. Also, technological issues were clarified to resolve from the perspective of whether the necessary safety functions can be secured, whether storage can be stably conducted for long periods of time, etc.

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

3.1 Implementation items

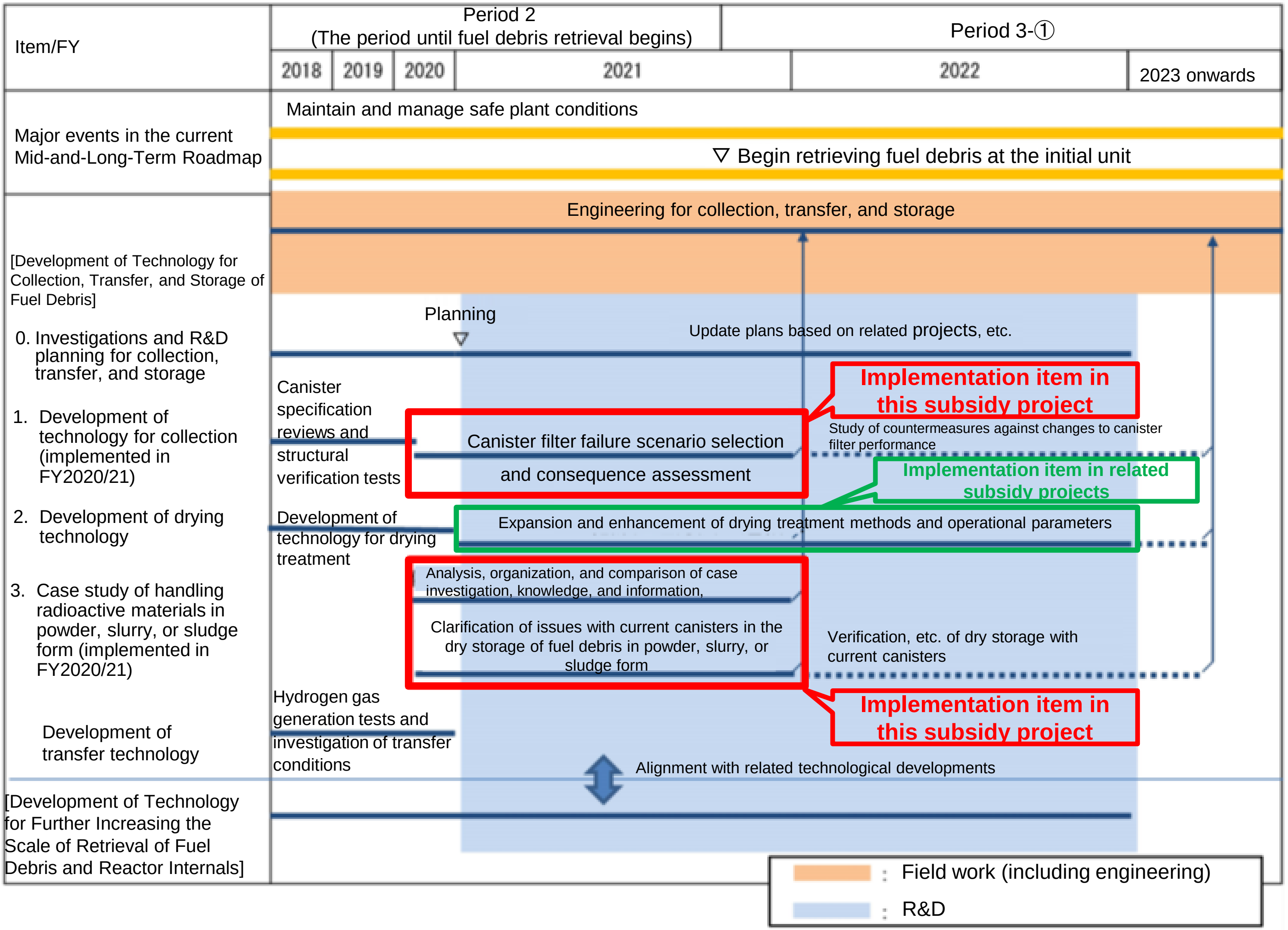
(3) Performance assessment of canister filters

In addition to verifying the necessary specifications for filters studied in other related research and development projects, the required specifications were broadly reviewed and consistency between the selection process for the filters and the evaluation results of the filters were confirmed. Furthermore, failure scenarios (i.e., corrosion, etc.) that impact filter performance were selected and the test conditions for evaluating those scenarios were studied.

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

3.2 Relevance between implementation items

(Target schedule) B3④: Development of Technology for Collection, Transfer, and Storage of Fuel Debris



Item/FY

Period 2
(The period until fuel debris retrieval begins)

Period 3-①

2018 | 2019 | 2020 | 2021 | 2022 | 2023 onwards

Major events in the current Mid-and-Long-Term Roadmap

Maintain and manage safe plant conditions

▽ Begin retrieving fuel debris at the initial unit

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

Engineering for collection, transfer, and storage

0. Investigations and R&D planning for collection, transfer, and storage

Planning ▽

Update plans based on related projects, etc.

1. Development of technology for collection (implemented in FY2020/21)

Canister specification reviews and structural verification tests

Canister filter failure scenario selection and consequence assessment

Implementation item in this subsidy project

Study of countermeasures against changes to canister filter performance

2. Development of drying technology

Development of technology for drying treatment

Expansion and enhancement of drying treatment methods and operational parameters

Implementation item in related subsidy projects

3. Case study of handling radioactive materials in powder, slurry, or sludge form (implemented in FY2020/21)

Analysis, organization, and comparison of case investigation, knowledge, and information,

Clarification of issues with current canisters in the dry storage of fuel debris in powder, slurry, or sludge form

Verification, etc. of dry storage with current canisters

Implementation item in this subsidy project

Development of transfer technology

Hydrogen gas generation tests and investigation of transfer conditions

Alignment with related technological developments

[Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Reactor Internals]

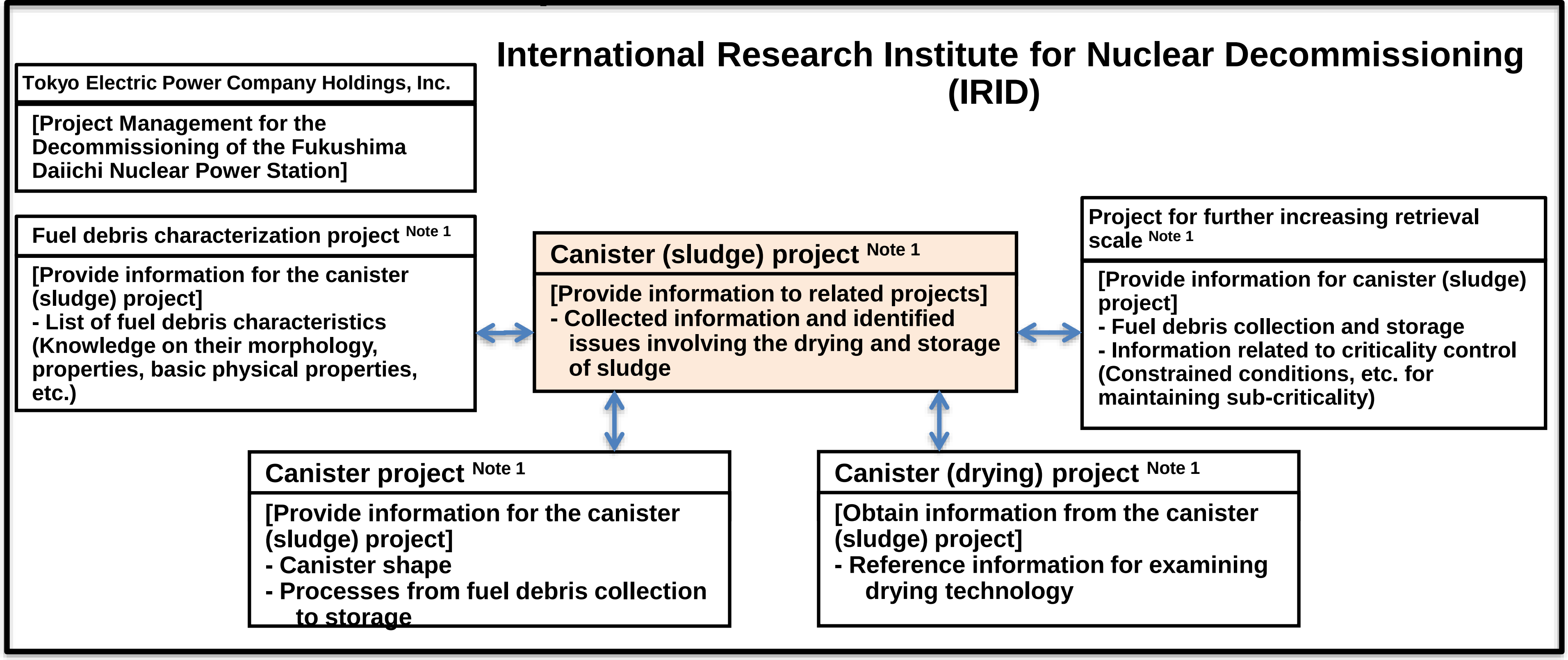
🟧 : Field work (including engineering)

🟦 : R&D

Team Meeting for Countermeasures for Decommissioning and Contaminated Water Treatment / Secretariat Meeting (86th meeting) Materials "FY2021 Decommissioning R&D Plan," Added to "(Target schedule) B3④: Development of Technologies for Containing, Transfer, and Storage of Fuel Debris"

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

3.2 Relevance between implementation items



International Research Institute for Nuclear Decommissioning (IRID)

Tokyo Electric Power Company Holdings, Inc.

[Project Management for the Decommissioning of the Fukushima Daiichi Nuclear Power Station]

Fuel debris characterization project Note 1

[Provide information for the canister (sludge) project]
- List of fuel debris characteristics (Knowledge on their morphology, properties, basic physical properties, etc.)

Canister (sludge) project Note 1

[Provide information to related projects]
- Collected information and identified issues involving the drying and storage of sludge

Project for further increasing retrieval scale Note 1

[Provide information for canister (sludge) project]
- Fuel debris collection and storage
- Information related to criticality control (Constrained conditions, etc. for maintaining sub-criticality)

Canister project Note 1

[Provide information for the canister (sludge) project]
- Canister shape
- Processes from fuel debris collection to storage

Canister (drying) project Note 1

[Obtain information from the canister (sludge) project]
- Reference information for examining drying technology

Note 1:

Project for further increasing retrieval scale: "Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals" Project
Fuel debris characterization project: "Development of Analysis and Estimation Technology for Fuel Debris Characterization" Project
Canister project: "Development of Technologies for Containing, Transfer, and Storage of Fuel Debris" Project
Canister (drying) project: "Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)" Project
Canister (sludge) project: "Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (for fuel debris in powder, slurry, or sludge form)" Project

Consistent results can be obtained by sharing and coordinating **information from related projects within IRID and the information provided by this project.**

4. Implementation schedule

Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (for fuel debris in powder, slurry, or sludge form)

	FY2020			FY2021											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
1. Investigation into cases of handling radioactive materials in powder, slurry, or sludge form															
① Investigation planning(examination of investigation targets, investigation items, etc.)	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥									
② Investigation			🟦	🟦	🟦	🟦	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥			
③ Organization of investigation results										🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥		
2. Identification of issues involving the storage of fuel debris in powder, slurry, or sludge form															
① Identification of targets and items to organize	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥									
② Identification of evaluations and issues				🟦	🟦	🟦	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥		
③ Evaluation based on Japan and overseas investigation results										🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥
3. Performance assessment of canister filters															
① Identification of environments and conditions	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥								
② Study of filter life evaluation methods		🟦	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥				
③ Study of test methods and conditions										🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥	🟦 🟥
4. Progress report, etc.									▼		▼				▼

🟦 Planned schedule 🟥 Actual schedule

IRID

5. Project organization

(As of the end of March 2022)

Tokyo Electric Power Company Holdings, Inc.

○ Project Management for the Decommissioning of the Fukushima Daiichi Nuclear Power Station

International Research Institute for Nuclear Decommissioning (IRID) (Head Office)

○ Formulation of an overall plan and technology management
○ Technology management such as the progress of technological developments

Mitsubishi Heavy Industries, Ltd.	Toshiba Energy Systems & Solutions Corporation	Hitachi-GE Nuclear Energy, Ltd.
(1) Case study of handling radioactive materials in powder, slurry, or sludge form	(1) Investigation into cases of handling radioactive materials in powder, slurry, or sludge form	(1) Investigation into cases of handling radioactive materials in powder, slurry, or sludge form
(2) Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form	(2) Identification of issues involving the storage of fuel debris in powder, slurry, or sludge form	(2) Identification of issues involving the storage of fuel debris in powder, slurry, or sludge form
(3) Performance assessment of canister filters (review)	(3) Performance assessment of canister filters	(3) Performance assessment of canister filters (review)

MHI-NS
- Literature translation and organization

Related development projects

- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Reactor Internals
- R&D on Solid Waste Treatment and Disposal
- Development of Technology for Containing, Transfer, and Storage of Fuel Debris
- Development of Technology for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)

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

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

6.3 Performance assessment of canister filters

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

① Purposes and goals

The purpose of the project is to investigate the cases necessary to obtain the information and knowledge for reviewing the experience, knowledge, and information on the handling and storage of radioactive materials in powder, slurry, or sludge form, and identify and organize precautions in the handling of the fuel debris.

② Comparison with existing technology

In the Development of Technologies for Containing, Transfer, and Storage of Fuel Debris project conducted up to FY2020, technologies were developed for the safe handling and storage of fuel debris in particle or lump form using canisters. However, fuel debris in powder, slurry, or sludge form is expected to be collected when retrieving fuel debris, so it is important to identify issues in safely storing them in the same way as fuel debris in particle or lump form and to clarify the technological issues to resolve.

From the perspective of implementing the above, it is useful to collect and analyze the experience, knowledge, and information on the handling and storage of radioactive materials in powder, slurry, or sludge form.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

a. Investigation planning(1/2)

Potential investigation targets and items was reviewed to obtain the experience, knowledge, and information on the handling and storage of radioactive materials in powder, slurry, or sludge form.

<Potential investigation targets>

USA

Cases of radioactive materials discharged from contaminated water treatment during retrieval of TMI-2 fuel debris

Cases of slurry and sludge in the decommissioning of the Hanford Site (K-Basin)

UK

Cases of slurry and sludge in the decommissioning of the Sellafield facility

Japan

Japan Atomic Energy Agency: Cases of radioactive materials discharged from liquid waste treatment

Japan Nuclear Fuel Limited: Cases of radioactive materials discharged from liquid waste treatment at a reprocessing plant

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

a. Investigation planning(2/2)

<Investigation items>

Investigation items from the perspective of safe transferring and storage

Shielding, maintaining sub-criticality, heat removal, confinement, structural integrity, long-term integrity, hydrogen countermeasures, fire

Investigation items from the perspective of handling and processes

Specifications (structure, etc.) for canisters and handling equipment and specifications for drying, etc. processes and the equipment for such processes

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

b. Investigation (1/2)

An investigation format was created to organize investigation items and cases involving the handling and storage of radioactive materials in Japan and abroad were surveyed.

[Overview of the entire plant]

- **Basic information (background, purposes, information on target substance, etc.)**

[Outline of each process]

- **Overview of the process (purposes, flow, etc.)**
- **Safety assessments (structure, heat removal, confinement, shielding, criticality, heat removal, hydrogen countermeasures, etc.)**
- **Permission and authorization (regulatory requirements, inspection items, etc.)**

<Investigation format sample (example)>

Overview of the entire plant

				Investigation results (including ideas on the establishment, etc.)	Source (related literatures)
①			Basic information		
	a.		Background/Circumstances/Purposes, etc.		
	b.		Positioning (Practical application complete In planning Research purpose, etc.)		
	c.		Information on the target substance (the source of the sludge)		
		(a)	Fuel type (plate fuel, uranium dioxide fuel, fuel debris, etc.)		
		(b)	Chemical components and composition of sludge (assumed)		
		(c)	What kind of treatments were used in transferring and storing? If drying was used, the specifications of components and the reason for the process Details of treatment for solidification, etc. If concentrated, the specifications of components, etc.		
		(d)	Has the sludge been processed into a form for transferring and storing (composition and moisture content)?		
	d.		Method used to transfer (pipeline, etc.) sludge to the storage facility (tank, etc.)		
	e.		Sludge storage method (storage inside a tank, etc.)		
②			Permission and authorization		
	a.		Whether regulatory requirements exist		
	b.		Permission and authorization procedure and examination period		
	c.		Inspection items before shipment or before/during storage		
③			Planned schedule		
	a.		Future plan		

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

b. Investigation (2/2)

Investigations on the handling and storage of radioactive materials, etc. in powder, slurry, or sludge form have organized the following items from the perspective of both handling and processes and the safe transfer and storage of fuel debris in powder, slurry or sludge form.

<Investigation items>

- Maintaining sub-criticality, shielding, heat removal, structure, hydrogen, fire, confinement, long-term integrity, drying

<Investigation targets>

USA

A case of radioactive materials discharged from contaminated water treatment during retrieval of TMI-2 fuel debris

A case of slurry and sludge in the decommissioning of the Hanford Site (K-Basin)

UK

A case of slurry and sludge in the decommissioning of the Sellafield facility

France

A case of slurry and sludge at the La Hague reprocessing plant

Japan

Japan Atomic Energy Agency: A case of radioactive materials discharged from liquid waste treatment

Japan Nuclear Fuel Limited: A case of radioactive materials discharged from liquid waste treatment at a reprocessing plant

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (1/8)

The main results from investigation into Japan and overseas cases involving the handling and storage of radioactive materials, etc. in powder, slurry, or sludge form are shown below.

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (1/8)

Investigation items	Investigation target	Investigation results
Maintaining sub-criticality	TMI-2	- Even when a coagulator was added to the canister (collection container), the boron materials installed inside the canister safely ensures criticality. - The canister (collection container) can be transferred in a transfer cask. Analysis using an evaluation model verified that sub-criticality for the canister and transfer cask can be maintained.
Shielding	IAEA	- Spent fuel/damaged fuel is mainly stored in wet storage, with more than 80% of spent fuel stored in wet storage. Wet storage management primarily employs shielding and cooldown and heat removal with pool water. Safety measures and calibration inspections are easy to incorporate and it is assumed that continuous SAFSTOR can be established through pool water conditions and analysis.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (2/8)

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (2/8)

Investigation items	Investigation target	Investigation results
Heat removal	IAEA	- Spent fuel/damaged fuel is mainly stored in wet storage, with more than 80% of spent fuel stored in wet storage. Wet storage management primarily employs shielding and cooldown and heat removal with pool water. Safety measures and calibration inspections are easy to incorporate and it is assumed that continuous SAFSTOR can be established through pool water conditions and analysis.
	Hanford (K-Basin)	- It was verified that concentrically arranging highly radioactive waste that has undergone washing, dehydration, drying, etc. treatments in a scrap basket facilitates heat removal.
	Sellafield	- It was verified that increasing the surface areas of fins on the Magnox fuel element improved the efficiency of heat removal.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (3/8)

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (3/8)

Investigation items	Investigation target	Investigation results
Structure	Hanford (K-Basin) [KW-Basin]	- A separation treatment for sludge collected from the bottom of the Basin by using the pump was conducted through the Integrated Water Treatment System (IWTS) (spent fuel: grains 1/4 inch (0.64 cm) or larger, powder (sludge)): coagulation sedimentation, ions: ion exchange resin) after transporting the sludge into the storage container through the transportation piping (Hose-in-Hose). Pu content in the collected sludge was verified below a certain value and then cement solidification was carried out in drum cans. - From the viewpoint of maintaining criticality, particles collected by coagulation sedimentation were collected in tanks (settle tanks) with an outer diameter of 20 inches (0.5 m) and a length of 16 ft (5 m). Surplus water was discharged via high-pressure washing and 99.7% of sludge was collected.

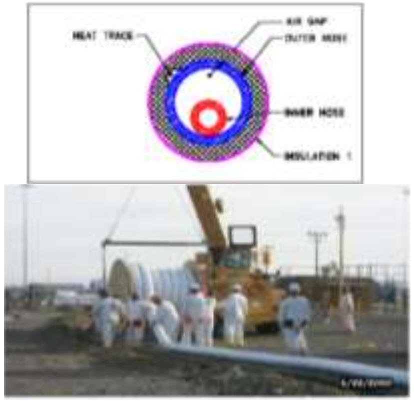


Figure 1 Hose-in-Hose Note1 used for sludge transportation

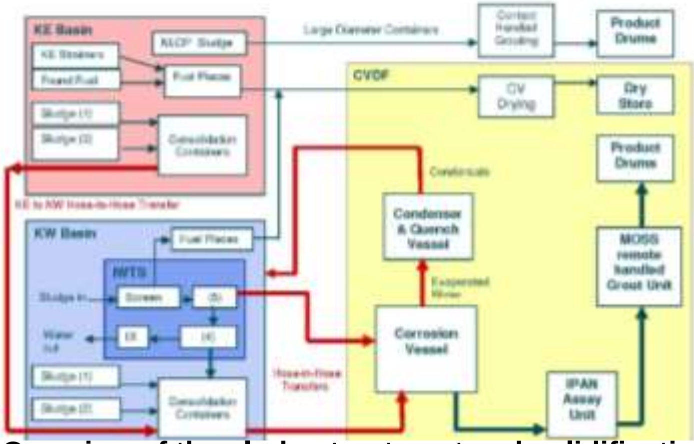


Figure 2 Overview of the sludge treatment and solidification system installed at K-West-Basin Note 1

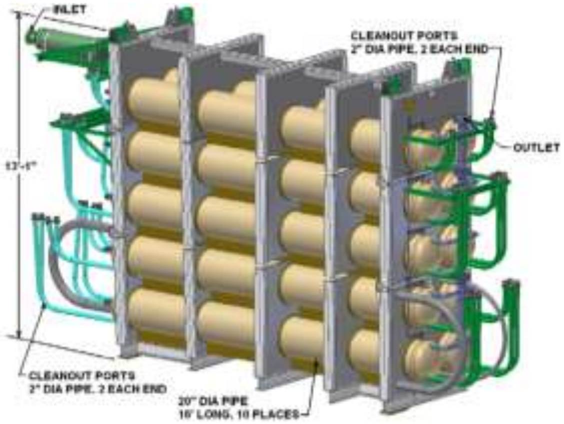


Figure 3 Settle Tanks Note 2

Note 1: From P.Knollmeyer et al. Waste Management 2006 Conference, February 26 - March 2, 2006, Tucson, AZ. Progress with K Basins Sludge Retrieval, Stabilization and Packaging at Hanford Nuclear Site, 2006

Note 2: From Eric G et al. Waste Management 2011 Conference, February 27 - March 3, 2011, Phoenix, AZ. Sludge Retrieval from Hanford K-West Basin Settler Tanks, – 11449. 2011.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (4/8)

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (4/8)

Investigation items	Investigation target	Investigation results
Hydrogen	Hanford (K-Basin)	- A physical model evaluated the possibility of gas accumulation in the solid-liquid bed when K-Basin sludge was stored in a high-level radioactive liquid waste storage tank, and the relational expression of the hydrogen concentration is examined. - The relational expression between the rate of hydrogen gas generation and temperature was examined, factoring in the thermal decomposition of organic matter inside the high-level radioactive liquid waste storage tank, the radioactive decomposition of water, corrosion of tank steel, and more. - It was verified the event in which the gas generated by the radioactive sludge was capped by the radioactive sludge and was not released, resulting in a gas accumulation. Study of the relationship between the volume of gas retained in sludge and the yield stress of sludge.

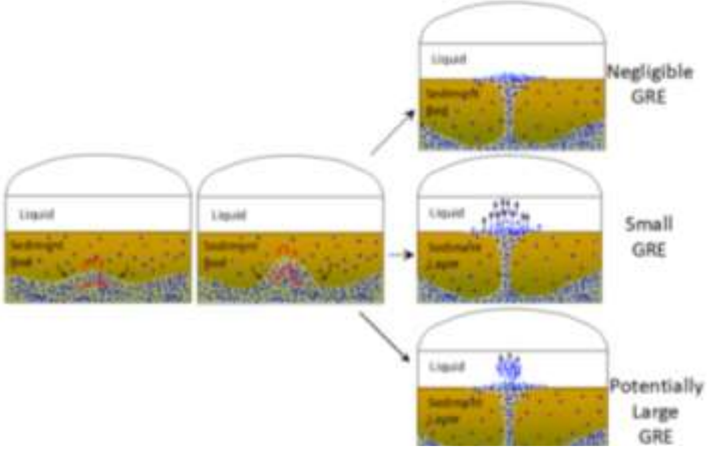


Figure 1 Hydrogen discharge event (GRE: Gas Release Event) Note 1 in tanks at the Hanford Site

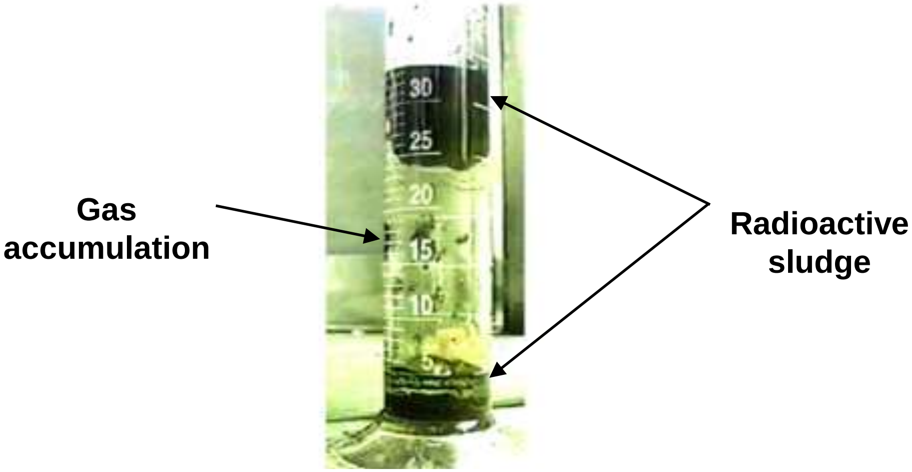


Figure 2 Gas accumulation formed by radioactive sludge within a sludge bed Note 2

Note 1: From PA Gauglitz et al. PNNL-24255 WTP-RPT-238 Rev.0. Hydrogen Gas Retention and Release from WTP Vessels: Summary of Preliminary Studies, 2015.

Note 2: From G.Terrones et al. PNNL-13805. Vessel-Spanning Bubble Formation in K-Basin Sludge Stored in Large-Diameter Containers, 2002.

6. Implementation details

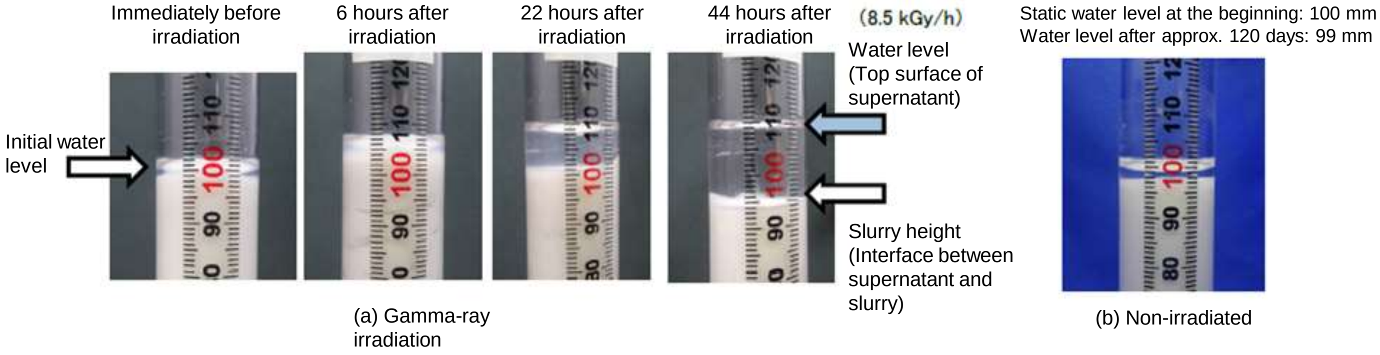
6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (5/8)

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (5/8)

Investigation items	Investigation target	Investigation results
Hydrogen	Savanna River Site	-When the agitator was suspended during treatment of high-level radioactive liquid waste, a behavior model of hydrogen gas that accumulated in liquid waste and released upon the resumption of the agitator was evaluated.
	Sellafield	- In the hydrogen formed by the corrosion of shavings during the dismantling of Magnox fuel, the amount and form of hydrogen accumulated in the $Mg(OH)_2$ slurry of corrosion products were examined in the test.
	JAEA	- It was verified that gamma-ray irradiation causes hydrogen gas to accumulate within the carbonic acid slurry, and that the volume expands.



(a) Gamma-ray irradiation

(b) Non-irradiated

Figure 1 Rise in water level and increase in accumulated water from gamma-ray irradiation to a simulated carbonate slurry in HIC Note 1

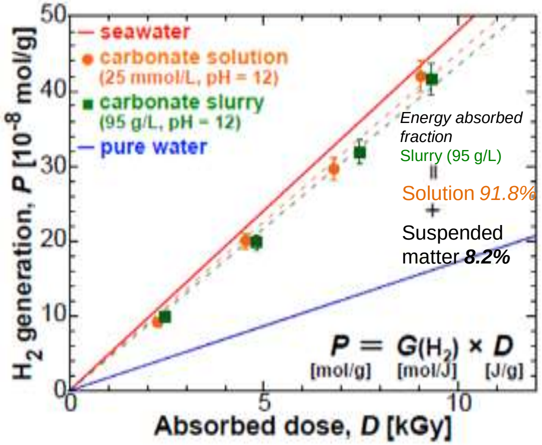


Figure 2 Relationship between absorbed dose and the amount of hydrogen generated from gamma-ray irradiation to a simulated carbonate slurry in HIC Note 2

Note 1: From Takafumi Motooka et al., Atomic Energy Society of Japan Proceedings 2I20, Spring 2016, Irradiation Experiments of Simulated Carbonate Slurry in HIC (2) Gas Retention Behavior of Simulated Carbonate Slurry under Gamma Ray Irradiation, 2016.

Note 2: From Ryuji Nagaishi et al., Atomic Energy Society of Japan Proceedings 2I21, Spring 2016, Irradiation Experiments of Simulated Carbonate Slurry in HIC (3) Studies on Radiolysis Behavior of Simulated

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (6/8)

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (6/8)

Investigation items	Investigation target	Investigation results
Fire	La Hague	- Asphalt solidification with a large volume of waste filling was studied as a treatment method for radioactive sludge, but French regulatory authorities did not allow permission due to the issue of gas generation from the radioactive decomposition of asphalt. An alternative measure, having the sludge dried via a Drying/Compress process, pelletized, and then collected in a container with sand, is currently under consideration. - Construction of a facility that is designed for retrieving the graphite and magnesium waste (approximately 600 m^3) used in the uranium fuel cladding stored at the La Hague reprocessing plant was completed and the retrieval begun.

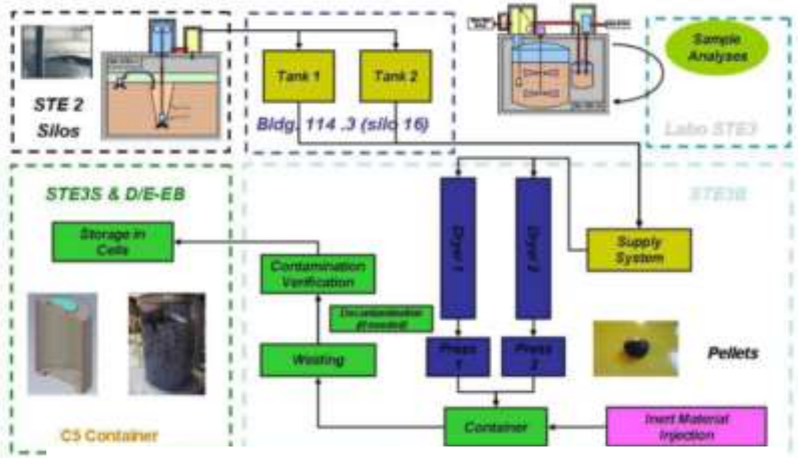


Figure 1 Drying/Compress process Note 1

Figure 2 Magnesium waste storage container Note 2

Note 1: From Elisa LEONI et al. WM2019 Conference, March 3 – 7, 2019, Phoenix, Arizona, USA. La Hague STE2 Sludge Retrieval and Conditioning Strategy -19229. 2019.

Note 2: From Bruno VILTARD et al. WM2020 Conference, March 8 - 12, 2020, Phoenix, Arizona, USA. Start-up of Silo 130 Waste Retrieval at La Hague: 1st Step Towards Reducing Legacy Inventory -20020. 2020.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (7/8)

Table Investigation results on the handling and storage of radioactive materials in powder, slurry, or sludge form (7/8)

Investigation items	Investigation target	Investigation results
Confinement	Hanford (K-Basin)	- A container called an MCO (Multi Canister Overpack) for collecting highly radioactive sludge has been designed based on the ASME Class 1 vessels (equivalent to a reactor pressure vessel) and ensures airtightness in the collection, transfer, and storage of sludge (in an interim storage facility).
	Sellafield	- High-level radioactive liquid waste generated when reprocessing Magnox spent fuel and spent oxidized fuel is concentrated in an evaporator, denitrified, and then pulverized and vitrified. The vitrified material is injected into a stainless steel container and the lid is welded shut to seal in the radioactive material.
	TMI	- After retrieving fuel debris, each target substance is packaged in a dedicated fuel debris canister. - Analysis of pressure and temperature fluctuations when a canister was dropped or transported verified that fuel debris would not leak.
Long-term integrity	Hanford (K-Basin)	- The internal pressure load is an influential factor in the long-term integrity of MCO and reducing the temperature (maintaining temperatures below 60℃, including when drying), dehydration (adding magnesium oxide or calcium oxide as a dehydration agent), suppressing corrosive reactions (adding nitrite or phosphate to the solution), and adding supplements (adding nitrate (NO_3^-) or nitrite (NO_2^-) to the solution) are recommended to reduce the generation of hydrogen gas.
Drying	Hanford (K-Basin)	- Low-temperature vacuum drying (pressure conditions: 8 Torr (1 kPa), temperature conditions: 40 to 50℃, drying time: 50 hours) was used to limit fuel damage from the rapid oxidation of uranium in collected sludge.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

③ Implementation items and results

c. Organization of investigation results (8/8)

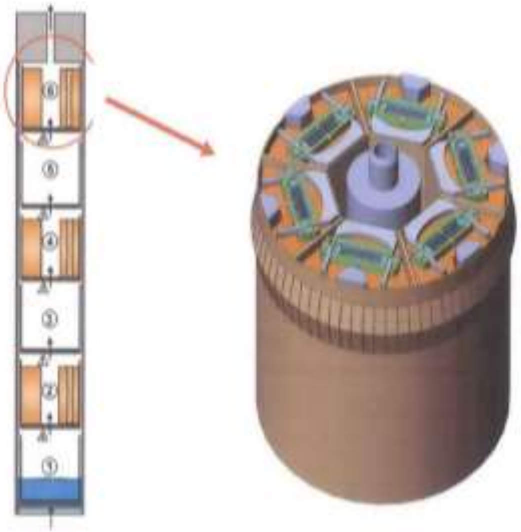


Figure 1 Hanford's MCO (Multi Canister Overpack) and a scrap basket to be collected in the MCO Note 1

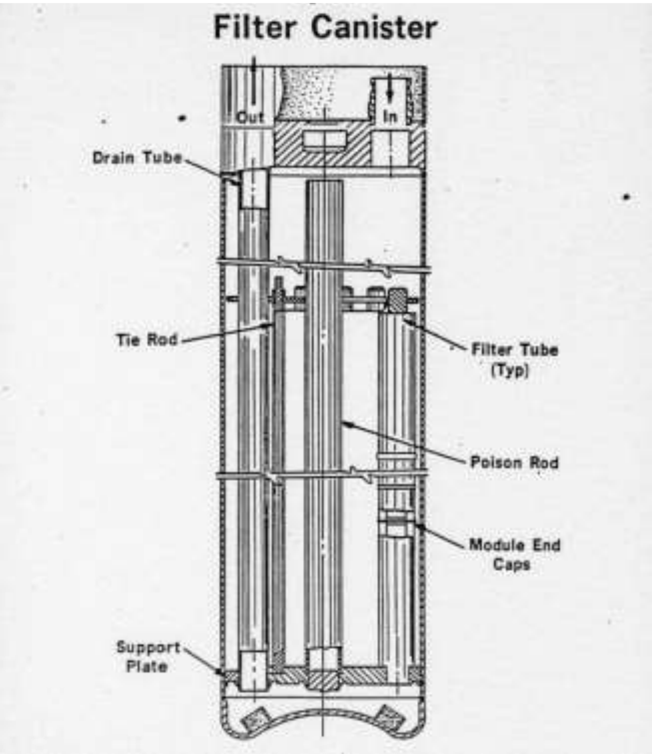


Figure 2 TMI-2 filter canister Note 2

(Size of collected particles: 0.5 to 800 μm)

Note 1: JCH2MH ILL (2012): "Knock Out Pot Material Multi-Canister Overpack Proof of Dryness (OCRWM), Sludge Treatment Project KOP Disposition, PRC-STP-00210, Revision 2"

Note 2: "THI-2 Defueling Canisters Final Design Technical Report" 77-1153937-04

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

④ Contribution of outcomes to relevant study areas

The results of investigations of cases involving the handling and storage of radioactive materials in powder, slurry, or sludge form were summarized to contribute to identifying issues in the handling and storage of powdery, slurry and sludge type radioactive materials.

⑤ Analysis with respect to the on-site applicability

These case investigations are useful references when examining the handling of fuel debris in powder, slurry, or sludge form, which are the forms assumed to be collected during fuel debris retrieval.

⑥ Goal achievement level

It can be concluded that goals have been achieved since the following indicator was met.

- Analyze overseas cases of handling radioactive materials in powder, slurry, or sludge form and organize specific precautions, ways to ensure safety, etc. for the handling of radioactive materials in powder, slurry, or sludge form.

⑦ Issues to be addressed

As examples of investigations on the handling and storage of radioactive materials in powder, slurry, or sludge form in Japan and abroad, the investigation was primarily conducted at TMI-2 and the Hanford Site in the United States and the Sellafield facility in the United Kingdom. Further information acquisition and analysis on the La Hague reprocessing plant in France and similar facilities in Japan would be useful.

6. Implementation details

6.1 Case study of handling radioactive materials in powder, slurry, or sludge form

⑧ Summary

- Case studies were conducted based on literatures regarding the handling and storage of radioactive materials in powder, slurry, or sludge form at TMI-2 and the Hanford Site in the United States, Sellafield in the United Kingdom, and others.

- Based on the results of the investigation, the evaluation items, evaluation methods, and countermeasures necessary for safely handling and storing fuel debris in powder, slurry, or sludge form are classified according to safety assessments and handling for each item (maintaining sub-criticality, shielding, heat removal, structure, hydrogen, confinement, long-term integrity, drying), and organized by precautionary points, etc.

- Further investigations of the experience, knowledge, and information regarding the handling and storage of radioactive materials in powder, slurry, or sludge form will be conducted in FY2022 and will target the La Hague reprocessing plant in France and similar facilities in Japan. Investigating this knowledge and information is planned as a continuation project of this subsidy project.

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

① Purposes and goals

The purpose and goals of the project is to identify issues involving safe, reliable, and rational storage conditions and clarify technological issues to resolve when using a canister for dry storing fuel debris in powder, slurry, or sludge form in a similar way as fuel debris lumps or fuel debris particles.

② Comparison with existing technology

In the Development of Technologies for Containing, Transfer, and Storage of Fuel Debris project conducted up to FY2020, technologies were developed for the safe handling and storage of fuel debris in particle or lump form using canisters.
However, fuel debris in powder, slurry, or sludge form is expected to be collected when retrieving fuel debris, so it is important to identify issues in safely storing them in the same way as particulate or lump-shaped fuel debris and to clarify the technological issues to resolve.

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

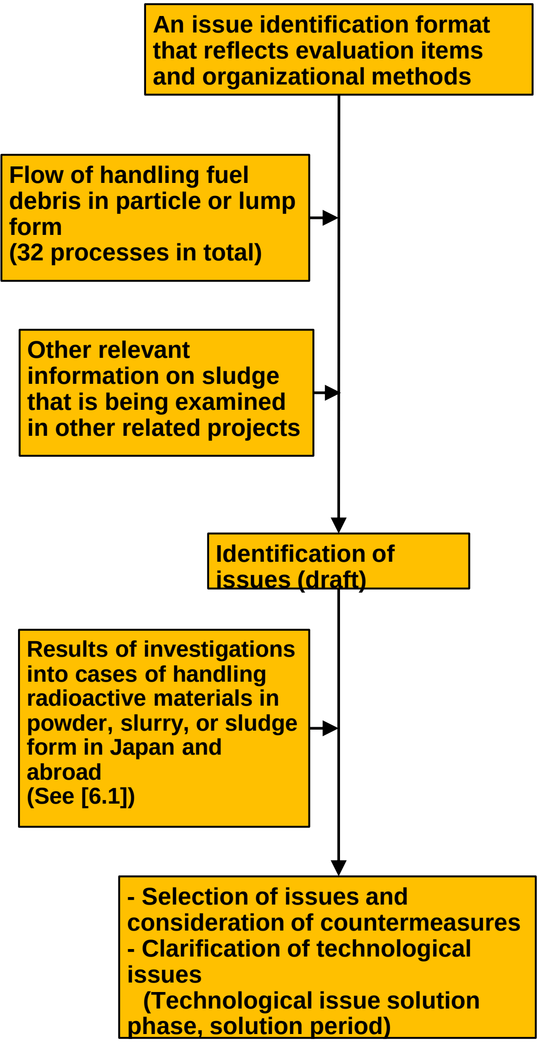
a. Identification of targets and items to organize (1/8)

It is assumed that different type of issues exist between the containing, transfer, and storage of powdery, slurry or sludge type fuel debris and particulate or lump shaped fuel debris. From the perspective of clarifying issues, items will be identified assuming transfer and storage using the same procedures, e.g. using the canisters for fuel debris in particle or lump form, which are the result of FY2020 technological developments.

Therefore, a series of handling processes (see No. 29 and 30) for fuel debris in particle or lump form were considered and organizational methods and items to evaluate were examined for each handling process (a total of 32 processes, from retrieving fuel debris in reactors to long-term storage), and also a format for identifying issues (see No. 31) was formulated. These were conducted from the perspective of comprehensively identifying issues involved in bringing fuel debris in powder, slurry, or sludge form (See No. 32 and 33) into safe and long-term stable storage, including sludge collected during proposed retrieval task, coagulation sedimentation sludge in water circulation systems, matter captured on filters, oxide particles of various configuration materials, particles such as processing abrasives and neutron absorbers for maintaining sub-criticality.

<Items to be evaluated>

1. **Analysis and identifying of issues from the perspective of safe and long-term stable storage**
   Evaluation perspectives: Shielding, maintaining sub-criticality, heat removal, confinement (contamination), structural integrity, long-term integrity, hydrogen countermeasures, fire
2. **Analysis and identifying of issues from the perspective of handling and processes**
   Evaluation perspectives: Canister structure (lid structure, filter, etc.), drying and hydrogen concentration measurements



An issue identification format that reflects evaluation items and organizational methods

Flow of handling fuel debris in particle or lump form (32 processes in total)

Other relevant information on sludge that is being examined in other related projects

Identification of issues (draft)

Results of investigations into cases of handling radioactive materials in powder, slurry, or sludge form in Japan and abroad (See [6.1])

- Selection of issues and consideration of countermeasures
- Clarification of technological issues (Technological issue solution phase, solution period)

Issue identification flow

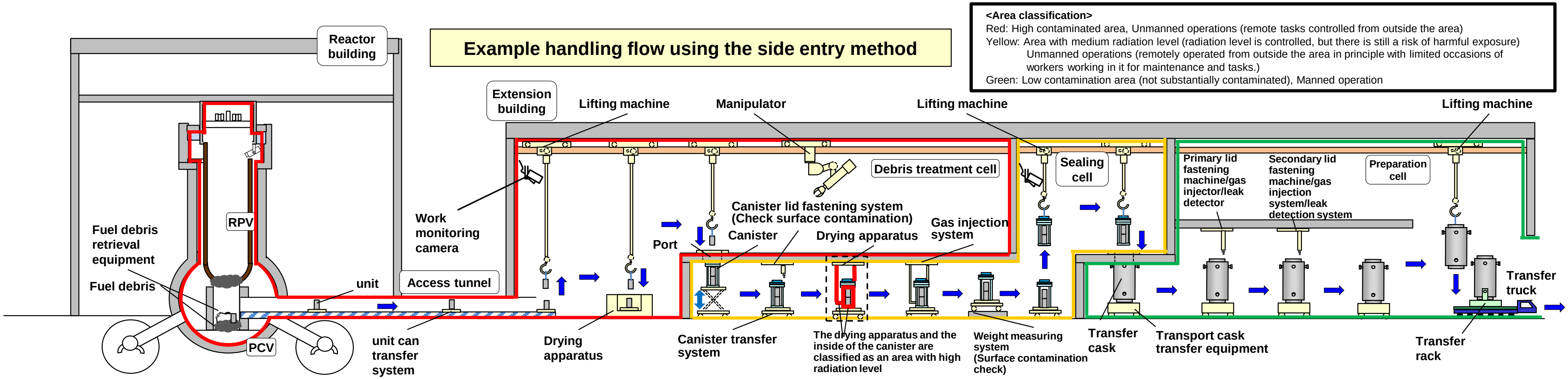
6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

a. Identification of targets and items to organize (2/8)

- A series of handling processes for fuel debris in particle or lump form
  (Fuel debris retrieval from inside reactors ~ Transferring inside the premises: 17 processes)



Example handling flow using the side entry method

<Area classification>
Red: High contaminated area, Unmanned operations (remote tasks controlled from outside the area)
Yellow: Area with medium radiation level (radiation level is controlled, but there is still a risk of harmful exposure) Unmanned operations (remotely operated from outside the area in principle with limited occasions of workers working in it for maintenance and tasks.)
Green: Low contamination area (not substantially contaminated), Manned operation

Inside the reactor

[1] Cut and process discharged materials
[2] Visually verify discharged materials
[3] Collect fuel debris with the fuel debris retrieval equipment and load it into a unit can (hereafter "unit can")
[4] Dewater and dry fuel debris
[5] Transfer the unit can out of the reactor building (transfer out of the pedestal)

Access tunnel

[5] Transfer the unit can out of the reactor building (pass through the access tunnel) *1

*1: In addition to fuel debris, waste such as reactor internals moves from inside the reactor to the extension building through the access tunnel.

Debris treatment cell

[6] Dry fuel debris
(Load the unit can into the drying system ~ Drying treatment)

Sealing cell

[7] Load the unit can into the canister
[8] Fasten the canister lid
(Affix inner lid ~ Move to lid fastening system ~ Fasten lid - Verify lid seal)
[9] Verify surface contamination on the canister
(Dry fuel debris
(Connect the canister to drying system ~ drying treatment *2))
[10] Inject inert gas into the canister
(Connect the canister to the gas injection system ~ Inject inert gas into the canister~)
[11] Measure the amount of hydrogen generated *3
[12] Verify that the canister has been delivered
(Measure weight, etc.)
[13] Load the canister into the transfer cask
(Move the canister to the top of the port)

*2: Executed if drying within the fuel debris treatment cell is not possible
*3: Considering executing this when injecting inert gas

Preparation cell

[13] Load the canister into the transfer cask
(assume they are stacked)
[14] Fasten the transfer cask lid
(Fasten lid (primary lid) ~ Inject inert gas (inside cavity) ~ Verify lid seal (primary lid) ~ Fasten lid (secondary lid) ~ Inject inert gas (between primary and secondary lids) ~ Verify lid seal (secondary lid))
[15] Measure the amount of hydrogen generated *4
[16] Verify delivery of the transfer cask
[17] Load the transfer cask onto the transfer vehicle

Inside the premise

- Transfer inside the premises

*4: Considering executing this when inert gas is injected into the cavity

Figure Handling process for fuel debris in particle or lump form (1/2)

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

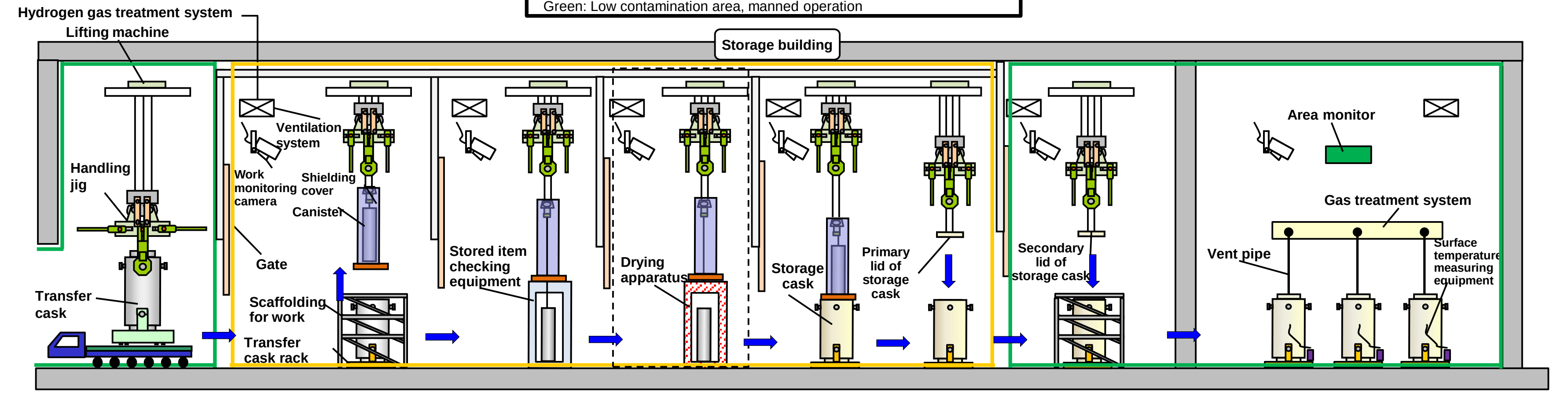
③ Implementation items and results

a. Identification of targets and items to organize (3/8)

- A series of handling processes for fuel debris in particle or lump form (Bringing the transfer cask into the storage building ~ Long-term storage: 15 processes)

Example handling flow using the side entry method

<Area classification>
Red: none
Yellow: Medium contamination area, unmanned operation (remote tasks controlled from outside the area)
Green: Low contamination area, manned operation



[18] Receive the transfer cask at the truck bay door
[19] Unload the transfer cask from the transfer vehicle
[20] Verify that the transfer cask has been received

[21] Measure the amount of hydrogen generated [*5]
[22] Open transfer cask lid (Remove secondary lid ~ Remove primary lid)
[23] Retrieve the canister from the transfer cask [*6]
[24] Verify that the canister has been received

*5: Execute after removing the secondary lid
*6: Cover the canister with a shield cover and move

[25] Verify the stored item[*7] (Load the canister into the stored item checking equipment ~ Verify)

*7: Assume the dose rate measurement

Dry fuel debris [*8] (Load the canister into the drying system ~ Drying treatment)

*8: Execute if drying is required prior to storage

[26] Verify prior to storing canister
[27] Load the canister into the storage container (assume they are stacked)
[28] Fasten the storage container lid (Fasten lid (primary lid) ~ Inject inert gas (inside cavity) ~ Verify lid seal (primary lid))

[28] Fasten the storage container lid (Fasten lid (secondary lid) ~ Inject inert gas (between primary and secondary lids) ~ Verify lid seal (secondary lid))
[29] Verify confinement

[30] Connect a vent pipe to the storage container
[31] Verify vent pipe seal
[32] Long-term storage

Figure Handling process for fuel debris in particle or lump form (2/2)

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

a. Identification of targets and items to organize (4/8)

<Issue identification format>

[Components subject to evaluation]
- Unit cans, canisters, unit can, and systems that handle canisters

[Evaluation perspective]
- Design concepts, safety design policies, issues

Step			Technological elements	Concepts and policies from a technological standpoint						Proposed issues		
				Basic requirements	Considerations for the basic requirements	Systems concepts		Permission and authorization (safety design) policies				
No	Locations	Details of implementation				unit can	Canister	unit can	Canister	unit can	Canister	Other components (Systems that handle components other than unit can and canisters)
1	Inside the reactor	Cutting and processing of discharged materials	① Structure	- Structural strength shall be able to maintain the basic requirements in ② to ⑦ against loads from the assumed events.								
			② Heat removal	- Fuel debris shall not melt from decay heat. - Heat removal functions shall be able to maintain the basic requirements of ① and ③ to ⑦.								
			③ Confinement (Contamination)	- Leakage of radioactive materials shall be prevented.								
			④ Shielding	- The necessary shielding capabilities shall be in place to prevent radiation sickness.								
			⑤ Criticality	- There shall be no risk of fuel debris reaching criticality.								
			⑥ Hydrogen	- Hydrogen explosion shall be prevented.								
			⑦ Fire	- Fires shall be prevented from occurring.								
			⑧ Measuring	Measures for the material accountancy and protection of nuclear fuel materials shall be enacted.								
			⑨ Long-term integrity	- The basic requirements of ① to ⑧ shall be able to be maintained even when accounting for aging.								
			⑩ Other necessary items for handling operations	- The necessary functions for fuel debris retrieval and collection shall be in place.								
2	Inside the reactor	Visual verification of discharged materials	① Structure	- Structural strength shall be able to maintain the basic requirements in ② to ⑦ against loads from the assumed events.								
			② Heat removal	- Fuel debris shall not melt from decay heat. - Heat removal functions shall be able to maintain the basic requirements of ① and ③ to ⑦.								
			③ Confinement (Contamination)	- Leakage of radioactive materials shall be prevented.								
			④ Shielding	- The necessary shielding capabilities shall be in place to prevent radiation sickness.								
			⑤ Criticality	- There shall be no risk of fuel debris reaching criticality.								
			⑥ Hydrogen	- Hydrogen explosion shall be prevented.								
			⑦ Fire	- Fires shall be prevented from occurring.								
			⑧ Measuring	Measures for the material accountancy and protection of nuclear fuel materials shall be enacted.								
			⑨ Long-term integrity	- The basic requirements of ① to ⑧ shall be able to be maintained even when accounting for aging.								
			⑩ Other necessary items for handling operations	- The necessary functions for fuel debris retrieval and collection shall be in place.								

Identify issues in each process for target components

Identifying issues for each fuel debris handling process (32 processes)

[Evaluation items] - Safety assessments (structure, heat removal, confinement (contamination), shielding, criticality, hydrogen, measuring, long-term integrity)
- Requirements for handling operations

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

a. Identification of targets and items to organize (5/8)

- Information on the fuel debris in powder, slurry, or sludge form that is expected to be discharged during fuel debris retrieval (characteristics, amount generated, properties, safety requirements, etc.) was exchanged at joint project meetings.

<Summary of information on fuel debris in powder, slurry, or sludge form expected to be discharged during fuel debris retrieval (excerpt from the table)>

No.	Types	Properties	Location of generation	Amount generated	Frequency of generation	Timing of generation	Properties of the target substance when collected in a collection container (including additives other than fuel debris)					Candidate collection containers (unit cans, canisters, others)	Existence of collection container treatment	If "yes" in the left column, the treatment method	Form of collection into the collection container	Location of collection into the collection container	Proposed transfer route of collection container	Transfer frequency of collection container	Safety requirements when handling collection containers (including storage)
							Contained materials (including percentage)	Shape (including fuel debris size)	Density	Moisture content	Void ratio								
1	Coagulation sediment in coarse filter liquid waste	High volume of particles with large particle size and high specific gravity	Sedimentation separation system inside the extension building	11 [m3/y]	0.055 [m3/day]	Further Increase of retrieval scale (1/3 units)	- Molten fuel - Core structures - Concrete - Other solids (earth and sand, precipitates, insoluble neutron absorbers, solidified materials, abrasives, etc.) - Aluminum sulfate (1000 ppm) - Boric acid components	- Particle form (particle diameter: 100 to several tens of μm)	Approx. 1 [g/cm3]	90 to 95 [vol%]	Almost 0 [vol%]	- Sludge collection container (Φ200 × H400) - Waste storage container	None	—	Direct collection	Sedimentation separation tank in the extension building	Transfer from the extension building through the interior of the hot cell	1 [pcs/day]	- Control shape to maintain sub-criticality - Use venting, etc. to maintain hydrogen concentration levels below the explosion lower limit
2	Coagulation sediment in intermediate and final treatment filter liquid waste	High volume of particles with small particle size and low specific gravity	Sedimentation separation system inside the extension building	54 to 7 [m3/y]	0.27 to 0.035 [m3/day]	Further Increase of retrieval scale (1/3 units)	- Molten fuel - Core structures - Concrete - Other solids (earth and sand, precipitates, insoluble neutron absorbers, solidified materials, abrasives, etc.) - Aluminum sulfate (1000 ppm)	- Particle form (particle size: several tens to 0.1 μm)	Approx. 1 [g/cm3]	90 to 95 [vol%]	Almost 0 [vol%]	- Sludge collection container (Φ200 × H400) - Waste storage container	None	—	Direct collection	Sedimentation separation tank in the extension building	Transfer from the extension building through the interior of the hot cell	1 to 8 [pieces/day]	- Control shape to maintain sub-criticality - Use venting, etc. to maintain hydrogen concentration levels below the explosion lower limit
3	Coagulation settings in RO concentrated water	Dominated by powder adsorbents on the order of several μm	Sedimentation separation system inside the extension building	310 [m3/y]	1.6 [m3/day]	Further Increase of retrieval scale (1/3 units)	- Powder adsorbents (titanic acid, titanium silicate, activated carbon, hematite, magnetite) - High base PAC (1000 ppm)	- Particle form (Particle size: several μm)	Approx. 1 [g/cm3]	90 to 95 [vol%]	Almost 0 [vol%]	- Sludge collection container (Φ200 × H400) - Waste storage container	Yes	In technological development (target moisture content of 60 vol% or less; provisional setting)	Direct collection	Sedimentation separation tank in the extension building	Transfer from the extension building through the interior of the hot cell	111 [pcs/day]	- Control shape to maintain sub-criticality - Use venting, etc. to maintain hydrogen concentration levels below the explosion lower limit
4	Gas phase sludge	Generated by collecting dust debris floating in the air with a metal HEPA filter in a gas phase system and using backwashing to remove it. Currently considering treatment in a liquid phase system sedimentation separation tank as one proposal.	Metallic HEPA filter in a gas phase system			Further Increase of retrieval scale (1/3 units)	- Dust debris - Others	- Particle form (particle size: unknown, but assumed to be particles that float in the air)											
5	Neutron absorbers for maintaining sub-criticality	Solid-type absorbents (Gd particles, glass materials containing B/Gd) and solidified-type absorbents (sodium silicate) that have been processed together with debris and changed to a powder or sludge form	Location of debris retrieval task such as pedestal, etc.	The amount of Gd particles and glass materials containing B/Gd used is estimated to be 2.5% of the volume of debris. Assuming that an additional 1% of this turns into sludge, the volume ratio to debris is 2.5% × 1% = 0.025%. The amount of sodium silicate used is estimated to be 5% of the volume of debris, so the volume ratio to debris is 5% × 1% = 0.05%. (M3V-2019-000230, rev1, The usage methods of non-soluble neutron absorbers)	The amount of Gd particles and glass material containing B/Gd used per day is estimated to be 1.5 liters (1.5 E - 3 [m^3/day]). Assuming that 1% of this turns into sludge, then 1.5 E - 5 [m^3/day] The amount of sodium silicate used per day is estimated to be 3.0 liters (3.0 E - 3 [m3/day]). Assuming that 1% of this turns to sludge, then 3.0 E - 5 [m3/day] (M3V-2019-000230, rev1, The usage methods of non-soluble neutron absorbers)	Further Increase of retrieval scale (1/3 units)	- Gd2O3 - Bismuth borate glass (Glass material containing B/Gd) - Sodium silicate (Na2O, SiO2, CaO, Al2O3, Fe2O3, CaSO4, NaH2PO4)	- Gd particles: Particle form (Particle size: up to 500 μm) - Glass material containing B/Gd: Particle form (particle size: up to 1 mm) - Sodium silicate: Sludge form after solidification (particle size: up to 100 μm)	- Gd2O3 particles: 4.3 [g/cm3] - Glass material containing B/Gd: 4.29 [g/cm3] - Sodium silicate: 2.1 [g/cm3] (M3V-2019-000230, rev1, The usage methods of non-soluble neutron absorbers)	For Gd2O3 and glass material containing B/Gd, water content is 0% Unknown for sodium silicate, but thought to be high (Will revise if data is obtained in the 2021-2022 project)	For Gd2O3 and glass material containing B/Gd, void ratio is 0% Unknown for sodium silicate, but thought to be low (Will revise if data is obtained in the 2021-2022 project)	There is no size limit for containers that collect absorbents (Absorbents will not be collected separately after retrieval, but will be collected along with fuel debris)	The containers that collect absorbents can be disposed of as general industrial waste.	None (no need to consider) No special treatment is required for collection containers with added absorbents.	None (no need to consider) Collected along with debris.	None (no need to consider) Collected along with debris.	None (no need to consider) Collected along with debris.	- Gd particles: Transfer 5.5 [L] once a year 1.5 E-5 [m3/day] × 365 [days] = 5.5 [L/year] - Sodium silicate: Transfer 11 [L] once a year 3.0 E-5 [m3/day] × 365 [days] = 11 [L/year]	None (no need to consider) The government R&D project verified the safety of the absorbents and their impact on collection and storage. (M3V-2020-000265, Summary of performance assessment of insoluble neutron absorber)

(Remarks) Classification of colored cells in the table

🟨 : Items that can be provisionally set based on future desk studies, etc.

🟪 : Items that are considered difficult to judge (provisionally set) further (requires actual fuel debris information)

🟦 : Items that do not require further consideration (does not require criticality control and collection container)

Listing of the fuel debris in powder, slurry, or sludge form expected to be discharged (19 types) Assume the amount generated, properties, collection form, etc., and color-code according to the following classifications

- **Yellow: Items that can be provisionally set based on future desk studies, etc.**
- **Pink: Items that are considered difficult to judge (provisionally set) further (requires actual fuel debris information)**
- **Blue: Items that do not require further consideration (does not require criticality control and collection containers)**

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

a. Identification of targets and items to organize (6/8)

<Example of fuel debris in powder, slurry, or sludge form expected to be discharged when retrieving sorted fuel debris>

No.	Types	Properties	Location of generation	Amount generated	Frequency of generation	Timing of generation	Properties of the target substance when collected in a collection container (including additives other than fuel debris)				
							Contained materials (including percentage)	Shape (including fuel debris size)	Density	Moisture content	Void ratio
1	Coagulation sediment in coarse filter liquid waste	High volume of particles with large particle size and high specific gravity	Sedimentation separation system inside the extension building	11 [m3/y]	0.055 [m3/day]	Further Increase of retrieval scale (1/3 units)	- Molten fuel - Core structures - Concrete - Other solids (earth and sand, precipitates, insoluble neutron absorbers, solidified materials, abrasives, etc.) - Aluminum sulfate (1000 ppm) - Boric acid components	- Particle form (Particle size: 100 to several tens of μm)	Approx. 1 [g/cm3]	90 to 95 [vol%]	Almost 0 [vol%]
2	Coagulation sediment in intermediate and final treatment filter liquid waste	High volume of particles with small particle size and low specific gravity	Sedimentation separation system inside the extension building	54 to 7 [m3/y]	0.27 to 0.035 [m3/day]	Further Increase of retrieval scale (1/3 units)	- Molten fuel - Core structures - Concrete - Other solids (earth and sand, precipitates, insoluble neutron absorbers, solidified materials, abrasives, etc.) - Aluminum sulfate (1000 ppm) - Boric acid components	- Particle form (Particle size: several tens to 0.1 μm)	Approx. 1 [g/cm3]	90 to 95 [vol%]	Almost 0 [vol%]
3	Coagulation settings in RO concentrated water	Dominated by powder adsorbents on the order of several μm	Sedimentation separation system inside the extension building	310 [m3/y]	1.6 [m3/day]	Further Increase of retrieval scale (1/3 units)	- Powder adsorbents (titanic acid, titanium silicate, activated carbon, hematite, magnetite) - High base PAC (1000 ppm)	- Particle form (Particle size: several μm)	Approx. 1 [g/cm3]	90 to 95 [vol%]	Almost 0 [vol%]

No.	Types	Candidate collection containers (unit cans, canisters, others)	Existence of collection container treatment	If “yes” in the left column, the treatment method	Form of collection into the collection container	Location of collection into the collection container	Proposed transfer route of collection container	Transfer frequency of collection container	Safety requirements when handling collection containers (including storage)
1	Coagulation sediment in coarse filter liquid waste	- Sludge collection container (Φ200 × H400) - Waste storage container	None	-	Direct collection	Sedimentation separation tank in the extension building	Transfer from the extension building through the interior of the hot cell	1 [pcs/day]	- Control shape to maintain sub-criticality - Use venting, etc. to maintain hydrogen concentration levels below the explosion lower limit
2	Coagulation sediment in intermediate and final treatment filter liquid waste	- Sludge collection container (Φ200 × H400) - Waste storage container	None	-	Direct collection	Sedimentation separation tank in the extension building	Transfer from the extension building through the interior of the hot cell	1 to 8 [pieces/day]	- Control shape to maintain sub-criticality - Use venting, etc. to maintain hydrogen concentration levels below the explosion lower limit
3	Coagulation settings in RO concentrated water	- Sludge collection container (Φ200 × H400) - Waste storage container	Yes	In technological development (target moisture content of 60 vol% or less; provisional setting)	Direct collection	Sedimentation separation tank in the extension building	Transfer from the extension building through the interior of the hot cell	111 [pcs/day]	- Control shape to maintain sub-criticality - Use venting, etc. to maintain hydrogen concentration levels below the explosion lower limit

[Information on the organization of fuel debris in a powder, slurry, or sludge form]

- **Type**
- **Characteristics**
- **Location of generation, amount generated, frequency of generation, time of generation**
- **Properties (Contained materials, shape, density, moisture content, void ratio)**
- **Candidate collection containers**
- **Existence of collection container treatment and treatment method**
- **Form of collection into collection container, collection location**
- **Collection container transfer route and transfer frequency**
- **Safety requirements when handling and storing collection containers**

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

a. Identification of targets and items to organize (7/8)

- Information on the advantages and disadvantages of drying treatment for powdery fuel debris was exchanged at joint project meetings

Items	Advantages	Disadvantages
Hydrogen countermeasures	- Since the amount of hydrogen generated can be reduced by using drying treatment to reduce the volume of water contained in fuel debris, it can be collected in collection containers (including canisters) to achieve values below the lower explosion limit of hydrogen (4 vol%).	- When fuel debris becomes clay-like due to residual moisture from insufficient drying, hydrogen pools will form in the fuel debris, and one of the following reasons could cause hydrogen concentration to rise sharply by hydrogen being suddenly discharged from hydrogen pools. ○ Vibration caused by handling fuel debris ○ Discharge caused by the hydrogen pool expansion (depends on the viscosity of fuel debris) In addition, because it is assumed that the hydrogen pools cause fluctuations in the hydrogen concentration of the gas phase section, it may be difficult to understand the amount of hydrogen generated based on results from hydrogen concentration measurements.
Confinement (Contamination)	- By reducing the volume of water contained in fuel debris through drying treatment, fuel debris can be collected in collection containers (including canisters) and handled in a sealed state, and it is also possible to suppress the discharge or radioactive materials.	- There is a possibility that the drying treatment will disperse dried radioactive materials in powder form inside the canister and clog the hydrogen discharge filter installed in the lid. - There is a possibility that an increase in the amount of dispersion of radioactive materials in powder form will require a larger off-gas treatment system. In addition, there is a possibility that the maintenance (decontamination) frequency for equipment that handles canisters such as transfer casks and storage containers will increase. - Radioactive gas (FP) could be released from fuel debris if the drying temperature is high (200 to 300℃).
Criticality	- Reducing the volume of water contained in fuel debris through drying treatment is advantageous from the viewpoint of maintaining sub-criticality.	—
Shielding	—	- Since the amount of moisture with shielding effect is reduced, less water will increase surface dose and exposure levels. - There is a possibility that dispersion of radioactive materials in powder form will increase the dose in handling areas.
Long-term integrity	- Reducing the volume of water contained in fuel debris through drying treatment can reduce the risk of corrosion during long-term storage.	—
Fire	—	- The drying treatment makes it easier for fuel debris in powder form to rise, which may increase the risk of dust fires.
Others	- The drying treatment reduces the volume of fuel debris, so storage efficiency is expected to improve. - Reducing the volume of water (ideally, completely drying) facilitates uniform solidification, which increases stability and makes it easier to estimate properties, etc. compared to non-uniform solidification when not dried or partially dried.	- Drying treatment facility (drying system, off-gas treatment system, temporary storage system (areas) suitable for drying treatment speed, etc.) is required. - There is a possibility that drying treatment will cause fuel debris in powder form to stick to the unit can and canister, making it impossible to retrieve when the final treatment method is determined.

6. Implementation details

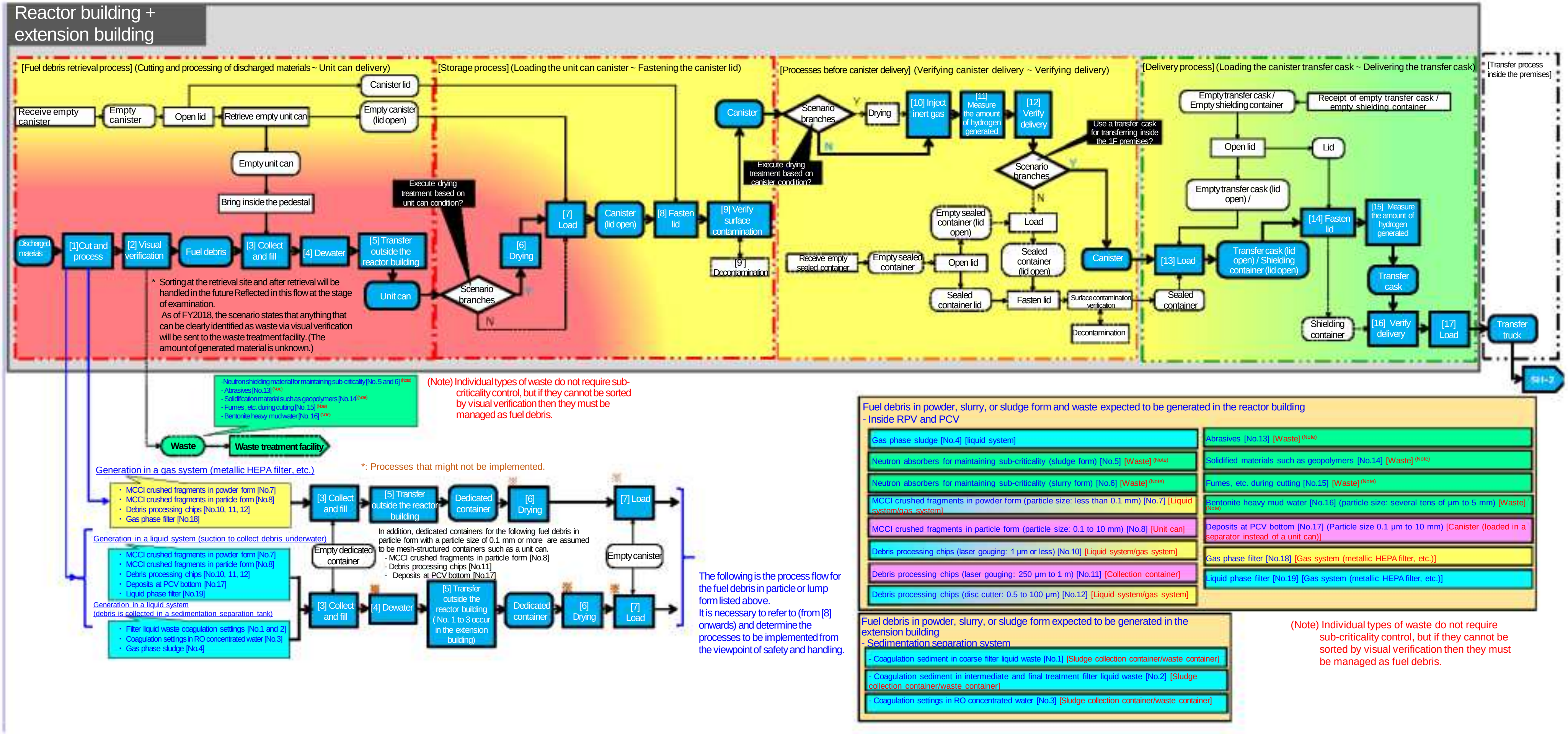
6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

a. Identification of targets and items to organize (8/8)

- Creation of a draft process flow that adds the handling of fuel debris in powder, slurry, or sludge form expected to be discharged during fuel debris retrieval to the series of processes for handling fuel debris in particle or lump form.

<Assumed process flow for fuel debris in powder, slurry, or sludge form (draft)>



* Sorting at the retrieval site and after retrieval will be handled in the future Reflected in this flow at the stage of examination. As of FY2018, the scenario states that anything that can be clearly identified as waste via visual verification will be sent to the waste treatment facility. (The amount of generated material is unknown.)

(Note) Individual types of waste do not require sub-criticality control, but if they cannot be sorted by visual verification then they must be managed as fuel debris.

*: Processes that might not be implemented.

In addition, dedicated containers for the following fuel debris in particle form with a particle size of 0.1 mm or more are assumed to be mesh-structured containers such as a unit can.
- MCCI crushed fragments in particle form [No.8]
- Debris processing chips [No.11]
- Deposits at PCV bottom [No.17]

The following is the process flow for the fuel debris in particle or lump form listed above. It is necessary to refer to (from [8] onwards) and determine the processes to be implemented from the viewpoint of safety and handling.

Fuel debris in powder, slurry, or sludge form and waste expected to be generated in the reactor building
- Inside RPV and PCV

Gas phase sludge [No.4] [liquid system]

Neutron absorbers for maintaining sub-criticality (sludge form) [No.5] [Waste] (Note)

Neutron absorbers for maintaining sub-criticality (slurry form) [No.6] [Waste] (Note)

MCCI crushed fragments in powder form (particle size: less than 0.1 mm) [No.7] [Liquid system/gas system]

MCCI crushed fragments in particle form (particle size: 0.1 to 10 mm) [No.8] [Unit can]

Debris processing chips (laser gouging: 1 μm or less) [No.10] [Liquid system/gas system]

Debris processing chips (laser gouging: 250 μm to 1 m) [No.11] [Collection container]

Debris processing chips (disc cutter: 0.5 to 100 μm) [No.12] [Liquid system/gas system]

Abrasives [No.13] [Waste] (Note)

Solidified materials such as geopolymers [No.14] [Waste] (Note)

Fumes, etc. during cutting [No.15] [Waste] (Note)

Bentonite heavy mud water [No.16] (particle size: several tens of μm to 5 mm) [Waste] (Note)

Deposits at PCV bottom [No.17] (Particle size 0.1 μm to 10 mm) [Canister (loaded in a separator instead of a unit can)]

Gas phase filter [No.18] [Gas system (metallic HEPA filter, etc.)]

Liquid phase filter [No.19] [Gas system (metallic HEPA filter, etc.)]

Fuel debris in powder, slurry, or sludge form expected to be generated in the extension building
- Sedimentation separation system

- Coagulation sediment in coarse filter liquid waste [No.1] [Sludge collection container/waste container]
- Coagulation sediment in intermediate and final treatment filter liquid waste [No.2] [Sludge collection container/waste container]
- Coagulation settings in RO concentrated water [No.3] [Sludge collection container/waste container]

(Note) Individual types of waste do not require sub-criticality control, but if they cannot be sorted by visual verification then they must be managed as fuel debris.

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

b. Evaluation/issue identification (including evaluations based on Japan and overseas investigation results) (1/6)

- Issues in each process for handling fuel debris in powder, slurry, or sludge form were identified based on the issue identification format.

<Example of issue identification based on the issue identification format>

Step			Technological elements	Concepts and policies from a technological standpoint						Proposed issues		
				Basic requirements	Considerations for the basic requirements	**Systems concepts**		**Permission and authorization (safety design) policies**				
No	Locations	Details of implementation				unit can	**Canister**	unit can	**Canister**	unit can	**Canister**	Other components (systems that handle components other than unit can and canisters)
3	Inside the reactor	Collect fuel debris with the fuel debris retrieval equipment and fill unit can	① Structure	- Structural strength shall be able to maintain the basic requirements in ② to ⑦ against loads from the assumed events.	- For the basic requirements in ② to ⑦, guarantee either the unit can, canister, transfer cask, storage container, or cell.	- Although the structure should be able to maintain the basic requirements of ② and ⑤, if the unit can is stored within the canister, it will be maintained by the canister.	—	- Although it is assumed that system redundancies, etc. will prevent the assumed events such as overturning or falling during handling and the policy is not to consider them, a structural strength evaluation must be conducted if becomes necessary to consider them.	—	- The current unit can structure proposal uses a mesh structure for dewatering, making it difficult to collect fuel debris in slurry or sludge form. - Since the current unit can structure proposal does not have a lid (the upper part is open), vibrations or shaking may cause fuel debris in slurry or sludge form collected inside the unit can to spill out of the unit can.	—	—
			② Heat removal	- Fuel debris shall not melt from decay heat. - Heat removal functions shall be able to maintain the basic requirements of ① and ③ to ⑦.	- The cells within the building have sufficient ventilation capacity to remove decay heat inside the unit can.	- Because the amount of heat generated is small and heat is removed by ventilation, active heat removal is not guaranteed.	—	- The amount of heat generated by fuel debris is considered to be small, so verify that ventilation can satisfy the permissible temperature for melting fuel debris, etc.	—	- The amount of heat generated by fuel debris is small and the ventilation should be able to remove it, but verify that there are no significant issues on the heat removal side.	—	**<Building issues>** Verify that there are no significant issues in using building ventilation to ensure the permissible temperature for melting fuel debris, etc. (Since the amount of heat generated is considered to be small, it is thought that no significant issues exist.)
			③ Confinement (Contamination)	- Leakage of radioactive materials shall be prevented.	- The cells within the building have sufficient confinement performance to prevent contamination (confinement).	- The unit can does not guarantee confinement performance.	—	- The unit can does not guarantee confinement performance.	—	- There is no issue because the confinement performance is not guaranteed.	—	**<Building (hot cell) issues>** - Dried debris in powder form discharged outside the unit can is likely to be dispersed and it may be necessary to strengthen confinement performance inside the hot cell. (However, other projects are examining the handling of fuel debris in powder form inside the reactor, so it may not be an issue.)
			④ Shielding	- The necessary shielding capabilities shall be in place to prevent radiation sickness.	- Cell shielding is designed to prevent radiation exposure to radiation personnel and the general public caused by radiation emitted from debris. - Because the cell bears primary responsibility shielding functions, the thickness of the canister should be the thickness required from the perspective of structure, etc..	- There is no particular guarantee as it is provided by the cell boundary.	—	- There is no particular guarantee as it is provided by the cell boundary.	—	- No issue exists because there is no guarantee	—	**<Building (hot cell) issues>** Verify the shielding guarantee at the cell boundary. (However, other projects are examining the handling of fuel debris in powder form inside the reactor, so it may not be an issue.)
			⑤ Criticality	- There shall be no risk of fuel debris reaching criticality.	- Maintain sub-criticality in the unit can geometrical shape. - Maintain sub-criticality even in the event of spillage, etc.	- Maintain sub-criticality in the unit can geometrical shape. - It is assumed that measures will be taken on the equipment end to prevent the unit can from overturning.	—	- Maintain sub-criticality in the unit can geometrical shape.	—	- Verify the validity of the unit can's assumed dimensions with respect to criticality evaluation conditions (debris distribution, arrangement, etc.)	—	- Verify that measures will be taken on the equipment end to prevent overturning with the handling of unit can.
			⑥ Hydrogen	- Hydrogen explosion shall be prevented.	- Maintain hydrogen concentration inside fuel debris collection, transfer, and storage containers below the lower explosion limit of 4 vol.%.	- Hydrogen is constantly discharged inside the reactor when the unit can is not covered, so maintain hydrogen concentration below the lower explosion limit of 4 vol.% by ventilating the inside of the reactor. - When the unit can is covered, conduct hydrogen diffusion evaluations, etc. to verify that hydrogen generated in the unit can is discharged properly.	—	- When the unit can is not covered, hydrogen concentration will be maintained by ventilating the inside of the reactor. - When the unit can is covered, hydrogen concentration will be maintained by ventilating the inside of the reactor. Conduct hydrogen diffusion evaluations, etc. as necessary to verify that hydrogen generated in the unit can is below the lower explosion limit of 4 vol.%.	—	- As fuel debris becomes finer, the contribution rate of α-rays, which have a large impact on water radiolysis, increases, and there is a possibility that the amount of hydrogen generated will increase compared to the currently assumed particle size of 0.1 mm or larger. - There is no problem because the current unit can structure proposal does not have a lid (the top is open), but if it is changed to one with a lid (sealed), it may be difficult to achieve hydrogen concentration of less than 4 vol% in the unit can. - Because fuel debris in slurry or sludge form is viscous, it is possible that hydrogen pools will form in the interior and intermittently discharge hydrogen, causing hydrogen concentration in the gas phase section inside the unit can to rise suddenly.		
			⑦ Fire	- Fires shall be prevented from occurring.	- Fires are prevented by creating an inert gas atmosphere inside the reactor.	- Fires are prevented by creating an inert gas atmosphere inside the reactor. - The high moisture content of fuel debris is expected to suppress dust fires.	—	- Fires are prevented by creating an inert gas atmosphere inside the reactor.	—	- There is no issue, because fuel debris in slurry or sludge form contains moisture and so will suppress dust fires.	—	—
			⑧ Measuring	Measures for the material accountancy and protection of nuclear fuel materials shall be enacted.	- Material accountancy will not be conducted when handling unit cans that have collected fuel debris. (material accountancy will be conducted after loading into the canister)	- All efforts will be made to design the unit can so that fuel debris does not spill.	—	—	—	- There is no issue because material accountancy is not conducted with the unit can.	—	**<Issues with material accountancy and nuclear fuel material measuring equipment>** - It is possible that measuring nuclear fuel materials (including fuel debris in slurry or sludge form) collected in the canister may not be correct because of other materials such as concrete and moisture contained in the fuel debris. (However, other projects are examining methods for measuring nuclear materials, so it may not be an issue.)
			⑨ Long-term integrity	- The basic requirements of ① to ⑧ shall be able to be maintained even when accounting for aging.	- There is no problem with material integrity caused by corrosion, etc. of structural components in the environment during handling.	- Select materials that can maintain structural integrity for the expected unit can usage environment.	—	- Select materials (SUS316L, etc.) considering environmental conditions and use analysis and testing to evaluate integrity.	—	- The retrieval period is short and corrosion risk is not assumed to materialize.	—	**<Building (hot cell) and related component issues>** - There is the possibility of problems with material integrity caused by corrosion, etc. of structural components in the environment during handling. (However, other projects are examining the handling of fuel debris in powder form inside the reactor, so it may not be an issue.)
			⑩ Other necessary items for handling operations	- The necessary functions for fuel debris retrieval and collection shall be in place.								

Yellow markers indicate issues selected from issues (draft) for each fuel debris handling process (32 processes)

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

b. Evaluation/issue identification (including evaluations based on Japan and overseas investigation results) (2/6)

<Main issues identified involving the storage of fuel debris in powder, slurry, or sludge form>

[Target equipment: unit can (unit can)]

Items	Selected issues	Proposed measures	Technological issues, solution phase, and solution period [Note1]
Structure	- Since the current unit can structure proposal uses a mesh structure for dewatering, it is difficult to collect fuel debris in powder, slurry, or sludge form (hereinafter referred to as “powdery fuel debris”).	- Study of containers without mesh structure interiors for filling powdery fuel debris.	- Study of container interiors for powdery fuel debris (alternative containers for unit can) ⇒ **Study of using related subsidy project (drying project) and subsidy project starting in 2022*** * It is also necessary to examine the safety requirements for handling unit cans and canisters in related subsidy projects that are reviewing the discharge of fuel debris in powder, slurry, or sludge form.
	- Since the current unit can structure proposal does not have a lid (the upper part is open), powdery fuel debris may spill out during handling.	- Implement countermeasures to prevent spills, such as a unit can structure with a lid.	
	- Because powdery fuel debris has a very small particle size, it is difficult to dewater by having water fall from the unit can’s mesh part via gravity.	- Develop drying procedures or dewatering methods because it is difficult to dewater via gravity.	- Study of drying systems for powdery fuel debris ⇒ **Study of using related subsidy project (drying project)**
Hydrogen	- In case of fine fuel debris, the contribution rate of α-rays, which have a large impact on water radiolysis, increases, and there is a possibility that the amount of hydrogen generated will increase compared to the currently assumed particle size of 0.1 mm or larger.	- Verify whether the amount of hydrogen generated from powdery fuel debris is greater than that from fuel debris in particle or lump form. - Study of the discharge characteristics of hydrogen generated from powdery fuel debris. - Measure hydrogen concentration and determine the subsequent handling methods (reducing the amount of collection, etc.) based on results of actual measurements.	- Study of the amount of hydrogen generated and hydrogen discharge characteristics of powdery fuel debris ⇒ **Study of using subsidy project starting in FY2022 and actual machine engineering** - Study of methods for measuring hydrogen concentration in powdery fuel debris ⇒ **Study of using actual machine engineering**
	- Because powdery fuel debris is viscous, it is possible that hydrogen pools will form in the interior and intermittently discharge hydrogen, causing hydrogen concentration in the gas phase section inside the unit can to rise suddenly.	- Study of the discharge characteristics of hydrogen generated from powdery fuel debris.	- Study of discharge characteristics of hydrogen generated from powdery fuel debris ⇒ **Study of using subsidy project starting in FY2022 and actual machine engineering**
	- If the unit can is changed to the one with a lid (sealed), it may be difficult to achieve hydrogen concentration of less than 4 vol% in the unit can.	- If unit can structure will have a lid, examine using a lid with a vent.	- Study of container interiors for powdery fuel debris (alternative containers for unit can) ⇒ **Study of using related subsidy project (drying project) and subsidy project starting in FY2022**

Note 1: - Related subsidy project (drying project) : Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)
- Subsidy project starting in FY2022 : Development of Technologies for Containing, Transfer, and Storage of Fuel Debris
(development of the necessary technologies to the storage of fuel debris in powder, slurry, or sludge form)
- Actual machine engineering : Study of after the characterization of fuel debris in powder form*
(*in the subsidy project, the properties of fuel debris in powder form were examined under assumed conditions)

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

b. Evaluation/issue identification (including evaluations based on Japan and overseas investigation results) (3/6)

<Main issues identified involving the storage of fuel debris in powder, slurry, or sludge form>
[Target equipment: canister] (1/2)

Items	Selected issues	Proposed measures	Technological issues, solution phase, and solution period Note1
Structure	- When powdery fuel debris is dried, drying could blow the finely powdered fuel debris and disperse it inside the cell, increasing contamination. In addition, because the fine powder passes through the canister's vent filter, the risk of the canister filter clogging could increase.	- Development of a method for solidifying powdery fuel debris that becomes finer powder after drying treatment. However, considering final disposal, a reversible solidification method is required.	- Study of a solidification method for powdery fuel debris ⇒ **Study of using subsidy projects (TBD) or actual machine engineering**
Confinement (Contamination)	- When powdery fuel debris is dried, drying could blow the finely powdered fuel debris, which could then pass through the canister's vent filter, resulting in high radiation contamination of the drying equipment and the equipment that handles the canister.	- Evaluation of the behavior of fine powdery fuel debris during drying treatment (e.g., floating up) and the amount of filter clogging and material that passes through.	- Study of the dispersion characteristics of powdery fuel debris in canisters during drying ⇒ **Study of using subsidy project starting in FY2022**
		- Study of a drying method to suppress the amount of powdery fuel debris that the fuel debris can pass through the filter, or containing and handling methods that do not involve drying treatment (such as a packaging method for stable storage).	- Study of drying systems for powdery fuel debris ⇒ **Study of using related subsidy project (drying project) and subsidy project starting in FY2022** - Study of handling methods (packaging methods) for powdery fuel debris ⇒ **Study of using subsidy project starting in FY2022**
Hydrogen	- When fuel debris becomes fine, the contribution rate of α-rays, which have a large impact on water radiolysis, increases, and there is a possibility that the amount of hydrogen generated will increase compared to the currently assumed particle size of 0.1 mm or larger. - Because powdery fuel debris is viscous, it is possible that hydrogen pools will form in the interior and intermittently discharge hydrogen, causing hydrogen concentration in the gas phase section inside the canister to rise suddenly.	- Response to hydrogen generation by using the canister, which is the same measure using the unit can. (See No. 37)	- Response to hydrogen generation by using the canister, which is the same measure to solve technological issues of the unit can at the period of solution. (See No. 37)

Note 1: - Related subsidy project (drying project) : Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)
- Subsidy project starting in FY2022 : Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (development of the necessary technologies to the storage of fuel debris in powder, slurry, or sludge form)
- Subsidy project (TBD) : A subsidy project not currently planned that may be conducted in the future
- Actual machine engineering : Study of after the characterization of fuel debris in powder form*
(*in the subsidy project, the properties of fuel debris in powder form were examined under assumed conditions)

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

b. Evaluation/issue identification (including evaluations based on Japan and overseas investigation results) (4/6)

<Main issues identified involving the storage of fuel debris in powder, slurry, or sludge form>
[Target equipment: canister] (2/2)

Items	Selected issues	Proposed measures	Technological issues, solution phase, and solution period Note1
Fire	- The risk of dust fires may increase when drying powdery fuel debris because drying makes it easier for fuel debris to rise.	- Maintaining of an inert gas atmosphere inside the cell.	- Study of the atmosphere inside cells for handling powdery fuel debris ⇒ **Study of using actual machine engineering**
		- Development of a method to solidify powdery fuel debris that becomes finer powder after drying treatment. However, considering final disposal, a reversible solidification method is required.	- Study of a solidification method for powdery fuel debris ⇒ **Study of using subsidy projects (TBD) or actual machine engineering**
Measuring	- Depending on the properties of the powdery fuel debris collected in the canister, nuclear fuel materials may be discharged outside the canister, making appropriate material accountancy impossible.	- Study of material accountancy procedures based on nuclear fuel materials being discharged outside the canister.	- Study of material accountancy procedures for canisters ⇒ **Study of using actual machine engineering**
Long-term integrity	- Short-term handling, such as transfer using canisters (material SUS316L) collecting powdery fuel debris, is considered to have a low risk of corrosion, but with long-term storage, environmental conditions like temperature, residual water, and moisture within ingredients increases the risk of canister corrosion.	- Evaluation of the possibility of canister corrosion occurring, factoring in the storage method and environment assumed during long-term storage of powdery fuel debris. If there is a risk of corrosion occurring, countermeasures such as corrosion control are considered.	- Study of assumed environment and corrosion countermeasures during long-term storage of powdery fuel debris ⇒ **Study of using subsidy projects (TBD) or actual engineering**

Note 1:

- Related subsidy project (drying project)	**: Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)**
- Subsidy project starting in FY2022	**: Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (development of the necessary technologies to the storage of fuel debris in powder, slurry, or sludge form)**
- Subsidy project (TBD)	**: A subsidy project not currently planned that may be conducted in the future**
- Actual machine engineering	**: Study of after the characterization of fuel debris in powder form* (*in the subsidy project, the properties of fuel debris in powder form were examined under assumed conditions)**

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

b. Evaluation/issue identification (including evaluations based on Japan and overseas investigation results) (5/6)

<Main issues identified involving the storage of fuel debris in powder, slurry, or sludge form>

[Target equipment: other equipment]

Items	Selected issues	Proposed measures	Technological issues, solution phase, and solution period Note1
Structure	- The flow of drying gas could disperse a large amount of fine powder inside the unit can into the drying equipment (including the exhaust gas treatment system).	- Drying treatment at a slow flow rate that does not disperse fine powder. - Assuming that a large amount of fine powder is dispersed, develop equipment where filters can be replaced quickly and remotely, with a multi-line filter configuration.	- Study of drying systems for powdery fuel debris ⇒ **Study of using related subsidy project (drying project) or actual machine engineering** - Study of the dispersion characteristics of powdery fuel debris in canisters during drying ⇒ **Study of using subsidy project starting in FY2022** - Study of the system of each component and the dispersion characteristics of fine powdery fuel debris within each component ⇒ **Study of using actual machine engineering**
	- When powdery fuel debris is dried, a large amount of fine powder within a canister could be dispersed inside handling components (transfer casks, storage containers, etc.) and equipment used in preparing canisters (inert gas injection equipment, hydrogen concentration measuring equipment, etc.).	- Development of a method to solidify powdery fuel debris that becomes finer powder after drying treatment. However, considering final disposal, a reversible solidification method is required.	- Study of a solidification method for powdery fuel debris ⇒ **Study of using subsidy projects (TBD) or actual machine engineering**
Confinement (Contamination)	- When powdery fuel debris is dried, a large amount of fine powder within a canister could disperse inside canister handling areas (expansion building hot cells, etc.) and handling components (transfer casks, storage containers, etc.), possibly creating high radiation contamination.	- Evaluation of the behavior (floating up, etc.) of fine powdery fuel debris during drying treatment. Based on the results of these evaluations, the confinement performance of each area and component, countermeasures to prevent the spread of contamination, maintenance methods, etc. are considered.	- Study of the dispersion characteristics of powdery fuel debris in each area and component, and the confinement performance, countermeasures to prevent the spread of contamination, and maintenance methods ⇒ **Study of using actual machine engineering**
Hydrogen	- As fuel debris becomes finer, the contribution rate of α-rays, which have a large impact on water radiolysis, increases, and there is a possibility that the amount of hydrogen generated will increase compared to the currently assumed particle size of 0.1 mm or larger. - Because powdery fuel debris is viscous, it is possible that hydrogen pools will form in the interior and intermittently discharge hydrogen, causing hydrogen concentration in the gas phase section inside each component to rise suddenly.	- Response to hydrogen generation by using the canister, which is the same measure using the unit can. (See No. 37)	- Response to hydrogen generation by using the canister, which is the same measure to solve technological issues of the unit can at the period of solution. (See No. 37)

Note 1: - Related subsidy project (drying project) : Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)
- Subsidy project starting in FY2022 : Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (development of the necessary technologies to the storage of fuel debris in powder, slurry, or sludge form)
- Subsidy project (TBD) : A subsidy project not currently planned that may be conducted in the future
- Actual machine engineering : Study of after the characterization of fuel debris in powder form*
(*in the subsidy project, the properties of fuel debris in powder form were examined under assumed conditions)

6. Implementation details

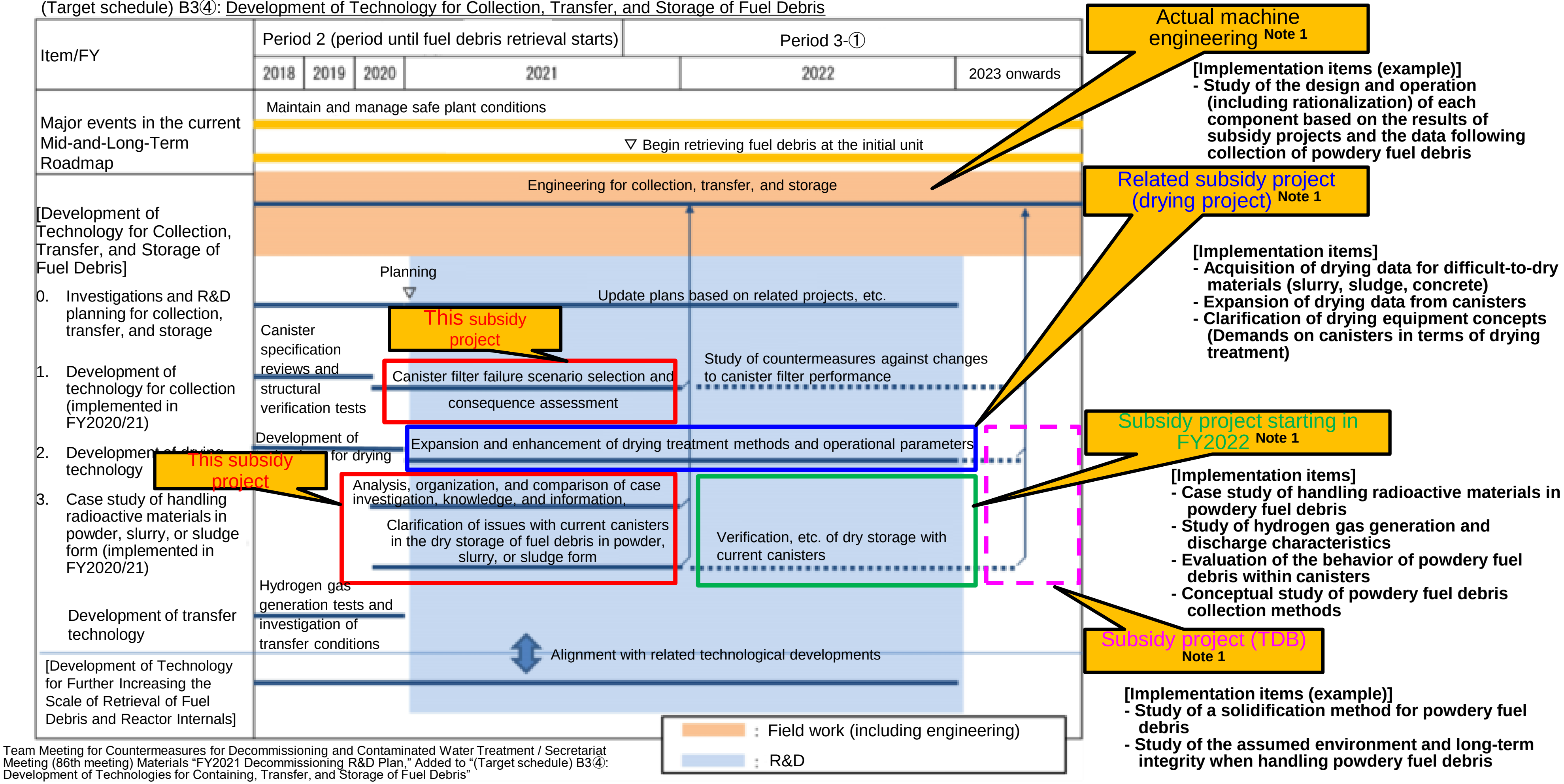
6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

③ Implementation items and results

b. Evaluation/issue identification (including evaluations based on Japan and overseas investigation results) (6/6)

- The solution phase and solution period for the selected issues are shown below.

(Target schedule) B3④: Development of Technology for Collection, Transfer, and Storage of Fuel Debris



Actual machine engineering Note 1

[Implementation items (example)]
- Study of the design and operation (including rationalization) of each component based on the results of subsidy projects and the data following collection of powdery fuel debris

Related subsidy project (drying project) Note 1

[Implementation items]
- Acquisition of drying data for difficult-to-dry materials (slurry, sludge, concrete)
- Expansion of drying data from canisters
- Clarification of drying equipment concepts (Demands on canisters in terms of drying treatment)

Subsidy project starting in FY2022 Note 1

[Implementation items]
- Case study of handling radioactive materials in powdery fuel debris
- Study of hydrogen gas generation and discharge characteristics
- Evaluation of the behavior of powdery fuel debris within canisters
- Conceptual study of powdery fuel debris collection methods

Subsidy project (TBD) Note 1

[Implementation items (example)]
- Study of a solidification method for powdery fuel debris
- Study of the assumed environment and long-term integrity when handling powdery fuel debris

Team Meeting for Countermeasures for Decommissioning and Contaminated Water Treatment / Secretariat Meeting (86th meeting) Materials "FY2021 Decommissioning R&D Plan," Added to "(Target schedule) B3④: Development of Technologies for Containing, Transfer, and Storage of Fuel Debris"

Note 1:

- Related subsidy project (drying project)	**: Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)**
- Subsidy project starting in FY2022	**: Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (development of the necessary technologies to the storage of fuel debris in powder, slurry, or sludge form)**
- Subsidy project (TBD)	**: A subsidy project not currently planned that may be conducted in the future**
- Actual machine engineering	**: Study of after the characterization of fuel debris in powder form* (*in the subsidy project, the properties of fuel debris in powder form were examined under assumed conditions)**

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

④ Contribution of outcomes to relevant study areas

The results of identification of issues related to the storage of fuel debris in powder, slurry, or sludge form were summarized to contribute to the clarification of technological issues to resolve in order to ensure the necessary safety functions and implement long-term stable storage. For example, reference information on the drying and storage of sludge.

⑤ Analysis with respect to the on-site applicability

Solving the technological issues related to the storage of fuel debris in powder, slurry, or sludge form assumed to be collected during fuel debris retrieval is beneficial because it will lead to technologies that can be applied on-site.

⑥ Goal achievement level

It can be concluded that TRL Level 1 was achieved as planned because the following indicator to judge goal achievement was satisfied:

- Identification of issues involving safe, reliable, and rational storage conditions when using a canister for dry storing fuel debris similar to that for fuel debris in particle or lump form.

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

⑦ Issues to be addressed

Issues and countermeasures for each process up to storage were examined for dry storage of fuel debris using similar canisters to those used for fuel debris in particle or lump form, and the following technological issues to resolve were clarified.
(See No. 37 to 40)
In addition, related subsidy project and the continuation project of this subsidy project are planned to solve the above technological issues after FY2022.

[Technological issues]

- ✓ Study of the interior of containers for powdery fuel debris (alternative containers for unit can)
- ✓ Study of the amount of hydrogen generated and the discharge characteristics of hydrogen generated from powdery fuel debris
- ✓ Study of methods for measuring hydrogen concentration in powdery fuel debris
- ✓ Study of drying systems for powdery fuel debris
- ✓ Study of the dispersion characteristics of powdery fuel debris in canisters during drying
- ✓ Study of the systems in each component
- ✓ Study of the dispersion characteristics of powdery fuel debris in each area and component, and the confinement performance, countermeasures to prevent the spread of contamination, and maintenance methods
- ✓ Study of handling methods (collection methods) for powdery fuel debris
- ✓ Study of the atmosphere inside cells for handling of powdery fuel debris
- ✓ Study of assumed environment and corrosion countermeasures during long-term storage of powdery fuel debris
- ✓ Study of material accountancy procedures for canisters
- ✓ Study of a solidification method for powdery fuel debris

6. Implementation details

6.2 Identifying issues involving the storage of fuel debris in powder, slurry, or sludge form

⑧ Summary

- To comprehensively identify issues involved in safe and long-term stable storage of fuel debris in power, slurry, or sludge form, evaluation items and organizational methods for a series of handling processes and the canisters for particulate or lump-shaped fuel debris were studied and the issue identification format was created .

- Information was exchanged at joint meetings with the related project, and information involving fuel debris in powder, slurry, or sludge form expected to be discharged during fuel debris retrieval was organized.

- Based on the above information and issue identification format, the technological issues related to the storage of fuel debris in powder, slurry, or sludge form as well as their solution phases and solution periods were clarified.

- Related subsidy project and the continuation project this subsidy project are planned to solve the above technological issues after FY2022.

6. Implementation details

6.3 Performance assessment of canister filters

① Purposes and goals

Although it is assumed that the powdery fuel debris collected in canisters alongside fuel debris in particle or lump form will be blown around the inside of the canister during various handling and treatments (drying treatment, inspection, measurement, etc.) until final storage in a storage facility, designs are progressing so that this dust will be captured by a filter installed on the lid of the canister. Depending on the amount of powdery fuel debris captured, the flow rate of hydrogen gas discharged outside the canister may decrease, or in the worst case scenario, the canister may become clogged and the concentration of hydrogen gas inside the canister may exceed the standard value.

In addition to the verification of the required specifications for filters that has been studied in the related R&D project, “Development of Technologies for Containing, Transfer, and Storage of Fuel Debris,” a broad range of the required specifications is reverified under this project. Concepts of selecting filters that are being considered and consistency with evaluation results of the filters are examined.

Furthermore, failure scenarios (i.e., corrosion, etc.) that impact filter performance are selected and test conditions for evaluating those scenarios are considered.

② Comparison with existing technology

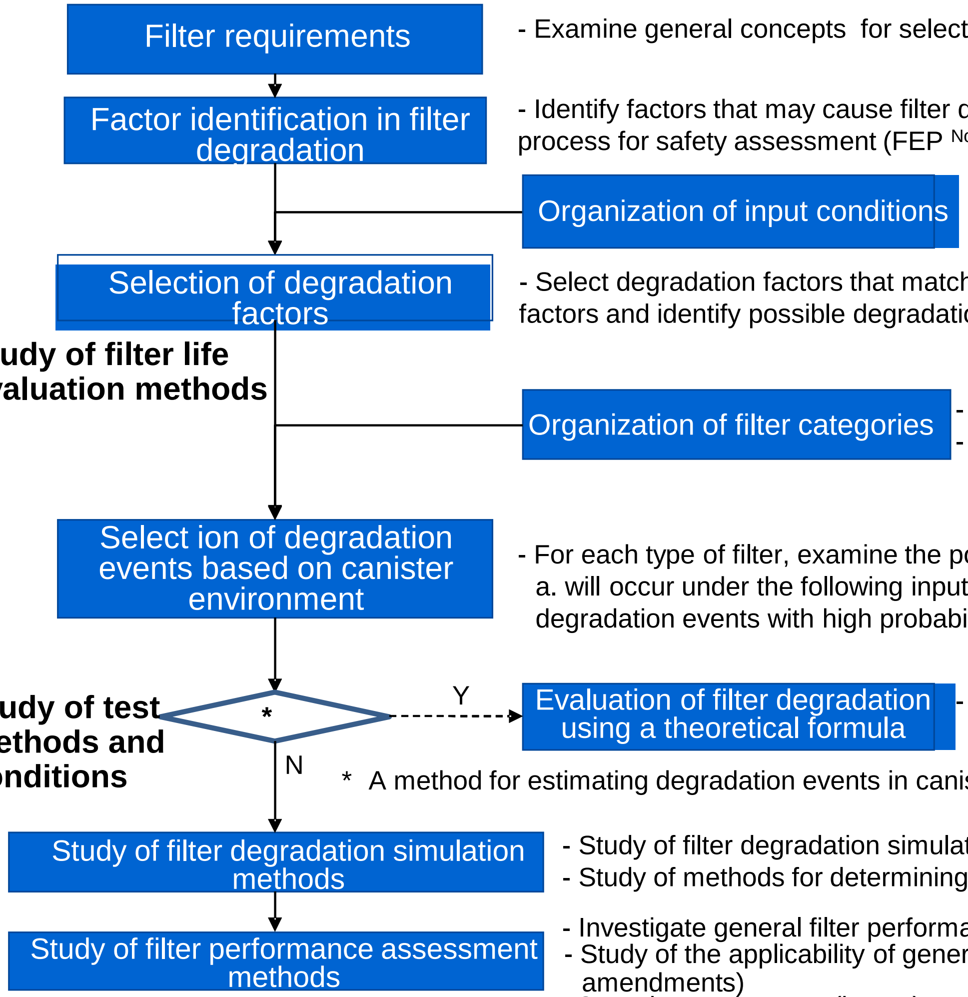
The TMI-2 case study of vent filters was conducted to acquire knowledge, but information on the effects of degradation due to a long-term use on filter performance is insufficient.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

Setting of a study flow and study of each implementation item



a. Identification of environments/conditions

Filter requirements

- Examine general concepts for selecting filter specifications

Factor identification in filter degradation

- Identify factors that may cause filter degradation by referring to the scenario development process for safety assessment (FEP Note 1) used in designing disposal facilities

Organization of input conditions

- Refer to and organize the environment, fuel debris properties, and canister specifications as input conditions from past projects (canisters and fuel debris properties)

Selection of degradation factors

- Select degradation factors that match input conditions from among filter degradation factors and identify possible degradation events

b. Study of filter life evaluation methods

Organization of filter categories

- Sort general filter properties
- Sort necessary requirements for evaluating each filter life

Select ion of degradation events based on canister environment

- For each type of filter, examine the possibility that the degradation events identified in a. will occur under the following input conditions from retrieval to storage, and select degradation events with high probability of occurring

c. Study of test methods and conditions

Evaluation of filter degradation using a theoretical formula

- Use a theoretical formula to evaluate filter performance affected by degradation from retrieval to storage

* A method for estimating degradation events in canister environments has been established

Study of filter degradation simulation methods

- Study of filter degradation simulation methods
- Study of methods for determining the degree of degradation

Study of filter performance assessment methods

- Investigate general filter performance assessment methods (JIS, etc.)
- Study of the applicability of general methods (inapplicable ⇒ consider amendments)
- Organize parameters (inputs) and issues required for testing

Note 1:

A method of organizing individual events by summarizing scenario characteristics (Feature), events (Event), and processes (Process) in a list

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (1/11)

(i) Filter requirements

- Functions that confine fuel debris particles

→ Selected a filter with a capture rate that can guarantee the set DF for the fuel debris particle size to be captured.

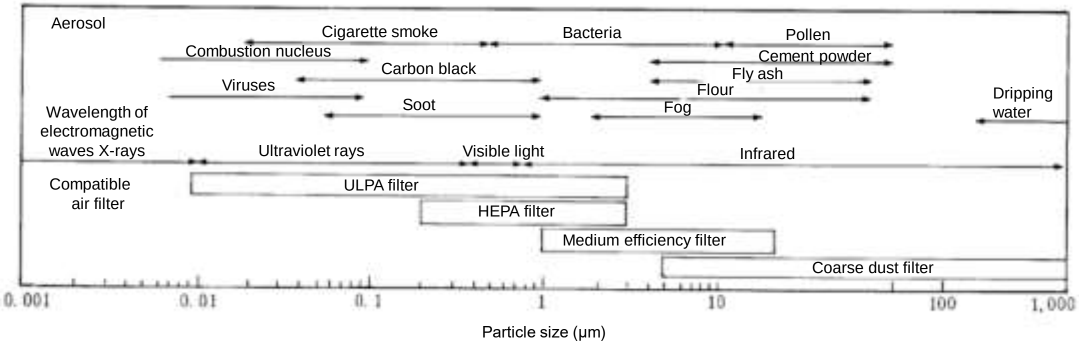


Figure 1 Filter unit performance and particle size captured Note 1

- Functions that release hydrogen generated by water radiolysis

→ Selected a filter with a hydrogen permeation performance that allows the generated hydrogen to escape by diffusion so that hydrogen concentration in the canister remain below the lower explosion limit (4 vol% or less at room temperature and pressure).

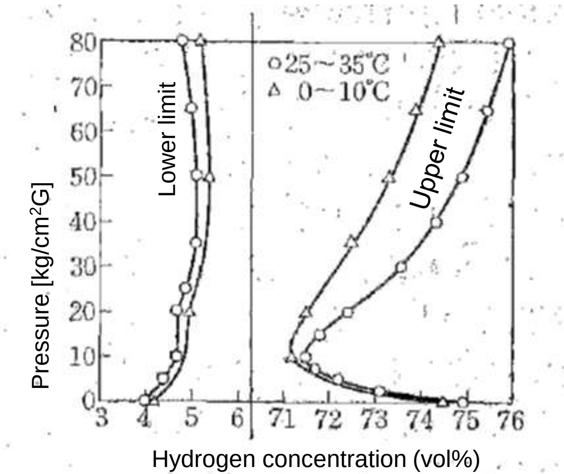


Figure 2 Flammability limit of binary hydrogen-air system Note 2

Note 1: Kamishima, "Performance of Air Filter Units" Aerosol Research Vol.4, No.4 (1989)
Note 2: Yagyu et al., "Effect of High Pressure on the Flammability Limits of Hydrogen," Safety Engineering Vol.8, No.5 (1969)

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (2/11)

(ii) Identifying factors in filter degradation

- Arranged into 5 environmental categories with regard to the scenario development process for safety assessment (FEP)
(radiation environment, thermal environment, stress environment, chemical environment, external environment)
- Arranged possible causes and events of filter degradation for each environmental category

Environmental category	Cause	Events	Event details	Degradation mode
Radiation environment	Radiolysis	Hydrogen generation	Radiolysis of fuel debris generates hydrogen and particles are blown into the atmosphere, clogging the filter.	Clogged
			Radiolysis of fuel debris generates hydrogen and particles are blown into the atmosphere, clogging the filter and thereby increasing internal pressure and filter damage.	Damaged
		Embrittlement	Prolonged exposure to hydrogen generated by the radiolysis of the water that accompanies waste causes hydrogen embrittlement and filter damage.	Damaged
	Radiation	Radiation degradation	Radiation of fuel debris causes filter material to degrade and become damaged.	Damaged
Thermal environment	Decay heat	Thermal alteration	The temperature of fuel debris rises due to decay heat and heat conduction causes the temperature of the filter to rise, resulting in thermal alteration and filter damage.	Damaged
		Thermal deformation (container)	The temperature of fuel debris rises due to decay heat and heat conduction causes the temperature of the container to rise, exerting stress on and damaging the affixed filter.	Damaged
		Thermal convection	Thermal convection causes powder of fuel debris to rise in the atmosphere and clog the filter.	Clogged
Stress environment	Vibration during transportation or from an earthquake	Impact	Impacts such as collisions and drops during transportation or earthquakes can deform or damage the container and filter, resulting in the loss of filter functionality.	Damaged
		Dust generated by vibration	Vibrations caused by transportation or earthquakes cause fuel debris particles to rise and clog the filter.	Clogged
Chemical environment	Corrosion	Thickness reduction	Corrosive substances attaching to the filter cause corrosion and wastage.	Damaged
		Oxide film generation	Corrosion on the surface of filter fibers causes an oxide film to form, which increases fiber diameter (decreases pore diameter) and results in clogging.	Clogged
		Salt precipitation	Prolonged exposure to vapors containing corrosive substances causes the accumulation of corrosive substances on the filter, resulting in clogging.	Clogged
		Electric corrosion	A potential difference is created between the filter and the contact surface of the container or metal fuel debris, resulting in electric corrosion of the filter and weakening or damage.	Damaged
External environment	Differences between the canister interior and the outside environment	Microbial membrane	Microorganisms such as mold grow inside and outside the filter, forming a biofilter that clogs the filter and prevents hydrogen permeation.	Clogged
		Water film	Temperature differences between the inside and outside of the filter cause a film of water to form on the surface of the filter that clogs the filter and prevents hydrogen permeation.	Clogged
		Aerosol deposition	Aerosols such as sea salt particles are dispersed and deposited on the outer surface of the filter, clogging it.	Clogged
		Powder dispersion	Pressure differences between the inside and outside of the filter generate an air flow, causing powder to fly around and clog the filter.	Clogged
	UV in the environment	UV degradation	UV in the environment degrades and damages filter material.	Damaged

17 degradation events in total were identified.

6. Implementation details

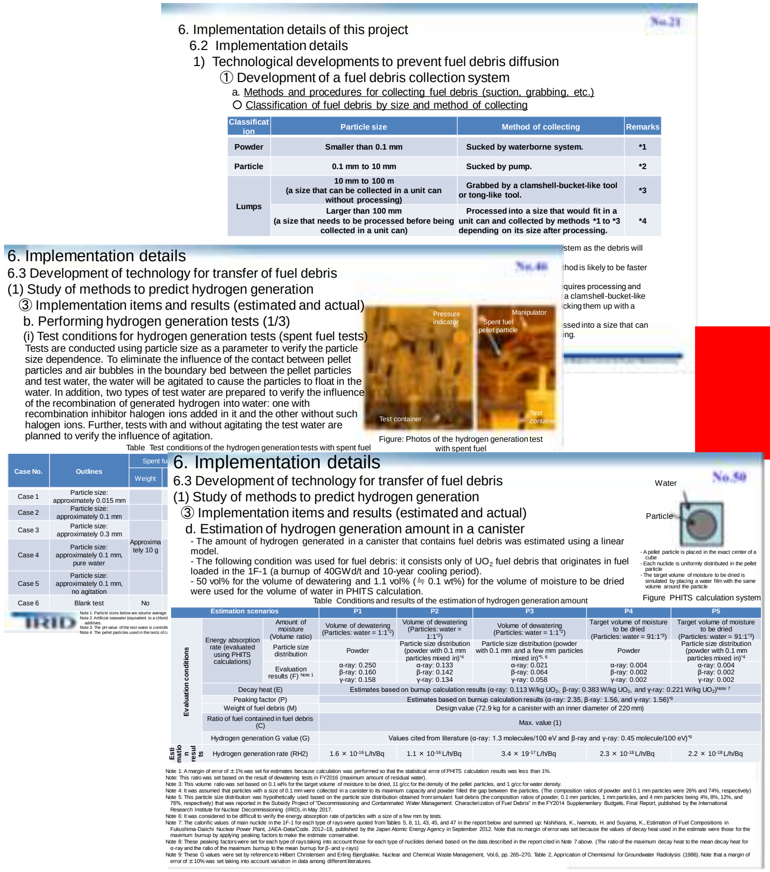
6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (3/11)

(iii) Organization of input conditions (1/3)

Input conditions (fuel debris properties, container specifications, environment conditions inside and outside canisters) were identified from information in past projects.



6. Implementation details of this project

6.2 Implementation details

1) Technological developments to prevent fuel debris diffusion

① Development of a fuel debris collection system

a. Methods and procedures for collecting fuel debris (suction, grabbing, etc.)

○ Classification of fuel debris by size and method of collecting

Classification	Particle size	Method of collecting	Remarks
Powder	Smaller than 0.1 mm	Sucked by waterborne system.	*1
Particle	0.1 mm to 10 mm	Sucked by pump.	*2
Lumps	10 mm to 100 m (a size that can be collected in a unit can without processing)	Grabbed by a clamshell-bucket-like tool or tong-like tool.	*3
	Larger than 100 mm (a size that needs to be processed before being collected in a unit can)	Processed into a size that would fit in a unit can and collected by methods *1 to *3 depending on its size after processing.	*4

stem as the debris will

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quires processing and a clamshell-bucket-like cking them up with a

ssed into a size that can ing.

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. Performing hydrogen generation tests (1/3)

(i) Test conditions for hydrogen generation tests (spent fuel tests)

Tests are conducted using particle size as a parameter to verify the particle size dependence. To eliminate the influence of the contact between pellet particles and air bubbles in the boundary bed between the pellet particles and test water, the water will be agitated to cause the particles to float in the water. In addition, two types of test water are prepared to verify the influence of the recombination of generated hydrogen into water: one with recombination inhibitor halogen ions added in it and the other without such halogen ions. Further, tests with and without agitating the test water are planned to verify the influence of agitation.

Pressure indicator

Manipulator

Spent fuel pellet particle

Test container

Test container

Figure: Photos of the hydrogen generation test with spent fuel

Table Test conditions of the hydrogen generation tests with spent fuel

Case No.	Outlines	Spent fu
		Weight
Case 1	Particle size: approximately 0.015 mm	
Case 2	Particle size: approximately 0.1 mm	
Case 3	Particle size: approximately 0.3 mm	Approximately 10 g
Case 4	Particle size: approximately 0.1 mm, pure water	
Case 5	Particle size: approximately 0.1 mm, no agitation	
Case 6	Blank test	No

Note 1: Particle sizes below are volume average

Note 2: Artificial seawater (equivalent to a chlorid additives.

Note 3: The pH value of the test water is controlle

Note 4: The pellet particles used in the tests of c

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)

d. Estimation of hydrogen generation amount in a canister

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

Water

Particle

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

Figure PHITS calculation system

Table Conditions and results of the estimation of hydrogen generation amount

Estimation scenarios			P1	P2	P3	P4	P5
Evaluation conditions	Energy absorption rate (evaluated using PHITS calculations)	Amount of moisture (Volume ratio)	Volume of dewatering (Particles: water = 1:1*2)	Volume of dewatering (Particles: water = 1:1*2)	Volume of dewatering (Particles: water = 1:1*2)	Target volume of moisture to be dried (Particles: water = 91:1*3)	Target volume of moisture to be dried (Particles: water = 91:1*3)
		Particle size distribution	Powder	Particle size distribution (powder with 0.1 mm particles mixed in)*4	Particle size distribution (powder with 0.1 mm and a few mm particles mixed in)*5, 6	Powder	Particle size distribution (powder with 0.1 mm particles mixed in)*4
		Evaluation results (F) Note 1	α-ray: 0.250 β-ray: 0.160 γ-ray: 0.158	α-ray: 0.133 β-ray: 0.142 γ-ray: 0.134	α-ray: 0.021 β-ray: 0.064 γ-ray: 0.058	α-ray: 0.004 β-ray: 0.002 γ-ray: 0.002	α-ray: 0.004 β-ray: 0.002 γ-ray: 0.002
	Decay heat (E)		Estimates based on burnup calculation results (α-ray: 0.113 W/kg UO_2, β-ray: 0.383 W/kg UO_2, and γ-ray: 0.221 W/kg UO_2)Note 7				
	Peaking factor (P)		Estimates based on burnup calculation results (α-ray: 2.35, β-ray: 1.56, and γ-ray: 1.56)*8				
	Weight of fuel debris (M)		Design value (72.9 kg for a canister with an inner diameter of 220 mm)				
	Ratio of fuel contained in fuel debris (C)		Max. value (1)				
	Hydrogen generation G value (G)		Values cited from literature (α-ray: 1.3 molecules/100 eV and β-ray and γ-ray: 0.45 molecule/100 eV)*9				
Estimation results	Hydrogen generation rate (RH2)		1.6×10^{-16} L/h/Bq	1.1×10^{-16} L/h/Bq	3.4×19^{-17} L/h/Bq	2.3×10^{-18} L/h/Bq	2.2×10^{-18} L/h/Bq

Note 1: A margin of error of ±1% was set for estimates because calculation was performed so that the statistical error of PHITS calculation results was less than 1%.

Note: This ratio was set based on the result of dewatering tests in FY2016 (maximum amount of residual water).

Note 3: This volume ratio was set based on 0.1 wt% for the target volume of moisture to be dried, 11 g/cc for the density of the pellet particles, and 1 g/cc for water density.

Note 4: It was assumed that particles with a size of 0.1 mm were collected in a canister to its maximum capacity and powder filled the gap between the particles. (The composition ratios of powder and 0.1 mm particles were 26% and 74%, respectively)

Note 5: This particle size distribution was hypothetically used based on the particle size distribution obtained from simulant fuel debris (the composition ratios of powder, 0.1 mm particles, 1 mm particles, and 4 mm particles being 4%, 8%, 12%, and 76%, respectively) that was reported in the Subsidy Project of "Decommissioning and Contaminated Water Management: Characterization of Fuel Debris" in the FY2014 Supplementary Budgets, Final Report, published by the International Research Institute for Nuclear Decommissioning (IRID), in May 2017.

Note 6: It was considered to be difficult to verify the energy absorption rate of particles with a size of a few mm by tests.

Note 7: The calorific values of main nuclide in the 1F-1 for each type of rays were quoted from Tables 5, 8, 11, 43, 45, and 47 in the report below and summed up: Nishihara, K., Iwamoto, H. and Suyama, K., Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant, JAEA-Data/Code. 2012–18, published by the Japan Atomic Energy Agency in September 2012. Note that no margin of error was set because the values of decay heat used in the estimate were those for the maximum burnup by applying peaking factors to make the estimate conservative.

Note 8: These peaking factors were set for each type of rays taking into account those for each type of nuclides derived based on the data described in the report cited in Note 7 above. (The ratio of the maximum decay heat to the mean decay heat for α-ray and the ratio of the maximum burnup to the mean burnup for β- and γ-rays)

Note 9: These G values were set by reference to Hilbert Christensen and Erling Bjergbakke, Nuclear and Chemical Waste Management, Vol.6, pp. 265–270, Table 2, Apprication of Chemisimul for Groundwater Radiolysis (1986). Note that a margin of error of ±10% was set taking into account variation in data among different literatures.

Table Results of identifying fuel debris properties

Items		Properties	Remarks 2
Component	Molten fuel debris Main component 1	UO2	Data obtained from accident progression analysis of Unit 1
	Molten fuel debris Main component 2	ZrO2	Data obtained from accident progression analysis of Unit 1
	MICCI Main component 1	SiO2	Data obtained from accident progression analysis of Unit 1
	MICCI Main component 2	Fe2O3	Data obtained from accident progression analysis of Unit 1
	MICCI Main component 3	UO2	Data obtained from accident progression analysis of Unit 1
	Metal fuel debris Main component 1	Fe	Data obtained from accident progression analysis of Unit 1
	Metal fuel debris Main component 2	Ni	Data obtained from accident progression analysis of Unit 1
	Metal fuel debris Main component 3	Ru	Data obtained from accident progression analysis of Unit 1
Properties	Molten and resolidified material Particle or pebble form	6 to 11 g/cm3	Data obtained from accident progression analysis of Unit 1
	Molten and resolidified material Lump form	6 to 11 g/cm3	Data obtained from accident progression analysis of Unit 1
	Molten and resolidified material Bedrock form	6 to 11 g/cm3	Data obtained from accident progression analysis of Unit 1
	MCCI product Powder or pebble form	6 to 11 g/cm3	Data obtained from accident progression analysis of Unit 1
	MCCI product Lump form	2 to 11 g/cm3	Data obtained from accident progression analysis of Unit 1
	MCCI product Bedrock form	2 to 11 g/cm3	Data obtained from accident progression analysis of Unit 1
	Particle size (powder form)	Smaller than 0.1 mm	Fuel Debris Retrieval (Fundamental Technology) Project FY2018 Final Report Material No.21
	Particle size (particle form)	0.1 mm to 10 mm	Fuel Debris Retrieval (Fundamental Technology) Project FY2018 Final Report Material No.21
	Particle size (lump form)	10 mm to 100 mm	Fuel Debris Retrieval (Fundamental Technology) Project FY2018 Final Report Material No.21
Accompanying liquid	Chloride ion	5.6 × 10^-4 mol/L	Canister Project FY2020 Final Report Material No. 46
	Iodide ion	1.0 × 10^-4 mol/L	Canister Project FY2020 Final Report Material No. 46
	pH	9 to 10	Canister Project FY2020 Final Report Material No. 46
	Moisture content (before drying)	50 vol.%	Canister Project FY2020 Final Report Material No. 50
	Moisture content (after drying)	0.1 wt%	Canister Project FY2020 Final Report Material No. 50
Hydrogen generation	Hydrogen generation rate (before drying)	1.6 × 10-16 L/h/Bq	Canister Project FY2020 Final Report Material No. 50
	Hydrogen generation rate (after drying)	2.3 × 10-18 L/h/Bq	Canister Project FY2020 Final Report Material No. 50
Others	Total inventory	2.18 × 10^15 Bq/t	JAEA/CRIEPI "Research on the Sophistication of Statistical Inventory Estimation Method"

Extracted from

Subsidy Project of "Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)" in the FY2018 Supplementary Budgets, Final Report, June 2021

Subsidy Project of "Decommissioning and Contaminated Water Management (Upgrading of Fundamental Technology for Retrieval of Fuel Debris and Reactor Internals)" in the FY2016 Supplementary Budgets, Final Report, July 2019

JAEA/CRIEPI "Research on the Sophistication of Statistical Inventory Estimation Method"

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (4/11)

(iii) Organization of input conditions (2/3)

Table 1 Results of identifying canister specifications

Items	Specifications	Remarks
Material	Stainless steel (SUS316L)	June 2021 Canister Project Final Report Material No.112
Seal material	Elastomer resin (EPDM)	June 2021 Canister Project Final Report Material No.115
Heat removal method	Drying	June 2021 Canister Project Final Report Material No.106
Internal diameter	220 mm	June 2021 Canister Project Final Report Material No.114
Height	800 mm	June 2021 Canister Project Final Report Material No.114
Unit can outer diameter	210 mm	June 2021 Canister Project Final Report Material No.114
Unit can height	400 mm	June 2021 Canister Project Final Report Material No.114
Capacity	0.03 m^3	Approximate value from the above dimensions
Filling rate	30% (Fuel debris capacity: 0.01 m^3)	June 2021 Canister Project Final Report Material No.26
Confinement function	Filter installation	June 2021 Canister Project Final Report Material No.108
Gas processing function	Recombination catalyst	June 2021 Canister Project Final Report Material No.112

Vent filter (temporary values)

Items	Specifications	Remarks
Material	SUS316	June 2021 Canister Project Final Report Material No.108
Mesh diameter	0.3 µm	June 2021 Canister Project Final Report Material No.108

Recombination catalyst (temporary values)

Items	Specifications	Remarks
Material	Platinum catalyst (TKK H1P)	June 2021 Canister Project Final Report Material No.120
Catalyst bed thickness	20 mm	June 2021 Canister Project Final Report Material No.112

Table 2 Results of identifying transfer cask specifications

Items	Specifications	Remarks
Material	Not specified	—
Seal material	Not specified	—
Heat removal method	Drying	June 2021 Canister Project Final Report Material No.94
Internal diameter	1700 mm	June 2021 Canister Project Final Report Material No.94
Height	1200 mm	June 2021 Canister Project Final Report Material No.94
Capacity	12 canisters can be enclosed	June 2021 Canister Project Final Report Material No.94
Confinement function	Sealing	June 2021 Canister Project Final Report Material No.52
Gas processing function	No	June 2021 Canister Project Final Report Material No.52

Table 3 Results of identifying storage container specifications

Items	Specifications	Remarks
Material	Not specified	—
Seal material	Not specified	—
Heat removal method	Drying	June 2021 Canister Project Final Report Material No.5
Internal diameter	Not specified	—
Height	Not specified	—
Capacity	Not specified	—
Confinement function	Vent pipe	June 2021 Canister Project Final Report Material No.5
Gas processing function	There is a gas treatment system in the later stage	June 2021 Canister Project Final Report Material No.5

Extracted from the Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2018 Supplementary Budgets, Final Report, June 2021

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (5/11)

(iii) Organization of input conditions (3/3)

Table Results of identifying environmental conditions inside and outside canisters

Canister interior

Process	**Sealing cell**	**Drying treatment**	**Preparation cell**	**Receiving area**	**Storage area**	Remarks
Temperature	Up to 300℃	Up to 300℃	Up to 300℃	Up to 300℃	Up to 300℃	March 2017 Canister Project Final Report Material No.50
Pressure	Negative pressure	Not specified	Normal pressure	Negative pressure	Not specified	June 2021 Canister Project Final Report Material No.4-5
Humidity (before drying)	100 %	—	100 %	100 %	—	June 2021 Canister Project Final Report Material No.4-5
Humidity (after drying)	Sufficiently low value	Sufficiently low value	Sufficiently low value	Sufficiently low value	Sufficiently low value	June 2021 Canister Project Final Report Material No.4-5, 98
Atmosphere gas	Same as building atmosphere	—	Inert gas injection	Inert gas injection	Inert gas injection	June 2021 Canister Project Final Report Material No.4-5, 100-101
Cooling method	Dry natural cooling	—	Dry natural cooling	Dry natural cooling	Dry natural cooling	June 2021 Canister Project Final Report Material No.4-5
Exterior environment	Building	Drying apparatus	Building → transfer cask	Transfer cask → building → storage container	Storage cask	June 2021 Canister Project Final Report Material No.4-5
Confinement function	Filter	Filter	Filter + seal	Filter	From the vent pipe to the outside of the building through the gas treatment system	June 2021 Canister Project Final Report Material No.4-5
Assumed period	Not stated (expected to be a few days)	Up to 10 days	Not stated (expected to be a few days)	Not stated (expected to be a few days)	Maximum 50 years	June 2018 Canister Project Final Report Material No. 49

Exterior environment

Process	Sealing cell	Drying treatment	Preparation cell	Receiving area	Storage area	Remarks
Temperature	Room temperature	200℃	Room temperature	Room temperature	Room temperature	June 2021 Canister Project Final Report Material No.4-5
Pressure	Negative pressure	Not specified	Normal pressure	Negative pressure	Negative pressure	June 2021 Canister Project Final Report Material No.4-5
Humidity	Properly managed	—	Properly managed	Properly managed	Properly managed	June 2021 Canister Project Final Report Material No.4-5

Extracted from
Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2014 Supplementary Budgets, Final Report, March 2017
Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2015 Supplementary Budgets, Final Report, March 2018
Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2018 Supplementary Budgets, Final Report, June 2021

6. Implementation details

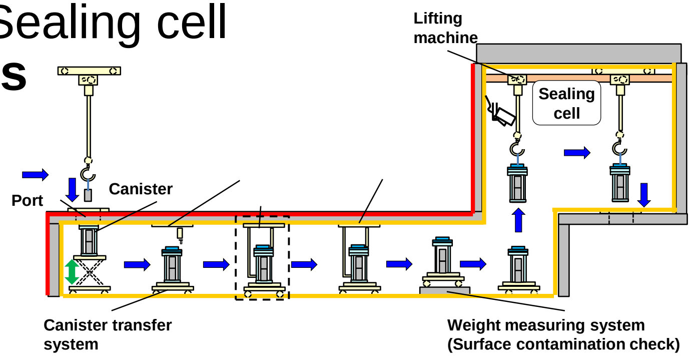
- Sealing cell

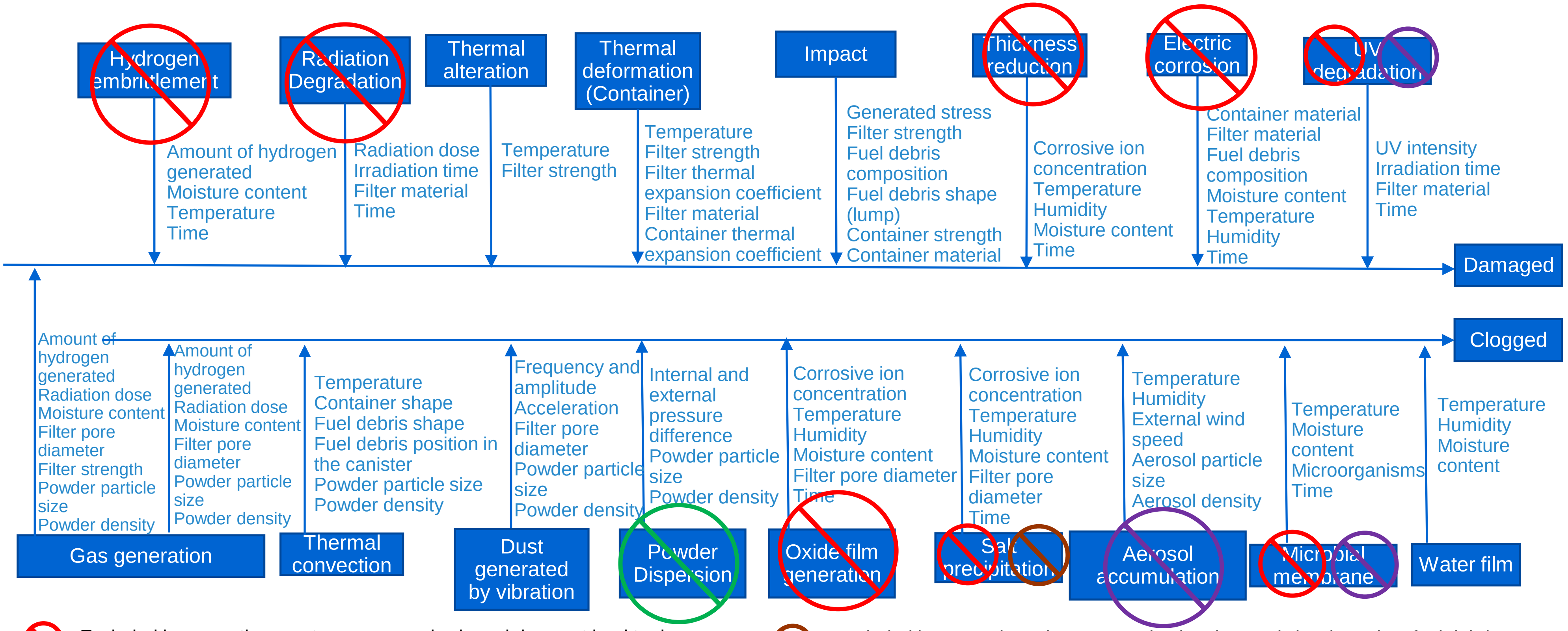
6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (6/11)

(iv) Selection of degradation factors (1/6)





Hydrogen embrittlement
Amount of hydrogen generated
Moisture content
Temperature
Time

Radiation Degradation
Radiation dose
Irradiation time
Filter material
Time

Thermal alteration
Temperature
Filter strength

Thermal deformation (Container)
Temperature
Filter strength
Filter thermal expansion coefficient
Filter material
Container thermal expansion coefficient

Impact
Generated stress
Filter strength
Fuel debris composition
Fuel debris shape (lump)
Container strength
Container material

Thickness reduction
Corrosive ion concentration
Temperature
Humidity
Moisture content
Time

Electric corrosion
Container material
Filter material
Fuel debris composition
Moisture content
Temperature
Humidity
Time

UV degradation
UV intensity
Irradiation time
Filter material
Time

Damaged

Amount of hydrogen generated
Radiation dose
Moisture content
Filter pore diameter
Filter strength
Powder particle size
Powder density

Amount of hydrogen generated
Radiation dose
Moisture content
Filter pore diameter
Powder particle size
Powder density

Gas generation

Temperature
Container shape
Fuel debris shape
Fuel debris position in the canister
Powder particle size
Powder density

Thermal convection

Frequency and amplitude
Acceleration
Filter pore diameter
Powder particle size
Powder density

Dust generated by vibration

Internal and external pressure difference
Powder particle size
Powder density

Powder Dispersion

Corrosive ion concentration
Temperature
Humidity
Moisture content
Filter pore diameter
Time

Oxide film generation

Corrosive ion concentration
Temperature
Humidity
Moisture content
Filter pore diameter
Time

Salt precipitation

Temperature
Humidity
External wind speed
Aerosol particle size
Aerosol density

Aerosol accumulation

Temperature
Moisture content
Microorganisms
Time

Microbial membrane

Temperature
Humidity
Moisture content

Water film

Clogged

🚫 Excluded because the event progresses slowly and does not lead to damage or clogging while in the area

🚫 Excluded because there is no difference in pressure between the inside and outside of the canister in the area

🚫 Excluded because the area is indoors

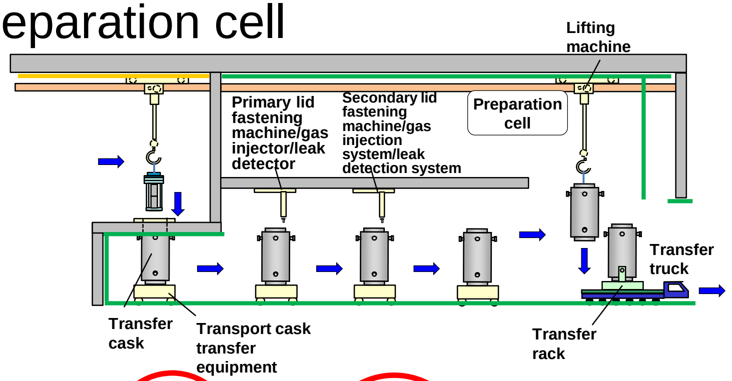
🚫 Excluded because the salt concentration is adequately low based on fuel debris properties

17 degradation events ⇒ 10 items excluded, so 7 items to be examined.

6. Implementation details

6.3 Performance assessment of canister filters

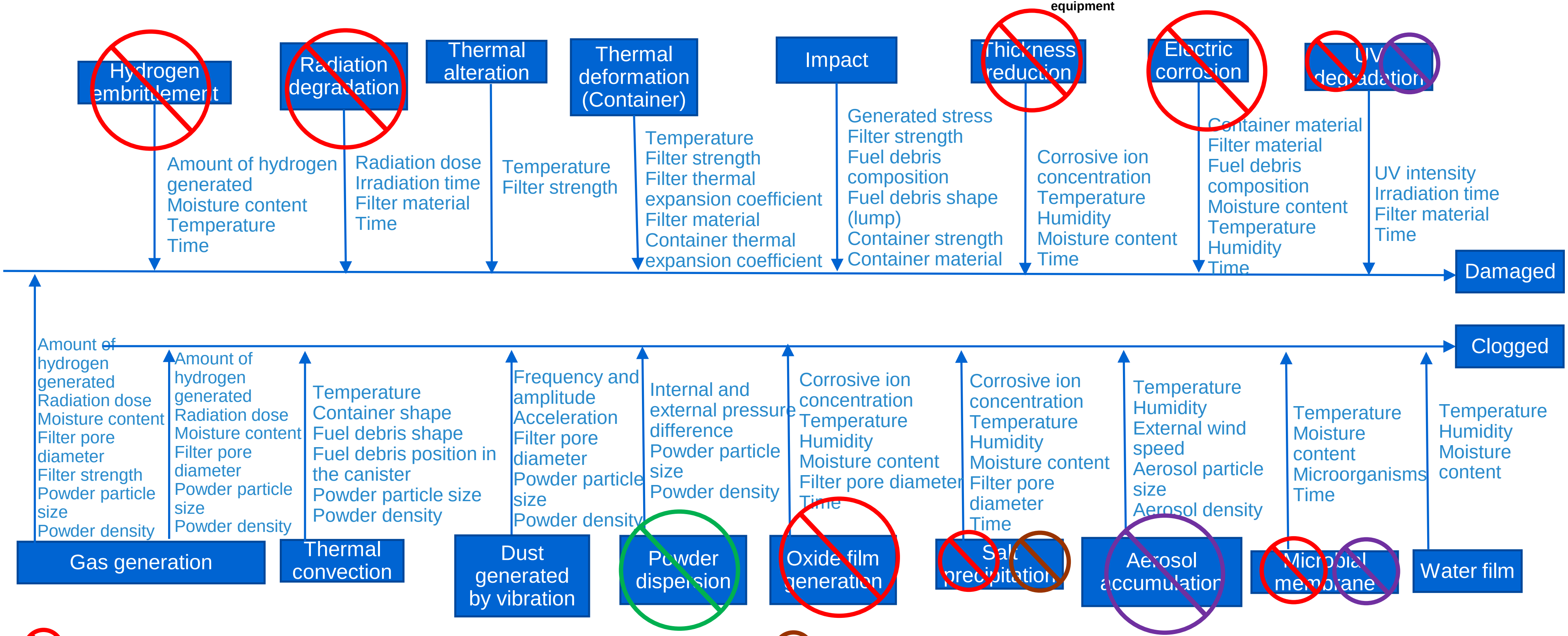
- Preparation cell



③ Implementation items and results

a. Identification of environments and conditions (7/11)

(iv) Selection of degradation factors (2/6)



Hydrogen embrittlement
- Amount of hydrogen generated
- Moisture content
- Temperature
- Time

Radiation degradation
- Radiation dose
- Irradiation time
- Filter material
- Time

Thermal alteration
- Temperature
- Filter strength

Thermal deformation (Container)
- Temperature
- Filter strength
- Filter thermal expansion coefficient
- Filter material
- Container thermal expansion coefficient

Impact
- Generated stress
- Filter strength
- Fuel debris composition
- Fuel debris shape (lump)
- Container strength
- Container material

Thickness reduction
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Time

Electric corrosion
- Container material
- Filter material
- Fuel debris composition
- Moisture content
- Temperature
- Humidity
- Time

UV degradation
- UV intensity
- Irradiation time
- Filter material
- Time

Damaged

Gas generation
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Filter strength
- Powder particle size
- Powder density

- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Powder particle size
- Powder density

Thermal convection
- Temperature
- Container shape
- Fuel debris shape
- Fuel debris position in the canister
- Powder particle size
- Powder density

Dust generated by vibration
- Frequency and amplitude
- Acceleration
- Filter pore diameter
- Powder particle size
- Powder density

Powder dispersion
- Internal and external pressure difference
- Powder particle size
- Powder density

Oxide film generation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Salt precipitation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Aerosol accumulation
- Temperature
- Humidity
- External wind speed
- Aerosol particle size
- Aerosol density

Microbial membrane
- Temperature
- Moisture content
- Microorganisms
- Time

Water film
- Temperature
- Humidity
- Moisture content

Clogged

⊘ Excluded because the event progresses slowly and does not lead to damage or clogging while in the area

⊘ Excluded because there is no difference in pressure between the inside and outside of the canister in the area

⊘ Excluded because the area is indoors

⊘ Excluded because the salt concentration is adequately low based on fuel debris properties

17 degradation events ⇒ 10 items excluded, so 7 items to be examined

6. Implementation details

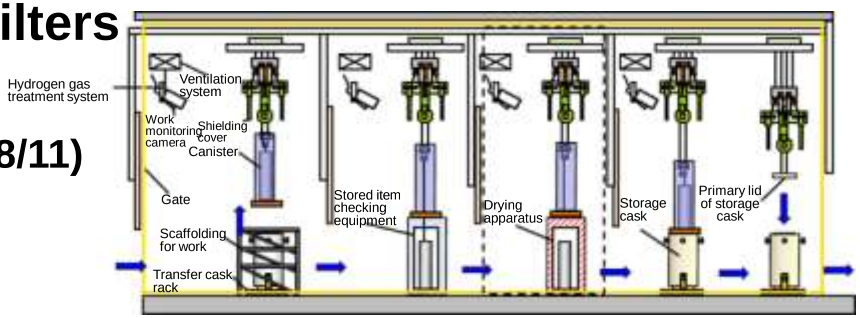
- Receiving area

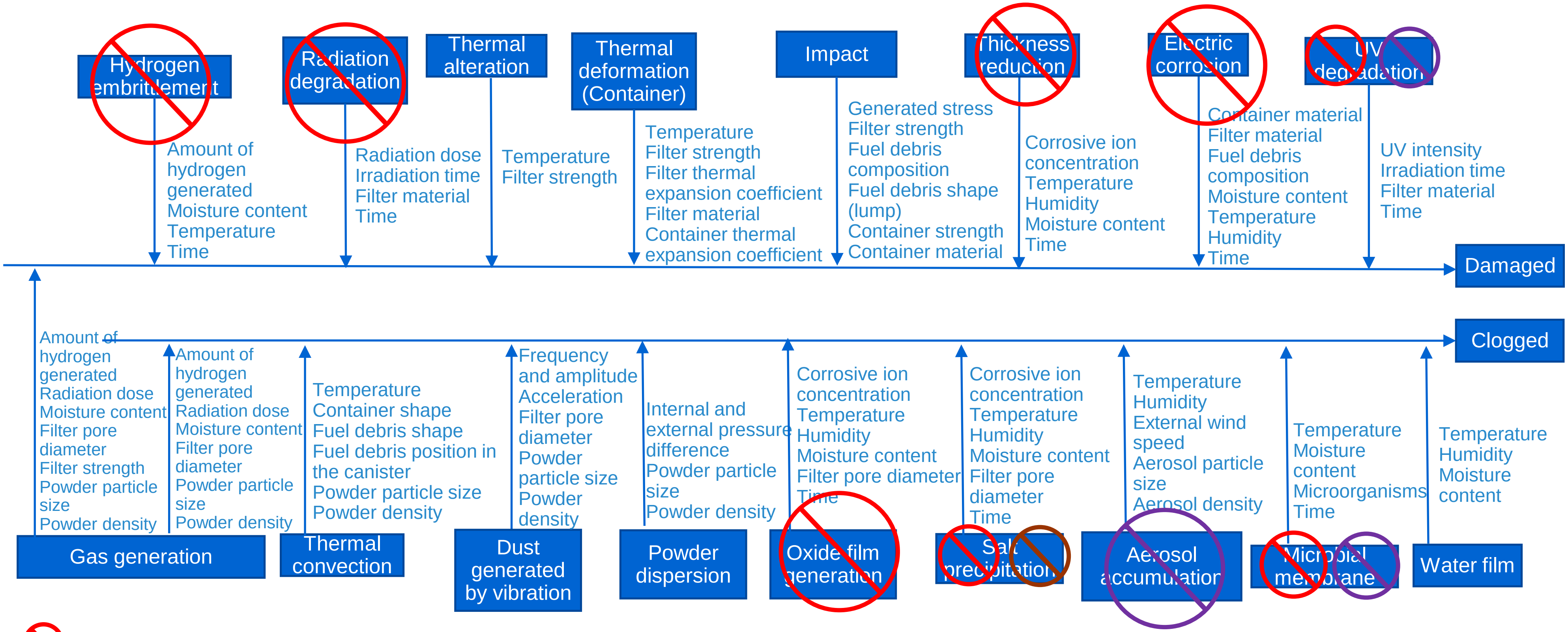
6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (8/11)

(iv) Selection of degradation factors (3/6)





Hydrogen embrittlement
- Amount of hydrogen generated
- Moisture content
- Temperature
- Time

Radiation degradation
- Radiation dose
- Irradiation time
- Filter material
- Time

Thermal alteration
- Temperature
- Filter strength

Thermal deformation (Container)
- Temperature
- Filter strength
- Filter thermal expansion coefficient
- Filter material
- Container thermal expansion coefficient

Impact
- Generated stress
- Filter strength
- Fuel debris composition
- Fuel debris shape (lump)
- Container strength
- Container material

Thickness reduction
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Time

Electric corrosion
- Container material
- Filter material
- Fuel debris composition
- Moisture content
- Temperature
- Humidity
- Time

UV degradation
- UV intensity
- Irradiation time
- Filter material
- Time

Damaged

Clogged

Gas generation
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Filter strength
- Powder particle size
- Powder density

Thermal convection
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Powder particle size
- Powder density

Dust generated by vibration
- Temperature
- Container shape
- Fuel debris shape
- Fuel debris position in the canister
- Powder particle size
- Powder density

Powder dispersion
- Frequency and amplitude
- Acceleration
- Filter pore diameter
- Powder particle size
- Powder density

Oxide film generation
- Internal and external pressure difference
- Powder particle size
- Powder density

Salt precipitation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Aerosol accumulation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Microbial membrane
- Temperature
- Humidity
- External wind speed
- Aerosol particle size
- Aerosol density

Water film
- Temperature
- Moisture content
- Microorganisms
- Time

- Temperature
- Humidity
- Moisture content

🚫 Excluded because the event progresses slowly and does not lead to damage or clogging while in the area

🚫 Excluded because the area is indoors

🚫 Excluded because the salt concentration is adequately low based on fuel debris properties

17 degradation events ⇒ 9 items excluded, so 8 items to be examined

6. Implementation details

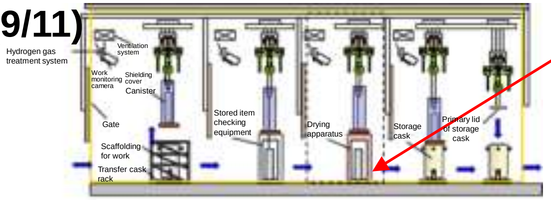
6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (9/11)

(iv) Selection of degradation factors (4/6)

- Drying treatment



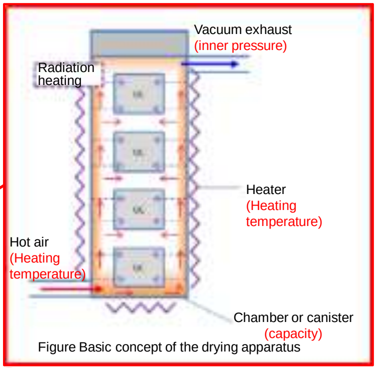
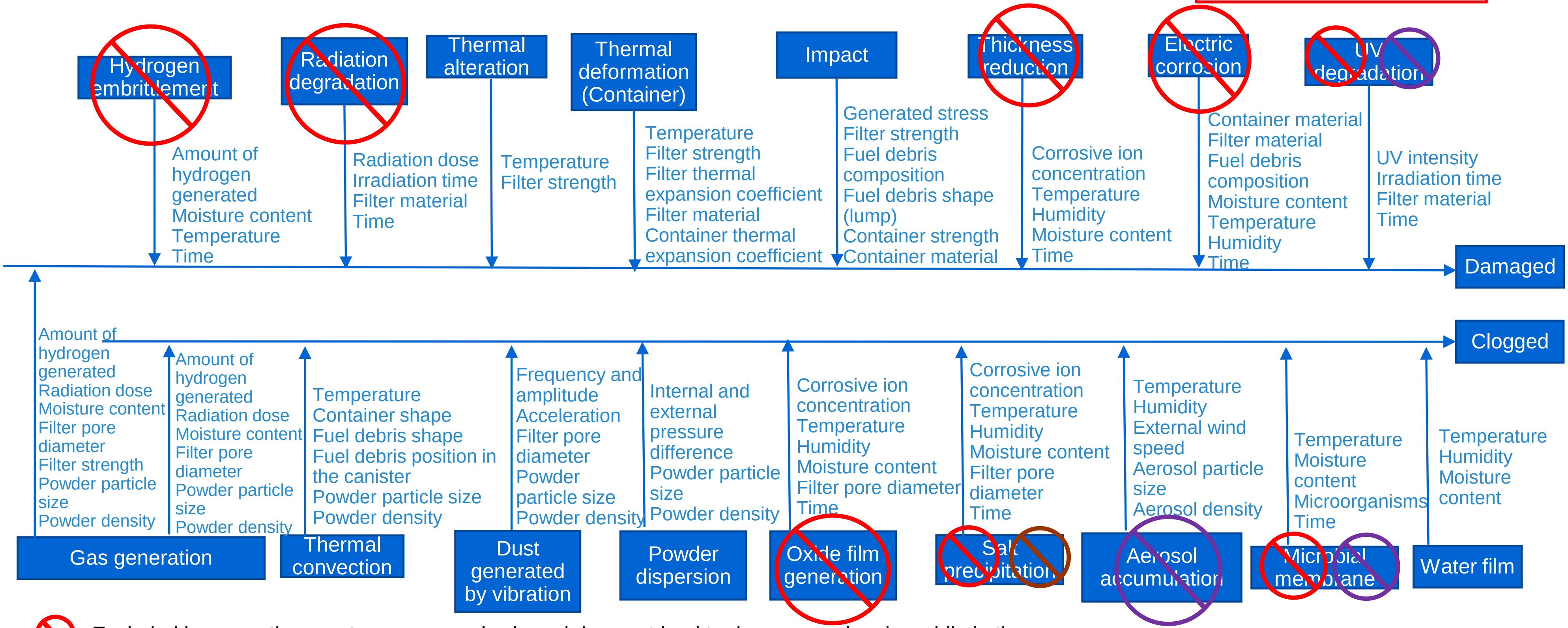


Figure Basic concept of the drying apparatus



Hydrogen embrittlement
- Amount of hydrogen generated
- Moisture content
- Temperature
- Time

Radiation degradation
- Radiation dose
- Irradiation time
- Filter material
- Time

Thermal alteration
- Temperature
- Filter strength

Thermal deformation (Container)
- Temperature
- Filter strength
- Filter thermal expansion coefficient
- Filter material
- Container thermal expansion coefficient

Impact
- Generated stress
- Filter strength
- Fuel debris composition
- Fuel debris shape (lump)
- Container strength
- Container material

Thickness reduction
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Time

Electric corrosion
- Container material
- Filter material
- Fuel debris composition
- Moisture content
- Temperature
- Humidity
- Time

UV degradation
- UV intensity
- Irradiation time
- Filter material
- Time

Damaged

Clogged

Gas generation
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Filter strength
- Powder particle size
- Powder density

Thermal convection
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Powder particle size
- Powder density

Dust generated by vibration
- Temperature
- Container shape
- Fuel debris shape
- Fuel debris position in the canister
- Powder particle size
- Powder density

Powder dispersion
- Frequency and amplitude
- Acceleration
- Filter pore diameter
- Powder particle size
- Powder density

Oxide film generation
- Internal and external pressure difference
- Powder particle size
- Powder density

Salt precipitation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Aerosol accumulation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Microbial membrane
- Temperature
- Humidity
- External wind speed
- Aerosol particle size
- Aerosol density

Water film
- Temperature
- Moisture content
- Microorganisms
- Time

- Temperature
- Humidity
- Moisture content

🚫 Excluded because the event progresses slowly and does not lead to damage or clogging while in the area

🚫 Excluded because the area is indoors

🚫 Excluded because the salt concentration is adequately low based on fuel debris properties

17 degradation events ⇒ 9 items excluded, so 8 items to be examined

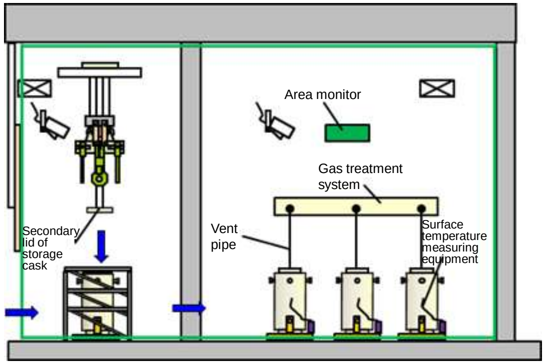
6. Implementation details - Storage area

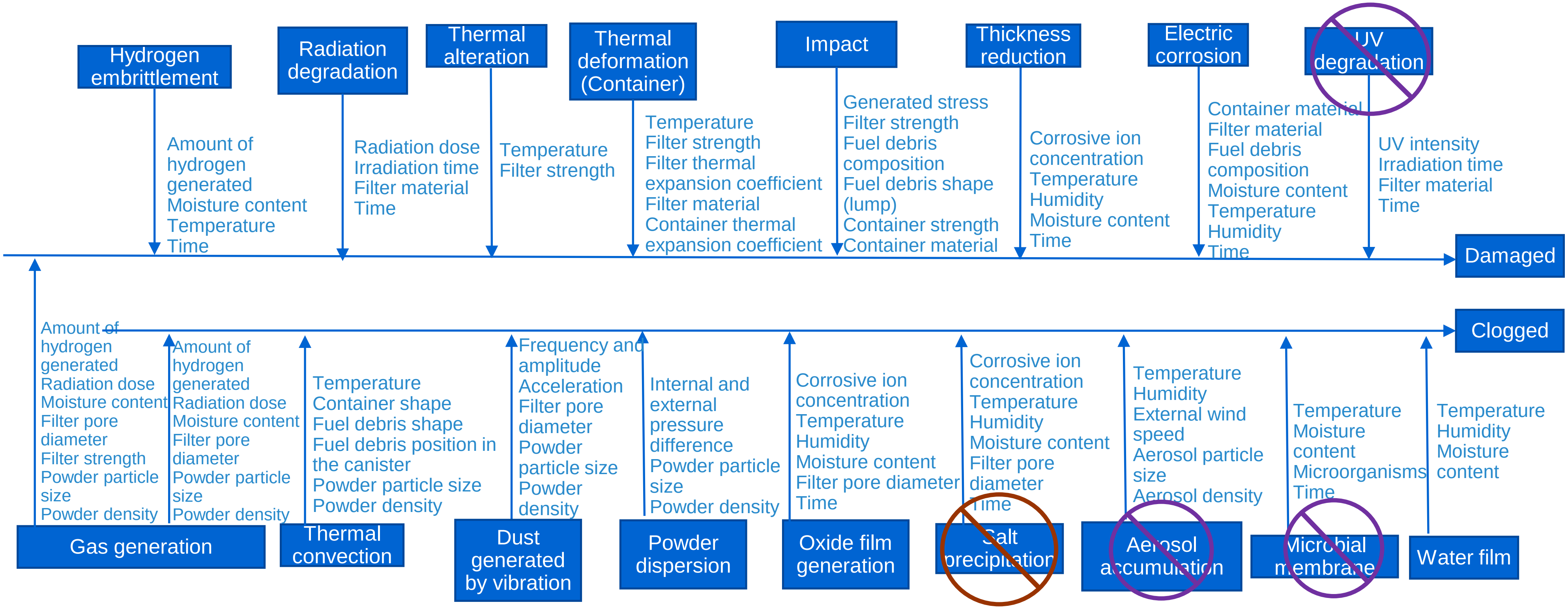
6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (10/11)

(iv) Selection of degradation factors (5/6)





Hydrogen embrittlement
- Amount of hydrogen generated
- Moisture content
- Temperature
- Time

Radiation degradation
- Radiation dose
- Irradiation time
- Filter material
- Time

Thermal alteration
- Temperature
- Filter strength

Thermal deformation (Container)
- Temperature
- Filter strength
- Filter thermal expansion coefficient
- Filter material
- Container thermal expansion coefficient

Impact
- Generated stress
- Filter strength
- Fuel debris composition
- Fuel debris shape (lump)
- Container strength
- Container material

Thickness reduction
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Time

Electric corrosion
- Container material
- Filter material
- Fuel debris composition
- Moisture content
- Temperature
- Humidity
- Time

UV degradation
- UV intensity
- Irradiation time
- Filter material
- Time

Damaged

Clogged

Gas generation
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Filter strength
- Powder particle size
- Powder density

Thermal convection
- Amount of hydrogen generated
- Radiation dose
- Moisture content
- Filter pore diameter
- Powder particle size
- Powder density

Dust generated by vibration
- Temperature
- Container shape
- Fuel debris shape
- Fuel debris position in the canister
- Powder particle size
- Powder density

Powder dispersion
- Frequency and amplitude
- Acceleration
- Filter pore diameter
- Powder particle size
- Powder density

Oxide film generation
- Internal and external pressure difference
- Powder particle size
- Powder density

Salt precipitation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Aerosol accumulation
- Corrosive ion concentration
- Temperature
- Humidity
- Moisture content
- Filter pore diameter
- Time

Microbial membrane
- Temperature
- Humidity
- External wind speed
- Aerosol particle size
- Aerosol density

Water film
- Temperature
- Moisture content
- Microorganisms
- Time

- Temperature
- Humidity
- Moisture content

⊘ Excluded because the area is indoors

⊘ Excluded because the salt concentration is adequately low based on fuel debris properties

17 degradation events ⇒ 4 items excluded, so 13 items to be examined

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

a. Identification of environments and conditions (11/11)

(iv) Selection of degradation factors (6/6)

Process	Sealing cell	Drying treatment	Preparation cell	Receiving area	Storage area
Hydrogen generation					
Hydrogen embrittlement	×	×	×	×	
Radiation degradation	×	×	×	×	
Thermal alteration					
Thermal deformation (container)					
Thermal convection					
Impact					
Dust generated by vibration					
Thickness reduction	×	×	×	×	
Oxide film generation	×	×	×	×	
Salt precipitation	×	×	×	×	×
Electric corrosion	×	×	×	×	
Microbial membrane	×	×	×	×	×
Water film					
Aerosol deposition	×	×	×	×	×
Powder dispersion	×		×		
UV degradation	×	×	×	×	×

×: Items determined to not require examination based on the input environmental conditions

Since salt precipitation, microbial membrane, aerosol deposition, and UV degradation are excluded from all processes, they are excluded from examinations after 6.3 ③ b.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (1/27)

(i) Organization of filter categories

Intended use	Primary manufacturer	Manufacturing method and filter media	Particle capture function	Hydrogen permeation performance
Atomic filters USA WIPP France La Hague Japan 1F HIC	Nuclear Filter Technology, Inc. (NFT) Ultra Tech, Inc. Poral etc.	Sintered metal Carbon composite	> 99.97% for 0.3 to 0.5 μm particles (example from WIPP)	1.85 - 92.5 × 10^{-6} (m/s/mf) @NFT 3.66 × 10^{-6} (m^2/s) @Poral
Metal gas filters	Fuji Filter Manufacturing Co., Ltd. Nippon Seisen Co., Ltd. etc.	Powdered sintered body Long-fiber sintered body Short-fiber sintered body Multilayered metal sintered body	0.1 to 1000 μm Controllable depending on filter type No specification for accuracy	Based on the filter specifications (pressure loss), the hydrogen permeation performance is assumed to be about the same as that of atomic filters
Ceramic gas filters	NGK Insulators, Ltd. Ibiden Co., Ltd. etc.	Aluminum oxide Zeolite Cordierite	Lower capture efficiency for 0.1 to 0.3 μm particles It is estimated that HEPA-equivalent performance can be achieved by controlling pores	Based on the filter specifications (pressure loss), the hydrogen permeation performance is assumed to be about the same as that of atomic filters
Glass or resin gas filters	Japan Air Filter Co., Ltd. Cambridge Filter Japan Ltd. etc.	Glass fiber Polypropylene Olefin PTFE	HEPA: 99.97% or better for 0.3 μm particles ULPA: 99.9995% or better for 0.15 μm particles	Based on the filter specifications (pressure loss), the hydrogen permeation performance is assumed to be about the same as that of atomic filters

The biggest difference in filter specifications is the quality of the filter media.
The required particle capture performance determines the manufacturing method and configuration of the filter media.
Filter life depends largely on the quality of the filter media.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (2/27)

(ii) Selection of degradation events based on canister environment (1/26)

Scenarios that would lead to degradation for each degradation process are organized.

A broad range of degradation scenario conditions were examined by considering two stages of conditions (moderate and severe).

Degradation process	Scenarios leading to degradation	
	Scenario 1 (moderate conditions)	Scenario 2 (severe conditions)
Hydrogen generation	Hydrogen is generated via radiolysis of residual moisture within waste after drying and fuel debris particles rise, clogging the filter and causing it to lose its functionality.	Collecting undried or insufficiently dried waste generates more hydrogen than when dried, causing fuel debris particles to rise, clogging the filter and causing it to lose its functionality.
Hydrogen embrittlement	The generated hydrogen is absorbed and reaches a concentration that causes embrittlement within the storage period, destroying the filter.	The generated hydrogen is absorbed and moisture is generated, reaching a concentration that causes embrittlement within the storage period, destroying the filter.
Radiation degradation	Filter material absorbs radiation energy and degrades, reducing the strength of the material.	Filter material absorbs radiation energy and degrades, damaging the filter material.
Thermal alteration	The temperature of fuel debris rises due to decay heat. When the temperature reaches 200℃ (the temperature during drying), the filter deforms and loses its functionality.	The temperature of fuel debris rises due to decay heat. When the temperature reaches 300℃ (the temperature specification of the canister), the filter deforms and loses its functionality.
Thermal deformation (Container)	The temperature of fuel debris rises due to decay heat. The temperature reaches 200℃, the temperature during drying. The container is thermally deformed and the affixed filter becomes stressed, resulting in damage.	The temperature of fuel debris rises due to decay heat. The temperature reaches 300℃, the temperature specification of the canister. The container is thermally deformed and the affixed filter becomes stressed, resulting in damage.
Thermal convection	Thermal decay raises the temperature of the fuel debris to 200℃ and heat convection occurs inside the container, leading to fuel debris particles rising and clogging the filter, which causes the filter to lose its functionality.	Thermal decay raises the temperature of the fuel debris to 300℃ and heat convection occurs inside the container, leading to fuel debris particles rising and clogging the filter, which causes the filter to lose its functionality.
Impact	The container and/or filter become deformed or damaged from a mild collision or impact during transportation or an earthquake and the filter loses its functionality.	The container and/or filter become deformed or damaged from a collision or from being dropped from a height of several meters during transportation or an earthquake and the filter loses its functionality.

Degradation process	Scenarios leading to degradation	
	Scenario 1 (moderate conditions)	Scenario 2 (severe conditions)
Dust generated by vibration	Vibrations during transportation or an earthquake cause waste particles to rise, covering and/or blocking the filter surface and causing the filter to lose its functionality.	The container overturns during transportation or an earthquake, causing waste particles to press against the filter surface, covering and/or blocking the filter surface and causing the filter to lose its functionality.
Thickness reduction	Condensation, etc. brings moisture into the filter and a phenomenon like chloride ions adhering to the filter occurs, causing pitting corrosion that generates corrosion products that clog the filter.	Condensation, etc. brings moisture into the filter, causing a phenomenon like a large amount of powder from the waste adhering to the filter, which causes crevice corrosion that generates corrosion products that clog the filter.
Oxide film generation	The temperature of fuel debris rises due to decay heat. When the temperature reaches 200℃ (the temperature during drying), an oxide film forms and clogs the filter.	The temperature of fuel debris rises due to decay heat. When the temperature reaches 300℃ (the temperature specification of the canister), an oxide film forms and clogs the filter.
Electric corrosion	Condensation, etc. brings moisture into the filter, causing a phenomenon like chloride ions adhering to the filter.	Condensation, etc. brings moisture into the filter, causing a phenomenon like chloride ions adhering to the filter and corroding a portion of the filter, leading to a difference in electrical potential in the area.
Water film	Condensation creates a water film that blocks part of the filter, reducing flow path surface area.	Condensation creates a water film that blocks the entire filter.
Powder dispersion	Differential pressure caused by ventilation in the canister storage building generates a flow inside the storage container, which causes fuel debris particles to rise and clog the filter.	Ventilation in the canister storage building and the exhaust operations of the transfer cask generate a flow inside the storage container, which causes fuel debris particles to rise and clog the filter.

The necessity for selection as a degradation event was examined for each degradation process.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (3/27)

(ii) Selection of degradation events based on canister environment (2/26)

Event: **Hydrogen generation** Degradation mode: Clogged & Damaged

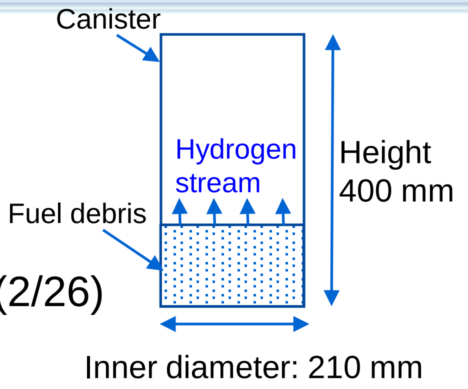


Figure 1 Unit can schematic diagram

- Evaluation of filter clogging caused by powdery fuel debris increasing due to hydrogen generation.

  ⇒ The hydrogen generation rate and particle settling velocity are calculated and evaluated.

- Flow rate from hydrogen generation

From input conditions, the flow rate from hydrogen generation was calculated to be 9.03 × 10^{-5} [L/h]

(Calculation formula)

Hydrogen generation rate [L/h/Bq] × total inventory [Bq/ton] × fuel debris density [ton/m^3] × fuel debris volume [m^3])

(Input conditions)

- Hydrogen generation rate: 2.3 × 10^{-18} [L/h/Bq] (moisture content after drying is 0.1 wt%)
- Total inventory: 2.18 × 10^{15} [Bq/ton],
- Fuel debris density: 4.0 [g/cm^3] (MCCI average density)
- Fuel debris volume: 0.0045 [m^3] (30% of unit can volume)

Hydrogen rises 0.038 [m^2] in a cross section of a canister with an inner diameter of 210 mm

The hydrogen flow velocity is calculated at 6.6 × 10^{-10} [m/s].

The hydrogen flow velocity is sufficiently smaller than the particle settling velocity, so filter degradation from hydrogen generation can be ignored.

- Rising velocity of powder

The settling velocity of the particles is calculated by using the Stokes' law.

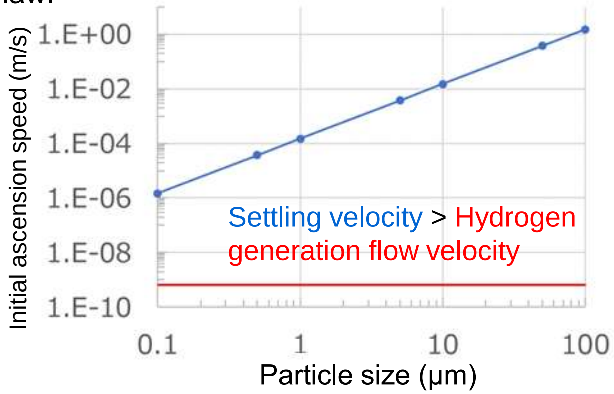


Figure 2 Results of calculating the settling velocity

(Calculation formula) Stokes' law $v_s = D_P^2 (\rho_P - \rho_f) g/18\eta$

(Input conditions)

- Terminal velocity v_s [m/s]
- powder diameter D_P [m]: 0.1 to 100 [μm]
  Upper limit: 0.1 mm or less according to the definition of particles
  Lower limit: Set with regard to filter performance regulations (HEPA 0.3 μm, ULPA 0.15 μm)
- Particle density ρ_P [kg/m^3]: Fuel debris density 4.0 [g/cm^3]
- Fluid density ρ_f [kg/m^3]: 1.205 (20℃ atmosphere)
- Fluid viscosity η [Pa·s]: 1.82 × 10^{-5} (20℃ atmosphere)
- Gravitational acceleration g[m/s^2]: 9.8

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (4/27)

(ii) Selection of degradation events based on canister environment (3/26)

Event: **Hydrogen embrittlement** Degradation mode: Damaged

- **Evaluation of hydrogen partial pressure in a container**

  To examine hydrogen solubility in various materials, the hydrogen partial pressure inside a storage container for each hour was obtained from the hydrogen generation rate and the proportion of hydrogen in the atmosphere.
  Hydrogen pressure in the storage container = hydrogen in the atmosphere + hydrogen generated in the storage container, so (the ratio hydrogen pressure outside the container) : (the ratio of hydrogen in the atmosphere) equals 0.00005%, meaning that hydrogen pressure is 0.05 Pa.
  Hydrogen pressure in the container: PV = nRT (calculated using P: pressure, V: volume, n: mol, R: gas constant, T: temperature.
  Assuming that the temperature is 300℃, hydrogen partial pressure in the storage container is 1.4 Pa using the hydrogen generation rate.
  Therefore, **hydrogen pressure inside the container at a temperature of 300℃. is 1.45 Pa** (1.4 × 10^{-5} atm).

- **For stainless steels and Ni-based alloys**

  - As Figure 1 shows, considering the hydrogen pressure inside the container, the hydrogen solubility of SUS304L is lower than 5 ppm even at a temperature of 300℃ Note 1. Since the hydrogen solubility of austenitic stainless steel shows virtually no difference between steel type, SUS316 and SUS316L can be considered to have the same solubility.
  - Hydrogen embrittlement does not occur with SUS316L, even if it absorbs several hundred ppm at room temperature, and several tens of ppm at 85℃ Note 2.
  - The solubility of Ni-based alloys varies depending on the composition, but the amount of Ni at a temperature of 400℃ is approximately 85%, which is about five times that of Fe. Since it has been reported that the solubility of hydrogen in Fe does not differ much from that of SUS Note 3, it is estimated that the hydrogen solubility of 85% Ni at a temperature of 300℃ is 30 ppm or less.

  The same can be assumed for SUS316.

At these concentrations, hydrogen embrittlement is unlikely to occur.

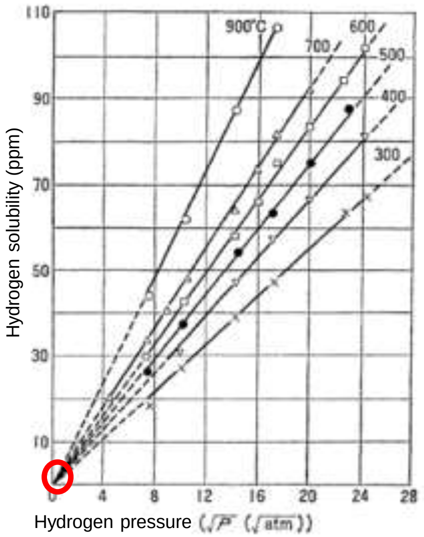


Figure 1 Relationship between hydrogen solubility and hydrogen pressure for 304 L Note 1

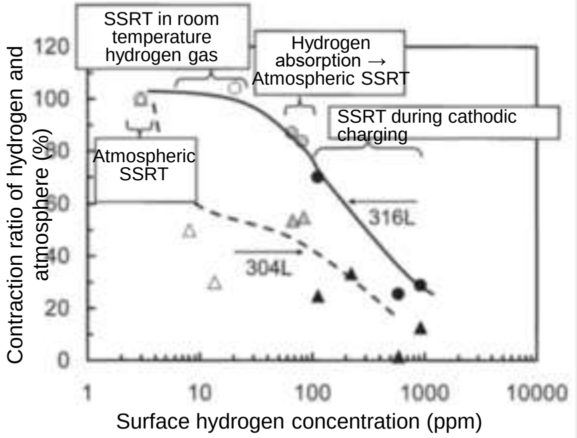


Figure 2 Effect of surface hydrogen concentration on hydrogen embrittlement characteristics Note 2

Note 1: Nomura et al., Journal of the Japan Institute of Metals and Materials, Vol. 15, No. 9, p.563-570 (1976)
Note 2: Ohmura, Nakamura, Materials and Environments, 60, 241-247 (2011)
Note 3: Yoshida et al., Journal of the Japan Institute of Metals and Materials, Vol. 11, No. 7, p.533-548 (1972)

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (5/27)

(ii) Selection of degradation events based on canister environment (4/26)

Event: **Hydrogen embrittlement** Degradation mode: Damaged

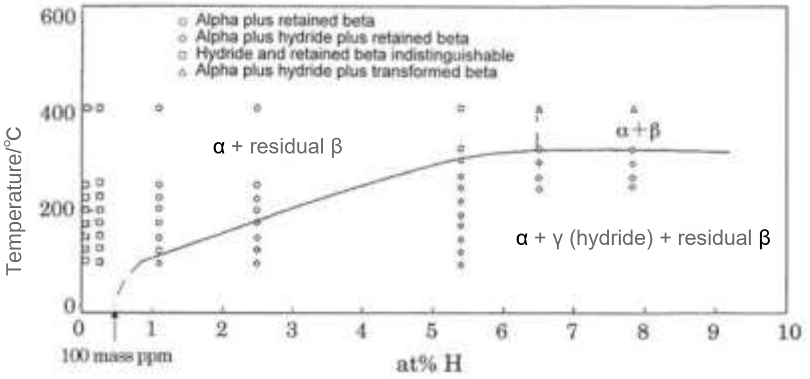


Figure 1 Hydrogen content and phase composition of commercially pure titanium ASTM Gr.3 containing 0.3% Fe

- For Ti

From Figure 1, the hydrogen solubility of Ti is approximately 10 ppm at room temperature and 100 mass ppm for industrial Ti (containing Fe: 0.3%). Considering that the concentration at which hydrogen embrittlement occurs is 100 to 300 ppm, hydrogen embrittlement may occur at room temperature depending on type Note 1.

Since the hydrogen solubility exceeds 1000 ppm at the high-temperature of 300℃, embrittlement may occur if used for a long periods of time in an environment where hydrogen is generated constantly. In addition, hydrides are formed when the temperature falls below 300℃, which may cause embrittlement Note 1.

- **For ceramics**

Table 1 shows reported examples of films that function as hydrogen barriers Note 2. Alumina, a ceramic, has the property of reducing the hydrogen permeation levels, and its application as a film for suppressing hydrogen embrittlement for metals, etc. is being examined. It has also been reported that embrittlement of crystalline alumina does not occur in a hydrogen environment Note 3. No reports on hydrogen embrittlement of cordierite and zeolite were found.

Table 1 Reported examples of films that function as hydrogen barriers

Type of film	Hydrogen permeation reduction rate
Al_2O_3	10 to 10000
TiC	10 to 10000
TiN	10 to 10000
Cr_2O_3	10
BN	100

Note 1: Fujii et al., Materials and Environments, 60, 248-253 (2011)

Note 2: NEDO "Fundamental Research Project on Advanced Hydrogen Science Interim Evaluation Report (2008)"

Note 3: JST/ Funds for Promoting Science and Technology, "Research on Function of Hydrogen in Environmental Embrittlement of Structural Materials" 2001-2002: 2nd term)

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (6/27)

(ii) Selection of degradation events based on canister environment (5/26)

Event: **Hydrogen embrittlement** Degradation mode: Damaged

- Glass fibers

No reports on the degradation behavior of hydrogen with glass fibers were found. There are reports that crystalline silica glass fibers do not embrittle in a hydrogen environment[*1].

However, since the heat resistance of glass fibers varies depending on the product, the maximum temperature of 300℃ within the storage container must be considered when selecting materials.

- Macromolecules

There are no reports **on polypropylene and its behavior is unknown**

The High Pressure Gas Safety Institute of Japan has reported that **polyethylene** can be used for hydrogen gas piping and that **it does not embrittle** [Note 2].

PTFE is generally approved for use in a hydrogen gas environment **and does not embrittle** [Note 3].

Liquid	PTFE	Joint material				Permeable
		CS	SUS304	SUS316	Brass	
Diisobutylene	—	—	●	●	●	
Diethyl phthalate	●	—	●	●	●	
Carbonic acid tetrachloride	●	×	△	△	△	
Dioctyl phthalate	●	●	●	●	●	
Cyclohexanone	●	—	●	●	—	
Cyclohexane	●	●	●	●	●	
Dimethylaniline	●	—	—	—	●	
Dimethyl phthalate	●	—	—	—	●	
Potassium dichromate	●	—	●	●	—	
Oxalic acid	●	×	△	●	×	
Bromine water	●	×	×	×	×	
10% Nitric acid	●	×	△	△	×	
70% Nitric acid	●	×	△	△	×	
Ferrous nitrate	●	—	●	●	—	
Ferric nitrate	●	×	●	●	—	
Potassium nitrate	—	×	△	●	—	
Calcium nitrate	●	●	●	●	●	
Silver nitrate	●	△	●	●	△	
Sodium nitrate	●	●	△	△	△	
Zinc acetate	●	●	●	●	●	
Zinc chloride	●	×	△	●	×	
Vinegar	●	×	△	●	×	
Mercury	●	●	●	●	×	
Magnesium hydroxide	●	●	●	●	●	
Hydrogen gas	●	●	●	●	●	C
Steam	●	△	—	△	△	A

● : Good △: Can be used for limited periods of time × : Not recommended — : No test data

Figure Usability of PTFE in each environment [Note 3]

Note 1: Funds for Promoting Science and Technology, "Research on Function of Hydrogen in Environmental Embrittlement of Structural Materials" 2001-2002: 2nd term)

Note 2: Tabata, Hydrogen Energy Systems, Vol.35, No.4 (2010)

Note 3: From the Chunichi Giken Products website

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (7/27)

(ii) Selection of degradation events based on canister environment (6/26)

Event: **Radiation degradation** Degradation Mode: Damaged

Study of the possibility that irradiation from radiation generated by the fuel debris changes the mechanical characteristics of the filter material after fuel debris is collected in a canister.

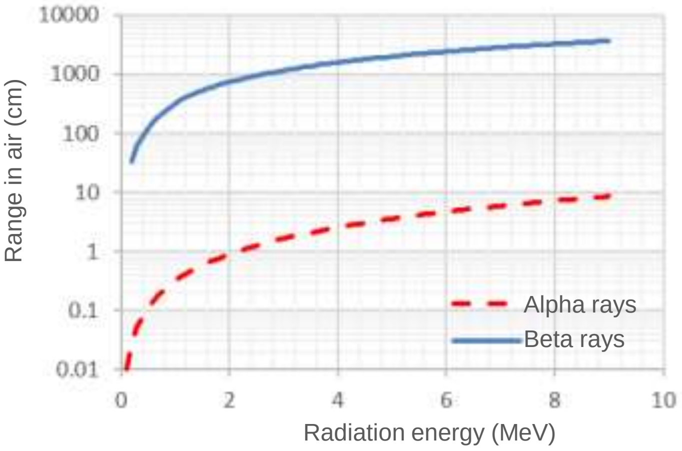


Figure Range of alpha and beta rays in air

Radiation generated by fuel debris

- Alpha rays, beta rays, and gamma rays derived from actinides, fission products, and activation materials are discharged from fuel debris.
- The range of alpha rays from actinide (approximately 5 to 7 MeV) is several centimeters in air and several micrometers in solids and water. They are discharged only from the surface of fuel debris. They do not impact anything other than fuel debris near the filter, and even if they adhere to the filter, they will not affect anything other than the surface of the material.
- Beta rays and gamma rays have a longer range than alpha rays, and since gamma rays have particularly high permeability, they are also irradiated from fuel debris far away from the filter.

Tasks that may cause radiation degradation

Constantly irradiated after fuel debris is collected in a canister.

The effects of radiation on filters

The mechanical characteristics of materials can change when exposed to irradiation from radiation.

If an impact is applied to a filter whose mechanical characteristics have been changed by irradiation from radiation, **the filter may be damaged and lose its functionality.**

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (8/27)

(ii) Selection of degradation events based on canister environment (7/26)

Event: **Thermal alteration** (maximum temperature 200℃) Degradation mode: Clogged & Damaged

Study ofd the possibility of the temperature of fuel debris rising due to decay heat and heat conduction causing the temperature of the filter to rise, resulting in thermal alteration and filter damage.

Evaluation was performed by comparing the maximum temperature with the melting point and softening point of the filter media. If available, information on the heat resistance temperature, etc., was also taken into consideration.

		Melting point [℃]	Softening point [℃]	Other [℃]	Evaluation	
Metal	**SUS304**	1398 to 1453 Note 1	—	—	○	Melting point is sufficiently high for 200℃ and thermal alteration does not occur. Filter damage is unlikely.
	SUS316	1370 to 1397 Note 1	—	—		
	Alloy600	1371 to 1427 Note 1	—	—		
	Ti	1668 Note 2	—	—		
Ceramics	**SiC**	—	—	Heat resistance temperature 1600 Note 4	○	Melting point, heat resistance temperature, and fire resistance are sufficiently high for 200℃, and thermal alteration does not occur. Filter damage is unlikely.
	Al_2O_3	2015 Note 3	—	—		
	Cordierite	—	—	Fire resistance 1400 Note 3		
Glass	**E-glass**	—	840 Note 5	Maximum operating temperature 280 Note 6	(○)	Softening point and maximum operating temperature are sufficiently high for 200℃, and thermal alteration does not occur. Filter damage is unlikely. Attention must be paid to the maximum operating temperature of each individual product.
	C-glass	—	749 Note 5	—		
	S-glass	—	970 Note 5	—		
	D-glass	—	771 Note 5	—		
Macromolecules	**Polyethylene**	65 to 140 Note 7	—	Normal heat resistance temperature 70 to 110 Note 8	×	**Melting point is less than 200℃ and normal heat resistance temperature is less than 200℃, so they cannot withstand use at 200℃.**
	Olefin	65 to 168 Note 7	—	Normal heat resistance temperature 70 to 140 Note 8		
	PTFE (Teflon)	327 Note 7	—	Normal heat resistance temperature 260 Note 8	○	Melting point and normal heat resistance temperature are high for 200℃, and thermal alteration does not occur. Filter damage is unlikely

○: No need to consider the test method because there is no possibility of occurrence ×: Need to consider the test method

Note 1: Handbook of Stainless Steel
Note 2: Daido Steel: https://www.daido.co.jp/products/titanium/properties/index.html
Note 3: Inorganic Chemistry Handbook, Gihodo Shuppan Co., Ltd.
Note 4: Ceramic New Materials of SiC System, Japan Society for the Promotion of Science
Note 5: Central Glass Fiber Co., Ltd.: http://www.centralfiberglass.com/jp/glass_fiber/outline/index.html
Note 6: For filter bags - Nitto Boseki (nittobo.co.jp): https://www.nittobo.co.jp/business/glassfiber/industrial/heatresistant/filter.html
Note 7: New Edition Points for Selecting Plastic Materials, Japanese Standards Association
Note 8: The Japan Plastics Industry Federation: http://www.jpif.gr.jp/2hello/conts/youto.pdf

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (9/27)

(ii) Selection of degradation events based on canister environment (8/26)

Study ofd the possibility of the temperature of fuel debris rising due to decay heat and heat conduction causing the temperature of the filter to rise, resulting in thermal alteration and filter damage.

Evaluation was performed by comparing the maximum temperature with the melting point and softening point of the filter media. If available, information on the heat resistance temperature, etc., was also taken into consideration.

Event: **Thermal alteration** (maximum temperature 300℃)
Degradation mode: Clogged & Damaged

		Melting point [℃]	Softening point [℃]	Other [℃]	Evaluation	
Metal	**SUS304**	1398 to 1453 Note 1	—	—	○	Melting point is sufficiently high for 300℃, and thermal alteration does not occur. Filter damage is unlikely.
	SUS316	1370 to 1397 Note 1	—	—		
	Alloy600	1371 to 1427 Note 1	—	—		
	Ti	1668 Note 2	—	—		
Ceramics	**SiC**	—	—	Heat resistance temperature 1600 Note 4	○	Melting point, heat resistance temperature, and fire resistance are sufficiently high for 300℃, and thermal alteration does not occur. Filter damage is unlikely.
	Al_2O_3	2015 Note 3	—	-		
	Cordierite	—	—	Fire resistance 1400 Note 3		
Glass	**E-glass**	—	840 Note 5	Maximum operating temperature 280 Note 6	(X)	Softening point is sufficiently high for 300℃, and thermal alteration of filter media does not occur. Some materials have a maximum operating temperature of less than 300℃, **so attention must be paid to the maximum operating temperature of each individual product.**
	C-glass	—	749 Note 5	—		
	S-glass	—	970 Note 5	—		
	D-glass	—	771 Note 5	—		
Macromolecules	**Polyethylene**	65 to 140 Note 7	-	Normal heat resistance temperature 70 to 110 Note 8	×	**Melting point is less than 300℃ (type 2) and normal heat resistance temperature is less than 300℃, so they cannot withstand use at 300℃.**
	Olefin	65 to 168 Note 7	-	Normal heat resistance temperature 70 to 140 Note 8		
	PTFE (Teflon)	327 Note 7	-	Normal heat resistance temperature 260 Note 8		

○: No need to consider the test method because there is no possibility of occurrence ×: Need to consider the test method

Note 1: Handbook of Stainless Steel
Note 2: Daido Steel: https://www.daido.co.jp/products/titanium/properties/index.html
Note 3: Inorganic Chemistry Handbook, Gihodo Shuppan Co., Ltd.
Note 4: Ceramic New Materials of SiC System, Japan Society for the Promotion of Science
Note 5: Central Glass Fiber Co., Ltd.: http://www.centralfiberglass.com/jp/glass_fiber/outline/index.html
Note 6: For filter bags - Nitto Boseki (nittobo.co.jp): https://www.nittobo.co.jp/business/glassfiber/industrial/heatresistant/filter.html
Note 7: New Edition Points for Selecting Plastic Materials, Japanese Standards Association
Note 8: The Japan Plastics Industry Federation: http://www.jpif.gr.jp/2hello/conts/youto.pdf

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (10/27)

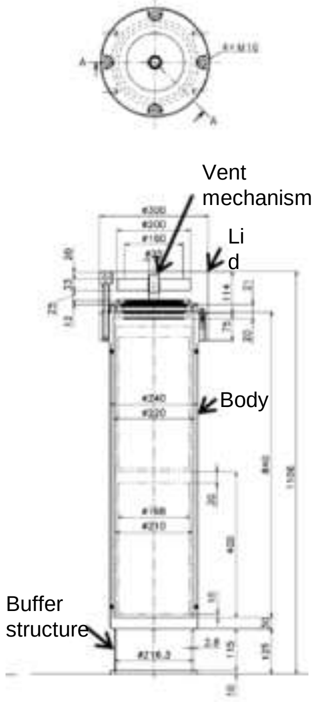
(ii) Selection of degradation events based on canister environment (9/26)

Event: **Thermal deformation** (container) Degradation mode: Clogged & Damaged

Study of the possibility of the temperature of fuel debris rising due to decay heat and heat conduction causing the temperature of the container to rise, exerting stress on and damaging the affixed filter and causing it to lose functionality.

Canister and filter media: Assuming the following conditions

- The canister is made of SUS316L (linear thermal expansion coefficient, 16.2×10^{-6} [/°C] Note 1) and has a cylindrical shape
- The same material is used for canister and the outer frame of the filter
- The filter is fixed rigidly to the canister
- Outer diameter of filter media is 200 mm and the outer diameter of canister (and filter frame) is 300 mm
- The filter media is dense



Inner diameter: 220 mm

Figure Canister (assumed) Note 2

The thermal stress on the filter media at maximum operating temperature for each scenario was evaluated based on the above assumptions.

Note 1: Japan Stainless Steel Association: http://www.jssa.gr.jp/contents/faq-article/q6/

Note 2: Taken from the Subsidy Project of "Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)" in the FY2018 Supplementary Budgets, Final Report, June 2021

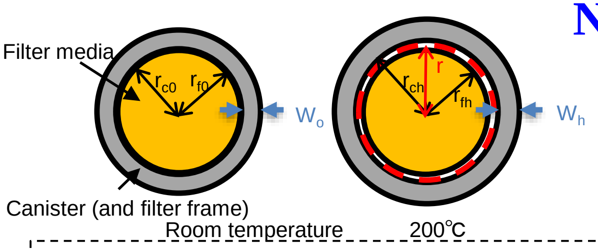
6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (11/27)

(ii) Selection of degradation events based on canister environment (10/26)



<Model>
- Impacts from thickness are not taken into consideration (filter thickness = canister thickness)
- The filter media and filter frame as well as the filter outer frame and the inner diameter of the canister are rigidly connected
- The filter material is dense (no gaps).
- The outer frame of the filter and the canister are made of the same material.
- The outside diameter of the filter media is 200 mm, and the outside diameter of the canister (and filter frame) is 300 mm.
- Evaluate the stress (as thermal stress) required to extend the radius of the filter media (r_{fh}) after free expansion to the equilibrium position (r)

Event: **Thermal deformation** (container) (maximum temperature 200℃) Degradation mode: Clogged & Damaged

		Linear thermal expansion coefficient of filter media Note 14, α_f [10^{-6} / ℃]	Young's modulus of filter media Note 14 E_f [GPa]	Stress on filter media σ_c [MPa]	Tensile strength of filter media Note 14 σ [MPa]	Impact assessment Note 15	
Metal	**SUS316**	16.2 Note 1	193 Note 1	0	470 Note 4	×	If the canister is not made of SUS316L (thermal expansion is not the same), thermal stress will occur and **there is a possibility of damage.**
	SUS304	17.8 Note 1	193 Note 1	-36	470 Note 4		If the canister is made of SUS316L, the thermal expansion of the filter media and the canister are the same, stress applied to the filter media is low, and the tensile strength of the filter media is low, so the impact is considered to be small. However, stress will increase **if the volume ratio of the filter media decreases and there will be a possibility of damage**.
	Alloy600	13.3 Note 2	157 Note 2	56	600 to 1200 Note 2		
	Ti	8.4 Note 3	106 Note 3	112	240 Note 5	×	The thermal expansion of the filter media is smaller than that of the canister, so thermal stress (tensile) is generated. Although the thermal stress is low compared to the material strength, stress will increase **if the volume ratio of the filter media decreases and there will be a possibility of damage**.
Ceramics	**SiC**	3.7 Note 6	447 Note 8	447	390 Note 10	×	The thermal expansion of the filter media is smaller than that of the canister, so thermal stress (tensile) is generated. The thermal stress is high compared to the material strength, and **there is a possibility of damage**.
	Al_2O_3	7.7 Note 6	370 Note 9	277	120 Note 11		
	Cordierite	1.1 Note 7	88 Note 7	188	25 to 40 Note 7		
Glass	**E-glass**	5.5 Note 12	72.5 Note 12	113	3430 Note 12	×	The thermal expansion of the filter media is smaller than that of the canister, so thermal stress (tensile) is generated. Although the thermal stress is low compared to the material strength, stress will increase **if the volume ratio of the filter media decreases and there will be a possibility of damage .**
	C-glass	7.3 Note 12	68.6 Note 12	90	2744 Note 12		
	S-glass	2.9 Note 12	84.3 Note 12	159	4655 Note 12		
	D-glass	3.1 Note 12	51.9 Note 12	104	2450 Note 12		
Macromolecules	**Polyethylene**	—	—	—	—	×	Thermal stress (compression) occurs in PTFE because the thermal expansion of the filter media is greater than that of the canister. Compressive stress will rise **if the volume ratio of the filter media decreases and there will be a possibility of damage.**
	Olefin	—	—	—	—		
	PTFE	100 Note 13	0.4 Note 13	-6	14 Note 13		

○: No need to consider the test method because there is no possibility of occurrence ×: Need to consider the test method

Note 1: Japan Stainless Steel Association: http://www.jssa.gr.jp/contents/faq-article/q6/
Note 2: Takayama Co., Ltd.: http://www.takayama-industry.com/inconel/
Note 3: Daido Steel: https://www.daido.co.jp/products/titanium/properties/index.html
Note 4: Handbook of Stainless Steel
Note 5: Kobe Steel: https://www.kobelco.co.jp/products/titan/files/details.pdf
Note 6: Kyocera: https://www.kyocera.co.jp/prdct/fc/list/tokusei/bouchou/
Note 7: Inorganic Chemistry Handbook, Gihodo Shuppan Co., Ltd. (as cordierite porcelain, linear thermal expansion is the value between 20 to 100℃)
Note 8: Ferrotec Material Technologies Corporation: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwioqeK3xcTzAhWdwosBHZa-CKkQFnoECAQQAQ&url=https%3A%2F% 2Fft-mt.co.jp%2Fassets%2Fpdf%2Fjp%2Fcvd_sic%2Fcvd_sic_performance.pdf&usg=AOvVaw0eZTi5AELcG7hFkH0TsKj0
Note 9: Japan Fine Ceramics Co., Ltd.: https://www.japan-fc.co.jp/products/cate01/cate0101/al2o3-995-al2o3-999.html
Note 10: Fujisawa, Matsusue, Takahara: Tensile Strength of Engineering Ceramics Vol.35, No.397 (1986) p. 1112
Note 11: Sakaguchi E.H VOC Corp.: https://sakaguchi-dennetsu.co.jp/assets/files/PDF/lineup/other/taikabutsu_sankou.pdf
Note 12: Nanjo, Journal of the Japan Society for Composite Materials, Vol.33, No.4 (2007) p.141 - 149
Note 13: Kayo Corporation: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiLi4DdttjzAhWSHXAKHStnCScQFnoECAYQAQ&url=https%3A%2F%2Fkayo-corp.co.jp%2Fcommon%2Fpdf%2Fpla_propertylist01.pdf&usg=AOvVaw2Vxk2pSVEW3Vcqf-4O4ONL
Note 14: Underlined figures may be data for temperatures other than 200℃
Note 15: Differs depending on design conditions

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

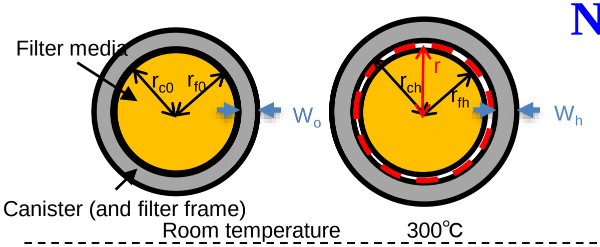
③ Implementation items and results

b. Study of filter life evaluation methods (12/27)

(ii) Selection of degradation events based on canister environment (11/26)

Event: **Thermal deformation** (container) (maximum temperature **300℃**)

Degradation mode: Clogged & Damaged



<Model>
- Impacts from thickness are not taken into consideration (filter thickness = canister thickness)
- The filter media and filter frame as well as the filter outer frame and the inner diameter of the canister are rigidly connected
- The filter material is dense (no gaps).
- The outer frame of the filter and the canister are made of the same material.
- The outside diameter of the filter media is 200 mm, and the outside diameter of the canister (and filter frame) is 300 mm.
- Evaluate the stress (as thermal stress) required to extend the radius of the filter media (r_{fh}) after free expansion to the equilibrium position (r)

		Linear thermal expansion coefficient of filter media Note 14 **, α_f [10^{-6} /℃]**	**Young's modulus of filter media** Note 14 **E_f [GPa]**	**Stress on filter media σ_c [MPa]**	**Tensile strength of filter media** Note 14 **σ [MPa]**	**Impact assessment** Note 15	
Metal	**SUS316**	16.2 Note 1	193 Note 1	0	470 Note 4	×	If the canister is not made of SUS316L (thermal expansion is not the same), thermal stress will occur and there is a possibility of damage.
	SUS304	17.8 Note 1	193 Note 1	-56	465 Note 4		If the canister is made of SUS316L, the thermal expansion of the filter media and the canister are the same, stress applied to the filter media is low, and the tensile strength of the filter media is low, so the impact is considered to be small. However, stress will increase **if the volume ratio of the filter media decreases and** there will be a possibility of damage.
	Alloy600	13.3 Note 2	157 Note 2	88	600 to 1200 Note 2		
	Ti	8.4 Note 3	106 Note 3	177	170 Note 5	×	The thermal expansion of the filter media is smaller than that of the canister, so thermal stress (tensile) is generated. The thermal stress is high compared to the material strength, and there is a possibility of damage.
Ceramics	**SiC**	3.7 Note 6	447 Note 8	705	385 Note 10	×	The thermal expansion of the filter media is smaller than that of the canister, so thermal stress (tensile) is generated. The thermal stress is high compared to the material strength, and there is a possibility of damage.
	Al_2O_3	7.7 Note 6	370 Note 9	437	120 Note 11		
	Cordierite	1.1 Note 7	88 Note 7	296	25 to 40 Note 7		
Glass	**E-glass**	5.5 Note 12	72.5 Note 12	178	3430 Note 12	×	The thermal expansion of the filter media is smaller than that of the canister, so thermal stress (tensile) is generated. Although the thermal stress is low compared to the material strength, stress will increase **if the volume ratio of the filter media decreases and** there will be a possibility of damage.
	C-glass	7.3 Note 12	68.6 Note 12	141	2744 Note 12		
	S-glass	2.9 Note 12	84.3 Note 12	251	4655 Note 12		
	D-glass	3.1 Note 12	51.9 Note 12	163	2450 Note 12		
Macromolecules	**Polyethylene**	—	—	—	—	×	Thermal stress (compression) occurs in PTFE because the thermal expansion of the filter media is greater than that of the canister. Compressive stress will rise **if the volume ratio of the filter media decreases and** there will be a possibility of damage.
	Olefin	—	—	—	—		
	PTFE	100 Note 13	0.4 Note 13	-9	14 Note 13		

○: No need to consider the test method because there is no possibility of occurrence ×: Need to consider the test method

Note 1: Japan Stainless Steel Association: http://www.jssa.gr.jp/contents/faq-article/q6/
Note 2: Takayama Co., Ltd.: http://www.takayama-industry.com/inconel/
Note 3: Daido Steel: https://www.daido.co.jp/products/titanium/properties/index.html
Note 4: Handbook of Stainless Steel
Note 5: Kobe Steel: https://www.kobelco.co.jp/products/titan/files/details.pdf
Note 6: Kyocera: https://www.kyocera.co.jp/prdct/fc/list/tokusei/bouchou/
Note 7: Inorganic Chemistry Handbook, Gihodo Publishing Co., Ltd. (as cordierite porcelain. Linear thermal expansion is the value of 20-100℃)
Note 8: Ferrotec Material Technologies Corporation: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwioqeK3xcTzAhWdwosBHZa-CKkQFnoECAQQAQ&url=https%3A%2F% 2Fft-mt.co.jp%2Fassets%2Fpdf%2Fjp%2Fcvd_sic%2Fcvd_sic_performance.pdf&usg=AOvVaw0eZTi5AELcG7hFkH0TsKj0
Note 9: Japan Fine Ceramics Co., Ltd.: https://www.japan-fc.co.jp/products/cate01/cate0101/al2o3-995-al2o3-999.html
Note 10: Fujisawa, Matsusue, Takahara: Tensile Strength of Engineering Ceramics Vol.35, No.397 (1986) p. 1112
Note 11: Sakaguchi E.H VOC Corp.: https://sakaguchi-dennetsu.co.jp/assets/files/PDF/lineup/other/taikabutsu_sankou.pdf
Note 12: Nanjo, Journal of the Japan Society for Composite Materials, Vol.33, No.4 (2007) p.141 - 149
Note 13: Kayo Corporation: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiLi4DdttjzAhWSHXAKHStnCScQFnoECAYQAQ&url=https%3A%2F%2Fkayo-corp.co.jp%2Fcommon%2Fpdf%2Fpla_propertylist01.pdf&usg=AOvVaw2Vxk2pSVEW3Vcqf-4O4ONL
Note 14: Underlined figures may be data for temperatures other than 300℃
Note 15: Differs depending on design conditions

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (13/27)

(ii) Selection of degradation events based on canister environment (12/26)

Event: **Thermal Convection** Degradation Mode: Clogged & Damaged

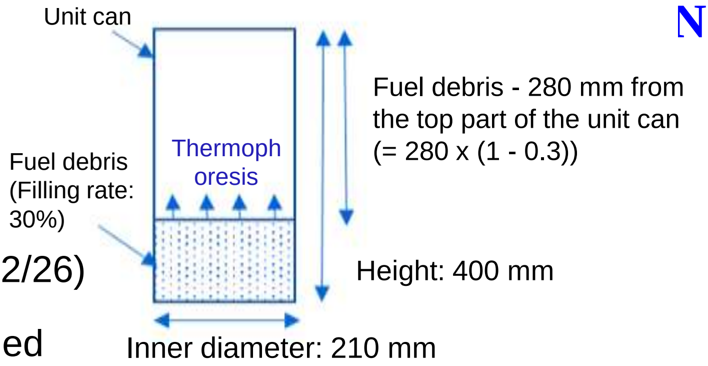


Figure 1 Dust generation by thermophoresis

- When the maximum temperature of fuel debris is assumed to be 300℃ and the upper part of the unit can is room temperature, creating a temperature gradient in the gas phase section of the unit can where a force toward the low temperature side (thermophoresis) is exerted on the particles contained in the fuel debris, evaluate whether an event that degrades the filter occurs by comparing it against the settling velocity of particles.
- The rising velocity of the particles and the thermophoretic velocity in the unit can environment caused by thermophoresis were evaluated, which were compared with the settling velocity based on Stokes' law.

Thermophoretic velocity

The Waldmann equation Note 1

$$U_T = K_{th} \bullet v \bullet \nabla T / T$$

U_T: Thermophoretic velocity [m/s]
K_{th}: Thermophoretic coefficient*
v: Kinematic viscosity coefficient of gasses [m^2/s]
= Viscosity coefficient of fluids [Pa·s] / Density of fluids [kg/m^3]
⇒ 20℃, use the value for air
∇T: Temperature gradient [K/m]
⇒ Fuel debris surface at 300℃, upper part of unit can at 25℃ (room temperature)
Use the value 982 K/m divided by 280 mm, the distance between the fuel debris and the top of the unit can
T: Absolute temperature [K]

Note 1: Suzuki, Dobashi, et al., Estimation Method of Thermophoretic Behavior of Soot, Journal of the Combustion Society of Japan, Vol.52, No.59 (2010) p. 68 - 75

*About the thermophoretic coefficient K_{th}

- It depends on the degree of coarseness when the particles are agglomerated. Coarseness is expressed by the degree of dimensionless, which is the ratio of bulk density to true density. The smaller the degree of dimensionless (the coarser the aggregation of the particles), the more likely it is that particles will be affected by thermophoresis, and thermophoretic coefficient K_{th} will be larger.
- Since the degree of dimensionless for fuel debris particles inside the canister is unknown, K_{th} = 1 is conservatively set here in order to increase thermophoretic velocity.
- This should be re-evaluated as soon as details on fuel debris information become available.

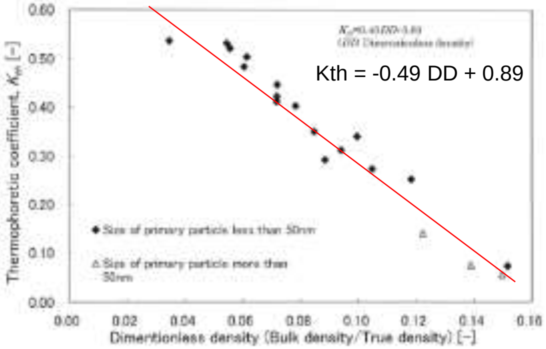


Figure 2 Correlation between the degree of dimensionless and the thermophoretic coefficient Note 1

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (14/27)

(ii) Selection of degradation events based on canister environment (13/26)

Event: **Thermal Convection** Degradation Mode: Clogged & Damaged

- The thermophoretic velocity is 5 × 10^{-5} m/s, which exceeds the particle rising velocity for particles of 1 μm or less (particles are dispersed by thermophoresis).
- The travel distance of particles dispersed by thermophoresis is 1 × 10^{-8} mm, which is a very small distance and less than the distance to the filter.

⇒ **The distance particles rise due to thermal convection is sufficiently small, so filter degradation from thermal convection can be ignored.**

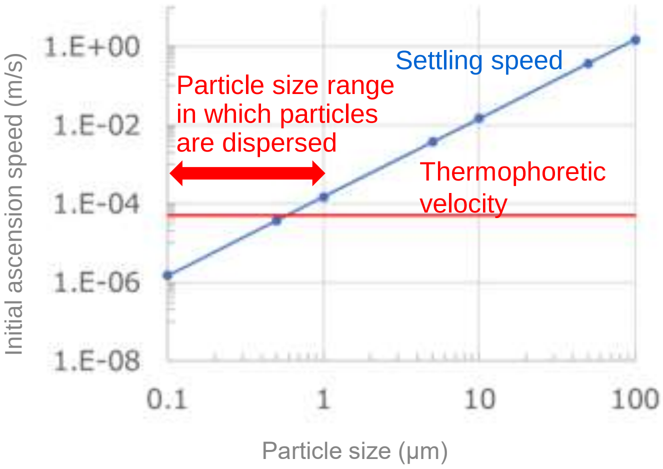


Figure 1 Comparison of thermophoretic velocity and settling velocity

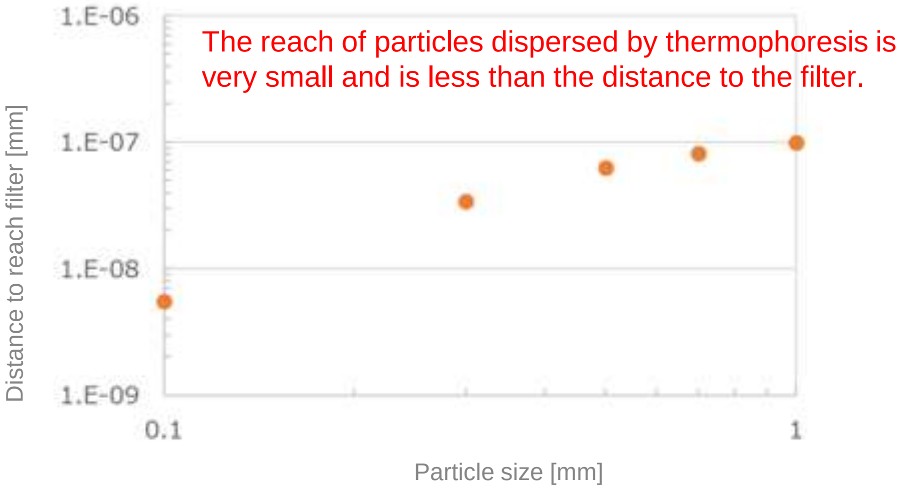


Figure 2 Result of evaluation on distance reached by particles

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (15/27)

(ii) Selection of degradation events based on canister environment (14/26)

Event: **Impact** Degradation Mode: Clogged & Damaged

Study of the possibility of loss of filter functionality and deformation or damage to containers and filters from impacts such as collisions and being dropped during transportation and earthquakes.

Canister weight

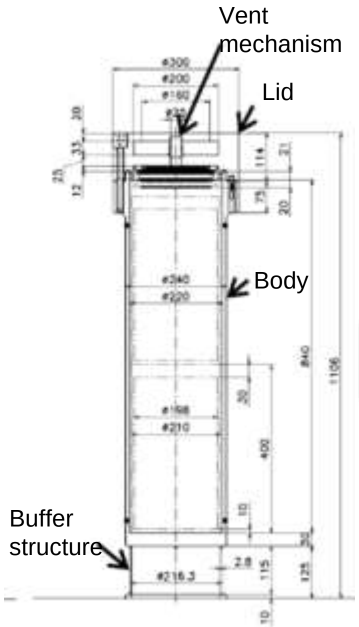
- The following specifications were assumed for the metal part.

	Lid	Body	Interference structure	Unit can
Material	SUS316L (Density: 8.0 g/cm^3)	SUS316L (Density: 8.0 g/cm^3)	SUS316L (Density: 8.0 g/cm^3)	SUS316L (Density: 8.0 g/cm^3)
Outer dimensions	Φ300 mm × 114 mm	Φ240 mm × 840 mm	Φ240 mm × 840 mm	Φ210mm × 400 mm
Thickness	50 mm	10 mm	2.8 mm	6 mm

- Fuel debris is assumed to have a filling rate of 50% and a density of 11 g/cm^3.

The above specifications were used to calculate the weight of the unit can and the canister containing the fuel debris.

The canister weight is assumed to be approximately 300 kg.



Inner diameter: 220 mm

Figure 1 Canister structure example Note 1

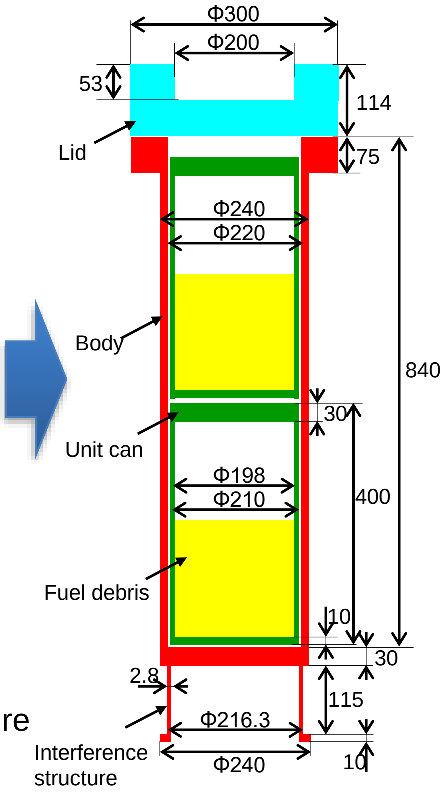


Figure 2 Assumed canister structure

Note 1: Taken from the Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2018 Supplementary Budgets, Final Report, June 2021

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (16/27)

(ii) Selection of degradation events based on canister environment (15/26)

Event: **Impact** Degradation Mode: Clogged & Damaged

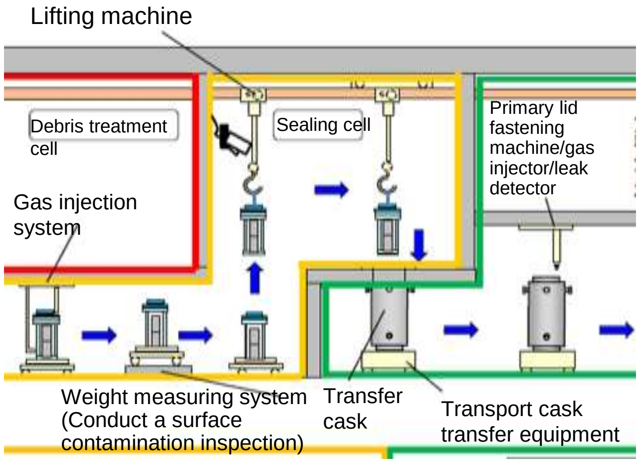


Figure Example task during the canister handling flow (assumed) Note 1

Tasks that may cause an impact

- Falls after lifting a canister (including earthquakes)
- Collision to the side of the canister caused by shaking when transferring a canister or shaking due to an earthquake

The effects of impacts on filters

- When a canister (approximately 300 kg) is dropped from a height of several meters, **the impact and deformation of the canister could deform or damage the filter and cause it to lose functionality.** The state of deformation and/or damage depends on the height of the fall, movement speed, point of impact (dropped from the bottom of the canister, overturning, etc.), and how the filter is affixed.

- **The filter may become deformed and/or damaged and lose its functionality during an impact**. In addition, the state of deformation and/or damage depends on the movement speed at the time of impact, the point of impact, how the filter is affixed, etc.

- Depending on the specifications of the unit can and the specifications of the filter mounting part (the shape of the mounting part, any baffle plates and their specifications, etc.), **deformation, damage, and/or clogging of the filter due to unit cans or splashing of fuel debris must be considered.**

→ **Test methods and conditions are studied as degradation events that should be considered.**

Note 1: Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2018 Supplementary Budgets
Extracted and edited from Final Report Material June 2021

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (17/27)

(ii) Selection of degradation events based on canister environment (16/26)

Event: **Dust generated by vibration** Degradation mode: Clogged & Damaged

- When the initial velocity (determined by earthquake motion and seismic cycle) acts perpendicularly to the particles, the dust generated by earthquake motion is considered to have an effect when the height reached by the particles exceeds the distance between the fuel debris and the filter.
- Using the below formula, the initial velocity of the Great East Japan Earthquake was 4.4 m/s.

Initial velocity [m/s] = Maximum seismic acceleration of 29.33 [m/s^2]

× (Seismic cycle 1/3.3 [s] × Time period of upward force 0.5 [-])

- The height to reach pores with an initial velocity of 4.4 m/s was evaluated by solving the equation of motion Note 2 for the rising and settling of a particle

- Equation of motion for a particle during rising

$$\rho_P V_P \frac{dv}{dt} = -\rho_P V_p g + F_b - R_f \ldots(1)$$

ρ_P, V_P, v are particle density, volume, and velocity, respectively
t is time, g is gravitational acceleration,
F_b is buoyancy, R_f is fluid resistance

(Positive indicates upward movement)

Maximum seismic acceleration during the Great East Japan Earthquake = 29.33 m/s^2 Note 1

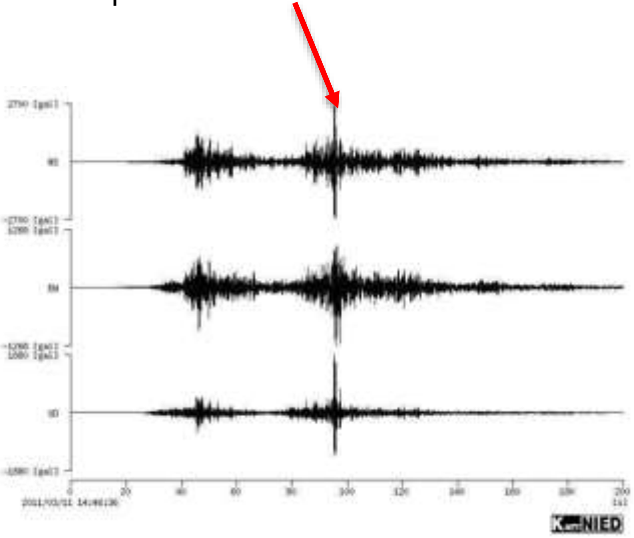
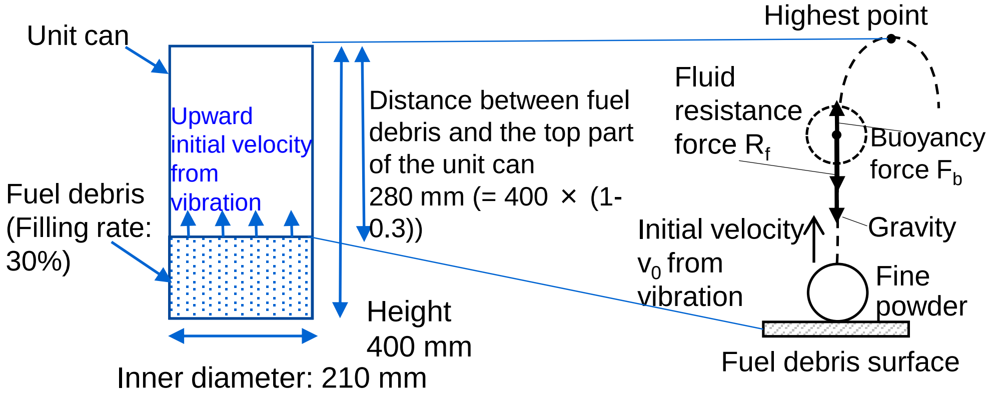


Figure 1 Strong vibrations from the Great East Japan Earthquake Note 1



Schematic of Unit can **Physical model**

Figure 2 Unit can schematic and physical model of dust generation from vibration

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Note 1: Kunugi et al., Strong Motion Characteristics of the 2011 Tohoku-Oki Earthquake, National Research Institute for Earth Science and Disaster Resilience Major Disaster Investigation No. 48 (2012)

Note 2: Kohei Ogawa, Series <New Chemical Engineering> 1, "Fluid Transport Analysis" First Edition, Asakura Publishing Co., Ltd., (2011) p. 58

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (18/27)

(ii) Selection of degradation events based on canister environment (17/26)

Event: **Dust generated by vibration** Degradation mode: Clogged & Damaged

- The distance reached by fuel debris' upward motion is calculated when receiving an initial vertical velocity of 4.4 m/s from earthquake motion.
- The reach for target particles of 100 μm or less is generally small, approximately 320 mm for 100 μm particles.
- Because this result returns a similar distance, the **influence of the earthquake motion cannot be ignored.**

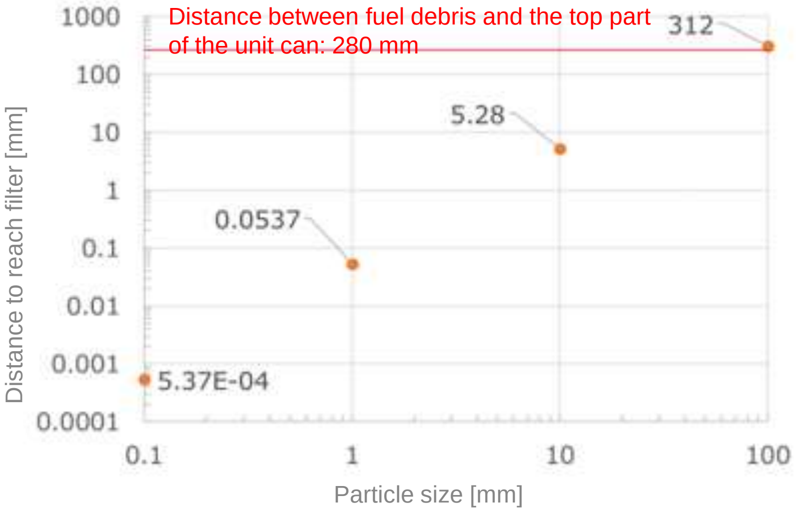


Figure Result of calculations on the maximum height reached by particles from vibration

→ Test methods and conditions are studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (19/27)

(ii) Selection of degradation events based on canister environment (18/26)

Event: **Thickness reduction** Degradation Mode: Damaged

Moisture evaporates at temperatures above 100℃, so the events here examined a scenario below 100℃.

- For metal filters

The pitting corrosion potential and pitting corrosion resistance index of **various stainless steels** shown in Figure 1 show that the corrosion resistance is that of a 625 alloy, which is SUS304 < SUS316L < Ni-based alloy. Figure 2 shows that crevice corrosion does not occur in SUS as long as the chloride ion concentration remains under 300 ppm. Figures 3 and 4 show that Ni-based alloys and Ti have a higher resistance to crevice corrosion than SUS, so it is assumed that corrosion is less likely to occur.

However, condensation always generates moisture, and particles derived from chlorides and waste adhere locally, which will increase the corrosion potential in that area only. **Corrosion can occur if the pitting corrosion potential or crevice corrosion potential is exceeded.** The possibility exists with SUS, which has a relatively low corrosion resistance, and so test evaluations should be conducted.

There is almost no difference between SUS316 and SUS316L in terms of pitting corrosion resistance index and corrosion potential, so evaluations on wastage are considered to be the same.

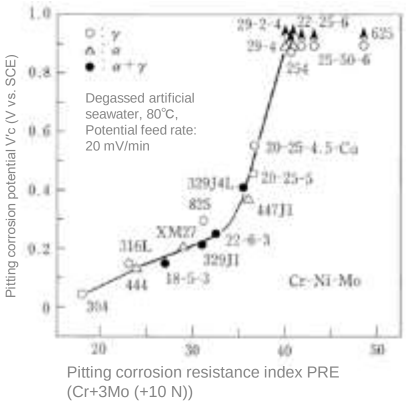


Figure 1 Pitting corrosion potential and pitting corrosion resistance index of various stainless steels

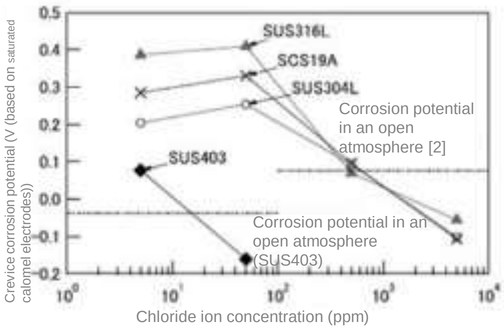


Figure 2 Relationship between crevice corrosion potential and chloride ion concentration Note 1

Note 1:Central Research Institute of Electric Power Industry Report Q12001 April 2013

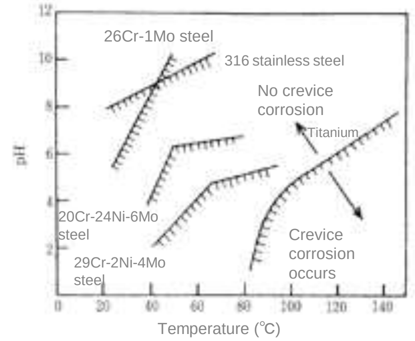
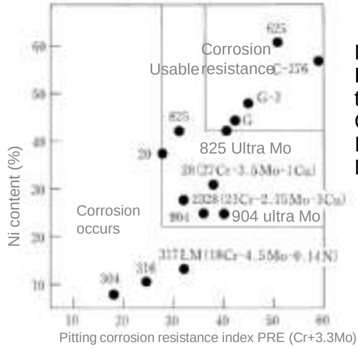


Figure 3 The maximum occurrence of crevice corrosion in Ti and various stainless steels inside a saturated sodium chloride aqueous solution environment Note 2

Note 2: Hiroshi Sato et al., The Piping Engineering, 24, 66 (1982)



Note 3: Proceedings of the Japan Concrete Institute, Vol.30, No.1 (2008)

Figure 4 Relative comparison of applicability of various Ni alloys and stainless steels to stress corrosion cracking and crevice corrosion in cooling zone lines Note 3

6. Implementation details

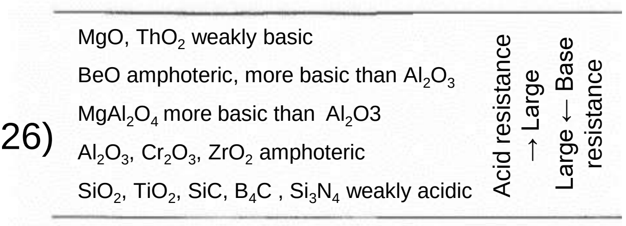
6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (20/27)

(ii) Selection of degradation events based on canister environment (19/26)

Event: **Thickness reduction** Degradation Mode: Damaged



MgO, ThO_2 weakly basic

BeO amphoteric, more basic than Al_2O_3

$MgAl_2O_4$ more basic than Al_2O3

Al_2O_3, Cr_2O_3, ZrO_2 amphoteric

SiO_2, TiO_2, SiC, B_4C , Si_3N_4 weakly acidic

Acid resistance → Large

Large ← Base resistance

Figure 1 Corrosion resistance of ceramics against acids and bases Note 1

- For **Ceramics**

Aluminum oxide (Al_2O_3)

Good corrosion resistance in acid solutions, but poor corrosion resistance in alkaline solutions.

The higher the purity, **the better the corrosion resistance** (reported in high-temperature water).

Cordierite ($2MgO \bullet 2Al_2O_3 \bullet 5SiO_2$)

Reports state that it has **less corrosion resistance** than aluminum oxide and is strong against alkalis.

Zeolites (based on SiO_4 and AlO_4 tetrahedral structures)

There are no reports on its corrosion resistance, and its behavior is unknown.

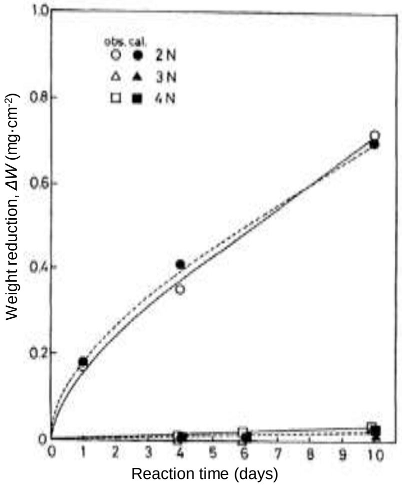


Figure 2 Relationship between weight change and reaction time due to corrosion of alumina ceramics in 300℃ water Note 1

- For **Glass**

E, C, S, and D types of glass fiber filters exist, but only C-type is manufactured with corrosion resistance in mind. **There are no reports on its corrosion resistance, and its behavior is unknown.**

Note 1: Yoshio et al., Materials and Environments, 44, 405 - 415 (1995)

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (21/27)

(ii) Selection of degradation events based on canister environment (20/26)

Event: **Thickness reduction** Degradation Mode: Damaged

- For **Macromolecule filters**

Polyethylene, polypropylene and PTFE show **good corrosion resistance to** salt water as shown in the table.

Therefore, they can be used so long as attention is paid to the operating temperature (polyethylene: max. 130℃, polypropylene: max. 160℃, PTFE: max. 260℃).

Table 1 Corrosion resistance of polyethylene, polypropylene, and PTFE Note 1

Type of plastic material	Thermal grease														
	Polyvinyl chloride		Polyvinylidene chloride	Polyvinyl alcohol	Polyvinyl acetate	Polystyrene	ABS	Polyethylene	Polypropylene	Polyisobutylene	Polyamide (Nylon)	Polyoxymethylene (Paraformaldehyde / Polyoxymethylene)	Methacrylic (acrylic)	Polycarbonate	Fluorine (Teflon)
	Soft	Hard													
Oil/Solvent/Chemicals (arranged phonetically) Temperature/Weight % & Temperature ℃	PVC	PVC	PVdC	PVA	PVAc	PS	ABS	PE	PVC	PIB	PA	POM	PMMA	PC	PIFE
Potassium chloride	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Calcium chloride	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Mercuric chloride	○	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Stannic chloride	○	◎	◎	◎			○	◎	◎	x	○	○	○	○	◎
Ferric chloride	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Copper chloride	○	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Thionyl chloride	x	x					x	x	x	x	x				◎
Nickel chloride	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Barium chloride	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Benzyl chloride	x	△					x			x	x				◎
Magnesium chloride	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Methyl chloride	x	x	x	x	x	x	x	x	△	x	x	x	x	x	◎
Hydrochloric acid [10•RT]	○	◎	◎	◎			◎	◎	◎	◎	○		○	◎	◎
Hydrochloric acid [20•RT]	○	◎	◎	◎			○	◎	◎	◎	△		○	○	◎
Hydrochloric acid [20•80]	x	△	△	△	x	x	△	△	○	△	x	x	△	△	◎
Hydrochloric acid [38•RT]	△	◎	◎	◎			△	◎	◎	◎	x		○	△	◎
Salt water	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Chlorine gas (dry)	△	○	○			◎	x	△	△	x	x	x	○	x	○
Chlorine gas (wet)	△	○	○				x	△	△	x	x	x	△	x	○
Chlorinated solvents	x	x	x	x	x	x	x	x	x	x	x	x	x	x	◎○

◎ represents that corrosion resistance is particularly good for polyethylene, polypropylene, and PTFE (○: good; △: not good; x: bad)

Note 1: Excerpt from Kayo Corporation
http://www.kayo-corp.co.jp/

→ **Test methods and conditions are studied as degradation events that should be considered.**

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (22/27)

(ii) Selection of degradation events based on canister environment (21/26)

Event: **Oxide film generation** Degradation mode: Clogged

Macromolecule materials cannot be used because they exceed the heat resistance temperature.

Evaluate metal filters, ceramics, and glass fibers.

- **Metal filters**

  High-temperature oxidation of alloys containing Cr increases slightly up to 700℃.

  It is several nanometers for Ti, even after one hour of oxidation treatment. However, keeping the filter at 200 to 300℃ for 50 years may cause an oxide film to grow **and clog the filter**.

- **Ceramics**

  Ceramics have excellent heat resistance, so **they almost never form an oxide film in an environment of 200℃ or 300℃.**

- **Glass fibers**

  The table shows the characteristics of various glass fibers. They have a high softening point, but general heat resistance temperature is between 250 and 350℃ and so the **possibility of use in this temperature range is low.**

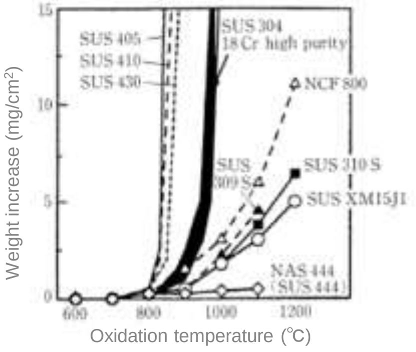


Figure 1 Oxidation behavior of various stainless steels in the atmosphere Note 1

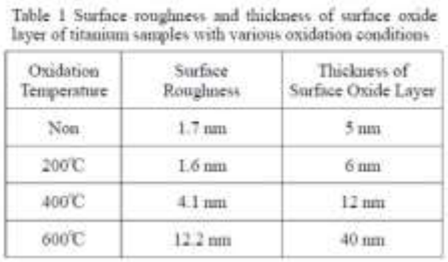


Table 1 Surface roughness and thickness of surface oxide layer of titanium samples with various oxidation conditions

Oxidation Temperature	Surface Roughness	Thickness of Surface Oxide Layer
Non	1.7 nm	5 nm
200℃	1.6 nm	6 nm
400℃	4.1 nm	12 nm
600℃	12.2 nm	40 nm

Figure 2 Surface roughness and thickness of surfaceoxide layer of titanium samples with various oxidation conditions Note 2

Table Characteristics of glass fibers Note 3

Glass type		E-glass	C-glass	S-glass	D-glass
Chemical composition (wt%)	SiO2	53	65	64	72
	Al2O3	15	4	25	1
	CaO	21	14	-	1.0
	MgO	2	3	10	-
	B2O3	8	6	-	23
	Na2O+K2O	0.3	8	0.3	2.5
Properties	Specific gravity	2.55	2.49	2.49	2.16
	Softening point (℃)	840	749	970	771
	Dielectric constant 1 MHz 22℃	6.13	6.79	5.21	4.00
	Young's modulus (GPa)	72.6	68.6	8S.3	52.0
Properties		Electrical insulation, general purpose	Acid resistance	High strength	Low dielectric constant

Note 1: Ryohei Tanaka, Ed.: Data Sheet for High-Temperature Characteristics of Heat-Resistant Steel, Japan Stainless Steel Association (1978)
Note 2: Shimada et al., Yamaguchi University Joint Research, H23-012
Note 3: Fiber Overview [General Characteristics of Long Glass Fibers] | Central Glass Fiber Co., Ltd. Long fiber site (centralfiberglass.com)

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (23/27)

(ii) Selection of degradation events based on canister environment (22/26)

Event: **Electric corrosion** Degradation mode: Damaged

Electric corrosion occurs only in metal filters and not in insulators such as ceramics, glass fibers, and macromolecules. Therefore, only metal filters are examined.

Figure 1 shows an example of filter structure. Electric corrosion does not occur when the filter housing is made of an SUS or Ni-based alloy. Ti has electropositive potential, so Ti housing sides will corrode.

This can be explained by the potential difference of various metals in seawater.

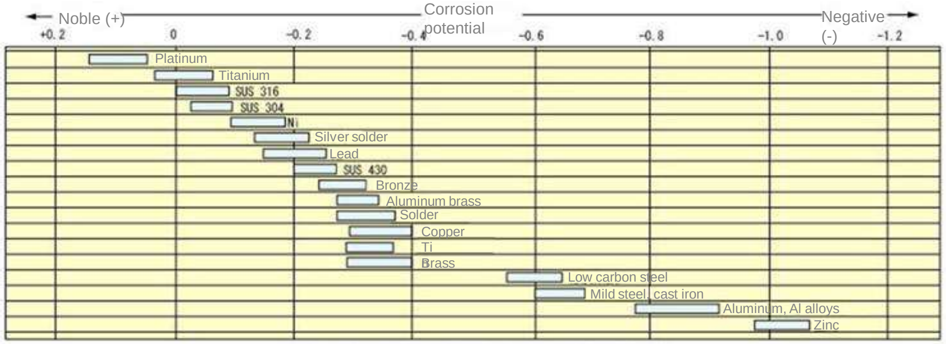


Figure 2 Potential difference of metals in seawater (temperature 25℃) Note 1

Note 1: Urban Steel Study Group, "Guide to Iron and Steel Landscape Materials" 1997.7

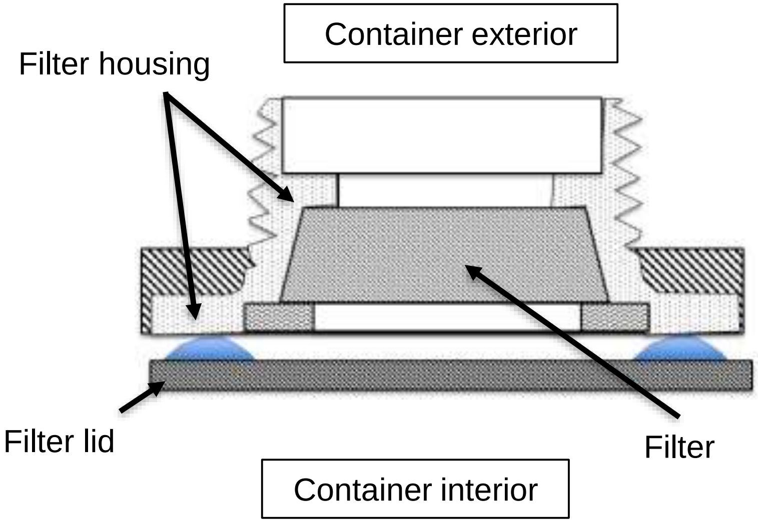


Figure 1 Example of the filter structure

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (24/27)

(ii) Selection of degradation events based on canister environment (23/26)

Event: **Water film** Degradation mode: Clogged

When humidity around the filter is high and there is a large temperature difference caused by an abnormality in the air conditioning system, moisture in the air will condense and form a water film on the surface of the filter, which will in turn block the filter.

Condensation conditions

- The presence of condensation and the volume of water generated by condensation depend on humidity and temperature.
- Condensation occurs when the temperature drops below the dew point temperature (the saturation temperature of vapor in the air).
- M_1 (g/m_3) is the amount of vapor in the air at temperature T_1 (℃) and M_2 (g/m_3) is the amount of saturated vapor at temperature T_2 (℃) ($T_2 < T_1$). If $M_2 < M_1$, then ($M_1 - M_2$) amount of condensation occurs.
- Condensation does not occur if $M_2 > M_1$, even with large changes in temperature.
- The presence of condensation depends on environments, therefore, it is different from time-related degradation events.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (25/27)

(ii) Selection of degradation events based on canister environment (24/26)

Event: **Water film** Degradation mode: Clogged

Operations that may generate water films

Operation when fuel debris is stored in the canisters. When an abnormality occurs in the air conditioning system in the winter and the temperature around the canister changes.

The effects of water film on filters

When condensation creates a water film that covers the filter surface, flow path area is reduced and that **could reduce hydrogen discharge performance.** The degree of performance degradation depends on the area covered.

→ Test methods and conditions shall be studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (26/27)

(ii) Selection of degradation events based on canister environment (25/26)

Event: **Particle dispersion** Degradation mode: Clogged & Damaged

- Occurrence of particle dispersion caused by the air supply is evaluated.
- When storing canisters, configurations that allow for the venting and supply of hydrogen is being considered, and two types of canister configurations are anticipated, one with an air supply mechanism and one without (the figure on the right is a type with an air supply mechanism).
- When the hydrogen inside the canister is supplied to the gas treatment system via a gas flow, gas flows from the bottom to the top of the canister, which could cause particles to rise, depending on the flow velocity.
- With particles 100 μm or less (powdery fuel debris), the ease with which particles will float increases with particle size. As a result, the air supply velocity for 100 μm particles to reach the distance between the fuel debris and the filter was evaluated at 5 m/s.
- Therefore, air flow velocity of 5 m/s or higher presents **a possibility of filter degradation from the dispersion of particles.**

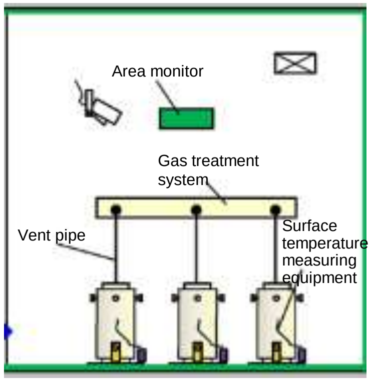


Figure 1 Canister and air supply system Schematic diagram

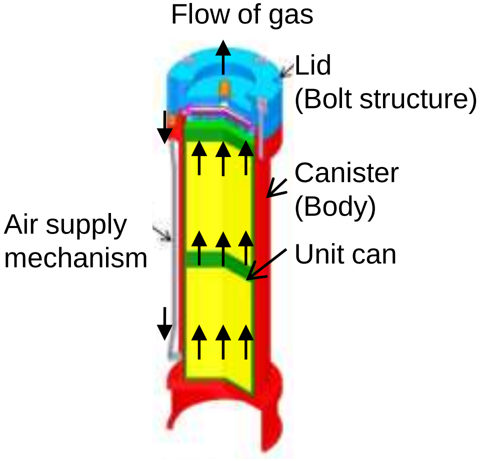


Figure 2 Schematic diagram :Canister with air supply mechanism

→ Test methods and conditions shall be studied as degradation events that should be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

b. Study of filter life evaluation methods (27/27)

(ii) Selection of degradation events based on canister environment (26/26)

Summary

Degradation factors	Metal			Ceramics			Glass				Macromolecules		
	Stainless steel	Nickel-based alloy	Titanium alloy	Aluminum oxide	Cordierite	Zeolite	E-glass	C-glass	S-glass	D-glass	Polyethylene	Polypropylene	PTFE
Hydrogen generation	—	—	—	—	—	—	—	—	—	—	—	—	—
Hydrogen embrittlement	—	—	◎	—	◎	◎	◎	◎	◎	◎	—	◎	—
Radiation degradation	—	—	—	—	—	—	—	—	—	—	◎	◎	◎
Thermal alteration	—	—	—	—	—	—	○	○	○	○	◎	◎	○
Thermal deformation (container)	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Thermal convection	—	—	—	—	—	—	—	—	—	—	—	—	—
Impact	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎	◎
Dust generated by vibration	○	○	○	○	○	○	○	○	○	○	○	○	○
Thickness reduction	◎	◎	◎	—	◎	◎	◎	◎	◎	◎	—	—	—
Oxide film generation	○	○	○	—	—	—	—	—	—	—	—	—	—
Electric corrosion	—	—	—	—	—	—	—	—	—	—	—	—	—
Water film	○	○	○	○	○	○	○	○	○	○	○	○	○
Powder dispersion	○	○	○	○	○	○	○	○	○	○	○	○	○

◎: Study of test methods is required for both Scenarios 1 and 2
○: Study of test methods is required for Scenario 2 only
--: Study of test methods is not required because there is no possibility that either Scenario 1 or 2 will occur

Study of test methods based on the combination of degradation factors and materials to be considered.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (1/13)

(i) Study of filter degradation simulation methods **(1/10)**

Event: **Hydrogen embrittlement**

Test overview (draft)

- Hydrogen is charged under 2 to 3 conditions based on the amount of hydrogen generated in each material during using the filter and then materials are placed on the filter performance assessment equipment and tested. The appropriate method is used for each material though there are a variety of charging methods, including an electrolytic method, a high pressure method, and other such methods. (Figure 1)
- Performance assessment and the amount of charged hydrogen are verified. Thermal desorption analysis is used as the method. (Figure 2)

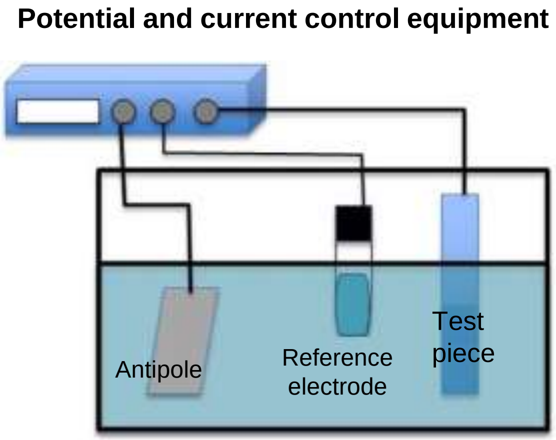


Figure 1 Example of hydrogen charge (example of electrolytic hydrogen charging)

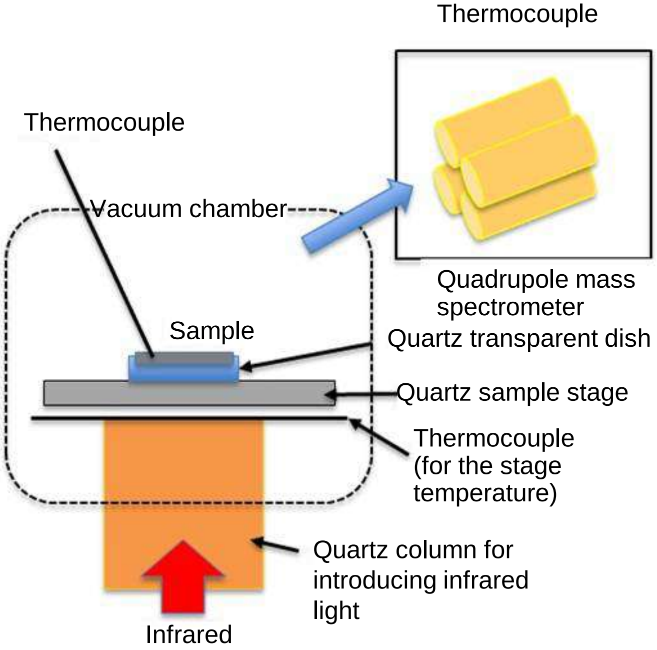


Figure 2 Example of thermal desorption analysis system

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (2/13)

(i) Study of filter degradation simulation methods (2/10)

Event: **Radiation degradation**

Irradiation is simulated assuming that fuel debris is collected in the canister and changes in mechanical characteristics are verified.

Test overview (draft)

- The target material is irradiated with the assumed radiation dose and the mechanical characteristics before and after irradiation are investigated.
- The assumed stress when using a filter is investigated to satisfy the above mechanical characteristics.
- JIS stipulates tension tests for organic substances (plastics) and materials are evaluated in accordance with the stipulated method.

  (JISK7161:2014 Plastics - Determination of tensile characteristics)

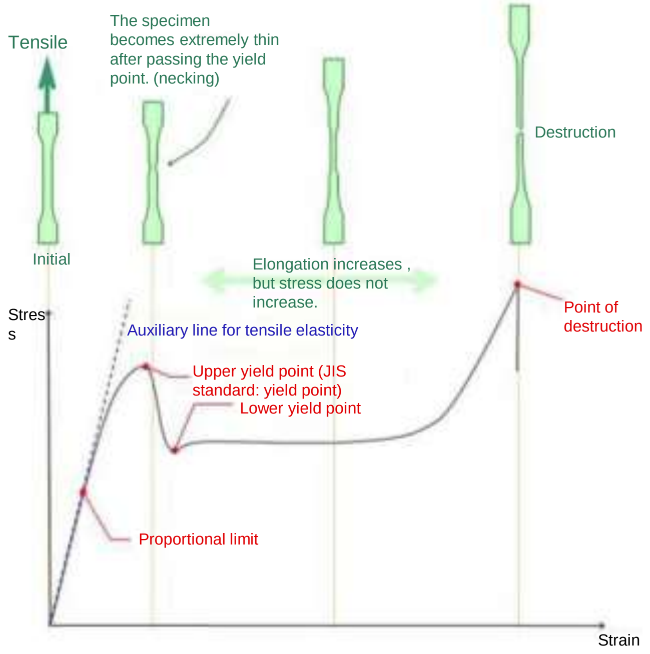


Figure 1 Example of a stress-strain diagram from a tensile test

Figure Example of a stress-strain chart from a tension test Note 1

Note 1: DJK Corporation website
https://www.djklab.com/service/koubunshibussei/323

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (3/13)

(i) Study of filter degradation simulation methods (3/10)

Event: **Thermal deformation** (container), **Thermal alteration**

It is assumed that the filter is exposed during a work flow of the canister handling.
The integrity of the filter is verified in the temperature environment.

Test overview (draft)

- A filter is fixed to the structure that simulates the canister (hereinafter referred to as a simulated canister).
- Heating mechanism is installed with the simulated canister or the simulated canister is installed in heating equipment.
- The simulated canister is heated up to the predetermined temperature.
- The integrity of the filter is verified after heating. (appearance, filter performance tests, etc.)

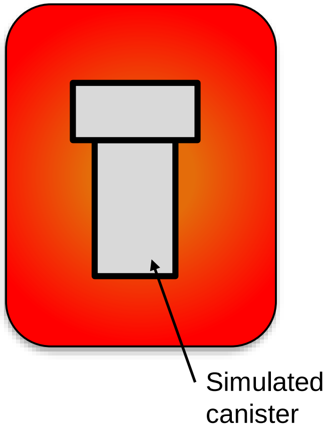


Figure Overview of heating tests

An analysis using FEM (finite element method) to gauge the influence of thermal deformation (container) can be carried out before conducting the test.

The test results may differ depending on a method for fixing the canister lid, the shape and dimensions of the storage container, the method for fixing the canister lid, the shape of the inner container, etc. and so tests should be conducted after the detailed specifications have been determined.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (4/13)

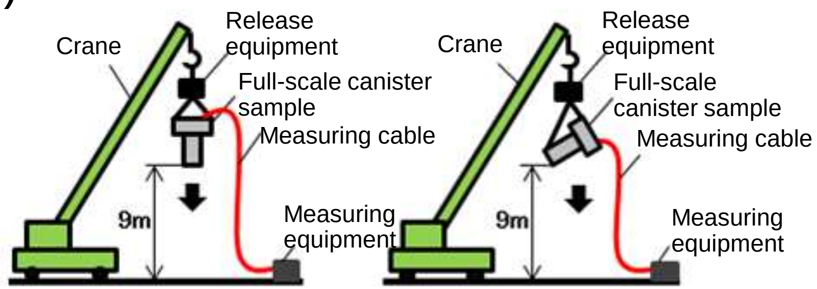
(i) Study of filter degradation simulation methods (4/10)

Event: **Impact**

The filter is subjected to an impact assumed possible to occur during a work flow of canister handling. The integrity of the filter is verified after impact.

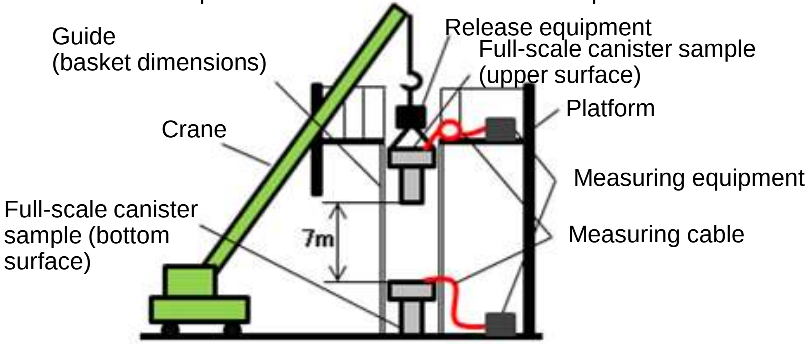
Test overview (draft)

- A filter is fixed to the structure that simulates the canister (hereinafter referred to as a simulated canister).
- A lifting tool raises the simulated canister to a predetermined height.
- The simulated canister is separated from the hanger and allowed a free fall.
- The integrity of the filter is verified after the fall. (appearance, filter performance tests, etc.)



(a) Dropping the canister from a vertical position

(b) Dropping the canister from an inclined position



(c) Dropping a canister onto the top of the another canister from a vertical position

Figure Examples of falling orientation for a simulated canister object in an impact test
(Test system diagram for structural verification tests of full-scale canister samples*)

The test results may differ depending on a method for fixing the canister lid, the shape and dimensions of the storage container, the method for fixing the canister lid, the shape of the inner container, etc. and so tests should be conducted after the detailed specifications have been determined.

Note 1: Subsidy Project of “Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transfer and Storage of Fuel Debris)” in the FY2018 Supplementary Budgets
Extracted from the Final Report Materials June 2021

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (5/13)

(i) Study of filter degradation simulation methods (5/10)

Event: **Dust generation from vibration** (dust generation from earthquake motion)

An unit can containing fuel debris (simulated) that includes powdery fuel debris in a canister with a filter is placed. Then a vibration test simulating earthquake motion is conducted to simulate filter degradation caused by dust generated by earthquake motion.

Test overview (draft)

- Fuel debris (simulated) that includes powdery fuel debris is filled in the unit can.
  (The fuel debris density, particle size, and filling volume are simulated.)
- The unit can is placed in a canister and then the canister lid is closed after installing a filter.
- The canister is attached on a vibration table that can simulate earthquake motion.
- The canister is fixed on the vibration table with a fixing jig to prevent the container from overturning.
- A vibration test that simulates earthquake motion is conducted.

(The input ground motion should be implemented based on the storage area and equipment environment, for example, input ground motion should be a wave equivalent to the design basis earthquake motion.)

- After the vibration test, the canister lid is opened to remove the filter. The deposition amount can be evaluated by the weight of the filter.
- A performance assessment is conducted to evaluate the performance accordingly.

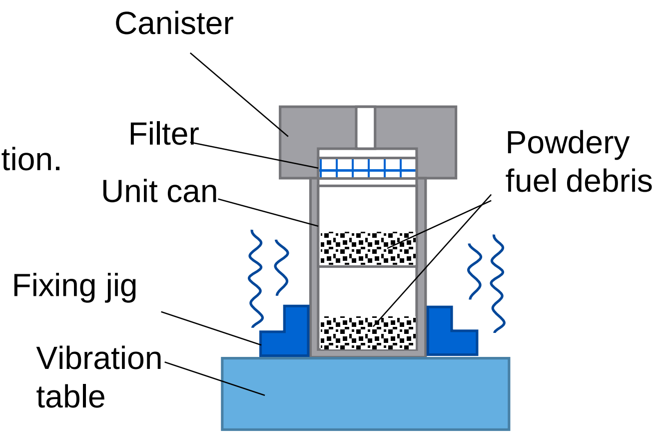


Figure Overview of filter degradation simulation test caused by dust generation due to earthquake motion

The test results may differ depending on a method for fixing the canister lid, the shape and dimensions of the storage container, the method for fixing the canister lid, the shape of the inner container, etc. and so tests should be conducted after the detailed specifications have been determined.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (6/13)

(i) Study of filter degradation simulation methods (6/10)

Event: **Thickness reduction**

Test overview (draft)

The following two types of thickness reduction evaluation can be considered.

- The filter is immersed in the assumed environment, and the corrosion rate is calculated from the amount of change in weight over time to predict the state of thickness reduction
- Assuming that corrosive ions will adhere as the wet/dry environment cycle repeats, a combined cycle test (JIS K 5600_7_9) is used to repeat a salt spray, drying, and humidification as one cycle

In the combined cycle test, a filter is installed in the equipment shown in the Figure below and then corroded.

However, as a foundation for the performance assessment, filters with different corrosion progressions rates must be manufactured and tested to evaluate whether filter performance can be maintained.

Examining corrosion rates and results of combined cycle tests together with the above performance assessment results make it possible to determine whether a filter can be used as a filter in a canister storage container.

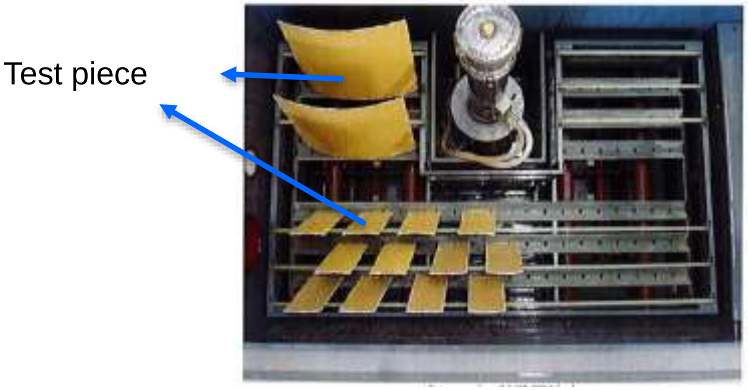


Figure Example of combined cycle test equipment

A filter is installed in the equipment shown in the left side of the Figure.The filter is corroded through a combined cycle.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (7/13)

(i) Study of filter degradation simulation methods (7/10)

Event: **Oxide film generation**

Test overview (draft)

Oxide film measurement test

The oxide film growth rate on the applicable filter material is measured at a temperature of 300℃ in normal atmospheric conditions.

The materials to be measured are placed in the heat treatment furnace. The oxide film growth rate is measured from the increase in weight before and after heat treatment, setting three or more conditions for the heat treatment period.

The oxide film thickness 50 years later is calculated based on those values. Then, a performance assessment on the filter is conducted under accelerated conditions (excessively high oxygen conditions) where calculated values of the oxide film thickness is added.

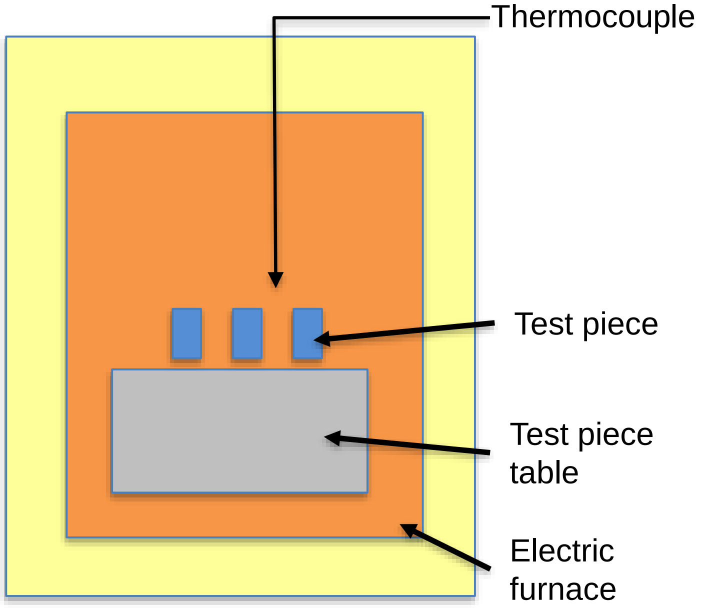


Figure Example of a heat treatment furnace

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (8/13)

(i) Study of filter degradation simulation methods (8/10)

Event: **Water film**

Air permeability is verified under conditions that simulate the formation of a water film due to condensation on the filter.

Test overview (draft)

- The pressure to emit gases inside the container is investigated when a water film is formed on the filter.
- The filter can be evaluated by applying a method for fiber waterproof test. (See the Figure on the right)
- The fixed filter is pressurized with water, then the pressure at the time of emitting air is measured.

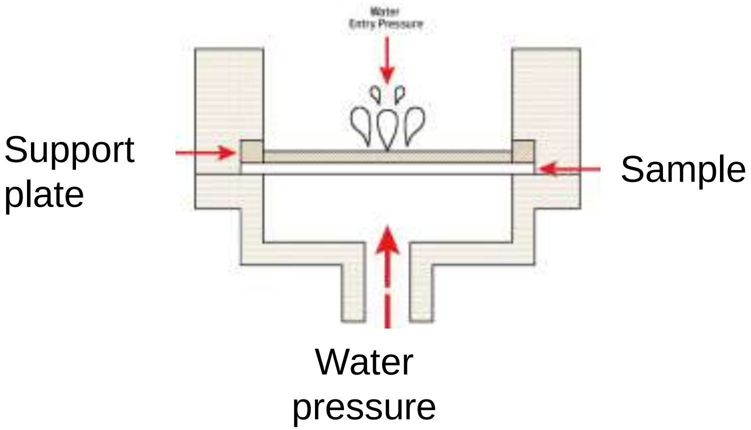


Figure: Illustration of an air permeability test for a clogged filter Note 1

Note 1: W. L. Gore & Associates. materials (https://www.gore.co.jp/sites/g/files/ypyipe116/files/2016-04/PTV-TechInfo-WEP-Testing-US.pdf)

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (9/13)

(i) Study of filter degradation simulation methods (9/10)

Event: **Powder dispersion** (dust generation due to ventilation)

The canister with filters is contained with fuel debris (simulated) that includes powdery fuel debris and filled with upward air flow simulating supplying air in the canister. Then filter degradation can be simulated by air supply from upstream caused from dust generation during ventilation.

Test overview (draft)

- Preparation of a vertical reaction tube with a powder support plate, filter, and particle concentration counter as shown in the right Figure on the right.
- Reaction tube filling with powdery fuel debris (simulated) and installation of a filter.
- Air supply at a flow rate equivalent to ventilation (use the air supply gas).
- Verification of the particle dispersion by counting particles during gas flow using the particle concentration measuring instrument placed in front of the filter based on the number of particles before testing.
- When particles disperse, filter performance could be affected. In such cases, the lid of the canister is opened to remove the filter after ventilation and particle adhesion can be evaluated from measurement of the filter weight.
- The filter performance is evaluated by evaluation tests accordingly.

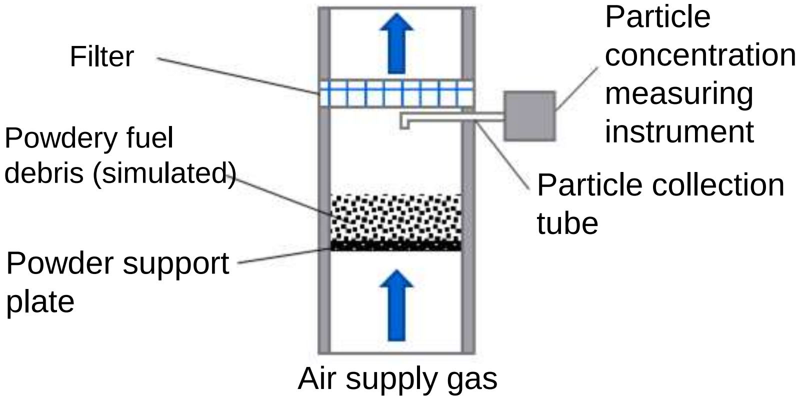


Figure Overview of a test system for simulating dust generation from vibration

Test results may differ depending on the ventilation flow rate, the location where air supply mechanisms are installed, the configuration of the container such as its shape and dimensions, the fuel debris filling method, etc. and so the test should be conducted after the detailed specifications have been determined.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (10/13)

(i) Study of filter degradation simulation methods (10/10)

Summary

- A test method to simulate filter degradation for each degradation process was organized because it is difficult to evaluate the degree of degradation in the 10 identified degradation processes from theoretical formulas.

- It is difficult to simulate filter degradation without inputs (environmental conditions, fuel debris properties, etc.), treatment process, detailed specifications, required performance, and filter type. Once these information are consolidated, it is necessary to re-evaluate the possibility of degradation occurrence at each process and conduct degradation simulation tests for evaluation of degradation rate, and evaluate the life of various filters in order to select a filter.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (11/13)

(ii) Study of filter performance assessment methods (1/3)

Particle capture performance assessment method

- Particle capture performance assessment method is stipulated for general filter performance assessment methods, and JIS includes the following:

JIS B 9908-2: 2019 Test method of air filter units for ventilation and electric air cleaners for ventilation - Part 2: Measurement of fractional efficiency and air flow resistance

- Based on this method, as shown in the Figure on the right, the particle capture performance of a filter can be evaluated by running an airflow that contains particles through the filter and measuring the particle concentration before and after.

(Test method)

- Temperature and humidity maintains constant, and a blower pushes a dry current through the filter at a constant flow rate.
- Particles adjusted to a certain particle size are used as test particles in the air flow.
- The particle number concentration before and after filtering is measured to evaluate the capture efficiency rate of the filter.

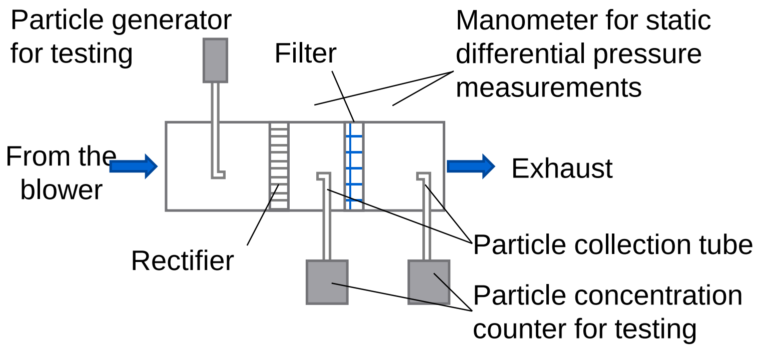


Figure Filter performance assessment test Overview

(Assessment criteria)

- Assessment criteria is determined by satisfying the specified performance of the particle capture efficiency.
- References of a performance guideline results equivalent to a JIS HEPA filter (capture performance 99.97% @ 0.3 μm) or a HIC vent filter (NucFil® 019-HCR, particle capture performance > 99.97% @ 0.3 to 0.5 μm DOP, specified flow rate: 210 ml/min @ 330 Pa).

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (12/13)

(ii) Study of filter performance assessment methods (2/3)

Hydrogen permeation performance assessment method (general industry)

1) General filter performance evaluation method

- JIS stipulates the following for general filter performance assessment test methods:
  JIS 9908:2011 Test method of air filter units for ventilation and electric air cleaners for ventilation
  This standard is a performance assessment method for air filters that remove dust floating in air **and does not describe the assessment of hydrogen permeation performance.**

- The following regulation pertains to filters for nuclear facilities:
  JISZ 4812-1995 HEPA Filters for radioactive aerosols
  This standard is used for the purpose of removing radioactive aerosols in the exhaust systems, ventilation air conditioning systems, etc. of nuclear facilities.
  It stipulates that high-performance air filters (hereafter referred to as high-performance air filters) must be flame-retardant to protect against fire. **Assessment of hydrogen permeation performance was not described in the standard.**

In this investigation, any JIS standard regarding the assessment method for hydrogen permeability was not found.

6. Implementation details

6.3 Performance assessment of canister filters

③ Implementation items and results

c. Study of test methods and conditions (13/13)

(ii) Study of filter performance assessment methods (3/3)

Hydrogen permeation performance assessment method (nuclear)

2) Method for assessing hydrogen permeation performance of filters

In the United States, test methods have been established for hydrogen discharge filters used in radioactive waste and TRU waste containers Note 1. A container with filter is filled with hydrogen at a specified concentration (4%), and the hydrogen concentration in the static container is measured 7 times every 5 minutes.

A permeability **performance assessment is made based on hydrogen diffusivity (D) obtained from the following formula.**

$$D = \frac{PV}{tRT}\left(\frac{Ln_H}{0_{Ht}}\right)$$

D: hydrogen diffusion coefficient (mol/sec/mol fraction)
P: pressure (atm), V: container volume (L), t: time (seconds),
R: gas constant of an ideal gas (0.082 Latm/molK),
T: temperature (K), H_0: initial hydrogen concentration,
H_t: Hydrogen concentration at time t

In the United States, the WIPP (Waste Isolation Pilot Plant) stipulates the performance of filters used in waste containers

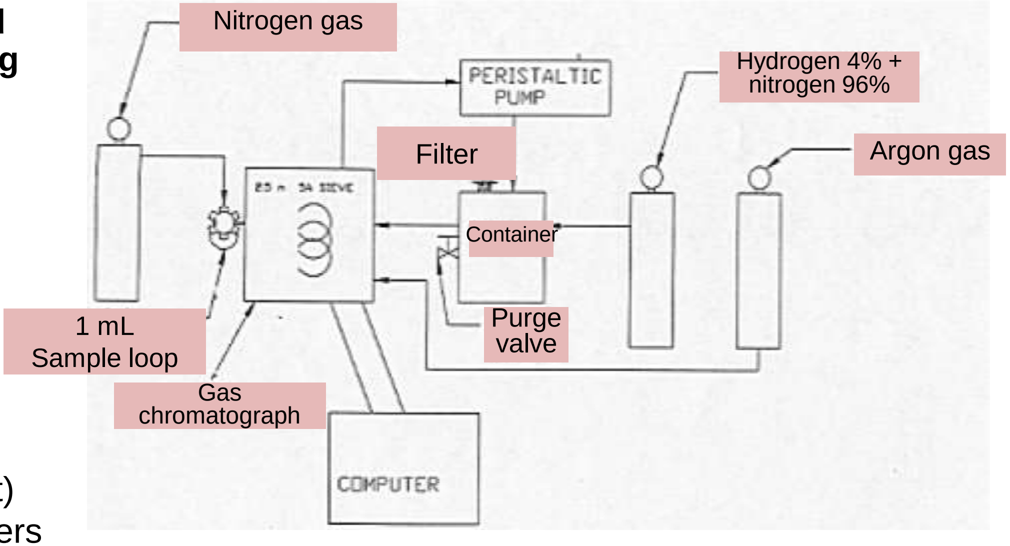


Figure Schematic diagram of hydrogen diffusivity test equipment

Note 1: Terry Wickland and John Schierloh Hydrogen Diffusivity through Drum and Liner Venting Filters WM98 (http://archive.wmsym.org/1998/html/sess27/27-37/27-37.htm)

6. Implementation details

6.3 Performance assessment of canister filters

④ Contribution of outcomes to relevant study areas

This data is useful when selecting filters in the design phase.

⑤ Analysis with respect to the on-site applicability

In terms of on-site applicability, the effects of degradation are evaluated based on test results from the filter degradation simulation methods and filter performance assessment methods that are the outcomes of this project, and those evaluation results are used to select filters that satisfy performance requirements even after degradation.

⑥ Goal achievement level

It can be concluded that TRL Level 1 was achieved as planned because the following indicator to judge goal achievement was met:

- The environments and conditions that affect canister filter life must be understood and organized. Also, the test methods and conditions for any item that must be tested to evaluate filter life must be examined and any relevant existing knowledge must be organized.

⑦ Issues to be addressed

Once information such as inputs (environmental conditions, fuel debris properties, etc.), treatment processes, required filter performance, etc. is aggregated, it is necessary to reevaluate of the possibility of each degradation process occurring, evaluate the effect of superimposed processes, conduct degradation simulation tests to evaluate the rate of degradation, etc., before evaluating the life of each filter and finally selecting a filter.

6. Implementation details

6.3 Performance assessment of canister filters

⑧ Summary

- The functions for confining fuel debris particles and functions for releasing hydrogen generated by the radiolysis of water were identified as filter requirements.
- The filter degradation factors were figured out and 17 degradation processes were identified. Using existing knowledge as input conditions, the four processes of salt precipitation, microbial membrane, aerosol deposition, and UV degradation were excluded from the target processes based on fuel debris properties, container specifications, and environmental conditions inside and outside the canister. Scenarios were defined in which the selected 13 processes lead to degradation based on the canister environment.
- Among the degradation processes, the three events of hydrogen generation, thermal convection, and electric corrosion were evaluated as not occurring, and the evaluations of filter degradation using theoretical formulas were attempted for the other 10 events, but since no method for estimating degradation events has been established, testing methods for simulating degradation were examined and filter degradation simulation methods for each degradation process were presented.
- As methods for determining degrees of degradation, particle capture performance and hydrogen permeation performance, both of which are required as filter performance, were examined and developed as general assessment method proposals.
- Once information such as inputs (environmental conditions, fuel debris properties, etc.), treatment processes, required filter performance, etc. is aggregated, it is necessary to reevaluate of the possibility of each degradation process occurring, evaluate the effect of superimposed processes, conduct degradation simulation tests to evaluate the rate of degradation, etc., before evaluating the life of each filter and finally selecting a filter.

7. Summary

- The experience, knowledge, and information on the handling and storing of radioactive materials, etc. in powder, slurry, or sludge form at TMI-2 and the Hanford Site in the US, Sellafield in the UK, and other sites, which are considered to be useful for identifying issues related to the storage of powdery, slurry or sludge fuel debris, were collected and analyzed.

- Issues and countermeasures in each process up to storage when conducting dry storage with canisters similar to those for fuel debris in particle or lump form were examined. The technological issues related to the storage of fuel debris in powder, slurry, or sludge form as well as their solution phases and solution periods were also clarified.

- Potential degradation processes were identified from the environment and conditions in which the canister filters are placed. A simulated degradation method was provided for each degradation process and performance assessment test method plan were proposed.