IRID

Subsidy Project of Decommissioning and Contaminated Water Management in the FY2016 Supplementary Budgets

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

FY2018 Final Research Report

June 2019

International Research Institute for Nuclear Decommissioning (IRID)

Contents

1. Research Background and Purpose

1.1. Background

- Technology for collecting, transferring and storing fuel debris retrieved for decommissioning of the Fukushima Daiichi Nuclear Power Station (1F), in a safe and effective manner, is required.
- Fuel debris contains nuclear fuel material, therefore, it is necessary to consider, in particular, confinement of radioactive materials (preventing spread of contamination) and sub-criticality in the handling of the debris.
- When the Three Mile Island Nuclear Power Station Unit 2 (TMI-2), in the US, was decommissioned, fuel debris was retrieved in specialized containers (canisters) and handled by the canister. This effectively fulfilled requirements, such as confinement of radioactive materials, by using existing technologies for transfer and storage of spent fuel and management of radioactive waste. This example led to the belief that it is reasonable to use existing technologies effectively by developing canisters to meet individual conditions. Based on this approach, it has been decided to focus the development of canisters for the decommissioning of 1F.
- The plant type of 1F is different from that of TMI-2. In addition, seawater was injected during the initial phase of the accident, and the molten core reached the pedestal at the bottom of the reactor pressure vessel. Therefore, the requirements for 1F canisters are more complex and advanced compared to TMI-2. Development of specialized canisters for 1F is required to contain, transfer, and store fuel debris safely and effectively.
- In previous studies, elemental technologies were evaluated for a basic design of the canister. However, since there is limited information on 1F after the accident, such as the amount of fuel debris including high radiation waste, it is important to lay down design conditions for the canisters and reflect updated knowledge as occasion arises to optimize 1F decommissioning.

1.2. Purpose

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

1. Research Background and Purpose

<Comparison with precedents>

The precedent of TMI-2, wherein the containing, transfer, and storage of fuel debris generated earlier in the core meltdown accident was accomplished, is an excellent reference; however, it is different from 1F in the following points:

- **Fuel debris in 1F is distributed from the reactor pressure vessel (RPV) to the pedestal inside the primary containment vessel (PCV).**
  - ⇒ Products of concrete interaction (Molten Core Concrete Interaction (MCCI)) and adherence of fuel debris to concrete during containing need to be considered.
  - ✓ <u>The alkaline component in concrete must also be taken into account.</u>
- **Seawater was injected into the 1F reactor.**
  - ✓ <u>Residual salt (chlorine) in fuel debris needs to be considered.</u>
- **Working environment may be severe due to the damage to the buildings. RPV and PCV may be damaged.**
  - ⇒ Containing of fuel debris by methods other than the submersion-top entry method such as partial submersion side entry method, are being studied.
  - ✓ <u>Studies appropriate for methods other than the submersion-top entry method, such as the partial submersion-side entry method, (for example, fuel debris canister design, know-how on handling of canisters) are necessary.</u>
- **Concentration is high.**
  - ⇒ The canister's inner diameter will be smaller to maintain sub-criticality. It is difficult to place canisters side by side.
  - ✓ <u>Considerations on workability suitable for retrieval and containing of fuel debris and reduction in storage area are important.</u>
  - ⇒ Risk of re-criticality when retrieving fuel debris needs to be considered.
  - ✓ <u>The possibility of adding neutron absorbent to the fuel debris during retrieval also needs to be considered.</u>
- **Burn-up (radiation source intensity) is high.**
  - ✓ <u>Measures against increase in amount of hydrogen generated by radiolysis of water are necessary.</u>
- **Amount of fuel debris is larger.**
  - ✓ <u>Considerations on workability suitable for retrieval and containing of fuel debris and reduction in storage area are important.</u>

2. Research Goals

2.1. The overall goal of the project

Assuming the retrieval of fuel debris in 2021, the goal is to establish methods to contain, transfer, and store fuel debris safely and efficiently.

2.2. Goals for end of FY2018

The project aims to develop a plan for how fuel debris will be contained, transferred, and stored safely and effectively. The canister specifications, developed mainly from the perspective of safety design during FY2015 and 2016, will be evaluated and improved for the fuel debris retrieval methods and transferring tasks. The canister specifications (prototype) will be established by performing verification through tests.

(Pending issues)

From the previous studies, the following issues remain and must be taken on:

(1) Optimization in terms of safe and efficient containing, transfer, and storage

In the previous technical development, the issues were identified in terms of safety assessment by referring to examples such as TMI-2. Study conditions were postulated based on expert opinions, and a provisional draft of canister specifications and multiple storage methods was proposed. However, in order to store the retrieved fuel debris smoothly, optimization in terms of treatment capacity and practical equipment, is necessary. In addition, effective measures against the possibility of conditions exceeding projections, such as fuel debris characterizations, etc. must be proposed from the aspects of management and equipment. (⇒This will be studied in the implementation items (1) and (2) on the next slide.)

(2) Safety evaluation with consideration given to the system

In the previous technical development, evaluations focusing on element tests was performed to round up the basic canister design and the transfer/storage system. However, evaluation of the entire system is necessary. In addition, some of the tests require evaluations that will be added to previously acquired knowledge. (⇒This will be studied in the implementation item (3) on the next slide.)

(3) Management of fuel debris retrieved during water and gas treatment

In the previous technical development, block, granular, and powder fuel debris contained by the retrieval equipment were targeted. However, as fuel debris is also contained from water and gas treatment of the incidental equipment of fuel debris retrieval, measures are required to store them. (⇒This will be studied in the implementation item (4) on the next slide.)

3. Implementation Items, their Correlations, and Relations with Other Research and Development

3.1. Implementation Items

The following implementation items will be conducted for the test manufacturing of canister prototype for mock-up tests, and to conduct final verifications of safety and handling of the canister by performing the mock-up tests.

(1) Investigation and establishment of research plans for transfer and storage

The latest information on the situation, along with knowledge of related projects and sites, will be acquired. Further analysis and consolidation of overseas technical requirements related to safety will be performed based on already obtained information. These will be reflected in the research plan along with expert opinions in IRID. In addition, if further information is required, additional investigation will be conducted, such as organizing workshops with foreign engineers.

(2) Study of safety requirements, specifications and storage systems for the transfer and storage of fuel debris canisters

Prerequisite technical requirements for the safety of transport containers and storage facilities will be established to transfer and store fuel debris safely and effectively in canisters. In addition, processing capacity of each task and other related conditions will be evaluated and reflected in the requirement specifications for the handling flow and the transfer/storage system. It will also be reflected in the specifications of devices for handling canisters.

(3) Development of safety evaluation methods and verification of safety

Based on the studies in (2) and (4), safety verification using a partial model of canisters and analysis will be carried out, and feasibility of the canister and transfer/storage system will be confirmed.

(4) Study of fuel debris containing method

Based on the study in (2), a containing method that is adapted to the fuel debris properties and a fuel debris retrieval method will be determined with related technical development to transfer and store fuel debris safely and effectively. The method will be reflected in the specifications for each part of the canister.

3. Implementation Items, their Correlations, and Relations with Other Research and Development

Background and Purpose of R&D

① Establish containing, transfer, and storage flow (Confirm/Review)
- Overseas examples of work flow for damaged fuels (for example, TMI-2)
- Establish flow proposals based on 1F conditions

② Develop the concept of the containing, transfer, and storage system (Confirm/Review)
- Develop the concept of the storage system (wet / dry) based on 1F conditions

③ Establish the evaluation method and share of safety functions required for the canisters and the system
- Survey systems developed overseas for evaluation methods and share of safety functions
- Develop methods for examining the applicability to 1F (identifying issues), evaluating hydrogen etc., and develop measures

④ Develop specifications based on the safety assessment (Confirm/Review)
- Alignment of methods with safety design
- Specify requirements based on parametric analysis

Previous technical developments will be verified and updated with the latest knowledge for optimization.

Start of this subsidized project

- **Reflect study results and knowledge of related projects[*1] to canister specifications**
- **Optimize the system specifications with considerations to safety, treatment performance, etc.**

Exchange of information with related projects[*1]
Support from experts

Verification of canisters using partial model and analysis (evaluation of functional feasibility)

Finalize the basic canister specifications

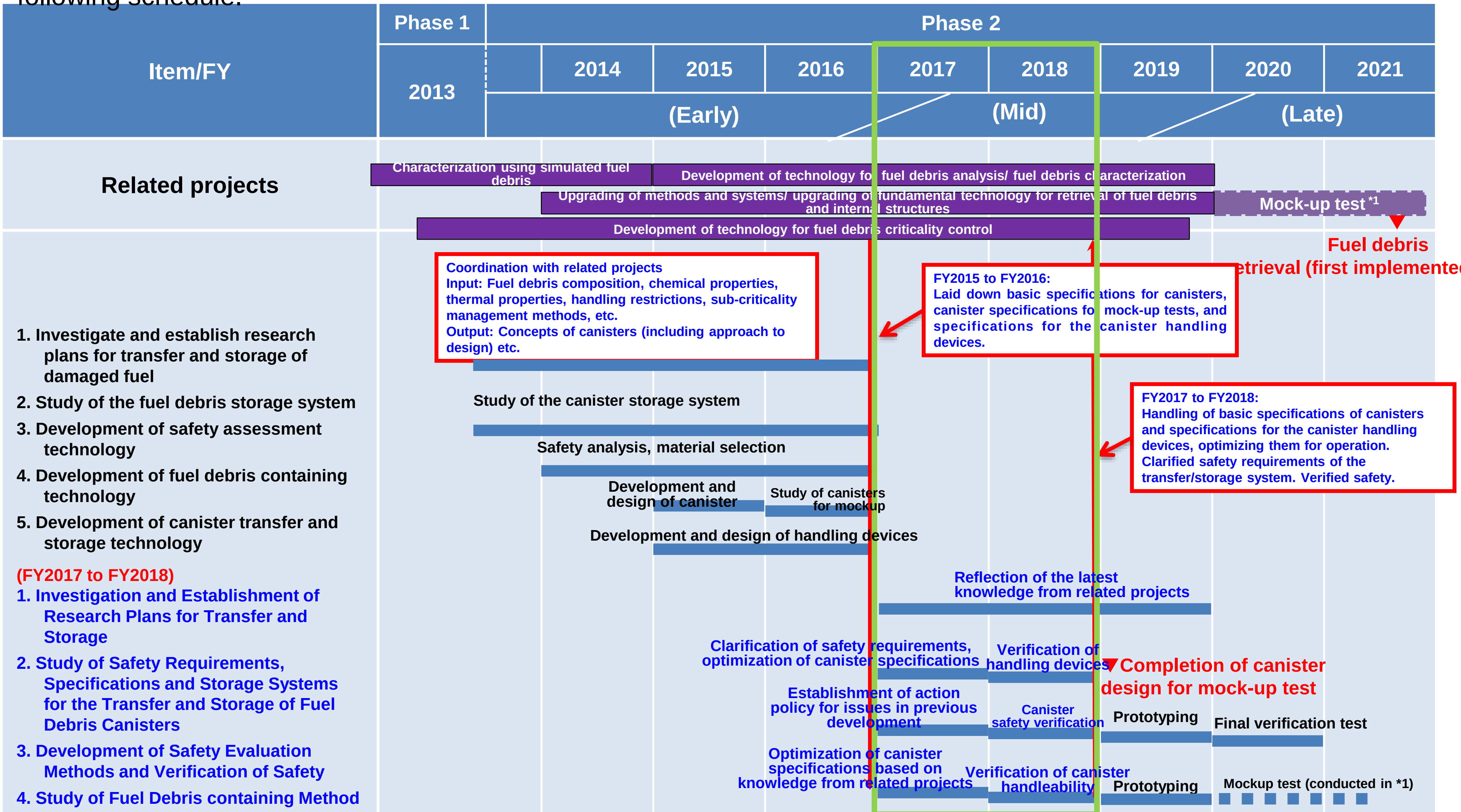
After FY2019

Verification of the validity of the canister design (overall verification)

*1: Related projects
Method PJ, Fundamental Technology PJ, Fuel Debris Characterization PJ,
Method (Criticality Control) PJ, Waste PJ

3.2. Relation of Implementation Items (1/2)

Assuming the retrieval of fuel debris from the first implemented unit in FY2021, development will be pursued by the following schedule.



Implementation scope of this project

3.2.Relation of Implementation Items (2/2)

International Research Institute for Nuclear Decommissioning (IRID)

Fuel Debris Characterization Project

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

Waste Project

[Information provided to the Canister Project Team]
Knowledge on waste sorting, etc.

Canister Project

[Information provided to related project teams]
(1)Study of safety requirements, specifications and storage systems for the transfer and storage of fuel debris canisters
・Details of inspections for safety assessment
(4) Study of fuel debris containing method
・Canister specifications
・Conditions of structure, weight, dimensions, etc.
・Basic canister handling method
・Canister handling device* specifications
・Handling method of canister handling devices*
* Canister lid closing device, canister hoisting device, etc

Fuel Debris Retrieval Method Project/Fundamental Technology

[Information provided to the Canister Project Team]
Limiting conditions while handling fuel debris
・Conditions for dimensions and weight limitations
Fuel debris containing location and procedures
・Canister installation location
・Canister hoisting information
Fuel debris containing method
・Knowledge of fuel debris cutting, particle size, etc.
・Containing method (for example, pump suction)
Handling procedure of special tools

Fuel Debris Retrieval Method (Criticality Control) Project

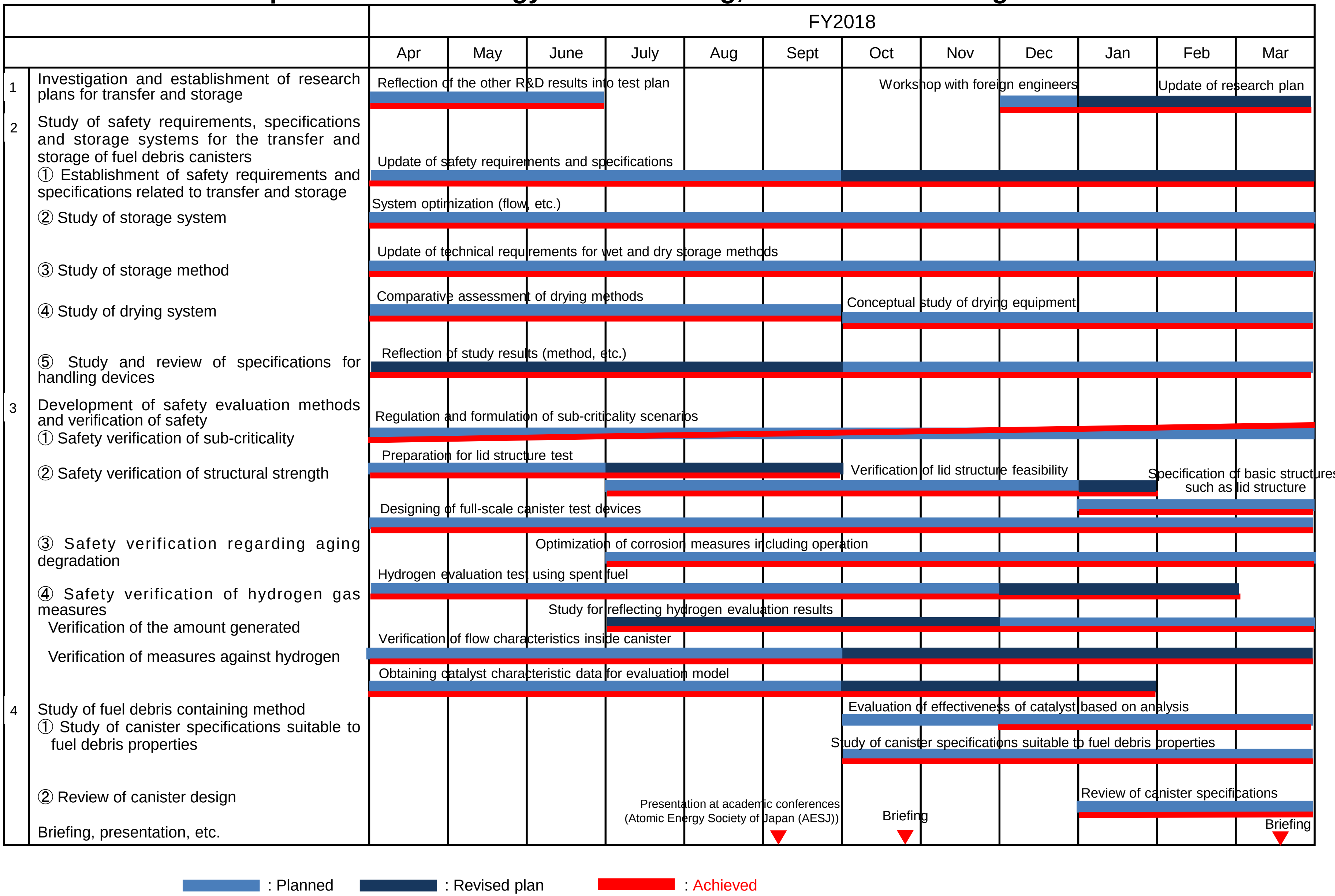
[Information provided to the Canister Project Team]
Limiting conditions to maintain sub-criticality
Neutron absorption material used to maintain sub-criticality

Note)
Method Project Team : Project on fuel debris retrieval method and system
Method (Criticality Control) PJ Team : Project on fuel debris retrieval method and system (Criticality Control)
Fundamental Technology Project Team : Project on fundamental technologies for fuel debris
retrievalcontainingaracterization Project Team : Project on fuel debris characterization
Waste Project Team : Project on treatment and disposal of solid waste
Canister Project Team : Project on containing, transfer, and storage of fuel debris

Consistent results are obtained by sharing information provided from related projects of IRID and information delivered by this project, working in cooperation and coordinating with those projects.

4. Schedule

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



5. Project Organization Chart (as of the end of March 2019)

International Research Institute for Nuclear Decommissioning (Head Office)

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

Tokyo Electric Power Company Holdings, Inc.

Mitsubishi Heavy Industries, Ltd. | **Toshiba Energy Systems & Solutions Corporation** | **Hitachi-GE Nuclear Energy, Ltd.**

(1) Investigation and establishment of research plans for transfer and storage
(2) Study of safety requirements, specifications and storage systems for the transfer and storage of fuel debris canisters
(3) Development of safety evaluation methods and verification of safety
(4) Study of fuel debris containing method

Relevant projects

- Development of Technology for Fuel Debris Analysis/ Fuel Debris Characterization
- Upgrading of Method and Systems for Retrieval of Fuel Debris and Internal Structures
- Upgrading of Fundamental Technology for Retrieval of Fuel Debris and Internal Structures
- R&D for Treatment and Disposal of Solid Radioactive Waste

Under Mitsubishi Heavy Industries, Ltd.:

NDC
• Development of MCCI products and physical properties of fuel debris on to design parameter
• Study on measures for fuel debris against hydrogen generation

MHI-NS
• Study on basic specifications of canisters (including analysis), preparation of design and drawing of canisters and handling devices

Soltec
• Tests related to degradation of material, performance of hydrogen recombination catalyst and hydrogen adsorption alloy, heat transfer and heat flow inside canister

RSG
• Analysis related to heat transfer and heat flow

Under Toshiba Energy Systems & Solutions Corporation:

Fuji Electric Co., Ltd.
• Study on specifications for transfer and storage of fuel debris canisters

MPR Associates, Inc.
• Study on safety requirements for transfer and storage of fuel debris canisters

Under Hitachi-GE Nuclear Energy, Ltd.:

Toko Corporation
• Validation of the structure of canister lid

Toko Corporation
• Verification of structural integrity of the canister

GNF
• Study on evaluation of the amount of hydrogen generated using spent fuel

Pacific Northwest National Laboratory
• Study on the effect of alpha rays on the evaluation of the amount of hydrogen generated

NDC: Nuclear Development Corporation
MHI-NS: MHI-NS Engineering Co., Ltd.
Soltec: MHI Solution Technologies Co., Ltd.
RSG: Ryoyu System Engineering Co., Ltd.
GNF: Global Nuclear Fuel Japan Co., Ltd.

6. Implementation Details

6.1 Investigation and Establishment of Research Plans for Transfer and Storage

6.2 Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters
(2) Study of storage system
(3) Study of storage method
(4) Study of drying system
(5) Study and review of specifications for handling devices

6.3 Development of Safety Evaluation Methods and Verification of Safety

(1) Safety verification of sub-criticality
(2) Safety verification of structural strength
(3) Safety verification regarding aging degradation
(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated)
(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen)

6.4 Study of Fuel Debris Containing Method

(1) Study of canister specifications suitable to fuel debris properties
(2) Review of canister design

6. Implementation Details

6.1. Investigation and Establishment of Research Plans for Transfer and Storage

① Purpose and goals

The investigation and research plans for transfer and storage will be established and updated based on the latest on-site situation and the progress of other R&D projects, such as the Fuel Debris Retrieval Method Project, Fundamental Technology Project, etc.

② Comparison with existing technologies

The technical requirements and assessment technology for the transfer and storage of spent fuel have been established, but there is no provision for fuel debris, therefore, formulation and update of the investigation and research plans is necessary for the furtherance of this technical development, taking the 1F fuel debris properties into account.

③ Implementation items and results

For the study of safety evaluation and safety verification in the design for 1F fuel debris canisters, latest knowledge on related technical development was contained, domestic and international case studies were conducted, and a workshop (WS) was held for exchange of information with foreign engineers with the experience and knowledge of decommissioning. The results were reflected in the technical development for canisters and the proposed basic specifications for canisters gained support.

a. Collecting the latest knowledge on related technical development

On establishing the flow from retrieval to storage of fuel debris, information was exchanged in a joint meeting among the Fuel Debris Retrieval Method Project Team, Fundamental Technology Project Team, and Waste Project Team and by a review conducted by IRID experts. The latest knowledge was gathered and reflected in the work-flow. For reference, Supplement-1 shows Proposed Handling Flow for Fuel Debris Canisters (Method of Accessing the Debris from the Side of the Reactor).

b. Domestic and international case studies

The licensing application of Japan Nuclear Fuel Limited (JNFL) waste management facilities was inspected and the technical literature on drying methods, etc. adopted in overseas facilities was verified. This was used as reference for the study on canisters and related handling devices.

c. Workshop with foreign engineers (1/2)

The knowledge on fuel debris properties, etc. is limited and design studies are being carried out based on hypothetical situations. However, to avoid major rework in future studies, workshops were was conducted at Idaho National Laboratory (INL) in the US with foreign engineers having decommissioning experience and knowledge, in order to get their opinions on the TMI-2 experience (including dry storage experience at INL). Apart from receiving suggestions on the study of unique technologies, the proposed basic specifications for canisters gained support..

6. Implementation Details

6.1. Investigation and Establishment of Research Plans for Transfer and Storage

③ Implementation items and results

c.Workshop with foreign engineers (2/2)

At the workshop (WS), discussions were held on unique technologies that are expected to determine the rate of the target processing capacity (hereinafter referred to as throughput), transfer volume, and storage efficiency for the containing, transfer, and storage of fuel debris.

<Main topics and outcomes of WS>

- Criticality evaluation: The applicability of the conventional sub-criticality maintenance and evaluation method considering fuel debris particle size and moisture content was confirmed
- Measures against hydrogen:
  - Acquiring data on amount of hydrogen generated at TMI-2, which serves as a reference for the proposal and evaluation of methods for evaluating the hydrogen generation amount.
  - Obtaining information on catalysts used in TMI-2 and proposal for evaluation when considering catalysts as a measure against hydrogen
- Drying method: Information on heated vacuum drying performed at TMI-2 (including manufacturer information on dryers)
- Canister design: Support for proposed canister specifications (including hypothetical situations) that are being studied, including the development of above-mentioned unique technologies

④ Reflection of results

The latest knowledge contained on the related technical development, results of reviews by IRID experts, and information provided by foreign engineers were reflected in each technical development item to move ahead with the plan.

⑤ Analysis from the viewpoint of applicability to the site

Applicability will be determined and coordinated in the process of future implementation.

⑥ Level of achievement compared to the goal

The research plans for canister development were verified and updated by collecting the latest knowledge on related technical development, having the research plans reviewed by experts, and holding WS with foreign engineers, and it was concluded that the goals have been attained.

⑦ Future issues

There were no issues in executing the current plan.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (1/8)

① Purpose and goals

The share of safety functions and requirements will be clarified for designing the fuel debris transfer and storage system.

② Comparison with existing technologies

The requirements for transfer and storage of spent fuel have been established, but there is no provision for fuel debris, so the requirements must be specified taking into account the differences between spent fuel and fuel debris.

③ Implementation items and results (1/7)

From the viewpoint of clarifying the requirements for safety in designing the fuel debris transfer and storage system, a proposal of safety requirements was established in FY2018 based on the details of the safety requirements studied in the previous year. In organizing the requirements, the safety requirements to be achieved (1) during transport, (2) during handling, and (3) during storage were established with details assuming plant conditions of level 1 to level 3 based on the accident levels defined below.

Level 1: Prevention of deviation from normal operation, prevention of failure of facilities important to safety
Level 2: Detection and control of deviation from normal operation
Level 3: Control of events assumed in design basis

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (2/8)

③ Implementation items and results (2/7)

The following items a. to d. were studied in sequence:

a. Organization of share of safety functions
b. Formulation of requirements that satisfy functions to be shared (level 1 requirement)
c. Identification of abnormal events leading to loss of functions that must be satisfied
d. Formulation of requirements for the occurrence of abnormal events (level 2/3 requirement)

a. Organization of roles of safety functions (1/2)

The following safety functions that must be maintained in the transfer and storage of fuel debris canisters were studied:

(a) Preventing excessive release of radioactive materials

i. Confinement of radioactive materials (confinement)
ii. Prevention of abnormal, additional generation of radioactive material
   - Prevention of additional nuclear fission reactions (criticality prevention)
   - Prevention of abnormal super-heating (heat removal)

(b) Prevention of excessive and internal exposure to radiation (shielding)

(c) Responding to hazards among design considerations

⇒Responding to fires and explosions caused by combustible gases (prevention of hydrogen explosion)

The above safety functions were to be ensured for the following equipment:

・Unit can (UC), ・Canisters, ・Transport containers, ・Storage facilities

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (3/8)

③ Implementation items and results (3/7)

a. Organization of share of safety functions (2/2)

Share of safety functions also depends on the state (during transport, during handling, during storage), hence "which equipment will ensure the safety functions to be studied in each state" (= share of functions) was specified by organizing the information in the table on the right.
For the relationship between the unit can (UC), canisters, transport containers, and storage facilities described in the table on the right, refer to Slide No.126 "[Supplement-1] Proposed handling flow for fuel debris".

Table: Results of organization of share of safety functions under normal conditions

Share function	Status	Unit cans	Canisters	Transport containers	Storage facilities
Confinement	During transport	×	○	○	/
Confinement	During handling	×	○	/	○
Confinement	During storage	/	×	/	○
Criticality prevention	During transport	○	○	△	/
Criticality prevention	During handling	○	○	/	△
Criticality prevention	During storage	/	○	/	△
Heat removal	During transport	○	○	○	/
Heat removal	During handling	○	○	/	○
Heat removal	During storage	/	○	/	○
Shielding	During transport	×	×	○	/
Shielding	During handling	×	×	/	○
Shielding	During storage	/	×	/	○
Prevention of hydrogen explosion	During transport	×	○	○	/
Prevention of hydrogen explosion	During handling	×	○	/	○
Prevention of hydrogen explosion	During storage	/	○	/	○

○: Safety functions are ensured in target equipment and facilities
△: Safety functions are ensured in target equipment and facilities conditionally
x: Safety functions are not ensured in target equipment and facilities

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (4/8)

③ Implementation items and results (4/7)

b. Establishment of requirements that satisfy functions to be shared (level 1 requirement)

In order to satisfy the safety function, the requirements for the applicable equipment (unit cans, canisters, transport containers, and storage facilities) marked as "〇" in the share of safety functions organized in section a., have been established as shown in the table on the next slide.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (5/8)

③ Implementation items and results (5/7)

Table: Requirements for applicable equipment to satisfy safety functions

Share function	Status	Unit cans	Canisters	Transport containers	Storage facilities
Confinement	During transport	(Not required)	· Prevent the leakage of radioactive materials from inside the canister, except through vent pipe · Appropriately reduce the leakage of radioactive materials associated with discharge of hydrogen gas from the vent pipe	· Appropriately reduce the leakage of radioactive materials	-
	During handling			-	· Prevent the leakage of radioactive materials from inside the canister, except through vent pipe · Appropriately reduce the leakage of radioactive materials associated with discharge of hydrogen gas from the vent pipe
	During storage	-	(Not required)		
Criticality prevention	During transport	· Criticality must be in a preventable form	· Criticality must be in a preventable form	When necessary, maintain the distance between canisters so that criticality can be prevented	-
	During handling			-	· When necessary, maintain the distance with the canisters that can prevent criticality
	During storage	-			
Heat removal	During transport	· Can maintain the fuel debris temperature appropriately	· Can maintain the fuel debris temperature appropriately	· Can bring about natural heat dissipation so that the debris temperature does not rise	-
	During handling			-	· Can bring about natural heat dissipation so that the debris temperature does not rise
	During storage	-			
Shielding	During transport	(Not required)	(Not required)	· Must be designed to reduce worker and public exposure related to the transport operation	-
	During handling			-	· Must be designed to reduce worker and public exposure related to the handling and storage operations
	During storage	-			
Prevention of hydrogen explosion	During transport	(Not required)	· Must be designed to be able to keep the hydrogen concentration inside the canister lower than the design value	Must be designed to be able to keep the hydrogen concentration inside the transport canister lower than the design value	-
	During handling			-	· Must be designed to be able to keep the hydrogen concentration in the storage facility lower than the design value
	During storage	-			

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6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (6/8)

③Implementation items and results (6/7)

c. Identification of abnormal events leading to loss of functions that must be satisfied

With respect to the requirements for equipment specified in section b., the "initiating events where the required functions cannot be maintained leading to abnormal events" were identified as described in the table on the right.
And, in this table, 3< (3 or more) is defined as an event that exceeds the control of the events assumed in Level 3: design basis.
The events at this level are believed to occur even less frequently than multiple equipment failure, such as loss of the confinement function and shielding function due to a fall accident.
(For Level 3< as well, the same treatment requirements as for Level 3 were established as shown on the next page.)

Table: Identification of abnormal events and initiating events

Item	Status	Initiating event leading to abnormal event	Level	Approach for establishing the levels
Confinement	During transport During handling	Loss of confinement function due to damage caused by dropping, etc.	3<	Assume that the confinement function will not be lost due to the event caused by the dropping accident and if it occurs, set it as an event exceeding "Level 3: Control of events assumed in design basis"
	During handling During storage	Loss of confinement function due to multiple failures of air conditioning equipment	3	Assume that the possibility of multiple failures is quite low, and set it as "Level 3: Control of events assumed in design basis"
	During storage	Loss of confinement function due to single failure of air conditioning equipment	2	Assume that the event occurs due to a single failure of the air conditioning equipment, and set it as "Level 2: Detection and control of deviations from normal operation"
Criticality prevention	During transport During handling	(Not required)	-	-
	During storage	Occurrence of criticality due to increase in moisture content or failure of array	3<	Assume that increase in moisture content and array failure will not occur at the same time and if it occurs, set it as an event exceeding "Level 3: Control of events assumed in design basis"
Heat removal	During transport During handling During storage	Loss of heat removal function when the external environment reaches a high temperature and natural heat dissipation is not possible	3	Assume that the frequency of abnormal rise in temperature is quite low, and set it as "Level 3: Control of events assumed in design basis"
Shielding	During transport During handling During storage	Loss of shielding function due to damage to container caused by dropping of the canister / dropping of heavy object (including when transport container is sealed)	3<	Assume that the shielding function will not be lost due to the event caused by the dropping accident and if it occurs, set it as an event exceeding "Level 3: Control of events assumed in design basis"
Prevention of hydrogen explosion	During transport	The amount of generated hydrogen exceeds the specified value when the specified transport time is exceeded due to vehicle problems, etc.	3	Assume that the occurrence frequency is kept at a low level, and set it as "Level 3: Control of events assumed in design basis"
	During handling	Hydrogen concentration exceeds the specified value due to loss of venting function caused by the dropping of a heavy object, etc.	3	Assume that the possibility of a dropping accident is quite low, and set it as "Level 3: Control of events assumed in design basis"
		Hydrogen concentration exceeds the specified value due to multiple failures of air conditioning equipment		Assume that the possibility of multiple failures is quite low, and set it as "Level 3: Control of events assumed in design basis"
	During storage	Hydrogen concentration exceeds the specified value due to multiple failures of air conditioning equipment	3	Assume that the possibility of multiple failures is quite low, and set it as "Level 3: Control of events assumed in design basis"

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (7/8)

③ Implementation items and results (7/7)

d. Formulation of requirements for the occurrence of abnormal events (Level 2/3 requirement)

In response to the "Initiating events where the required functions cannot be maintained leading to abnormal events" identified in section c., "Requirements for the management of abnormal events" were established as Level 2/3 requirements, as described in the table on the right.

Table: Requirements for the management of abnormal events

Item	Status	Safety requirements
Confinement	During transport	The design must be able to maintain the necessary confinement function even if the assumed dropping accident occurs. (Level 3)
	During handling	
	During handling	The design must keep the possibility of loss of confinement function due to loss of air conditioning function, low. In addition, the design must satisfy the Level 3 criteria for worker and public exposure even if loss of confinement function is assumed due to multiple failures. (Level 3)
	During storage	
	During storage	The design must satisfy the Level 2 criteria for worker and public exposure even in the event of a single failure in the air conditioning equipment. (Level 2)
Criticality prevention	During transport	(Not required)
	During handling	The design must be able to prevent criticality even in the case of an assumed combination of moisture content and canister distance.(Level 3)
	During storage	
Heat removal	During transport	The design must be such that even if the building temperature rise is assumed, the temperature inside the canister must not exceed the allowable temperature.(Level 3)
	During handling	
	During storage	
Shielding	During transport	The design must be able to maintain the shielding function during an assumed dropping accident. (Level 3)
	During handling	
	During storage	
Prevention of hydrogen explosion	During transport	The design must be such that the hydrogen concentration does not exceed the specified value even if every assumed event during transport is considered. (Level 3)
	During handling	The design must be such that the venting function of the canister is not lost even if the assumed events during handling are considered. (Level 3)
		The design must be such that the hydrogen concentration does not exceed the specific value, even if an air conditioning function loss is assumed.(Level 3)
	During storage	The design must be such that the hydrogen concentration in the storage facility does not exceed the specific value, even if an air conditioning function loss is assumed.(Level 3)

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canisters (8/8)

④ Reflection of results

The results will be reflected in the basic design specifications for the canisters, transport containers, and storage facilities.

⑤ Analysis from the viewpoint of applicability to the site

Applicability will be determined and coordinated in the process of future implementation of the design for fuel debris transfer and storage systems.

⑥ Level of achievement compared to the goal

The share of safety functions has been clearly specified and interfaces between canisters and facilities and equipment have been organized in Slide No.16 “Table: Results of organization of share of safety functions under normal conditions”.
In addition, Slide No.18 “Table: Requirements for applicable equipment to satisfy safety functions” and Slide No.20 “Table: Requirements for the management of abnormal events” lay down the technical requirements of facilities and equipment and the specifications to be provided from the viewpoint of safety during transfer and storage of fuel debris in canisters.
From the above, it is concluded that the goals have been achieved.

⑦ Future issues

Appropriate corrections must be made as necessary based on the progress of the study on the transfer and storage of canisters.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (1/7)

① Purpose and goals

Based on the process flow draft established in FY2017 for the development of a series of system concepts related to storage of canisters, the processing capacity, risks, and applicability of facilities for each process will be analyzed, evaluated, and optimized from the viewpoint of safe and effective containing, transport and storage of fuel debris.

In addition, the technical requirements for safety based on the sharing of safety functions between canisters and storage facilities (handling facilities and buildings) will be reviewed as necessary from the viewpoint of achieving a reasonable result.

② Comparison with existing technologies

Study needs to be conducted considering the unique conditions at 1F or the differences between the preconditions and the existing storage facilities, which result from those unique conditions, using the technical information on the TMI-2 fuel debris storage facilities and on the existing storage facilities such as the spent fuel interim storage facilities in Japan, as reference.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (2/7)

③ Implementation items and results (1/5)

a. Optimization of processes (scenarios) (1/2)

While consulting with related project teams, the following reviews were conducted to analyze, evaluate, and optimize the processing capacity, risks, and effectiveity of each process.

(a) Consider dry storage as the main idea and wet storage as an option

In FY2017, before dry storage, a process involving wet storage by remodeling the existing pools at 1F was studied, however, considering the following preconditions, remodeling cost, time, technical difficulties, etc., it was concluded that wet storage is not reasonable. The scenario was then revised so that dry storage was considered as the main idea and wet storage as an option.

- ✓ To use the existing 1F pools, it is necessary to secure an alternative storage location for the spent fuel, etc. currently under storage.
- ✓ The canister storage capacity that can be secured is limited.
- ✓ Countermeasures (enhancement of pool water purification function, leakage countermeasures, etc.) assuming the outflow of fuel debris components (particularly alpha nuclides) from the canisters to the pool water, are required.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (3/7)

③ Implementation items and results (2/5)

a. Optimization of processes (scenarios) (2/2)

(b). Ensuring the use of unit cans to fill fuel debris in the canisters

In FY2017, a scenario in which fuel debris was directly filled into canisters was studied and incorporated into the process as a plan as well. However, when the canister is directly filled, the canister needs to be brought inside the fuel debris retrieval site, which increases the risk of contamination on the surface of the canister. In addition, the Method Project Team and Fundamental Technology Project Team are conducting studies on the precondition that unit cans that are smaller and easier to handle than canisters are used for fuel debris retrieval. Hence in order to reduce the risk of canister surface contamination and in keeping with the progress of the studies in the Method Project and Fundamental Technology Project, the scenario was revised to ensure the use of unit cans for filling the canisters with fuel debris.

(c). Review of sorting at the fuel debris retrieval site

In FY2017, the scenario of sorting fuel debris and waste at the fuel debris retrieval site was studied and incorporated into the process. However, from the viewpoint of processing capacity and technical feasibility, this scenario will be incorporated into the process again in the future when the study, including the feasibility of the sorting technology, has progressed, and as of FY2018, fuel debris and waste are classified by area basically as shown in Slide No. 25, however, for the discharge from areas marked as fuel debris, the scenario was revised to treat the discharge that can be clearly determined as waste by visual inspection, as waste.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (4/7)

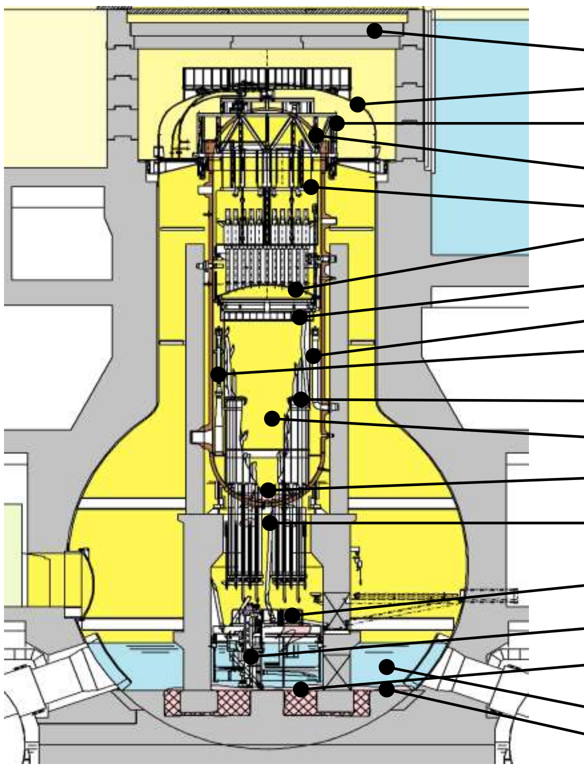
③ Implementation items and results (3/5)

b. Study of the need to revise the throughput study conditions (1/2)

On confirming the progress of the studies in related projects, it was found that there is no change in the approach towards the classification of fuel debris and waste and the conditions such as fuel debris weight and distribution, etc., and the same conditions as in FY2017 were used.

<Throughput study conditions> (Same as in FY2017)

✓ Fuel debris and waste are classified by the area of generation, and the area below the upper grid plate is assumed to be "fuel debris".



No.	Discharge	Classification
1	Shield plug	Waste
2	PCV head	Waste
3	RPV insulation material	Waste
4	RPV head	Waste
5	Steam dryer	Waste
6	Shroud head	Waste
7	Upper grid plate	Fuel debris
8	Shroud	Fuel debris
9	Jet pump	Fuel debris
─	Core support plate	Fuel debris
10	Core fuel debris	Fuel debris
11	RPV bottom fuel debris	Fuel debris
12	Fuel debris adhering to RPV lower part / CRD housing	Fuel debris
13	Internal pedestal structure	Fuel debris
14	CRD switch	Fuel debris
15	Fuel debris inside pedestal	Fuel debris
16	External pedestal structure	Waste
17	Fuel debris outside pedestal	Fuel debris

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (5/7)

③ Implementation items and results (4/5)

b. Study of the need to review throughput study conditions (2/2)

<Throughput study conditions (continued)> (Same as in FY2017)

- ✓ Fuel debris retrieval will be completed in 10 years for all units.
- ✓ Fuel debris retrieval will start at the same time and in parallel in all Units
- ✓ Working days in one year: 200 days
- ✓ Operating hours in one day: 24 hours
- ✓ All processe lines from fuel debris retrieval to the storage will be the same.
- ✓ Fuel debris filling rate (containing efficiency): 30%*1
- ✓ Canister dimensions: Internal diameter 220 mm x Internal height 800 mm*2
- ✓ Dimensions of a unit can are 90% of a canister. Two unit cans are loaded in a canister
- ✓ 12 canisters are loaded in a transport container, and 48 canisters are loaded in a storage container (metal cask)
- ✓ The component density of fuel debris is assumed to be as follows based on the study results of the Characterization Project:

  Fuel (UO_2): 11 ton/m^3 Metal: 8 ton/m^3 Concrete: 2.5 ton/m^3

*1: Target value assumed from TMI-2 results (20 to 30%)

*2: Set from the minimum canister height currently under study (external dimensions 1,000 mm)

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (6/7)

③ Implementation items and results (5/5)

c. Update of process flow

The process flow created in FY2017 was updated, reflecting the preconditions described in sections a. and b. The results are shown in Supplement-2.

d. Study of the need to revise the technical requirements for safety

Based on the results of the process optimization study, it was confirmed that there are no changes in the technical requirements for safety on the basis of the sharing of safety functions between canisters and storage facilities, and there is no need to revise (update) the results of studies conducted until FY2017.

④ Reflection of results

The results will contribute to the establishment of requirement specifications and input conditions for the basic design and detailed design of fuel debris storage facilities in the future.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(2) Study of storage system (7/7)

⑤ Analysis from the viewpoint of applicability to the site

The applicability (possibility) of the study results to the 1F site, such as with respect to securing the space necessary for the installation of storage facilities on the 1F premises, etc. will need to be determined and coordinated in the future.

⑥ Level of achievement compared to the goal

With respect to the indicators for determining the achievement of goals, optimization studies were carried out for each process from containing to storage of fuel debris from the viewpoint of processing capacity, risk, applicability, etc. In addition, the need to change the throughput study conditions was studied and the process flow was updated.

And, based on the results of the process optimization study as well, it was confirmed that the technical requirements for safety based on the sharing of safety functions between canisters and the canister handling facilities and building facilities, need not be revised from the results of studies conducted until FY2017, and that they have been set such that they are reasonably achievable.

From the above, it is concluded that the goals have been achieved.

⑦ Future issues

From the viewpoint of further streamlining and optimizing the storage system, sorting of fuel debris and waste and a highly accurate understanding of the weight and distribution of fuel debris is believed to be an issue for R&D in the future.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(3) Study of storage method (1/3)

① Purpose and goals

Based on the results of Section 6.2.(2) "Study of storage system", the technical requirements for safety will be updated as necessary for the dry storage and wet storage methods that have been studied until FY2017.

② Comparison with existing technologies

Study needs to be conducted considering the unique conditions at 1F or the differences between the preconditions and the existing storage facilities, which result from those unique conditions, using the technical information on the TMI-2 fuel debris storage facilities and on the existing storage facilities such as the spent fuel interim storage facilities in Japan, as reference.

③ Implementation items and results

The process optimization study was conducted in Section 6.2.(2) "Study of storage system", but it was confirmed that there were no changes in dry storage and wet storage methods that would affect the technical requirements for safety and there was no need to update the results of studies conducted until FY2017.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(3) Study of storage method (2/3)

④ Reflection of results

The results will contribute to the establishment of requirement specifications and input conditions for the basic design and detailed design of fuel debris storage facilities in the future.

⑤ Analysis from the viewpoint of applicability to the site

Decision and coordination related to the applicability of the study results to the 1F site will be necessary in the future.

⑥ Level of achievement compared to the goal

With respect to the indicators for determining the achievement of goals, the consolidation of wet and dry storage methods and the technical requirements for the storage methods (refer to Supplement-3) was completed by FY2016, and it was confirmed that there was no need to update the consolidated information even in light of the results of the study of storage systems (process optimization).

From the above, it is concluded that the goals have been achieved.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(3) Study of storage method (3/3)

⑦ Future issues

As shown on Slide No. 23, it is necessary to continue studying the technical development issues, including management and operation related to fuel debris storage, considering dry storage as the main idea.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (1/12)

① Purpose and goals

Dry storage of fuel debris is believed to be effective because it can reduce the moisture content that can cause hydrogen generation and corrosion, and can, thus, serve as a hydrogen countermeasure and reduce the likelihood of repairs due to corrosion. In order to achieve this, it is essential to establish a technology for drying fuel debris.

The goal of this technical development is to summarize the basic concept of the drying equipment based on simulations and tests using substitute materials that can be implemented under cold conditions, with the aim of contributing to the design and verification of dryers for actual debris.

② Comparison with existing technologies

TMI-2 has experience in drying of fuel debris, but it did not include Molten Core Concrete Interaction (MCCI) products expected in 1F. In addition, since data on drying of actual debris is limited, it is necessary to conduct studies taking conditions specific to 1F into account.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (2/12)

③ Implementation items and results (1/10)

Previous studies

・ In the transfer of fuel debris, hydrogen generated by radiolysis of the accompanying water may accumulate in the canister or the transport container, which may limit the capacity of the transport container. The literature and the findings of tests conducted in this technical development indicate that almost no hydrogen is generated from crystal water contained in concrete, and it is believed that free water elimination by drying is effective in controlling the amount of generated hydrogen.

・Based on the results of TMI-2, fuel debris is assumed to be porous, and considering that it is crushed and contained, it is necessary to consider the moisture remaining in the pores inside the particles and the moisture remaining between the particles, for the drying of fuel debris in the canister (unit can).

・The drying tests that were conducted in the Fuel Debris Characterization Project included the drying of the porous solid focusing on the drying of moisture remaining in the pores of the particles, and the powder drying test focusing on the drying of moisture remaining between particles.

・In the drying test of the porous solids, element tests were performed with aluminum oxide, zirconium dioxide, and uranium dioxide. The results produced show that porous solids with pore size of 1μm or more could be dried to almost zero moisture in all the test devices, although zirconium dioxide containing pores of 0.1 μm took slightly longer than other test devices. In addition, even a drying test using a powder of 1 μm has produced results showing that drying of all test devices was possible in spite of events such as channeling during heating (during the drying process, when hot air passes through the dried material and transfers heat, the hot air lacks uniformity and evenness, and hence drying progresses in the form of a rathole).

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4)Study of drying system (3/12)

③Implementation items and results (2/10)

Study flow

This technical development (subsidized project)

Element testing with substitute materials (φ10 mm) (Debris Characterization Project)	Drying behavior in case of porous ceramics (such as Al_2O_3) and powder ⇒ Mainly constant-rate drying; dryness can be expected. Crystal water is difficult to dry.
Setting of drying goals	It was confirmed that little hydrogen is generated from concrete (crystal water). (Influence of alpha rays was studied additionally) ⇒Free water elimination was considered as the goal for the drying process.
Academic study of drying conditions	The drying methods were studied through analysis focusing on the estimation of the drying characteristics. ⇒Hot-air drying and heated decompression (vacuum) drying were selected as efficient drying methods.
FP behavior (Debris Characterization Project)	
Assume drying conditions based on simulation, tests with substitute material, etc. and set the basic conditions for the device	Study of drying conditions ⇒The drying characteristics were studied through element tests.
Verify the drying behavior based on tests with simulated debris (cold) and create the basic equipment design	Verification of the drying behavior by scaling up (actual scale) and creation of the basic equipment design.
Verify the drying conditions based on tests with actual debris (hot) and reflect in the equipment design	Confirmation of the drying time and drying level with real debris on a small scale Confirmation of the degree of dispersion of radioactive materials by aerosol, etc.
Final confirmation with real debris and actual equipment	Confirmation of the drying time and drying level with real debris on a full scale.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (4/12)

③ Implementation items and results (3/10)

[Reference]

a. Preheating period (Decompression period in vacuum drying)(I):

The period during which the water inside starts to boil due to heating (in vacuum drying, the water inside will start to boil due to the decompression in the container)

The time it takes is determined by the heat input and the heat capacity of the fuel debris. (In vacuum drying, it will be determined by the discharge capacity of the vacuum pump and the capacity of the container.)

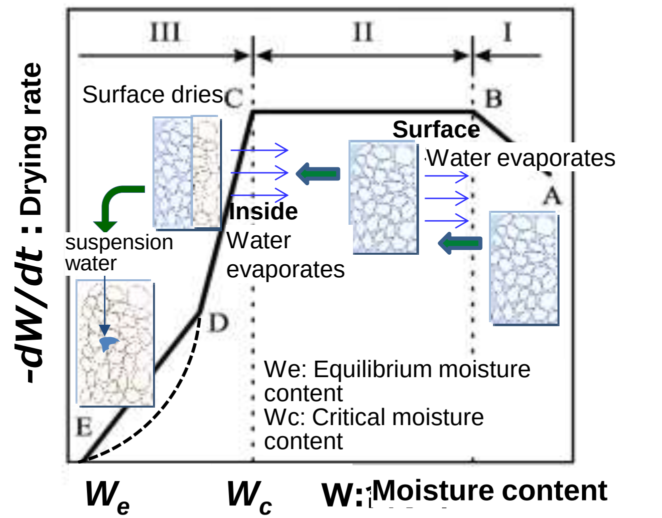
b. Constant-rate drying period (II):

Since water starts to boil and drying progresses to balance the external heat input and the evaporation latent heat, the moisture content will decrease at a fixed rate with respect to time.

The evaporation time can be calculated by dividing the residual water volume by the evaporation rate.

c. Falling-rate drying period (III):

Drying is dominated by the amount of mass transfer, such as water evaporation, expansion, and seepage in narrow parts. The shape of the fuel debris (state of water in the narrow parts) is unknown, and the elaboration presumes verification of the actual debris. (III) will also be qualitatively short if (II) is short.



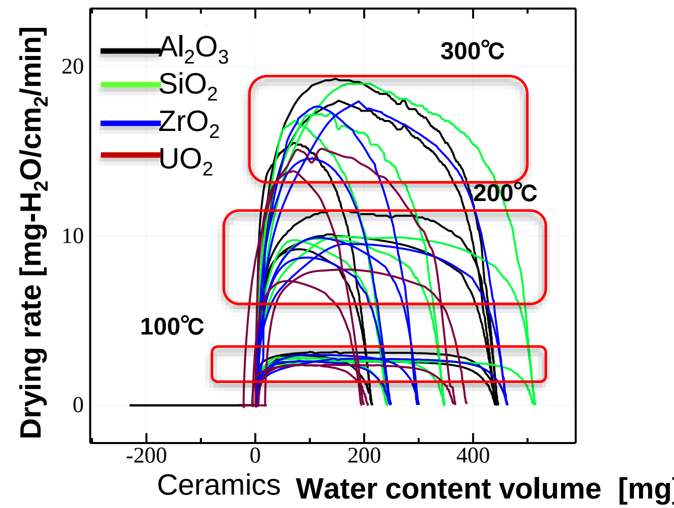


Figure: Drying characteristics with fuel debris substitute material

Reference: FY2016 study results of the Fuel Debris Characterization Project

Note: The graph shows that the drying rate changes as water content volume decreases (dries) (decreases from right to left)

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (5/12)

③ Implementation items and results (4/10)

In the study for the Debris Characterization Project, the element test of porous solids (zirconium dioxide, etc.: pore size 0.1 μm onwards) confirmed drying, but the pore size could be even smaller. Therefore, the drying behavior of test devices with fine pore size was confirmed.

⇒ Drying characteristics data was contained using zeolite (0.06μm) with a fine pore size. For comparison, the data on zirconium dioxide and aluminum oxide was also contained.

<Test procedures>

○ Decompression environment

① A test device (about 20 to 120 mg) impregnated with water was weighed and placed in the chamber.

② The pressure inside the chamber was reduced to the order of 10^{-2} torr (maintained for 30 minutes). After 30 minutes, the chamber was isolated.

③ The chamber was then heated up to the specified temperature, and after reaching the specified temperature, the temperature was maintained for 10 hours.

④After 10 hours, the chamber was reheated, and when the temperature rose, it was maintained for 10 minutes, and then the weight of the test device was measured.

○ Inert gas environment

① A test device (about 20 mg) impregnated with water was weighed and placed in the chamber.

② The chamber was aerated with nitrogen gas (maintained for 30 minutes).

③ The chamber was heated to the specified temperature while circulating the gas, and after reaching the specified temperature, the temperature was maintained for 10 hours.

④ After 10 hours, the chamber was reheated, and when the temperature rose, it was maintained for 10 minutes, and then the weight of the test device was measured.

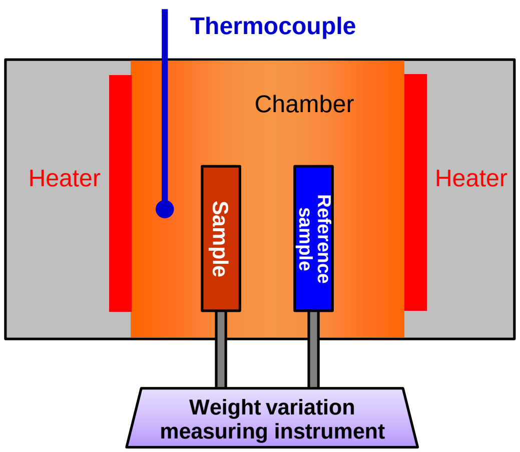


Figure: Overview of test for the falling-rate drying period

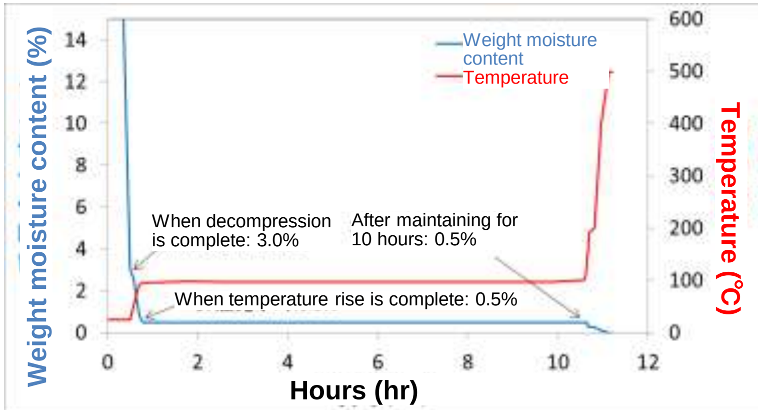
6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

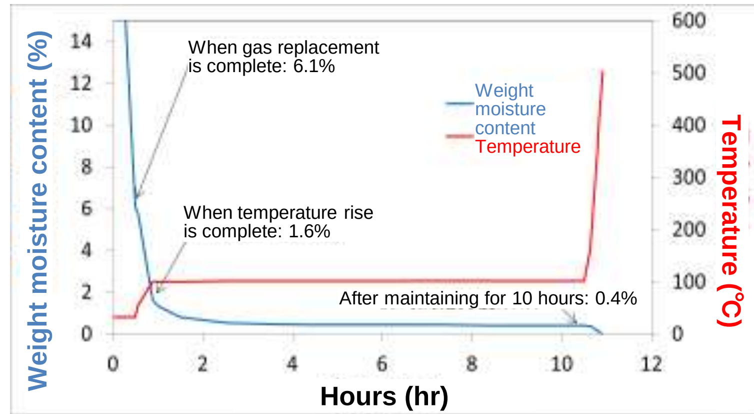
(4) Study of drying system (6/12)

③ Implementation items and results (5/10)

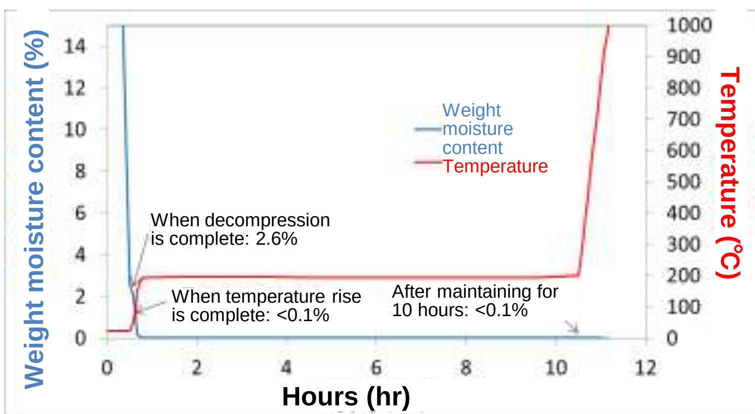
In the case of zeolite which has a fine pore size (pore size 0.06 μm), the drying rate was asymptotically reduced to zero at 100℃ and the event of prolonged drying was observed. This event was not observed at 200℃.
⇒ It is necessary to consider the possibility of similar events occurring in fuel debris with fine pores.



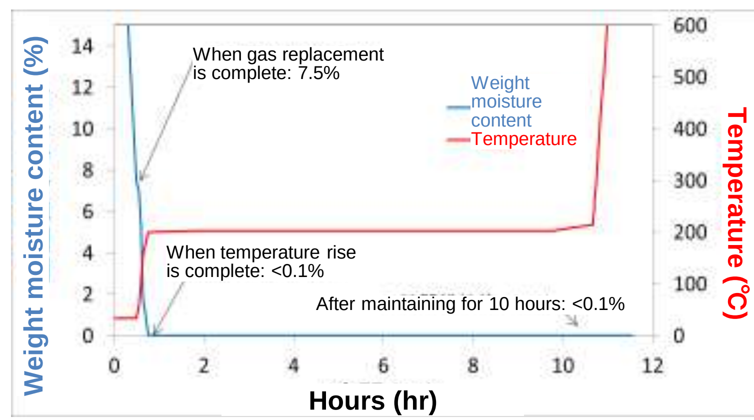
Decompression drying (100℃)



Inert gas environment (100℃)



Decompression drying (200℃)



Inert gas environment (200℃)

Figure: Drying behavior of zeolite

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (7/12)

③ Implementation items and results (6/10)

Table: Weight moisture content of the test devices during the drying process

Material of the test device (Pore size)	Conditions	Weight moisture content (%)		
		When decompression or gas replacement is complete	When temperature rise is complete	After 10 hours hold
Zeolite 0.06 μm	Decompression environment 100℃	3.0	0.5	0.5
	Decompression environment 200℃	2.6	<0.1	<0.1
	Inert environment 100℃	6.1	1.6	0.4
	Inert environment 200℃	7.5	<0.1	<0.1
Zirconium dioxide 0.1 to 1 μm	Decompression environment 100℃	0.3	<0.1	<0.1
	Decompression environment 200℃	0.6	<0.1	<0.1
	Inert environment 100℃	<0.1	<0.1	<0.1
Aluminum oxide 10 μm	Decompression environment 100℃	<0.1	<0.1	<0.1
	Inert environment 100℃	<0.1	<0.1	<0.1

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (8/12)

③ Implementation items and results (7/10)

(Study of heating methods)
Assuming heating at 200℃, the drying time was estimated and studied from a calorimetric viewpoint.
The drying time was calculated by dividing the evaporation latent heat by the heat input.

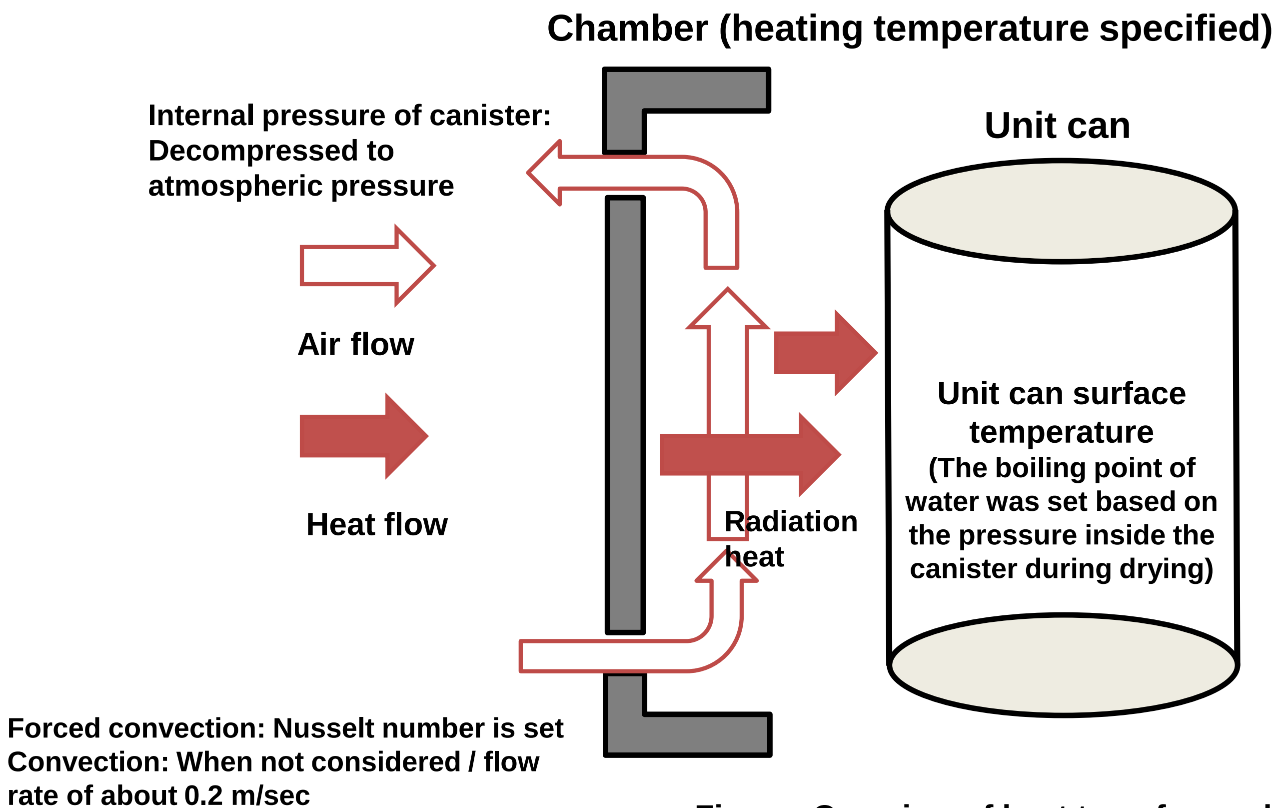


Figure: Overview of heat transfer model (when drying in unit can)

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (9/12)

③ Implementation items and results (8/10)

As one of the effective drying methods, the time obtained by dividing the latent heat of evaporation by the heat input based on the heat transfer calculation, was estimated, and the heat input methods were compared for arranging the apparatus.

Without heat input, the drying time would be greatly extended, so the study was conducted presuming heat drying. Decompression drying lowers the boiling point of water, so it can be expected to be effective in shortening the drying time, such as easy input of heat due to the difference in temperature from the outside surface. Meanwhile, hot-air drying is a commonly used drying method and arrangement of apparatus is believed to be easier in the case of this method. In addition, drying in a canister form is disadvantageous in terms of drying time, but is advantageous from the viewpoint of controlling the spread of contamination.

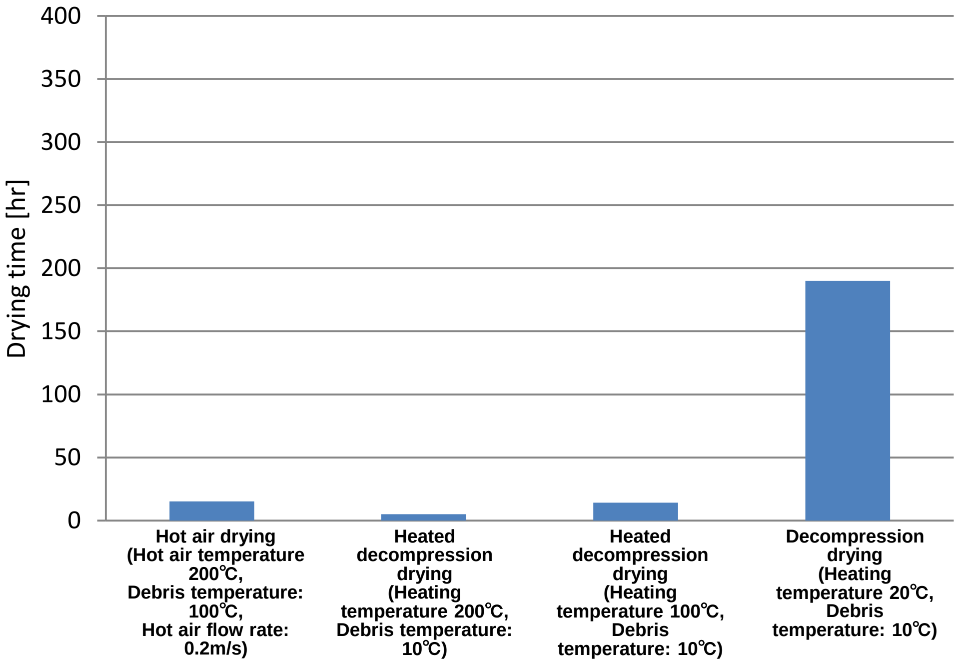


Figure: 1 Estimated drying time when fuel debris is directly heated (in a unit can)

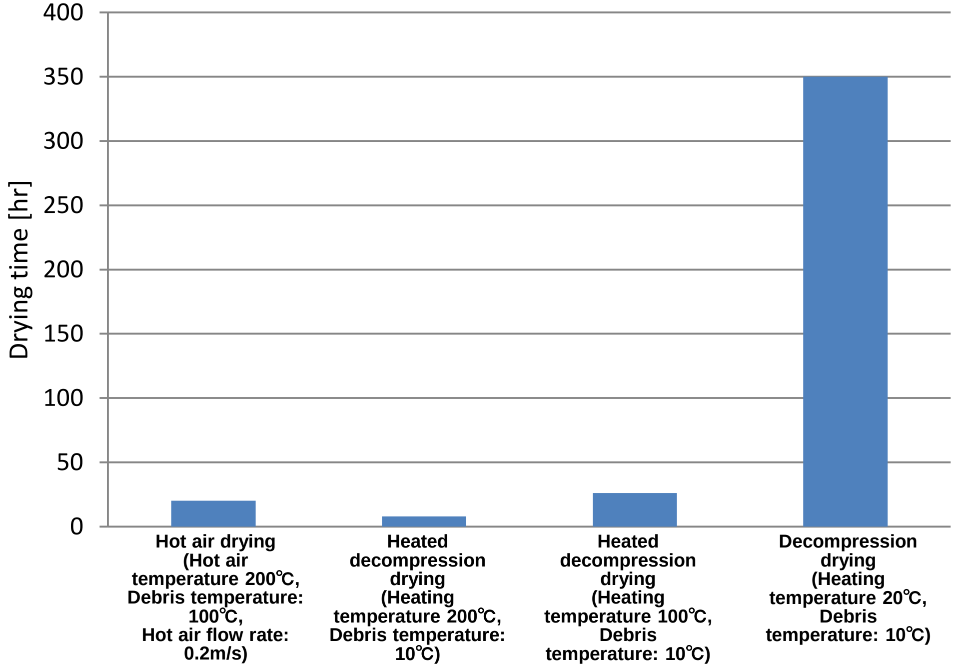


Figure: 2 Estimated drying time when unit can is placed in the canister

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

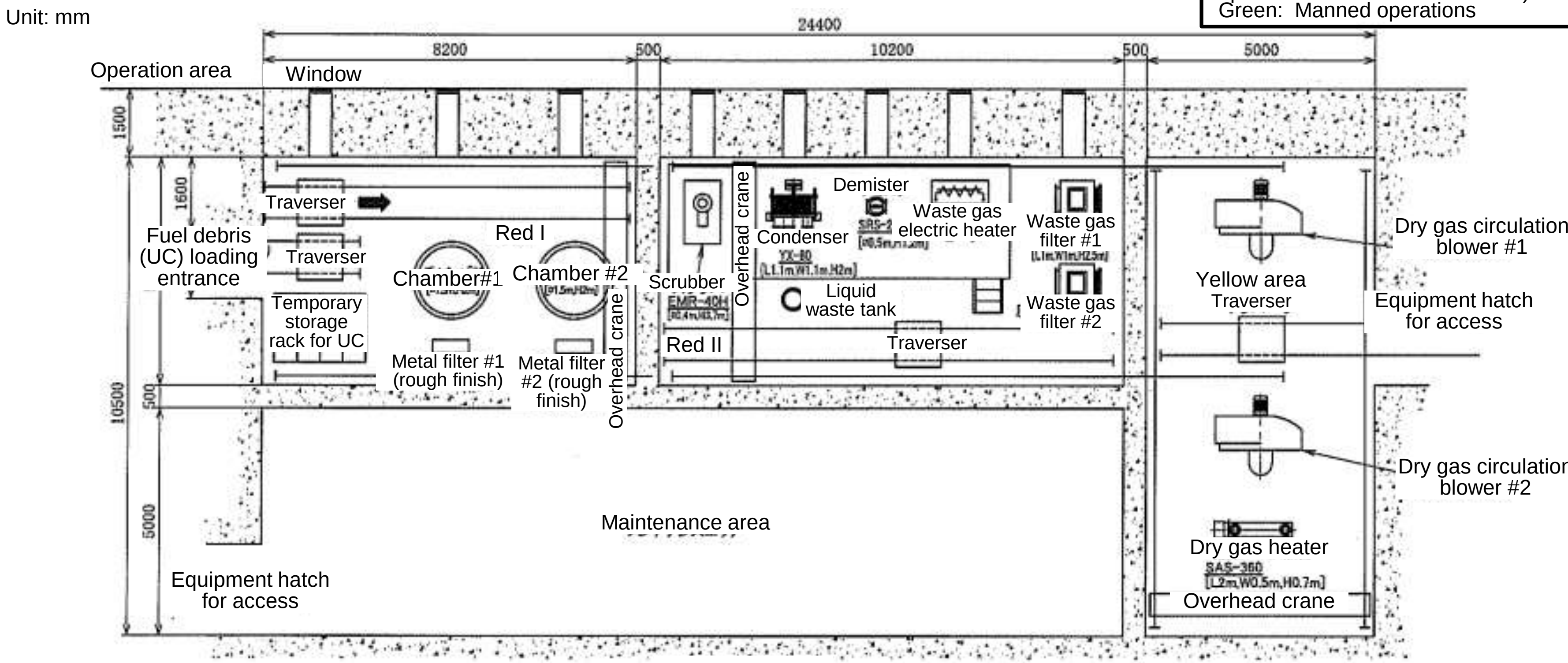
(4) Study of drying system (10/12)

③ Implementation items and results (9/10)

In order to identify future issues, possible equipment configurations based on the amount of evaporation were studied and a conceptual plan was compiled.

⇒ It is necessary to contain and improve the data on the behavior of fuel debris during the drying process and to substantiate the specifications for individual equipment.

<Area classification>
Red: Unmanned operations (remote operations from outside the area)
Yellow: Unmanned operations (remote operations from outside the area)
Green: Manned operations



Floor plan

Figure: Example of a conceptual plan for a dryer

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (11/12)

③ Implementation items and results (10/10)

Conclusion

- Heating zeolite (pore size0.06μm) at 200℃ results in asymptotically reducing the drying rate to zero and controlling the occurrence of prolonged drying. If it can be assumed that the fuel debris is a substance that tends to dry more easily than zeolite, drying at 200℃ can be considered to be an effective means.
- Fuel debris may have a high initial moisture content. Assuming that 30 vol% of the apparent fuel debris volume is moisture, when the drying time based on heating at 200℃ is estimated using the evaporation latent heat and the heat input based on the heat transfer calculation, the results indicate that the drying time can be shortened by heating.
- Since information on the shape, pore form, hydrophilicity, etc. of the 1F fuel debris has not been obtained at this time, it cannot be denied that 1F fuel debris may be harder to dry than zeolite. In addition, knowledge on the behavior associated with drying, such as that of FP gas or finer fuel debris getting converted to gas, is also limited. Therefore, until the 1F fuel debris is contained and the information on drying is obtained, the study will be conducted without focusing on the fuel debris conditions.
- In FY2017, hot-air drying and heated decompression (vacuum) drying were selected from the viewpoint of drying efficiency, and from FY2019 onwards as well, studies will continue considering both of these cases.

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(4) Study of drying system (12/12)

④ Reflection of results

The concept of a dryer for fuel debris will be summarized, thereby contributing to the practical use of dry storage.

⑤ Analysis from the viewpoint of applicability to the site

Applicability will be determined in the process of future implementation.

⑥ Level of achievement compared to the goal

The drying time was estimated from the calorimetric viewpoint, and it was concluded that the goals have been achieved.

⑦ Future issues

The study on substantiating individual components of a device will be undertaken from FY2019, however, following issues should be considered.

- Drying control method based on drying behavior during the process of drying the fuel debris
- Setting the conditions for the off-gas treatment system
- Reflecting equipment operation and maintenance methods

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(5) Study and review of specifications for handling devices (1/6)

① Purpose and goals

A handling system presuming remote operation for handling of canisters will be developed. In particular, the handling devices used for lid closing and hoisting are specialized to the canisters, therefore, as part of the system study, the proposed structure of the handling devices (lid closing device, canister suspension jig) will be determined along with the structural study of the canisters.

② Comparison with existing technologies

Although the lid closing device itself can be designed within the application range of the existing technology, the design needs to consider compatibility with the lid structure, remote operability, and restrictions on the canister handling system, etc.

Even the canister suspension jig can be designed within the application range of the existing technology, but just like the lid closing device, the design needs to consider compatibility with the lid structure, remote operability, and restrictions on the canister handling system.

In the present technical development, two types of lid structures, a bolt fastening structure and a simple installation structure (lid closure by rotation), are being studied.

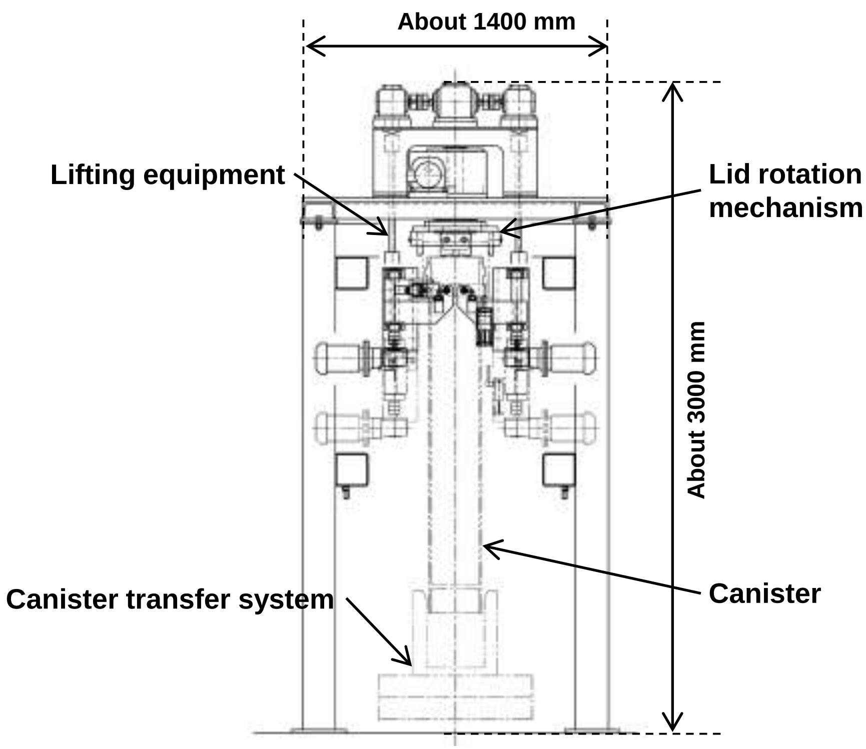
6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(5) Study and review of specifications for handling devices (2/6)

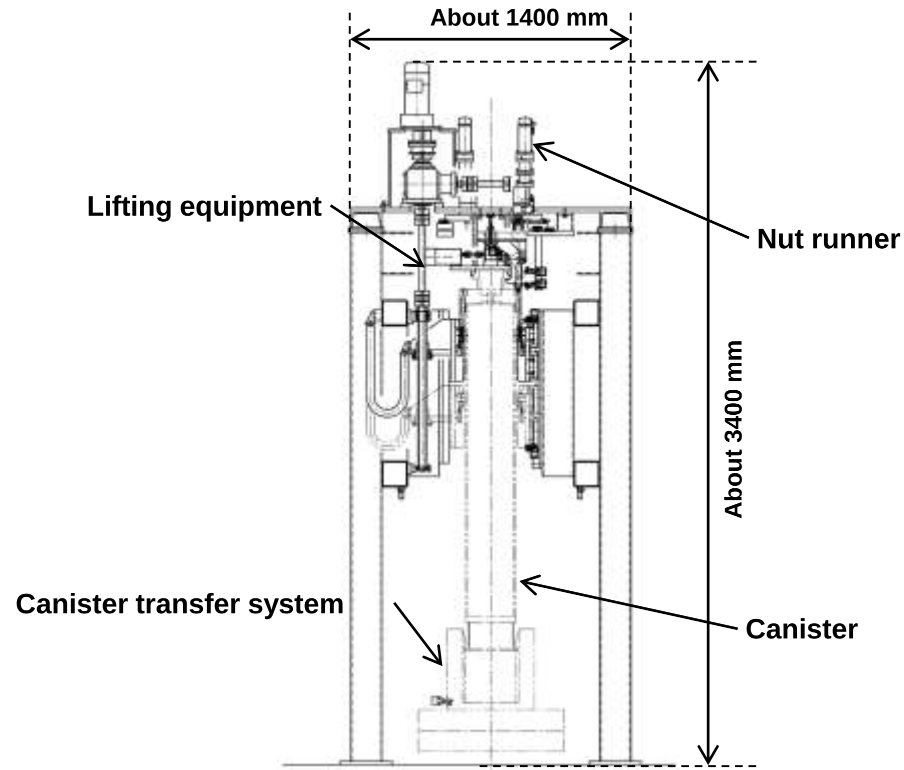
③ Implementation items and results (1/4)

a. Study of canister handling devices (lid closing device)

In accordance with the progress of the study on lid structures (simple installation structures, bolt fastening structures) discussed in Section 6.3(2)③a.(a)., handling devices (lid closing device, canister suspension jig) were proposed.



(a) Example of a simple installation structure with internal diameter of 220 mm



(b) Example of bolt fastening structure with internal diameter of 220 mm

Figure: Examples of designs of lid closing devices

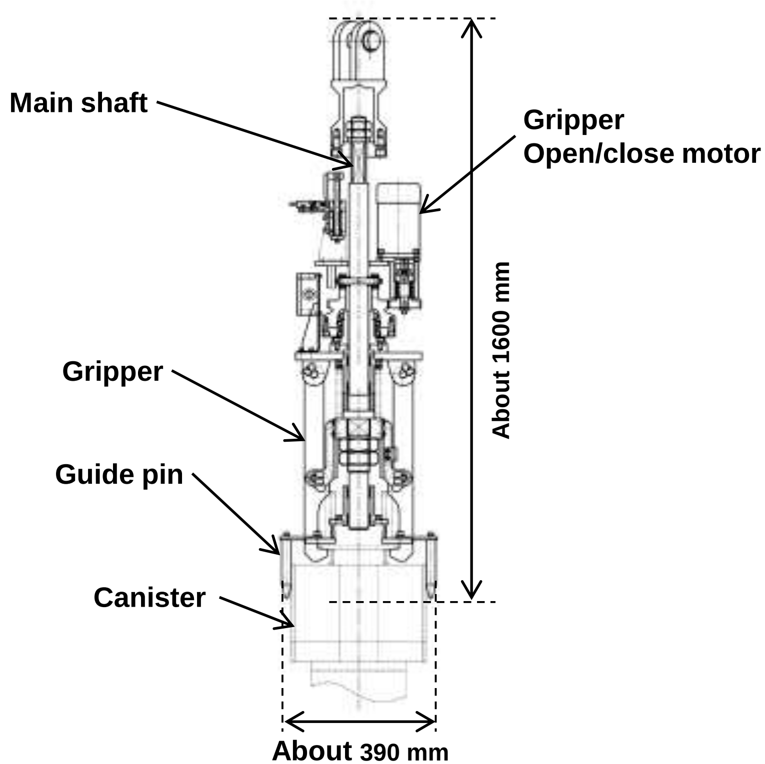
6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(5) Study and review of specifications for handling devices (3/6)

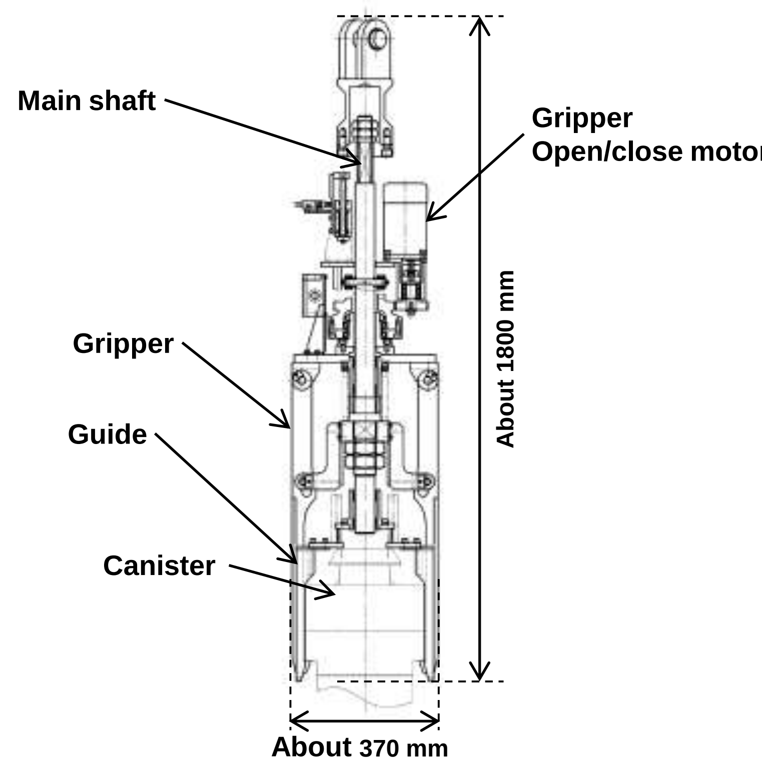
③ Implementation items and results (1/4)

a. Study of canister handling devices (lid closing device)

In accordance with the progress of the study on lid structures (simple installation structures, bolt fastening structures) discussed in Section 6.3(2)③a.(a)., handling devices (lid closing device, canister suspension jig) were proposed.



(a) Example of a simple installation structure with internal diameter of 220 mm



(b) Example of bolt fastening structure with internal diameter of 220 mm

Figure: Example of canister suspension jig

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

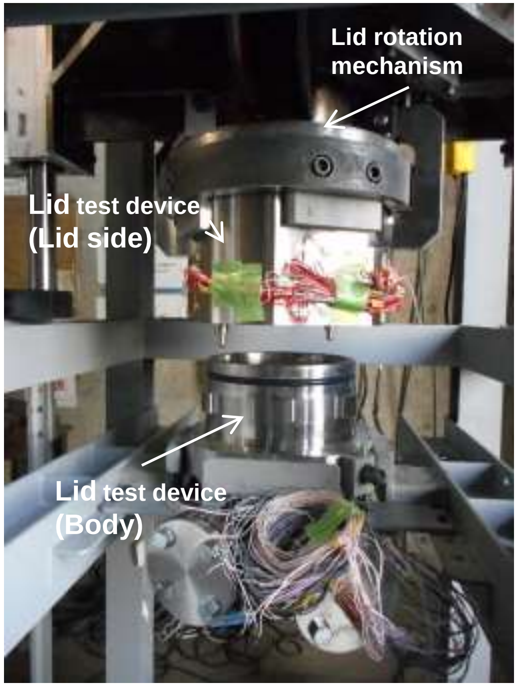
(5) Study and review of specifications for handling devices (4/6)

③ Implementation items and results (3/4)

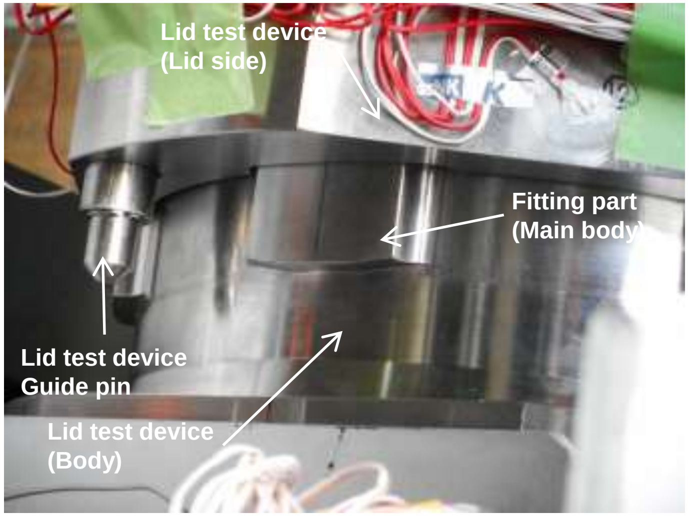
b. Verification of canister handling devices (Lid closing device)

The handleability was verified during the test for confirming the feasibility of the lid structure (simple installation structure) implemented in Section 6.3(2)③a.(f). At that time, jigs (such as jigs for manual operations simulating only the joint with the lid structure) simulating some of the handling devices (lid closing device, canister suspension jig) were developed, tests were conducted, and basic operations related to handleability were verified. The lid rotation torque used for closing the lid was obtained as basic data contributing to the selection of specifications for the components of the actual handling devices.

(a) Appearance of lid closing device



(b) Lid closing test status 1



(c) Lid closing test status 2

Figure: Example of lid closing test status

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

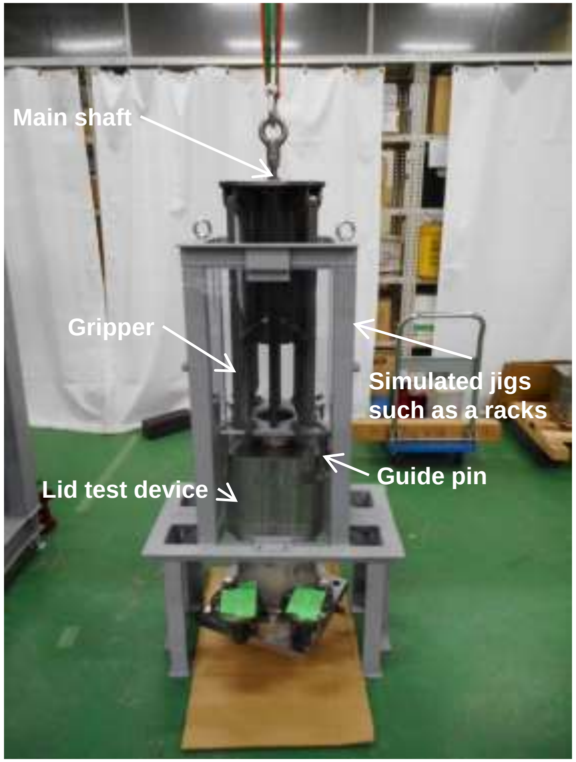
(5) Study and review of specifications for handling devices (5/6)

③ Implementation items and results (4/4)

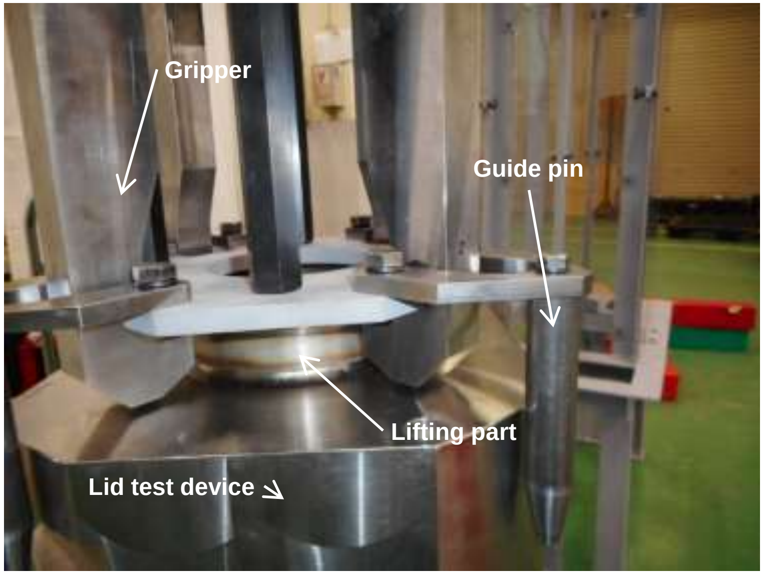
b. Verification of canister handling devices (Canister suspension jig)

The handleability was verified during the test for confirming the feasibility of the lid structure (simple installation structure) implemented in Section 6.3(2)③a.(f). At that time, jigs (such as jigs for manual operations simulating only the joint with the lid structure) simulating some of the handling devices (lid closing device, canister suspension jig) were developed, tests were conducted, and basic operations related to handleability were verified.The operability of opening and closing of the gripper and the extent of engagement were verified as basic data contributing to the selection of specifications for the components of the actual handling devices.

(a) Canister suspension jig



(b) Suspended canister



(c) Gripper

Figure: Example of canister hoisting test status (for internal diameter 220 mm)

6. Implementation Details

6.2. Study of Safety Requirements, Specifications and Storage Systems for the Transfer and Storage of Fuel Debris Canisters

(5) Study and review of specifications for handling devices (6/6)

④ Reflection of results

Decision on the proposed structure of the handling devices (lid closing device, canister suspension jig) will provide information that contributes to the study of the handling devices and the related facilities (additional buildings, storage facilities, hoist, etc.).

⑤ Analysis from the viewpoint of applicability to the site

Although the handling device specifications take into account remote operations conducted on site, final confirmation through mock-up etc. considering compatibility with the installed facilities such as additional buildings, is necessary.

⑥ Level of achievement compared to the goal

With respect to the indicators for determining the achievement of goals, the specifications of the handling devices (lid closing device, canister suspension jig) were proposed based on the lid structure plan and the latest handling flow plan studied in Section 6.3(2). From the above, it is concluded that the goals have been achieved.

⑦ Future issues

Although the feasibility of the handling device mechanism itself was confirmed, compatibility with the additional building, which is the location where the handling device is installed in consideration of remote operations, and reflection of operability in the actual device are believed to be issues in the designing and manufacturing of the actual handling devices.

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(1) Safety verification of sub-criticality(1/5)

① Purpose and goals

The following studies were carried out until FY2017 for the purpose of developing a sub-criticality maintenance scenario for fuel debris in a series of fuel debris containing, transfer and storage processes:

- Developing a sub-criticality maintenance scenario in terms of canister shape management (internal diameter of canister of 220 mm or less) based on the results of criticality evaluation under conditions for safety.
- Study of measures to increase the internal diameter of canisters while maintaining sub-criticality, and developing a practical scenario from the viewpoint of effectivity and handleability.

In FY2018, the new knowledge and the progress made in studies for related projects, such as the results of the fuel debris containing method studied in the Fuel Debris Retrieval Method Project and the Fundamental Technology Project, will be reflected as necessary in the measures to increase the internal diameter of canisters, studied until FY2017, and the development of appropriate sub-criticality maintenance scenario will be completed.

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(1) Safety verification of sub-criticality(2/5)

② Comparison with existing technologies

As a condition for safety, in the TMI-2 fuel debris canister design, the internal diameter of the canister was limited so that the sub-criticality state could be maintained even under the optimum deceleration condition that assumes pellets with the highest enrichment in the TMI-2 loaded fuel. At present, the 1F canisters also follow the same design concept.

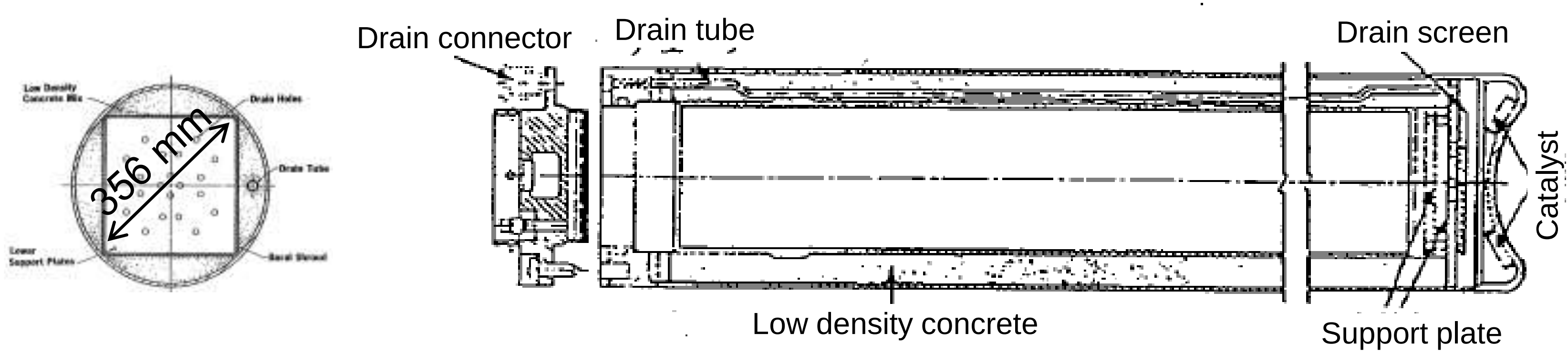


Figure:: TMI-2 fuel canister

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(1) Safety verification of sub-criticality(3/5)

③ Implementation items and results (1/2)

The progress of related projects and the results of workshops with US engineers were reflected, as necessary, in the measures to increase the internal diameter of canisters, established up to FY2017, and the development of an appropriate sub-criticality maintenance scenario was completed.

a. Investigation of related projects

The related projects were investigated and their application to sub-criticality evaluation conditions was studied. New knowledge that could ease the evaluation conditions from the work conditions, etc. with certainty, could not be obtained. In addition, although the neutron absorbent studied in the Fuel Debris Retrieval Method (Criticality Control) Project is useful from the viewpoint of criticality prevention, its operation has not yet been determined, and hence it was concluded that it cannot be considered as an evaluation condition for the Canister Project at present.

b. Workshop with US engineers

Through discussions at the workshop, the appropriateness of the current evaluation conditions taking into account the non-uniformity of BWR fuel, was confirmed. It was agreed that easing of the evaluation conditions requires sufficient data to support it.

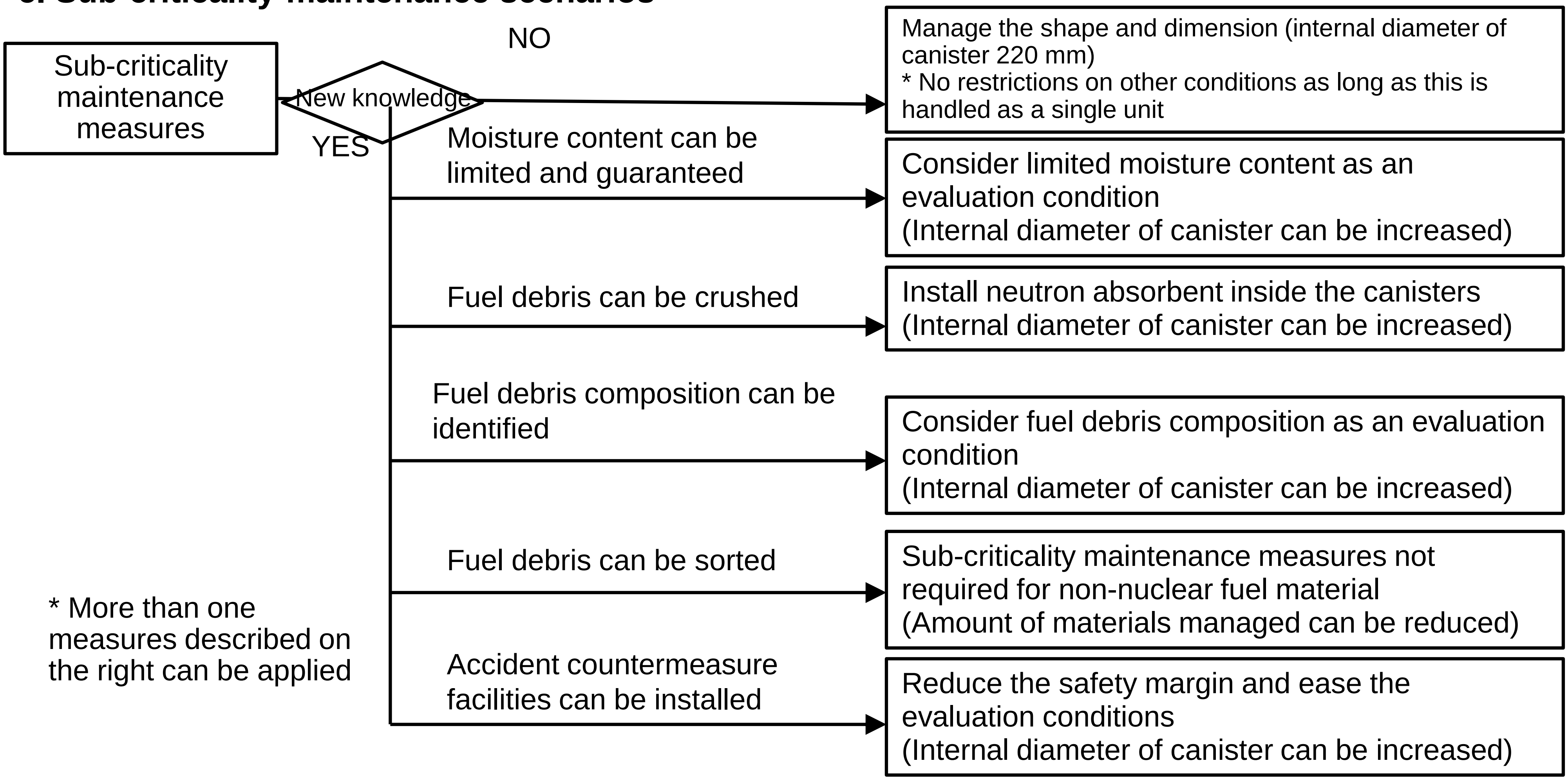
6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(1) Safety verification of sub-criticality(4/5)

③ Implementation items and results (2/2)

c. Sub-criticality maintenance scenarios



* More than one measures described on the right can be applied

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(1) Safety verification of sub-criticality(5/5)

④ Reflection of results

- Establishing sub-criticality maintenance scenarios clarifies design options and application conditions.
- If the measures to increase the internal diameter of canister are enacted, the throughput of fuel debris retrieval may improve.

⑤ Analysis from the viewpoint of applicability to the site

In order to create the sub-criticality maintenance scenarios, their applicability to the site will be analyzed mainly from the following viewpoints:

- Fuel debris properties based on the results of internal investigation and sampling
- Restrictions on actual operations assumed for fuel debris retrieval and storage

⑥ Level of achievement compared to the goal

The progress in the study of related projects such as Fuel Debris Retrieval Method Project, Fundamental Technology Project, etc. was investigated. In addition, through the workshop with US engineers, the appropriateness of the conventional sub-criticality maintenance evaluation method (an example is shown in Supplement-4), which considers the particle size and moisture content of fuel debris, was studied. Taking these findings into account, the formulation of the draft sub-criticality maintenance scenarios was completed. From the above, it is concluded that the current year's plan has been achieved.

⑦ Future issues

None.

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (1/19)

① Purpose and goals

A plan for the lid structure of the canister for collecting, transferring and storing the fuel debris will be determined. For this purpose, the lid structure will be re-examined based on the results of the FY2017 study, and the feasibility of the lid structure will be verified by means of a load test and by confirming its handleability using a lid structure test device. Based on these results, a design plan for the lid structure will be presented at the end of FY2018.

In addition, as preparation for the full-scale canister load test, which is under study for implementation in FY2020, full-scale canister test devices will be designed and a test plan will be drawn up.

② Comparison with existing technologies

Among the lid structures studied in FY2017, the bolt fastening structure is a method of closing the lid by tightening the bolts, and can be designed within the application range of the existing technology.

Meanwhile, the simple installation structure is a method of closing the lid by rotating the lid, and although it has been used in ultra-high pressure vessels, there are concerns about its remote handleability or its structural integrity in events such as falling over, therefore, verification must be carried out according to the 1F conditions.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (2/19)

③ Implementation items and results (1/17)

a. Validation of canister lid structure

(a) Requirements for canister and canister lid (1/2)

In the study of lid structure, the requirements for lids were reconfirmed against the requirements for canisters with respect to safety functions.

Table: Requirements for canisters and lids

Safety Functions		Requirements for canister	Requirements for lid
Sub-criticality		Sub-criticality shall be maintained for individual canisters. During arrangement, sub-criticality shall be maintained using other equipment.	The lid shall not release fuel debris pieces outside the canister from the viewpoint of sub-criticality maintenance.
Cooling	Heat removal	There is no special requirement (installation of fins, etc. to improve heat removal) as the amount of heat generated is less than the same level of spent fuel and can be removed by static natural cooling.	-
Confining	Confinement	The canister shall have an opening to prevent the accumulation of hydrogen. Measures to prevent the spread of contamination shall be implemented during actual operations (installation of filters, etc.), but from the viewpoint of a robust boundary, confinement function shall not be required for safety evaluation.	The lid shall not release fuel debris pieces outside the canister as a measure to prevent the spread of contamination.
	Shielding	Shielding function shall not be required from the viewpoint of handleability of the canister.	-
Other (for maintaining the above functions)	Structure Material integrity	The structure shall have the integrity to maintain the safety functions of the canister. However, it shall maintain minimum strength from the viewpoint of handleability.	The lid shall be able to maintain the following structural strengths to ensure confinement: ・Shall be able to maintain integrity against the internal pressure of the canister *1 . ・The lid shall not open or break even when the canister receives an impact (e.g., toppling).
	Hydrogen	Shall be able to release the generated hydrogen outside the canister.	(A vent mechanism shall be provided on the lid when necessary.)
	Fire protection	As confinement function is not required for the canister against residual zirconium fire, maintaining an inert atmosphere or flooded state shall not be required.	-

*1: Although airtightness is not required for the canister, as one of the lid's structural design conditions, it is required to withstand a certain level of internal pressure.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (3/19)

③ Implementation items and results (2/17)

a. Validation of canister lid structure

(a) Requirements for canister and canister lid (2/2)

In the study of the lid structure, the requirements for remote handling were set as follows based on the canister handling flow plan.

- Lid can be opened and closed under the condition partially or completely submerged using remote control.
- Lid can be closed with simple movements (e.g., turning the lid) from the viewpoint of workability.

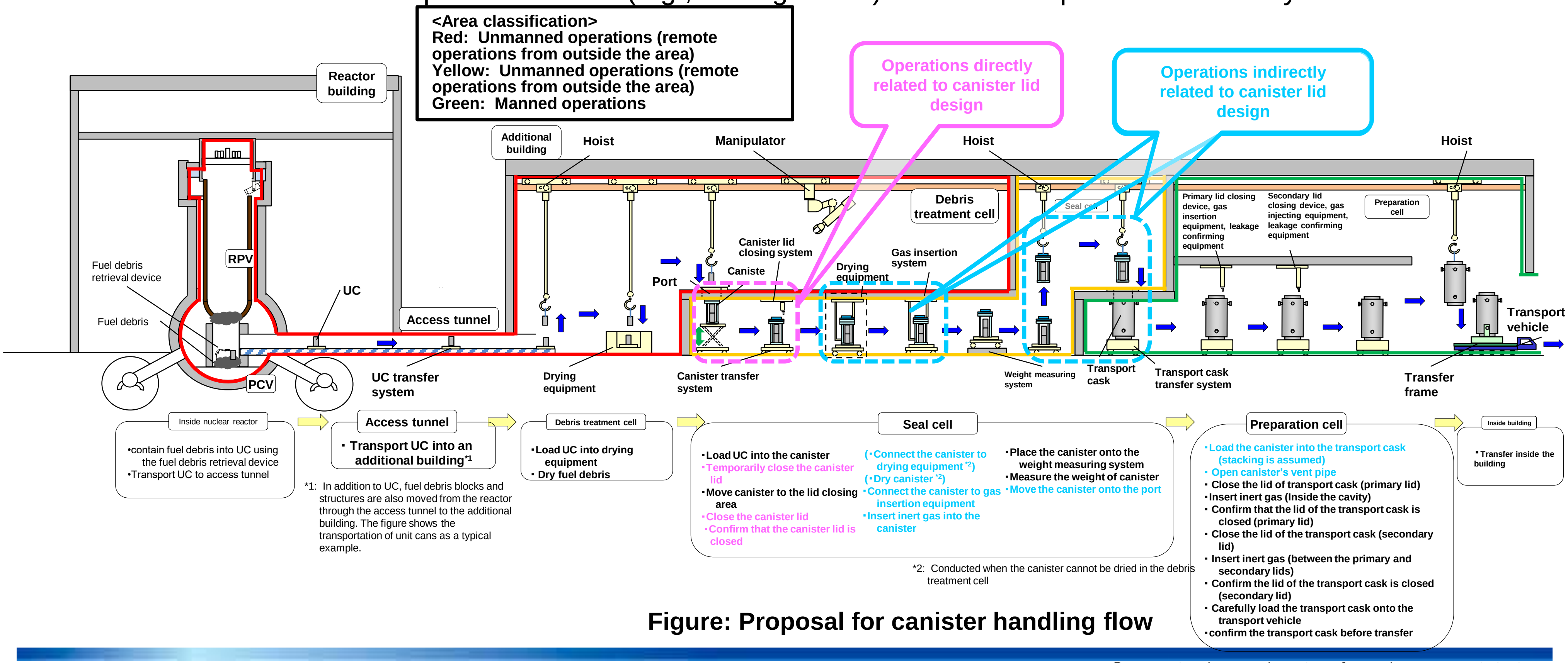


Figure: Proposal for canister handling flow

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (4/19)

③ Implementation items and results (3/17)

a. Validation of canister lid structure

(b) Design concept of canister lid structure (1/2)

The proposed design concept for the lid structure was set based on the requirements for the canister lid structure and the results of studies in FY2017.

Table: Design concept of canister lid structure (1/2)

Items	Requirements for lid	Design conditions	Proposed design concept for lid structure
Sub-criticality Confinement	The lid shall not release fuel debris pieces outside the canister from the viewpoint of sub-criticality maintenance.	The design shall confine fuel debris pieces (solids). In addition, the confinement properties of liquid and gas shall be secured in the transport cask, storage container, building, etc. and not in the canister.	The design shall provide a sealing material to prevent release of fuel debris pieces (solid) that pass through the gap between the canister body and the lid. In addition, the confinement properties of liquid and gas shall not be secured by the canister, but by the sealing material. When the lid is provided with a vent mechanism, fuel debris pieces (solid) passing through the vent mechanism shall be confined by closing the flow path of the vent mechanism and the filters. In addition, the confinement properties of liquid and gas are not secured by the canister, but as per design, the liquid and gas will be confined by closing the flow path of the vent mechanism.
Structure	Shall be able to maintain integrity against the internal pressure of the canister.	The design shall be able to maintain integrity against the increase in temperature and increase in pressure (about 1.3 MPa *1) caused by the generation of hydrogen.	A thickness, closing force, etc., to withstand the design pressure conditions shall be ensured.
	The lid shall not open or break even when the canister receives an impact (e.g., toppling).	The grip of the lid shall not damage when a lifting load (static load of about 3G *2) is applied to the lid.	A thickness, closing force, etc., to withstand the design load conditions shall be ensured.
		The lid shall not open or break even when an impact load (static load of about 100G *3) is applied due to the toppling of a canister.	It shall be ensured that the lid does not open or break even when it is subjected to an impact load (static load of about 100 G). And it shall be ensured that there are no gaps in the sealing surface.

*1: Provisionally set in consideration of the increase in temperature and the increase in pressure caused by the generation of hydrogen.
*2: Provisionally set with reference to the existing handling conditions of spent fuel transport casks.
*3: Provisionally set with reference to the existing dropping conditions of spent fuel transport casks.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (5/19)

③ Implementation items and results (4/17)

a. Validation of canister lid structure

(b) Design concept of canister lid structure (2/2)

The proposed design concept for the lid structure was set based on the requirements for the canister lid structure and the results of studies in FY2017.

Table: Design concept of canister lid structure (2/2)

Items	Requirements for lid	Design conditions	Design concept proposal for lid structure
Handleability	The lid shall be able to be opened and closed under the condition partially or completely submerged using remote control.	The lid shall be able to be closed remotely. In addition, closure of the lid shall be able to be confirmed.	Structures that can be closed remotely shall be studied. Also, it shall be ensured that the lid closure can be confirmed visually.
		In addition, containing, transfer and storage of fuel debris shall be able to be handled.	It shall be ensured that the lid can be used for lifting.
			It shall be ensured that the lid can be connected to the drying equipment and gas insertion system.
			The lid shall fit in with the bottom structure of the canister so that it can be stacked during transport and storage.
			It shall be ensured that hydrogen can be released outside the canister during transport and storage.
	The lid shall be able to be closed with simple movements (e.g., turning the lid) from the viewpoint of workability.	The lid shall be able to be closed in a few operations.	As an idea for a closing structure, a simple structures where the lid can be closed by turning the lid shall be studied.

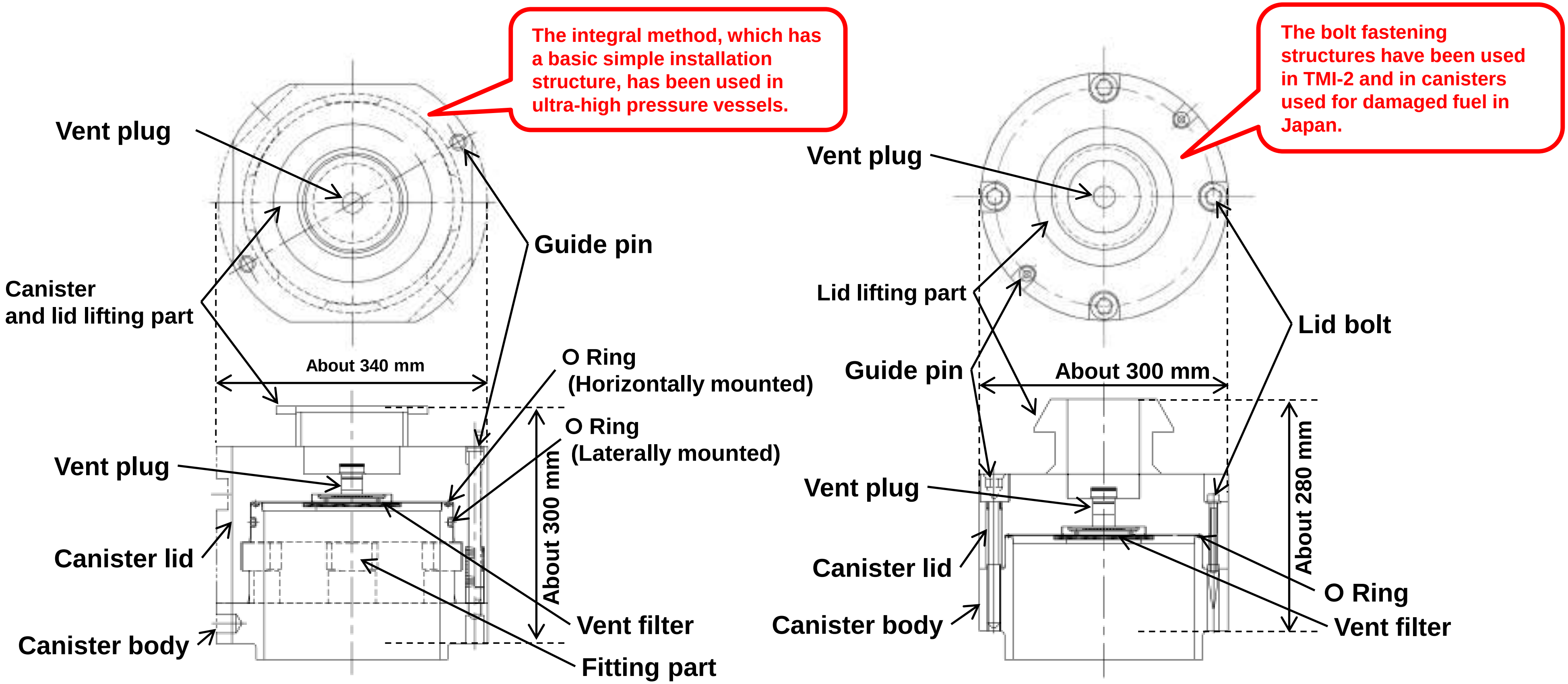
(2) Safety verification of structural strength (6/19)

③ Implementation items and results (5/17)

a. Verification of feasibility of canister lid structure

(c) Study of lid structure

A lid structure proposal was designed based on the proposed design concept for the lid structure. The basic shape and structure of the lid for canisters of internal diameters 220 mm and 400 mm are the same.



(a) Simple installation structure

(b) Bolt fastening structure

Figure Examples of the lid structure designs (when the internal diameter of the canister is Φ 220 mm)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (7/19)

③ Implementation items and results (6/17)

a. Validation of canister lid structure

(d) Plan for validation tests (1/2)

In order to verify the feasibility of the lid structure, handling verification and load tests (events to be evaluated, identified in FY2017, included vertical dropping, toppling, and vertical dropping of a canister on top of another canister) were conducted as validation tests. The test conditions for conducting these tests were determined based on the handling flow of canisters.
Further, the tests were conducted using a test device of the lid structure with simple installation structure, wherein there were concerns about the structural integrity during remote handling or during events such as toppling, etc., and with the bolt fastening structure, wherein events such as toppling, were evaluated through analysis.

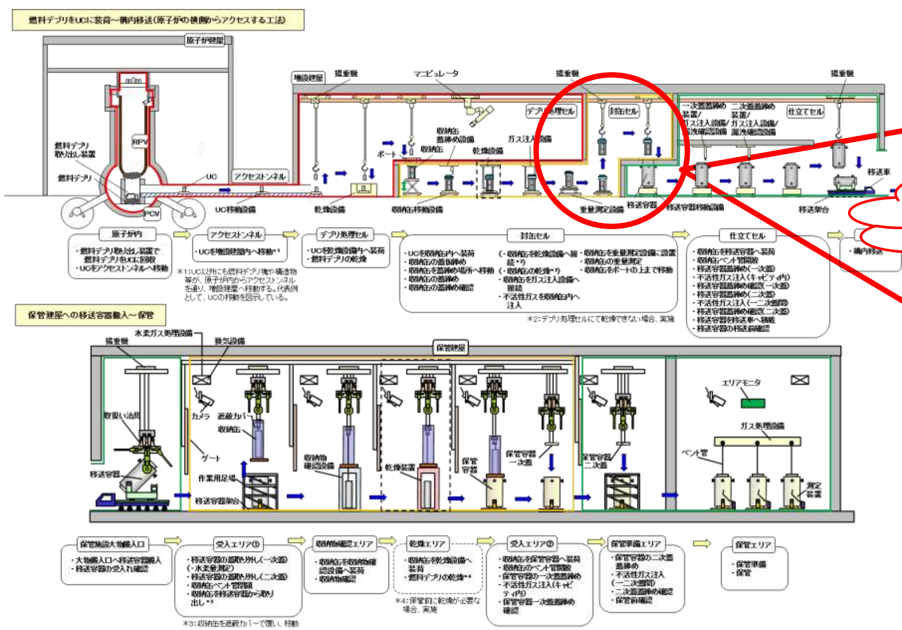


Figure: Proposal for canister handling flow

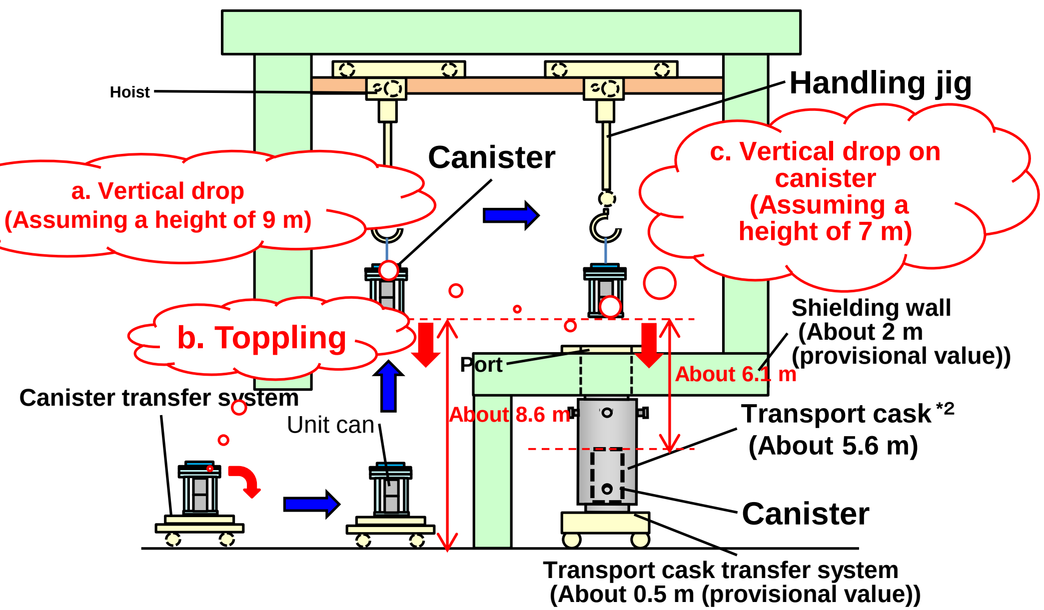


Figure: Example of event identification*1

*1: Confirmed that events in the storage facility are the same or include these events
*2: Assuming existing spent fuel transport casks

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (8/19)

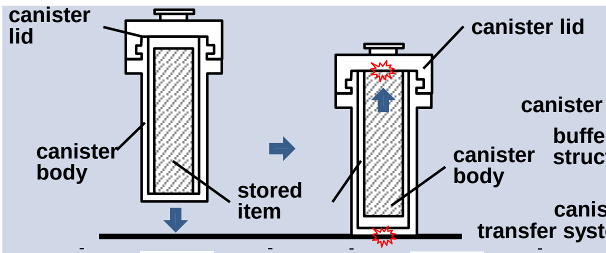
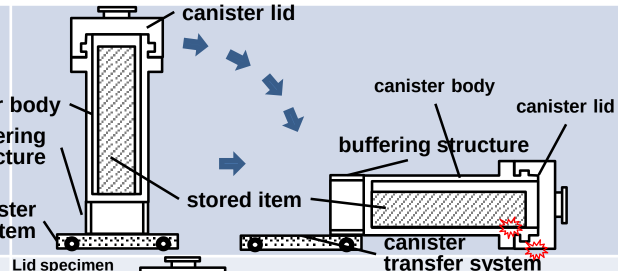
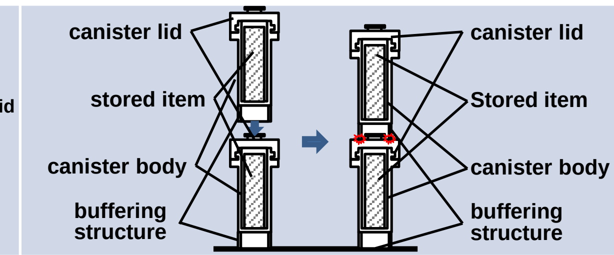
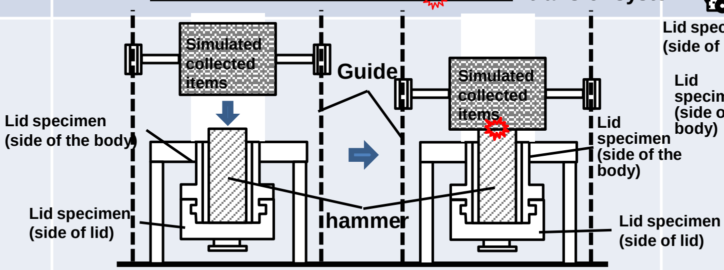
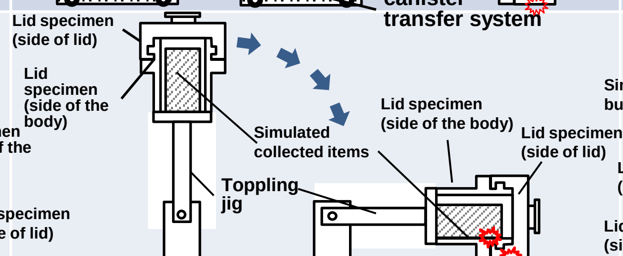
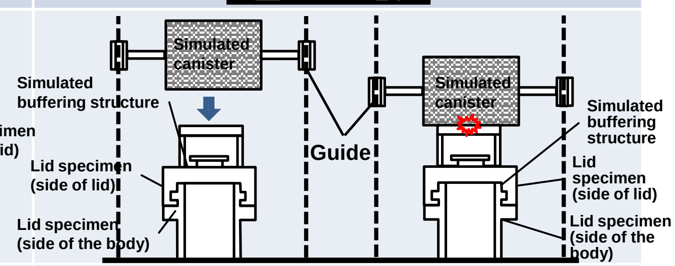
③ Implementation items and results (7/17)

a. Verification of feasibility of canister lid structure

(d) Plan for feasibility confirmation tests (2/2)

In the load test, the test system was set up so as to be able to simulate the actual conditions while taking into account the restrictions, etc. on testing. At that time, the dynamic analysis results of the test system and the actual conditions were compared, and it was confirmed that the load test included the actual conditions.

Table Comparison of actual conditions and test system

	Vertical drop (Collision of stored item with the lid)	Toppling	Vertical drop of a canister on the top of another canister
Actual conditions			
Test system			
Approach towards setting up the test system	In the actual system, the collision speed of the stored item is uncertain and difficult to measure. ⇒ Conduct a test where the stored item is turned upside down and dropped, colliding with the inner surface of the lid. Calculate the collision speed of the stored item by dynamic analysis and set the drop height to achieve that collision speed.	In the actual system, the supporting point at the time of toppling is not stable, and it is difficult to get the lid to collide properly with the floor. ⇒ Conduct a test by attaching the toppling jig to the lid structure specimen, with the lower end as the supporting point. Set the weight and length of the toppling jig and the weight of the stored item such that the load is the same as in the actual conditions.	In the actual system, it is difficult to drop the canister properly on the upper surface of the lid. ⇒ Conduct a test by installing a simulated bottom buffering structure on the top of the lid structure and by dropping the simulated weight on it. Conduct a conservative test without the bottom buffering structure of the canister on the collided side (bottom canister).

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6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

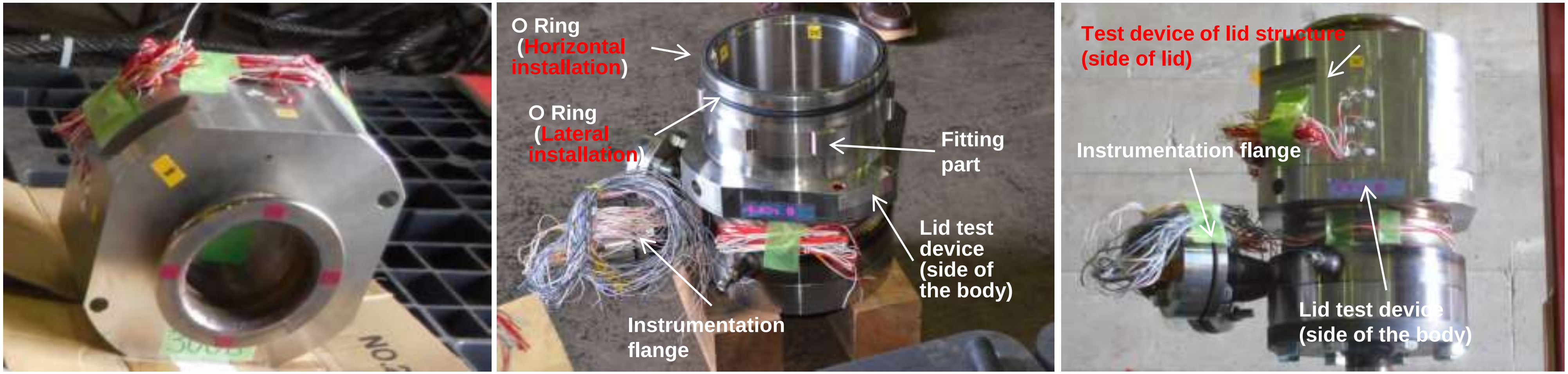
(2) Safety verification of structural strength (9/19)

③ Implementation items and results (8/17)

a. Validation of canister lid structure

(e) Production of lid test device for validation test

The lid test device to be used for the load test was manufactured. Actual-sized lid test devices with an internal diameter of 220 mm, as well as test devices with an internal diameter of 400 mm, considering an expanded internal diameter, were manufactured and the test was conducted. The handling test described in Section 6.2(5) was performed before and after the load test to confirm the handleability.



(a) Side of lid　　(b) Side of main body　　(c) Installing lid

Figure:: Example of test device of lid structure (For toppling test)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

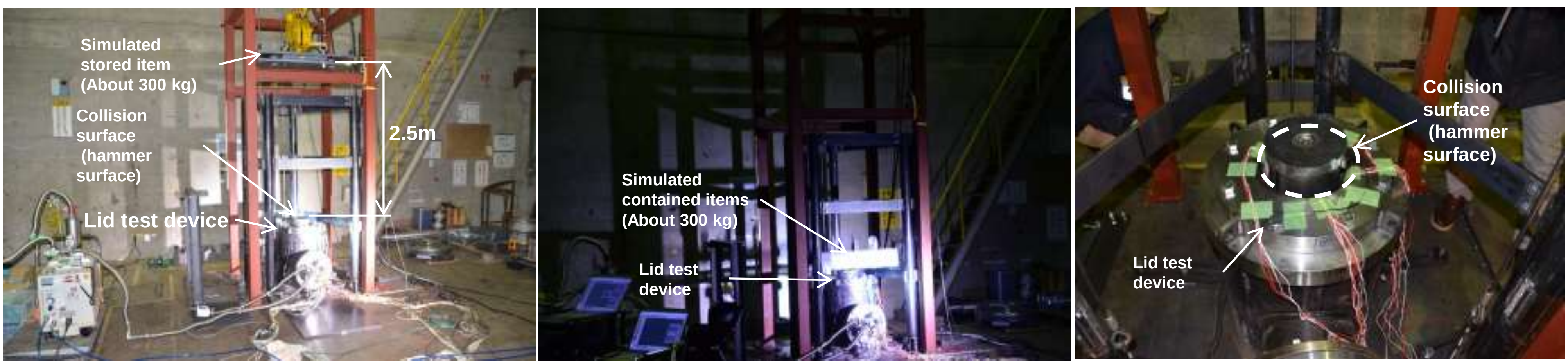
(2) Safety verification of structural strength (10/19)

③ Implementation items and results (9/17)

a. Validation of canister lid structure

(f) Implementation of validation test (Vertical drop (collision of stored item with the lid))

Tests simulating vertical drop (collision of stored item with the lid) were conducted. From the results of measuring the dropping speed of the simulated stored item, it is believed that the test was completed as planned.



(a) Overview of the test (b) Test status (c) Example of lid test device after the test

Figure: Status of validation tests of lid structure (Vertical drop (Collision of stored item with the lid, internal diameter of canister: 220 mm))

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (11/19)

③ Implementation items and results (10/17)

a. Validation of canister lid structure

(f) Implementation of validation test (Vertical drop (collision of stored item with the lid))

The integrity of the lid structure with an internal diameter of 220 mm was confirmed using tests simulating a vertical drop (collision of stored item with the lid). Moreover, when the test was conducted on a canister with an internal diameter of 400 mm, the lid could not be opened after the test. However, the deformation impacting the opening of the lid was not seen in the analysis carried out by simulating actual equipment. Hence this was presumed to be an event that did not occur in the actual equipment, and it was concluded that there were no issues with the integrity of the lid.

Table: Overview of results of vertical drop (collision of stored item with the lid) test

Items	Evaluation criteria	Internal diameter 220 mm		Internal diameter 400 mm		Remarks
Damage to lid	Deformation is below the tolerance	The difference in dimensions before and after the test was below the tolerance	○	Not confirmed as the lid could not be opened	-	
Falling of lid	There is no damage	Deformation was seen in the fitting part, but there was no damage that could lead to falling of the lid.	○	Not confirmed as the lid could not be opened	-	
Leakage from seal	The deformation of the gap near the seal surface is below the tolerance	The difference in dimensions before and after the test was below the tolerance	○	Not confirmed as the lid could not be opened	-	
	Leakage rate is 3x10^{-2} ref cm^3/s or less	Leakage rate was about 1x10^{-7} ref cm^3/s both before and after the test, hence there was no leakage	○	Leakage rate was about 1x10^{-7} ref cm^3/s both before and after the test, hence there was no leakage	○	Evaluation criteria of 1 atm and 25°C were set with reference to existing transport casks
	The strain near the seal surface is within the elasticity range	Measured strain was within the elasticity range	○	Some plastic strain was measured	△	With an internal diameter of 400 mm, some plastic strain was measured, but no leakage was observed.
	There is no damage to the O ring	No damage was observed	○	Not confirmed as the lid could not be opened	-	
Momentary leakage from the seal	-	There was no pressure fluctuation before and after the test, and momentary leakages were not identified	○	There was no pressure fluctuation before and after the test, and momentary leakages were not identified	○	The requirement for measures against the prevention of momentary leakage has not been decided.
Opening the lid	-	The lid could be opened	○	The lid could not be opened	x	Deformations impacting the opening of lid were seen even in the analysis conducted by simulating tests using canisters with internal diameter of 400 mm, but deformations were not seen in the analysis conducted by simulating actual equipment (presumed to be due to the higher impact load used for the test as compared to the actual equipment)
Lifting	There is no deformation in the lid lifting part	No deformation in the lid lifting part	○	No deformation in the lid lifting part	○	

○: No problem, △: Results exceeding the evaluation criteria were seen as well, but these were not considered as problems on the whole, based on the other results, x: Problem exists, -: Could not be confirmed

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

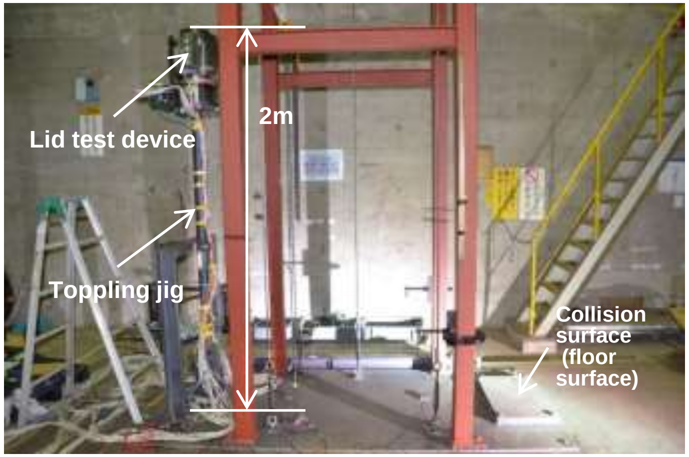
(2) Safety verification of structural strength (12/19)

③ Implementation items and results (11/17)

a. Validation of canister lid structure

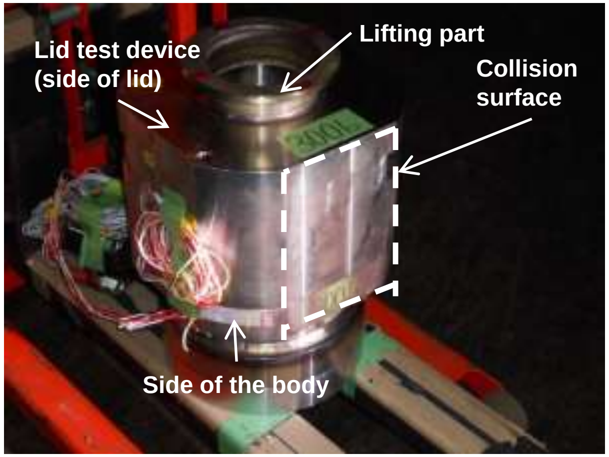
(f) Implementation of validation test (toppling)

A test simulating toppling was conducted. From the measurement results of the toppling speed of the lid test device, it was concluded that the test was completed as planned.



(a) Overview of the test

(b) Test status



(c) Example of lid test device after the test

Figure: Status of validation tests on lid structure (toppling of canister, internal diameter of canister 220 mm)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (13/19)

③ Implementation items and results (12/17)

a. Validation of canister lid structure

(f) Implementation of validation test (toppling)

The integrity of the lid structure was confirmed as follows by means of a test simulating toppling.

Table: Summary of toppling test results

Items	Evaluation criteria	Internal diameter 220 mm		Internal diameter 400 mm		Remarks
Damage to lid	Deformation is below the tolerance	The difference in dimensions before and after the test was below the tolerance	○	The difference in dimensions before and after the test was below the tolerance	○	
Falling of lid	There is no damage	No damage was observed	○	No damage was observed	○	
Leakage from seal	The deformation of the gap near the seal surface is below the tolerance	The difference in dimensions before and after the test was below the tolerance	○	The difference in dimensions before and after the test was below the tolerance	○	
	Leakage rate is 3×10^{-2} ref cm^3/s or less	Leakage rate was about 1×10^{-7} ref cm^3/s both before and after the test, hence there was no leakage	○	Leakage rate was about 1×10^{-7} ref cm^3/s both before and after the test, hence there was no leakage	○	Evaluation criteria of 1 atm and 25ºC were set with reference to existing transport casks
	The strain near the seal surface is within the elasticity range	Some plastic deformation was measured	△	Some plastic strain was measured	△	Some plastic strain was measured, but no leakage was observed
	There is no damage to the O ring	No damage was observed	○	No damage was observed	○	
Momentary leakage from the seal	-	Pressure fluctuation was identified before and after the test, but it was determined to be due to the volume fluctuation caused by the impact, etc.	○	Pressure fluctuation was identified before and after the test, but it was determined to be due to the volume fluctuation caused by the impact, etc.	○	The requirement for measures against the prevention of momentary leakage has not been decided
Opening the lid	-	The lid could be opened	○	The lid could be opened	○	
Lifting	There is no deformation in the lid lifting part	No deformation in the lid lifting part	○	No deformation in the lid lifting part	○	

○: No problem, △: Results exceeding the evaluation criteria were seen as well, but these were not considered as problems on the whole, based on the other results, x: Problem exists, -: Could not be confirmed

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

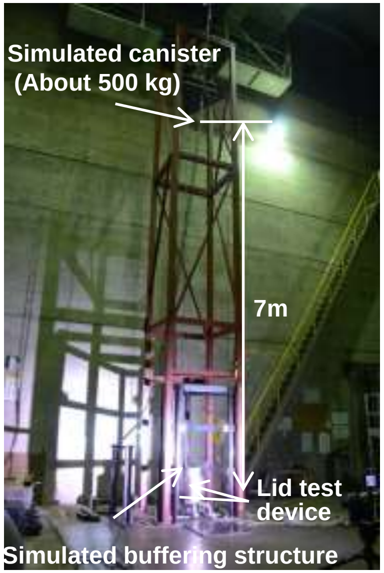
(2) Safety verification of structural strength (14/19)

③ Implementation items and results (13/17)

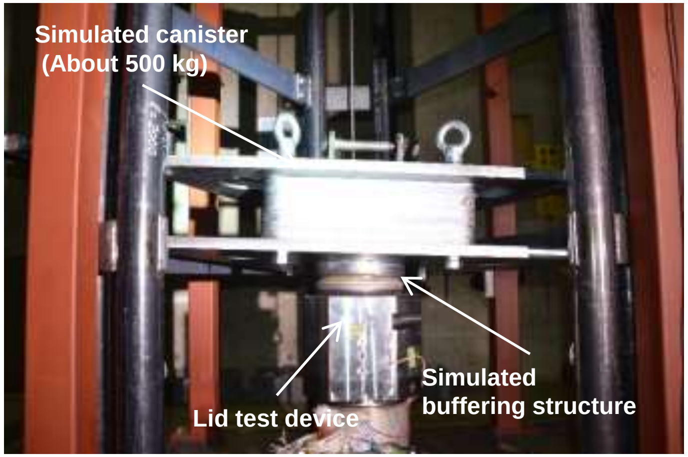
a. Validation of canister lid structure

(f) Implementation of validation test (vertical dropping of a canister on top of another canister)

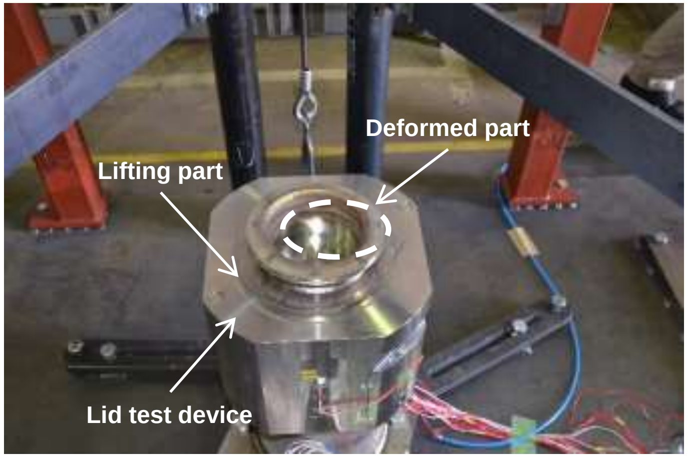
A test simulating the vertical dropping of a canister on top of another canister was conducted. The object to be dropped could be dropped almost vertically during the test. From the results of measuring the dropping speed of the dropped object, it is believed that the test was completed as planned.



(a) Overview of the test



(b) Test status



(c) Example of lid test device after the test

Figure: Status of validation tests on lid structure (Vertical dropping of a canister on top of another canister, internal diameter of canister 220 mm)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (15/19)

③ Implementation items and results (14/17)

a. Validation of canister lid structure

(f) Implementation of validation test (vertical dropping of a canister on top of another canister)

The integrity of the lid structure with respect to the confinement function was confirmed by means of a test simulating the vertical dropping of a canister on top of another canister. Further, it is believed that the deformation of the lid lifting part that could no longer be lifted, can be handled by appropriately designing the buffering structure or the lid lifting part.

Table: Vertical dropping of a canister on top of another canister

Items	Evaluation criteria	Internal diameter 220 mm		Internal diameter 400 mm		Remarks
Damage to lid	Deformation is below the tolerance	The difference in dimensions before and after the test was below the tolerance	○	The difference in dimensions before and after the test was below the tolerance	○	
Falling of lid	There is no damage	No damage was observed	○	No damage was observed	○	
Leakage from seal	The deformation of the gap near the seal surface is below the tolerance	The difference in dimensions before and after the test was below the tolerance	○	The difference in dimensions before and after the test was below the tolerance	○	
	Leakage rate is $3x10^{-2}$ ref cm^3/s or less	Leakage rate was about $1x10^{-7}$ ref cm^3/s both before and after the test, hence there was no leakage	○	Leakage rate was about $1x10^{-7}$ ref cm^3/s both before and after the test, hence there was no leakage	○	Evaluation criteria of 1 atm and 25°C were set with reference to transport casks
	The strain near the seal surface is within the elasticity range	Measured strain is within the elasticity range	○	Some plastic strain was measured	△	Some plastic strain was measured, but no leakage was observed
	There is no damage to the O ring	No damage was observed	○	No damage was observed	○	
Momentary leakage from the seal	-	Pressure fluctuation was identified before and after the test, but it was determined to be due to the volume fluctuation caused by the impact, etc.	○	Pressure fluctuation was identified before and after the test, but it was determined to be due to the volume fluctuation caused by the impact, etc.	○	The requirement for measures against the prevention of momentary leakage has not been decided
Opening the lid	-	The lid could be opened	○	The lid could be opened (The lid was opened after removing the simulated buffering structure stuck in the lid lifting part)	○	
Lifting	There is no deformation in the lid lifting part	The lid lifting part was deformed	△	The lid lifting part was deformed	△	Deformation was not seen during the analysis, so it was concluded that it was due to the diagonal dropping

○: No problem, △: Results exceeding the evaluation criteria were seen as well, but these were not considered as problems on the whole, based on the other results, x: Problem exists, -: Could not be confirmed

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (16/19)

③ Implementation items and results (15/17)

a. Validation of canister lid structure

(g) Conclusion

i. Evaluation of simple installation structure (Evaluation using validation test)

- Test device with internal diameter of 220 mm

  It was confirmed that the lid structure proposals designed in this project ensure the confinement property with respect to assumed events. In addition, it was confirmed that after the event, the lid could be opened without a problem and that there was no problem in handling the lifting process.

- Test device with internal diameter of 400 mm

  Although the design may need to be partially reviewed from the viewpoint of handling of lifting and lid opening, it was confirmed that the lid structure proposals designed in this project ensure the confinement property. Tests have confirmed that the test specimen falls slightly inclined during the vertical dropping of a canister on top of another canister; therefore, in the structural verification test (refer Slide No. 71) of a full-scale canister, it is necessary to take measures such as providing guides and controlling the inclination.

ii. Evaluation of bolt fastening structure (Evaluation using dynamic analysis)

For bolt fastening structures, evaluation was performed by dynamic analysis of assumed events.

- It was confirmed that the confinement property is ensured with respect to toppling and vertical dropping of a canister on top of another canister.
- Regarding the vertical drop, a gap was generated in the seal due the expansion of bolts caused by the collision with the lid of the stored item, and it was concluded that the confinement property cannot be ensured under the current condition and structure proposal. However, it was confirmed that collision with the lid of the stored item did not occur when a buffering structure was provided. Therefore, in a vertical drop, it was evaluated that there was no collision with the lid of the stored item and that the confinement property is ensured.

From the above results, the feasibility of the lid structure proposals designed in this project was confirmed.

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (17/19)

③ Implementation items and results (16/17)

b. Design of full-scale canisters

(a) Structure verification test plan for full-scale canisters

In order to confirm the integrity of the canister, a load test (vertical dropping, toppling, vertical dropping of a canister on top of another canister) is planned to be conducted in FY2020 as structure verification test of a full-scale canister.

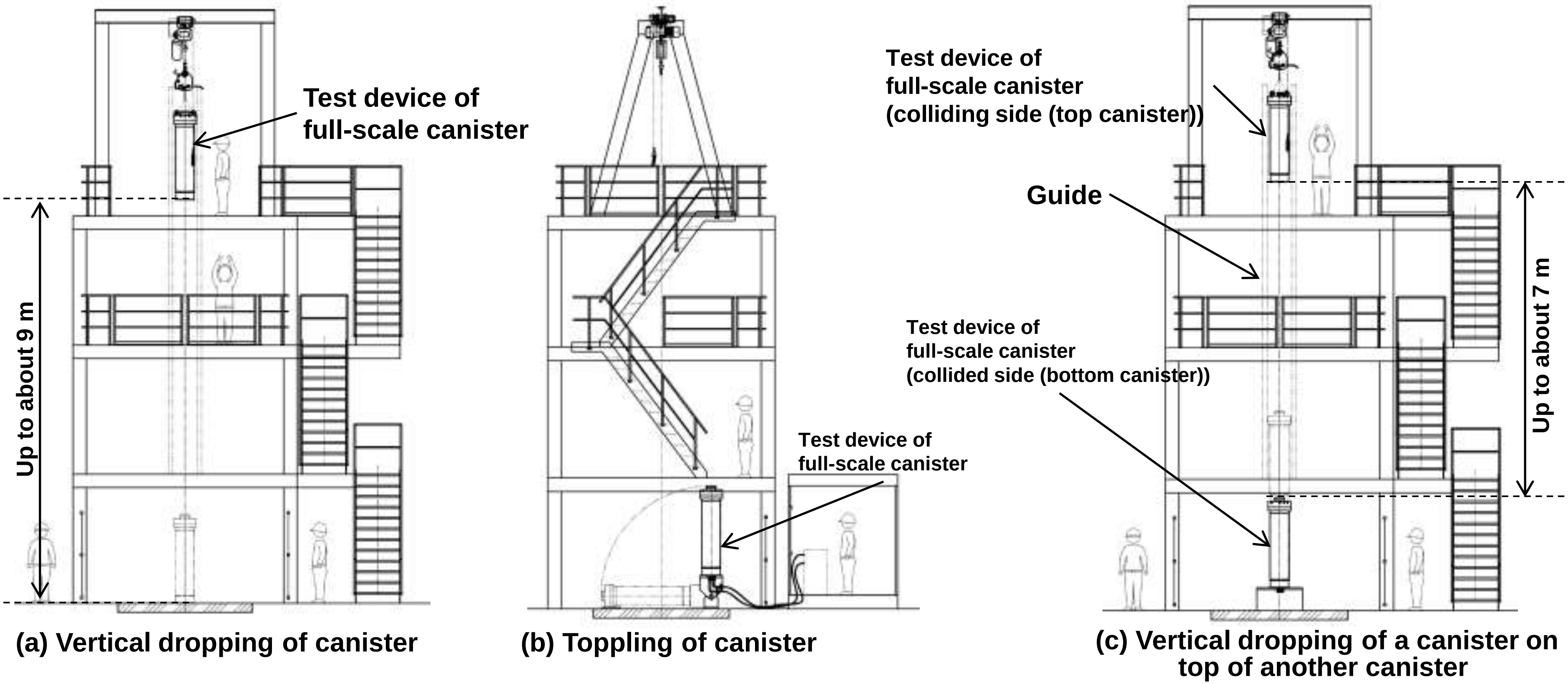


Figure: Schematic diagram of structure verification test proposals of full-scale canisters

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(2) Safety verification of structural strength (18/19)

③ Implementation items and results (17/17)

b. Design of full-scale canisters

(b) Schematic design of full-scale canister test devices

Reflecting the study results for lid structures, a schematic design of the full-scale canister structure suitable for conducting the canister structure verification tests, was created.

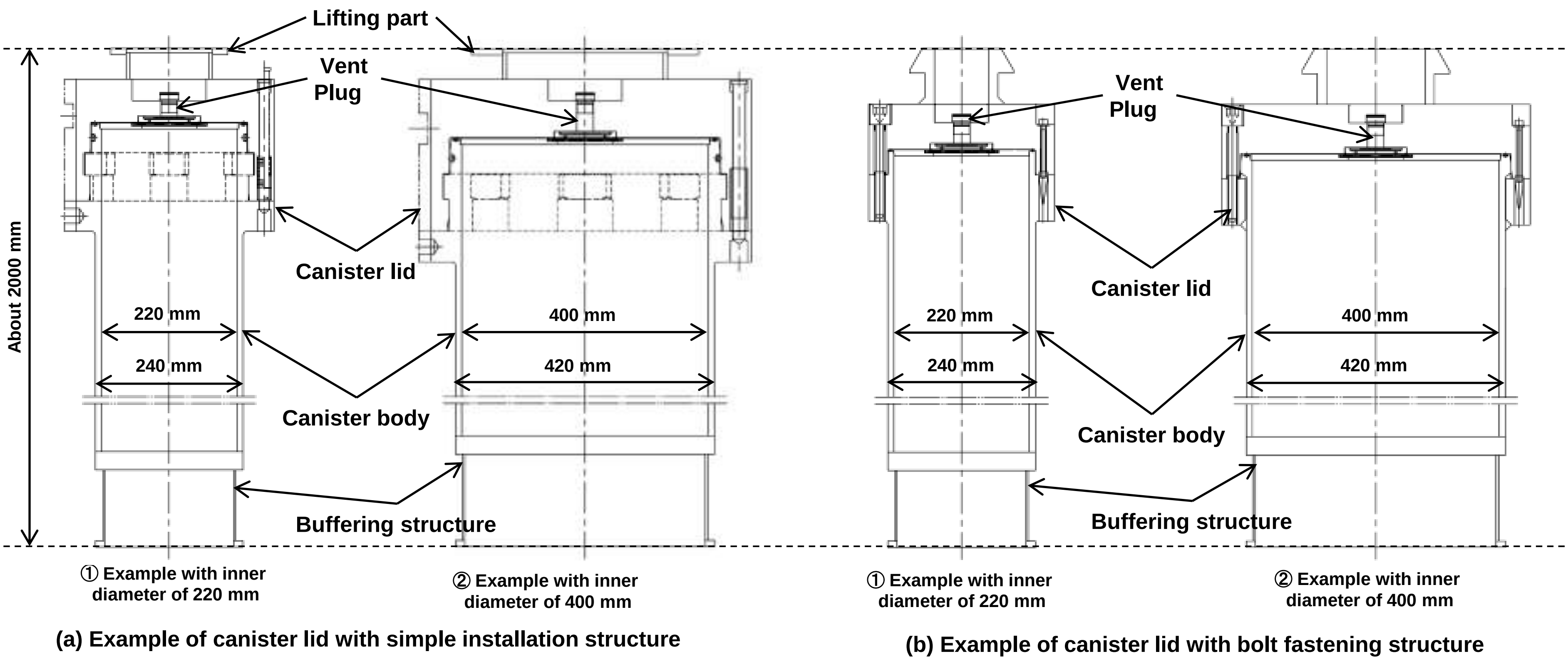


Figure: Proposed structure of full-scale canister

(2) Safety verification of structural strength (19/19)

④ Reflection of results

It is believed that the decision on the structure of canister (including the lid structure) will contribute to the study of canister related facilities (additional building, storage facilities, handling equipment, etc.).

⑤ Analysis from the viewpoint of applicability to the site

Applicability to the site is not believed to be a problem as the canister structure was studied based on its application to the site.

⑥ Level of achievement compared to the goal

With respect to the indicators for determining the attainment of goals, the goal was achieved by identifying the requirements for confinement and handleability of lid structure, by proposing a design plan for a lid structure that meets the requirements, and by confirming the feasibility through tests and analysis. In addition, a test plan was drafted and a schematic design of the full-scale canister test device was created for the structural integrity verification tests which will be conducted FY2019 onwards using the full-scale canister test devices.
From the above, it is concluded that the goals have been achieved.

⑦ Future issues

With regard to the canister design specifications obtained from element tests for each part so far, it will be a challenge to verify the feasibility of the entire canister with respect to operability etc.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(3) Safety verification regarding aging degradation (1/7)

① Purpose and goals

Considering the environmental conditions during the containing and storage of fuel debris in 1F, it is necessary to store fuel debris safely under environmental conditions such as presumed temperature and chloride ion concentration in the canister.

The purpose is to select canister materials that can be stored safely and stably under the presumed environmental conditions during containing and storage of fuel debris, and to develop countermeasures to be implemented during operation.

② Comparison with existing technologies

Although there is a lot of data on corrosion resistance of SUS304 / SUS316L that are being studied as options for canister material, there is no knowledge to determine the threshold values under individual, specific conditions in which crevice corrosion and SCC (Stress Corrosion Cracking) occur. Hence a study that takes into account the conditions unique to 1F is required.

③ Implementation items and results

As an option for canister material, additional information was contained on SUS316L, and SUS316L was re-evaluated as canister material the assumption of dry operation.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(3) Safety verification regarding aging degradation (2/7)

③ Implementation items and results

a. Evaluation results for each environment (Conclusion)

The evaluation results for the presumed environment are shown below. Crevice corrosion and SCC do not occur because of drying. In addition, though it is believed that corrosion is difficult even in flooded conditions, since there are still some uncertainties, it is recommended that the environment be quickly dried to a relative humidity of 20% or less.

Process	Inside canister*1	Expected period	Temperature	
Retrieval	Flooded	Max. 10 days	Ambient temperature	(○) There is a low risk of crevice corrosion and SCC.
	Water adhesion	Max. 10 days	Ambient temperature	(○) Since the period is short, the risk of crevice corrosion is low, and since the drying and enrichment environments are not active, the risk of SCC is also low.
Drying	Water adhesion	Max. 10 days	Max. 300°C	(○) Even assuming hydrogen peroxide, there is no problem when drying within the range of ambient temperature to 50°C. Generally, chloride SCC occurs when the temperature is 70°C or higher. Considering the results of chloride ion concentration in reactor water, cracks due to SCC are expected to appear at 100°C or higher. However, as cracks may appear even at lower temperatures depending on the concentration behavior of the ions and the concentration of hydrogen peroxide, it is necessary to keep welds with high stress away from water pool areas where the ions are concentrated or where hydrogen peroxide is easily formed. Also, as drying eliminates the possibility of SCC, shortening the duration of the 70 to 100°C environment for the operations shall be effective in improving reliability.
Transfer	Flooded	Max. 10 days	Ambient temperature to 150°C	(○) Ambient temperature or up to about 50°C is an environment equivalent to that of retrieval, and there is a low risk of crevice corrosion and SCC. Crevice corrosion may occur in higher temperatures; however, even if it occurs, it is likely to be minor as the time period is short. Given the results of chloride ion concentration, cracks caused by SCC are likely to appear at 100°C or higher. Though cracks may appear even at lower temperatures depending on the concentration of hydrogen peroxide, it is believed that they may be less apparent as the time period is short.
	Water adhesion	Max. 10 days	Ambient temperature to 150°C	(○) Same as the drying process. It is believed that crevice corrosion and SCC may be less apparent as the time period is short. However, unlike the drying process, the heat source is on the fuel debris side and moisture tends to remain in the canister until the fuel debris dries up. Therefore, drying the fuel debris and eliminating the water soon after transfer will be effective.
	Completely dry	Max. 10 days	Ambient temperature to 150°C	(○) Corrosion and SCC will not occur after fuel debris is dried.
Wet storage (pool)	Flooded	Max. 50 years	Max. 40°C (Temperature control by pool water)	(○) Since the temperature inside the canister is 40°C or lower like the retrieval environment, it is less susceptible to crevice corrosion and the risk of SCC is low as well.
	Water adhesion	Max. 50 years	Up to 40°C	(○) The temperature is low, so there is a low risk of crevice corrosion and SCC, same as in flooded storage.
Dry storage (inside hot cell, etc.)	Water adhesion	Max. 50 years	Ambient temperature to 150°C	(○) Same as transfer process under water adhesion condition. In the presence of high temperature and moisture, storing fuel debris for a long-term increases the risk of crevice corrosion and SCC; therefore, it is necessary to keep it away from pooled water and to ensure that it is accumulated only for a short period of time.
Dry storage	Completely dry	Max. 50 years	Ambient temperature to 150°C	(○) Corrosion and SCC will not occur after fuel debris is dried.

***1: Flooded: Water is not drained from the canister, Water adhesion: Water has been drained, but there is residual water adherence, Completely dry: Fuel debris is completely dried.**

6.3 Development of Safety Evaluation Methods and Verification of Safety

(3) Safety verification regarding aging degradation (3/7)

③ Implementation items and results

b. Results of occurrence of SCC in SUS304 (L) / SUS316 (L)

- From the following figure it can be seen that the occurrence of SCC can be controlled in SUS316 (L) up to 100ºC with a chloride ion concentration of 7 ppm, if the generation of hydrogen peroxide or the concentration of chloride ions is not considered. As described earlier, the chloride ion concentration of the stagnant water inside the primary containment vessel of Units 1 to 3 of 1F is about 0.1 to 19 ppm, and it is believed that the concentration will be 7 ppm or less after water purification in the future.
- With regard to storage of the drained fuel debris, it is believed that little moisture adheres to the general parts such as the canister body and the possibility of chloride ions getting concentrated is also low. Meanwhile, as generation of hydrogen peroxide and concentration can occur easily in water pool areas such as the bottom areas, etc., it will be effective to avoid welds in such areas to prevent residual stress that causes SCC. Moreover, while SCC is not apparent up to 100ºC in SUS316 (L), since water is converted to gas at 100ºC or more at normal pressure, it is excluded from the factors that cause corrosion.

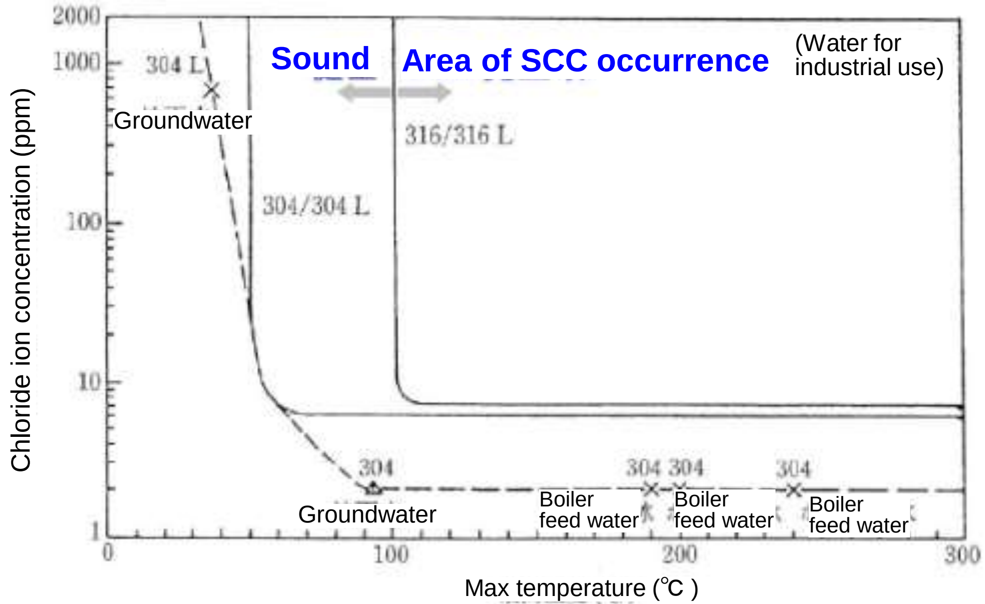


Figure: Effects of maximum ion, temperature and pH of the system on SCC in multi-pipe heat exchanger and effect of temperature and Cl-ion concentration in cooling / heating medium *1

*1: Joint Sub-committee formed by the Society of Chemical Engineers, Japan, Japan Society of Corrosion Engineering and Japan Stainless Steel Association: "Stress Corrosion Cracking of Multi-pipe Stainless Steel Heat-exchanger – List of Usage Results", Society of Chemical Engineers, Japan, Japan Society of Corrosion Engineering, Japan Stainless Steel Association, (1979), 32.

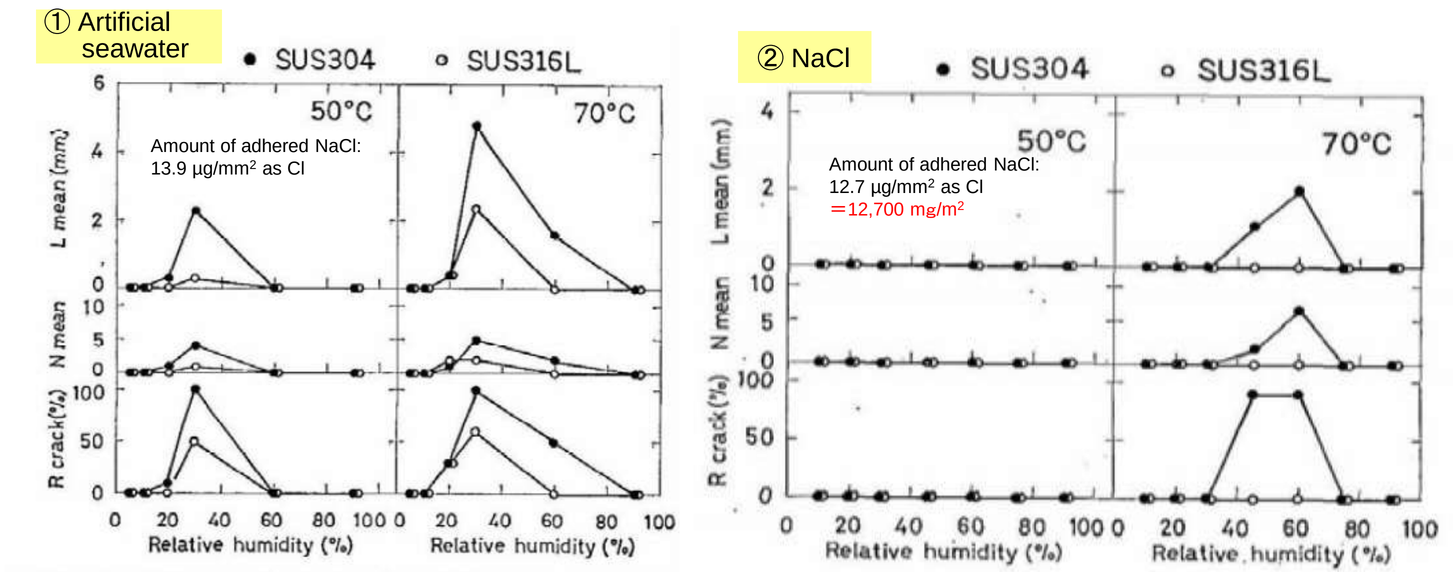
6. Implementation Details

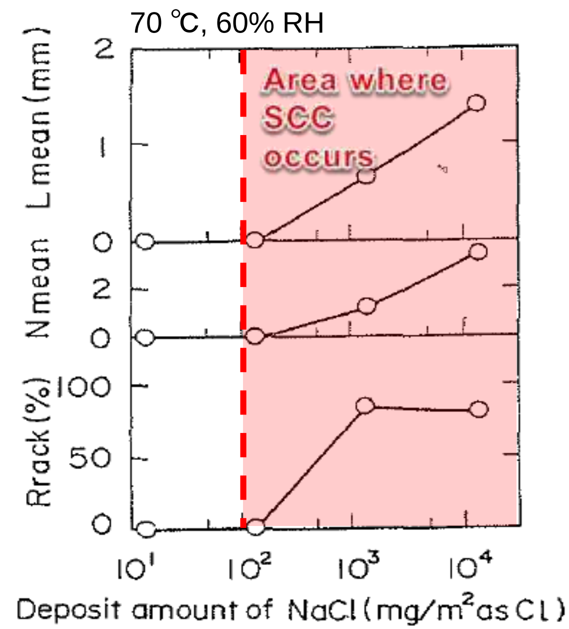
6.3 Development of Safety Evaluation Methods and Verification of Safety

(3) Safety verification regarding aging degradation (4/7)

c. Evaluation of atmospheric stress corrosion cracking of SUS304 / SUS316L

- Stress corrosion cracking in the atmosphere is sensitive to relative humidity, and depends on the temperature, relative humidity and concentration of chloride ions, etc. in a solution. Crack sensitivity is lost below criticality conditions. (Figure : 1, 2)
- The chloride ions in the canister are believed to be derived from sodium chloride. No cracks developed in SUS316L in the two-week test (at a temperature of 70℃, 12,700 mg/m^2 of NaCl deposit). From this it can be expected that by further reducing the concentration of chloride ions in a dry environment, cracks will not appear in SUS316L in a short period of time, even in a 70℃ or higher environment. Also, it is expected that cracks will not occur after the fuel debris is dried.





R_{crack} (%) : Crack rate, N_{mean}: Mean number of cracks, L_{mean} (mm): Mean length of largest crack

Figure: 1 U-bend SCC test results of SUS304 and SUS316 that were dripped with chloride solution and exposed to radiation for two weeks under constant temperature and humidity [*1]

Figure: 2 U-bend SCC test results of SUS304 that was dripped with NaCl solution and exposed to radiation for a week under constant temperature and humidity[*2]

*1: Shoji et al. (1986). Effects of Relative Humidity on Atmospheric Stress Corrosion Cracking of Stainless Steels. Corrosion Engineering. (35, 559-565)

*2: Shoji et al. (1988). Effects of Deposit Amount of Chlorides on Atmospheric Stress Corrosion Cracking of Stainless Steels. Proceeding of the 35th Japan Corrosion Conference (Japan Society of Corrosion Engineering). (263)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(3) Safety verification regarding aging degradation (5/7)

d. Evaluation of atmospheric stress corrosion cracking of SUS304 and SUS316L

- The chloride ion concentration of stagnant water inside the primary containment vessel of Units 1 to 3 of 1F is 0.1 to 19 ppm*1. From the diagram below, the concentration is assumed to be similar to fresh water, and 10,000 times lower than that of a solution with the amount of chlorine which would cause cracks. However, the drying environment (adherence environment) differs from the environment inside the canister, so it is unknown how many chloride ions will actually adhere inside the canister.
- According to the report in the previous section, cracks did not form on SUS316L during the two-week test under the adherence condition of 12,700 mg/m^2 of sodium chloride (70℃, 60% RH). Considering that this solution is diluted 10,000 times with respect to the chloride ion concentration of the solution which would cause cracks, it can be expected that the risk of cracks is extremely low.

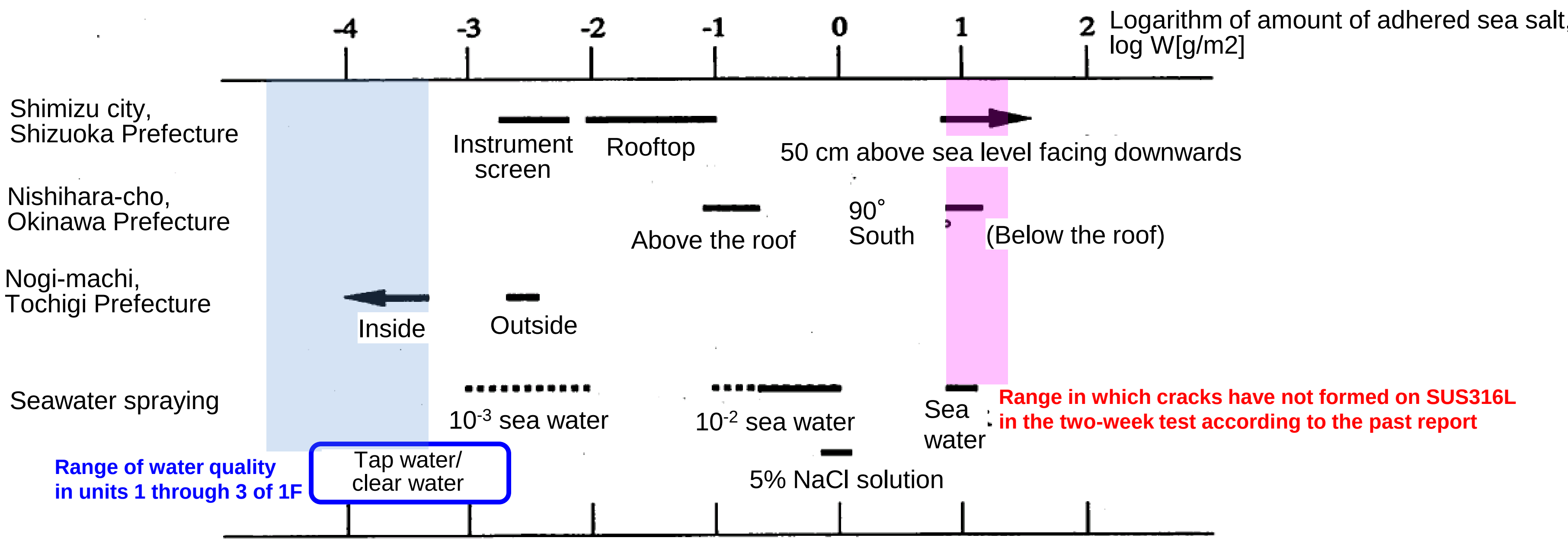


Figure: Amount of adhered sea salt in various environments*2

*1: Yuichi Fukaya, Katsuhiko Kumagai (2016): Current Status and Challenges Related to Corrosion Control of Containment Vessel and Piping at Fukushima Daiichi. The 63rd Japan Conference on Materials and Environments, (C-101)

*2: Shinohara, (1998) Evaluation of Corrosivity of Atmosphere (Monitoring of Corrosive Environment and Concepts on Corrosion Classification). Retrieved from JWTC (Proceeding of the 1998 Weathering Technology Research Presentations, (No.3, 15-24)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

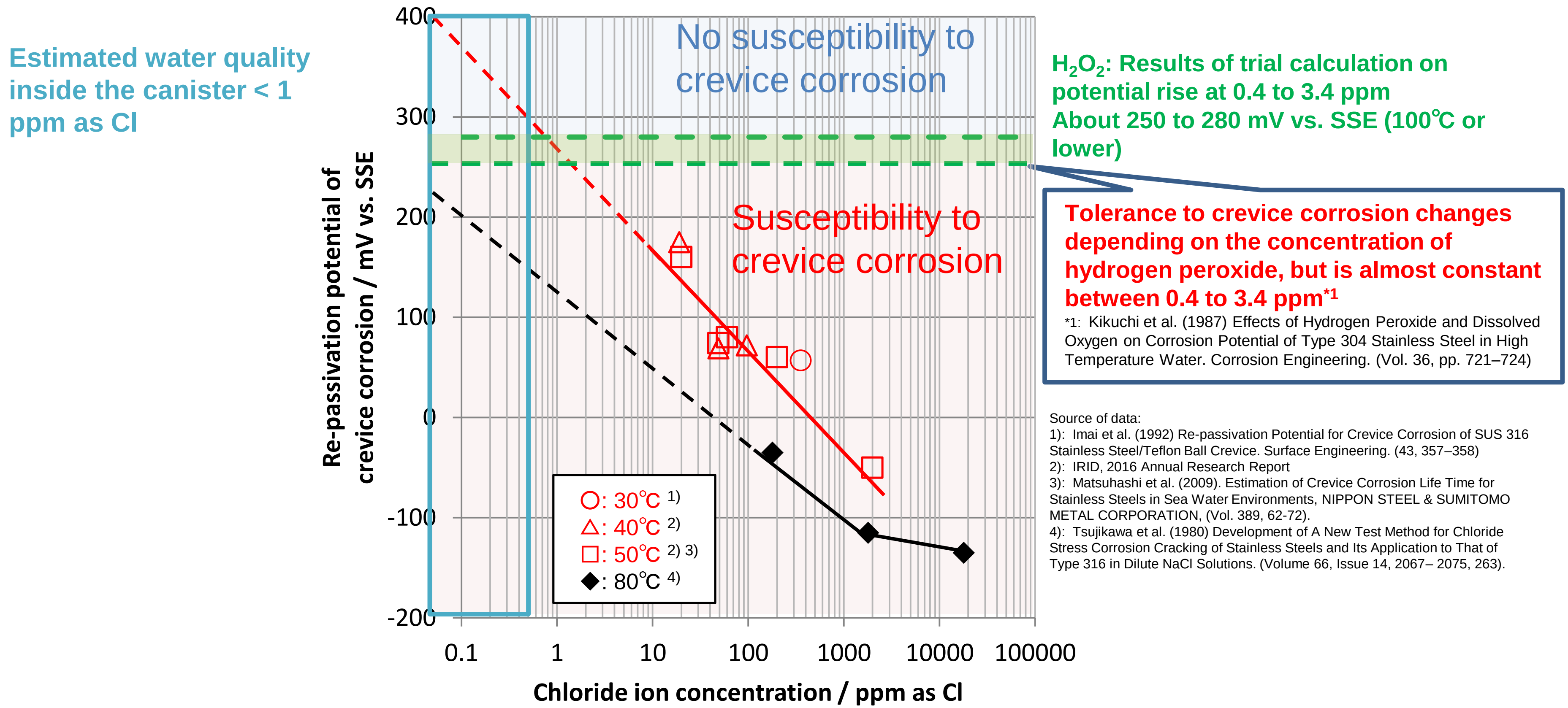
(3) Safety verification regarding aging degradation (6/7)

e. Evaluation results of crevice corrosion susceptibility of SUS316L (Under the condition of flooding)

- In temperatures between about 30 to 50℃, the risk of crevice corrosion is low even when the potential rises due to hydrogen peroxide.
- At about 80℃, crevice corrosion may occur even with a chloride ion concentration of 1 ppm when the potential rises due to hydrogen peroxide.

⇒ Possibility of crevice corrosion remains, however, it will not become apparent in a short period of time, so it will be handled through design and operations.

⇒ SUS316L can be used. However, although the risk of SCC is low, it is necessary to remove moisture, such as water pools, etc. quickly by drying the fuel debris.



Source of data:
1): Imai et al. (1992) Re-passivation Potential for Crevice Corrosion of SUS 316 Stainless Steel/Teflon Ball Crevice. Surface Engineering. (43, 357–358)
2): IRID, 2016 Annual Research Report
3): Matsuhashi et al. (2009). Estimation of Crevice Corrosion Life Time for Stainless Steels in Sea Water Environments, NIPPON STEEL & SUMITOMO METAL CORPORATION, (Vol. 389, 62-72).
4): Tsujikawa et al. (1980) Development of A New Test Method for Chloride Stress Corrosion Cracking of Stainless Steels and Its Application to That of Type 316 in Dilute NaCl Solutions. (Volume 66, Issue 14, 2067– 2075, 263).

Figure: Evaluation of crevice corrosion susceptibility (SUS316L) in each chloride ion concentration using crevice corrosion re-passivation potential

6.3 Development of Safety Evaluation Methods and Verification of Safety

(3) Safety verification regarding aging degradation (7/7)

④ Reflection of results

The production costs and maintenance costs for canisters can be reduced by realistic canister material selection that includes material design and on-site application, and formulation of corrosion measures.

⑤ Analysis from the viewpoint of applicability to the site

Proposed corrosion measures will be studied from the operations aspect, considering on-site applicability.

⑥ Level of achievement compared to the goal

Introduction of chloride ions beyond the assumed value was deemed unnecessary as water purification is performed during fuel debris removal. In addition to this, the areas, where the occurrence of crevice corrosion and SCC cannot be denied, were organized, proposed response measures scenarios incorporating the environmental conditions for transfer and drying and the water quality of the stagnant water inside the primary containment vessel of 1F, were compiled. It is concluded that the goals have been achieved.

⑦ Future issues

There were no issues in the execution of the current plan.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (1/29)

① Purpose, goal

A hydrogen measures proposal shall be created to control hydrogen generated inside the canister due to water radiolysis, in order for the safe containing, transfer and storage of fuel debris. For this reason, the amount of hydrogen generated inside the canister will be estimated, considering the conditions in 1F. In the case of fuel debris, the shielding effect of claddings cannot be expected as in sound spent fuel; therefore, it is necessary to confirm the effects of alpha rays, beta rays, and gamma rays. Particularly for alpha rays, as the effects of the following factors are expected, the effect [*1] of alpha rays under 1F conditions will be confirmed through tests using spent fuel pellet pieces.

- Presence of effect of alpha rays (conducted in FY2017)
- Effect of water volume (partly conducted in FY2017, additions conducted in FY2018)
- Effect of particle size (conducted in FY2018)
- Effect of moisture in concrete (incidental to MCCI product containing) (conducted in FY2018)
- Effect of water quality (verification of effect of water quality under low water conditions) (conducted in FY2018)

One of the hydrogen measures is to estimate the amount of hydrogen generated during transfer, in particular, and to contribute to the study related to restriction of transfer time.

② Comparison with existing technologies

Although the effect of alpha rays on water radiolysis has been confirmed, it is necessary to conduct studies considering conditions unique to 1F as there are few reported examples, in terms of knowledge on the coexistence systems with beta and gamma rays, including those from TMI-2.

***1: Although beta rays may have an effect when shielding by claddings cannot be expected, it is known that the effect of LET (linear energy transfer) of beta rays is similar to that of gamma rays (Spinks, J.W.T. and R.J.Woods, An introduction to radiation chemistry, 1990, Wiley), and knowledge of gamma rays may be applicable in terms of hydrogen generation by radiolysis of water.**

6. Implementation Details

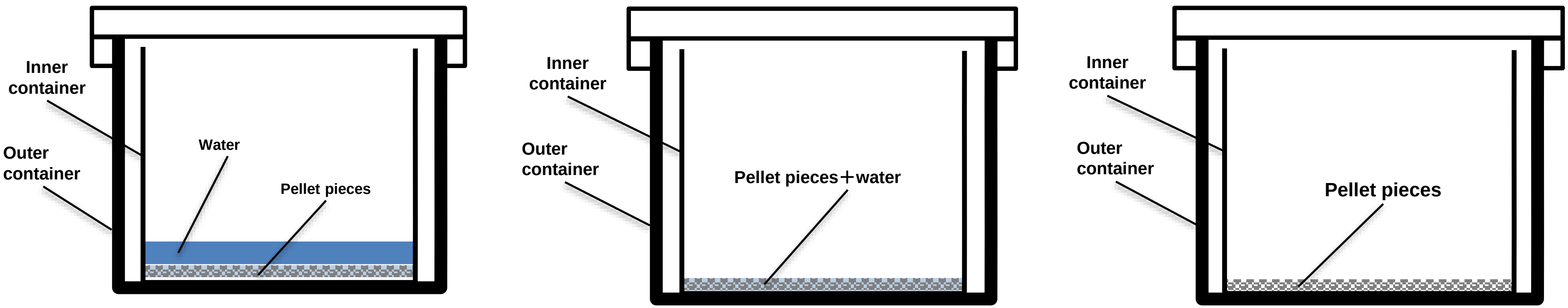
6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (2/29)

③ Implementation items and results (1/27)

a. Test system

In continuation from FY2017, the effects of water volume, particle size, moisture in concrete and water quality on the generation of hydrogen during water radiolysis, was confirmed through hydrogen evaluation tests using spent fuel. In addition, the effect of water quality in cases where the water is almost drained was studied as well.



(a) When pellet pieces are immersed in water

(b) When pellet pieces are immersed in small amount of water (almost-drained level)

(C) When pellet pieces are dried

Figure: Example of test system (Example of tests to confirm the effect of water volume)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (3/29)

③ Implementation items and results (2/27)

b. Test conditions (1/4)

In continuation from FY2017, the volume of water in which the pellet pieces are immersed was changed and its impact on hydrogen generation was confirmed. In the tests conducted in FY2017, the results showed that the almost-drained level of water did not produce a hydrogen reducing effect. The reproducibility of the test results was confirmed and in addition, the test was conducted with a further reduced water volume (equivalent to dry).

Table: Test conditions (Confirmation of the effect of water volume)

Item		Case 1 (Conducted in FY2017)	Case 2 (Reproducibility confirmed in FY2017)	Case 3	Remarks
Overview of tests		Immerse pellet pieces in water	Pellet pieces immersed in almost-drained level of water	Dry pellet pieces	Pellet pieces heated (about 100 ℃) until the mass changes to ± 0.1% or lesser are assumed to be dry
Sample	Weight of pellet pieces (g)	About 80	About 100		Spent fuel pellet pieces similar to those used in FY2017 were used, and in FY2018, the weight of the pellet pieces was increased
	Particle size of pellet pieces (μm)	20 to 300			Classified after being washed and dried (heated at about 100 ℃)
Test water	Water volume (mL)	100	10 (50 vol.% of pellet pieces)	0 (Equivalent to dry)	50 vol.% is based on the results of the draining test conducted in FY2016
	Seawater component concentration (mol/L)	Equivalent to 5.6×10^{-4} (20 ppm) as chloride ion concentration		-	Determined by the measurement results of Unit 1 (approx. 19 ppm)[*1]
	Iodine ion concentration (mol/L)	1.0×10^{-4}		-	Assumed that 10% of the iodine inventory[*2] will leach into the water
	pH	No adjustment		-	Measured the tests (Only case 1 was measured after the test)
Type of gas in gas phase / Initial internal pressure		Atmosphere / approximately the atmospheric pressure (no added pressure)			The pressure is atmospheric assuming a case where gas cannot be replaced
Period of immersion (days)		20 days (max.)			Specified with margin for the assumed transfer period of 10 days
Test temperature		Ambient temperature			No adjustment in temperature

*1: Tokyo Electric Power Company, Inc. (Oct. 22, 2012). Unit 1 Primary Containment Vessel (PCV) Internal Investigation Results.
*2: Kenji Nishihara, Hiroki Iwamoto, Kenya Suyama. (Sept. 2012). Estimation of Fuel Compositions in Fukushima Daiichi Nuclear Power Plant. Japan Atomic Energy Agency. (JAEA-Data/Code2012-18)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (4/29)

③ Implementation items and results (3/27)

b.Test conditions (2/4)

In order to confirm the effect of short-range alpha rays (as the particle size increases, the energy transfer ratio of alpha rays decreases relatively due to the self-shielding effect), the particle size of pellet pieces was changed and its effect on hydrogen generation was confirmed. In addition to the tests conducted in FY2017 with particle size of 20 to 300 µm, tests were conducted using pellet pieces with particle size of 1,000 to 4,000 µm, and the results were compared.

Table: Test conditions (Confirmation of the effect of particle size)

Items		Case 2		Case 4	Remarks
		Conducted in FY2017	Conducted in FY2018		
Overview of tests		Small particle size (20 to 300 µm)		Large particle size (1,000 to 4,000 µm)	
Sample	Weight of pellet pieces (g)	About 80	About 100		Spent fuel pellet pieces similar to those used in FY2017 were used, and in FY2018, the weight of the pellet pieces was increased
	Particle size of pellet pieces (µm)	20 to 300		1,000 to 4,000	Classified after being washed and dried (heating at about 100 ℃)
Water	Water volume (mL)	8 (50 vol.% of pellet pieces)	10 (50 vol.% of pellet pieces)		50 vol.% is based on the results of the draining test conducted in FY2016
	Seawater component concentration (mol/L)	Equivalent to 5.6×10^{-4} (20 ppm) as chloride ion concentration			Determined by the measurement results of Unit 1 (approx. 19 ppm)[*1]
	Iodine ion concentration (mol/L)	1.0×10^{-4}			Assumed that 10% of the iodine inventory[*2] will leach into the water
	pH	No adjustment			Measured before the tests
Type of gas in gas phase / Initial internal pressure		Atmosphere / approximately the atmospheric pressure (no added pressure)			The pressure is atmospheric assuming a case where gas cannot be replaced
Period of immersion (days)		20 days (max.)			Specified with margin for the assumed transfer period of 10 days
Test temperature		Ambient temperature			No adjustment in temperature

*1: Tokyo Electric Power Company, Inc. (Oct. 22, 2012). Unit 1 Primary Containment Vessel (PCV) Internal Investigation Results.
*2: Kenji Nishihara, Hiroki Iwamoto, Kenya Suyama. (Sept. 2012). Estimation of Fuel Compositions in Fukushima Daiichi Nuclear Power Plant. Japan Atomic Energy Agency. (JAEA-Data/Code2012-18)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (5/29)

③ Implementation items and results (4/27)

b.Test conditions (3/4)

The effect of moisture present in the concrete, which is likely to have been contained along with fuel debris and stored in the canisters, on hydrogen generation was confirmed. Tests were conducted with and without alpha rays and the effect of moisture present in the concrete was confirmed.

Table: Test conditions (Confirmation of the effect of concrete)

<table>
<tr><th colspan="2">Items</th><th>Case 3</th><th>Case 5</th><th>Case 6</th><th>Remarks</th></tr>
<tr><td colspan="2">Overview of tests</td><td>Without concrete</td><td>With concrete
(With alpha rays)</td><td>With concrete
(Without alpha rays)</td><td></td></tr>
<tr><td rowspan="4">Sample</td><td>Weight of pellet pieces (g)</td><td colspan="3">About 100</td><td>Spent fuel pellet pieces similar to those used in FY2017 were used, and in FY2018, the weight of the pellet pieces was increased</td></tr>
<tr><td>Particle size of pellet pieces (μm)</td><td colspan="3">20 to 300</td><td>Classified after being washed and dried (heated at about 100 ℃)</td></tr>
<tr><td>Weight of concrete (g)</td><td>-</td><td colspan="2">Weight equivalent to the volume of pellet pieces</td><td>For even mixing with the pellet pieces</td></tr>
<tr><td>Concrete particle size (μm)</td><td>-</td><td colspan="2">45 to 100</td><td>Retains free water in concrete and is equivalent to the pellet pieces</td></tr>
<tr><td rowspan="4">Water</td><td>Water volume (mL)</td><td>0 (Dry)</td><td colspan="2">Moisture in concrete</td><td>As a result of heating similarly-treated concrete and evaluating it based on the change in its weight, free water in the concrete was estimated to be about 1g (1mL).</td></tr>
<tr><td>Seawater component concentration (mol/L)</td><td colspan="3">-</td><td></td></tr>
<tr><td>Iodine ion concentration (mol/L)</td><td colspan="3">-</td><td></td></tr>
<tr><td>pH</td><td colspan="3">-</td><td>Measured the test</td></tr>
<tr><td colspan="2">Type of gas in gas phase / Initial internal pressure</td><td colspan="3">Atmosphere / approximately the atmospheric pressure (no added pressure)</td><td>The pressure is atmospheric assuming a case where gas cannot be replaced</td></tr>
<tr><td colspan="2">Period of immersion (days)</td><td colspan="3">20 days (max.)</td><td>Specified with margin for the assumed transfer period of 10 days</td></tr>
<tr><td colspan="2">Test temperature</td><td colspan="3">Ambient temperature</td><td>No adjustment in temperature</td></tr>
</table>

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (6/29)

③ Implementation items and results (5/27)

b.Test conditions (4/4)

The effect of water quality (additives that prevent recombination (seawater and iodine)) in low-water conditions (where probability of recombination is low) was confirmed.

Table: Test conditions (Confirmation of the effect of water quality)

Item		Case 2		Case 7	Remarks
		Conducted in FY2017	Conducted in FY2018		
Overview of tests		With seawater and iodine		Pure water (without seawater and iodine)	
Sample	Weight of pellet pieces (g)	About 80	About 100		Spent fuel pellet pieces similar to those used in FY2017 were used, and in FY2018, the weight of the pellet pieces was increased
Sample	Particle size of pellet pieces (µm)	20 to 300			Classified after being washed and dried (heated at about 100 ℃)
Water	Water volume (mL)	8 (50 vol.% of pellet pieces)	10 (50 vol.% of pellet pieces)		50 vol.% is based on the results of the draining test conducted in FY2016
Water	Seawater component concentration (mol/L)	Equivalent to 5.6×10^{-4} (20 ppm) as chloride ion concentration		-	Determined by the measurement results of Unit 1 (approx. 19 ppm)*1
Water	Iodine ion concentration (mol/L)	1.0×10^{-4}		-	Assumed that 10% of the iodine inventory*2 will leach into the water
Water	pH	No adjustment			Measured before the tests
Type of gas in gas phase / Initial internal pressure		Atmosphere / approximately the atmospheric pressure (no added pressure)			The pressure is atmospheric assuming a case where gas cannot be replaced
Period of immersion (days)		20 days (max.)			Specified with margin for the assumed transfer period of 10 days
Test temperature		Ambient temperature			No adjustment in temperature

*1: Tokyo Electric Power Company, Inc. (Oct. 22, 2012). Unit 1 Primary Containment Vessel (PCV) Internal Investigation Results.
*2: Kenji Nishihara, Hiroki Iwamoto, Kenya Suyama. (Sept. 2012). Estimation of Fuel Compositions in Fukushima Daiichi Nuclear Power Plant. Japan Atomic Energy Agency. (JAEA-Data/Code2012-18)

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (7/29)

③ Implementation items and results (6/27)

c. Test status

The test equipment configuration was the same as that used in FY2017 (pressure transducer was added). The pressure in the container during the test was measured, and after the test, the gas in gas phase, etc. were analyzed.

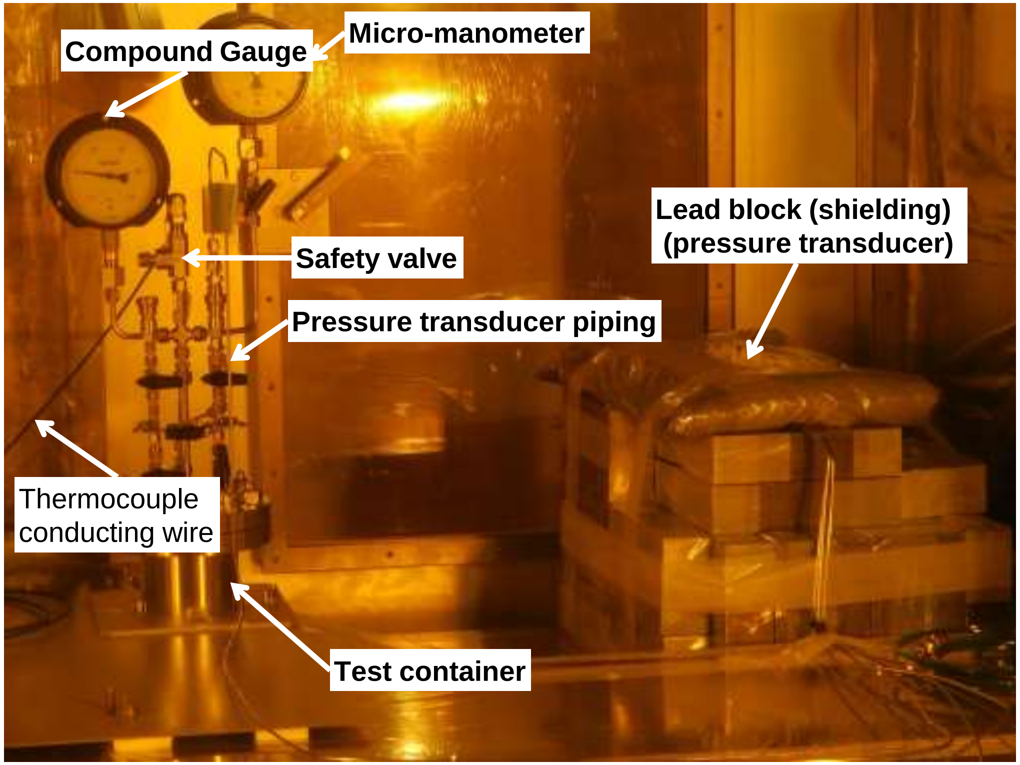
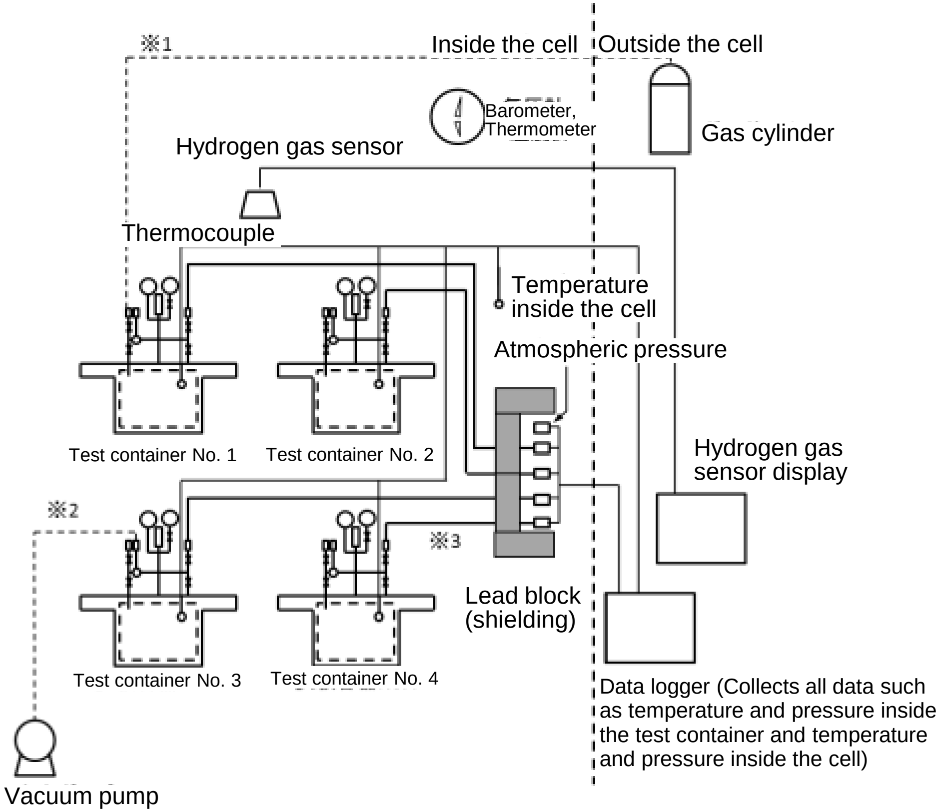


Figure: Appearance of test equipment



*1: Reconfigured and used during leakage confirm
*2: Reconfigured and used during gas containing
*3: Pressure transducer piping: Removed while opening and closing the lid

Figure: Test equipment configuration

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (8/29)

③ Implementation items and results (7/27)

d. Test results (1/4)

- In the test on water volume, wherein the water was at almost-drained level (Case 2 (Conducted in FY2018)), almost the same results as in FY2017 were obtained, and the validity of the FY2017 test results was confirmed. As a result, it was estimated that hydrogen would not be reduced even if the volume of water was reduced to almost-drained level.
- In the test where pellet pieces were dried (Case 3), hydrogen was not detected. As a result, it was confirmed that the amount of hydrogen generated can be reduced by drying the fuel debris.

Table: Test results (Confirmation of the effect of water volume: small particle size)

Item		Case 1*1 (Conducted in FY2017)	Case 2		Case 3 (Conducted in FY2018)	Remarks
			Conducted in FY2017	Conducted in FY2018		
Overview of tests		Pellet pieces immersed in water	Pellet pieces immersed in almost-drained level of water		Dry pellet pieces	Pellet pieces heated (about 100 ℃) until the mass changes to ± 0.1% or lesser are assumed to be dry
Evaluation Results	Amount of hydrogen generated (mL) *2	4/2 (5/3) *3	5 (6) *3	5	—	
	Hydrogen generation rate (L/h/Bq) *2	4.4×10^{-18}/3.5×10^{-18}	6.4×10^{-18}	6.1×10^{-18}	—	
Test results	Hydrogen concentration in gas phase (vol.%)	0.73/0.51 (0.91/0.64) *3	0.78 (0.98) *3	0.96	Below detection limit	
	Oxygen concentration in gas phase (vol.%)	17.9/18.1	18.6	16.6	19.4	
	Nitrogen concentration in gas phase (vol.%)	80.9/79.3	78.9	77.0	76.3	

*1: Test conducted twice under the same conditions
*2:Value converted at 25℃
*3:The value in () is the corrected value of increase in source strength (weight of pellet pieces) with respect to the FY2017 test results

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (9/29)

③ Implementation items and results (8/27)

d. Test results (2/4)

- The amount of hydrogen generated when the particle size was large (Case 4), was about half the amount generated when the particle size was small (Case 2). As a result, under this test condition, it was confirmed that the amount of hydrogen generated decreases when the particle size increases.
- On roughly evaluating the amount of hydrogen generated using pellets of average size particles and the G values, and on comparing it with the case, wherein it is assumed that all of the released energy is absorbed by water (solid line in the below figure), the test results (black dots in the below figure) showed that the difference was larger in the case of small size particles than in the case of large size particles. With small size particles, the filling rate is high and the water around the pellet piece particles decreases; therefore, it is estimated that the ratio of energy absorbed by water under actual conditions decreases as the particle size decreases.

Table: Test results (Confirmation of the effect of particle size)

Item		Case 2		Case 4 (Conducted in FY2018)	Remarks
		Conducted in FY2017	Conducted in FY2018		
Overview of tests		Small particle size (20 to 300 µm)		Large particle size (1,000 to 4,000 µm)	
Evaluation Results	Amount of hydrogen generated (mL) *1	5 (6) *2	5	2	
	Hydrogen generation rate (L/h/Bq) *1	6.4×10^{-18}	6.1×10^{-18}	2.7×10^{-18}	
Test results	Hydrogen concentration in gas phase (vol.%)	0.78 (0.98) *2	0.96	0.41	
	Oxygen concentration in gas phase (vol.%)	18.6	16.6	19.8	
	Nitrogen concentration in gas phase (vol.%)	78.9	77.0	74.9	

*1:Value converted at 25 ℃

*2:The value in () is the corrected value of increase in source strength (weight of pellet pieces) with respect to the FY2017 test results

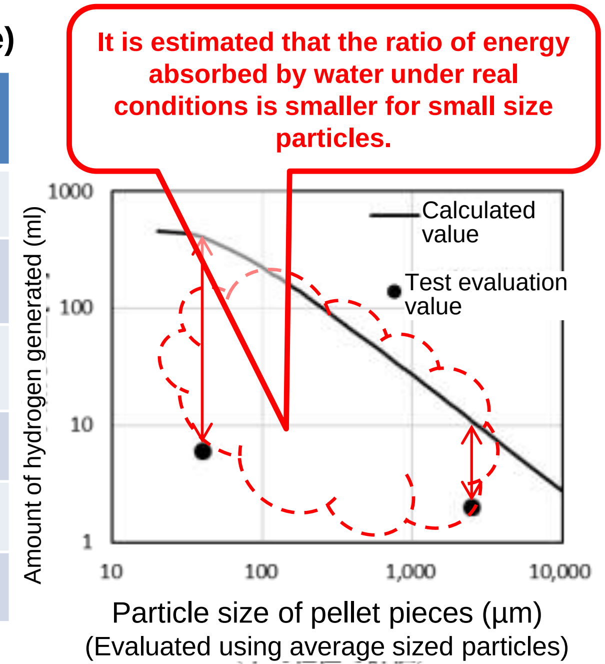


Figure: Relationship between particle size of pellet pieces and hydrogen generation

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (10/29)

③ Implementation items and results (9/27)

d. Test results (3/4)

- In the test where concrete pieces (with free water) were mixed with pellet pieces (dry), as against the result that the amount of hydrogen generated was below the detection limit when alpha rays were shielded (Case 6), the generation of hydrogen was confirmed when alpha rays were present (Case 5). Therefore, it was estimated that the generation of hydrogen in the presence of alpha rays (Case 5) was due to the effect of alpha rays.
- Hydrogen is presumed to have been generated by alpha ray radiolysis of water in the pores of concrete. However, considering the amount of free water (about 1 g*1) in concrete, the amount of hydrogen generated is considered to be high (hydrogen generation rate is about 1:2 for existing water amount of about 1:10) against the test results where pellet pieces were immersed in almost-drained water level (Case 2, amount of water: 10 g). A study on its causes needs to be conducted after FY2019.

Table: Test results (Confirmation of the effect of concrete: small particle size)

Item		Case 3 (Conducted in FY2018)	Case 5 (Conducted in FY2018)	Case 6 (Conducted in FY2018)	Remarks
Overview of tests		Without concrete	With concrete (With alpha rays)	With concrete (Without alpha rays)	Dry pellet pieces Concrete pieces with free water (About 1 g*1)
Evaluation Results	Amount of hydrogen generated (mol) *2	–	3	–	
	Hydrogen generation rate (L/h/Bq) *2	–	3.2×10^{-18}	–	
Test results	Hydrogen concentration in gas phase (vol.%)	Below detection limit	0.49	Below detection limit	
	Oxygen concentration in gas phase (vol.%)	19.4	18.8	19.9	
	Nitrogen concentration in gas phase (vol.%)	76.3	77.8	75.7	

*1:The difference in weight, when the concrete pieces prepared in similar way are dried at around 100℃ until there is no more change in weight, is estimated as the volume of free water.
*2: Value converted at 25℃

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (11/29)

③ Implementation items and results (10/27)

d. Test results (4/4)

- Compared to the condition wherein seawater and iodine were added (Case 2), almost double the amount of hydrogen was generated when seawater and iodine were not added (Case 7). In other tests, iodine was confirmed to have leached from the pellet pieces into the water. In this test as well, iodine leached into the water, so it is believed that the test was completed under the same water quality conditions.
- As mentioned in the confirmation of effects of the particle size, the energy absorption rate may change depending on the contact conditions between the particles. In this test, the reason for increase in the generated amount of hydrogen to almost double the amount, is estimated to be the effect of the difference in the contact conditions between the particles. However, further study needs to be conducted after FY2019.

Table: Test results (Confirmation of the effect of water quality)

Item		Case 2		Case 7 (Conducted in FY2018)	Remarks
		Conducted in FY2017	Conducted in FY2018		
Overview of tests		With seawater and iodine		Pure water (without seawater and iodine)	
Evaluation Results	Amount of hydrogen generated (mL) *1	5 (6) *2	5	13	
	Hydrogen generation rate (L/h/Bq) *1	6.4×10^{-18}	6.1×10^{-18}	1.5×10^{-17}	
Test results	Hydrogen concentration in gas phase (vol.%)	0.78 (0.98) *2	0.96	2.2	
	Oxygen concentration in gas phase (vol.%)	18.6	16.6	15.5	
	Nitrogen concentration in gas phase (vol.%)	78.9	77.0	77.9	

*1:Value converted at 25℃
*2:The value in () is the corrected value of increase in source strength (weight of pellet pieces) with respect to the FY2017 test results

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (12/29)

③ Implementation items and results (11/27)

e. Evaluation of energy absorption rate (1/2)

In the evaluation of the test results, the energy absorption rate in the test system was assessed using the following three methods:

(a) Evaluation through test results (hereinafter, “Test results”)

Energy absorption rate was evaluated based on the fuel calculation results of pellet pieces and the hydrogen generation amount obtained in the test. In this evaluation, all differences in the assumed and actual systems are expressed as energy absorption rates.

(b) Evaluation through particle size of pellet pieces (hereinafter, “considered particle size”)

A representative particle size was set based on the particle size distribution of pellet pieces, and evaluations were based on the assessment of the energy absorbed by water for various particle sizes, conducted in FY2016.

(c) Evaluation using transport code system (hereinafter, “transport system”)

The energy absorption rate was evaluated from the calculation results using Particle and Heavy Ion Transport Code System (PHITS) and the fuel calculation result of pellet pieces. The evaluation at that time was performed using a model (see the figure below) in which a pellet piece (assumed to be spherical) was placed in a cube (water) with the same center of gravity. In this evaluation, the volume of the cube was set so that the area volumes of both pellet piece and water became equal, and the boundary conditions were conservatively reflected.

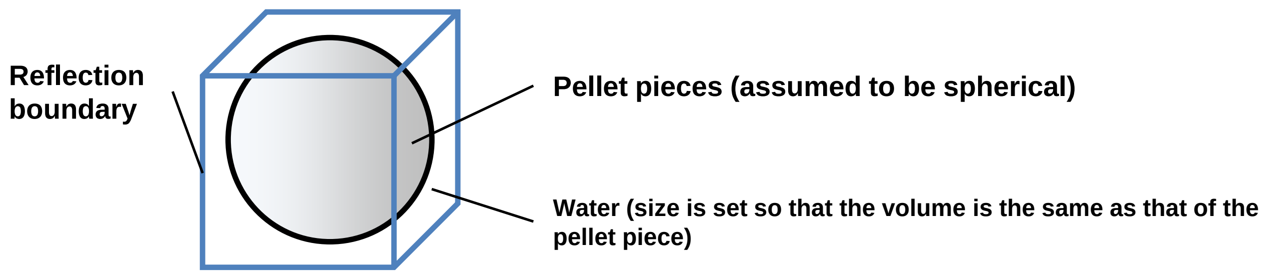


Figure: Calculation model in the transport system

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (13/29)

③ Implementation items and results (12/27)

e. Evaluation of energy absorption rate (2/2)

The energy absorption rates for small particle size (assumed particle size of 40 µm) and large particle size (assumed particle size of 2,500 µm) were evaluated.

The energy absorption rate evaluated through test results was particularly smaller than other evaluation methods. This is presumed to be due to the fact that in the test systems, various factors that greatly affect the generation of hydrogen, such as the state of the pellet pieces and the state of water present in the surroundings, which are not taken into account in the considered particle size and transport system, are included in the energy absorption rate.

Table: Energy absorption rate evaluation results

Particle size	Energy absorption rate *1				Remarks
	Evaluation method	α rays	β rays	γ rays	
Small particle size	Test results	0.01	0.002	0.002	Evaluated from the amount of hydrogen generated in the small particle size test
	Considered particle size	0.90	1.00	0.02	Evaluated assuming a particle size of 40 µm
	Transport system	0.18	0.14	0.14	Evaluated assuming a particle size of 40 µm
Large particle size	Test results	0.005	0.002	0.002	Evaluated from the amount of hydrogen generated in the large particle size test
	Considered particle size	0.02	0.42	0.02	Evaluated assuming a particle size of 2,500 µm
	Transport system	0.005	0.06	0.06	Evaluated assuming a particle size of 2,500 µm

*1: Rate of absorption in water with respect to the energy from each type of rays

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (14/29)

③ Implementation items and results (13/27)

f. Evaluation of the hydrogen generation rate (1/2)

The hydrogen generation rate evaluated from the hydrogen concentration in gas phase obtained from test results was compared with the hydrogen generation rate evaluated from the calculation based on the TMI-2 evaluation formula and radiolysis model. In the calculation using the TMI-2 evaluation formula and radiolysis model, the energy absorption rate evaluated in Section e. was used.

(a) TMI-2 evaluation formula

Assuming that the radiation energy corresponding to the amount of heat generation was absorbed by water, the hydrogen generation rate G_{H2} was evaluated by multiplying the absorbed energy by the G value of hydrogen generation. This was evaluated based on the following evaluation formula used for the evaluation of amount of hydrogen generated during TMI-2 fuel debris transfer:

$$G_{H2} = W \times P \times F \times (1 / (1.6 \times 10^{-19})) \times (G/100) \times (22.4 / (6.0 \times 10^{23})) \times 3600$$

W	: Amount of heat generation [W]
P	: Peak in the amount of heat generation (= 1.9)
F	: Energy absorption rate [-]
G	: Water splitting per 100 eV energy [molecule/100 eV]
3600	: 3600 [s/h]

(b) Calculation through radiolysis model

The hydrogen generation rate was evaluated based on conditions such as energy absorption rate, and calculation results using the water quality analysis code (SIMFONY).

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (15/29)

③ Implementation items and results (14/27)

f. Evaluation of the hydrogen generation rate (2/2)

- When evaluated using the energy absorption rate obtained from hydrogen generation test results, the hydrogen generation rate was almost the same as the hydrogen generation rate evaluated from test results regardless of the evaluation method (indicated by the green frame in the table).
- When evaluated using the energy absorption rate evaluated from the calculations (considered particle size and transport system), the hydrogen generation rate was about 20 to 100 times greater than that evaluated from the test results (indicated by the blue frame in the table).

Table: Hydrogen generation rate evaluation results

Particle size	Hydrogen generation rate evaluation method	Energy absorption rate *1			Hydrogen generation rate (L/h/Bq)	Remarks
		α rays	β rays	γ rays		
Small particle size	Test results	-	-	-	5.1×10^{-18}	Average hydrogen generation rate evaluated from the results of small particle size test
	TMI-2 evaluation formula	0.01	0.002	0.002	9.7×10^{-18}	When using the energy absorption rate evaluated from test results
		0.90	1.00	0.02	1.0×10^{-15}	When using the energy absorption rate obtained from the evaluation considering the particle size
		0.18	0.14	0.14	2.1×10^{-16}	When using the energy absorption rate obtained from the evaluation using the transport system
	Radiolysis model	0.01	0.002	0.002	5.0×10^{-18}	When using energy absorption rate evaluated from test results
Large particle size	Test results	-	-	-	2.7×10^{-18}	Hydrogen generation rate evaluated from results of large particle size test
	TMI-2 evaluation formula	0.005	0.002	0.002	5.2×10^{-18}	When using energy absorption rate evaluated from test results
		0.02	0.42	0.02	1.2×10^{-16}	When using the energy absorption rate obtained from the evaluation considering the particle size
		0.005	0.06	0.06	2.8×10^{-17}	When using the energy absorption rate obtained from the evaluation using the transport system
	Radiolysis model	0.005	0.002	0.002	2.7×10^{-18}	When using energy absorption rate evaluated from test results
(Reference) Evaluation of TMI-2		-	0.2		7.7×10^{-17}	When using energy absorption rate of TMI-2 fuel debris transfer evaluation

*1: Rate of absorption in water with respect to the energy from each type of rays

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (16/29)

③ Implementation items and results (15/27)

g. Trial calculation of the amount of hydrogen generated in real canisters (1/6)

Based on the hydrogen generation rate evaluated in Section f., trial calculation was performed on the amount of hydrogen generated inside a real canister during transfer, and the duration for which the hydrogen concentration in the canister did not exceed 4 vol.%, was calculated.

(a) Evaluation standard

The evaluation standards used in the trial calculation are as follows:

- Hydrogen concentration: Less than 4 vol.% (Less than lower explosion limit)
- Transfer duration: 7 days (168 hours)*1 (If the calculated time is less than 7 days (168 hours), study on providing canisters with vents (or transport casks), and on reducing the amount of debris stored in a canister or transport cask, needs to be conducted.)

(b) Method for evaluating amount of hydrogen generated

Similar to the evaluation in Section f., the evaluation was performed based on calculations using the TMI-2 evaluation formula and radiolysis model, in addition to the evaluation based on the hydrogen concentration in gas phase, obtained from the test results.

***1: Set values with a margin while taking problems at the time of transfer into account, based on the results of spent fuel retrieval from Unit 4 of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc.**

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (17/29)

③ Implementation items and results (16/27)

g. Trial calculation of the amount of hydrogen generated in real canisters (2/6)

(c) Conditions for canisters and transport casks

The conditions for canisters and transport casks used in the trial calculation are as follows:

Table: Conditions for canisters used in trial calculations

Conditions	Unit	Specifications	Remarks
Inner diameter of canister	mm	220	Specification values in this technical development from the viewpoint of preventing criticality (Same conditions as the <Throughput study conditions> shown in Slides No. 25 and No. 26)
Inner height of canister	mm	800	Same conditions as the <Throughput study conditions> shown in Slides No. 25 and No. 26
Inner volume of canister	m^3	0.030	Calculated from inner diameter and inner height
Volume of contained fuel debris	m^3	0.0067	Same conditions as the <Throughput study conditions> shown in Slides No. 25 and No. 26
Volume of water	m^3	0.0033	Calculated by setting to 50 vol.% of fuel debris volume (set based on the draining test conducted in FY2016), taking into account draining by unit cans
Volume of gas phase in canister	m^3	0.020	Value obtained by subtracting the volume of fuel debris and volume of water from the inner volume of canister

Table: Conditions for transport casks used in trial calculations

Conditions	Unit	Specifications	Remarks
Inner diameter of transport cask	mm	1,700	Provisional value
Inner height of transport cask	mm	1,200	Provisional value
Inner volume of transport cask	m^3	0.030	Calculated from inner diameter and inner height
No. of stored canisters	Number	12	Set taking into account the inner dimensions of the canister and transport cask (Single stacking) (Same conditions as the <Throughput study conditions> shown in Slides No. 25 and No. 26)
Volume of contained fuel debris	m^3	0.080	Sum of the volume of fuel debris inside the canisters
Volume of water	m^3	0.040	Sum of the volume of water inside the canisters
Volume of gas phase in transport cask	m^3	2.2	Value obtained by subtracting canister volume, canister fuel debris volume, and volume of water inside canister from inner volume of transport cask

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (18/29)

③ Implementation items and results (17/27)

g. Trial calculation of the amount of hydrogen generated in real canisters (3/6)

(d) Conditions for fuel debris

The fuel debris conditions used in the trial calculation are as follows:

- All the fuel debris was assumed to be UO_2. Therefore, the weight of fuel debris in the canister became 73 kg/canister, and the weight of fuel debris in the transport cask became 878 kg/transport cask.
  It is estimated that conditions, such as particle size, differ between the hydrogen generation test and actual fuel debris. However, in this evaluation, it was assumed that the test results can be applied as they are.
- The fuel debris source strength used, was obtained from the results of the combustion calculations performed in FY2016. The source strength that was calculated and used, is shown below:

Table: Source strength of fuel debris used in trial calculations

Items	α rays	β rays	γ rays
Source strength ($MeV/s/kg\text{-}UO_2$)	1.68×10^{12}	5.02×10^{12}	4.98×10^{12}

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (19/29)

③ Implementation items and results (18/27)

g. Trial calculation of the amount of hydrogen generated in real canisters (4/6)

(e) Energy absorption rate

The energy absorption rate used in the trial calculation included the following three cases:

i. Rate specified assuming that all of the energy is absorbed by water (hereinafter, "total absorption")

The energy absorption rate was set assuming that all of the energy is absorbed by water. The energy absorption rate of gamma rays that have a longer range, was set separately.

ii. Rate calculated with the transport code system considering the particle size of fuel debris (hereinafter, “transport system”)

From the particle size of the fuel debris (particle size 0.1 mm or more[*1]) stored in the canister, the particle size of all the fuel debris was conservatively assumed to be 0.1 mm, and the energy absorption rate was calculated and set using the transport code system.

iii. Rate set based on the test results (hereinafter, “test results")

The energy absorption rate was set on the basis of the ratio of the absorbed dose obtained from test results and the released energy obtained from the results of calculating the combustion of pellet pieces.

Table: Energy absorption rate[*2] used in trial calculation

Condition	α rays	β rays	γ rays
Total absorption	1	1	0.02
Transport system	0.09	0.13	0.13
Test results	0.01	0.002	0.002

*1: Current provisional value used in the Method Project
*2: Rate of absorption in water with respect to the energy from each type of rays

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (20/29)

③ Implementation items and results (19/27)

g. Trial calculation of the amount of hydrogen generated in real canisters (5/6)

(f) G Values

The G values used in the trial calculation are as follows:

Table: G values used in trial calculation

Condition	G value (Ambient temperature, unit / 100eV)								
	e^-	H	H_2	OH	H_2O_2	HO_2	O_2^-	H^+	OH^-
α rays*1	0.06	0.21	1.3	0.24	0.985	0.22	-	0.06	-
β rays, γ rays*2	2.75	0.60	0.44	2.81	0.71	-	-	2.75	-

In the trial calculation using TMI-2 evaluation formula, only the value of H_2 was used.

*1: Pastina, B., and LaVerne, J. A., (2001) : "Effect of molecular hydrogen on hydrogen peroxide in water radiolysis." The Journal of Physical Chemistry A, 105 (40), 9316-9322.
*2: "The Reaction Set, Rate Constants and g-Values for the Simulation of the Radiolysis of Light Water over the Range 20 to 350°C Based on Information Available in 2008." 153-127160-450-001.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (21/29)

③ Implementation items and results (20/27)

g. Trial calculation of the amount of hydrogen generated in real canisters (6/6)

(g) Results of trial calculation

- When evaluated with the conservative assumption that short-range alpha rays and beta rays are totally absorbed, the results showed that the number of canisters stored in a transport cask need to be reduced, and in addition, the amount of fuel debris stored in the canister needs to be reduced as well.
- When evaluated using the energy absorption rate assessed with the transport system, although the margin increased over that for total absorption, the results showed that the number of canisters stored in a transport cask needs to be reduced.
- When evaluated using the energy absorption rate obtained from the hydrogen generation test results, the results showed that the canisters can be sealed and transferred.

Table: Results of trial calculation

Hydrogen generation amount evaluation method	Energy absorption rate evaluation method	Time taken for hydrogen concentration inside the canister to reach 4 vol.%	Time taken for hydrogen concentration inside the transport cask to reach 4 vol.%	Evaluation	Remarks
Test results	-	About 9.3 days (Approx. 224 hours)	About 69 days (Approx. 1656 hours)	・Sealed transfer is possible for both canister and transport cask[*1].	
TMI-2 evaluation formula	Total absorption	About 0.04 days (Approx. 1.0 hour)	About 0.3 days (Approx. 7.1 hours)	・Sealed transfer is not possible. When assuming the case of sealing the canister in a transport cask, it is necessary to reduce the number of stored canisters to one, in addition to reducing the amount of contained fuel debris by 50%.	Trial calculation result A
	Transport system	About 0.2 days (Approx. 5.5 hours)	About 1.7 days (Approx. 41 hours)	・Sealed transfer is not possible. When assuming the case of sealing the canister in a transport cask, it is necessary to reduce the number of stored canisters to two.	Trial calculation result B
	Test results	About 5.8 days (Approx. 139 hours)	About 43 days (Approx. 1029 hours)	・Sealed transfer of canister is possible if the amount of contained fuel debris is reduced to about 80%[*1]. Sealed transfer is possible with a transport cask.	Trial calculation result C
Radiolysis Model	Test results	About 13 days (Approx. 305 hours)	About 94 days (Approx. 2262 hours)	・Sealed transfer is possible for both canister and transport cask[*1].	

*1: Vents are basic measures in canisters during storage

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (22/29)

③ Implementation items and results (21/27)

h. Transfer scenario (1/6)

Based on the trial calculation results for amount of hydrogen generated inside the canister described in Section g., transfer scenarios from the perspective of hydrogen measures were studied.

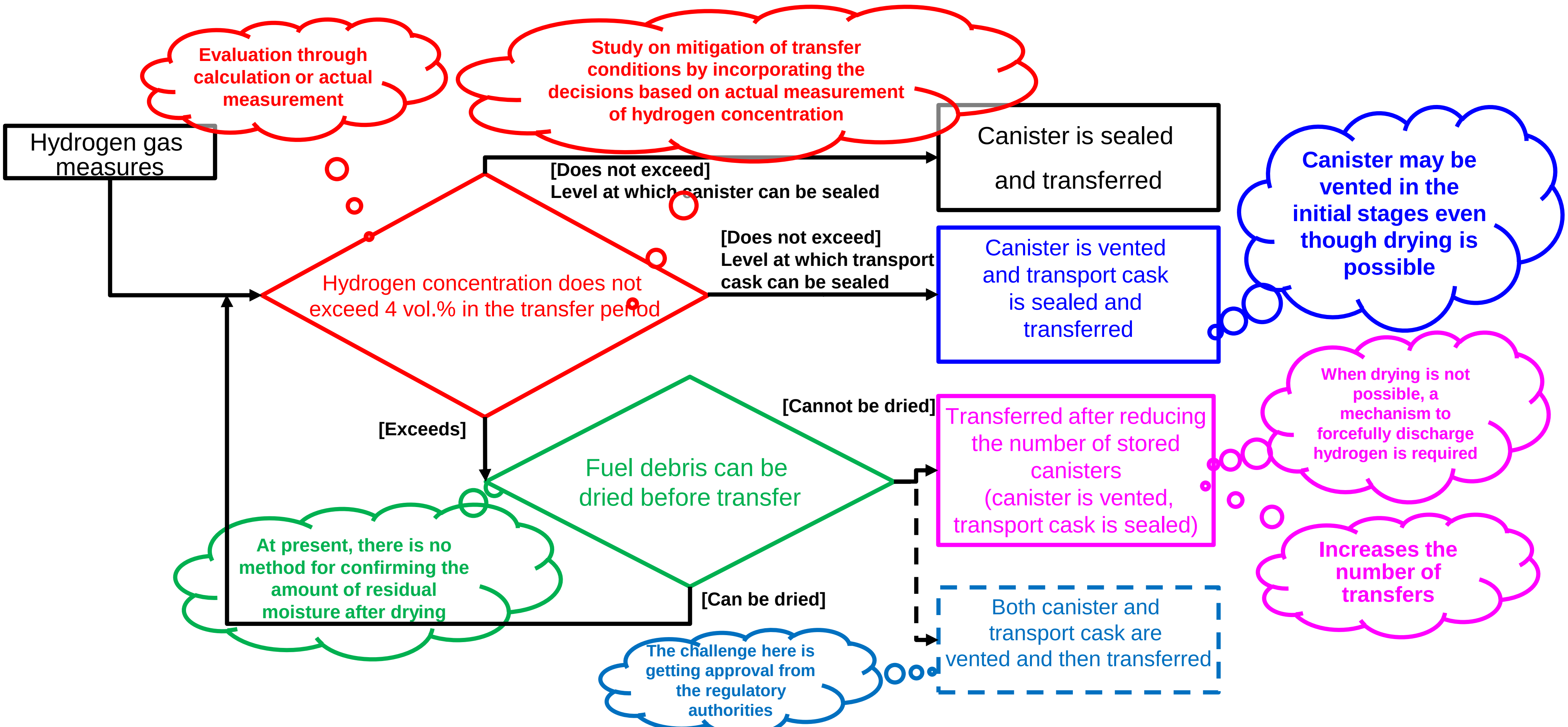


Figure: Basic approach towards hydrogen gas measures during transfer

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

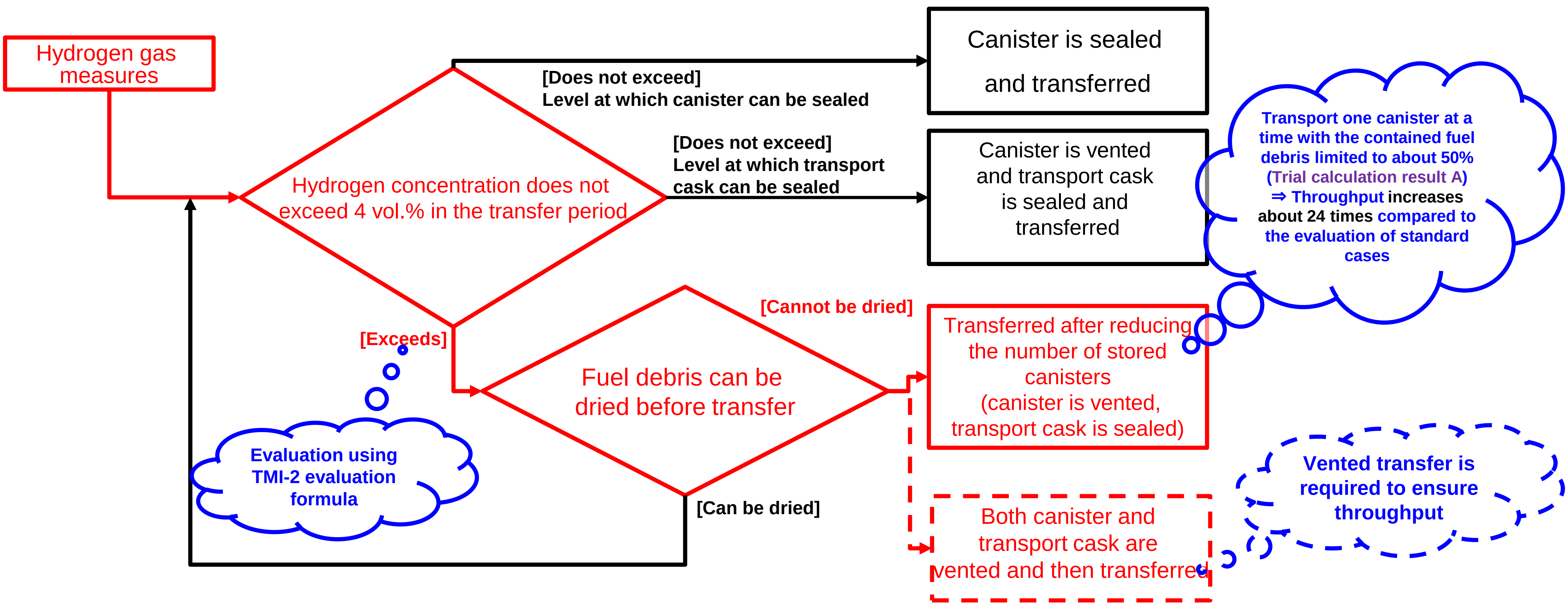
(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (23/29)

③ Implementation items and results (22/27)

h.Transfer scenario (2/6)

If the amount of hydrogen generated must be evaluated (using the TMI-2 evaluation formula) under the most conservative conditions (total absorption of alpha and beta rays), the number of stored canisters must be reduced and then transferred. Based on the trial calculation result A shown in Section g.(g), if fuel debris cannot be dried before transfer, one canister must be stored in the transport cask and transferred (the amount of fuel debris stored in the canister must be reduced to about 50% as well).

⇒ Case A



6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

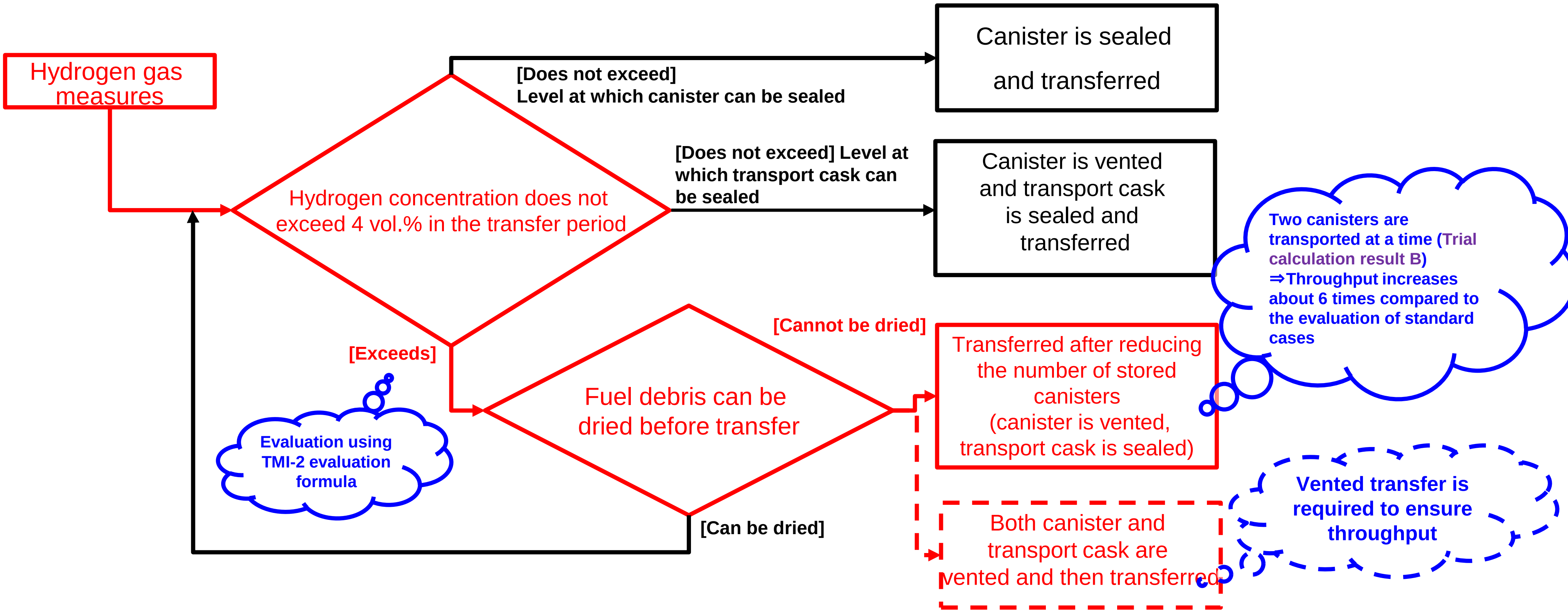
(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (24/29)

③ Implementation items and results (23/27)

h.Transfer scenario (3/6)

If the amount of hydrogen generated can be evaluated (using the TMI-2 evaluation formula) under conditions considering appropriate particle size (considered particle size), the number of stored canisters can be increased as compared to the most conservative evaluation in Case A. By using the energy absorption rate calculated taking the particle size into account, it is possible to transfer 2 canisters based on the **trial calculation result B** described in Section g.(g).

⇒ Case B



6. Implementation Details

6.3 Development of Safety Evaluation Methods and Verification of Safety

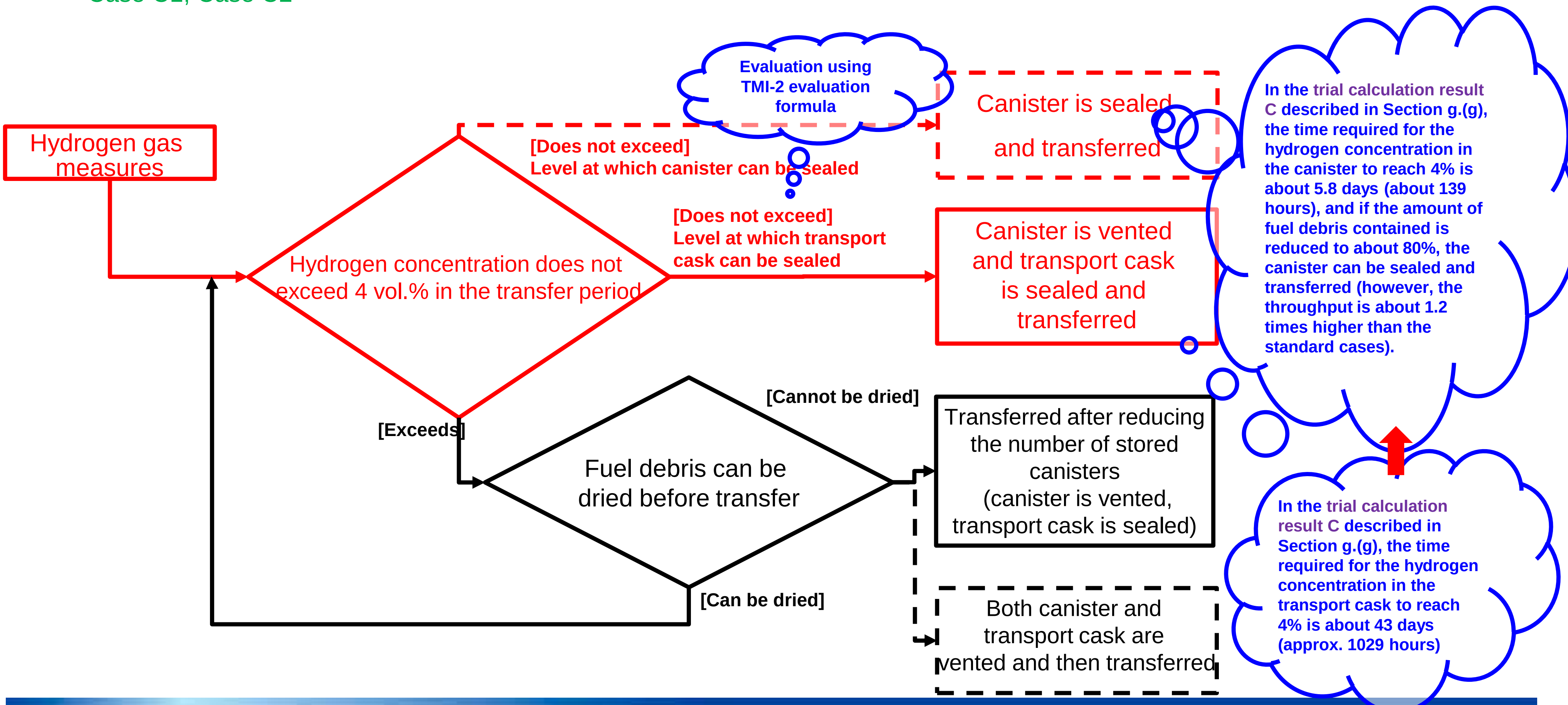
(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (25/29)

③ Implementation items and results (24/27)

h.Transfer scenario (4/6)

If the amount of hydrogen generated can be evaluated using the condition of energy absorption rate obtained from the test results (using the TMI-2 evaluation formula), it is possible to seal and transfer the transport casks irrespective of whether or not the fuel debris is dried before transfer. In addition, by reducing the amount of fuel debris stored in the canister to about 80%, it is possible to seal and transfer the canister.

⇒ Case C1, Case C2



6.3. Development of Safety Evaluation Methods and Verification of Safety

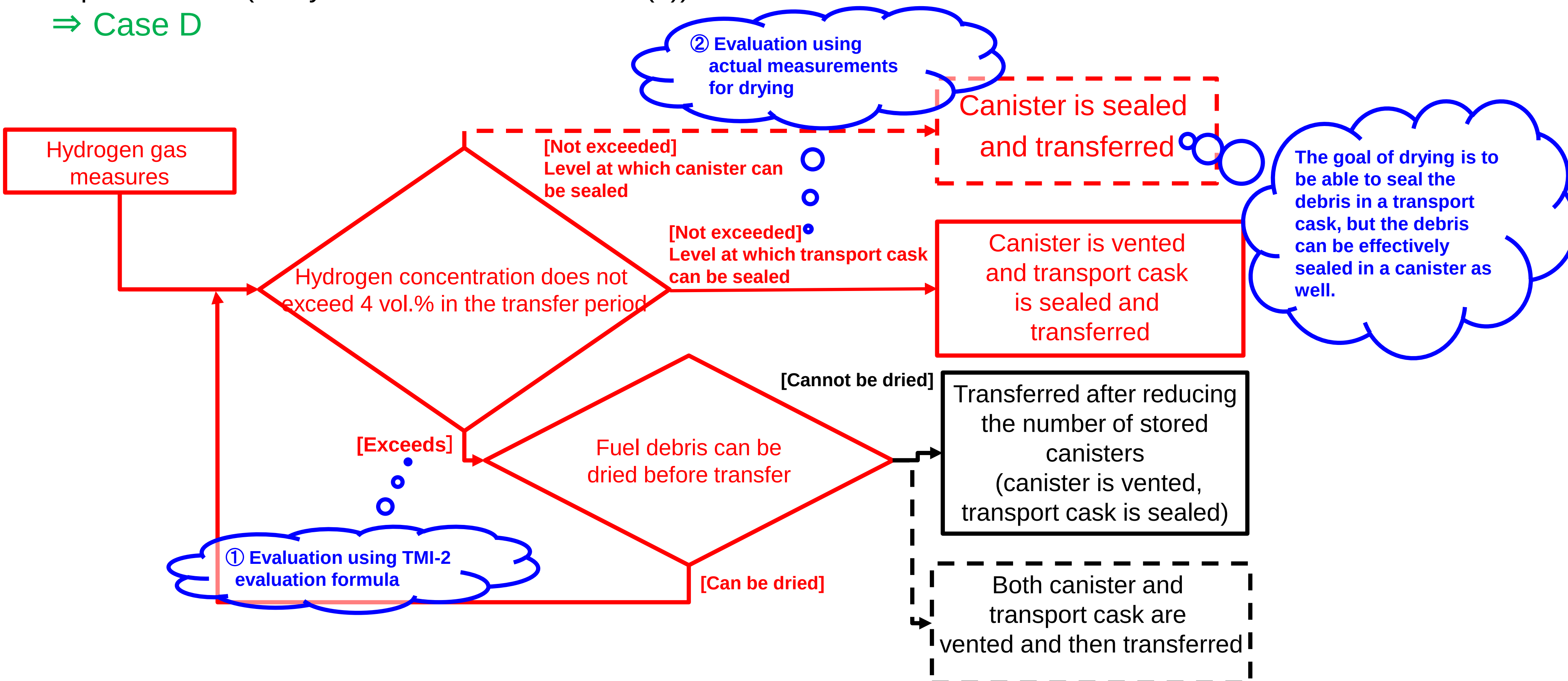
(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (26/29)

③ Implementation items and results (25/27)

h. Transfer scenario (5/6)

If the fuel debris can be dried before transfer, then based on the test results described in Section d., it is concluded that the transport cask (or canister) can be sealed and transferred. However, the drying of the fuel debris is a separate issue (study conducted in Section 6.2(4)).

⇒ Case D



6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (27/29)

③ Implementation items and results (26/27)

h. Transfer scenario (6/6)

・Establishment of pre-transfer drying (technical aspect and operational aspect)

Case A

<Transfer conditions>
・Storage capacity of canisters is limited
The number of canisters stored in the transport cask is limited
・Transport cask is sealed (Canisters are vented)

<Evaluation method for amount of hydrogen generated>
・TMI-2 evaluation formula
<Conditions for evaluation of amount of hydrogen generated>
・All fuel debris is UO_2
・Conservative energy absorption rate is adopted

<Impact on throughput>
・Increases about 24 times of the standard cases

Case B

<Transfer conditions>
・Storage capacity of canisters is not limited
The number of canisters stored in the transport cask is limited
・Transport cask is sealed (Canisters are vented)

<Evaluation method for amount of hydrogen generated>
・TMI-2 evaluation formula
<Conditions for evaluation of amount of hydrogen generated>
・Source strength of fuel debris is determined
・Energy absorption rate considering the fuel debris particle size is adopted

<Impact on throughput>
・Increases about 6 times of the standard cases

Case C1

<Transfer conditions>
・Both storage capacity of canisters and number of canisters stored in the transport cask are not limited
・The transport cask is sealed (Canisters are vented)

<Evaluation method>
・TMI-2 evaluation formula
<Evaluation conditions>
・Source strength of fuel debris is determined
・Energy absorption rate based on the test results is adopted

<Impact on throughput>
・No impact

Case D

<Transfer conditions>
・Both storage capacity of canisters and number of canisters stored in the transport cask are not limited
・The transport cask is sealed (Depending on the drying level, sealing in canisters can also be ensured)

<Evaluation method for amount of hydrogen generated>
・Actual measurements for drying
<Conditions for evaluation of the amount of hydrogen generated>
—

<Impact on throughput>
・No impact

Case X

<Transfer conditions>
・Both storage capacity of canisters and number of canisters stored in the transport cask are not limited
・Both canisters and transport casks are vented

<Evaluation method for amount of hydrogen generated>
・Not necessary (as safety evaluation)
<Evaluation conditions>
—

<Impact on throughput>
・No impact

・Setting the source strength (or nuclear mass) of fuel debris
・Method for setting the energy absorption rate considering the fuel debris particle size (Example: Validity of transport code system etc.)
・Estimation of fuel debris particle size

Case C2

<Transfer conditions>
・Storage capacity of canisters is limited, and the number of canisters stored in the transport cask is not limited
・Transport cask is sealed (Canisters are vented)

<Evaluation method for amount of hydrogen generated>
・TMI-2 evaluation formula
<Conditions for evaluation of the amount of hydrogen generated>
・Source strength of the fuel debris is determined
・Energy absorption rate based on the test results is adopted

<Impact on throughput>
・Increases about 1.2 times of the standard cases

・Setting the source strength (or nuclear mass) of fuel debris
・Validity of test results and energy absorption rate settings based on the test results
・Consistency between the test conditions and the actual fuel debris conditions

<Securing throughput is top priority>
・Approval from the regulatory authorities
・Measures against discharge of radioactive materials

6.3. Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated) (28/29)

③ Implementation items and results (27/27)

i. Conclusion

As a Verification of the amount of hydrogen gas generated, the following results were obtained from the hydrogen generation tests using spent fuel, etc.

・When small size particles (particle size of 20 μm to 300 μm) were used, it was seen that the hydrogen generation rate in the presence of alpha rays was about 10 times higher than in the absence of alpha rays. Therefore, the effect of alpha rays was confirmed under the present test conditions.

・It was found that by drying the pellet pieces until there is no more change in weight, generation of hydrogen can be inhibited by means of water radiolysis.

・It was found that the effect of the method of evaluating the energy absorption rate on the amount of hydrogen generated by water radiolysis is greater than the effect of the method of evaluating hydrogen generation amount. Therefore, it was estimated that if the energy absorption rate could be set in line with the conditions, then the amount of hydrogen generated could be assessed appropriately.

6.3. Development of Safety Evaluation Methods and Verification of Safety

(4) Safety verification of hydrogen gas measures (Verification of the amount of hydrogen gas generated)(29/29)

④ Reflection of results

The necessity of drying the fuel debris, evaluation standards, and hydrogen measures will be studied based on the test results. In addition, this information will contribute to the study of evaluation conditions for assessing the amount of hydrogen generated in full-scale canisters.

⑤ Analysis from the viewpoint of applicability to the site

Taking into account the differences between the conditions for full-scale canisters and the conditions for these tests, information contributing to the study of evaluation conditions for assessing the amount of hydrogen generated in full-scale canisters, will be obtained from these test results.

⑥ Level of achievement compared to the goal

With respect to the indicators for determining the achievement of goals, it was estimated that evaluation would be possible by carrying out gamma-ray irradiation test and using the primary G values of hydrogen generation even when the effect of reaction during the gas phase in the canister is taken into account. (reported in FY2017).
In addition, it was found that the contribution level of alpha rays to hydrogen generation was larger than that of beta rays and gamma rays for water volume where the particle size was less than a few mm and recombination could not be expected. It was estimated that even under such conditions, if the amount of energy absorbed by water could be set appropriately, then it would be possible to assess the amount of hydrogen generated.
From the above, it is concluded that the goals have been achieved.

⑦ Future issues

To propose a method for estimating the amount of hydrogen generated, it is necessary to study the approach towards setting the evaluation conditions (fuel debris condition, energy absorption rate, etc.) taking into account the 1F fuel debris conditions.

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (1/12)

① Purpose and goals

It is assumed that the canisters will be transported from the reactor building to the storage facility in a transport cask, and as the transport cask needs to be sealed during transfer, measures against explosion of residual hydrogen are necessary. In addition, confining the fuel debris to a canister as far as possible is effective in controlling the spread of contamination outside the canister. Therefore, as a measure against hydrogen, the possibility and effectiveness of the method of recombining hydrogen and oxygen generated in the can with a catalyst will be clarified as a method of treating hydrogen generated in the canister, within the same canister. Based on the results obtained until FY2017, a study was conducted with the following goals:

a. Selection of catalyst considering the environment inside the canister
b. Setting of the diffusion effect (transportation effect of hydrogen on the catalyst) of the generated hydrogen considering the flow inside the canister

② Comparison with existing technologies

Although there are examples of performance verification by means of flow test (forced convection) for the hydrogen recombining catalysts, there are almost no reported examples of knowledge on the diffusion effects and natural convection inside the canister. Therefore, studies taking into account the unique conditions at 1F, are necessary.

③ Implementation items and results (1/10)

a. Selection of catalyst considering the environment inside the canister (1/6)

Hydrogen is presumed to be generated from the non-dried fuel debris due to radiolysis of residual moisture.

Although transfers are carried out using transport casks, the operating conditions inside the canister wherein the catalyst is installed, are severe as compared to the environment under which standard catalysts are used, in that there is condensation and in addition the temperature is comparatively low (about ambient temperature).

Therefore, in order to verify the impact of the environment inside the canister, where hydrogen is presumed to be generated, on the recombining performance of the hydrogen recombining catalyst, in this test, the catalyst performance (possibility of oxidation reaction) under high humidity environmental conditions and when condensate water is present on the surface of the catalyst, was confirmed with the aim of conducting a primary evaluation of the applicability of the hydrogen recombining catalyst.

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (3/12)

③ Implementation items and results (2/10)

a. Selection of catalyst considering the environment inside the canister (2/6)

A catalyst developed by the catalyst manufacturer for low-temperature environment was placed in a chamber (closed system reaction container) simulating the environmental temperature, a predetermined amount of hydrogen, etc. was injected into the chamber, and when the internal pressure and the pressure fluctuation was stabilized, the hydrogen concentration was measured and the presence of recombination reaction was verified.

[Verification method for the recombination reaction]
・Measurement of pressure
・Measurement of hydrogen concentration

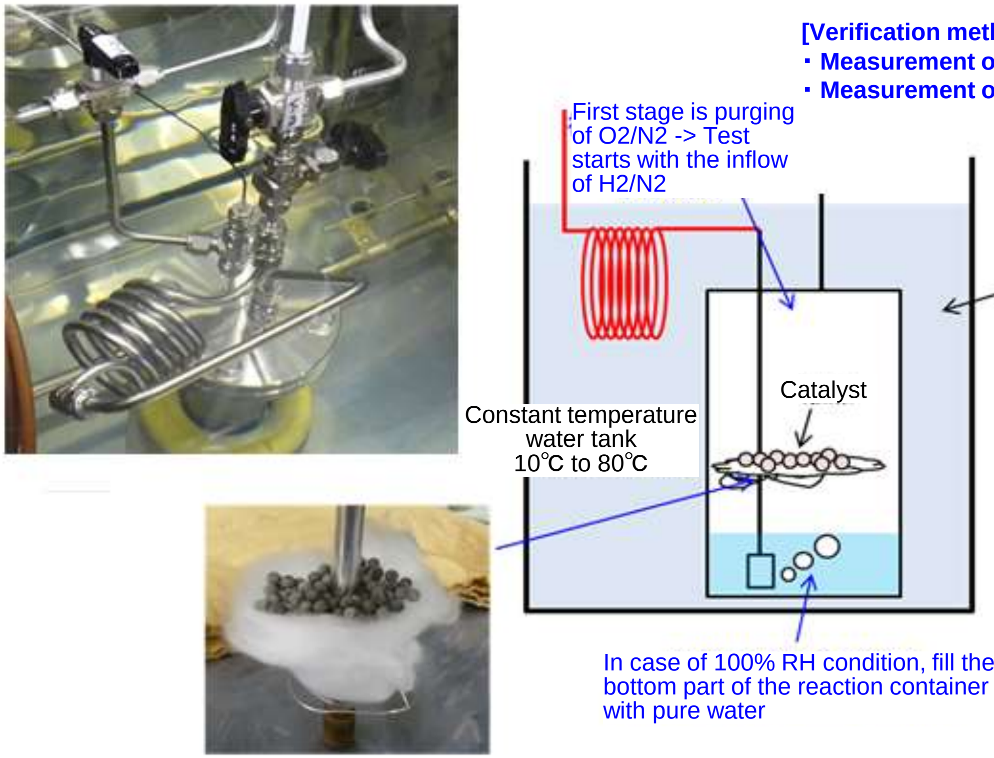


Figure: Method of performance verification element test for catalysts

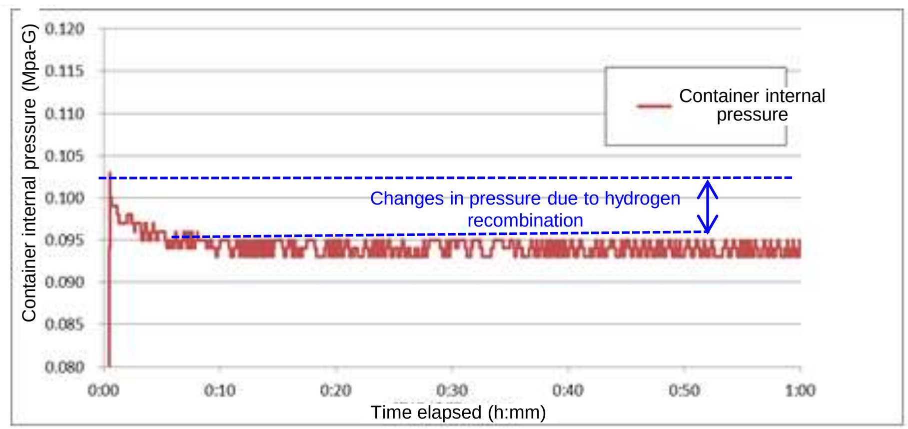


Figure: Example of changes in the internal pressure of the container with the passage of time

(Case: Catalyst ① (with water repellency treatment), hydrogen concentration 2 vol.%, relative humidity 100% RH, temperature 10°C, internal pressure of container 0.2 MPa-A, catalyst immersed)

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6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (4/12)

③ Implementation items and results (3/10)

a. Selection of catalyst considering the environment inside the canister (3/6)

The specifications of the catalysts being tested in the catalyst performance verification element test are shown in the table below, while their shapes are shown in the figures on the right.
Further, the commercial and sample catalysts that could be procured from catalyst manufacturers were used in the test to confirm whether or not any of those catalysts can be used in the canister environment.

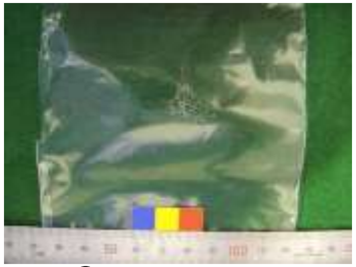
Table: Specifications of the catalysts under test

Catalyst No.	Name	Specifications
①	Pellet shaped ① (With water repellency treatment)	Developed by catalyst manufacturers, Catalyst: Pt, water repellency treatment, Equivalent to 2mL (water repellency treated product as a distinctive catalyst)
②	Pellet shaped ② (Without water repellency treatment)	Developed by Mitsubishi Heavy Industries, Catalyst: Pt, Equivalent to 2mL (Relatively low-temperature design without water repellency treatment)
③	Honeycomb catalyst ① (Without water repellency treatment)	Catalyst used for cars, Catalyst: Pt, Mesh is finer than the one in ⑥, Equivalent to 2mL (Selected because it is generally considered high performance)
④	Platinum wire (Without water repellency treatment)	Platinum wire: 0.05 mmΦ, Length 1 m (Water repellency of the material itself is expected)
⑤	Pt/CCF (Without water repellency treatment)	Pt/CCF: 0.04 umΦ, Equivalent to 2mL (Water repellency of the material itself is expected)
⑥	Honeycomb catalyst ② (Without water repellency treatment)	Developed by catalyst manufacturers, Catalyst ：Pt, Mesh: 30 cpsi, Equivalent to 2mL (2cm^2*1cm) (Relatively low-temperature design without water repellency treatment)
⑦	Pellet shaped ③ (Without water repellency treatment)	Developed by catalyst manufacturers, Catalyst: Pt, Catalyst support alumina carrier, Equivalent to 2mL (Relatively low-temperature design without water repellency treatment)

① Pellet shaped ①

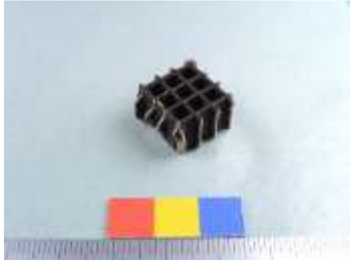
② Pellet shaped ②

③ Honeycomb catalyst ①

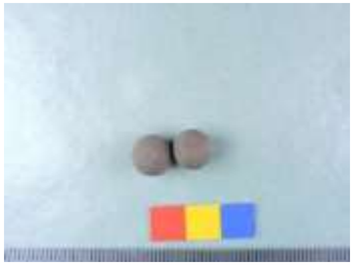


④ Platinum wire

⑤ Pt/CCF



⑥ Honeycomb catalyst ②



⑦ Pellet shaped ③

Figure: Shapes of catalysts under test

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6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (5/12)

③ Implementation items and results (4/10)

a. Selection of catalyst considering the environment inside the canister (4/6)

The conditions for evaluating the performance verification element tests for the catalysts are shown below.

Table: Conditions for evaluating the performance verification element tests for the catalysts

Item		Unit	Value	Remarks
Gas composition	**H_2**	**vol.%**	**2**	**Set a low explosion (conservative) with lower reactivity based on the lower explosion limit of hydrogen (4 vol.%)**
	O_2	vol.%	(0.25 to 1)	Adjust so that the ratio is $H_2:O_2=2:1$
	N_2	vol.%	Balance	-
Relative Humidity		**(%)**	**100**	**Implement in a saturated steam atmosphere as a conservative evaluation**
Quantity of catalyst		mL	2	The volume of the catalyst in this reaction container is derived from the ratio of the internal dimension of an actual canister to the volume of a canister in which the catalyst can be installed.
Evaluation temperature		**℃**	**10**	**For the canister transfer environment, set at a slightly lower temperature than that of the ambient environment.**
Gauge pressure		MPa-A	0.1+α, 0.2	**Use pressure (0.2 MPa) for preventing contamination during gas sampling and while supplying H_2 and O_2 gases to the normal pressure container. Implemented near normal pressure as well for conservative evaluation.**
Water-immersed catalyst		-	Yes, No	**Implement under saturated steam atmospheric conditions with and without water immersion**

Measurement items	Analysis methods
H_2 concentration, O_2 concentration	The gas is sampled from the sampling line and analyzed with gas chromatography.
Internal pressure of the reaction container	Measured with a pressure indicator (recorded with data logger)
Internal temperature of the reaction container	Measured with a thermo-couple (recorded with the data logger)

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (6/12)

③ Implementation items and results (5/10)

a. Selection of catalyst considering the environment inside the canister (5/6)

- Catalyst ① (Pellet shaped ① and with water repellency treatment) is confirmed to have a reaction rate*1 of 98% or more.
- In case of catalyst ② (Pellet shaped ②) and catalyst ⑥ (Honeycomb catalyst (Mesh: 30 cpsi)), the reaction stopped at a reaction rate of about 40%.
- As for other catalysts, the reaction rate was 10% or less.
  ⇒ The reaction is likely to be hindered due to adherence of condensate water associated with the hydrogen recombination reaction, on the surface of the catalyst.
- Catalyst ③ (used in cars) did not react even when it was not immersed in water.
  ⇒ The pore size of the honeycomb was small, so it is presumed that no reaction took place as the gas did not get diffused inside the pores under natural convection conditions.

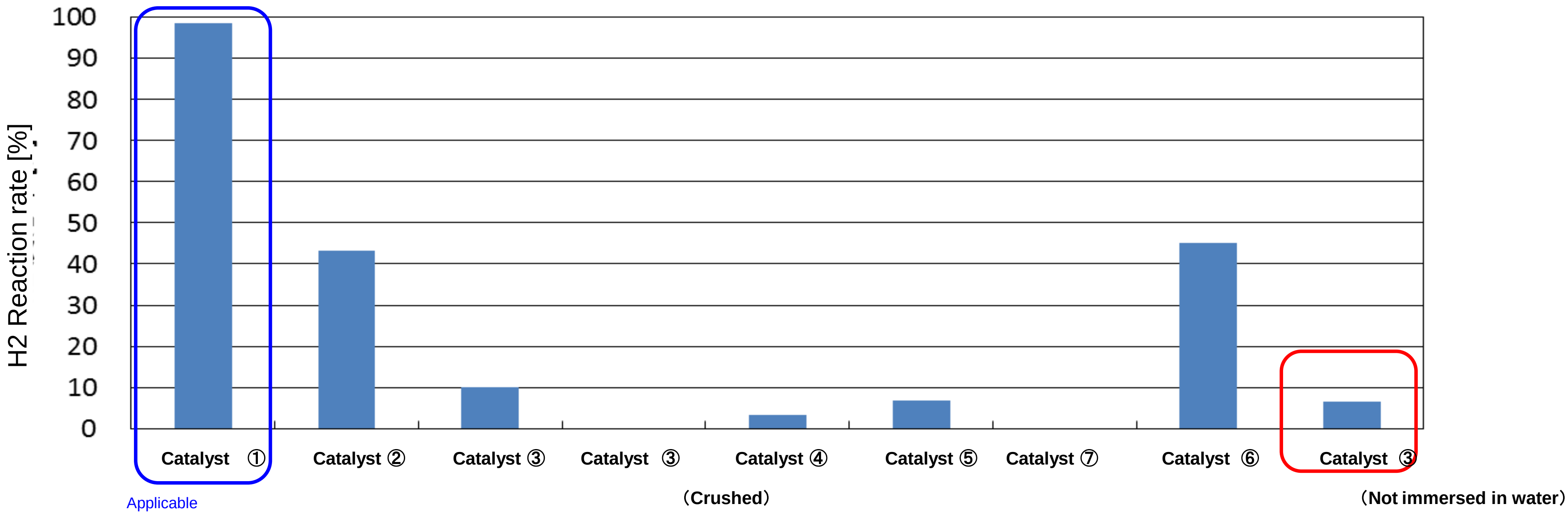


Figure: Relationship between catalyst and H_2 reaction rate

*1: Reaction rate = (Concentration of hydrogen reacting during the recombination reaction) / (Hydrogen concentration prior to the recombination reaction) [%]

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (7/12)

③ Implementation items and results (6/10)

a. Selection of catalyst considering the environment inside the canister (6/6)

Since Catalyst ① (pellet shaped and with water repellency treatment) had been treated for water repellency, it was conservatively irradiated for 10 days during the transfer period (assumed to be seven days), and the presence of a reaction was confirmed.

- It was confirmed that even after 500 kGy of gamma ray irradiation, the reaction rate was 95% or more.
- Even from the pressure change behavior, a decrease in pressure associated with the hydrogen recombination reaction was confirmed regardless of gamma ray irradiation.
- No distinct changes could be seen when the appearance before and after irradiation was compared as well.

⇒ Catalyst ① can be expected to perform even after considering the environment inside the canister.

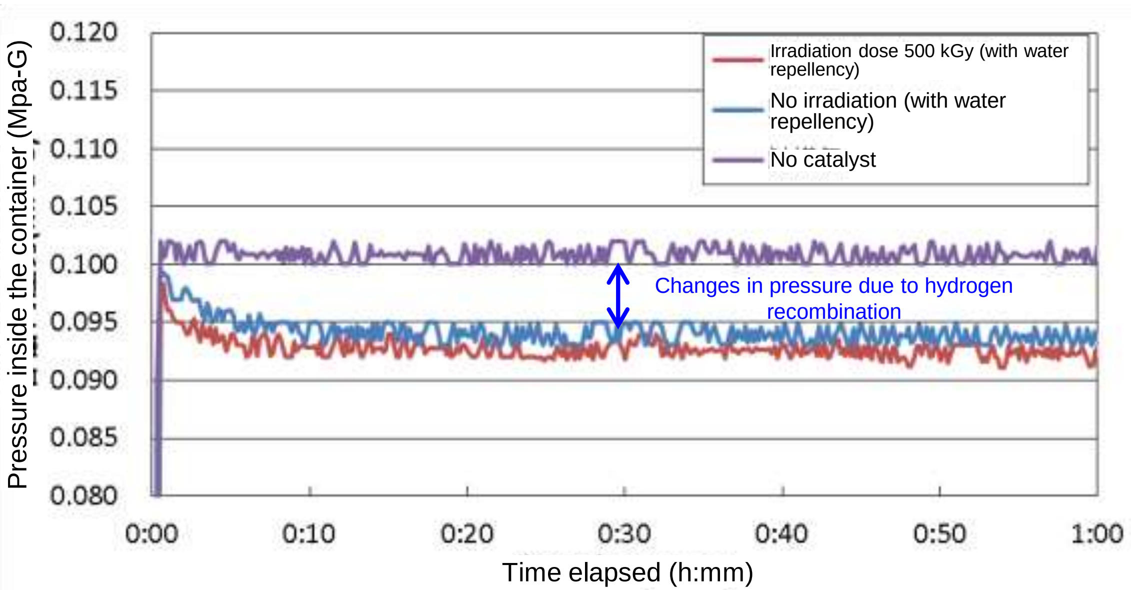
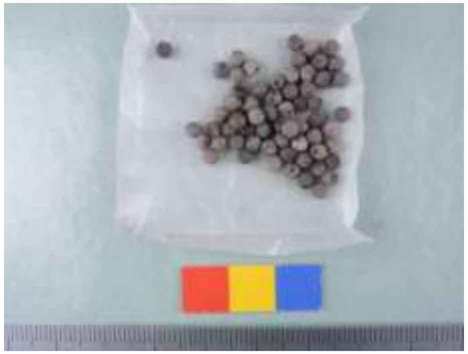


Figure: Catalyst ① Behavior of pressure inside the reaction container
(Red: There is gamma ray irradiation, Blue: There is no gamma ray irradiation)

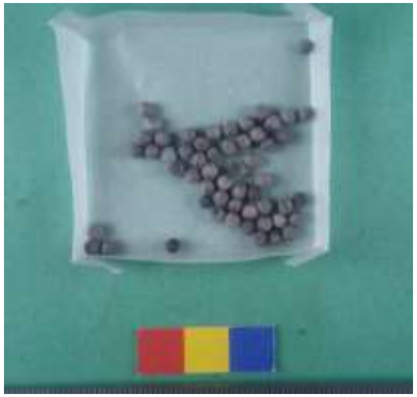
Table: Catalyst ① Gas concentration inside the reaction container

	H_2 (%)	O_2 (%)
Prior to reaction	2.1	0.9
After the reaction	<0.1	0.1

⇨ Reaction rate of 95% or more



Prior to gamma ray irradiation



After the gamma ray irradiation

Figure: Comparison of the appearance of catalyst ①

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (8/12)

③ Implementation items and results (7/10)

b. Setting of the diffusion effect (transportation effect of hydrogen on the catalyst) of the generated hydrogen considering the flow inside the canister (1/3)

・On the basis of a test conducted separately in the past (see Slide No.119), it was evaluated whether or not a flow could be expected inside the canister in the case of generation of highly concentrated hydrogen.

(Study of the required flow rate)

The amount of hydrogen generated is proportional to the amount of heat generated. Moreover, the effect of diffusion is also proportional to the flow rate. Therefore, the amount of heat generation and the required flow rate conditions in order to keep the concentration in the center of the canister at 4 vol.% or less, were organized.

<Study conditions>

・Inner height of the canister: 1.5 m

・Conditions for the amount of hydrogen generated: G-value = 0.45, Energy absorption rate = 0.6 (fine powder)

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (9/12)

③ Implementation items and results (8/10)

b. Setting of the diffusion effect (transportation effect of hydrogen on the catalyst) of the generated hydrogen considering the flow inside the canister (2/3)

[Reference] Method of deriving the necessary flow rate

When a hydrogen recombining catalyst is to be placed at both ends of the canister and it is presumed that hydrogen molecules move by diffusion alone, the hydrogen concentration in the central height of the canister is obtained by the following formula:

$$C = \frac{G}{2D}\left(\frac{H}{2}\right)^2 + C_s \quad (1)$$

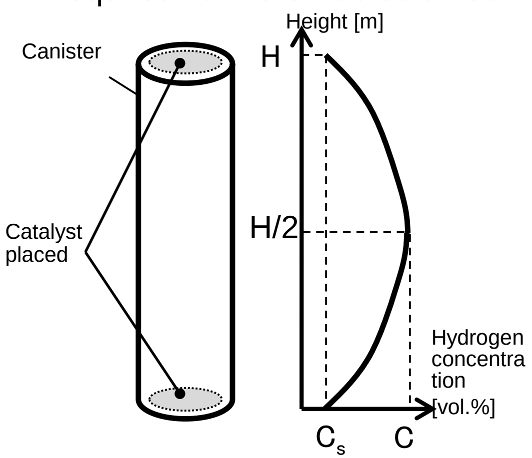
The amount of the hydrogen generated is obtained by the following formula:

$$G = \frac{Q}{V_{UC} + V_\delta} \times \frac{F}{E} \times \frac{G_e}{A_e} \times \frac{V_n}{N_A} \times 100 \qquad (2)$$

From the advection-diffusion equation, the magnitude correlation between the diffusion coefficient and the flow rate values is of the following order:

$$u = \frac{D}{H} \qquad (3)$$

The relation between the heat generation density of debris and the required flow rate was obtained from formulas (1) to (3).



(Symbols)

- C : Hydrogen concentration in the center of the canister [vol.%]
- G : Hydrogen generation rate [vol.%/s]
- D : Diffusion coefficient [m^2/s]
- H : Height of canister (=1.5 m)
- C_s : Hydrogen concentration on the surface of the catalyst [vol.%]
- Q : Amount of debris heat generation [W]
- V_{UC} : Volume [m^3] of air-space (30%) of the debris inside the UC can
- V_δ : Volume [m^3] of space in the annulus part
- F : Energy absorption rate (=0.6)
- E : Elementary electric charge (=1.6×10^{-16} J/eV)
- G_e : G value of hydrogen generation (=0.45)
- A_e : Absorbed energy (=100eV)
- V_n : Mole volume (=22.4×10^{-3} m^3/mol)
- N_A : Avogadro constant (=6×10^{23} mol^{-1})

Figure: Distribution of hydrogen concentration inside the canister

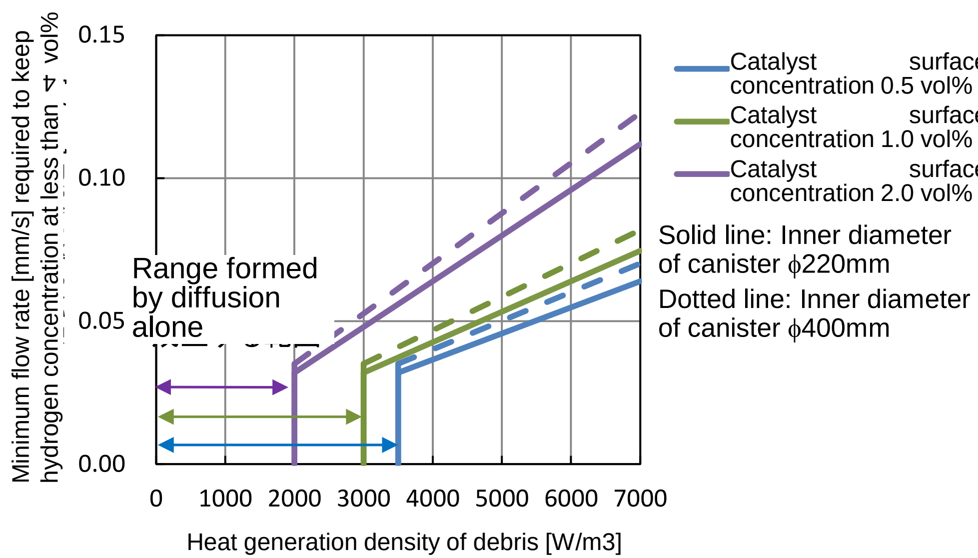


Figure: Relation between the heat generation density of debris and the flow rate

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (10/12)

③ Implementation items and results (9/10)

b. Setting of the diffusion effect (transportation effect of hydrogen on the catalyst) of the generated hydrogen considering the flow inside the canister (3/3)

・Overview of past studies

The following test devices were used to contain the flow condition data of the annulus:

Result: A flow of 2.0 mm/s was confirmed in 1000 W/m^3.

⇒ Based on the previous slide, it is revealed that this exceeds the required flow rate (0.12 mm/s) at a heat generation density that is assumed to be most severe*1, while the amount of hydrogen generated is less and the debris heat generation density (1000 W) can attain a level lower than the hydrogen concentration (4 vol%) in the canister by diffusion alone; and thus a sufficient flow can be expected.

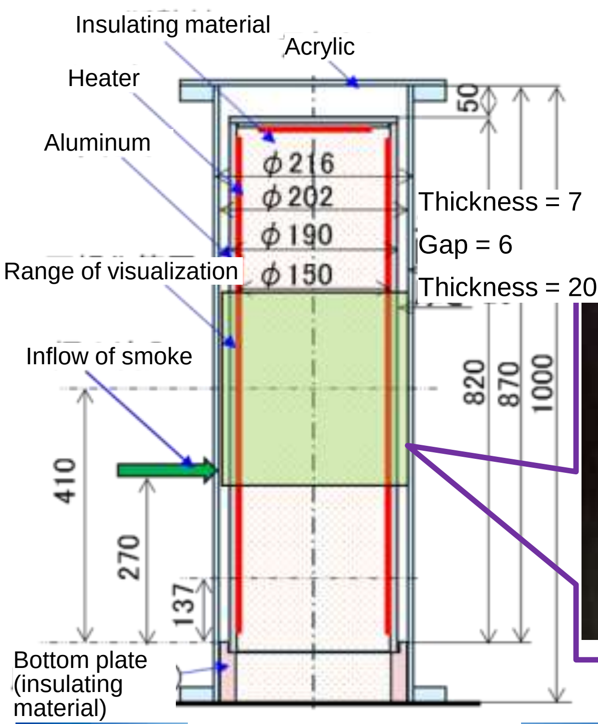


Figure: Shape of test device

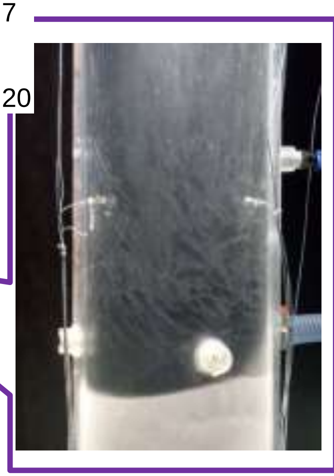


Figure: Flow status

Table: Comparison between actual canister and test device

	Item	Actual canister	test device
Canister dimensions	Inner diameter [mm]	Φ220～400	Φ202
	Annulus width [mm]	5～30	6
	Canister height [m]	0.8～4.0	0.87
	Height of upper space [mm]	50～100	50
	Canister thickness [mm]	約20(SUS)	7 (Acrylic)
Unit can	Height [m]	0.7～3.95	0.82
	Material	SUS mesh	Aluminum + heater
	Heat generation density [W/m3]	220～7000	220～6000
	Heat flux（1000、6000W/m^3）[W/m^2]	46、276	45、269
External fluid		Atmosphere	Atmosphere
Annulus pressure [MPa]		Higher than 0.1 MPa (Rise in internal pressure due to debris heating)	0.1 MPa (because of heat generation density of 220 W/m3)
Gases inside the canister		N2,He,Ar	Air

Conditions more conservative than the actual canister

・Annulus width: Equal to actual canister

・Height of test device: Lower than the actual canister (1.5 m) (Flow rate is not generated easily)

・Heat flux: Heat flux is smaller than the actual canister for the same heat generation density (Flow rate is not generated easily)

*1: When UO2 pellets of fuel assemblies with maximum burn-up (55 GWd/t) (10 years of cool down) are stored at a filling rate of 30 vol.% (Heat generation density of about 7000 W/m^3)

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (11/12)

③ Implementation items and results (10/10)

Conclusion

For a catalyst provided by the catalyst manufacturers, the transfer environment of the canister was assumed and the presence of the oxidation reaction of hydrogen was confirmed under conditions wherein the temperature was lower than the ambient temperature and the humidity was high (the initial catalyst was wet with water). As a result it was found that said catalyst undergoes oxidation reaction even in these environments and thus can be considered as a potential option.

Although this technical development is a study of ideal conditions in which the unit can is located at the center of the canister, convection sufficient to diffuse the hydrogen generated inside the canister to both ends of the canister, can be expected.

6. Implementation Details

6.3. Development of Safety Evaluation Methods and Verification of Safety

(5) Safety verification of hydrogen gas measures (Verification of measures against hydrogen) (12/12)

④ Reflection of results

These results will be studied as potential options for hydrogen measures during transfer of canisters.

⑤ Analysis from the viewpoint of applicability to the site

It is important to accumulate results pertaining to the reliability of the catalysts; therefore, for the time being, this will be studied as a backup.

⑥ Level of achievement compared to the goal

As described above, even when fuel debris equivalent to the fuel assembly pellets, which have the highest burn-up even inside a reactor, is stored, a flow without accumulated hydrogen has been confirmed, and hence it is concluded that goals have been achieved.

⑦ Future issues

It is necessary to study the catalyst in terms of its poison resistance, arrangement to place it compactly inside the canister, etc. And, with respect to the flow inside the canister, it is necessary to evaluate the impact on the conditions assumed in actual operation, such as eccentricity of unit cans, and to develop necessary measures. Furthermore, when the catalyst is placed at the bottom, water is likely to get accumulated and measures must be devised to avoid this; therefore, it is also beneficial to confirm the flow when the catalyst is placed only on the lid side.

6. Implementation Details

6.4 Study of Fuel Debris containing Methods

(1) Study of canister specifications suitable to fuel debris properties

① Purpose and goals

The basic specifications for canisters will be studied and updated for the canister type that is optimum depending on the fuel debris properties.

② Comparison with existing technologies

There are no specifications that assume the 1F fuel debris, so it is necessary to develop them taking into account the conditions unique to 1F.

③ Implementation items and results

The method of collecting powder fuel debris is being studied in the Fuel Debris Retrieval Method Project and Fundamental Technology Project, and at present, it has been decided to proceed with the study on using canisters for fuel debris blocks, regardless of the fuel debris shape (block, granular, and powder). At present, it has been confirmed that the proposed canister specifications can be applied to throughput or to the fuel debris properties and shapes.

④ Contribution of results to the technical development items

The results will help in the formulation of basic specifications corresponding to the fuel debris properties and shapes.

⑤ Analysis from the viewpoint of applicability to the site

Applicability will be determined and coordinated in the process of future implementation.

⑥ Level of achievement compared to the goal

Although in the FY2018 study, it was found that the indicators for determining the achievement of goals have been satisfied, review will continue to be carried out based on the latest study results of the related projects.

⑦ Future issues

There were no issues in the execution of the current plan.

6. Implementation Details

6.4 Study of Fuel Debris containing Methods

(2) Review of canister design (1/2)

① Purpose and goals

The canister design will be studied and updated for a canister shape that is optimum to the fuel debris properties.

② Comparison with existing technologies

There are no specifications that assume the 1F fuel debris, so it is necessary to develop them taking into account the conditions unique to 1F.

③ Implementation items and results

The method of collecting powder fuel debris is being studied in the Method Project and Fundamental Technology Project, and at present, it has been decided to proceed with the study on using canisters for fuel debris blocks, regardless of the fuel debris shape (block, granular, and powder). Proposed canister shapes reflecting the study results from Sections 6.2 and 6.3 were studied (see the next slide).

④ Contribution of results to the technical development items

The results will help to specify canister shapes corresponding to the fuel debris properties and shapes.

⑤ Analysis from the viewpoint of applicability to the site

Applicability will be determined and coordinated in the process of future implementation.

⑥ Level of achievement compared to the goal

Although in the FY2018 study, it was found that the indicators for determining the achievement of goals have been satisfied, review will continue to be carried out based on the latest study results of the related projects.

⑦ Future issues

There were no issues in the execution of the current plan.

6. Implementation Details

6.4 Study of Fuel Debris containing Methods

(2) Review of canister design (2/2)

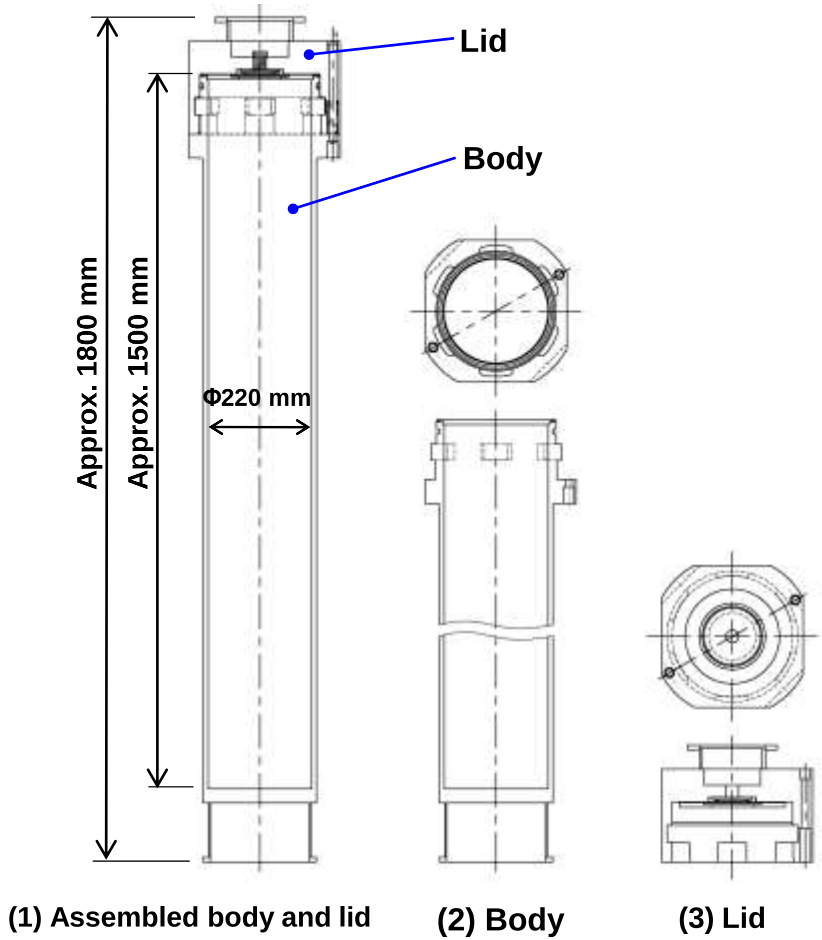


Figure: Proposed basic planned shape of a canister (lid with a simple installation structure (lid closure by rotation), inner diameter of canister 220 mm)

7. Overall Summary

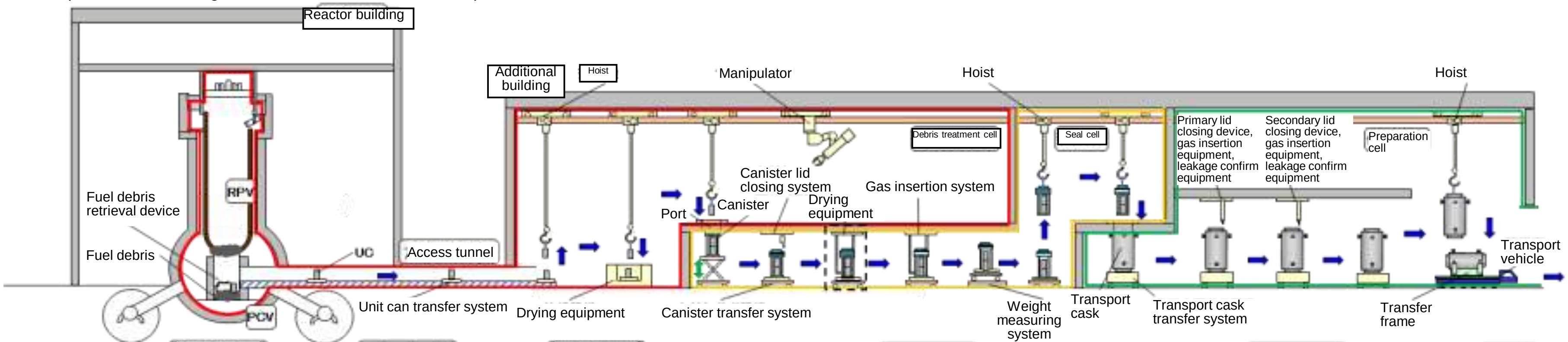
- To efficiently retrieve, collect, transfer, and store fuel debris, as provisionally determined in FY2017, a review was conducted based on the latest findings with respect to each work step and process flow.
- The evaluation method required for the safety assessment of transfer and storage system that is being conducted continuously from the previous research was verified.
- Canister specifications corresponding to the containing methods for the block, granular and powder fuel debris were established.
- Based on the above, from a more practical viewpoint, it is necessary to move on to the verification stage in the future.

<Studies needed in the future>

- Regarding the evaluation method required for the safety assessment of transfer and storage system, the canister structure verification tests will be established and the tests will be verified through implementation and evaluation. Thereafter, the results will be reflected in the canister design.
- The transfer conditions will be clarified by studying the hydrogen measurement methods and the hydrogen measures during transfer.
- The drying technology and systems will be developed by studying the drying treatment technology and the pre-storage treatment evaluation technology.
- Issues newly identified through the review of each work step and process flow etc. will be discussed with the related projects and reflected in the plans after FY2019.

[Supplement-1] Proposed Handling Procedures for Fuel Debris Canisters

After loading fuel debris into the unit can, transfer it inside building (method of accessing from the side of the nuclear reactor)



Inside Nuclear Reactor
- contain fuel debris into UC using the fuel debris retrieval device
- Transport UC to an access tunnel

Access tunnel
- Transport UC into an additional building*1

*1: Not just unit cans but fuel debris blocks and structures also go through the access tunnel to move from the nuclear reactor to the additional building. The figure shows the transportation of unit cans as a typical example.

Debris treatment cell
- Load UC into drying equipment
- Dry fuel debris

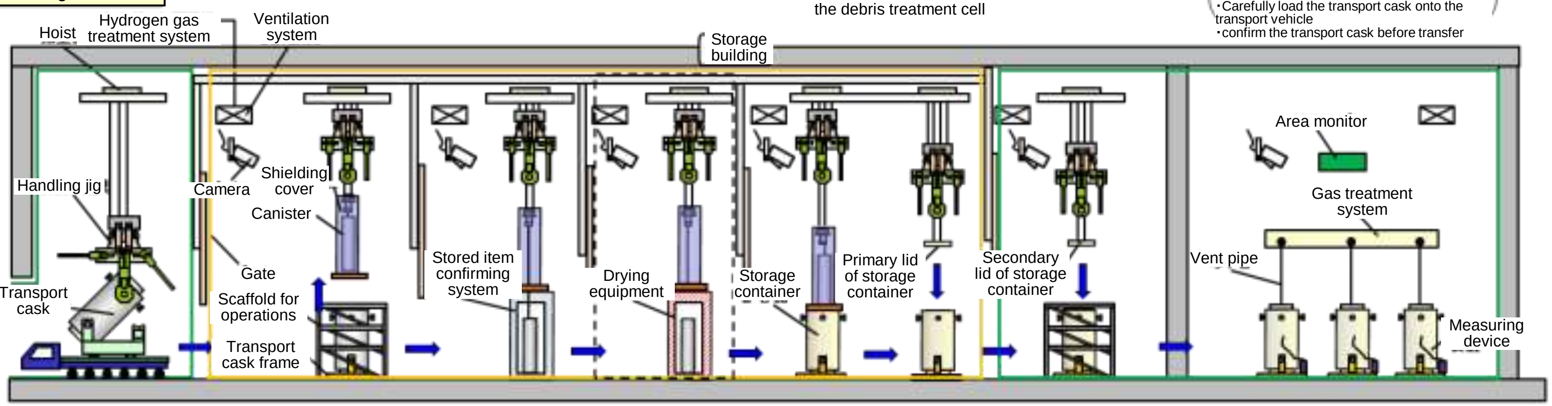
Seal cell
- Load UC into the canister
- Temporarily close the canister lid
- Move canister to the lid closing area
- Close the canister lid
- Confirm that the canister lid is closed
- (・Connect the canister to drying equipment *2)
- (・Dry canister *2)
- Connect the canister to gas insertion equipment
- Insert inert gas into the canister
- Place the canister onto the weight measuring system
- Measure the weight of canister
- Move the canister onto the port

*2: Conducted when the canister cannot be dried in the debris treatment cell

Preparation cell
- Load the canister into the transport cask
- Open canister's vent pipe
- Close the lid of transport cask (primary lid)
- Insert inert gas (Inside the cavity)
- Confirm the lid of the transport cask is closed (primary lid)
- Close the lid of the transport cask (secondary lid)
- Insert inert gas (between the primary and secondary lids)
- Confirm the lid of the transport cask is closed (secondary lid)
- Carefully load the transport cask onto the transport vehicle
- confirm the transport cask before transfer

Inside building
- Transfer inside the building

Carry in of transport cask into the storage building to storage



Storage facility entrance for large object
- Carry in transport cask through entrance for large object
- Confirm acceptance of the transport cask

Acceptance area ①
- Remove lid of transport cask (primary lid)
- (・Measure amount of hydrogen)
- Remove lid of transport cask (secondary lid)
- Close canister's vent pipe
- Take out canister from the transport cask*3

Stored item confirming area
- Load canister into stored item confirming system
- Confirm stored item

Drying area
- Load canister into drying equipment
- Dry fuel debris＊4

*4: Conduct if drying is necessary before storage

Acceptance area ②
- Load canister into the storage container
- Open canister's vent pipe
- Close primary lid of storage container
- Insert inert gas (inside cavity)
- Confirm primary lid of storage container is closed

Storage preparation area
- Close secondary lid of storage container
- Insert inert gas (between the primary and secondary lids)
- Confirm secondary lid is closed
- Confirm before storage

Storage area
- Prepare for storage
- Store

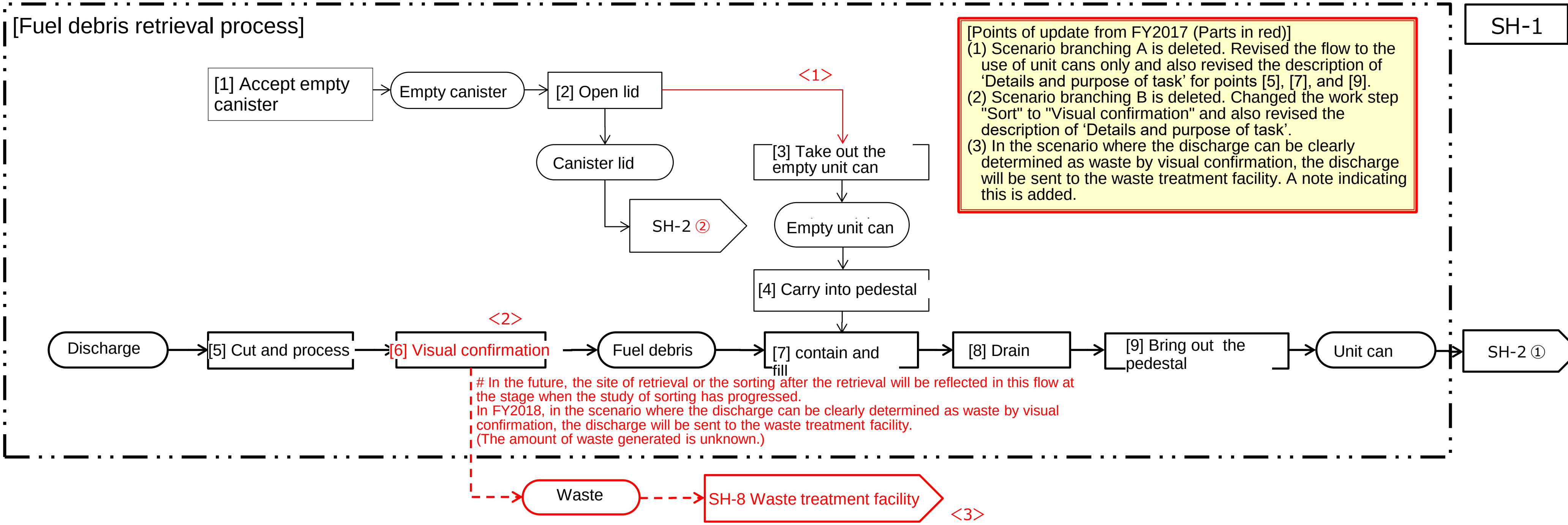
*3: Put the shielding cover on the canister and transfer

[Supplement-2] Flow of Processes (Updated Results)

<Purpose of process flow creation>

- To create a flow of a series of work steps (scenarios) involved in the containing, transfer and storage systems.
- To clarify how the work steps fit-in (interface) with the related projects by studying the related projects, such as the Fundamental Technology Project, etc., including the scope of areas that such projects are responsible for.
- To clarify the details of tasks assumed at each work step. And by doing so, to clarify the presence of any technical issues in achieving the task details, and to identify the necessary technical development items.
- To clarify the points (scenario branching) where multiple alternatives are possible in the flow of the work steps (scenarios) at the present point in time (example: whether or not fuel debris will be dried, if it is to be dried, then where will the process be executed (fuel debris retrieval building or storage facility)); and to identify the issues in studying the scenarios.
- To clarify the presence of any bottlenecks in the work steps and the need for ensuring a buffer etc. by separately evaluating the processing volume required at each work step.

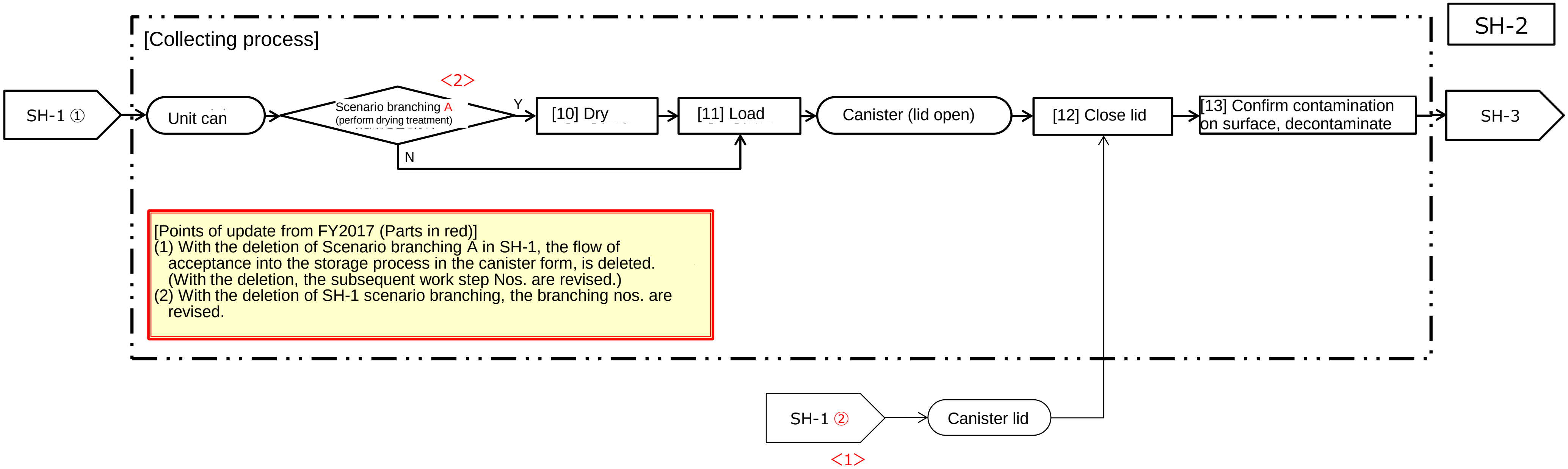
[Supplement-2] Flow of Processes (Updated Results)



No.	【1】	【2】	【3】	【4】	【5】	【6】	【7】	【8】	【9】
Handled item	Empty canister	Canister lid	Empty the unit can	Empty the unit can	Discharge	Discharge	Fuel debris	Unit can	Unit can
Details and purpose of task	Carry an empty canister in which fuel debris can be stored, in the specified position in the fuel debris retrieval storage cell.	Open the lid of the empty canister before collecting fuel debris.	From the empty canister, take out an empty unit can for storing fuel debris.	To place and store discharges, bring the unit can from the fuel debris retrieval storage cell into the pedestal and have it stand by in a predetermined position.	Cut and process the discharge into a shape and dimension that will fit in the unit can. <1>	confirm the cut and processed discharge visually. (The discharge determined as waste by visual confirmation will be transported to the waste treatment facility.) <2>	contain the fuel debris and place it in a unit can. <1>	Reduce entrained water when collecting and placing fuel debris for purposes including reduction of the amount of hydrogen generated and relaxation of the initial drying treatment conditions.	Transport the unit cans filled with fuel debris to the fuel debris retrieval storage cell that is outside the pedestal. <1>

Example of process flow: Retrieving fuel debris ~ storing in the unit can

[Supplement-2] Flow of Processes (Updated Results)

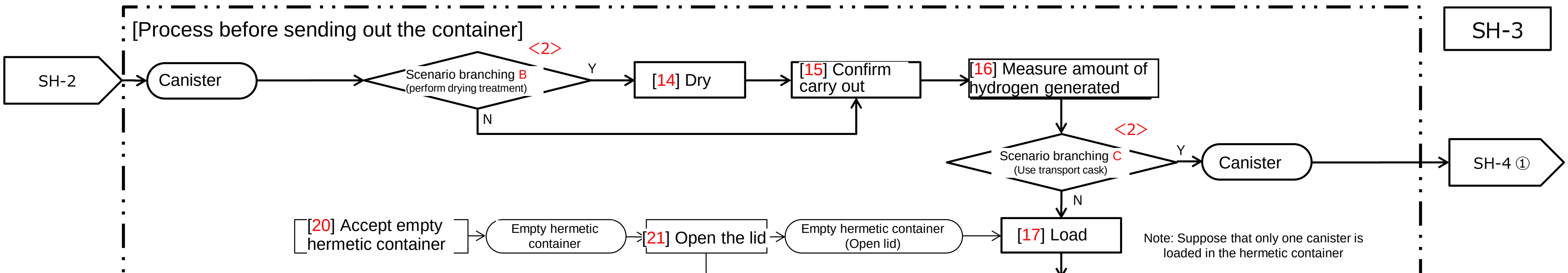


No.	【10】	【11】	【12】	【13】
Handled item	Unit can	Unit can	Canister	Canister
Details and purpose of task	Dry the entrained water and reduce the amount of water at an early stage before the unit can is stored in the canister to reduce the risk of criticality (during arrangement), risk of corrosion, the amount of hydrogen generated, etc.	Load the unit can into the canister.	Close the lid of the canister.	Confirm contamination on the surface of the cleaned canister. Decontaminate if contamination is confirmed.

Scenario branching A
[Branching details] Perform or do not perform drying treatment on the unit can form prior to placing it in the canister.
[Merits and Demerits] It is believed that as compared to the canister, the drying efficiency of the unit can is higher. Also, by carrying out the drying treatment at the unit can stage, it becomes possible to reduce the risk of hydrogen generation or corrosion etc. early on during the subsequent processes. However, since the unit can does not have the confinement function, the risk of dropping or scattering of fuel debris particles due to drying is presumed. Moreover, in addition to the drying facility, from the viewpoint of feasibility of throughput as well, it is believed that securing the space for the temporary placement of the canister is also necessary and thus securing that space becomes a prerequisite. If the debris will go through wet storage during the process, the value and necessity of drying prior to carrying the canister out, is reduced. If drying is not performed. securing the area is not necessary and there is no impact on feasibility of throughput. However, the risk of hydrogen generation etc. needs to be considered on an ongoing basis.

Example of process flow: Storing the unit can in the canister ~ closing the lid of the canister
(Work step [No.11] onwards illustrates "Storing")

[Supplement-2] Flow of Processes (Updated Results)



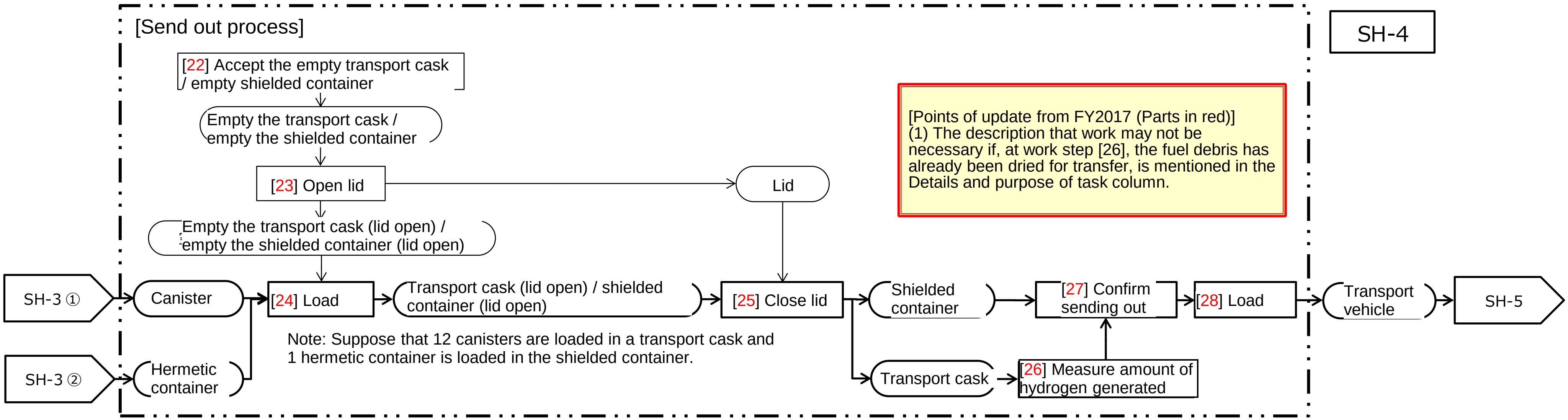
[Points of update from FY2017 (Parts in red)]
(1) The description that work may not be necessary if, at work step [16], the fuel debris has already been dried for transfer, is mentioned in the Details and purpose of task column.
(2) With the deletion of SH-1 scenario branching, the branching nos. are revised.
(3) The execution of confinement inspection is added in work step [18].

No.	【14】	【15】	【16】	【17】	【18】	【19】	【20】	【21】
Handled item	Canister	Canister	Canister	Canister	Hermetic container lid	Hermetic container	Empty hermetic container	Hermetic container lid
Details and purpose of task	Dry the entrained water and reduce the amount of water to reduce the risk of criticality (during arrangement), risk of corrosion, the amount of hydrogen generated, etc.	On carrying out the canister to the storage facility, confirm the canisters to contain and link data and conditions of each canister (mass measurement, surface dose rate measurement, visual inspection (including verification of canister ID).	Measure the amount of hydrogen generated to confirm that the hydrogen concentration inside the canister will not reach the lower explosion limit within a specified time when transferring to the storage facility. (If the debris has already been dried, then this may not be required.) <1>	Load the canister into the hermetic container.	Close the lid of the hermetic container. After closing the lid, implement confinement inspection (Example: Leak confirm) <3>	After loading the canister, confirm for contamination on the surface of the hermetic container. Decontaminate if contamination is confirmed.	To ensure the container's fuel confinement property (including gas) at an early stage, carry in the empty hermetic container, that seals the canister, to a specified position.	Open the lid of the empty hermetic container before sealing in the canister.

Scenario branching B	Scenario branching C
[Branching details] Perform or do not perform drying treatment on the canister form prior to carrying out the container.	[Branching details] Store the container in a dual container (hermetic container + shielded container) that share the functions between the two or store the canister in the transport cask only (double lid).
[Merits and Demerits] Drying prior to carrying out the canister, can reduce risk especially from the perspective of hydrogen generation. Note that, if the drying process is performed prior to carrying out the canister, then in addition to the drying facility, from the viewpoint of feasibility of throughput as well, it is believed that securing the space for the temporary placement of the canister is also necessary and thus securing that space becomes a prerequisite. Moreover, if the debris will go through wet storage during the process, the value and necessity of drying prior to carrying the canister out, is reduced. It is presumed that drying will be difficult compared to that for the unit can. If drying is not performed, securing the area is not necessary and there is no impact on feasibility of throughput. However, the risk of hydrogen generation etc. needs to be considered on an ongoing basis.	[Merits and Demerits] By storing the canister in dual containers, it is possible to ensure dual boundaries even during transfer in 1F. Moreover, the function of confinement of fuel debris containing gas is allocated to the hermetic canister while the shielding function is allocated to the shielded container respectively, but both have confinement and shielding functions to a certain extent, so even if there is a failure in any one of the containers, a certain extent of mitigation of impact can be expected from the other container that is intact. Meanwhile, two different types of containers become necessary for operations. Since the work of storage in the containers has to be done twice, throughput feasibility is hampered. In the case of the transport cask, since there is only one container, the storage work is done only once and therefore the impact on the throughput feasibility is less. However, since it cannot be strictly said that a dual boundary has been configured, if there is any failure, there is a possibility of losing the confinement as well as the shielding function at the same time.

Example of process flow: Confirming of the closed canister ~ preparation of transferring the canister

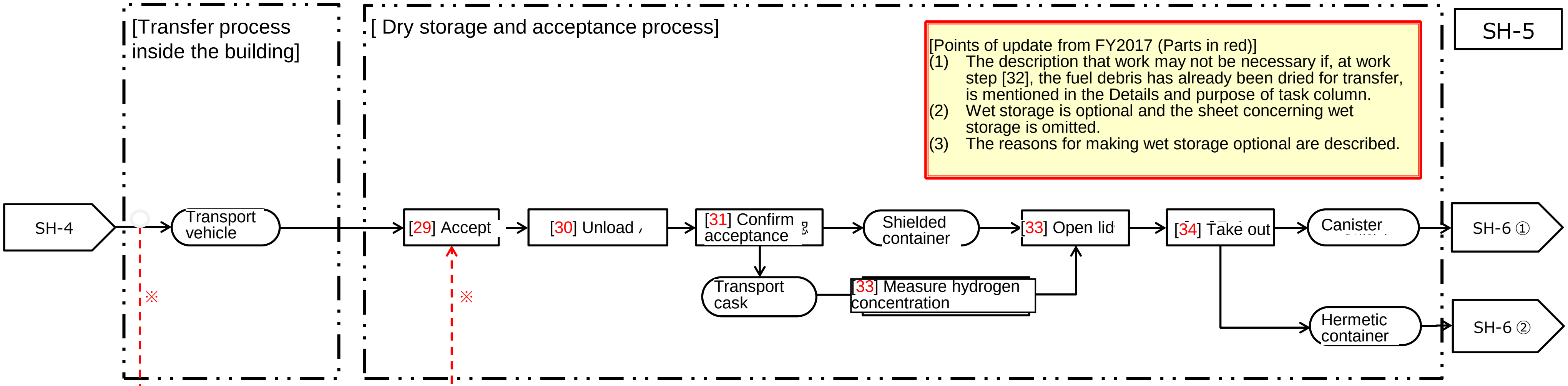
[Supplement-2] Flow of Processes (Updated Results)

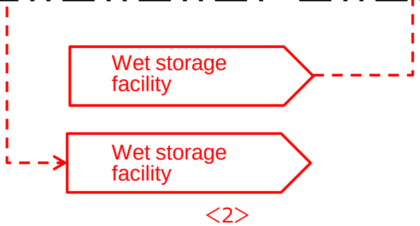


No.	【22】		【23】		【24】		【25】		【26】	【27】		【28】	
Handled item	Empty the transport cask	Empty the shielded container	Transport cask lid	Shielded container lid	Canister	Hermetic container	Transport cask lid	Shielded container lid	Transport cask	Transport cask	Shielded container	Transport cask	Shielded container
Details and purpose of task	On transferring the canister / hermetic container to the storage facility, carry in the transport cask / shielded container for external transportation to a specified position.		Open the lid of the container before storing the canister / hermetic container in the transport cask / shielded container. (Open both the primary and secondary lids of the transport cask.)		Load a specified number of canisters / hermetic containers in the transport cask / shielded container.		Once the specified number of canisters / hermetic containers are loaded, close the lid of the transport cask / shielded container. (Close both the primary and secondary lids of the transport cask.)		On sending out the container, measure the amount of hydrogen generated per transport cask, and confirm that the hydrogen concentration will not reach the lower explosion limit within the specified time. (If the debris has already been dried, then this may not be required.) <1>	On transporting the container inside the premises of 1F, confirm the containers for any problem (confinement confirmation, inspection for contamination on surface, decontamination, surface dose rate measurement, visual inspection (including confirmation of canister ID)).		Load and secure the transport cask / shielded container onto the transport vehicle.	

Example of process flow: Loading the canister ~ preparation for sending out the transport cask
(Work step [No.28] onwards illustrates "Transfer")

[Supplement-2] Flow of Processes (Updated Results)





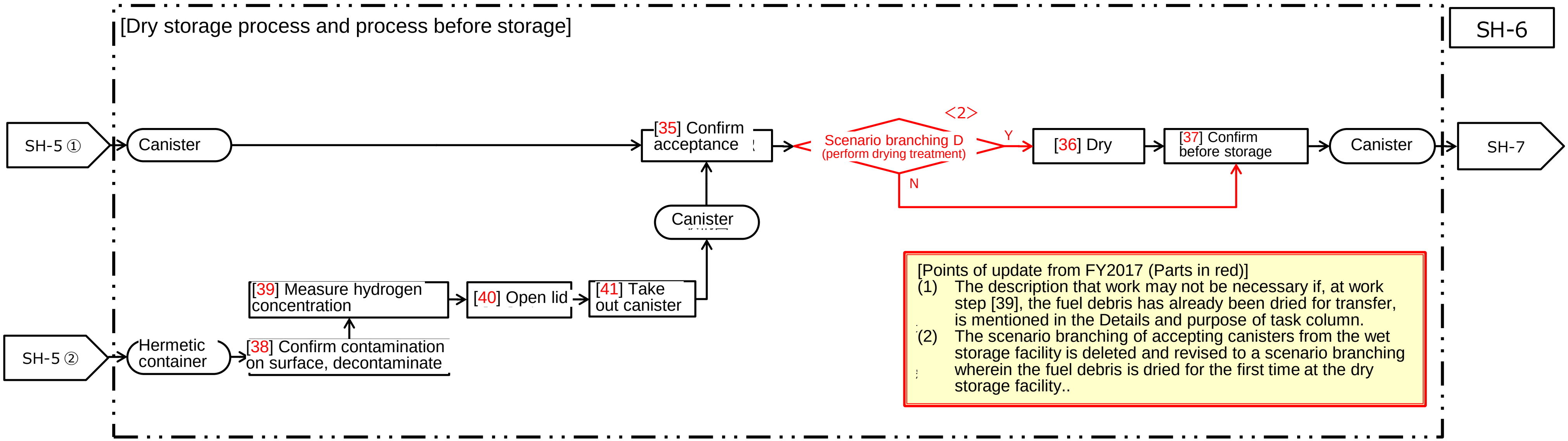
<3>

#The wet storage using the existing pool at 1F has low effectiveity from the following viewpoints and is considered optional.
・If the existing pool at 1F (example: 1F-6, SFP) is to be remodeled and used, then it becomes necessary to secure an alternative storage location for the spent fuel currently in storage.
・The canister storage capacity that can be secured is limited (depending on the storage form of canisters (flat or stacked)).
・Measures (reinforcement of purification function, leakage measures) etc. are necessary assuming the discharge of fuel debris components (especially alpha nuclides) from the canisters into the pool water.
If these assumed remodeling details, period, expenses or technical difficulties in remodeling are taken into account, temporary (short-term) wet storage has low effectiveity due to redirection of the use of the existing 1F pool.
(If wet storage is to be adopted, it is necessary to plan and study a new facility on the premise of long-term storage, for 10 years at a time, focusing on the start of full-scale retrieval of fuel debris.)

No.	【29】		【30】		【31】		【32】	【33】		【34】	
Handled item	Transport cask	Shielded container	Transport cask	Shielded container	Transport cask	Shielded container	Transport cask	Transport cask lid	Shielded container lid	Canister	Hermetic container
Details and purpose of task	Accept the transport vehicle with the transport cask / shielded container into the dry storage facility.		Unload the transport cask / shielded container from the transport vehicle to specified location.		Confirm the accepted transport casks / shielded containers for any problem (inspection for contamination on surface, decontamination, surface dose rate measurement, visual inspection (including confirmation of canister ID)).		On opening the transport cask lid, measure the amount of hydrogen generated inside the cask, and confirm that the hydrogen concentration has not reached the lower explosion limit. (If the debris has already been dried, then this may not be required.) <1>	Open the lid of the transport cask / shielded container. (Open both the primary and secondary lids of transport casks).		Take out the canister / hermetic container from the transport cask / shielded container.	

Example of process flow: Transfer on site ~ receiving canister into dry storage facility ~ taking out canister (Work step [No.29] onwards illustrates "Storage")

[Supplement-2] Flow of Processes (Update Results)



[Points of update from FY2017 (Parts in red)]

(1) The description that work may not be necessary if, at work step [39], the fuel debris has already been dried for transfer, is mentioned in the Details and purpose of task column.

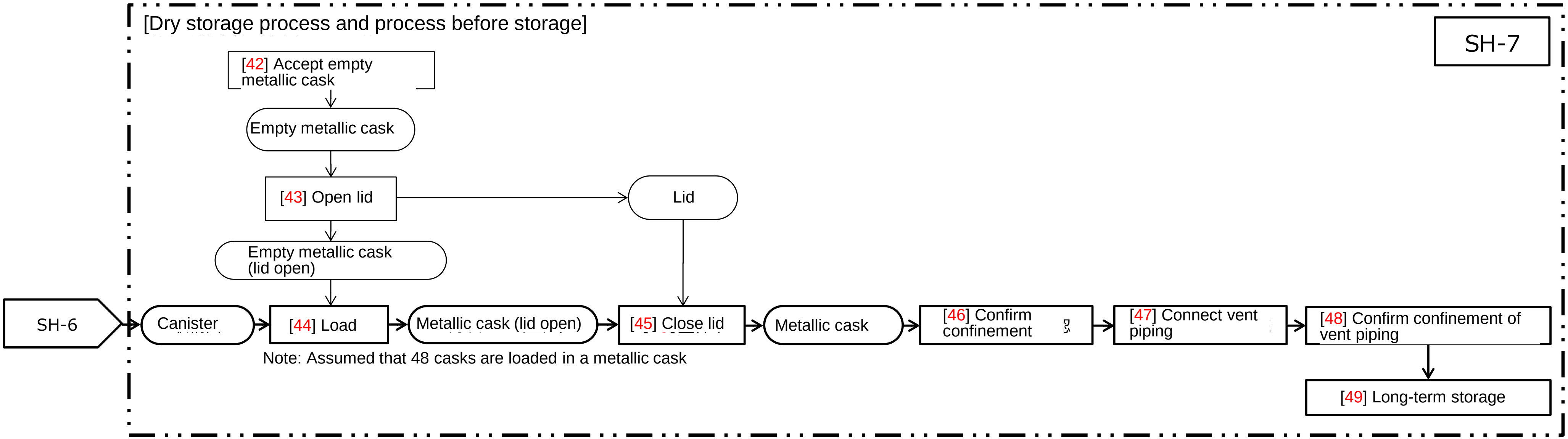
(2) The scenario branching of accepting canisters from the wet storage facility is deleted and revised to a scenario branching wherein the fuel debris is dried for the first time at the dry storage facility..

No.	【35】	【36】	【37】	【38】	【39】	【40】	【41】
Handled item	Canister	Canister	Canister	Hermetic container	Hermetic container	Hermetic container lid	Canister
Details and purpose of task	Confirm the accepted canister for any problem (inspection for contamination on surface, decontamination, surface dose rate measurement, visual inspection (including confirmation of canister ID)).	Dry out the water inside the canister to reduce the amount of hydrogen generated, risk of corrosion, etc.	On storing the canister, confirm the canister for any problem (mass measurement, inspection for contamination on surface, decontamination, surface dose rate measurement, visual inspection (including confirmation of canister ID)).	confirm for any contamination on the surface of the accepted hermetic container. Decontaminate if contamination is confirmed.	On opening the lid of the hermetic container, measure the amount of hydrogen generated inside the container, and confirm that the hydrogen concentration has not reached the lower explosion limit. (If the debris has already been dried, then this may not be required.) <1>	Open the lid of the hermetic container to take out the canister.	Take the canister out from the hermetic container.

Scenario branching D
[Branching details] Perform drying treatment at the dry storage facility for the first time or Do not perform drying treatment as it has already been implemented.
[Merits and Demerits] Since the dry storage facility is new, securing the area and installing facilities will be easier than at the carrying out side (inside the reactor building or the additional building). Meanwhile, it is believed that a canister is more difficult to dry due to its shape as compared to the unit can and therefore, there is a possibility that at the time of drying, it may be necessary to open the lid of the canister and remove the unit can. Moreover, since the drying treatment is not implemented before carrying out, there will be the issue of managing the hydrogen concentration (to prevent it from exceeding 4%) during transfer on site.

Example of process flow: Confirmation of acceptance of canister ~ confirmation before storage

[Supplement-2] Flow of Processes (Update Results)



No.	[42]	[43]	[44]	[45]	[46]	[47]	[48]	[49]
Handled item	Empty metallic cask	Metallic cask lid	Canister	Metallic cask lid	Metallic cask	Metallic cask	Metallic cask	Metallic cask
Details and purpose of task	Carry in an empty metallic cask in which the canister will be stored for a long period, to the specified position.	Open the lid of the empty metallic cask before storing canisters.	Load a specified number of canisters inside the empty metallic cask.	Once the specified number of canisters are loaded, close the lid of the metallic cask.	Confirm that the metallic cask satisfies the specified confinement function.	Connect the vent piping to the metallic cask. The piping releases gas inside the metallic cask outside in a managed manner.	Confirm that the vent pipe connected to the metallic cask satisfies the prescribed confinement function.	Store the canister inside the metallic cask in a stable state for a long period of time

Example of process flow: Preparation for dry storage ~ dry storage*1

*1: Describes the process flow proposal when assuming that a metallic cask is used to store the canisters.
As of FY2018, the canister storage method has not been decided. In the future, it will be necessary to revise the process flow according to the storage method.

[Supplement-3] Technical Requirements for Wet and Dry Storage (1/5)

[Study results up to FY2016]

The safety functions that must be provided in the containing, transfer and storage systems for handling fuel debris have been set up as shown in the following table.

Table: Safety functions to be provided in the containing, transfer and storage systems

Safety Functions		Required Safety Functions
Sub-criticality		Maintenance of sub-criticality
Cooling	Heat removal	Handling at or below the maximum temperature of fuel debris so as not to impede safety (generation of toxic gases, etc.)
Confining	Shielding	Prevention of exposure of workers and public to radiation
	Confinement	Prevention of exposure of workers and public caused due to discharge of radioactive materials
Functions required for maintaining the safety functions of shut down, cooling and confinement	Structure	Appropriate structural strength to maintain the necessary safety functions while taking handling etc. into consideration
	Hydrogen	Prevention of explosion of hydrogen generated due to radiolysis of water caused by the radiation from fuel debris (prerequisite for maintaining the structural strength)
	Aging degradation	Maintenance of structural strength etc. against corrosion during storage (prerequisite for maintaining the structural strength)
	Prevention of fire	Fire prevention using powdered metals such as zircalloy etc. (prerequisite for maintaining the structural strength)

[Supplement-3] Technical Requirements for Wet and Dry Storage (2/5)

[Study results up to FY2016]

The share of safety functions of other equipment, pertaining to the safety functions that must be provided in the containing, transfer and storage systems for handling fuel debris, has been established as described in the following table.

Table: Share of safety functions to be provided in the containing, transfer and storage systems (1/2)

Safety Functions		Design Targets	Share of Safety Functions		Approach
			Canister	Other equipment	
Sub-criticality		Maintenance of sub-criticality	○	○	It is more reasonable that maintenance of the geometric shape, which is a sub-criticality condition, be handled with containers (canisters) having a common handling mode. (Refilling of fuel debris is a major task) During arrangement, sub-criticality shall be maintained using other equipment.
Cooling	Heat removal	Ensuring the properties of canisters, fuel debris, etc.		○	Since the amount of heat generation is less than the same level of spent fuel and as the canister can be cooled by static natural cooling, no special heat removal device, etc. is provided.
Confining	Confinement	Prevention of worker and public exposure		○	The canister must have an opening to prevent accumulation of hydrogen. Filters are installed to prevent the spread of contamination during actual operations, but from the viewpoint of a robust boundary, no confinement function is required for safety evaluation.
	Shielding	Prevention of worker and public exposure		○	Adding a shielding function to the canister increases the weight, leading to an increase in the size of the handling equipment and a reduction in storage efficiency. This has been seen at TMI-2 as well. But there are no significant disadvantages with respect to the assumed handling flow.

The share of safety functions may be revised as it is influenced by the fuel debris properties and the canister handling procedures.

[Supplement-3] Technical Requirements for Wet and Dry Storage (3/5)

[Study results up to FY2016]

The share of safety functions of other equipment, pertaining to the safety functions that must be provided in the containing, transfer and storage systems for handling fuel debris, has been established as described in the following table.

Table: Share of safety functions to be provided in the containing, transfer and storage systems (2/2)

Safety Functions		Design Targets	Share of Safety Functions		Approach
			Canister	Other equipment	
Other (Maintenance of shut down, cooling and confinement functions)	Structure	Structural strength to maintain safety functions	○	○	Minimum strength needs to be maintained for the effective canister handling equipment, etc. Moreover, the loading and corrosion conditions of canisters will be eased by other equipment.
	Material integrity	Maintenance of structural strength, etc.	○	○	
	Hydrogen	Prevention of explosion of hydrogen generated by radiolysis of water	○ (Catalyst)	○	Since the space inside the canister is small and the hydrogen concentration rises, as a mechanism to discharge hydrogen outside of the canister, scavenging, etc. is performed by another equipment.
	Prevention of fire	Fire prevention with residual zirconium		○	Maintenance of an inert atmosphere and flooding conditions cannot be added for a canister. (Because it does not have the confinement function)

The share of safety functions may be revised as it is influenced by the fuel debris properties and the canister handling procedures.

[Supplement-3] Technical Requirements for Wet and Dry Storage (4/5)

[Study results up to FY2016]

The validity of the share of safety functions for wet transfer and wet storage of the 1F fuel debris was confirmed by comparing with the results of TMI-2.
Excluding confinement, the approach is the same as that for 1F.
The wet storage building at TMI-2 does not have the boundary function and flooding inside the canister is the only boundary for discharge into the environment. At 1F, buildings are provided with the boundary function, even the gas inside the canister is discharged after treatment and the discharge is monitored.

Table: Comparison between the share of safety functions at TMI-2 and 1F for wet transfer and wet storage

Safety Functions		Design Targets	TMI-2		1F	
			Canister	Other equipment	Canister	Other equipment
Sub-criticality		Maintenance of sub-criticality	In case of single canister	Transport cask basket and pool rack in case of arrangement of multiple canisters	Same as TMI-2	
Cooling	Heat removal	Ensuring the properties of canisters, fuel debris, etc.	Natural cooling	Transport cask natural cooling / pool cooling equipment	Same as TMI-2	
Confining	Confinement	Prevention of worker and public exposure	Transfer: No	Transfer: Transport cask / building	Same as TMI-2	
			Storage: Flooding inside the canister	None	Internal: Flooding inside the canister, vent pipe	Internal: Cell or pool External: Building gas treatment
	Shielding	Prevention of worker and public exposure	No	Transport cask / building / pool water	Same as TMI-2	

[Supplement-3] Technical Requirements for Wet and Dry Storage (5/5)

[Study results up to FY2016]

The validity of the share of safety functions for drying / dry storage of the 1F fuel debris was confirmed by comparing with the results of TMI-2.

Excluding confinement, the approach is the same as that for 1F.
During wet storage at TMI-2, gas is discharged via the canister and cask filter.
At 1F, a boundary function is provided even for external buildings etc. and the gas is treated, taking into account contamination while connecting the vent pipe. The process is monitored as well.

Table: Comparison between the share of safety functions at TMI-2 and 1F for drying / dry storage

Safety Functions		Design Targets	TMI-2		1F	
			Canister	Other equipment	Canister	Other equipment
Sub-criticality		Maintenance of sub-criticality	Single canister	Basket (arrangement)	Same as TMI-2	
Cooling	Heat removal	Ensure the properties of canisters, fuel debris, etc.	Natural cooling	Storage module	Same as TMI-2	Storage container
Confining	Confinement	Prevention of worker and public exposure	Filter*1	Canister (Filter)	(Filter)	Gaseous waste treatment system / storage building
	Shielding	Prevention of worker and public exposure	No	Storage module	No	Storage container

***1: The filter inside the canister in a filter-type canister ensures this function, and therefore, filter is not attached to the vent or drain hole.**

[Supplement-4] Study of sub-criticality maintenance evaluation method (1/3)

① Relation of the inner diameter of a canister with the moisture content and relation of the inner diameter of a canister with fuel debris enrichment

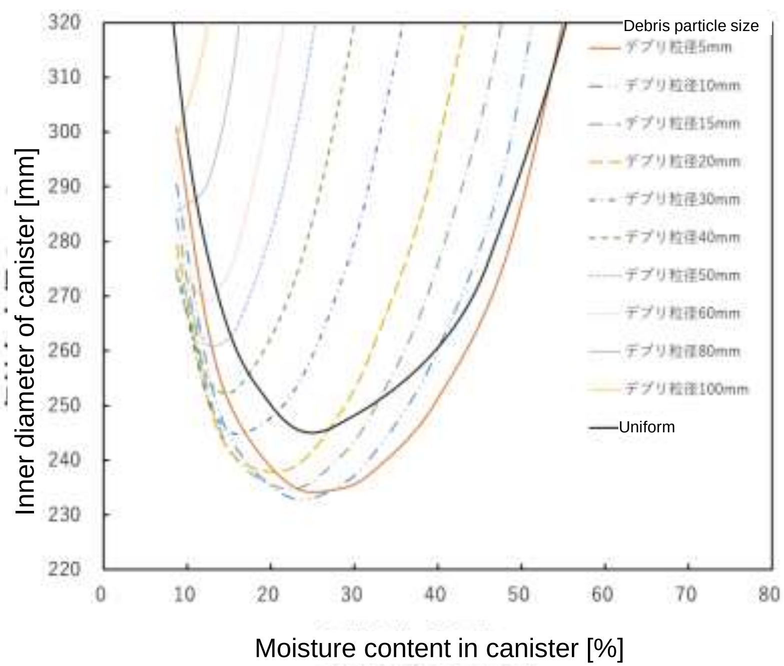
(1) The inner diameter of a canister was evaluated with respect to the moisture content by changing the particle size of the fuel debris.

(2) Assuming that fuel debris enrichment could be understood, the maximum radius was evaluated with respect to the enrichment.

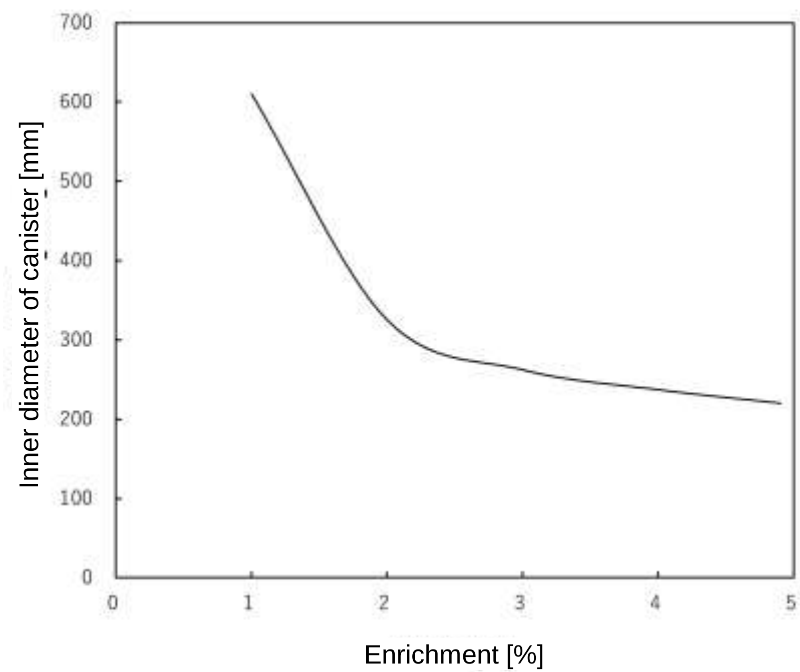
<Evaluation results>

(1) Sub-criticality could be maintained by using a canister with an inner diameter of about 220 mm irrespective of the fuel debris particle size or moisture content.

(2) In order to make the inner diameter of the canister 400 mm, the fuel debris enrichment must be less than 1.7 wt%.



(1) Relation of the inner diameter of a canister with the moisture content based on each particle size of fuel debris (Non-homogeneous model)



(2) Relation of the inner diameter of a canister with fuel debris enrichment (Homogeneous model)

[Supplement-4] Study of sub-criticality maintenance evaluation method (2/3)

② Criticality evaluation assuming dry storage (infinite array condition)

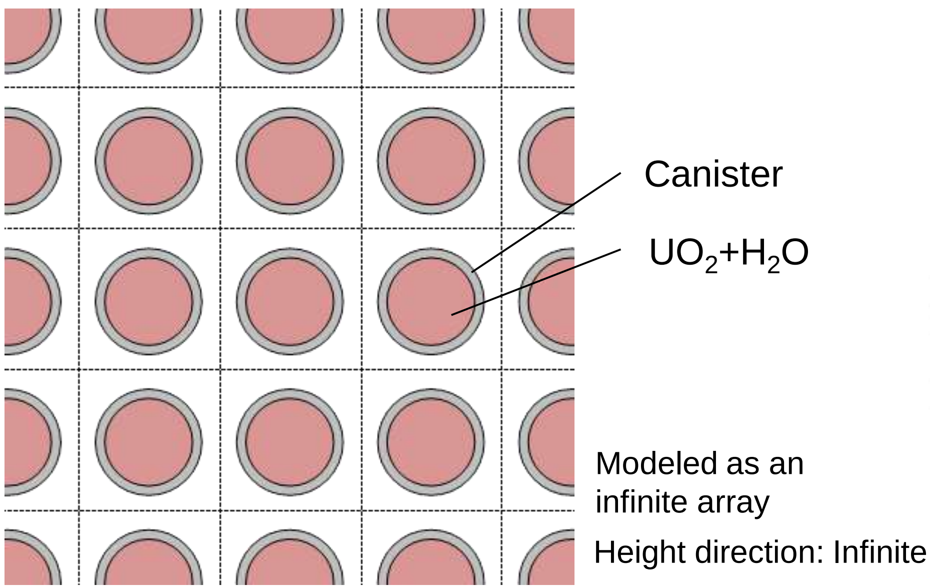
Assuming dry storage, criticality evaluation was performed by modeling a situation where an infinite number of canisters were arranged.

<Evaluation conditions>

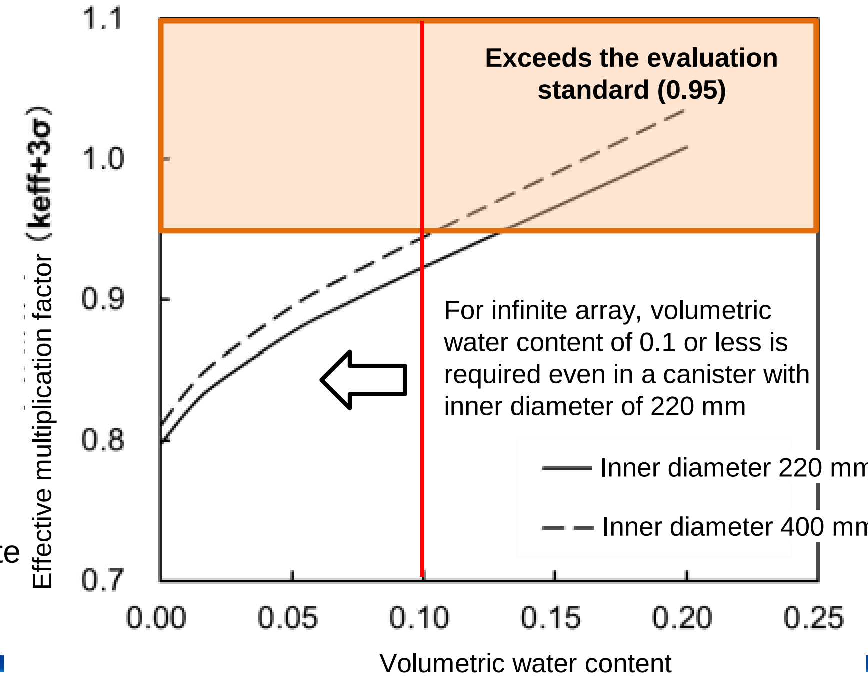
- Assumed that fuel (uranium enrichment of about 4.9 wt%) and water (residual water after drying treatment) are an even and homogeneous mixture.
- Assumed that the volumetric water content is reduced to 0.2 or less by sufficient drying.
- As a condition for safety, a model of canisters arranged in an infinite array was created (see the Computational model below)

<Evaluation results>

Even with a canister with an inner diameter of 20 mm, which can maintain sub-criticality on its own, the effective multiplication factor will increase when multiple canisters are arranged. Under the conditions in this evaluation, even if the inner diameter of the canister is 220 mm, moisture needs to be removed by drying treatment down to a volumetric water content of 0.1 or lower (margin considered) to maintain sub-criticality.



<Computational model >



[Supplement-4] Study of sub-criticality maintenance evaluation method (3/3)

③ Criticality evaluation assuming dry storage (finite array condition)

Assuming temporary canister storage, a criticality evaluation was performed by modelling a situation where a finite number of canisters were arranged.

<Evaluation conditions>

- Assumed that fuel (uranium enrichment of about 4.9 wt%) and water (residual water after drying treatment) are an even and homogeneous mixture.
- Assumed that volumetric water content is reduced to 0.2 or less by sufficient drying.
- Assuming temporary storage, a model of canisters arranged in a finite array (10 x 10 array) was created

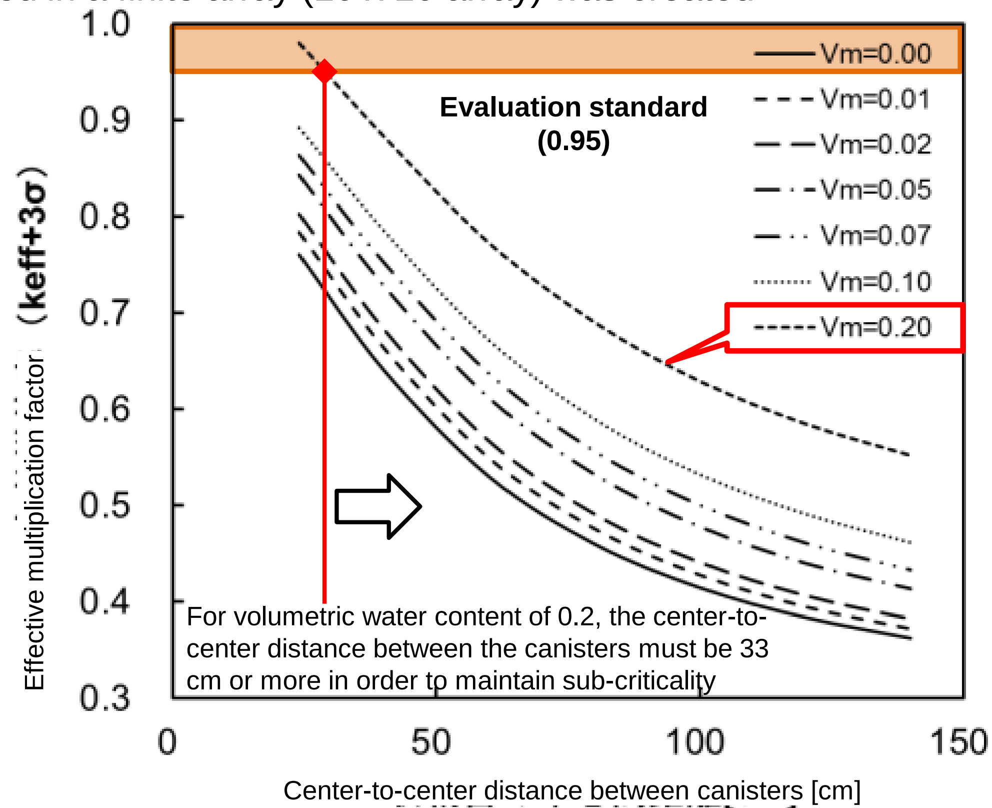
<Evaluation results>

When volumetric water content is 0.2 for canisters with inner diameters of 220 mm, if center-to-center distance of 33 cm or greater is ensured between the canisters, sub-criticality can be maintained in a 10 x 10 arrangement as well.

Meanwhile, if volumetric water content can be reduced to 0.1 or less, canisters can be placed side by side in contact with each other (maximum area efficiency).

The results showed that the storage efficiency[*1] in this case did not depend on the inner diameter and was about 0.7[*2].

*1: Storage efficiency is the area occupied in the canister per unit area
*2: Assume that the thickness of the canister is 10 mm



(Example of a canister with inner diameter of 220 mm, 10 x 10 array system)

[Supplement-5] Preconditions of the Study (1/3)

For the canisters specified in this technical development, the canister specifications were mainly established from the viewpoint of safety evaluation based on the information on the fuel debris properties obtained at that point of time and the requirements from the Fuel Debris Retrieval Method Project and the Fundamental Technology Project. In the future, the specifications will be revised by reflecting the results of the achievements of the Fuel Debris Characterization Project, Fundamental Technology Project, and Fuel Debris Retrieval Method Project. When specifying the shape of the canisters, the following conditions were presumed based on the information etc. provided by the Fuel Debris Characterization Project Team.

[Fuel debris properties]

- Composition of fuel debris (excluding MCCI products):
  Uranium dioxide (includes FP associated with irradiation), zirconium alloys, stainless steel, low alloy steel, nickel-based alloys, concrete, B_4C and sea-water.
- Salinity
  About 100 ppm max. (salinity of stagnant water was set conservatively between 10 to 20 ppm)
  ⇒ Assumed more realistically to be about 3 ppm during the corrosion evaluation.
- Zirconium
  Traces remain in a metallic form (considering the possibility of fire)
- Properties of MCCI products
  Products resulting from concrete mixed with the above-mentioned fuel debris (physical turbidity of concrete components is presumed for evaluation although it is believed that there were reactions such as loss of crystal water and gas generation, etc. due to heat from the fuel debris.)
- Stability of fuel debris (stability in -20 to 300°C (nitrogen atmosphere) environment)
  It is assumed that behavior greatly affecting safety, such as a large change in volume due to vaporization of components included in the fuel debris, and release of a large amount of corrosive substances and radioactive gases, does not occur. (The materials are assumed to have been stabilized in the above-mentioned environment)
- Shapes
  Block, granular or powdered solids
- Corrosion inhibitor and neutron absorber
  Sodium pentaborate, etc. (response discussed as and when required)

[Supplement-5] Preconditions of the Study (2/3)

When specifying the shape of the canisters, the following conditions were presumed based on the opinions of the Fundamental Technology Project Team, the Fuel Debris Retrieval Method Project Team and experts.

[Fuel debris containing methods]

- Block and granular fuel debris
  Fuel debris will be contained by means of griping, scooping, etc. and then stored.
- Powdered form of fuel debris
  The fuel debris will be contained in a type of unit can such as a mesh-like can placed inside a canister, and then stored in the fuel debris canister.
  (From the viewpoint of collecting powdered fuel debris efficiently, a study will be conducted presuming a filter cartridge the size of which is appropriate to be stored inside a canister, and issues will be identified from the perspective of containing.)
  Note that the filter must have thermal stability, such as a sintered stainless steel mesh, etc.
- Containing location
  There must be no flooding during containing work. The work should be carried out in spaces with boundaries such as hot cells etc.
- Fuel debris containing ~ carry out procedures
  During the work related to fuel debris retrieval, half the day will be allocated to cutting work, and the remaining half of the day will be allocated for collecting the fuel debris, storing it in canisters, and carrying out the canisters.

[Fuel debris transfer method]

- The fuel debris will be transferred via casks such as in case of the TMI-2 example or as in the case of spent fuel.
- The need to fill water in the transport casks and the limiting conditions for the transport casks will be specified in this project based on the technical studies.

[Supplement-5] Preconditions of the Study (3/3)

The following conditions were presumed based on the discussions with experts, etc.

[Storage of fuel debris]

- Storage methods

  Wet storage: Wet storage using the existing pool at 1F has few expected profits and is not considered to be highly effective considering remodeling costs, period and technical difficulties etc. Therefore, as of now it considered just as an option.

  Dry storage: Since as the storage method for spent fuel, dry storage is considered as a effective method in terms of operation management, such as maintenance, in addition to safety, there is a high possibility that this method would be advantageous for fuel debris as well, and hence, it is considered as the final storage method.

  In foreign countries, concrete casks are being used for storing spent fuel as well, but since there are no differences in the requirements with respect to the stored items, metallic casks will be studied as a typical example.

- Drying of the fuel debris

  During the study of dry storage, it is assumed that moisture remains in the fuel debris even after drying. Note that if the possibility of not being able to dry is considered, it would be easier to deploy the study with respect to a case of completely dry debris.

- Storage period of fuel debris using canisters

  50 years

  (Set as a period covering 30 years until the final treatment and disposal decision about the fuel debris set in the road-map. Note that, data on long-term integrity has been prepared at the spent fuel dry storage facility, assuming a storage period of about 50 years and a 10-year period of carrying in and out. This data is likely to be helpful.)