Subsidy Project of Decommissioning and Contaminated Water Management
in the FY2015 Supplementary Budgets

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

FY2017 Research Report

June 2018

International Research Institute for Nuclear Decommissioning (IRID)

CONTENTS

1. Research Background and Purposes

1.1 Background

Technology for collection, transfer and storage of fuel debris is required to retrieve fuel debris safety and efficiency for the decommissioning of the Fukushima Daiichi Nuclear Power Station (1F).

Fuel debris contains nuclear fuel, therefore it is necessary to consider, in particular, confinement of radioactive materials (prevention of spreading contamination) and sub-criticality.

When the Three Mile Island Nuclear Power Generation Station Unit 2 (TMI-2), in the United States, was decommissioned, fuel debris was collected in a dedicated container (canister) and handled by the canister. This rationally 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 us to believe that it is reasonable to use existing technologies effectively by developing canisters to meet individual circumstances. Based on the concepts, it has been decided to focus our development on canisters for decommissioning the 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 with TMI-2. To collect, transfer, and store fuel debris safely and rationally, a canister especially for 1F needs to be developed.

In previous studies, elemental technologies were evaluated and a basic canister design created. However, since there is limited information on 1F after the accident, it is important to lay down design conditions for the canister and reflect updated knowledge as occasion arises to optimize 1F decommissioning (e.g., the amount of fuel debris including high radiation waste).

1.2 Purpose

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

1. Research Background and Purposes

(Appendix) Compare to the precedent

The precedent of TMI-2 had completed to collect, transfer, and store fuel debris generated in the core meltdown accident. This achievement 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 to the pedestal inside the containment.**
  - ⇒ **Products of concrete interactions (MCCI) and adherence to concrete during collection need to be considered.**
  - ✓ **The alkaline component in concrete must also be taken into account.**
- **Seawater was injected into the 1F reactor.**
  - ✓ **Residual salt (chlorine) in fuel debris needs to be considered.**
- **The working environment may be severe due to damage on the building. RPV and PCV may be damaged.**
  - ⇒ **Collection of fuel debris by methods other than the submersion-top entry method, such as the partial submersion-side entry method, are being considered.**
  - ✓ **Studies appropriate for methods other than the submersion-top entry method, such as the partial submersion-side entry method, (e.g., fuel debris canister design, know-how on handling of canister) are necessary.**
- **Concentration is high.**
  - ⇒ **The canister's inner diameter will be smaller to maintain sub-criticality. It is difficult to place canisters side by side.**
  - ✓ **Considerations on workability suitable for retrieval and collection of fuel debris and reduction in storage area are important.**
  - ⇒ **Risk of re-criticality when retrieving fuel debris needs to be considered.**
  - ✓ **The possibility of adding neutron-absorbing material to the fuel debris when retrieved also needs to be considered.**
- **Burnup (source strength) is high.**
  - ✓ **Measures against increasing hydrogen generated by water radiolysis are necessary.**
- **Amount of fuel debris is large.**
  - ✓ **Considerations on workability suitable for retrieval and collection of fuel debris and reduction in storage area are important.**

2. Project Goals

2.1 The overall goal of the project

Assuming the retrieval of fuel debris in 2021, our goal is to **establish a method to collect, transfer, and store fuel debris safely and efficiently.**

2.2 Goal of FY2018E

The project aims to develop a plan for how fuel debris will be collected, transferred, and stored safely and rationally. The canister specifications, developed mainly from the perspective of safety design during FY2015 and 2016, will be evaluated and improved with an eye to the fuel debris retrieval methods and transferring tasks. The **canister specification (prototype) will be established** by performing verifications with tests.

(Remaining tasks)

As a result of the previous studies, the following tasks remain and must be taken on.

(1) **Optimization in terms of safe and efficient collection, 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 were proposed. However, in order to store the retrieved fuel debris smoothly, optimization in terms of treatment capacity and practical equipment is necessary.

In addition, rational measures against the possibility of conditions exceeding projections (e.g., fuel debris characterizations) must be proposed from the aspects of management and equipment. (-> This will be studied in the implementation items (1) and (2) on the next page.)

(2) **Safety evaluation with consideration given to the system**

In the previous technical development, evaluations focusing on element tests were 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 page.)

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

In the previous technical development, block, granular, and powder fuel debris collected by the equipment were targeted. However, as fuel debris is collected from water and gas treatment, conducted by 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 page.)

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

3.1 Implementation Item

The following verifications of safety and handling will be conducted from FY2019 with the canister prototype test manufacturing for mockup tests and performing the mockup 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 collected. Further analysis of technical requirements related to overseas 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 a workshop with foreign engineers.

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

Prerequisite technical requirements for the safety of transport casks and storage facility will be established to transfer and store fuel debris safely and rationally in canisters. In addition, each task’s processing capacity and other related conditions will be evaluated and reflected in the requirement specifications for 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 safety validation

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

(4) Study on fuel debris collection method

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

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

R&D Project

Revise as necessary

Results of internal PCV Survey
Results of internal RPV Survey
Results of fuel debris analysis

Set the basic conditions of fuel debris properties etc.
- Information on 1F, technical literature on TMI-2
- Results of Fuel Debris Characterization Project Team, etc.

Set a range of basic specifications for canisters (inner diameter, total height)

Organize the correlation with each design factors
Organize the correlation of the basic specifications for canisters with designs of other facility and equipment, work efficiency, and approximate cost

*1: Related projects
Method Project Team, Fundamental Technology Project Team, Fuel Debris Characterization Project Team, Criticality Control Project Team, Waste Project Team

(i) Establish collection, transfer, and storage flow (provisional)
- Examples of work flow for damaged fuels in overseas (e.g., TMI-2)
- Formulate flow proposals based on conditions of 1F

(ii) Formulate the concept of the collection, transfer, and storage system (provisional)
- Investigate foreign systems
- Formulate concept of the storage system (wet and dry) based on conditions of 1F

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

(iv) Draw up the specifications based on the safety assessment (provisional)
- Specify properties based on foreign examples
- Specify requirements based on parametric analysis

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.**

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

Inspection of canister using partial model and analyzation (evaluation on function feasibility)

Finalize the canister's basic specifications

FY2019 onwards

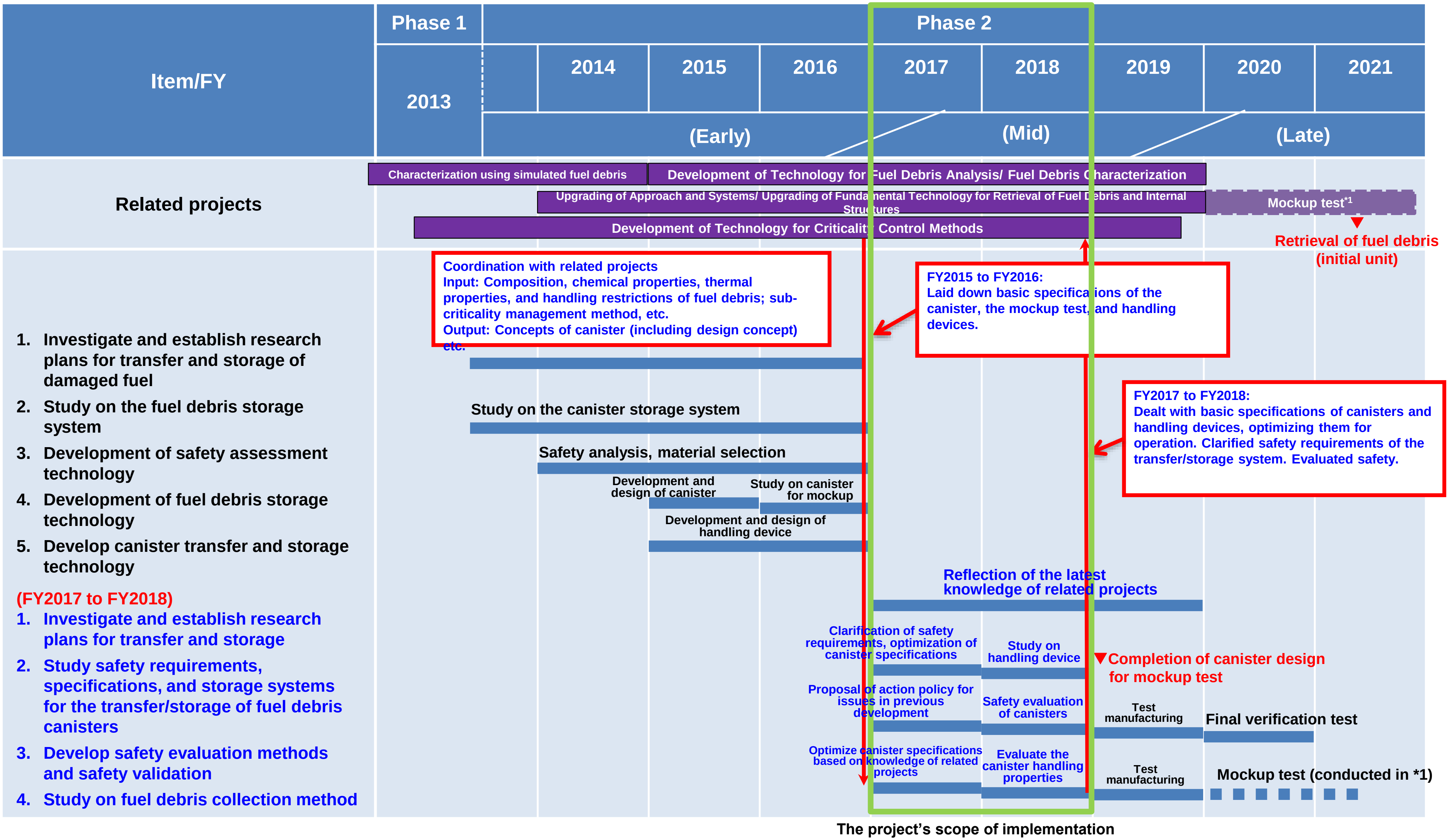
Verification of the canister design's validity (overall verification)

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

No.7

3.2. Relation of Implementation Items (1/2)

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



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

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 Management Project

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

Canister Project

[Information provided to related project teams]
(1) Studies of safety requirements, specifications, and storage systems for the transfer/storage of fuel debris canisters
• Details of inspections for safety assessment

(4) Study of fuel debris collection 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 Project

[Information provided to the Canister Project Team]
Limiting conditions for handling fuel debris
• Dimension conditions and weight limitations
Storage location and procedure for fuel debris
• Canister installation location
• Canister hoisting information
Fuel debris collection method
• Knowledge of fuel debris cutting, particle size, etc.
• Collection method (e.g., pump suction)
Handling procedure of special tools

Criticality Control Project

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

Note)

Method Project Team	:	Project on fuel debris retrieval method and system
Fundamental Technology Project Team	:	Project on fundamental technologies for fuel debris retrieval
Debris Characterization Project Team	:	Project on fuel debris characterization
Criticality Control Project Team	:	Project on fuel debris criticality control
Waste Project Team	:	Project on treatment and disposal of solid waste
Canister Project Team	:	Project on collection, transfer, and storage of fuel debris

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

4. Schedule

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

FY2017: April, May, June, July, August, September, October, November, December, January, February, March

		FY2017
1	Investigation and establishment of research plans for transfer and storage	Analyzation of other R&D results and evaluation of foreign safety requirements; Refinement of plan
2	Changes in safety requirements and specifications related to transfer and storage of fuel debris canisters	
	(1) Establishment of safety requirements and specifications related to transfer and storage	Study on safety requirements; System optimization (flow, etc.); Reflection of study results (method, etc.)
	(2) Study of storage system	Organization of technical requirements for wet and dry storage methods (continues in FY2018)
	(3) Study of storage method	Study of conditions; Preparation of model
	(4) Study of drying system	Study of drying procedure
	(5) Study and review of specifications for handling device	Reflection of study results (method, etc.)
3	Development of safety evaluation methods and safety validation	
	(1) Safety evaluation of sub-criticality	Inspection of water volume measurement technology; Study of applicability of water volume restriction; Survey of sub-criticality conditions
	(2) Safety evaluation of structural strength	Formulation of requirements for lids etc.; Preparation of materials for lid structure specimen (used in FY2018 test); Formulation of test plan using real size canisters
	(3) Safety evaluation regarding aging degradation	Study of stress corrosion cracking (SCC) conditions; Study of effect upon SCC; Optimization of corrosion measures including operation (continues in FY2018)
	(4) Safety evaluation of measures against hydrogen gas Verification of the amount generated	Inspection of gas phase reaction; Gamma-ray irradiation test; Study of alpha-ray effect; Hydrogen evaluation test using spent fuel (continues in FY2018)
	(5) Verification of measures against hydrogen	Study of countermeasures from an operational perspective; Study of flow characteristics inside canister
4	Study of fuel debris collection method	
	(1) Study of the canister's specification that suits fuel debris properties	Study of canisters that suit fuel debris properties
	(2) Review of canister design	Revision of canister specifications (continues in FY2018)
	Briefing, presentation, etc.	Presentation at academic conferences; Briefing; Briefing

5. Project Organization Chart (as of the end of March 2018)

External stakeholder

Tokyo Electric Power Company Holdings, Inc.

International Research Institute for Nuclear Decommissioning (Head Office)

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

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/storage of fuel debris canisters

(3) Development of safety evaluation methods and safety validation

(4) Study of fuel debris collection method

Relevant projects

- Development of Technology for Fuel Debris Analysis/ Fuel Debris Characterization
- Upgrading of Approach and Systems for Retrieval of Fuel Debris and Internal Structures
- Upgrading of Fundamental Technology for Retrieval of Fuel Debris and Internal Structures
- Development of Technology for Criticality Control Methods
- 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 onto 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 device

Soltec
- Tests related to heat transfer and heat flow inside canister

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 specifications for transfer and storage of fuel debris canisters

Under Hitachi-GE Nuclear Energy, Ltd.:

EIWA Corporation, Nippon Swagelok FST, Inc.
- Consumables used in tests on evaluation of the amount of hydrogen generated

GNF
- Study on concepts related to the storage system

Hitachi Power Solutions Co., Ltd.
- Verification of feasibility of canister lid structure

TOKO Corporation
- Study on method of handling canister lids

Hitachi Power Solutions Co., Ltd.
- Analyzation of specimen for tests to evaluate the amount of hydrogen generated

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

Pacific Northwest National Laboratory
- Study on the effect of alpha-ray on the evaluation on the amount of hydrogen generated

KOKUYO Co.,Ltd.
- Organization of documents and data

NDC: Nuclear Development Corporation

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

Soltec: MHI Solution Technologies Co., Ltd.

GNF: Global Nuclear Fuel Japan Co., Ltd.

6. Implementation Details

6.1 Investigation and Establishment of Research Plans for Transfer and Storage
(1) Gathering of the latest knowledge on other technical development
(2) Analyzation on foreign knowledge
(3) Formulation of research plan
6.2 Study of Safety Requirements and Specifications of Storage Systems for the Transfer/Storage of Fuel Debris Canisters
(1) Establishment of Safety Requirements and Specifications Regarding Transfer and Storage of Fuel Debris Canister
(2) Study of storage system
(3) Study of storage method
(4) Study of drying system
(5) Study and review of specifications for handling device
6.3 Development of Safety Evaluation ,Methods and Validation
(1) Safety evaluation of sub-criticality
(2) Safety evaluation of structural strength: Study of lid structure
(3) Safety evaluation regarding aging degradation: Study of canister materials
(4) Safety evaluation of measures against hydrogen gas
a. Verification of the amount generated
b. Verification of measures against hydrogen
6.4 Study on Fuel Debris Collection Method
(1) Study on the canister’s specifications that suit fuel debris properties
(2) Review of canister design

6. Implementation Details

6.1 Investigation and Establishment of Research Plans for Transfer and Storage

(1) Acquiring the latest knowledge on related technical development

On formulating the flow from retrieval to storage of fuel debris in 6.2 "Study of safety requirements, specifications, and storage systems for the transfer/storage of fuel debris canisters," information was exchanged in a joint meeting among the Method Project Team, Fundamental Technology Project Team, Waste Project Team, and experts of material accountancy from outside IRID. The latest knowledge (limiting conditions of the fuel debris retrieval method, amount of fuel debris, material accountancy and control policy for fuel debris, etc.) was gathered and reflected in the workflow.

(2) Analysis on knowledge obtained from overseas

The TMI-2 case was referenced in establishing safety requirements of 6.2 "Study on safety requirements and specifications and storage systems for the transfer/storage of fuel debris canisters."

In addition, on studying the shape of canister lids and other specifications in 6.4 "Study on fuel debris collection method," the approval application form of a domestic example (waste management facility of Japan Nuclear Fuel Limited reprocessing business) was obtained and referred.

(3) Formulation of research plan

The 4 "Schedule" was formulated as a research plan. Additionally, the 6.2 (2) "Study of the storage system" and individual topics were discussed to revise based on experts.

6. Implementation Details

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

No.13

(1) Establishment of safety requirements and specifications regarding transfer and storage of fuel debris canister

(i) Purpose and overview

In terms of clarifying the requirements for designing the fuel debris transfer/storage system, safety requirement proposals were formulated in the following terms based on the safety requirement proposals of fuel debris retrieval that share the same basic safety principles. In formulating the proposal, the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors was referred to, as well as requirements in the related laws concerning handling and storage of spent fuels.

- **Basic requirements**
  Have function necessary to ensure safety of the facility (e.g., preventive measure against leakage of radioactive materials)
- **External event and human event**
  Prevent human caused events (e.g., trespass) and damage caused by external event (e.g., earthquake, tsunami)
- **General design requirements for design basis facility**
  Give considerations to design in safety facilities (e.g., environmental conditions, reliability), prevent operational error, prepare countermeasure equipment for station blackout, ensure operation during abnormality, etc.
- **Individual design requirements for target facility**
  Prevent leakage of radioactive materials, retain integrity of the canister and canister handling facility, criticality control, cool fuel debris, prevent fire and explosion, etc.
- **Worker exposure**
- **Public exposure**

  $\Big\}$ **Reduce exposure dose as much as possible/keep as low as possible**
- **Transfer of canister and storage task**
  Manage so that works and operation that deviate from design limitations are not conducted
- **Prevention of escalation in design basis accident (DBA)**
  Identify accident event that triggers leakage of radioactive materials and re-criticality, prevent escalation when the event occurs, and take appropriate measures that satisfy the criteria
- **Laws and regulations**

(ii) Future plans

The task is to create specific design requirements from the safety requirement proposals formulated here. The evaluation of the fuel debris retrieval safety requirements will be coordinated with and the requirements of spent fuel storage facilities considered.

Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors
- Regulations for Transport of Nuclear Fuel Material Outside Plants
- The NRA Ordinance on Technical Standards for the Capabilities of Spent Fuel Interim Storage Facilities
- The NRA Ordinance on Standards for the Location, Structure and Equipment of Spent Fuel Interim Storage Facilities
- The NRA Ordinance on Standards for the Location, Structure, and Equipment of Commercial Power Reactors
- Ordinance on the Security of Nuclear Reactor Facilities and Protection of Specific Nuclear Fuel Material at the Fukushima Daiichi Nuclear Power Station
- The NRA Ordinance on Technical Standards for the Design and Construction Methods of Spent Fuel Interim Storage Facilities

Figure: Laws and regulations particularly referred to in the study

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

(2) Study on the storage system (1/13)

(i) Purpose

The focus of our study was the safety assessment methods that are necessary to design the transfer/storage system. However, to materialize these facilities, it is necessary to consider the demands and requirements from another point of view, including the operation of throughput. To fulfill these demands and requests, a provisional process flow up to the storage of fuel debris was laid down, based on expert opinions about related projects in IRID. In addition, the quantity which will be the premise of the throughput study is in the process of being studied.

(ii) Future plans

The validity of the system will be evaluated by related projects based on the provisional flow and quantity. Requirements for the canisters and transfer/storage system will be made concrete.

6. Implementation Details

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

(2) Study on the storage system (2/13)

Process flow establishment

On establishing a process flow, the basic concepts of boundaries (confinement boundary) and share of safety functions were reconfirmed.

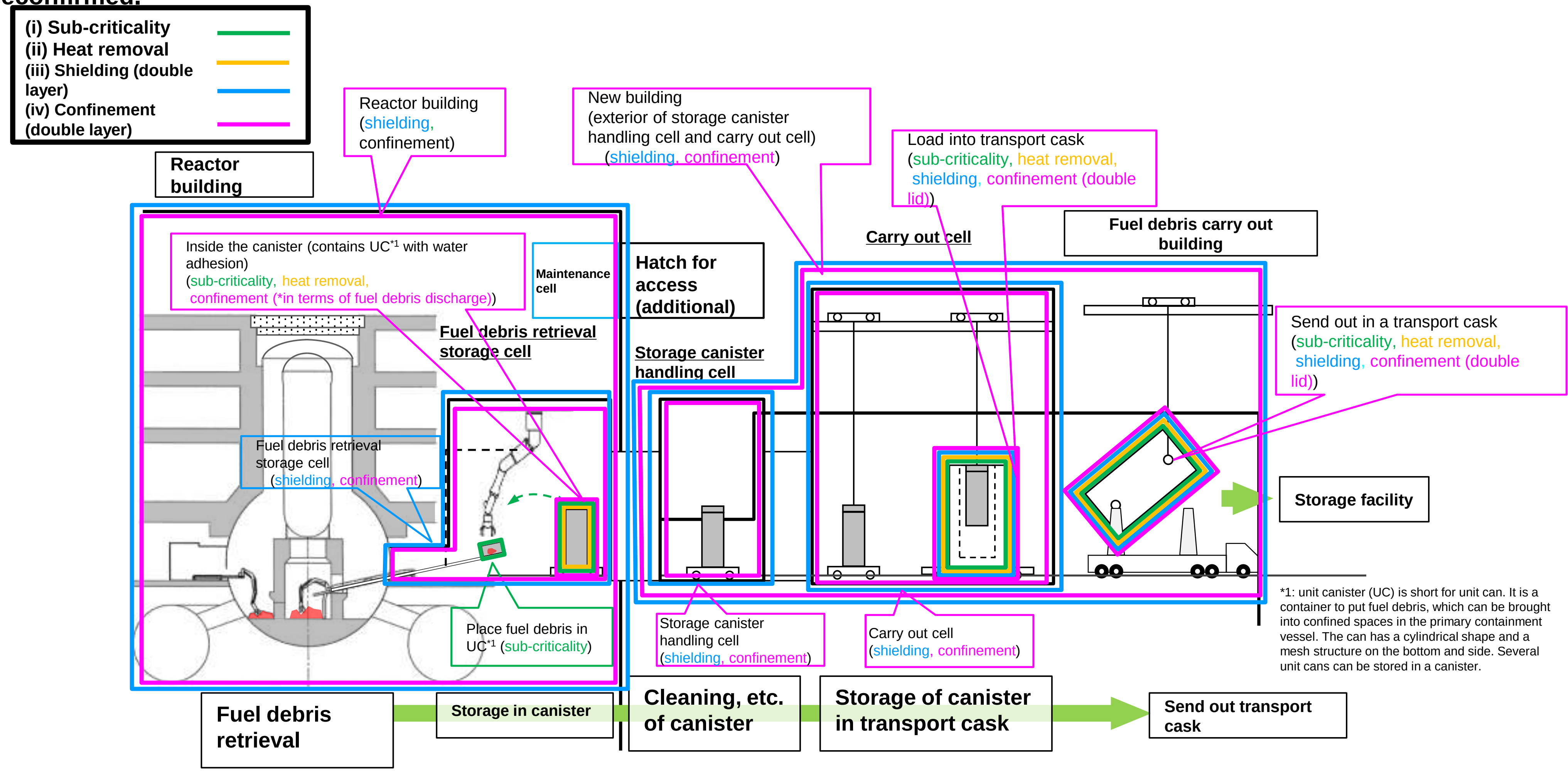


Figure: Canister management in 1F (example of partial submersion-side entry method)

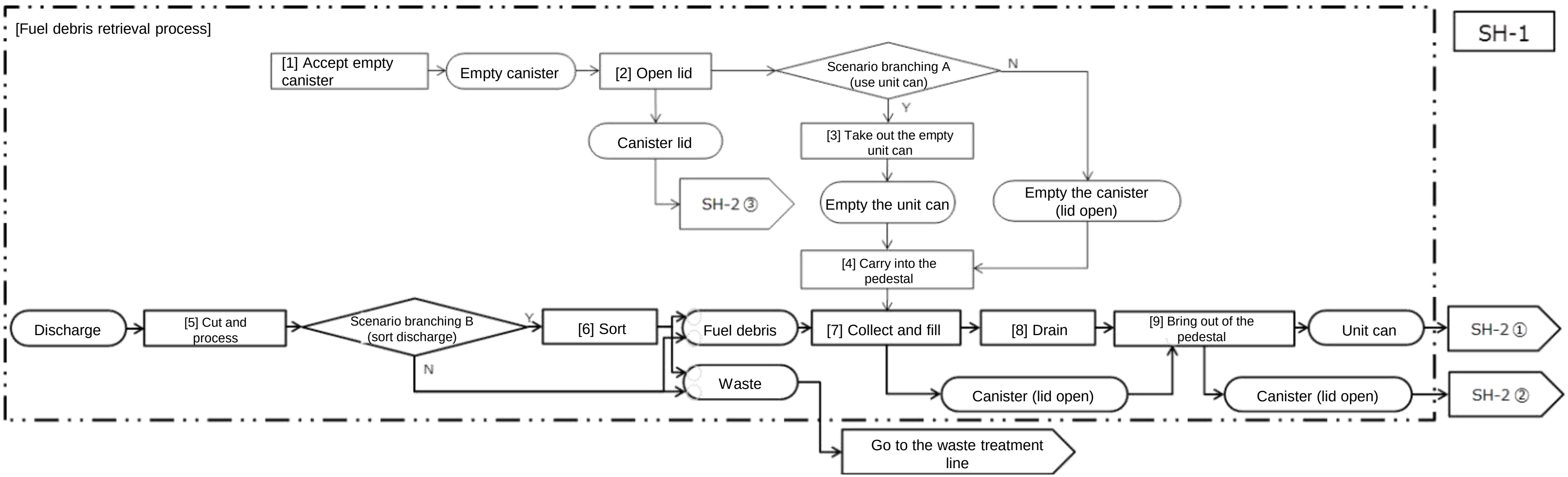
6. Implementation Details

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

(2) Study on the storage system (3/13)

Process flow setting

Based on the concepts of the basic system safety design as previously mentioned, a provisional flow was estimated by exchanging opinions among the Fuel Debris Retrieval Method Project Team, the Waste Project Team, and IRID experts to ensure safety. Several flows that would be necessary in processes such as sorting and wet (pool) storage were created in parallel.



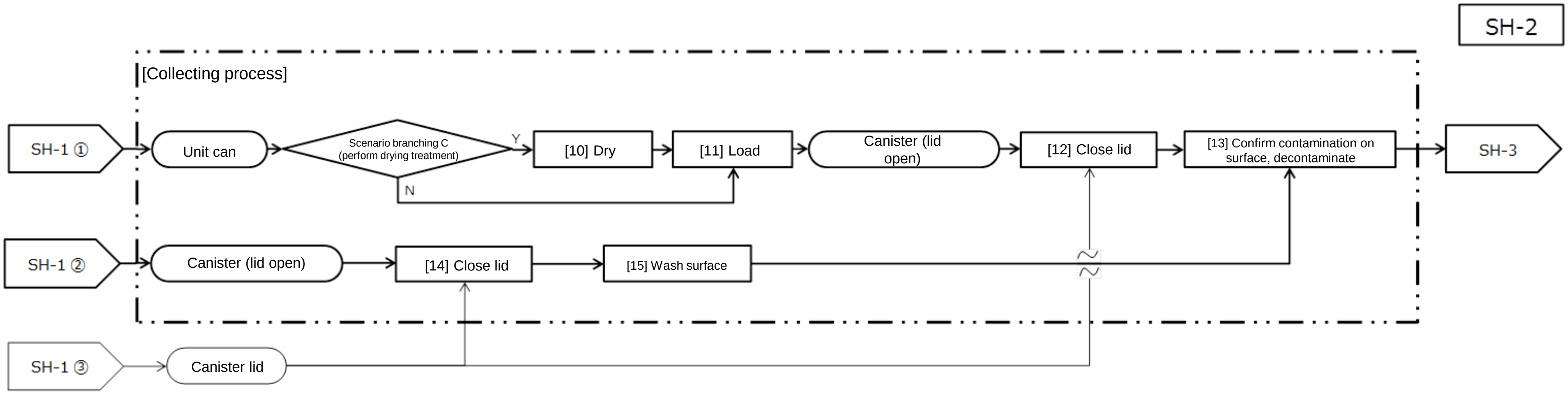
No.	[1]	[2]	[3]	[4]		[5]	[6]	[7]	[8]	[9]	
Handled item	Empty canister	Canister lid	Empty the unit can	Empty canister	Empty the unit can	Discharge	Discharge	Fuel debris	Unit can	Canister	Unit can
Details and purpose of task	Carry an empty canister in which fuel debris will be stored in the specified position 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 empty canister or 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 canister or unit can.	Sort the cut and processed discharge into fuel debris and waste.	Collect the fuel debris and place it in the empty canister or unit can.	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 canister or unit can filled with fuel debris to the fuel debris retrieval storage cell that is outside of the pedestal.	

Scenario branching A	Scenario branching B
[Details] “Bring the canister directly into the pedestal” or “bring the unit can into the pedestal”	[Details] “Sort the discharge into fuel debris and waste at the site, depending on whether criticality may occur or not” or “sort the discharge in advance into fuel debris and waste in the area where the discharge is located and not at the site of retrieval”

Figure: Example of process flow: Retrieving fuel debris ~ Storing in the unit can
(Details are studied by the Fuel Debris Retrieval Method Project team.)

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

(2) Study on the storage system (4/13)



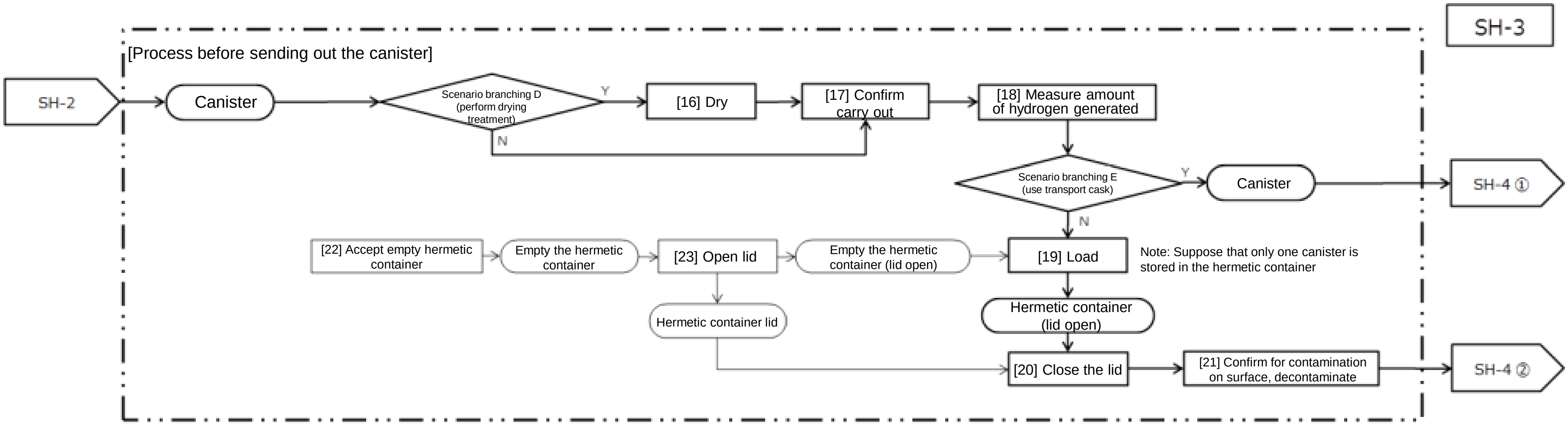
No.	[10]	[11]	[12]	[13]	[14]	[15]
Handled item	Unit can	Unit can	Canister	Canister	Canister	Canister
Details and purpose of task	Dry the entrained water and reduce the amount of water at an early stage before the unit can is stored in the canister to reduce the risk of criticality (during arrangement), risk of corrosion, the amount of hydrogen generated, etc.	Load the unit can into the canister.	Close the lid of the canister.	Confirm for contamination on the surface of the cleaned canister. Decontaminate if contamination is confirmed. Cut and process into an appropriate dimension.	Close the lid of the canister.	Wash the surface of the canister to prevent the spread of contamination.

Scenario branching C
[Details] “Perform drying treatment on the unit can” or “no drying treatment”

Figure: Example of process flow: Storing in the unit can ~ Closing lid of canister can

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

(2) Study on the storage system (5/13)



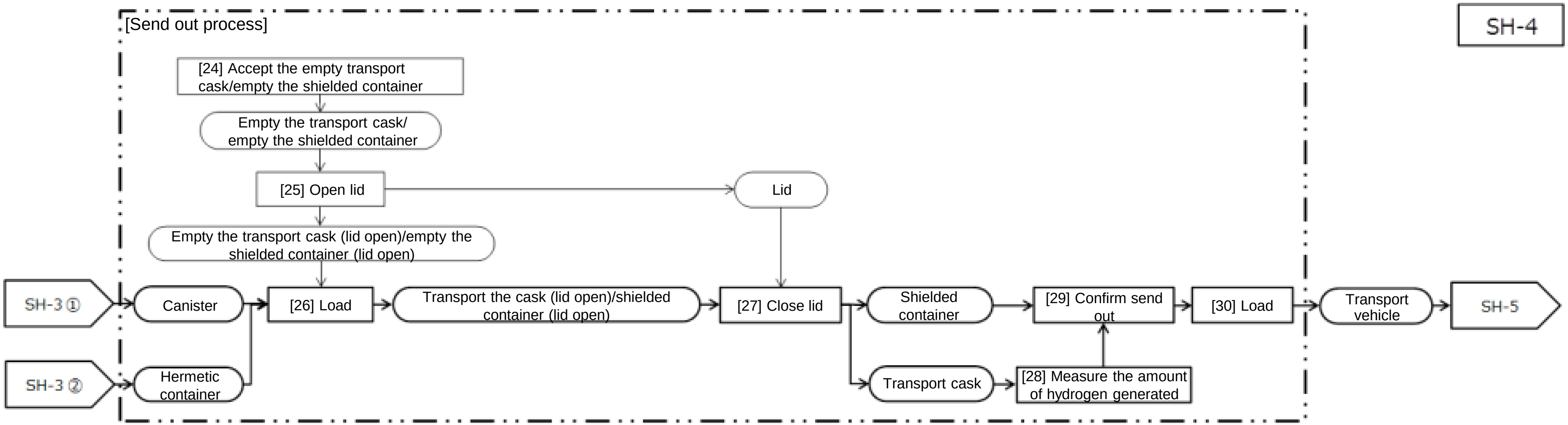
No.	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
Handled item	Canister	Canister	Canister	Canister	Hermetic container lid	Hermetic container	Empty the hermetic container	Hermetic container lid
Details and purpose of task	Dry the entrained water and reduce the amount of water to reduce the risk of criticality (during arrangement), risk of corrosion, the amount of hydrogen generated, etc.	On carrying out the canister to the storage facility, confirm the canisters to collect and link data and conditions of each canisters (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.	Load the canister into the hermetic container.	Close the lid of the hermetic container.	After loading the canister, confirm for contamination on the hermetic container surface. Decontaminate if contamination is confirmed.	To ensure the container's fuel debris confinement property (including gas) at an early stage, carry in the canister to a specified position inside the empty hermetic canister which the canister will be sealed inside.	Open the lid of the empty hermetic container before sealing in the canister.

Scenario branching D	Scenario branching E
[Details] “Perform drying treatment before carrying out the canister” or “no drying treatment”	[Details] “Store the canister in a dual container (hermetic canister + shielded container) that share the functions between the two” or “store the canister in the transport cask only (double lid)”

Figure: Example of process flow: Confirming of the closed canister ~ Preparation of transferring the canister

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

(2) Study on the storage system (6/13)

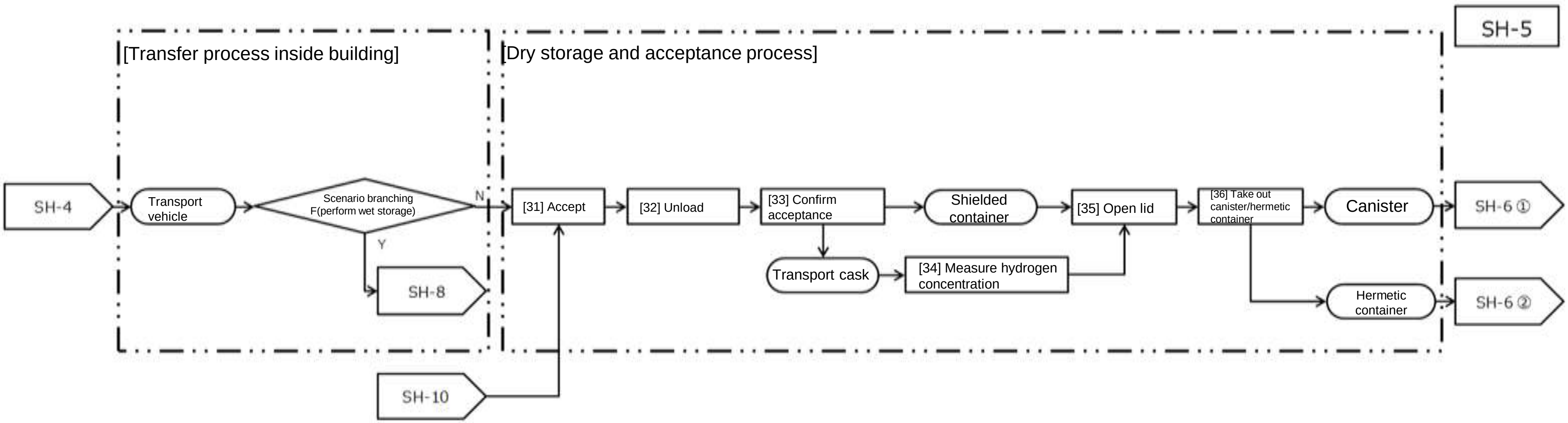


No.	[24]		[25]		[26]		[27]		[28]	[29]		[30]	
Handled item	Empty the transport cask	Empty the shielded container	Transport cask lid	Shielded container lid	Canister	Hermetic container	Transport cask lid	Shielded container lid	Transport cask	Transport cask	Shielded container	Transport cask	Shielded container
Details and purpose of task	On transferring the canister/hermetic container to the storage facility, carry in the transfer cask/shielded container for external transportation to a specified position.		Open the lid of the container before storing the canister/hermetic canisters 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.	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.	

Figure: Example of process flow: Loading the canister ~ Preparation to sending out the transport cask

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

(2) Study on the storage system (7/13)



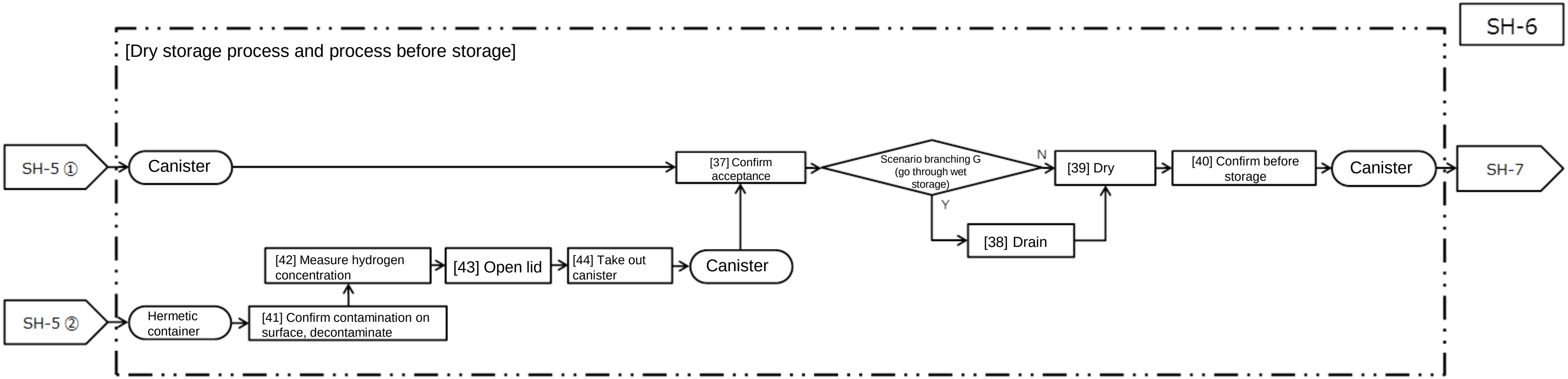
No.	[31]		[32]		[33]		[34]	[35]		[36]	
Handled item	Transport cask	Shielded container	Transport cask	Shielded container	Transport cask	Shielded container	Transport cask	Transport cask lid	Shielded container lid	Canister	Hermetic container
Details and purpose of task	Accept the transport vehicle with the transport cask/shielded container into the dry storage facility.		Unload the transport cask/shielded container from the transport vehicle to a specified location.		Confirm the accepted transfer casks/shielded containers for any problem (inspection for contamination on the 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 the hydrogen concentration has not reach the lower explosion limit.	Open the lid of the transport cask/shielded container. (Open both the primary and secondary lids of the transport cask.)		Take out the canister/hermetic container from the transport cask/shielded container.	

Scenario branching F
[Details] “Perform temporary wet storage” or “no wet storage”

Figure: Example of process flow: Transfer on site~ Receiving canister into dry storage facility ~ taking out canister

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

(2) Study on the storage system (8/13)



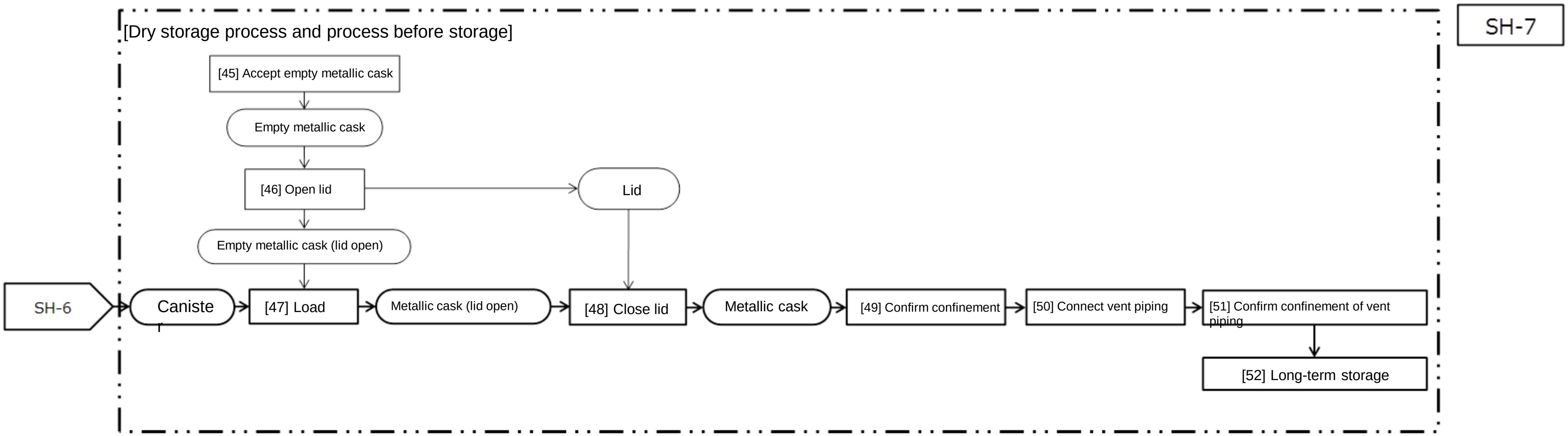
No.	[37]	[38]	[39]	[40]	[41]	[42]	[43]	[44]
Handled item	Canister	Canister	Canister	Canister	Hermetic container	Hermetic container	Hermetic container lid	Canister
Details and purpose of task	Confirm the accepted containers for any problem (inspection for surface contamination, decontamination, mass measurement, surface dose rate measurement, visual inspection (including confirmation of canister ID)).	After the canister has gone through wet storage, drain residual water from the canister through the drain pipe as much as possible to relax the initial conditions of drying treatment as much as possible.	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 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 the hydrogen concentration has not reach the lower explosion limit.	Open the lid of the hermetic container to take out the canister.	Take the canister out from the hermetic container.

Scenario branching G
[Details] "Go through wet storage" or "no wet storage"

Figure: Example of process flow: Confirmation for acceptance of canister ~ Confirmation before storage

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

(2) Study on the storage system (9/13)

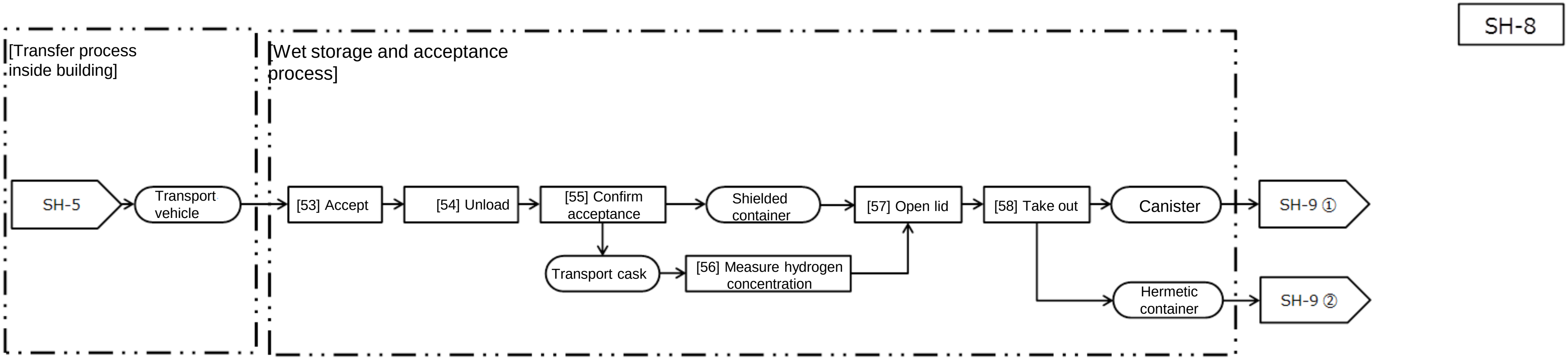


No.	[45]	[46]	[47]	[48]	[49]	[50]	[51]	[52]
Handled item	Empty metallic cask	Metallic cask lid	Canister	Metallic cask lid	Metallic cask	Metallic cask	Metallic cask	Metallic cask
Details and purpose of task	Carry in an empty metallic cask in which the canister will be stored for a long period to the specified 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 is loaded, close the lid of the metallic cask.	Confirm that the metallic cask satisfies the prescribed 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.

Figure: Example of process flow: Preparation for dry storage ~ Dry storage

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

(2) Study on the storage system (10/13)

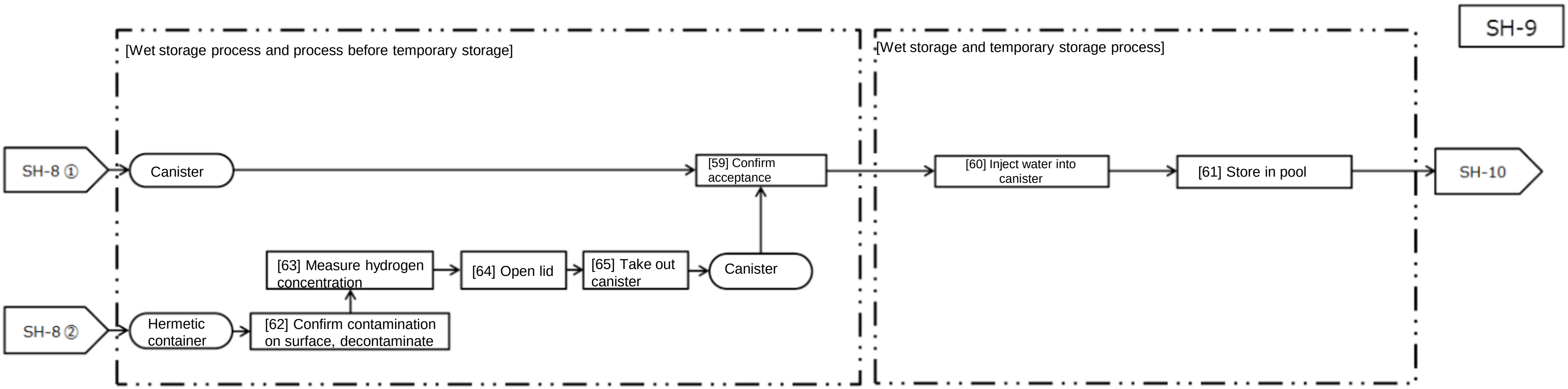


No.	[53]		[54]		[55]		[56]	[57]		[58]	
Handled item	Transport cask	Shielded container	Transport cask	Shielded container	Transport cask	Shielded container	Transport cask	Transport cask lid	Shielded container lid	Canister	Hermetic container
Details and purpose of task	Accept the transport vehicle with the transport cask/shielded container into the wet storage facility.		Unload the transport cask/shielded container from the transport vehicle to a specified location.		Confirm the accepted transfer casks/shielded containers for any problem (inspection for surface contamination, decontamination, surface dose rate measurement, visual inspection (including confirmation of canister ID)).		On opening the lid of the transport cask, measure the amount of hydrogen generated inside the transport cask and confirm that hydrogen concentration has not reach the lower explosion limit.	Open the lid of the transport cask/shielded container. (Open both the primary and secondary lids of the transport cask.)		Take out the canister/hermetic container from the transport cask/shielded container.	

Figure: Example of process flow: Transfer inside the premises ~ Receiving the canister in wet (pool) storage facility ~ Taking out the canister

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

(2) Study on the storage system (11/13)

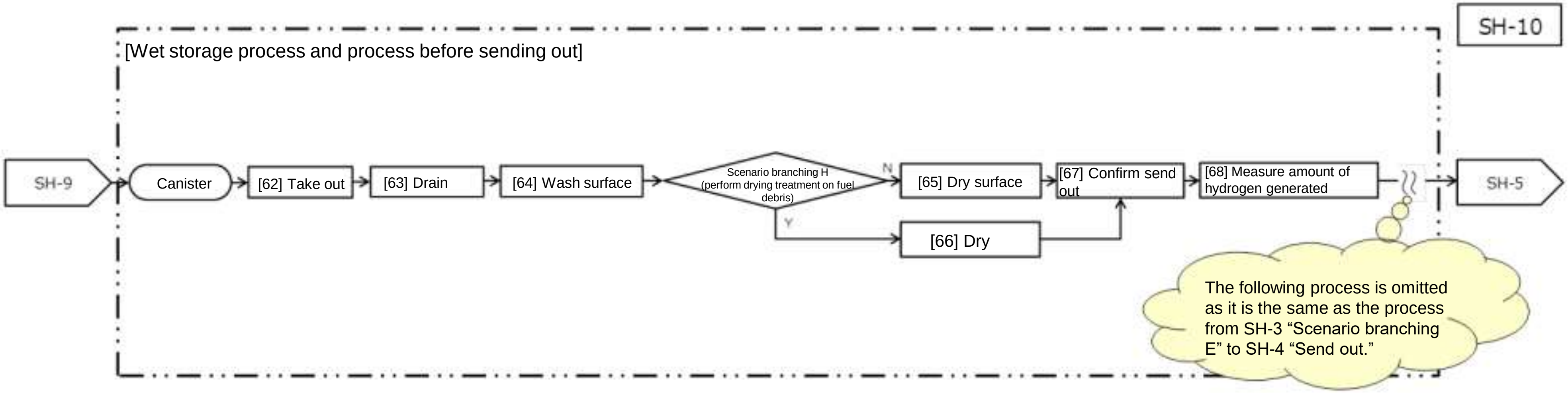


No.	[59]	[60]	[61]	[62]	[63]	[64]	[65]
Handled item	Canister	Canister	Canister	Hermetic container	Hermetic container	Hermetic container lid	Canister
Details and purpose of task	Confirm the accepted containers for any problem (inspection for surface contamination, decontamination, mass measurement, surface dose rate measurement, visual inspection (including confirmation of canister ID)).	On putting the containers in wet storage, inject water in the canister.	Transfer and settle the canister to a specified position in the pool. (Depending on the form of canister storage, connect a vent pipe to the canister.)	Confirm for 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 the hydrogen concentration has not reach the lower explosion limit.	Open the lid of the hermetic container to take out the canister.	Take the canister out from the hermetic container.

Figure: Example of process flow: Preparation of wet storage ~ Wet storage

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

(2) Study on the storage system (12/13)



No.	[62]	[63]	[64]	[65]	[66]	[67]	[68]
Handled item	Canister	Canister	Canister	Canister	Canister	Canister	Canister
Details and purpose of task	Take the canister out of the pool to transition to dry storage.	Discharge water inside the canister through the drain pipe for the purposes including reduction of the amount of hydrogen generated and risk of leakage, as well as relaxation of the initial conditions of drying treatment.	Wash the canister surface to prevent the spread of contamination.	Dry water on the canister surface to prevent the spread of contamination by water drops.	Dry the surface and inside of the canister to reduce the risk of criticality (during arrangement), risk of corrosion, the amount of hydrogen generated, etc. Confirm	On sending out the canister to the dry storage facility, confirm the canisters to collect and link data and conditions of each canisters again (mass measurement, inspection for contamination on surface, decontamination, surface dose rate measurement, visual inspection (including confirmation 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 dry storage facility.

Scenario branching H
[Details] "Perform drying treatment on the fuel debris before sending out the canister" or "no drying treatment"

Figure: Example of process flow: Taking out canister in a storage facility ~ Preparation for transport

6. Implementation Details

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

(2) Study on the storage system (13/13)

Issues that need to be solved to make the system work were identified based on the provisionally established process flow. (The figure below shows typical discussion topics.)

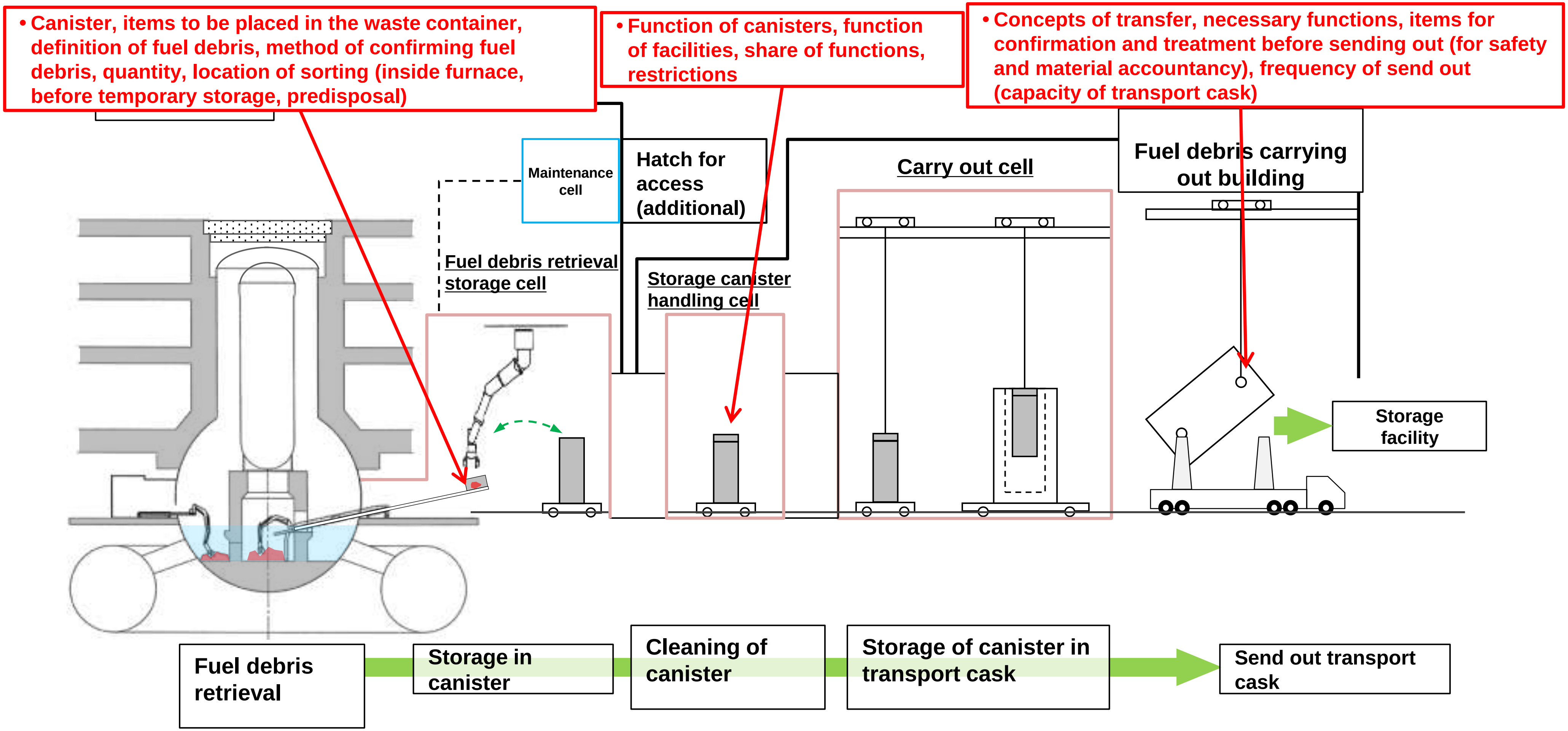


Figure: Bottom of the primary containment vessel; example of partial submersion-side entry method

6. Implementation Details

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

(3) Study of storage method

As an example, a case study was conducted and the decision flow of temporary storage (wet storage) organized in a joint meeting with external experts, experts of IRID, the Method Project Team, and the Waste Project Team. As a result, since wet storage may be required, it has been decided to continue negotiations in FY2018 and work on making the method concrete.

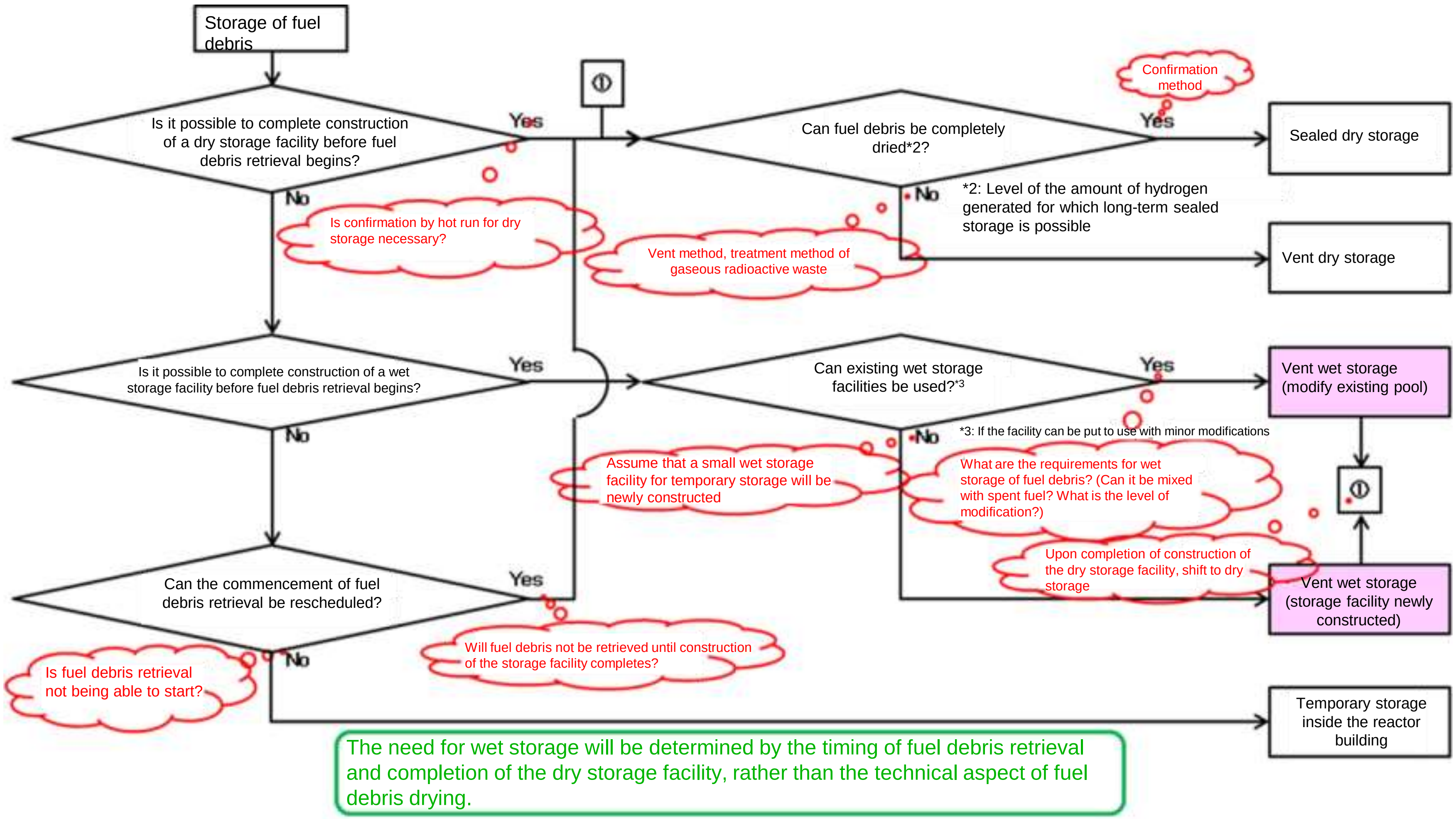


Figure: Decision flow of primary storage (wet storage)

6. Implementation Details

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

(4) Study on drying system (1/6)

(i) Purpose

Dry storage is a reasonable method for long-term storage of fuel debris. On the other hand, a method must be devised to dry the fuel debris for dry storage. To create the drying system's concept plan, this study aims to ensure throughput and provisionally determine a safe drying method, considering the basic requirements of the system (especially discharge of fission products).

(ii) Target drying conditions

Free water elimination was chosen as the drying goal.

The features of dry storage are that by drying fuel debris and storing it in an inert atmosphere, it suppresses aged deterioration (e.g., corrosion) and hydrogen generation by water radiolysis. This can be mostly achieved by eliminating free water contained in fuel debris. Crystal water contained in concrete (e.g., MCCI products) does not contribute to cell formation which causes corrosion. In addition, data from previous research shows that it does not contribute to hydrogen generation. For this reason, it was excluded from the subject.

(iii) Summary of FY2017 studies

In addition to heated vacuum drying conducted in TMI-2, high-temperature drying which heats the inside of the canister to a higher temperature and hot air drying that blows in hot air were studied.

- Regarding 1F, the method of storing collected fuel debris into a unit can and then storing that into a canister for reasons of workability is being studied. It is assumed that heat will not easily transfer to the fuel debris when the canister is heated.
- When drying the unit can, it is expected the fuel debris will dry faster due to direct heating. As for technical development, study results of drying method for canisters can be diverted so it will not be a subject for study as of now.

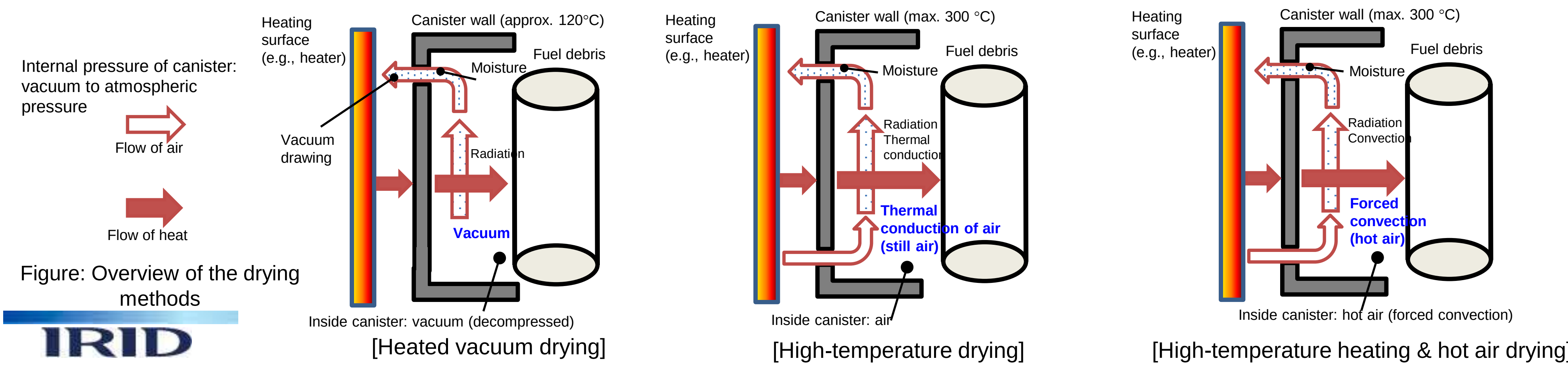


Figure: Overview of the drying methods

6. Implementation Details

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

(4) Study on drying system (2/6)

(iv) Concepts

Calculate the evaporation rate based on the constant rate drying period (area II in the right figure)

a. Preheating period (decompression period in vacuum drying) (I): Period in which the water inside starts to boil due to heating (in vacuum drying, the water inside will start to boil due to decompression inside 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.)

-> This phase is ignored in this study because the period is short.

b. Constant rate drying period (II): Since water starts to boil and drying progresses to balance the external heat input and 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.

-> External heat input is calculated by simulating a heat transfer model. (Assumed that the water volume is equivalent to 30 vol.% of fuel debris volume, storage efficiency is 30 vol.%, and heat generation of fuel debris is zero according to the draining test)

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 narrow parts) is unknown and elaboration is difficult without examining it. III will also be qualitatively short if II is short.

-> This phase is ignored since the period is short in the element test conducted in the Fuel Debris Characterization Project Team. However, the period may have been short since it was a small-scale test, so it will be our future task.

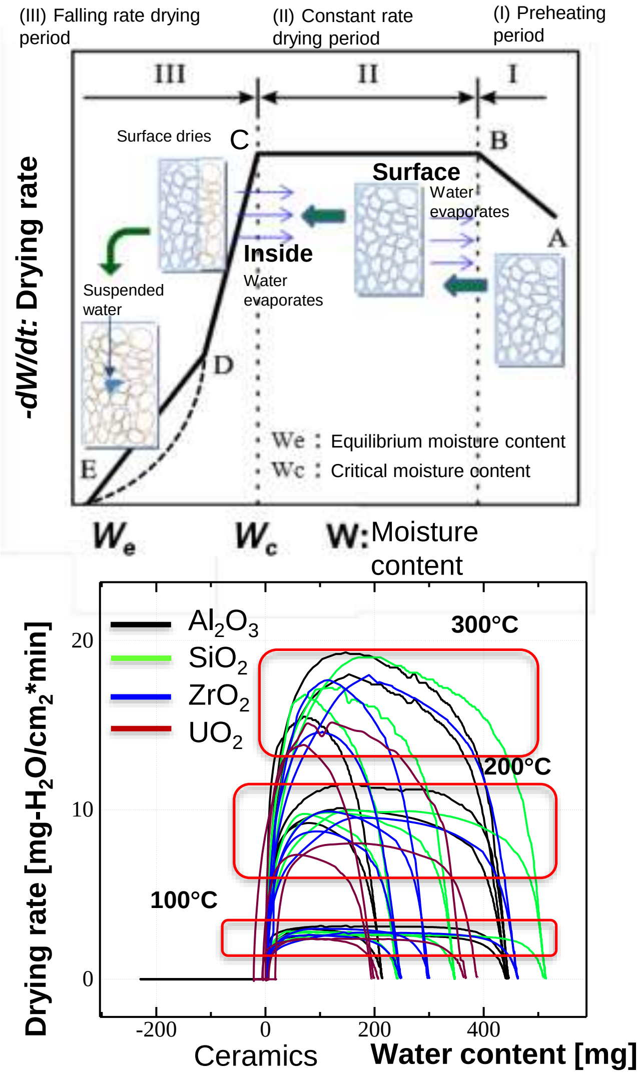


Figure: Drying characteristics (with fuel debris substitute material)
Reference: FY2016 study results of Fuel Debris Characterization Project Team
Note: The graph shows that the drying rate changes as water content decreases (dries) (decreases from right to left).

6. Implementation Details

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

(4) Study on drying system (3/6)

(v) Evaluation method

In the FY2016 fuel debris preliminary draining test, residual water was about 10 to 50 vol.% of the fuel debris volume even when drained. Parameters such as decompression and convection inside canisters under the premise of heating were surveyed, and the drying rates were compared. The drying rate was calculated by dividing the heat input to the fuel debris by the evaporation latent heat of water.

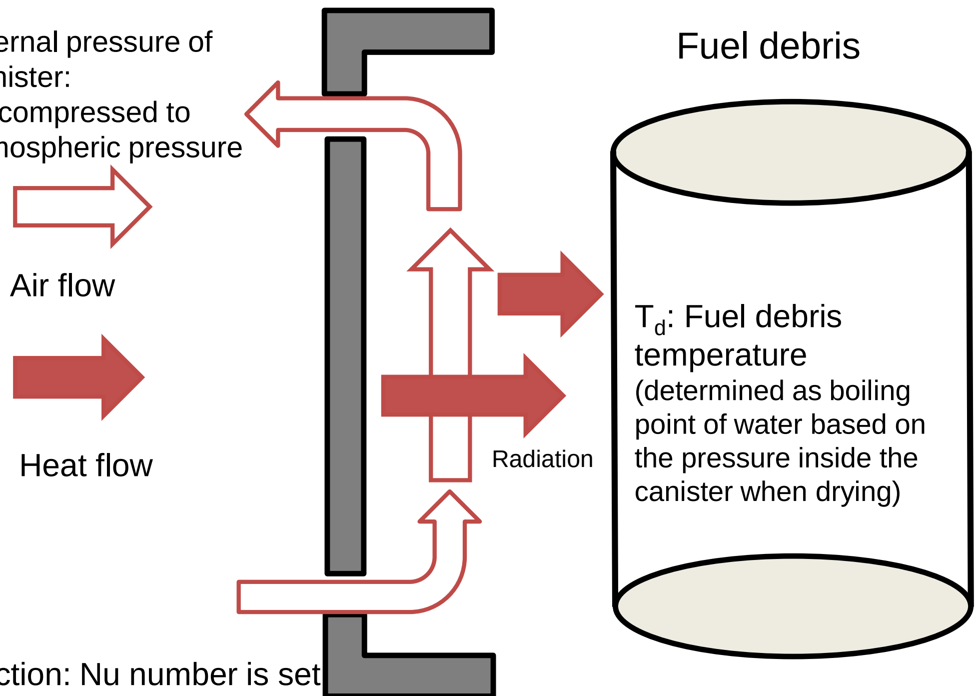


Figure: Overview of the heat transfer model

Study conditions: Assume that the constant rate drying period (II) is the only drying process

(no falling rate drying period)

Moisture inside the fuel debris is assumed to be supplied to the surface and heat input will all be used to evaporate the moisture (evaporation heat). Therefore, the fuel debris temperature will be the boiling point of water.

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

(4) Study on drying system (4/6)

(vi) Studied cases

The following cases were specified for study.

Heat drying (basic case)
Heated vacuum drying
High-temperature drying
High-temperature heating & hot air drying

Table: List of conditions of studied cases

List of conditions	Unit	Heat drying (basic case)	Heated vacuum drying	High-temperature drying	High-temperature heating & hot air drying
Canister temperature	°C	120	120	300*1	300
Warm air temperature at opening	°C	-	-	-	300*1
Fuel debris temperature (assumed to be the boiling point of water)	°C	100	11*2	100	100
Inner diameter of canister	mm	220	220	220	220
Flow rate of warm air	m/s	-	-	-	0.2

*1: A value provisionally specified as the upper limit based on the information on drying fuel debris in TMI-2
*2: A value specified on the assumption that the pressure during vacuum drying is 10 mmHg (boiling point of water at pressure of 10 mmHg)

6. Implementation Details

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

(4) Study on drying system (5/6)

(vii) Evaluation results

The drying time was compared between the drying systems.

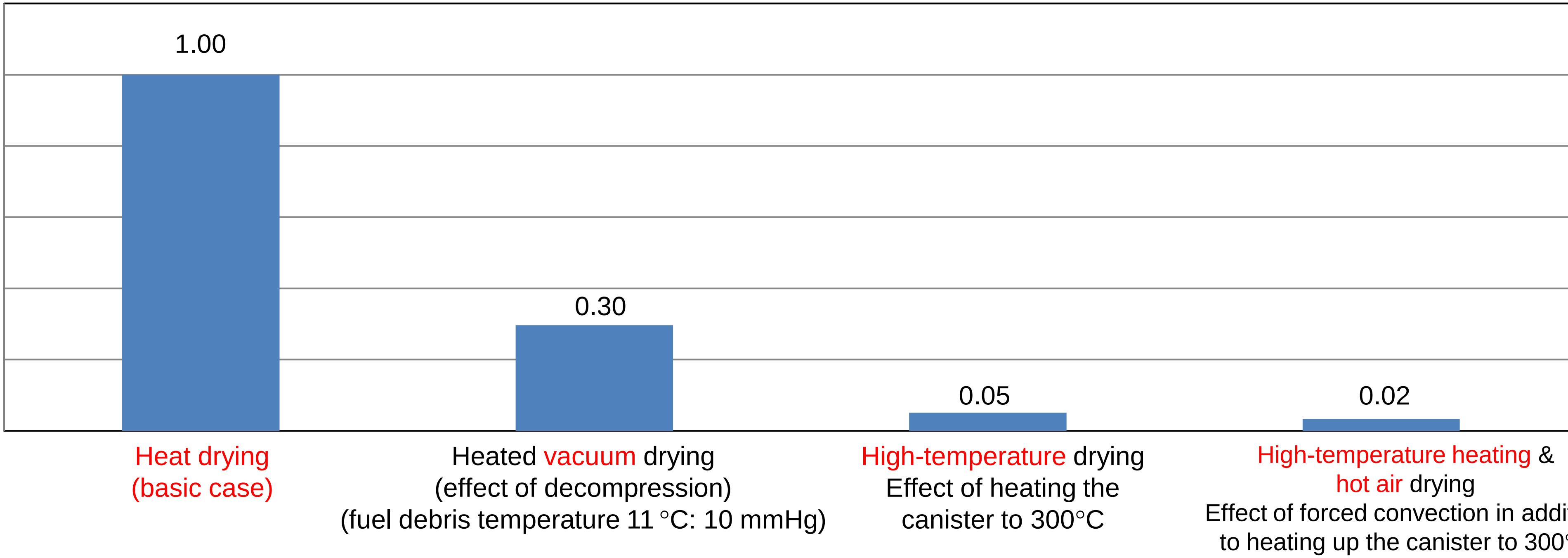


Figure: Comparison of drying time when heat drying (basic case) is expressed as 1
(Basic case: Fuel debris temperature 100°C (atmospheric pressure), canister temperature 120°C, time required without hot air)

In the basic case, when ⌀220 mm canister is filled up to 30% with fuel debris as well as 30 vol. % of water in respect to the fuel debris volume, the time required to dry is about 3 days (area II only). More time may be required if area III, which has a large uncertainty, is taken into consideration.

-> According to the results of trial calculation for the processing capacity, based on the quantity studied in 6.2.(2) (assuming 10.8 cans/day), rationalization of facilities and shortening of period may be important and, in this case, high-temperature heating and high-temperature heating & hot air drying are effective drying methods.

6. Implementation Details

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

(4) Study on drying system (6/6)

(viii) Conclusion

- **A heating method that is also effective to reduce pressure and warm air injection into the canister are effective in drying.**

(ix) Future plans

Along with heated vacuum drying which gave results in TMI-2, high-temperature drying and high-temperature heating & hot air drying will be studied since effect on ensuring throughput can be expected.

a. **Uptake results of fission product behavior (chemical form, volatility) of nuclide inside the fuel debris studied by the Fuel Debris Characterization Project Team and specify the drying temperature condition.**

b. **Study the drying method in terms of arranging apparatus for the drying system and examine the specification proposal for the drying equipment.**

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

(5) Study and review of specifications for handling device

(i) Purpose

When handling canisters, there are processes such as closing lids and hoisting canisters. Devices used for such processes are dedicated to the canisters and, as part of the system study, the basic specifications of these devices will be determined along with the canister specifications.

(ii) Summary of FY2017 studies

Examples of handling devices (lid closing device, canister hoisting attachment) based on the study on lid structure of 6.3 (2) as of now are shown below.

(iii) Future plans

The processing capacity study will be continued as the lid structure updates while taking requirements into consideration.

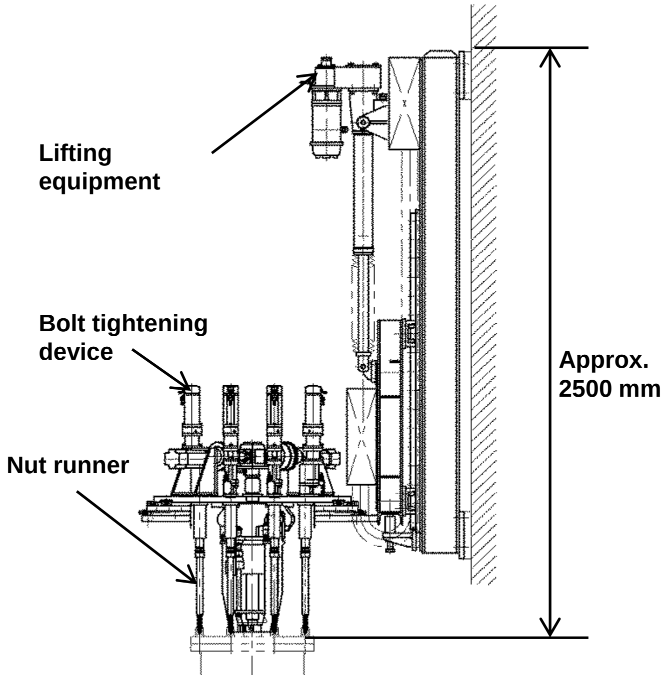


Figure: Example of lid closing device (for bolt structure 2)

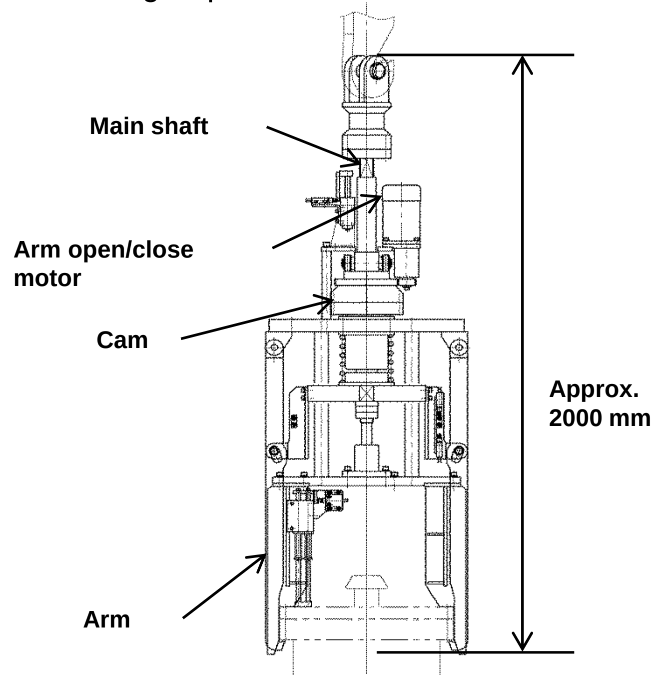


Figure: Example of canister hoisting attachment (when grabbing onto the canister itself)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(1) Safety evaluation on sub-criticality (1/5)

(i) Study on sub-criticality maintenance measures

Purpose: To select a sub-criticality maintenance measures necessary to expand the canister's inner diameter, feasibility will be evaluated in terms of inner diameter expansion effect and explainability of safety assessment.

	Fuel debris conditions	Inner diameter of canister		Explainability of safety assessment	
Base	Strictest conditions (Approx. 5 wt% UO2 + optimum deceleration state of water)	-	• Approx. 220 mm (10 mm thick, made of SUS)	⊙	• No problem in explainability
No.	Sub-criticality maintenance measures (design condition restriction items)	Inner diameter expansion effect (target inner diameter: 400 mm)		Explainability of safety assessment	
(i)	Decrease enrichment degree	△	• 400 mm cannot be achieved within the realistic range of settings for degree of enrichment. (Effect of inner diameter expansion is small between approx. 2 to 5 wt% and concentration must be reduced to about 1.7 wt% to achieve inner diameter of 400 mm.)	×	• Although it can be explained based on combustion results and fuel design specifications, they need to be guaranteed as a design condition. A low degree of enrichment with predictable effects cannot be guaranteed as the design condition. • The maximum degree of enrichment inside the reactor vessel with consideration to combustion depends on the outcome of the Criticality Control Project Team, but it is unlikely that significant reduction can be expected.
(ii)	Consider possibility of structure material mixing into fuel debris	○	• Effect is in a certain level. Expansion is dependent on mixture ratio of fuel debris and structure material inside canister.	×	• It needs to guarantee the mixture ratio of fuel debris and structure material and state of distribution as the design condition.
(iii)	Consider the possibility of neutron-absorbing material inside the reactor vessel (Gd/B4C) mixing into fuel debris	⊙	• The effect of inner diameter expansion is large. The diameter can expand to 400 mm depending on the condition but depends on the mixture ratio of fuel debris inside the canister and neutron-absorbing material inside the reactor vessel.	×	• It needs to guarantee the mixture ratio and state of distribution as the design condition.
(iv)	Inject boric acid solution	⊙	• The effect of inner diameter expansion is large. The diameter can expand to 400 mm depending on the condition.	○	• It needs to guarantee the concentration and state of distribution as the design condition. (Inspect possession of knowledge and conditions.)
(v)	Restrict water volume	○	• The effect is in a certain level. The expansion depends on the distribution condition of fuel debris and water inside the canister.	○	• It needs to guarantee the moisture content and water volume (amount of residual water) as the design condition by water volume measurement technology if applying to the 1F fuel debris retrieval site. • Less residual water compared to draining can be expected if put through dry treatment, but it needs to guarantee water volume after drying.
(vi)	Lay neutron-absorbing material inside the canister	⊙	• Inner diameter of the canister can be expanded to 400 mm by laying B-SUS plate and B4C pipe.	⊙	• The effect of accidents (e.g., deformation) needs to be confirmed, but it can basically be set as a design condition and has explainability.
(vii)	Change the canister material	△	• It is possible to expand the inner diameter by about 20 to 30 mm when the material is changed to B-SUS.	⊙	• There is explainability and sufficient usage achievement as materials for racks and baskets.

[Effect] C: Low possibility of reaching 400 mm, B: Medium possibility of reaching 400 mm, A: High possibility of reaching 400 mm, [Explainability] D: No explainability, C: Low explainability, B: Medium explainability, A: High explainability

In terms of explainability and effect, application of neutron-absorbing material is effective for expanding the inner diameter of the canister and preventing fuel debris re-criticality.
However, although restriction of water volume is simple, there is an issue in explainability. -> Consider restricting the water volume by draining the fuel debris.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(1) Safety evaluation on sub-criticality (2/5)

(ii) Study on operation of fuel debris water volume restriction (inspection on water volume measurement technology)

Purpose: To apply the restriction on water volume to enlarge the inner diameter of the canister, it was judged that quantitative guarantee by measurements is necessary since there is little margin in terms of criticality control with just draining the fuel debris. The water volume measurement methods were investigated and their applicability to 1F fuel debris retrieval at the site evaluated.

	Electric resistance	Electric capacity	Microwave	Near-infrared (light)	Neutron	Dry weight	Chemical measurement
Principle of moisture measurement	Calculated from the resistance value given when electricity is applied to the subject of measurement (insulator or semiconductor) through electrodes	Calculated from the change in electric capacity when AC voltage is applied to the subject of measurement	Calculated by irradiating the subject of measurement with microwaves and measuring the amount of energy before and after the wave passes	Calculated by irradiating infrared light on the subject of measurement and measuring its reflectivity	Calculated by irradiating fast neutrons on the subject of measurement and measuring the amount of neutrons that change their state into thermal neutrons	Measured the weight of the subject of measurement before and after drying	Standard method of moisture measurement Measured by titrating with the moisture of the subject of measurement and Karl Fischer reagent, and measuring the amount of titration which the polarization voltage changes drastically due to free iodine
Major applications (example of application)	Lumber, construction materials, sand, gravel	Construction materials, paper, gas, liquid	Lumber, construction materials, sand, gravel, food, sludge, powder	Food, minerals, chemicals, flour, sludge	Minerals, sintering raw materials, coke, sand, concrete	Food, lumber, coal, coke, minerals	Food, oil, fat, drugs
Applicability to fuel debris	Determined as not applicable for the following reasons ➢ Cannot be measured since there is a high possibility that metal from the structural materials (conductive materials) is mixed into the fuel debris ➢ Measurements are taken via unit can (steel container), so high accuracy is hard to obtain	Determined as not applicable for the same reasons as electric resistance	Determined as not applicable for the same reasons as electric resistance	Determined as not applicable for the following reasons ➢ Only the surface of the subject of measurement can be measured, so the moisture inside the fuel debris or fuel debris that is stacked up cannot be measured	Determined as not applicable for the following reasons ➢ Cannot be used as a measurement method to ensure sub-criticality since the measurement value fluctuates greatly depending on the composition of the fuel debris and accuracy cannot be guaranteed ➢ Performance cannot be guaranteed under high radiation environments	Determined as not applicable for the following reasons ➢ The fuel debris needs to be dried to measure its water volume, but it cannot be dried inside the pedestal or RPV ➢ It only measures the weight before and after the fuel debris is dried; however, it may still contain water after drying	Determined as not applicable for the following reasons ➢ Cannot be conducted inside the pedestal or RPV because reagents are very sensitive to atmospheric moisture and must be isolated from moist environment

- At the 1F fuel debris retrieval site (remotely, under radiation environment), **measurement method applicable to fuel debris, with indefinite properties, composition, and shape via canisters, was not confirmed**. Since water volume cannot be quantitatively guaranteed, water volume restriction cannot be applied to the design conditions of the criticality prevention function.

➡ **The results reveals that it is currently difficult to be designed for the condition of water volume restriction. However, water drain can be effective to reduce drying time, so this process will be applied.**

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(1) Safety evaluation on sub-criticality (3/5)

(iii) Criticality evaluation assuming dry storage (infinite array condition)

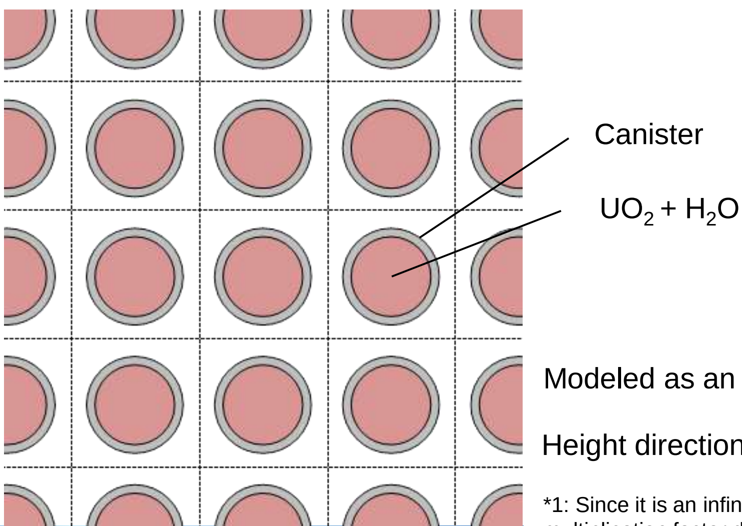
Purpose: To streamline the dry storage facility on the premise of drying, the close-packed storage conditions for canisters were clarified from the aspect of maintaining sub-criticality.

<Evaluation conditions>

- **Assumed that fuel (initial maximum concentration of pellet 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**
- **As a condition for safety, the model is created assuming the canister is arranged indefinitely (see the computational model below)**

<Evaluation results>

Even with a canister with a 220 mm inner diameter that can maintain sub-criticality on its own, the effective multiplication factor will increase when multiple canisters are arranged. In this evaluation condition, even if the inner diameter of the canister is 220 mm, water needs to be removed by drying treatment down to a volumetric water content of 0.1 or lower (margin considered) to maintain sub-criticality.-> Examine as a precondition of drying evaluation



Modeled as an infinite array*1

Height direction: Infinite

*1: Since it is an infinite array model, the effective multiplication factor does not depend on the center-to-center distance of canisters.

Figure: Computational model

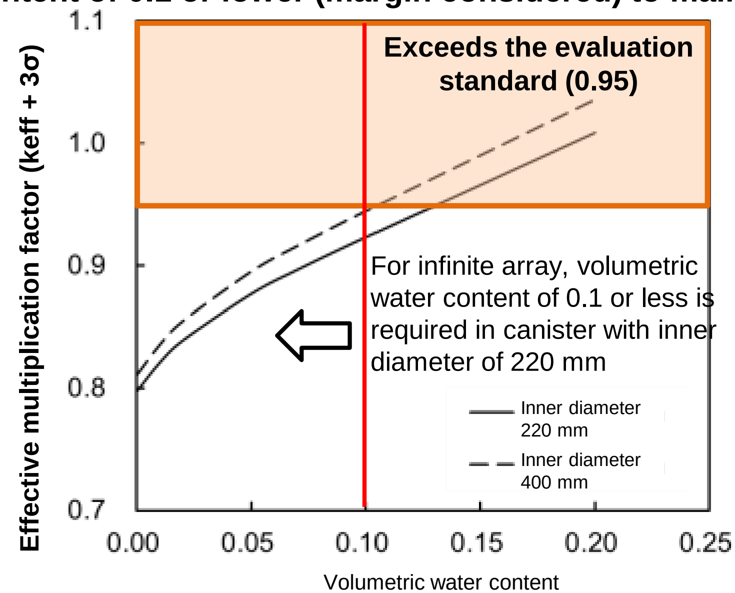


Figure: Evaluation results

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(1) Safety evaluation on sub-criticality (4/5)

(iv) Evaluation of criticality that assumes temporary storage (e.g., inside hot cell) (finite array conditions)

Purpose: Temporary storage of canisters, such as inside the R/B cell, is likely to be difficult, especially in terms of space. Close-packed storage conditions are clarified from the aspect of maintaining sub-criticality.

<Evaluation conditions>

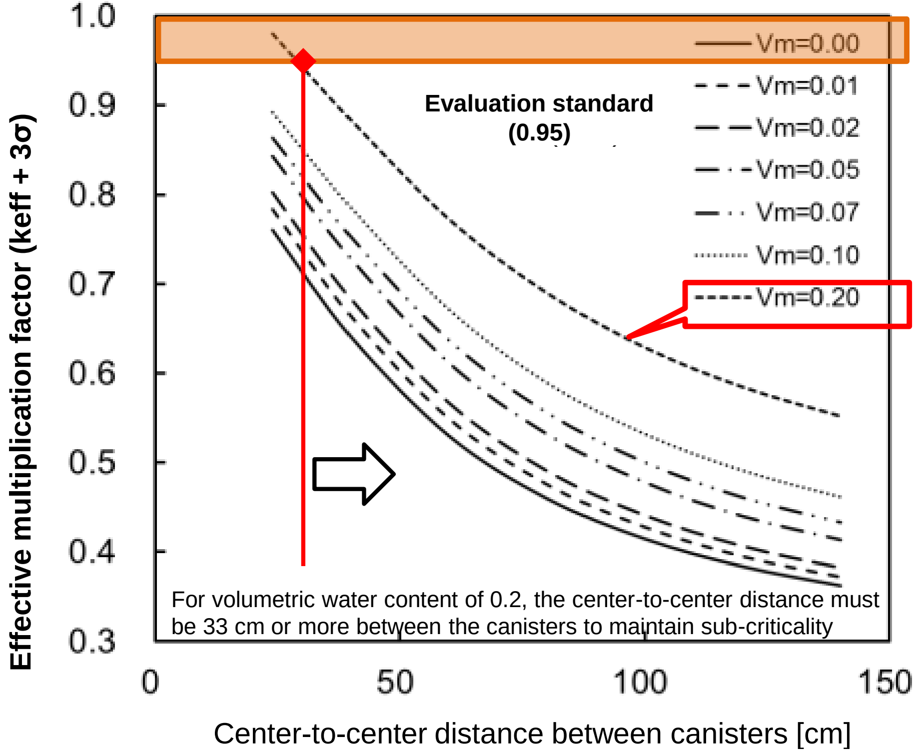
- **Assumed that fuel (initial maximum concentration of pellet 4.9 wt%) and water (residual water after drying treatment) are an even and homogeneous mixture**
- **Assumed that volumetric water content is reduced to 0.2 or less by sufficient drying**
- **Assuming temporary storage, modeled based on finite array for canister arrangement (10 × 10)**

<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 × 10 arrangement.

On the other hand, 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). Here, the storage efficiency[*1] does not depend on the inner diameter and is about 0.7[*2]. The increase in the diameter of the canister opening does not contribute to the improvement of storage efficiency.

*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 canister with inner diameter of 220 mm, 10 × 10 array system)

Figure: Evaluation results

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(1) Safety evaluation on sub-criticality (5/5)

(v) Conclusion

a. Study on sub-criticality maintenance measures

- Measures for maintaining sub-criticality when expanding the inner diameter of the canister were studied in terms of expansion effect and explainability of the safety assessment.
- As expansion of the inner diameter and the work volume of fuel debris retrieval are proportional, measures to be applied will be established in the future, taking into consideration the viewpoints other than maintenance of sub-criticality, such as requirements on handling.

b. Study on operation of fuel debris water volume restriction

- It was confirmed that restricting water volume is difficult as a means of maintaining sub-criticality when expanding the canister's inner diameter. However, as is assumed that draining fuel debris has merits in terms of operation, incorporating draining into the fuel debris handling process as a premise in each study at a degree which will not effect throughput or incidental equipment will be considered.

c. Criticality evaluation assuming dry storage

- If drying treatment performance can be obtained, the canisters can be arranged side by side. In addition to incorporating it as a requirement for examining the drying method, a sub-criticality maintenance scenario will be created, reflecting the study results of the Method Project Team, Fundamental Technology Project Team, Criticality Control Project Team, etc. concerning the handling of residual water.

(vi) Future plans

- Reflect the study results of the Method Project Team, Fundamental Technology Project Team, Criticality Control Project Team, etc. and decide on a sub-criticality maintenance scenario.

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (1/8)

(i) Purpose

The structure of a canister lid required to store fuel debris will be studied as part of the canister design. By FY2018E, a proposal of the lid's structural design will be provided, that achieves safety (necessary structural integrity), workability (necessary throughput), and other factors.

(ii) Required lid specifications

Based on the function required for canisters, proposals for required specifications of the lid structure were developed in FY2016 with consideration of remote control (see the table below).

⇒ Confinement that will not release fuel debris pieces outside the canister (includes structural integrity that guarantees confinement) and workability by remote control are necessary.

In FY2016, simple installation structures, bolt structures, and welded structures were selected as lid structures that satisfy these required specification proposals and their outlines were briefly studied.

Table: Proposal on required specifications of the canister lid structure

Items	Requirements
Confinement property	Fuel debris pieces shall not be released outside*1.
Structural strength	The lid shall not open or break even when the canister receives an effect (e.g., toppling).
	The canister shall maintain its integrity against internal pressure*2.
Workability	The lid shall be able to open and close above and under the water by remote control.
	The lid shall be able to close with simple movements (e.g., turning lid) from the aspect of workability.

*1: Since vents are basic measures of canisters against hydrogen, airtightness is not required of the lid area.
*2: Although airtightness is not required of the canister, as one of the conditions of the lid's structural design, it is required to withstand a certain level of internal pressure.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (2/8)

(iii) Organization of assumed events

Based on the latest study by experts inside and outside of IRID, the Fuel Debris Retrieval Method Project Team, and the Fundamental Technology Project Team, the canister handling flow (from retrieval to storage) was reviewed, and events that should be evaluated to ensure safety were re-identified.

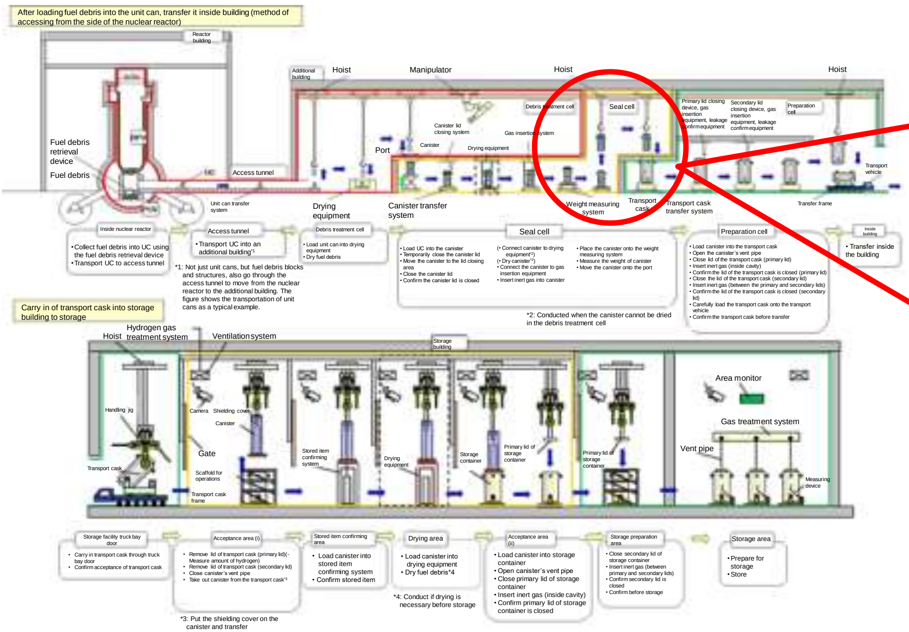


Figure: Proposal of canister handling flow

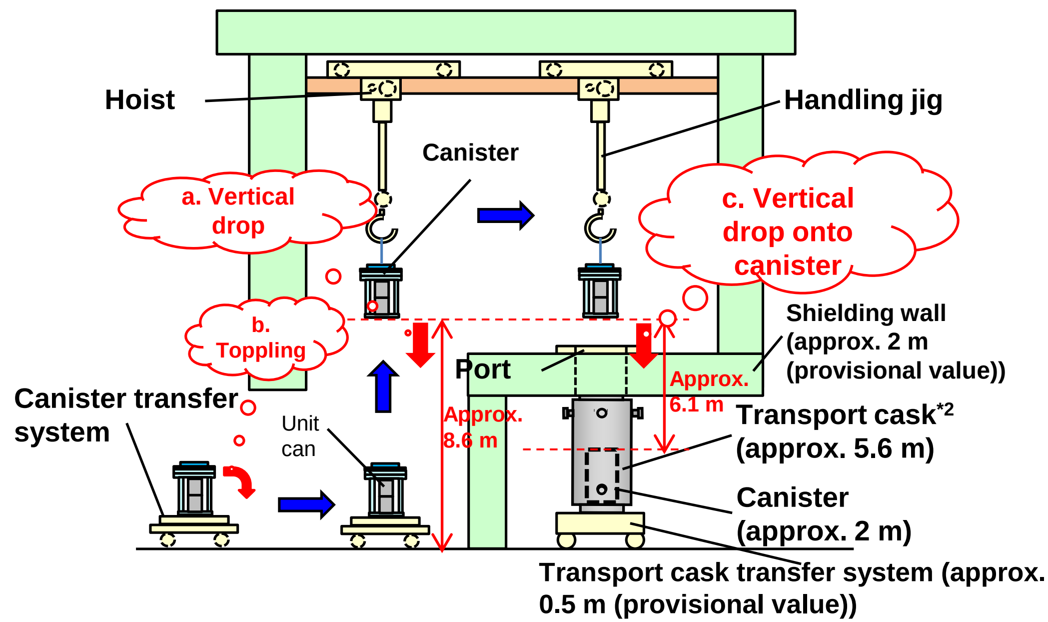


Figure: Example of event identification*1

*1: Confirmed that events in the storage facility is the same or includes these events
*2: Assumed double-stacked onto the existing spent fuel transport cask

Confirmed that a. vertical drop height is included in the 9-m height specified by FY2016 and identified that b. toppling and c. vertical drop onto canister (assume 7 m considering all events) as new events.

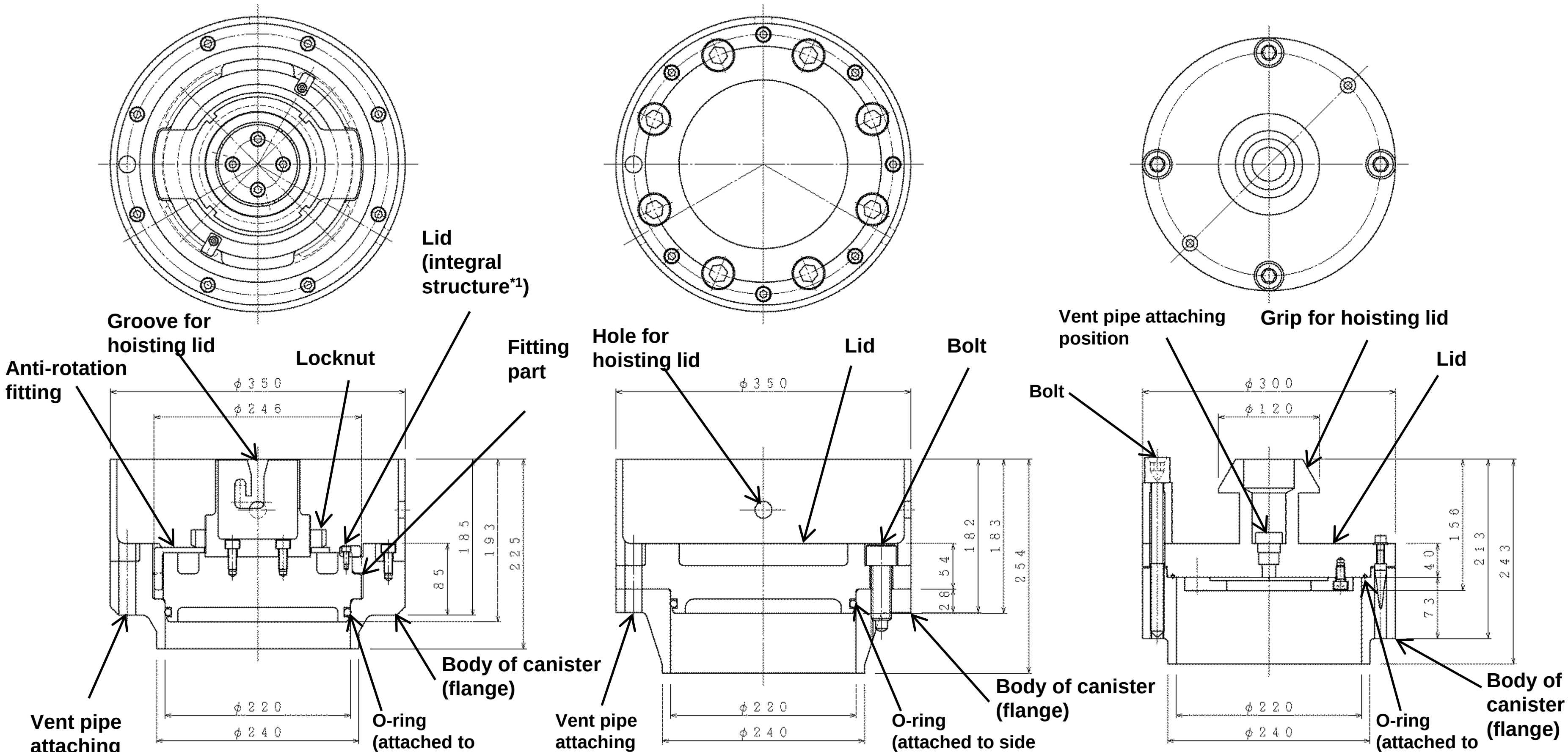
6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (3/8)

(iv) Example of lid structure design (1/2)

Along with the brief study conducted in FY2016, the lid structure proposals were studied with consideration of the radioactive waste containers. The study focused especially on the confinement property of fuel debris and workability in 1F.



(a) Simple installation structure

(b) Bolt structure 1

(c) Bolt structure 2

*1: A structure with an integrated barrel and clamp (binding) that fastens the lid plate.

Figure: Example of the lid structure design (when the inner diameter of the canister is 220 mm)

6. Implementation Details

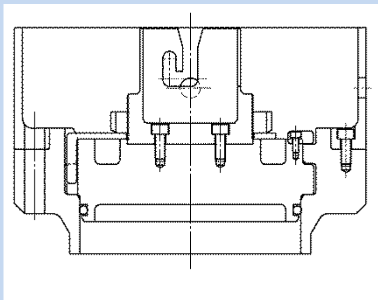
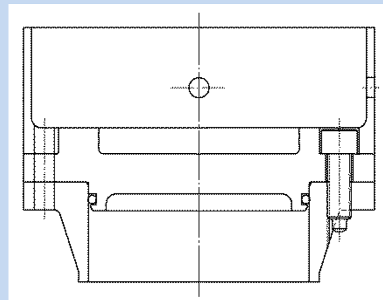
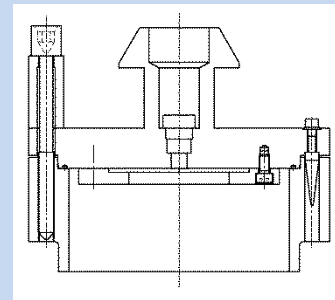
6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (4/8)

(iv) Example of lid structure design (2/2)

Comparisons were made on the designed lid structures and future evaluation policy was determined.

Table: Example of comparison between lid structure plans

Items	Simple installation structure	Bolt structure	Welded structure
Example sketch		 Bolt structure 1  Bolt structure 2	Not studied here since it will be studied in detail for weld groove
Features	<Workability> • Lid can be closed with simple steps (pushing, rotating). <Confinement property> • Confinement is ensured by squeeze of O-ring resulting from push-in of lid.	<Workability> • Remote bolt tightening is probably possible, but know-how, including torque management, is required. • Measures against galling of bolt are necessary. <Confinement property> • Confinement is ensured by squeeze of O-ring resulting from push-in of lid (bolt structure 1) or tightening of bolt (bolt structure 2).	<Workability> • There are actual results in remote welding, but the feasibility in 1F environment must be studied. <Confinement property> • Confinement is ensured by welded structure.
Example record of use	• Integral structure itself has been used in a super high pressure vessel, but changes need to be made to 1F canister (e.g., sealing method). • There are design examples for waste containers.	• Examples of remote control bolt structure containers include Rokkasho low-level waste container.	• Rokkasho glass solidified container • Canister for spent fuel (overseas)
Evaluation	This will continue to be taken into consideration as one of the options for its ease of installation. Feasibility of the proposed lid structures (e.g., structural integrity) will be evaluated in FY2018.	This will continue to be taken into consideration as one of the options for its robust lid structure. Throughput evaluation will be conducted on the lid closing task, and applicability will be evaluated in FY2018.	Considering the welding work environment, this proposal is difficult to adopt at the moment. However, there may be welding treatment at the storage facility for long-term storage, so evaluation will continue while keeping an eye on the specific progress of storage.

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (5/8)

(v) Study on a lid structure verification test (1/3)

Matters to be confirmed to assess the feasibility of designed lid structure proposals were evaluated.

Lid damage modes were studied from the aspect of the lid's confinement property (refer to the figure). The following damage modes were identified for events which the lid take effect load (e.g., drop).

a. Deformation of lid
b. Rupture of O-ring
c. Deformation of canister
d. Rupture of fitting part and bolt

Among these, regarding a., c., and d., evaluation by dynamic analysis was performed on the events identified in the study on events to be evaluated. For b., it is currently difficult to precisely simulate damage behavior of O-ring only with analysis and requires confirmation by tests.

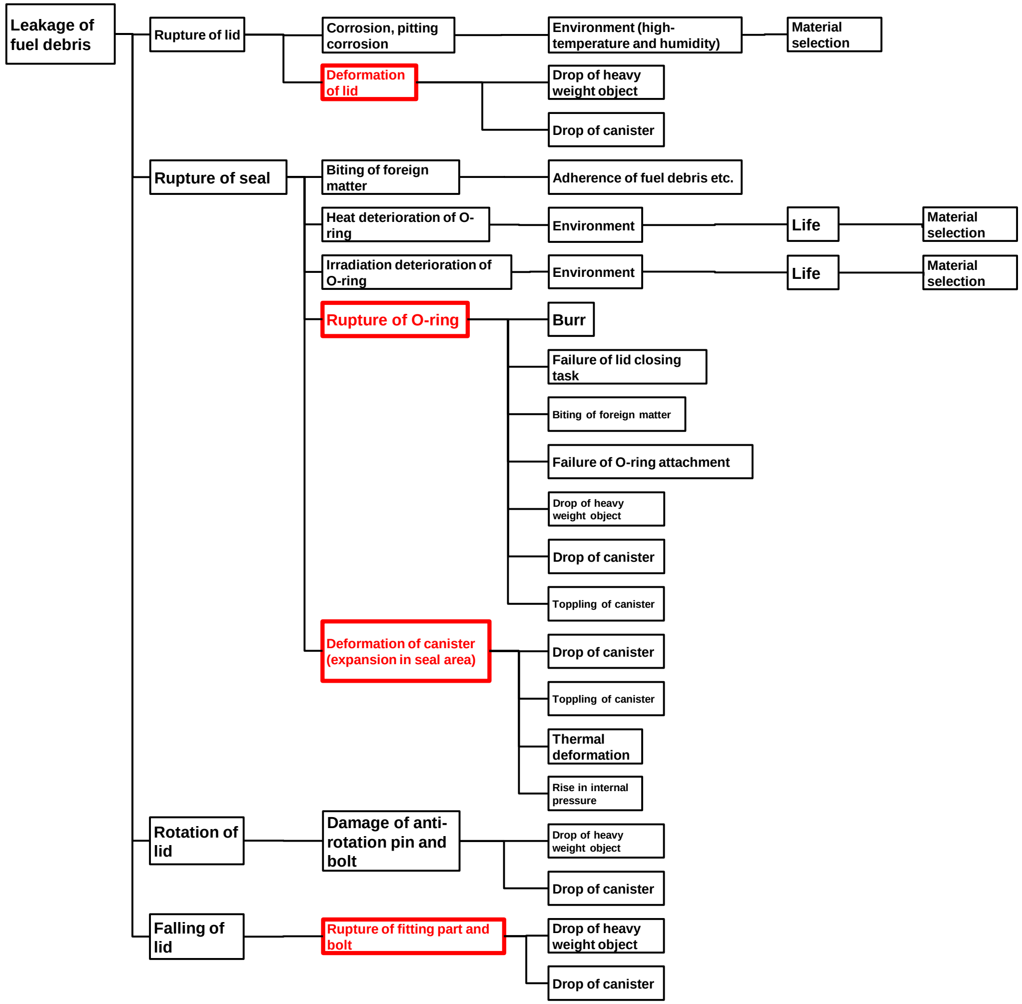


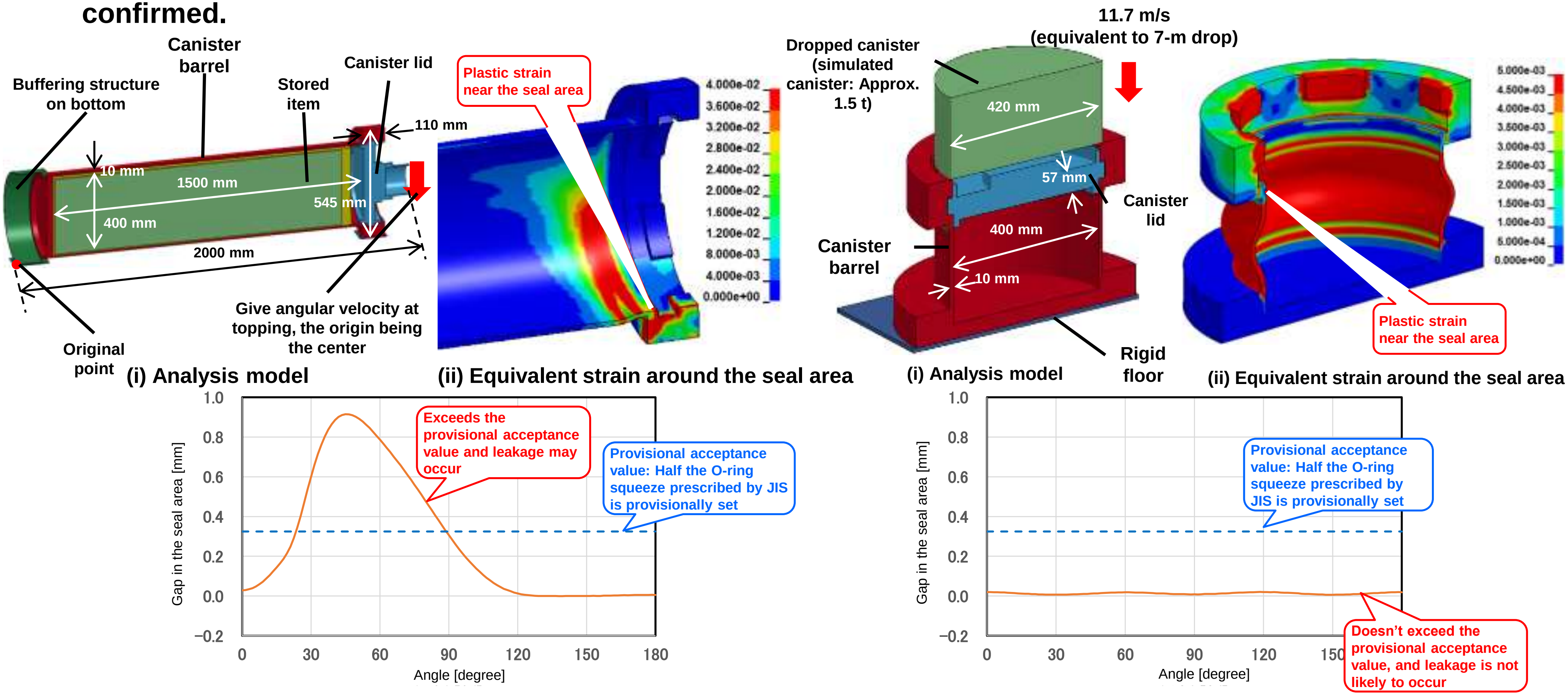
Figure: Example of identification of lid damage modes

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (6/8)

(v) Study on a lid structure verification test (2/3)

Dynamic analysis was conducted using the designed lid structure proposals on the events selected in (iii). Integrity of the confinement function against damage modes identified from the analysis results were confirmed.



(i) Analysis model | (ii) Equivalent strain around the seal area | (i) Analysis model | (ii) Equivalent strain around the seal area

(iii) Gap in the seal area*1 (180 degrees on the top)
(a) When toppled

(iii) Gap in the seal area*1
(b) Vertical drop onto canister (without buffer structure)

Figure: Example of dynamic analysis results (simple installation structure, inner diameter of canister 400 mm, temperature 300°C)

*1: Amount of gap is evaluated from the amount of deformation in the canister barrel and the lid near the sealing surface.

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (7/8)

(v) Study on a lid structure verification test (3/3)

From the analysis results, the integrity of the confinement function of the lid structure proposals was evaluated and a method of examining the validity of the evaluation results and dynamic analysis was studied.

Table: Example results of dynamic analysis of parts relevant to the confinement function of the lid (for simple installation structure) and proposal on the method of validation (for simple installation structure (inner diameter of canister: 400 mm))

Event			Deformations of lid/canister*1	Rupture of O-ring	Rupture of tab
Vertical drop	No buffering structure on bottom		No plastic deformation, approx. 0-mm gap (○)	- Cannot simulate failure behavior of the O-ring by analysis alone	No rupture*2
	Buffering structure on bottom		No plastic deformation, approx. 0-mm gap (○)		No rupture*2
	Collision between stored item and lid*3	No buffering structure on bottom	Plastic deformation, approx. 0-mm gap (○)	-	No rupture*2
		Buffering structure on bottom	No collision between stored item and lid		
Toppling			Plastic deformation, approx. 0.9-mm gap (×)	-	No rupture*2
Drop onto canister*4	No buffering structure on bottom		Plastic deformation, approx. 0.02-mm gap (○)	Cannot simulate failure behavior of the O-ring by analysis alone	No rupture*2
	Buffering structure on bottom		Plastic deformation, approx. 0-mm gap (○)	-	No rupture*2
Validity evaluation method proposal			Measure the dimensions near the sealing surface after the test by element test; confirm for leakages by leakage inspection	Confirm the condition of the O-ring after the test by element test; confirm for leakages by leakage inspection	Confirm the condition of the fitting part after the test by element test; confirm for leakages by leakage inspection

*1: Amount of gap is evaluated from the amount of deformation in the canister barrel and the lid near the sealing surface. Half the O-ring squeeze prescribed by JIS is set as the provisional acceptance value of the gap (0.325 mm). When smaller than the provisional value, ○ is given (no leakage) and when greater than the value, × is given (leakage).
*2: "No rupture" in the table means that the strain was 0.3 (30%) or less (provisional value) and was judged that rupture will not occur.
*3: An event in which the stored item jumps up and collides with inner part of the lid when the canister is dropped vertically.
*4: The collided canister is the subject of integrity evaluation of the confinement function.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(2) Safety evaluation on structural strength: Study on lid structure (8/8)

(vi) Conclusion

- Based on the latest study state of the containing, transfer, and storage WG, the Method Project Team, and the Fundamental Technology Project Team, the canister handling flow (from retrieval to storage) was reviewed and events that should be evaluated to ensure safety were re-identified.
- The lid structure proposals were studied from the aspect of confinement of fuel debris and workability in 1F.
- Regarding the identified events, lid damage modes were studied from the aspect of the lid's confinement property (release of fuel debris).
- Dynamic analysis was conducted for the damage modes and items to be evaluated were determined from the aspect of lid integrity.
- Methods to evaluate the validity of the evaluation items and integrity of the lid were studied for the specified evaluation items.

(vii) Future plans

Confirmation of feasibility including the handling of designed lid structures obtained from the study results of FY2017, and the study on integrity (especially the simple structure), validity of the evaluation items concerning the confinement property of the lid will be confirmed by element tests and analysis in FY2018. Specifically speaking, the following items will be implemented.

- Design and manufacturing of lid structure specimen
- Handling property verification test
- Structural integrity verification test (load test)

Proposal of the lid structure design will be provided based on these results.

Regarding the remote lid closing technology, since there is no need for development in the technology itself if the structure is remotely controllable, the handling confirmation test will confirm its structure.

In addition, separate from the lid structure study, a full-scale drop test scheduled for FY2020 (study of specimen design and test plan in FY2018) will be prepared.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(3) Safety evaluation regarding aging degradation: Study on canister material (1/6)

(i) Purpose

Purpose: Select canister material.

Fuel debris contains chloride ions attendant upon introduction of seawater. Taking this into account, material candidates will be selected from the aspect of crevice corrosion and chloride SCC occurrence.

(2) Details of study up to FY2016

- Nickel-based and titanium-based alloys were selected as candidates, assuming the fuel debris properties and environments with a margin. Not only is it still impossible to completely eliminate the possibility of corrosion as long as there is uncertainty in fuel debris properties, but it is also difficult to process and it was judged that it is not necessarily a rational choice.
- Taking this to account, the applicability of carbon steel and SUS316L that has been used before was evaluated. The retrieval and storage under water (pool), retrieval in air, and environment of dry storage from the aspect of crevice corrosion and SCC which are aging degradation modes of SUS316L were evaluated. The evaluation confirmed that there is almost no degradation.
  In addition, it was confirmed that sodium pentaborate that could possibly be used in terms of sub-criticality is also effective regarding corrosion resistance.

(iii) Details of study in FY2017

- The entire surface of carbon steel has corroded. Although a method to maintain structural integrity is established by defining corrosion margins from the estimated amount of corrosion, if stored in the pool for a long time, there is a possibility that corrosion occurred on the outer surface may cause difficulty in workability when re-opening the lid after storage, etc. ⇒ Carbon steel is not suitable for long-term pool storage.
- Additional evaluation was conducted mainly on SUS316L, which is effective for the still needed pool storage, since there were unstudied transfer and drying environments and the possibility of storing drained fuel debris in air was assumed. In these environments, condensation of chloride ions and high-temperature environment can be assumed. As the period is short, it may be a difficult condition for evaluation.

Reference: Chloride ion concentration record (Fukaya et al., Current Status and Challenges Related to Corrosion Control of Containment and Piping at Fukushima Daiichi, The 63rd Japan Conference on Materials and Environments, 2016)
Unit 1: 19 ppm (10/12/2012), Unit 2: 2.9 ppm (8/7/2013), Unit 3: < 1 ppm (10/22/2015)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(3) Safety evaluation regarding aging degradation: Study on canister material (2/6)

◆ **Evaluation results of corrosive resistance of SUS316L in the canister's usage environment**

There is no issue in temperatures up to about 50°C. However, crevice corrosion and cracks due to SCC become more apparent as temperature rises and their occurrence cannot be denied.

Case	Process	Period	Temperature	Evaluation
Flooded (fuel debris is flooded)	Retrieval	Max. 10 days	Ambient temperature	(○) There is a low risk of crevice corrosion and SCC.
	Transfer	Max. 10 days	Ambient temperature or up 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, it is likely to be minor as the time period is short. Given the results of the chloride ion concentration, cracks caused by SCC are likely to appear when the temperature exceeds 70°C but there is no concrete knowledge that allows us to determine a threshold. In addition, SCC tends to become more apparent as temperature increases.
	Wet storage (pool)	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, there is a low risk of crevice corrosion and SCC.
Dry (fuel debris is dry)	Drying	Max. 10 days	Max. 300°C	(△) There is no problem when dried at ambient temperature or up to about 50°C. Given the results of the chloride ion concentration, cracks caused by SCC is likely to appear when the temperature exceeds 70°C. However, since there is no concrete knowledge and cracks are dependent on the behavior of the ion concentration, a specific threshold cannot be determined. In the water pool inside the canister, crevice corrosion is also expected due to the rise of corrosion potential caused by hydrogen peroxide solution. However, since hydrogen peroxide is easy to escape into the gas phase at high temperatures and since the period is short (about 10 days), it is believed that it is unlikely that it will be an issue. However, there is no specific knowledge to base our judgment.
	Transfer	Max. 10 days	Ambient temperature or up to 150°C	(○) Corrosion and SCC will not occur after fuel debris is dried.
	Dry storage	Max. 50 years	Ambient temperature or up to 150°C	(○) Corrosion and SCC will not occur after fuel debris is dried.
Aerial (fuel debris is drained and wet)	Retrieval	Max. 10 days	Ambient temperature	(○) There is a low risk of crevice corrosion and SCC. In addition, since the drying and concentration environments are not active, the risk of SCC is low.
	Transfer	Max. 10 days	Ambient temperature or up to 150°C	(△) Same as the drying process.
	Wet storage (pool)	Max. 50 years	Up to 40°C	(○) The temperature is low so there is a low risk of crevice corrosion and SCC.
	Aerial storage (Inside hot cell etc.)		Ambient temperature or up to 150°C	(△) Moisture remains in the fuel debris. When it contains moisture and is stored in a high-temperature for a long period of time, hydrogen peroxide may generate. Therefore, compared with the drying process, there is a higher risk of crevice corrosion and formation of cracks caused by SCC.

○: Low risk of corrosion　　△: Cannot deny the possibility of corrosion at present

Common matters) Atmosphere: Nitrogen or argon gas atmosphere (Wet storage pool is assumed to be installed in an atmospheric environment)

Water quality: Chloride ion concentration around 1 ppm (real results), hydrogen peroxide around 3 ppm (set as ambient temperature based on documents)

Concentration of hydrogen peroxide is affected by the environment (e.g., temperature).

6.3 Development of Safety Evaluation Methods and Validation

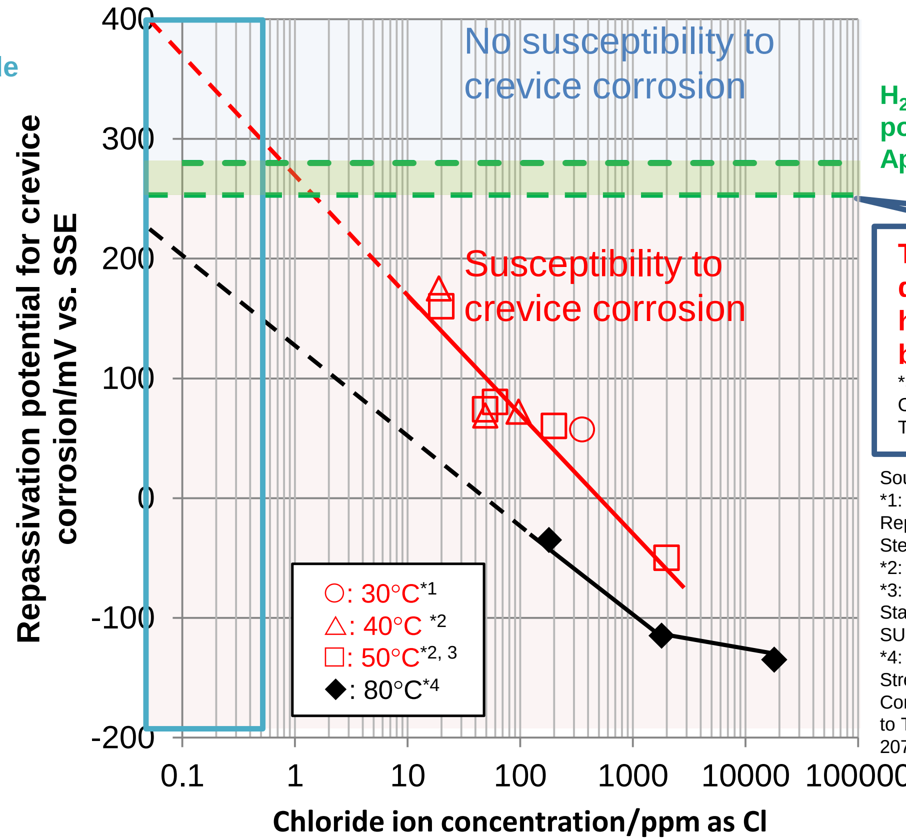
(3) Safety evaluation regarding aging degradation: Study on canister material (3/6)

◆ **Evaluation results of SUS316L crevice corrosion susceptibility**

- **In temperatures between about 30 and 50°C, the risk of crevice corrosion is low even when the potential rises due to hydrogen peroxide.**
- **At about 80°C, 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, the rise in potential will be minor in a short period of time, and the option of dealing with it by creating a design that will not increase the effect is available.

Estimated water quality inside canister < 1 ppm as Cl



H_2O_2: Results of trial calculation on rise of potential at 0.4 to 3.4 ppm
Approx. 250 to 280 mV vs. SSE (100°C or lower)

Tolerance to crevice corrosion changes depending on the concentration of hydrogen peroxide but is almost constant between 0.4 to 3.4 ppm*5

*5: Kikuchi et al. (1987). Effects of Hydrogen Peroxide and Dissolved Oxygen on Corrosion Potential of Type 304 Stainless Steel in High-Temperature Water. Corrosion Engineering. (Vol. 36, pp. 721–724)

Source of data
*1: Imai et al. (1992).
Repassivation Potential for Crevice Corrosion of SUS 316 Stainless Steel/Teflon Ball Crevice. Surface Finishing. (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 chlorine ion concentration using crevice corrosion re-passivation potential

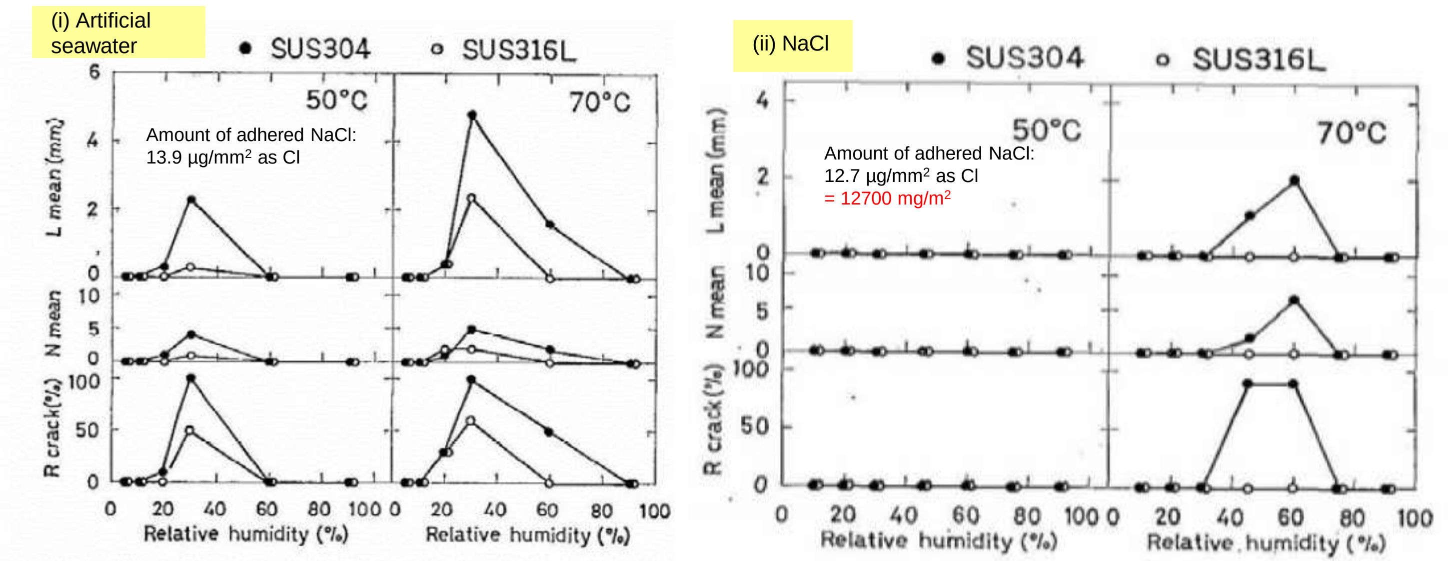
6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(3) Safety evaluation regarding aging degradation: Study on canister material (4/6)

◆ **Atmospheric stress corrosion cracking evaluation of SUS304 and SUS316L**

- **Stress corrosion cracking in the atmosphere is sensitive to relative humidity and depends on the temperature, relative humidity, and concentration of chloride ion etc. in a solution. Crack sensitivity is lost below criticality conditions. (Refer to the figure below)**
- **The chloride ions in the canister is thought to derive from sodium chloride. No cracks developed in SUS316L in the two-week test (70°C, 12,700 mg/m² of NaCl deposit). From this it can be expected that by further reducing the concentration of chloride ions, cracks will not appear in SUS316L in a short period of time, even in a 70°C environment.**
- **However, the threshold cannot be determined at this point because there is no knowledge in the existing documents that quantitatively shows the relationship between chloride ion concentration and occurrence of SCC in SUS316L in the temperature range (70°C or higher) that is assumed for 1F canisters.**



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

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

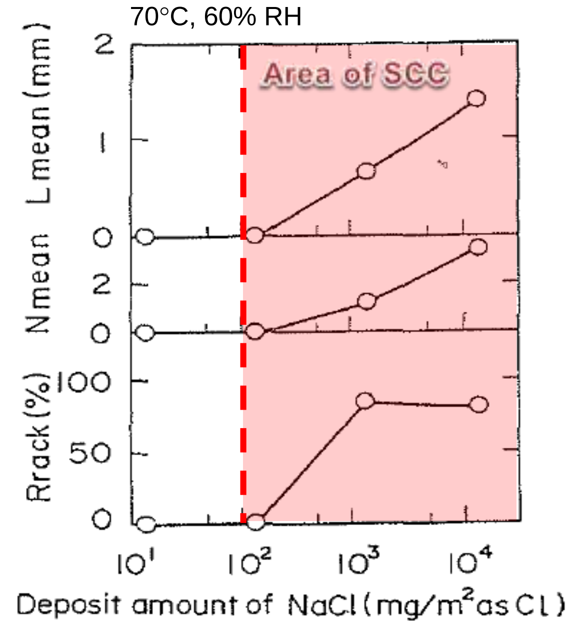


Figure: U-bend SCC test results of SUS304 that was dripped of NaCl solution and exposed to radiation for a week under constant temperature and humidity*2

*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 Validation

(3) Safety evaluation regarding aging degradation: Study on canister material (5/6)

◆ **Atmospheric stress corrosion cracking evaluation 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 10,000 times lower than that of a solution with the amount of chlorine which would cause cracks and similar to that of fresh water. However, the drying environment (adherence environment) differs from the environment inside the canister, so it is unknown how much 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/m² of sodium chloride (70°C, 60% RH) (condition in which cracks formed on SUS304). Considering that the water is diluted by 10,000 times with respect to the chloride ion concentration of the solution in which cracks form, it can be expected that the risk of cracks is extremely low.**
- **On the other hand, as mentioned in the previous section, since cracks caused by SCC tend to appear more as temperature rises, the possibility of cracks forming on SUS316L at 70°C or higher cannot be denied.**

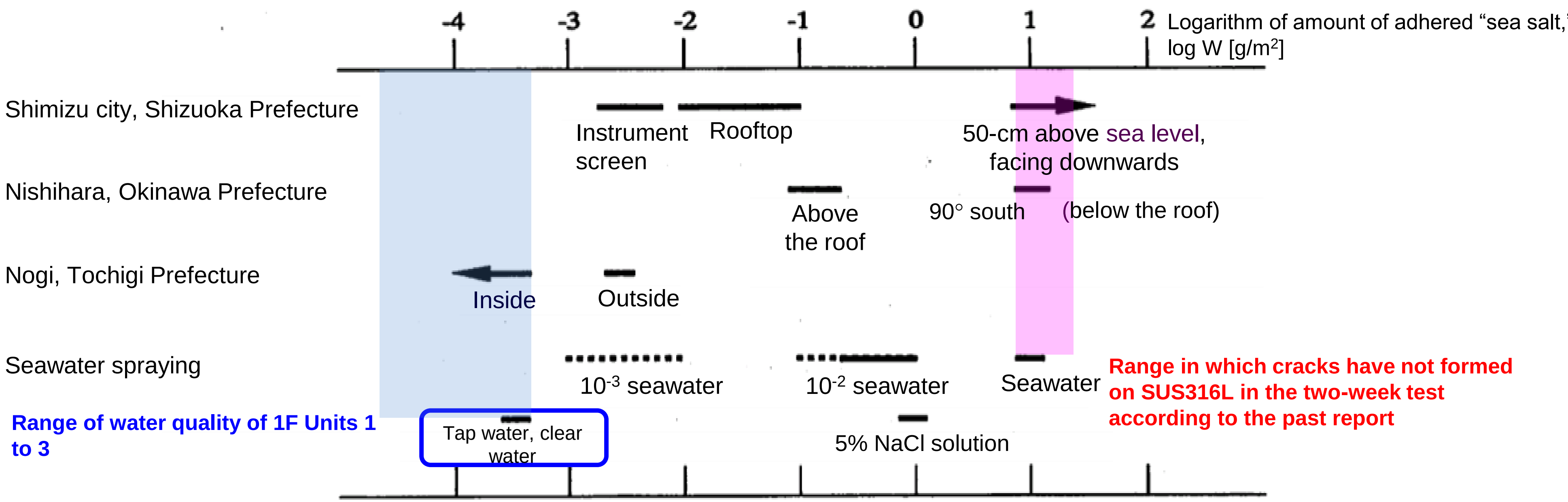


Figure: Amount of adhered sea salt in various environments[*2]

*1: Yuichi Fukaya, Katsuhiko Kumagai. (2016). Current Status and Challenges Related to Corrosion Control of Containment 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 the1998 Weathering Technology Research Presentation. (No. 3, 15-24)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(3) Safety evaluation regarding aging degradation: Study on canister material (6/6)

(iv) Future plans

In a high-temperature environment, risk of crevice corrosion and SCC in SUS316L material tend to increase. However, the risk can be dealt with by restricting the canister shape and handling method to prevent the effect of corrosion from surfacing, and a margin can be set so that minor damages on the canister will not effect safety. In addition, nickel-based alloys etc. with better corrosion resistance have issues such as difficulty in processing. For these reasons, SUS316L will be a candidate material and study of countermeasures (limiting conditions) will be prioritized.

Even if element tests are conducted as follows, the corrosive environment itself depends on the canister's design condition. Therefore, to confirm the possibility and degree of corrosion, the necessity of the test again based on the above study will be judged.

- Water resides for a long period of time in a high-temperature in aerial storage*1 and there is a possibility that hydrogen peroxide solution that greatly effects the occurrence of crevice corrosion will form. On the other hand, since the concentration of the hydrogen peroxide solution depends on the state of water, it is predicted that it will be affected by the canister shape. In addition, the assumed period of aerial storage*1 is not clear.
- Although it is believed there is margin in the concentration of chloride ions in the drying process, it is assumed that it will be affected by the drying method and canister shape.

*1: The fuel debris is drained and wet.

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (1/10)

(i) Purpose

Up to FY2016, the hydrogen generation that considers the 1F water quality conditions (seawater component, iodine, concrete) has been studied by gamma-ray irradiation test. As a result, the hydrogen generation under gamma-ray irradiation can be evaluated using the primary G value of hydrogen generation (0.45 molecules/100eV), even when taking 1F water quality conditions into account.
However, when the gas-liquid ratio is high, there is a possibility that the decline in pH of the liquid phase caused by the nitric acid generated by the radiolysis and oxidization of nitrogen in the gas phase effects the hydrogen generation.

In addition, in a condition where the hydrogen generation amount is small and the error will be large, there were cases where the apparent G value exceeded the primary G value of hydrogen generation (0.45 molecules/100eV).

Therefore, an additional gamma-ray irradiation test was conducted to confirm the effect of nitric acid production as well as evaluate the reason the apparent G value exceeded the primary G value of hydrogen genetation (0.45 molecules/100eV). It was aimed to reflect it as necessary to evaluate hydrogen generation amount.

(ii)Implementation details

Tests with different gasses in the gas phase (air, nitrogen, argon) were conducted to confirm its effect. In addition, considering the current chloride ion concentration, tests with reduced chloride ion concentration were conducted to confirm the effect of chloride ion.

Regarding the FY2016 test, it was confirmed the validity of the apparent G value obtained under the condition which the apparent G value exceeded the primary G value of hydrogen generation (0.45 molecules/100eV).

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

No.55

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (2/10)

(iii) Test method

Similarly to FY2016, gamma-ray was irradiated from the outside to the container which the test water was sealed in and the apparent G value was calculated from the pressure variation.

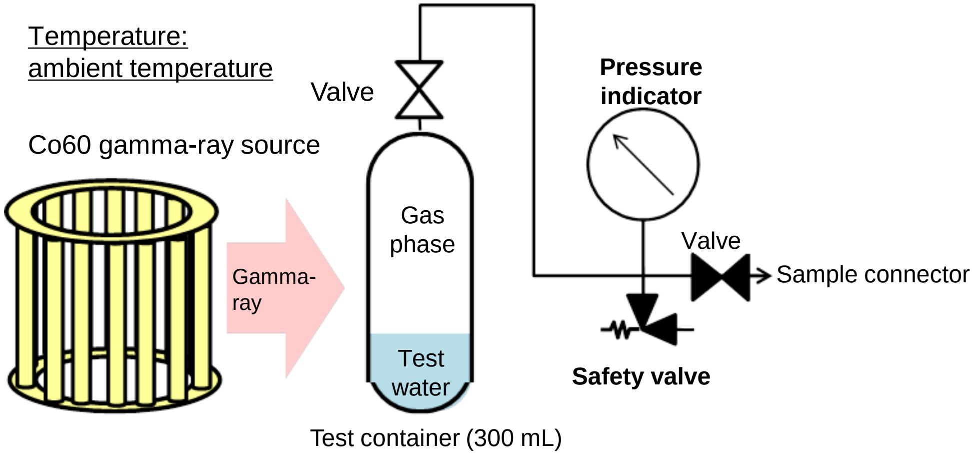


Figure: Overview of the test system

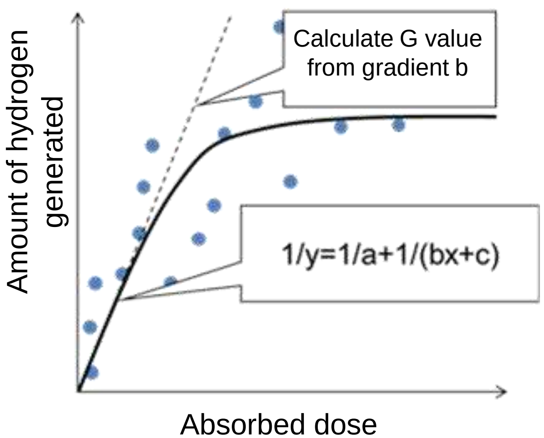


Figure: Calculation method of apparent G value

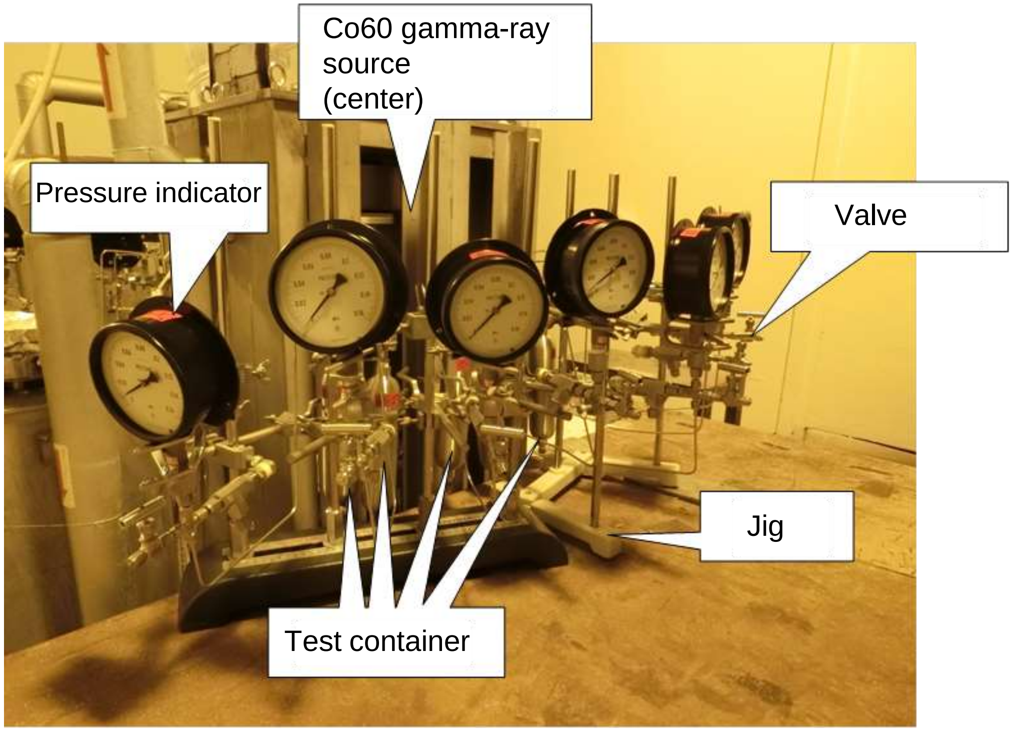


Figure: Test conditions

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (3/10)

(iv) effect assessment test on gas phase (1/2)

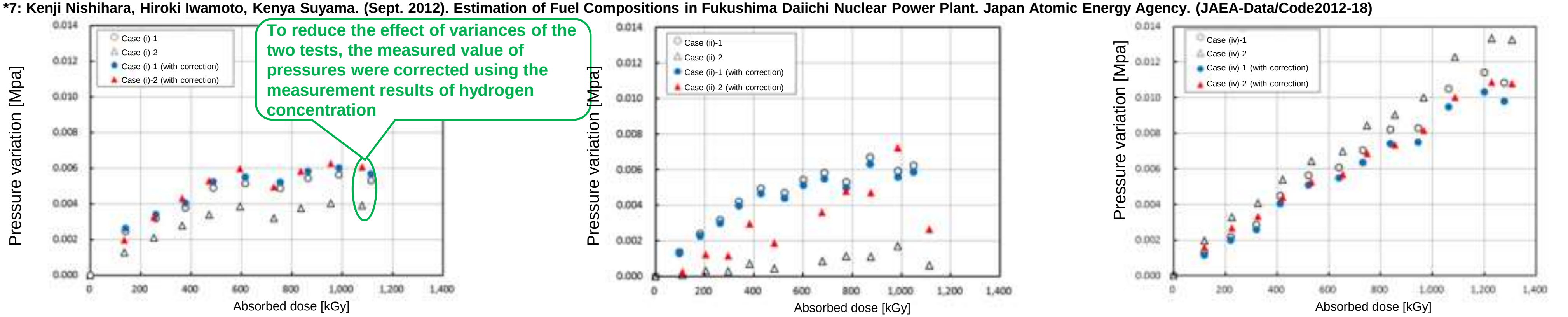
By FY2016, it was revealed that the decline in pH of the liquid phase caused by the nitric acid generated by radiolysis and oxidization of nitrogen in the gas phase under gamma-ray irradiation promotes the hydrogen generation in ~~a~~ the seawater component coexistence system.

-> The tests that charged the gas type in the gas phase conduct to confirm the effect on suppression of nitric acid and hydrogen generation.

Table: Test conditions for effect assessment of gas phase

Case	Gas in gas phase	Seawater component concentration*1 (chloride ion concentration) [mol/L]	Iodide ion concentration [mol/L]	Gas-liquid ratio*2 [%]	Temperature	Absorbed dose [kGy]	Number of tests	Notes
(i)	Air	2.8×10^{-3} *3	1.0×10^{-4} *4	900	Ambient temperature*5	Max. 1,000*5	2	Same conditions as FY2016
(ii)	Nitrogen	2.8×10^{-3} *3	1.0×10^{-4} *4	900	Ambient temperature*5	Max. 1,000*5	2	Conditions that exclude initial oxygen which causes nitric acid generation
(iii)	Nitrogen	2.8×10^{-3} *3	0	900	Ambient temperature*5	Max. 1,000*5	2	
(iv)	Argon	2.8×10^{-3} *3	1.0×10^{-4} *4	900	Ambient temperature*5	Max. 1,000*5	2	Conditions that exclude nitrogen which causes nitric acid generation
(v)	Argon	2.8×10^{-3} *3	0	900	Ambient temperature*5	Max. 1,000*5	2	

*1: Uses diluted artificial seawater*2: Volume of gas phase / volume of liquid phase*3: Equivalent to 100 ppm as chloride ion concentration, determined by the water quality criteria*6 of 1F stagnant water
*4: Determined on the assumption that 10% of the iodine inventory*7 in the core fuel of 1F leaches*5: Same conditions as FY2016
*6: Council for the Decommissioning of TEPCO's Fukushima Daiichi. (Mar. 28, 2013). Evaluation on the Early Realization of Circulation Loop in the Building and Reduction of Circulation Line. 1st Secretariat Meeting. (Material 3-1, Circulating Injection Cooling)
*7: 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)



(a) Case (i) (b) Case (ii) (c) Case (iv)

Figure: Example of pressure measurement (includes correction by hydrogen generation amount)

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (4/10)

(iv) effect assessment test on gas phase (2/2)

a. When iodine concentration is high: Regardless of the pH (the degree of nitric acid production), the apparent G values are about 0.20 and same when errors are considered.

-> Under iodine-dominant conditions, it is assumed that replacement of gas in the gas phase is ineffective.

b. When iodine concentration is low: There is a possibility that, in conditions which the pH declines (nitric acid generates), hydrogen generation is promoted by seawater component and in conditions which the pH does not change (nitric acid does not generate), hydrogen generation is suppressed.

-> It is assumed that replacement of gas in the gas phase is effective.

However, iodine is assumed to leach out from the fuel debris and cannot be controlled.

-> It is necessary to consider the presence of a certain amount of iodine.

Table: Test results of effect assessment of gas phase (evaluated based on the value corrected by the measured value of hydrogen concentration in gas phase*1)

Case2	Test conditions				Test results			
	Gas in gas phase	Seawater component concentration*2 (chloride ion concentration) [mol/L]	Iodide ion concentration [mol/L]	Gas-liquid ratio*3 [%]	Hydrogen concentration in gas phase*4 [vol/%]	Nitric acid ion concentration in liquid phase*4 [mg/L]	pH of test water*4, *5 [-]	Apparent G value*6 [molecules /100eV]
(i)	Air	2.8×10^{-3} *7	1.0×10^{-4} *8	900	3.78/4.05	130/130	3.4/3.3	0.09 ± 0.23
(ii)	Nitrogen	2.8×10^{-3} *7	1.0×10^{-4} *8	900	3.92/4.82	92/110	4.4/3.4	0.11 ± 0.29
(iii)	Nitrogen	2.8×10^{-3} *7	0	900	2.44/4.13	120/140	3.1/3.1	0.09 ± 0.04
(iv)	Argon	2.8×10^{-3} *7	1.0×10^{-4} *8	900	6.53/7.20	13/13	6.1/6.4	0.20 ± 0.05
(v)	Argon	2.8×10^{-3} *7	0	900	1.94/2.93	14/16	5.6/6.4	0.05 ± 0.02

a. Comparison between conditions with high iodine concentration

b. Comparison between conditions with low iodine concentration

*1: Corrected the measured value of pressure using the measurement results of hydrogen concentration in the gas phase*2: Uses diluted artificial seawater*3: Volume of gas phase / volume of liquid phase
*4: Two tests are conducted per case and both test results are shown*5: Value at water temperature of 25°C, pH value measured before the test was 6.5 (almost neutral)
*6: Results of the two tests are used as a single data to calculate the apparent G value*7: Equivalent to 100 ppm in chloride ion concentration, determined by the water quality criteria*9 of 1F stagnant water
*8: Determined on the assumption that 10% of the iodine inventory*10 in the core fuel of 1F leaches
*9: Council for the Decommissioning of TEPCO's Fukushima Daiichi. (Mar. 28, 2013). Evaluation on the Early Realization of Circulation Loop in the Building and Reduction of Circulation Line. 1st Secretariat Meeting. (Material 3-1, Circulating Injection Cooling)
*10: 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)

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount : Confirmation on effect of gas phase (gamma-ray irradiation test) (5/10)

(v) effect assessment of seawater (1/2)

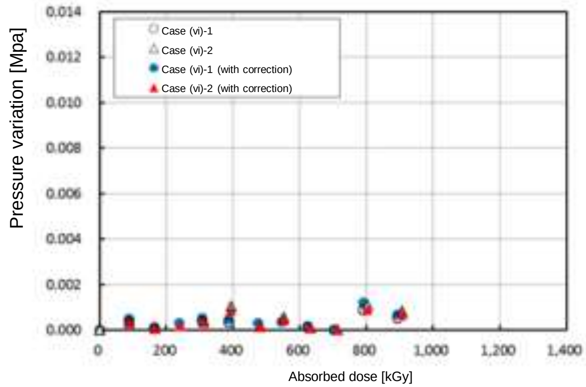
In the test conducted up to FY2016, the concentration of chloride ions was determined based on the water quality criteria of 1F stagnant water in the reactor building. Here considering the results of the investigation inside the PCV, the effect on hydrogen generation with reduced concentration of seawater component will be confirmed.

-> In the tests up to FY2016, the chloride ion concentration was 2.8×10^{-3} mol/L (equivalent to 100 ppm*1).
Tests were conducted with concentration of 0 mol/L (0 ppm) and 5.6×10^{-4} mol/L (equivalent to 20 ppm*2).

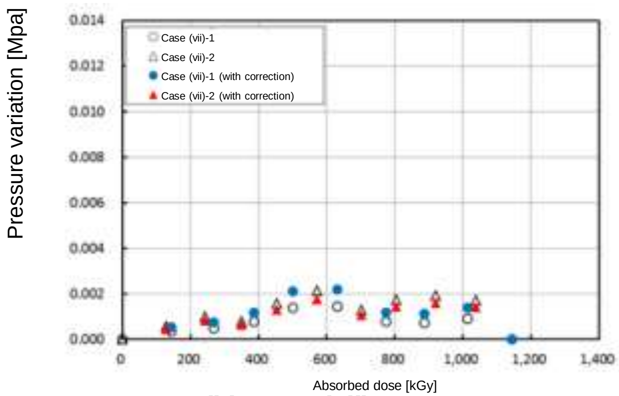
Table: Test conditions for effect assessment of seawater

Case	Gas in gas phase	Seawater component concentration*3 (chloride ion concentration) [mol/L]	Iodide ion concentration [mol/L]	Gas-liquid ratio*4 [%]	Temperature	Absorbed dose [kGy]	Number of tests	Notes
(vi)	Air	0 (0 ppm)	0*6	900	Ambient temperature*7	Max. 1,000*7	2	
(vii)	Air	5.6×10^{-4} *5	0*6	900	Ambient temperature*7	Max. 1,000*7	2	

*1: Determined by the water quality criteria*8 of 1F stagnant water*2: Determined by the measurement results of Unit 1 (approx. 19 ppm)*9*3: Uses diluted artificial seawater
*4: Volume of gas phase / volume of liquid phase*5: Equivalent to 20 ppm in chloride ion concentration*6: Iodine ion is not added so that effect of seawater can be observed
*7: Same conditions as FY2016
*8: Council for the Decommissioning of TEPCO's Fukushima Daiichi. (Mar. 28, 2013). Evaluation on the Early Realization of Circulation Loop in the Building and Reduction of Circulation Line. 1st Secretariat Meeting. (Material 3-1, Circulating Injection Cooling)
*9: 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)



(a) Case (vi)



(b) Case (vii)

Figure: Example of pressure measurement (includes correction by hydrogen generation amount

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (6/10)

(v) effect assessment of seawater (2/2)

Comparison between this test result and the test result of FY2016 shows that, even under a condition with reduced pH that would promote hydrogen generation, the apparent G value will be about 0 if the concentration of the seawater component is low (chloride ion concentration of 5.6 × 10^{-4} mol/L (equivalent to 20 ppm) or lower).

-> It was revealed that when the concentrations of seawater component and iodine are sufficiently low, the apparent G value will reduce due to progress in reaction of hydrogen recombination.

Table: Test results for effect assessment of seawater (evaluated based on the value corrected by the measured value of hydrogen concentration in gas phase*1 (results of FY2017 only))

Case	Test conditions				Test results			
	Gas in gas phase	Seawater component concentration*2 (chloride ion concentration) [mol/L]	Iodide ion concentration [mol/L]	Gas-liquid ratio*3 [%]	Hydrogen concentration in gas phase*4 [vol/%]	Nitric acid ion concentration in liquid phase*4 [mg/L]	pH of test water*4, *5 [-]	Apparent G value*6 [molecules /100eV]
(vi)	Air	0	0*7	900	0.80/0.68	160/160	2.9/2.9	0
(vii)	Air	5.6 × 10^{-4} *8	0*7	900	0.93/1.68	150/130	3.0/2.9	0.01 ± 0.02
Reference (FY2016 test results)	Air	2.8 × 10^{-3} *9	0	900	10.1	270	2.8	0.21 ± 0.01

*1: Corrected the measured value of pressure using the measurement results of hydrogen concentration in the gas phase
*2: Uses diluted artificial seawater
*3: Volume of gas phase / volume of liquid phase
*4: Two tests are conducted per case and both test results are shown; however, only one test is conducted in FY2016
*5: Value at water temperature of 25°C, pH value measured before the test was 6.5 (almost neutral)
*6: Results of the two tests are used as a single data to calculate the apparent G value; however, evaluation in FY2016 uses the result from a single test
*7: Iodine ion is not added so that effect of seawater can be observed
*8: Determined on the assumption that 10% of the iodine inventory*10 in the core fuel of 1F leaches
*9: Equivalent to 100 ppm in chloride ion concentration, determined by the water quality criteria*11 of 1F stagnant water
*10: 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)
*11: Council for the Decommissioning of TEPCO's Fukushima Daiichi. (Mar. 28, 2013). Evaluation on the Early Realization of Circulation Loop in the Building and Reduction of Circulation Line. 1st Secretariat Meeting. (Material 3-1, Circulating Injection Cooling)

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (7/10)

(vi) Verification of validity of G value (1/2)

In the FY2016 test, there were several cases where the apparent G values exceeded the primary G value of hydrogen generation (0.45 molecules/100eV).

It was revealed that, in conditions where rise in pressure is small, the apparent G value is more susceptible to changes in atmospheric pressure and temperature, and there are issues in measurement and evaluation accuracy.

-> Regarding the behavior in the initial phase of irradiation which has great effect on the evaluation of apparent G value, it was aimed to improve accuracy by measuring the hydrogen concentration directly.

*: In previous evaluations on the apparent G value by pressure measurement, changes over time can be observed without disturbing the system. It benefits us to see the changes in reaction when evaluating a closed system such as the canister during transfer. However, when the amount of hydrogen generation is small, changes in atmospheric pressure and temperature will be similar to the amount of hydrogen generation. This effects the measurement and causes greater errors. The method of measuring the hydrogen concentration at regular time intervals can evaluate the amount of hydrogen generation at that point in time very accurately, but sampling requirements disturb the system. In closed systems, the test would have to be terminated.

Table: Test conditions for verification of validity of G value

Case	Gas in gas phase	Seawater component concentration*1 (chloride ion concentration) [mol/L]	Iodide ion concentration [mol/L]	Gas-liquid ratio*2 [%]	Temperature	Absorbed dose [kGy]	Number of tests	Notes
(viii)	Air	2.8×10^{-3} *3	1.0×10^{-4} *4	500	Ambient temperature*5	10	3	
(ix)	Air	2.8×10^{-3} *3	1.0×10^{-4} *4	500	Ambient temperature*5	20	3	
(x)	Air	2.8×10^{-3} *3	1.0×10^{-4} *4	500	Ambient temperature*5	30	3	
(xi)	Air	2.8×10^{-3} *3	1.0×10^{-4} *4	500	Ambient temperature*5	300	3	Pressure was measured for reference in one of the three tests

*1: Uses diluted artificial seawater
*2: Volume of gas phase / volume of liquid phase
*3: Equivalent to 100 ppm in chloride ion concentration, determined by the water quality criteria*6 of 1F stagnant water
*4: Determined on the assumption that 10% of the iodine inventory*7 in the core fuel of 1F leaches
*5: Same conditions as FY2016
*6: Council for the Decommissioning of TEPCO's Fukushima Daiichi. (Mar. 28, 2013). Evaluation on the Early Realization of Circulation Loop in the Building and Reduction of Circulation Line. 1st Secretariat Meeting. (Material 3-1, Circulating Injection Cooling)
*7: 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)

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (8/10)

(vi) Verification of validity of G value (2/2)

In the test conducted in FY2017, **the apparent G value evaluated based on the measurement results of hydrogen concentration was 0.32 molecules/100eV. This is lower than the primary G value of hydrogen generation (0.45 molecules/100eV) and is about half the test result of FY2016** (0.57 molecules/100eV).
In addition, **the apparent G value evaluated from the pressure measurement results** as a reference value*1 **was 0.23 molecules/100eV.** This was **almost the same** as the apparent value evaluated based on the measurement results of hydrogen concentration.

-> It is assumed that the **apparent G value in the FY2016 test results** may have been evaluated larger.

*1: The data is of the initial phase of irradiation up to 300 kGy. There are only three points of pressure measurement and the apparent G values are reference values.

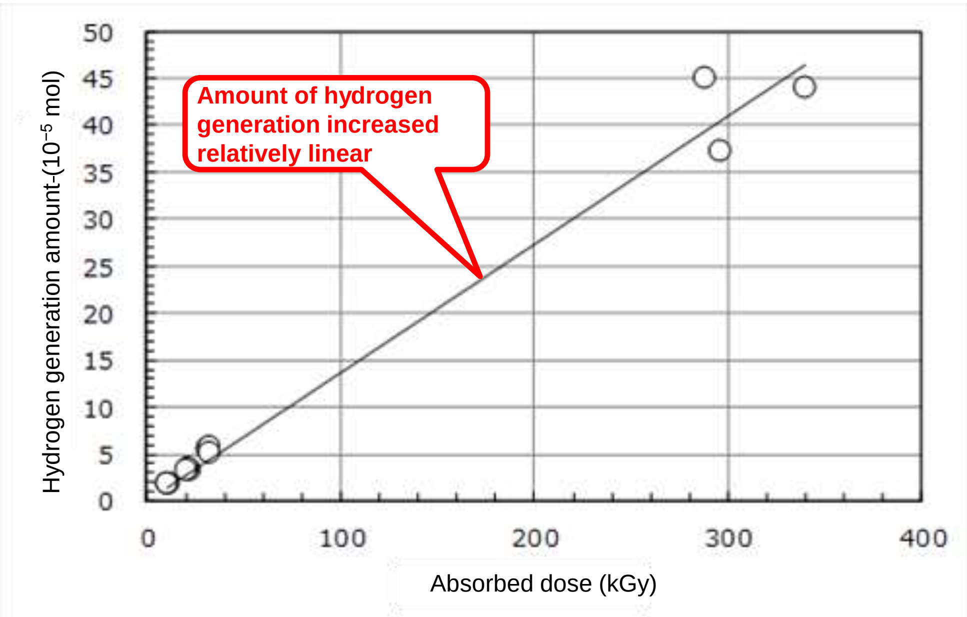


Figure: Dependency of hydrogen generation amount to absorbed dose (Cases (viii) to (xi))

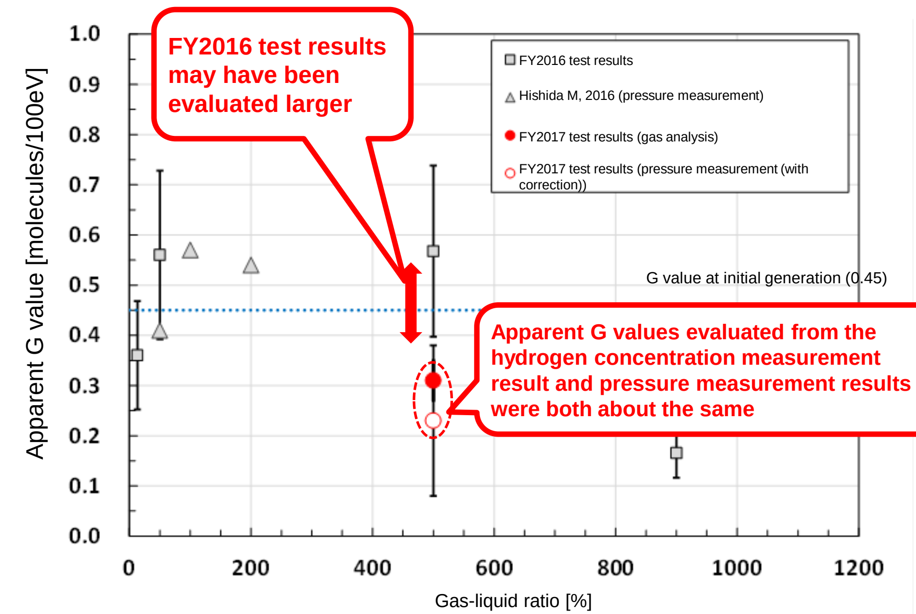


Figure: Dependency of apparent G value to gas-liquid ratio (error: 2σ) (iodine ion concentration: 1× 10^{-4} mol/L)

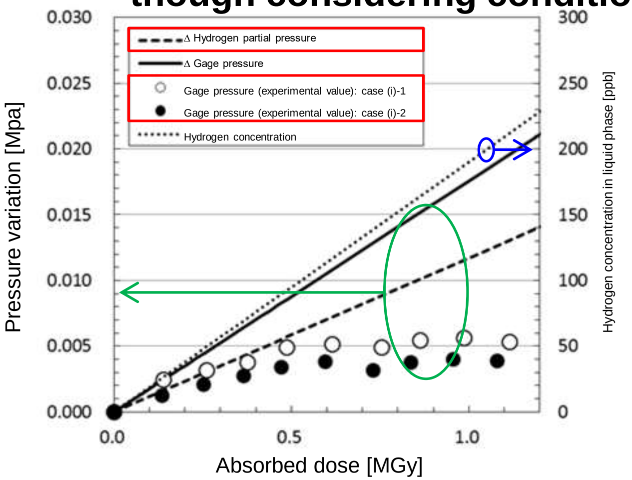
6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (9/10)

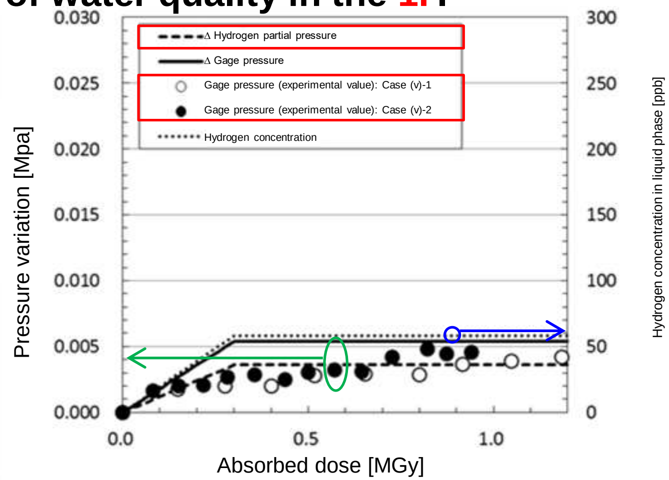
(vii) Comparison with analysis

The test result were compared to the analytical results using the evaluation method that combines the radiolysis model and the liquid-gas distribution with the equation of state and Henry's law (same as method used until FY2016). The primary G value of hydrogen generation (0.45 molecules/100eV) was used in the analysis.

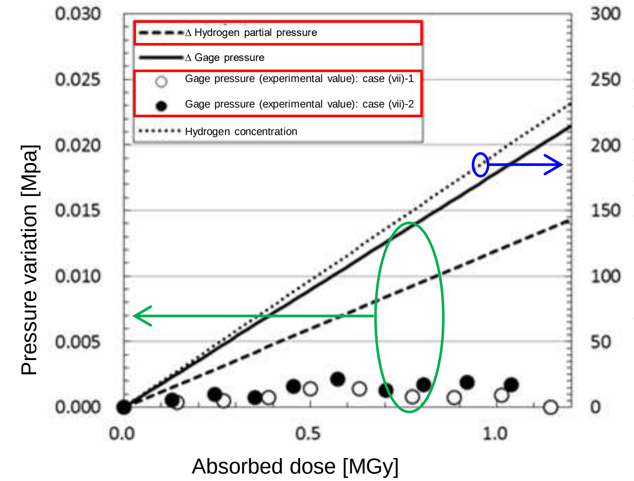
-> By using the primary G value of hydrogen generation (0.45 molecules/100eV) in each of the conditions, the analytical values enveloped the test results. This shows that the amount can be evaluated using the primary G value of hydrogen generation (0.45 molecules/100 eV) under gamma-ray irradiation, even though considering conditions of water quality in the 1F.



(a) Case (i)
(Chloride ion concentration: 2.8 × 10^{-3} mol/L, iodide ion concentration: 1 × 10−4 mol/L, gas phase gas: air, gas-liquid ratio: 900%)



(a) Case (v)
(Chloride ion concentration: 5.6 × 10^{-4} mol/L, no added iodine (0 mol/L), gas phase gas: argon, gas-liquid ratio: 900%)



(c) Case (vii)
(Chloride ion concentration: 5.6 × 10^{-4} mol/L, no added iodine (0 mol/L), gas phase gas: air, gas-liquid ratio: 900%)

Figure: Comparison between analysis results and measured hydrogen generation amount

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation on effect of gas phase (gamma-ray irradiation test) (10/10)

(viii) Conclusion

- Chloride and effect of gas phase showed that;
  - (a) When iodine concentration is high, hydrogen generation is dominantly affected by iodine and not by the type of gas in the gas phase.
  - (b) When iodine concentration is low, hydrogen generation is accelerated by the decline in pH caused by nitric acid production, so replacing gas with argon which does not produce nitric acid is effective in suppressing hydrogen generation.
- In a system which iodine does not coexist, the apparent G value of hydrogen generation will decrease when the seawater component has a chloride ion concentration of about 20 ppm, even if the gas phase is atmospheric.
- A high G value was observed in FY2016. When the amount of hydrogen generation is small, the error becomes larger in pressure measurement due to changes in atmospheric pressure and temperature, which may cause G value to be evaluated larger. It was confirmed that the apparent G value, evaluated based on the measurement results of hydrogen concentration conducted in FY2017, was lower than the primary G value of hydrogen generation (0.45 molecules/100eV).
- It was predicted that the evaluation method that combines the radiolysis model of water with the primary G value of hydrogen generation (0.45 molecules/100eV) and the liquid-gas distribution with equation of state and Henry's law can evaluate the amount of hydrogen generation that envelope the test results.

Based on the above results, as a result of evaluating the hydrogen generation amount under irradiation of gamma-ray with consideration to 1F water quality conditions (seawater, iodine, concrete) that have been considered up to FY2017, it was revealed that the hydrogen generation amount under gamma-ray irradiation can be evaluated using the primary G value of hydrogen generation (0.45 molecules/100eV), even when taking 1F water quality conditions into consideration.

Evaluation related to gamma-rays had finished in FY2017. Along with the results of the separately implemented evaluation on effect of alpha-rays, it was aimed to appropriately evaluate hydrogen generation inside 1F fuel debris canisters.

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the ~~amount generated~~ hydrogen generation amount: Confirmation of effect of alpha-ray (1/6)

(i) Purpose

Thus far, the data have been improved by the gamma-ray irradiation tests to evaluate the method to predict the amount of hydrogen generation inside the canister. However, effect of alpha-rays on fuel debris needs to be considered as claddings cannot be expected to shield the radiation*1. Therefore, the effect of alpha-ray under 1F conditions will be confirmed by conducting tests that use spent fuel pellet pieces.
In FY2018, based on these test results, the amount of hydrogen generation inside the canister will be predicted by hydrogen generation amount evaluation suitable for 1F condition (water quality and fuel debris conditions). Specifically, the hydrogen generation amount during transfer will be predicted and will be used to determine the time limit for transfer.

*1: Although beta-ray may have an effect when shielding by cladding 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 on gamma-rays may be applicable in terms of hydrogen generation by radiolysis of water.

(ii)Implementation details

The hydrogen generation amount by gamma-ray was estimated by the gamma-ray irradiation test and analysis up to FY2016 with consideration to the 1F conditions (water quality and mixed concrete pieces). Since alpha-rays is expected to contribute in hydrogen generation, tests using spent fuel pellet pieces will be conducted from FY2017 (continued in FY2018). The main effective factors identified are shown below.

- Presence or absence of alpha-ray (conducted in FY2017)
- Effect of water volume (conducted in FY2017 and FY2018) (FY2017 is preliminary study)
- Effect of particle size (conducted in FY2018)
- Effect of moisture in concrete (associated item when collecting MCCI products) (conducted in FY2018)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of hydrogen generation amount: Confirmation of effect of alpha-ray (2/6)

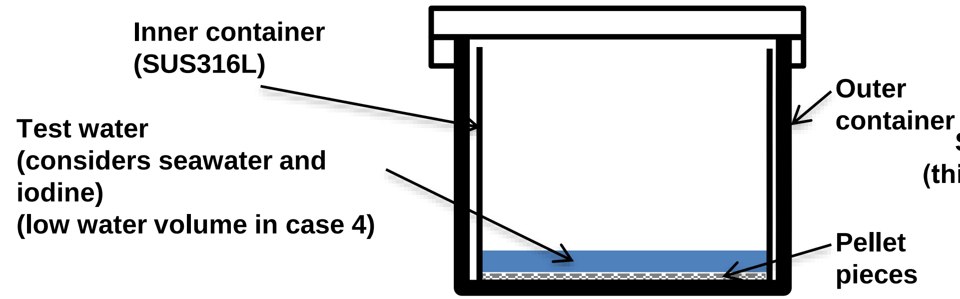
(iii) Test details

Using spent fuel pellet pieces, the hydrogen generation amount is measured for both conditions when alpha-ray is considered and when not. From the difference between the two amounts, contribution of the alpha-ray is verified. In addition, a preliminary test is conducted with a different water volume to roughly understand its effect which is used to set out the test conditions for FY2018.

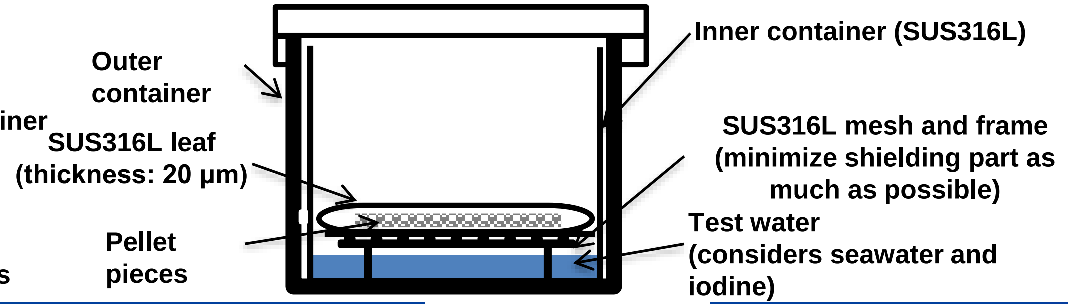
Table: Test conditions

Items		Cases 1 and 2	Case 3	Case 4	Notes
Test system		Immerse pellet pieces in sufficient amount of test water	No contact between pellet pieces and test water (shielding of alpha-ray)	Immerse pellet pieces in small amount of test water	Case 2 has same conditions since it is for confirming the reproducibility of case 1
Specimen weight/particle size		About 80 g/20 to 300 μm			Sized after being washed and dried (approx. 100°C, total of 6.5 hours)
Test water	Amount of water	100 mL		8 mL (50 vol.% of pellet pieces)	50 vol.% is based on the draining test conducted in FY2016
	Seawater component concentration	5.6×10^{-4} mol/L (Equivalent to 20 ppm) as chloride ion concentration			Determined by the measurement results of IF of Unit 1 (approx. 19 ppm)[*1]
	Iodide ion concentration	1×10^{-4} mol/L			Assumed that 10% of the iodine inventory[*2] will leach into the water
	pH	No adjustment			Measured before and after 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		Max. 20 days			Specified with margin for the assumed transfer period of 10 days
Test temperature		Ambient temperature			Temperature inside container (measurement during test): 18.3°C to 24.2°C

*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)



(a) Cases 1, 2, and 4



(b) Case 3

Figure: Overview of the test

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation of effect of alpha-ray (3/6)

(iv) Test conditions

Change of pressure in the container during the test was measured. After the test, the gas and test water were analyzed.

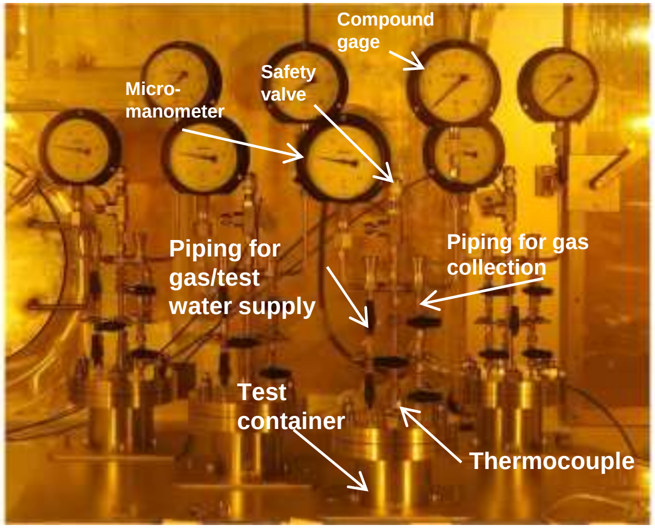


Figure: Appearance of test equipment

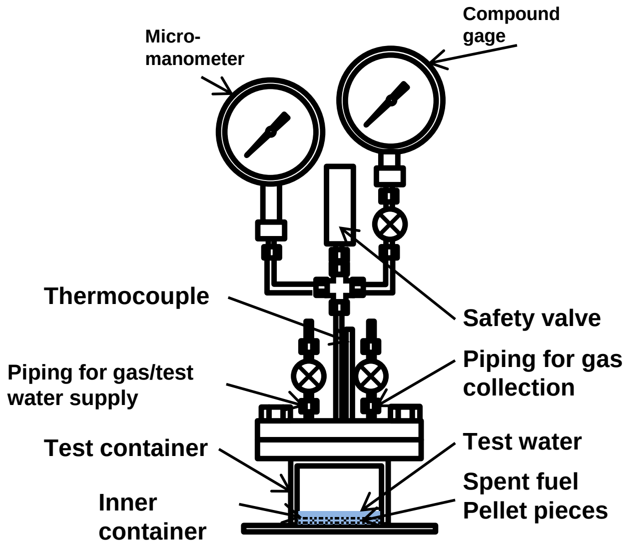


Figure: Test equipment diagram

Table: Specifications of spent fuel

	Spent fuel used for testing*1 (result of combustion calculation)	(Reference) 1F fuel (e.g., Unit 1)*2
Burnup	Approx. 57 GWd/t (fuel element average)	Approx. 26 GWd/t (reactor vessel average)
Cooling period	About 15 years	10 years
radioactivity	2.12×10^7 GBq/t	1.08×10^7 GBq/t
Decay heat	2.18×10^3 W/t	7.97×10^2 W/t
Gamma-ray intensity	5.56×10^{15} photon/s/t	3.04×10^{15} photon/s/t
Neutron intensity	1.86×10^9 neutron/s/t	1.07×10^8 neutron/s/t

*1: Used fuel pellet pieces separated from BWR 9 × 9 fuel (type A) LUA (Lead Use Assembly).
*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 Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the ~~amount generated~~ hydrogen generation amount: Confirmation of effect of alpha-ray (4/6)

(v) Test results

The hydrogen generation rate was evaluated and confirmed from the measurement results of hydrogen concentration inside the gas phase after the test.

- **In the condition that considers alpha-rays (cases 1 and 2) and condition that shields alpha-rays (case 3), the former had the hydrogen generation rate 10 times or greater than that of the latter.**
- **The hydrogen generation rate under the condition in which fuel pellets were immersed in small amount of water (case4), was greater than that under condition in which fuel pellets were immersed in sufficient amount of water (case1 and 2).**

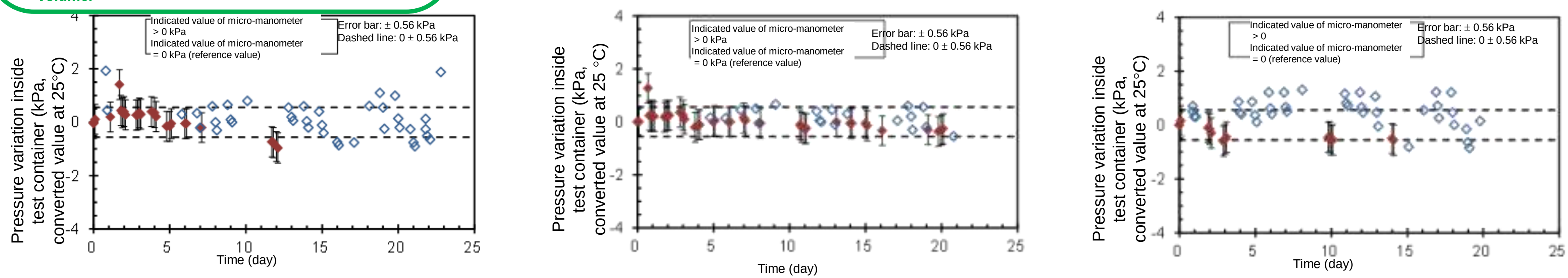
In this test condition, the pressure variation during the test is small and the hydrogen generation rate couldn't be evaluated from the pressure measurement in all the cases.

<Reference evaluation>
For example, in case 4, it takes about 2.5 days for the hydrogen concentration inside the canister to reach 4% (lower explosion limit) when evaluated under conservative conditions*2.
-> There is a prospect that safe transportation is possible by reviewing conditions etc.
*2: Inner diameter of canister: ⌀220 mm × 800 mm, fuel debris density: 11 t/m³ (equivalent to UO_2), filling rate: 50 vol.%, water volume: 50 vol.% relative to fuel debris volume.

Table: Evaluation results on the hydrogen generation rate

	Hydrogen generation rate*1	(Reference) Hydrogen concentration in gas phase (measured value)
Case 1	Approx. 7.5 × 10^{-8} L/h/gUO_2	Approx. 0.73%
Case 2	Approx. 6.0 × 10^{-8} L/h/gUO_2	Approx. 0.51%
Case 3	Approx. 4.6 × 10^{-9} L/h/gUO_2	Approx. 0.04%
Case 4	Approx. 1.1 × 10^{-7} L/h/gUO_2	Approx. 0.78%

*1: Calculated from the hydrogen concentration in the gas phase (measured value), volume of test container, weight of pellet piece, test period, etc. (converted value at 25°C)



(a) Case 1 (b) Case 3 (c) Case 4

Figure: Pressure variation inside the test container during the test (measured value)

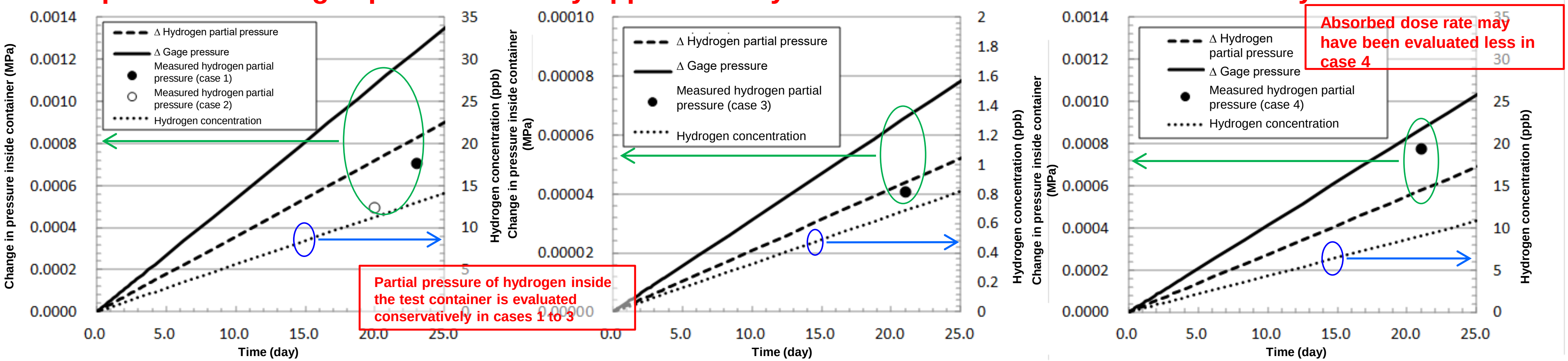
6. Implementation Details

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the hydrogen generation amount: Confirmation of effect of alpha-ray (5/6)

(vi) Comparison with analysis

The absorbed dose rate was specified based on the hydrogen generation rate (average value) obtained from the measurement results. An analysis using the radiolysis model was conducted under the test conditions and the hydrogen generation amount was evaluated. The results show that hydrogen partial pressure in the gas phase is usually approximately the same in both the test and the analysis.



(a) Cases 1 and 2 (b) Case 3 (c) Case 4

Figure: Example of comparison between test results and analysis results

Table: Analysis conditions

Items		Cases 1 and 2	Case 3	Case 4	Notes
Absorbed dose rate	Alpha-ray	21.5 Gy/h	-	263 Gy/h	Determined from the hydrogen generation rate (average value) obtained from the test results
	Beta-ray, gamma-ray	4.7 Gy/h	4.0 Gy/h	4.7 Gy/h	
Water volume		100 mL		8 mL	Used to calculate hydrogen concentration in gas phase (not considered in analysis by radiolysis model)
Seawater component concentration		5.6×10^{-4} mol/L (Equivalent to 20 ppm) as chloride ion concentration			Test conditions
Iodide ion concentration		1.0×10^{-4} mol/L			Test conditions
Temperature		25°C			Ambient temperature
Time		20 days			Test conditions

6.3 Development of Safety Evaluation Methods and Safety Validation

(4) Safety validation on countermeasures against hydrogen gas; a. Verification of the ~~amount generated~~ hydrogen generation amount: Confirmation of effect of alpha-ray (6/6)

(vii) Conclusion

- In the condition that considers alpha-rays (cases 1 and 2) and the condition that shields alpha-rays (case 3), the former had the hydrogen generation rate 10 times or greater than that of the latter, which confirms the effect of alpha-rays.
- The hydrogen generation rate under the condition in which fuel pellets were immersed in small amount of water (case4), was greater than that under condition in which fuel pellets were immersed in sufficient amount of water (case1 and 2). This result suggests that, in this test condition (fuel pellet particle size 20 to 300 μm), the alpha-ray is the dominant condition with small amount of water (small amount of water is the amount of extent to which drain water).
- Analysis by the radiolysis model that uses the absorbed dose rate which was specified based on the hydrogen generation rate (average value) obtained from the measurement showed that the results are usually about approximately the same in both the test and the analysis.

(viii) Future plans

The effect of alpha-ray on hydrogen generation for the identified effect factor shown below will continue to be confirmed by conducting tests using spent fuel.

- Study on effect of water volume
- Effect of particle size
- Effect of moisture in concrete (associated item when collecting MCCI products)

When doing so, test methods and test systems will be reviewed to solve the issues obtained in the evaluation conducted in FY2017 (establishment of absorbed dose rate, evaluation on evaluation method, and measurement of hydrogen generation rate) and conduct tests and evaluations.

Based on these results, the hydrogen generation evaluation method under 1F conditions will be summarized and test calculation on the hydrogen generation amount inside the canister will be performed.

6.3 Development of Safety Evaluation Methods and Validation

(5) Safety evaluation on measures against hydrogen gas; b. Verification of measures against hydrogen (1/6)

(i) Purpose

It is assumed that the canister will be transported from the nuclear reactor building to the storage facility in a transport cask. Therefore, as the transport cask needs to be sealed during transfer, measures against explosion of residual hydrogen is necessary.

In addition, confining the canister as much as possible is effective in suppressing spread of contamination outside the canister. Therefore, as a method which treats hydrogen generated in the canister while it is in the can (proposal for the measurement against hydrogen), the possibility and effectiveness of the measure that recombines oxygen with hydrogen generated inside the canister will be clarified.

(ii) Basic concepts

Catalysts and hydrogen absorption alloy are generally used for hydrogen treatment. However, since hydrogen absorption alloy has issues in capacity, our study on the catalyst will be started.

To effectively recombine the two with a catalyst, the following needs to be satisfied.

a. The performance related to recombination of the catalyst itself has the ability that meets the amount generated.

- Have recombination performance
  The hydrogen recombination rate per catalyst surface area is high and it is in a size that can be installed inside the canister.
- Functions effectively in the used environment
  The catalyst can maintain its performance that is necessary in terms of temperature, water repellency, radiation resistance, and resistance to poison (chlorine component derived from seawater, anti-poisoning property against iodine produced by fission).

b. The target gas (hydrogen/oxygen) is supplied to the catalyst effectively.
Gas is supplied to the catalyst by the flow inside the canister and the hydrogen concentration inside the canister is maintained to be or lower than the explosion limit.

-> In FY2017, evaluation was conducted focusing on b.

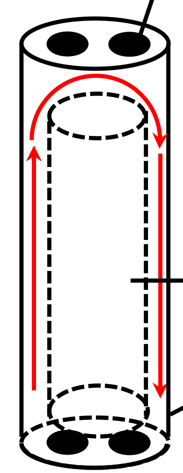


Figure: Flow inside canister and example of catalyst placement

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(5) Safety evaluation on measures against hydrogen gas; b. Verification of measures against hydrogen (2/6)

(iii) Process of evaluation

Taking into account the previous section, the evaluation proceeds in the following steps.

a. Conduct feasibility study assuming a realistic amount of hydrogen generated (conducted in FY2016)

Assuming an average fuel debris of 1F (average source strength of furnace vessel fuel, size distribution using core sampling of TMI-2), the required amount of catalyst was calculated, with respect to the amount of hydrogen generated and the concentration distribution inside the canister, when assuming that the catalyst on the ends of the canister will conservatively recombine by diffusion only. The hydrogen concentration at the center of the canister which had the highest concentration was lower than 4 vol. %.

b. Examine a feasibility study assuming hydrogen is generated under stricter conditions (details of study in FY2017)

When examining the hydrogen countermeasure scenario, the possibility that the conditions will be stricter cannot be denied (e.g., distribution of fuel concentration in fuel debris), so a scenario for such case will be constructed.

- **Study on effect of flow inside canister**
  The effect of the flow inside the canister will be analyzed and the placement of catalysts and gaps necessary inside the canister will be studied.

c. Verification assuming canister shape (details of study in FY2018)

- **Confirm the effectiveness of the catalyst by verification test on flow inside the canister.**
- **Obtain basic data of resistance against environmental conditions, such as resistance to radiation and poison, from the aspect of placing recombined hydrogen catalysts inside the canister.**

  In addition, consider the flow inside the canister and verify its effectiveness regarding the catalyst selected for its resistance to radiation and poison.

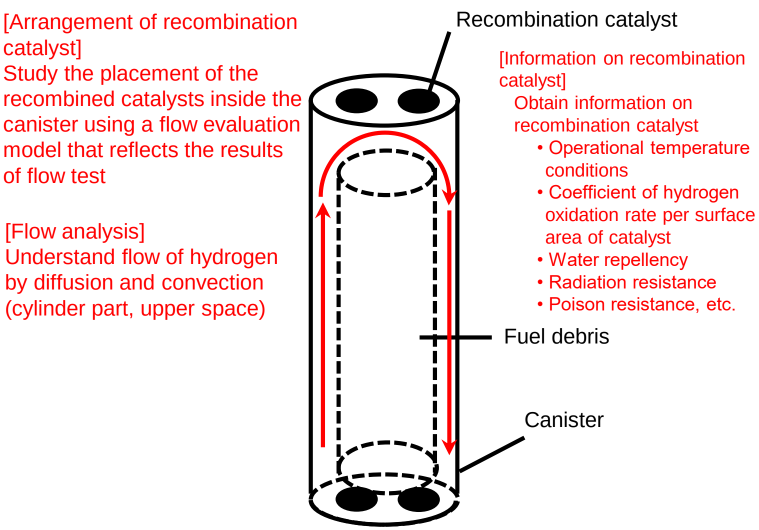


Figure: Study items regarding measures against hydrogen gas inside canister

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(5) Safety evaluation on measures against hydrogen gas; b. Verification of measures against hydrogen (3/6)

(iv) Hydrogen concentration inside the canister when hydrogen does not flow but spreads by diffusion alone

On conducting the study, the following is the hydrogen concentration in the center of the canister that is premised only on the amount of hydrogen assumed to generate inside the canister (trial calculation) and diffusion.

a. Concentration distribution of hydrogen

Catalysts will be placed on both ends inside the canister. Assuming that hydrogen molecules move by diffusion only when it generates from fuel debris, hydrogen concentration at an arbitrary position in the canister is given by a function of diffusion coefficient and the amount of hydrogen generated. Hydrogen is distributed in a parabolic shape and its concentration is the highest at the center of the canister.

b. Hydrogen concentration

The amount of hydrogen generated is calculated from the amount of heat generation, G value, and absorption rate, a method which was also used for TMI-2. Conservatively, G value was specified as (0.45) and absorption rate F as (0.6)[*1]. The amount of heat generated was also conservatively defined assuming that pellets of aggregates with maximum burnup (55 GWd/t) (10 years of cooldown) were the only fuel debris. In addition, it was assumed that the fuel debris filling rate is 30 vol.%.

The hydrogen concentration on the ends was assumed as 1 vol. % based on the general performance of the catalyst. As a result, the concentration in the center was evaluated to be 6.4 vol. %.

-> Convections actually generated inside the can and by making allowance for such feasibility under strict conditions can be expected.

-> Flex will be studied.

***1: F = 0.6 is for the assumption that fuel debris is a fine powder (from the study results of FY2016)**

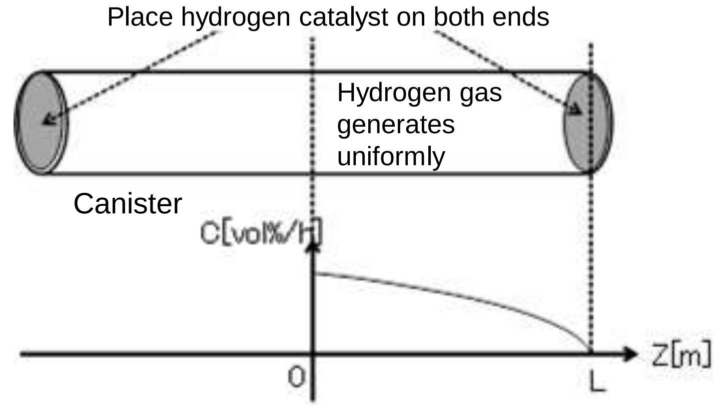


Figure: Concentration distribution inside the canister

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(5) Safety evaluation on measures against hydrogen gas; b. Verification of measures against hydrogen (4/6)

(v) Study on effect of convection (1/2)

a. Target convection flow rate

As shown in the previous page, if only hydrogen diffusion is assumed, the maximum concentration at the center of the canister was 6.4 vol.%. Given this situation, the target convection flow rate was evaluated in which effect of convection can be expected.

- **In order for the maximum concentration to go below 4 vol.% (the right figure), a flow that can diffuse hydrogen two times (or greater) more efficiently than the diffusion coefficient is necessary.**
- **Considering the relation between diffusion term and convection term in the diffusion equation, only a natural convection flow of the level of 0.01 mm/s (= 10^{-5} m/s) same as the diffusion coefficient is necessary. However, since it is likely that there will be great uncertainty in such flow rate, in the analysis the possibility that a flow of about 1 mm/s may be created was tentatively studied.**

Diffusion term of diffusion equation

$$\frac{D}{H^2} \qquad \frac{D}{H^2} = \frac{5 \times 10^{-5}}{1.5^2} \approx 10^{-5}$$

$u > 10^{-5}$ [m/s]

Convection term of diffusion equation

$$\frac{u}{H} \qquad \frac{u}{H\ >\ D} H \frac{2}{\times\ 2} \approx 10^{-5}$$

(Double or more)

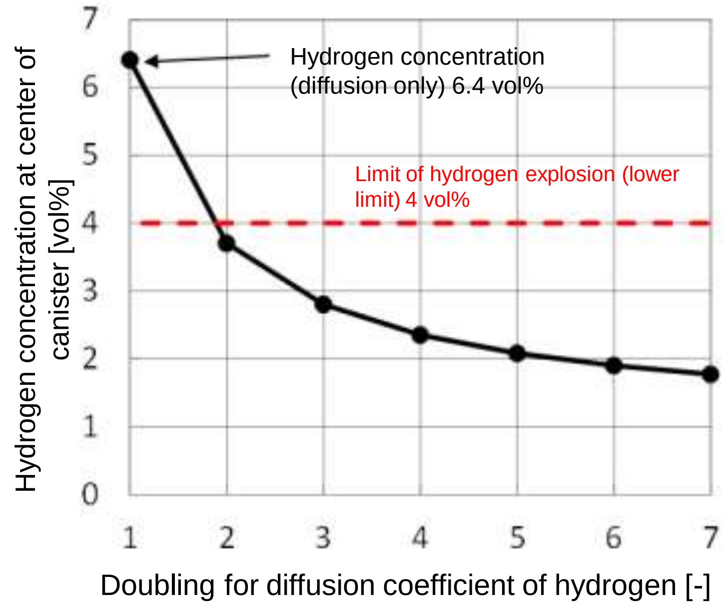


Figure: Relation between hydrogen diffusion coefficient and hydrogen concentration

<u>One-dimensional diffusion equation</u>

$$\frac{d\omega}{dt} + u\frac{d\omega}{dz} = D\frac{d^2\omega}{dz^2}$$

Convection term   Diffusion term

D: Hydrogen diffusion coefficient [m²/s]
H: Height of canister [m] (= 1.5 m)
t: Time [sec]
u: Flow rate [m/s]
z: Distance in direction of flow [m]
ω: Hydrogen concentration (mass fraction) [-]

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(5) Safety evaluation on measures against hydrogen gas; b. Verification of measures against hydrogen (5/6)

(v) Study on effect of convection (2/2)

b. Prediction of flow effect by analysis

From the results of thermal flow analysis, it was revealed that the average rising flow rate was 10 to 100 mm/s for gap of 20 mm (cases 1 to 4) and 1 to 4 mm/s for gap of 5 mm (case 5) and that flow can be expected.

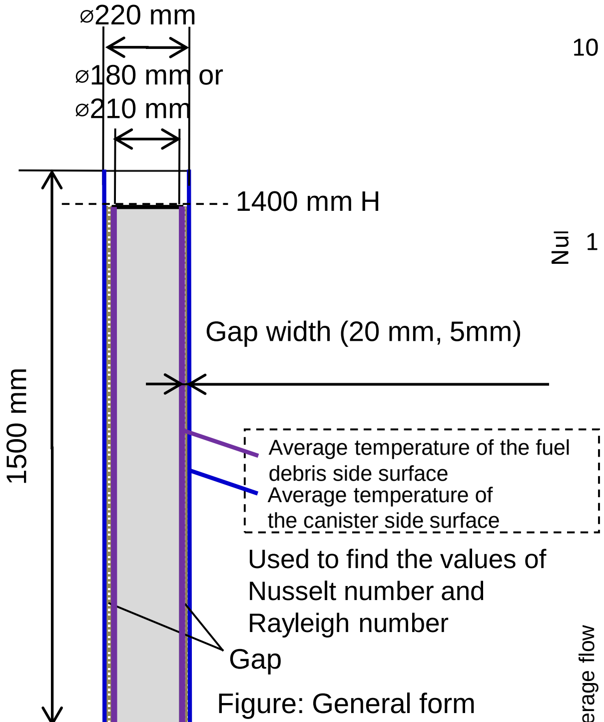


Figure: General form of the canister

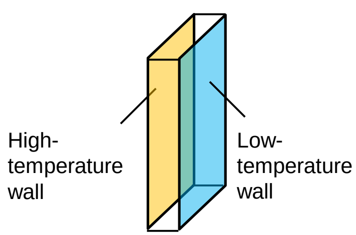
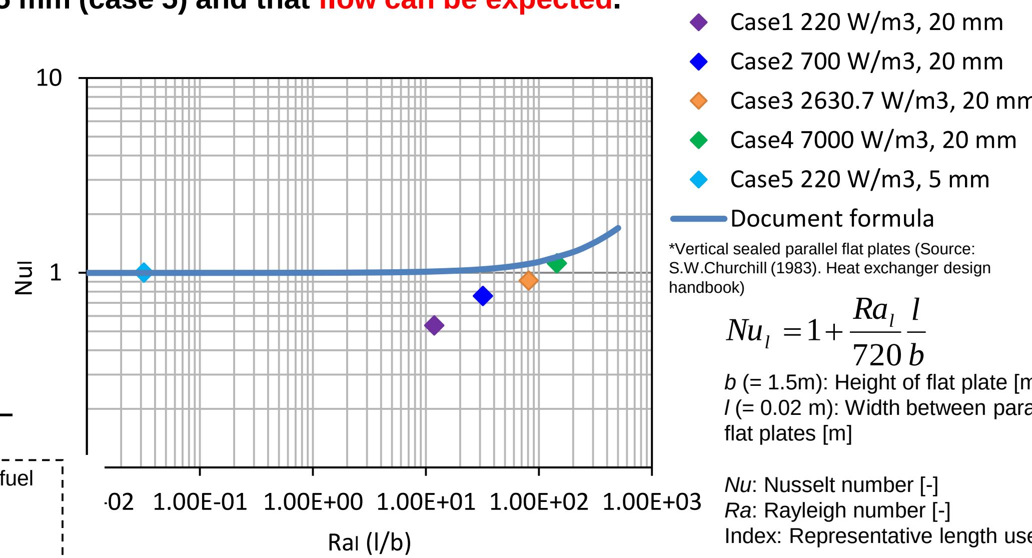


Figure: Vertical sealed parallel flat plates



*Vertical sealed parallel flat plates (Source: S.W.Churchill (1983). Heat exchanger design handbook)

$$Nu_l = 1 + \frac{Ra_l}{720}\frac{l}{b}$$

b (= 1.5m): Height of flat plate [m]
l (= 0.02 m): Width between paralle flat plates [m]

Nu: Nusselt number [-]
Ra: Rayleigh number [-]
Index: Representative length used

Figure: Document formula of vertical sealed parallel flat plates and analysis results of gap

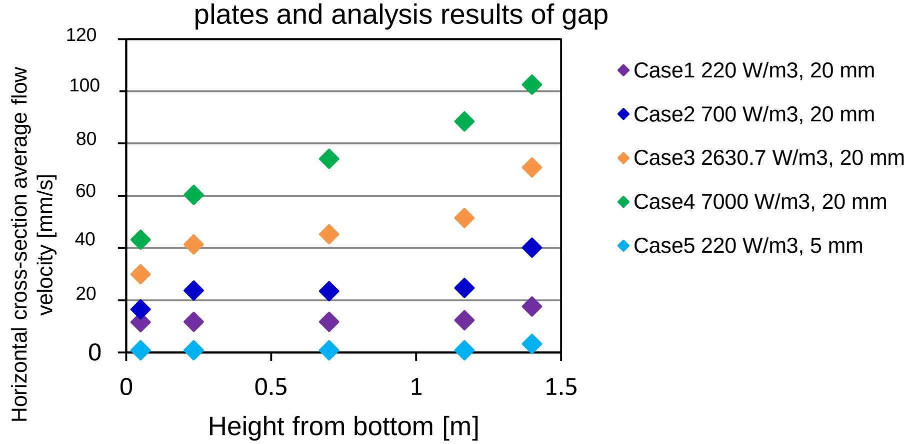
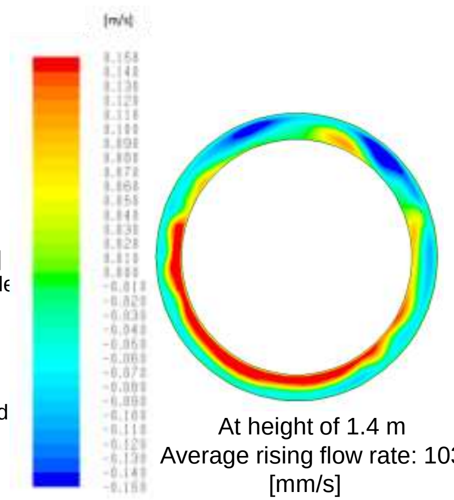


Figure: Rising flow rate of each cross-section in the gap



At height of 1.4 m
Average rising flow rate: 103 [mm/s]

Figure: Example on flow distribution in the direction of height

(Case 4)

6. Implementation Details

6.3 Development of Safety Evaluation Methods and Validation

(5) Safety evaluation on measures against hydrogen gas; b. Verification of measures against hydrogen (6/6)

(vi) Conclusion

Flow inside the canister is effective for promoting hydrogen diffusion. It was revealed that, by anticipating this effect, the hydrogen concentration in the canister can be expected to go below the lower explosion limit of 4 vol.% or less even with the amount of hydrogen generated based on conservative assumption.

(vii) Future plans

Measures will be organized using catalysts by the following studies and clarify the benefits if catalysts are adopted.

- **Study on analysis of flow inside the canister**
  From the analysis, flow is expected to be generated between the unit can and the canister wall. However, the gap between the two is narrow and as disclosed knowledge on natural flow has yet to be found, data on the effect of convection by tests will be collected and confirmed.

- **Organization of candidate catalyst (including consideration on poisoning, heat resistance, radiation resistance, etc.)**
  Catalysts are required of resistance to poison (e.g., chloride ion), heat, and radiation. To collect information on these properties from documents and tests, and to base our judgments on whether to adopt the catalysts, the environment during transfer must be considered and the validity of the catalyst candidate must be organized.

6. Implementation Details

6.4 Study on Fuel Debris Collection Method

(1) Study on the canister's specifications that suit fuel debris properties

(i) Purpose

A canister for block-like fuel debris has been developed to store an unit can after collecting fuel debris by griping or scooping in a basic way. On the other hand, there are powder type of fuel debris. In example of TMI-2, canisters with filters inside were used. Therefore, canisters that can be used to collect fuel debris of various forms will be developed.

(ii) Result of study

Currently, collection method of powder fuel debris is being studied in the Method Project Team and Fundamental Technology Project Team. As of now, it has been decided to proceed with our study on using canisters for fuel debris blocks, regardless of the fuel debris shape.

In this project, designing canisters for fuel debris blocks will be started. From FY2018 onwards, issues that arise when using canisters for block-like fuel debris to collect powder fuel debris will be shared and adjustments made.

6. Implementation Details

6.4 Study on Fuel Debris Collection Method
(2) Review of canister design

(i) Purpose

Develop design of canister that reflects the results of 6.2 “Study on safety requirements and specifications and storage systems for the transfer/storage of fuel debris canisters” and 6.3 “Development of safety evaluation methods and safety validation.”

(ii) Result of study

The study of 6.3.(2) “Safety evaluation on structural strength: Study on lid structure” will be reflected on the lid structure design as for now. The example of the reflected design is shown in the right figure.

In the future, requirements based on handling methods and safety assessment will be reflected to the design and summarized as the basic specification (study will continue in FY2018).

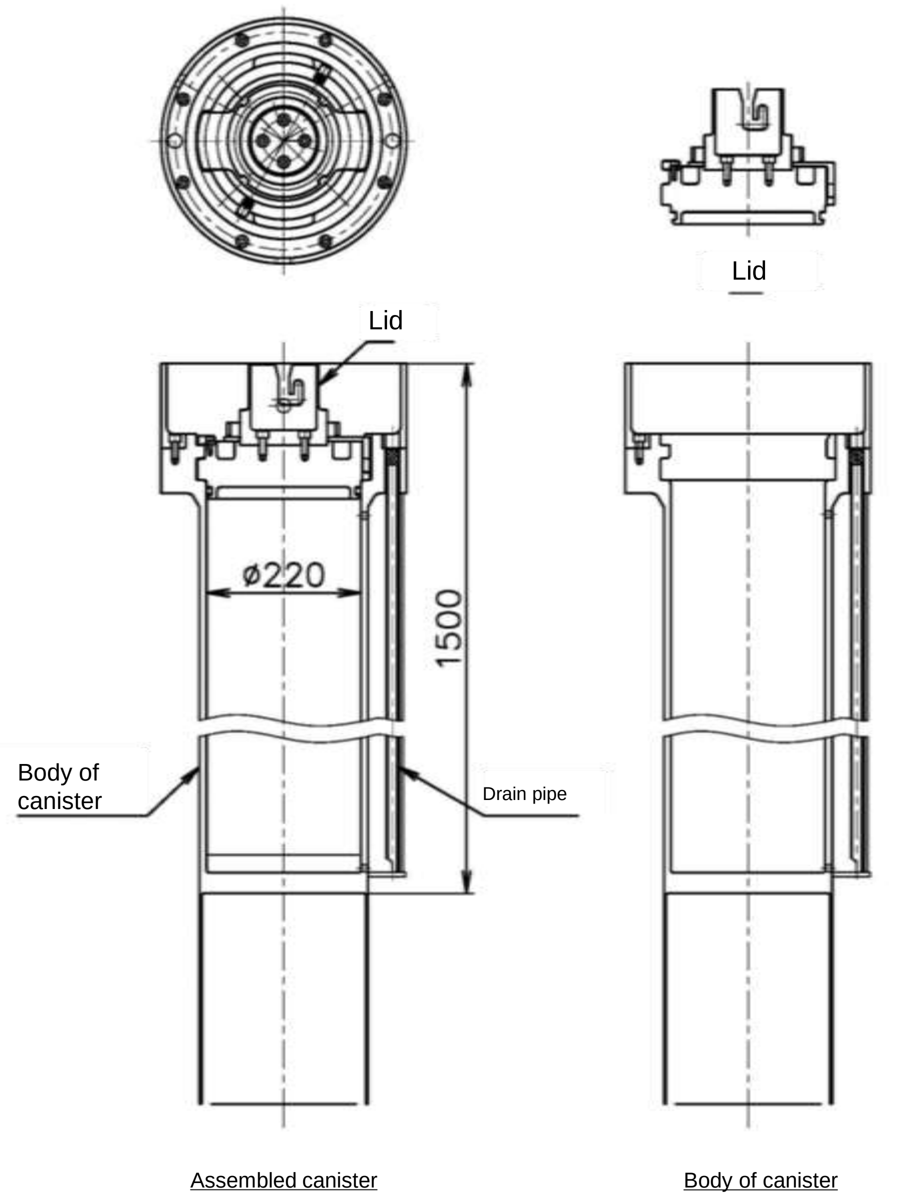


Figure: Canister design (example)

7. Overall Summary

- To efficiently retrieve, collect, transfer, and store fuel debris, steps of each task were defined and a reasonable process flow was provisionally determined. In addition, the amount of items to be treated was studied from the aspect of overall rationalization and evaluated from the aspect of future throughput. They will be responded to by reflecting it on the canister design and requirements of the transfer/storage system.

- Related projects will be consulted with on the issues newly identified in the above task and will reflect on the plans of FY2018 onwards.

- Regarding the evaluation method required for the safety assessment of transfer/storage system that is conducted continuously from the previous research, the evaluation will be continued for achieving results in FY2018. The results will be reflected to the canister specifications.

[Supplement-1] Positioning the Output

The conditions such as safety requirements, knowledge of fuel debris properties, and request for optimization will change in the future.
The canister to be developed should be a prototype. The protocol of the canister design will be reviewed to flexibly change the conditions.

Safety requirements (restrictions)

Protocol

Ensure sub-criticality

Size, guarantee on amount of content, absorption material…

Measures against hydrogen and fire

Structure of lid and vent, restriction of transfer time, hydrogen confinement…

Control of temperature increase

Heat removal design, guarantee on amount of heat generation, continuous immersion…

Discharge suppression

Structural strength, wet storage, high corrosion resistance material, building ventilation system (dry storage)

Change in design

Feedback

Requirements

Requirements for optimization (feasibility): All times

Improvement of work efficiency

Expansion of sizes of opening and storage
Manipulation (e.g., restriction in height direction)
Canisters for each target objects

Manufacturing process

Manufacturability (quality), manufacturing and inspection cost, production volume

Rationalization of storage management

Dry storage, external event, number of stored items, storage area, discharge control

Actual conditions of on-site work

Unknown factors

Change in basic conditions

Improvement of knowledge on fuel debris
Technological innovation