IRID

Subsidy Project of Decommissioning and Contaminated Water Management
Started From FY2021

Development of Technologies for Containing, Transfer and Storage of Fuel Debris
(Drying Technology for Fuel Debris)

Interim Report for FY2021

August 2022

International Research Institute for Nuclear Decommissioning
(IRID)

Contents

1. Background and purpose of the project

- Background

For the types and sizes of the fuel debris to be dried, the properties of the fuel debris (molten materials, Molten Core Concrete Interaction (MCCI), metallic debris and unmelted fuel assembly, etc.), porosity, volatile Fission Product (FP) release rate, primary element composition, etc. can all affect the drying treatment. The drying form and method can also be assumed to affect the drying treatment.

Under the subsidized project conducted in FY2019 to 2020, zeolite was used as a test piece of fuel debris assuming that fuel debris is porous based on the results of the TMI-2 accident. As for the drying equipment, with the aim of drying fuel debris in drying chambers that still contains the unit cans with mesh structure, hot air and decompression drying methods were studied from the viewpoint of an off-gas treatment for the fine particle fuel debris that accompanies the exhaust gas, while certain operations such as stirring processing are effective to promote drying. Based on those studies, assuming that objects are dried under conditions where the objects stand still as possible from the perspective of suppressing the range of contamination, data on the objects to be dried will be expanded by element tests and the applicability of the canister form will be examined in the full-scale test.

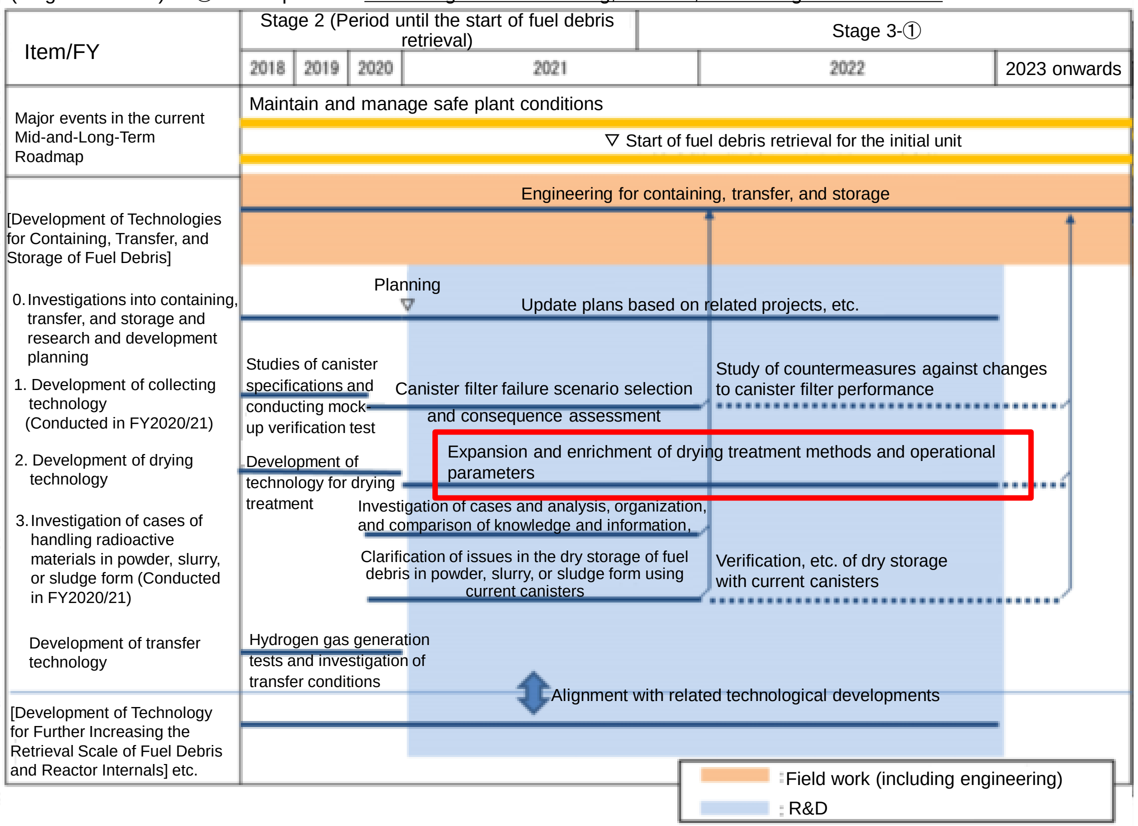
- Purpose

This project aims to develop technology for containing, transferring and storing fuel debris applicable to the actual situations of the Fukushima Daiichi Nuclear Power Station on the basis of the requirements and information provided from related projects to this project (input conditions) as well as information from this project to the related projects (output conditions), which are adjusted and set in cooperation with the projects.

1. Background and purpose of the project
(FY2021 decommissioning R&D plan)

- Retrieved fuel debris needs to be collected, transferred, and stored in a safe, reliable and effective manners.
- When fuel debris contains moisture, hydrogen gas would generate due to radiolysis.
- There is a trade-off between ensuring confinement during transfer and storage and venting as a measure to prevent hydrogen explosion, but the drying treatment to remove moisture are expected to act as a means to reduce such risks.
- A method for drying objects under the condition of stored state in the canister is more effective for direct drying treatment. To realize the method, data will be expanded and optimum operating conditions will be considered under this project.

(Target schedule) B3④ Development of Technologies for Containing, Transfer, and Storage of Fuel Debris



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

1. Background and purpose of the project

Excerpt from "Subsidy Project of Government-led R&D Program on Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget (Development of Technologies for Containing, Transfer, and Storage of Fuel Debris)" Final Report FY2020 (June, 2021)

The process of collecting, transferring, and storing fuel debris is shown below.

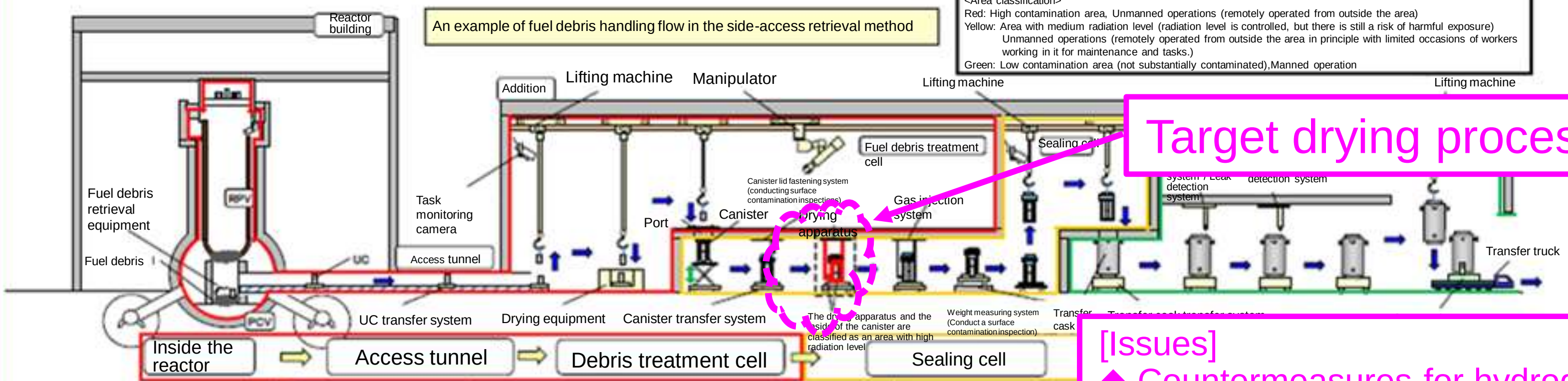
1. Background and objectives of the research

No.4

1.3 Considerations to date and remaining issues (1/4)

The process of collecting, transferring, and storing fuel debris and issues with the process are shown below.

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



Target drying process

[Issues]

- ◆ Countermeasures for hydrogen generation that can be implemented during transfer of airtight containers.
  - ⇒ Drying treatment to reduce moisture content rate
- ◆ Achieving a drying level that enables airtight containers for up to 7 days

Black: items that do not require technological development based on past achievements, etc.
Blue: items in which studies completed (and succeeded in the project at the actual site)
Brown: items to be terminated for studies in this subsidized project (and succeeded in the project at the actual site)
Red: items that require continuous study (items to be studied in a succeeding subsidized project or suggested to be so)
Numbers in parentheses indicate the chapters that describe each subject in detail

Note: Safety design and handling for "inside the reactor ~ fuel debris treatment cell" was examined in the project for further increasing retrieval

Note: RPV (abbreviation for Reactor Pressure Vessel)
PCV (abbreviation for Primary Containment Vessel)
UC (abbreviation for Unit Can)

Area / Canister		Sealing cell	Preparation cell (e… equipm…	
Safety design	Sub-criticality	Sub-criticality can be maintained by the geometric shape of canisters	Sub-criticality can be…	
	Heat removal	Canisters can be naturally cooled down using regular in-cell ventilation	Natural cooldown us… ventilation is possib… transfer c…	
	Confinement	Sealing materials for canisters (6.2) / Study of filters (6.2) / Confinement in the sealing cell (gas discharge is controlled)	Study of sealing mat… (6.2) / Study of filters … in the preparation ce… contro…	
	Shielding	Shielding in the sealing cell	Shielding in the pre…	
	Structure	Study into maintaining safety functions against damage caused by a fall of up to 9 m or the canister falling within the transfer cask (6.2)		Can respond to incidents during transfer (designed to be enveloped in a fall)
	Material	Safety functions can be maintained against deterioration from aging (examinations of corrosion based on metal materials. Neutron flux density is small and irradiation has no effect)		
	Hydrogen	- Study of vent diameter for discharging from the filtered vent on a canister to the cell (6.2) / Ventilation can suppress hydrogen concentration levels in the cell to less than the lower explosion limit - Study into reducing the moisture content rate of fuel debris via early drying of fuel debris for countermeasures for hydrogen generation during sealed transfer (the timing of drying in the fuel debris treatment cell is the first priority) (6.3) - Study into measuring hydrogen concentration levels inside the transfer cask to ensure that hydrogen concentration levels during transfer are 4 vol% or less (6.4)		- Drying to seal canisters or transfer casks for up to 7 days (6.3) - Study of methods to predict hydrogen generation during transfer (via evaluation formulas) (6.3) - Study of recombination catalyst (6.3)
	Fire prevention	An inert atmosphere can be maintained in the sealing cell, preparation cell, and transfer cask		
Ease of handling		Remote transportation and lid fastening are possible	Can be transported remotely	Can be contained in transfer casks
Improved collection capability		Enlarge the inner diameter of the canister to improve collection capability	No	

Handling processes for fuel debris in particle or lump form

2. Goals

The indicators to determine achievement goals at the end of FY2022 are as follows.

TRL: Technology readiness level

No.	Indicators for determining development goals
1	Drying data for difficult-to-dry slurry, sludge, and concrete must be prepared (Target TRL upon completion: Level 4)
2	The advantages and disadvantages of drying while material is inside the canister compared to the chamber method must be organized (Target TRL upon completion: Level 4)
3	Proposals for effective operating methods for porous media in a canister must be presented (Target TRL upon completion: Level 4)
4	Requirements (requests) for canisters on the drying treatment side must be organized (Target TRL upon completion: Level 4)

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

3.1 Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters

[Details in the solicitation information]

Analytical evaluation and tests for confirmation and verification are used to select the drying form and drying methods suitable for the types and sizes of fuel debris to be dried. The same analytical evaluation and tests for confirmation and verification are used to expand operational parameters.

Additionally, the storage form will also be considered by reviewing both individual drying of unit cans and canisters as well as simultaneous drying of them, which is considered useful for the scale of equipment and to ensure throughput. Requests for changes or improvements to the current structure or specifications of unit cans and canisters required for the drying treatment will be summarized as needed for the selected drying technology.

* The items following “Additionally” will be considered in Section 3.2

Details of implementation

① Types of materials to be dried and expansion of data

Assumed objects to be dried include difficult-to-dry materials such as slurry and sludge, considering the variety (properties and size) of fuel debris and its processed materials. Furthermore, the element tests or analytical evaluation were to understand the drying characteristics of each material to be dried and data on drying levels, drying times, etc. will be expanded.

[Results]

(1) Data on the drying characteristics of slurry and sludge (element test)

(2) Data on the drying characteristics of concrete (element test)

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

3.1 Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters

[Details in the solicitation information]
Analytical evaluation and tests for confirmation and verification are used to select the drying form and drying methods suitable for the types and sizes of fuel debris to be dried. The same analytical evaluation and tests for confirmation and verification are used to expand operational parameters.
Additionally, the storage form will also be considered by reviewing both individual drying of unit cans and canisters as well as simultaneous drying of them, which is considered useful for the scale of equipment and to ensure throughput.
Requests for changes or improvements to the current structure or specifications of unit cans and canisters required for the drying treatment will be summarized as needed for the selected drying technology.

* The items following “Additionally” will be considered in Section 3.2

Details of implementation

② Study of the applicability of drying methods

Based on the expanded test data, the applicability of drying treatment methods devised in subsidized projects so far was evaluated. For those materials to be dried that are difficult to be applied, prospective treatment methods and processes that can be considered as alternative candidates were also be proposed.

[Results]

(1) Range of application for drying concepts devised in subsidized projects (materials to be dried)

(2) Alternative treatment methods and processes when such concepts are hard to apply on the material to be dried

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

3.2 Concepts of drying equipment and the expansion of data required for setting operating conditions

[Details in the solicitation information]
The results of conceptual studies for drying equipment, facilities, and systems devised in subsidized projects to date will be actualized and the various data required for the setting of operating conditions will be expanded. The concepts for drying equipment, facilities, and systems that can adapt to differences in fuel debris properties (molten debris, MCCI debris, metal debris, unmelted fuel assembly, etc.), porosity, and volatile FP release rate will be studied and actualized. Additionally, the conceptual studies on the equipment, facilities, and systems for drying treatments that dry unit cans and canisters individually or in groups will also be conducted. Furthermore, for the concepts of equipment, facilities, and systems for the drying treatment that have been studied, the optimum operating conditions (range) from the viewpoint of conformity with safety requirements will be studied and proposed. Based on these results, the qualitative evaluation of advantages and disadvantages will be made from the viewpoint of conformity with safety requirements, conformity with the required throughput, the required site area, construction period, operations (frequency and duration of checks, inspection, and maintenance, the necessity and range of decontamination, replacement frequency of parts, etc.), and so forth.

Details of implementation

① Expansion of data for the canister form

A drying test plan [Note 1] for the effective canister form (effective for suppressing the range of contamination) was proposed and the drying treatment using full-scale canisters was conducted. In addition, drying levels, drying time, etc. were verified and the applicability of drying treatment using the canister was evaluated.

[Results]

(1) Results of verification tests for the canister form

Note 1: Includes modifications of the full-scale test equipment manufactured in subsidized projects

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

3.2 Drying equipment concept and the expansion of data required for setting operating conditions

[Details in the solicitation information]
The results of conceptual studies for drying equipment, facilities, and systems devised in subsidized projects to date will be actualized and the various data required for the setting of operating conditions will be expanded. The concepts for drying equipment, facilities, and systems that can adapt to differences in fuel debris properties (molten debris, MCCI debris, metal debris, unmelted fuel assembly, etc.), porosity, and volatile FP release rate will be studied and actualized. Additionally, the conceptual studies on the equipment, facilities, and systems for drying treatments that dry unit cans and canisters individually or in groups will also be conducted. Furthermore, for the concepts of equipment, facilities, and systems for the drying treatment that have been studied, the optimum operating conditions (range) from the viewpoint of conformity with safety requirements will be studied and proposed. Based on these results, the qualitative evaluation of advantages and disadvantages will be made from the viewpoint of conformity with safety requirements, conformity with the required throughput, the required site area, construction period, operations (frequency and duration of checks, inspection, and maintenance, the necessity and range of decontamination, replacement frequency of parts, etc.), and so forth.

Details of implementation

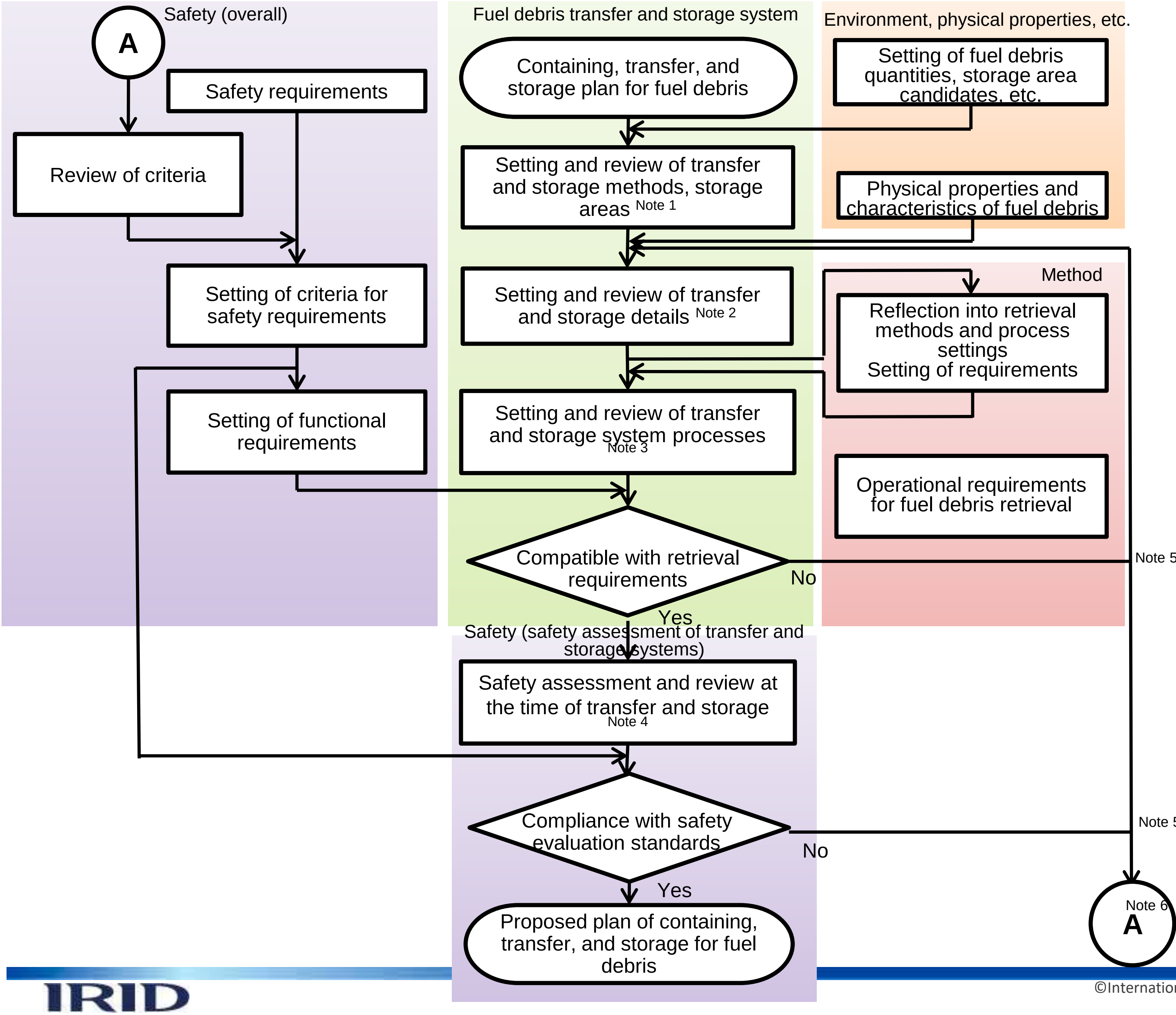
② Actualization of drying equipment concept

The concepts for drying equipment in the canister form were studied and the optimum operating conditions were crystallized. In addition, drying treatment using the canister was compared with using the chamber based on the results of test in 3.2① and then the advantages and disadvantages of the both treatments were evaluated from the perspective of drying time, safety requirements, etc. Essentially, multiple simultaneous drying can be applicable by increasing the number of drying lines at the actual construction stage, while issues to be considered for applying the treatment were consolidated. Furthermore, requirements (requests) [Note 1] for canister specifications were summarized from the viewpoint of drying treatment.

[Results]
(1) Concepts of drying equipment in the canister form
(2) Optimum operating conditions for the canister form
(3) Results of evaluation on advantages and disadvantages compared to the chamber method
(4) Issues to examine for multiple simultaneous treatment
(5) Requirements (requests) for the canister design

Note 1: The marker section is from section 3.1 in the solicitation information

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

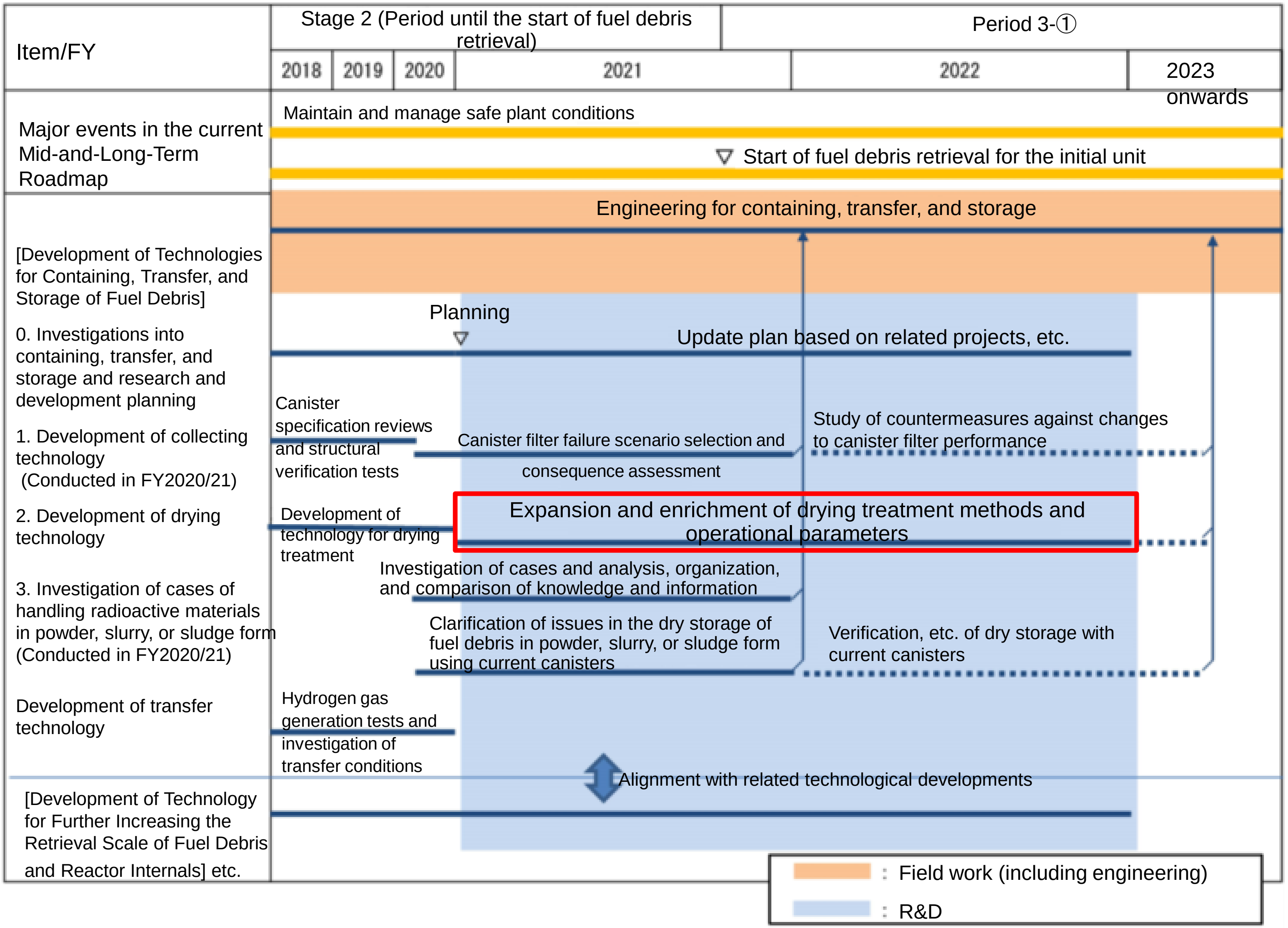


- Note 1:
  Setting basic storage policies such as wet storage and dry storage at new facilities
- Note 2:
  Specific storage methods such as dry vent storage and dry sealed storage
  Related technological development:
  Evaluation of the amount of hydrogen generated, countermeasures for hydrogen generation
- Note 3:
  Necessary processes for transfer and storage such as drying, etc.
  Related technological development:
  Drying equipment, hydrogen measurement technology
- Note 4:
  Safety assessment
  Related technological development:
  Structural evaluation, evaluation of the amount of hydrogen generated
- Note 5:
  Go up for "Setting and review of transfer and storage details"
  Go down for "Review of overall safety criteria"
  If it is both the cases, go up and down
- Note 6:
  If the overall safety criteria are tentatively set and considered, they may be reviewed as necessary to reflect the enhancement of knowledge and progress of studies from research and development

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

3.3 Relationship between Implementation items

(Target schedule) B3④ Development of Technologies for Containing, Transfer, and Storage of Fuel Debris



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

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

3.3 Relationship between Implementation items

Tokyo Electric Power Company Holdings, Inc.

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

International Research Institute for Nuclear Decommissioning (IRID)

Canister (drying) project

[Provide information to related projects]
(1) Study of equipment design and methods
- Details of examinations of equipment design and methods required from the viewpoint of the drying technology

(2) Concepts for containing, transfer, and storage equipment
- Study of storage conditions

Project for further increasing retrieval

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

[Obtain information from the canister (drying) project]
- Collection method requests

Fuel debris characterization project

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

Waste project

[Obtain information from the canister (drying) project]
- Understanding storage conditions

Canister (sludge) project

[Provide information for the canister (drying) project]
- Collected information and extracted issues involving sludge drying, storage, etc.

Water treatment project

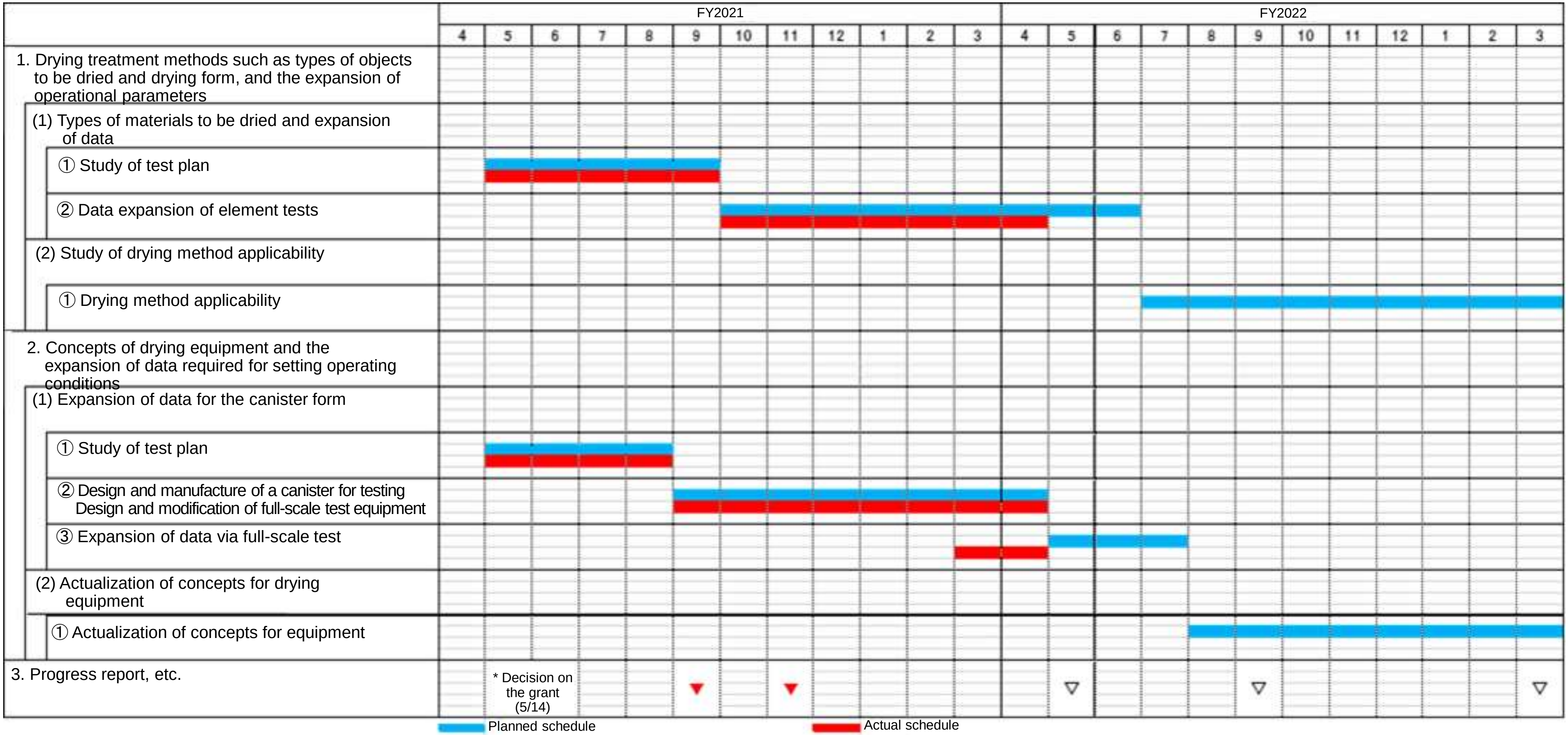
[Provide information for the canister (drying) project]
- Information on sludge to be dried generated in water treatment system
- Drying characteristics of sodium silicate neutron absorber

[Obtain information from the canister (drying) project]
- Drying goals, operating conditions, etc.

Note) These abbreviations are also used in the following slides.
Project for further increasing retrieval: "Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals" project
Fuel debris characterization project: "Development of Analysis and Estimation Technology for Fuel Debris Characterization" project
Waste project: "R&D for Treatment and Disposal of Solid Radioactive Waste" project
Water treatment project: "Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)" project
Canister (sludge) project: "Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Treatment for Fuel Debris in Powder, Slurry, or Sludge Form)" project
Canister (drying) project: "Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Drying Technology for Fuel Debris)" project

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

4. Implementation schedule



5. Project organization

(As of the end of March 2022)

Tokyo Electric Power Company Holdings, Inc.
- ○ Project Management for the Decommissioning of the Fukushima Daiichi Nuclear Power Station

International Research Institute for Nuclear Decommissioning (IRID) (Head Office)
- ○ Formulation of overall planning and technology management
- ○ Technology management such as the progress of technological developments, etc.

Related development projects
- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Development of Fuel Debris Retrieval Method
- R&D for Treatment and Disposal of Solid Radioactive Waste
- Development of Technologies for Containing, Transfer, and Storage of Fuel Debris (Treatment for Fuel Debris in Powder, Slurry, or Sludge Form)

Mitsubishi Heavy Industries, Ltd.	Toshiba Energy Systems & Solutions Corporation	Hitachi-GE Nuclear Energy, Ltd.
(1) Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters (2) Concepts of drying equipment and the expansion of data required for setting operating conditions	(1) Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters (review) (2) Concepts of drying equipment and the expansion of data required for setting operating conditions (review)	(1) Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters (review) (2) Concepts of drying equipment and the expansion of data required for setting operating conditions (review)

MHI-NS
- Canister design

Sol tec
- Element testing (acquisition of test data)

MHI-MS
- Study of modifications to full-scale drying equipment
- Design and manufacturing of modified full-scale drying equipment

RSG
- Canister flow analysis

Chugai Technos Corporation
- Element testing / full-scale drying tests (acquisition of test data)

Note)
MHI-NS: MHI NS Engineering Co., Ltd.
Sol tec: MHI Solution Technologies Co., Ltd.
MHI-MS: Mitsubishi Heavy Industries Machinery Systems, Ltd.
RSG: Ryoyu System Engineering Co., Ltd.

6. Implementation details

6.1 Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters

6.2 Concepts of drying equipment and the expansion of data required for setting operating conditions

Within the implementation details in this report, “Drying treatment methods such as types of objects to be dried and drying form, and the expansion of operational parameters” is called “**element tests**” and the results of such test were organized.

Within the implementation details in this report, “Concepts of drying equipment and the expansion of data required for setting operating conditions” is called a “**full-scale test**” and the results of such test were organized.

6.1 Element tests

① Purposes and goals

Note 1: Φ45 mm × 100 mmH scale
Note 2: 3.7 wt% in terms of fuel debris, target is 0.1 wt%
Note 3: Slurry and sludge were conducted at full-scale (the reason will be provided later)

FY2019/20 Implementation of element tests (beaker scale tests Note 1)

Obtained data on drying characteristics for porous media (zeolite), SUS beads, silica sand, and ZrO_2 slurry

ZrO_2 slurry was dried to 3.3 wt% Note 2 in 24 hours (requires a lot of time for drying)

Target: Clarify the applicable range of the drying treatment

Slurry and sludge

Concrete

Element tests Note 3

Deployment to other types

Impact assessments by analysis

(Test objective) Verify the applicability of drying treatment to material types containing difficult-to-dry substances and hydrates

(Results)

① Specify the types of materials that can undergo the drying treatment

② Alternative countermeasure proposal for hydrogen generation

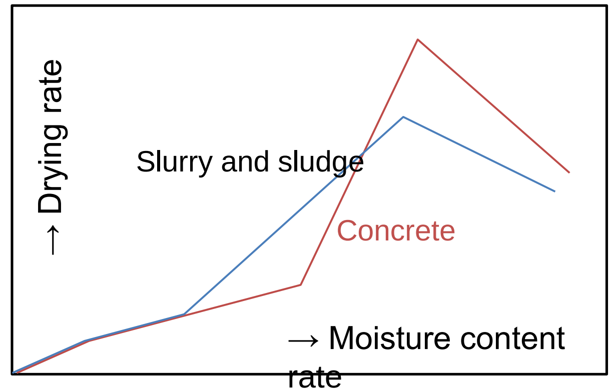


Image of the data obtained ① Drying characteristic curve

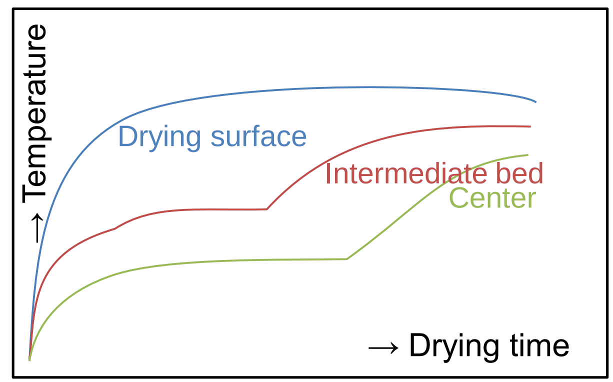


Image of the data obtained ② Internal temperature distribution

6.1 Element tests

② Comparison with existing technology

Under the project the Development of Technologies for Containing, Transfer, and Storage of Fuel Debris until FY2020, technology for safely handling and storing lump-like or particulate fuel debris using the canisters was developed. Additionally, conceptual studies of drying methods for difficult-to-dry-materials, zeolite, and drying equipment of the unit cans were conducted.

On the other hand, both fuel debris in powder, sludge, or slurry form as well as concrete are expected to be collected when retrieving fuel debris, so drying data must be obtained to study the possibility of such material drying in the same manner as fuel lump-like and particulate fuel debris.

6.1 Element tests

③ Implementation items and results

Note 1: Condition 1 was obtained as of FY2020. Data is expected to be expanded based on input from the FY2021-2022 water treatment project

(1) Study of test plan: Objects to be dried (1/2)

Status of data acquisition for each material to be dried

[red box] • • • range of FY2021-2022 data expansion

Classification	Process	Outlines	Photo image	Data acquisition status (up to FY2020)			
				Zeol.	SUS	Slurry	Conc.
Unmeted fuel assembly	Retrieval process	Pieces of broken fuel assemblies left unmelted		Obtained	—	—	—
Lump-like fuel debris and MCCI		Molten materials slowly cooled down into lump form		Obtained	—	—	Not obtained
Pebble-like fuel debris		Molten reactor core materials quickly cooled down into small pieces	 	Obtained	Obtained	—	—
Structures with adhered fuel debris		Pieces of broken structures left unmelted with fuel debris adhering to them		Obtained	Obtained	—	—
Slurry and sludge	Water treatment system	Fuel debris in powder and fine particle form		—	—	1 Condition (ZrO_2) Note 1	Not obtained
Water treatment filter		Filters with fuel debris in powder and fine particle form adhering to them		—	—	Not obtained	Not obtained
Gas treatment filter	Gas treatment system	Filters with dry fuel debris powder adhering to them		—	—	Not obtained	—

6.1 Element tests

③ Implementation items and results

(1) Study of test plan: Objects to be dried (2/2)

Study of assumed drying treatment conditions for materials to be dried with data as yet not obtained

① Materials for which drying characteristics data has not yet been obtained

a. Slurry and sludge containing treated and collected fuel debris mixed with concrete powder and fragments of core structure material

→ Flocculated and sedimented slurry and sludge with added flocculant, to reflect the study in the water treatment project

b. Fuel debris mixed with concrete pieces, fuel debris adhering to concrete pieces

c. Water treatment filters and gas treatment filters with fine powder fuel debris adhering to them

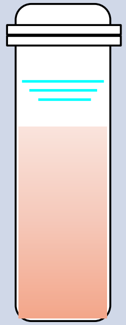
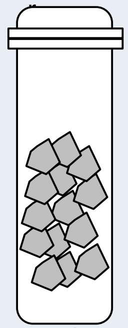
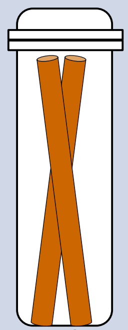
② Assumed state before drying treatment

a. A decanter, cyclone, or similar equipment is used to separate out some of the solid content before containing material in a canister

b. Concrete pieces (glass form) contained in a canister

c. Sintered metal filter media and HEPA filter media contained in canister

Assumed state before drying treatment (example)

Types	form	Conceptual drawing
a. Slurry and sludge	Canister	 Caniste
b. Concrete pieces	Canister	 Caniste
c. Filter media	Canister	 Canister

6.1 Element tests

③ Implementation items and results

(2) Study of test plan: Test policy

(Test objective) The test aims to verify the applicability of drying treatment to material types containing difficult-to-dry substances and hydrates

(Results)

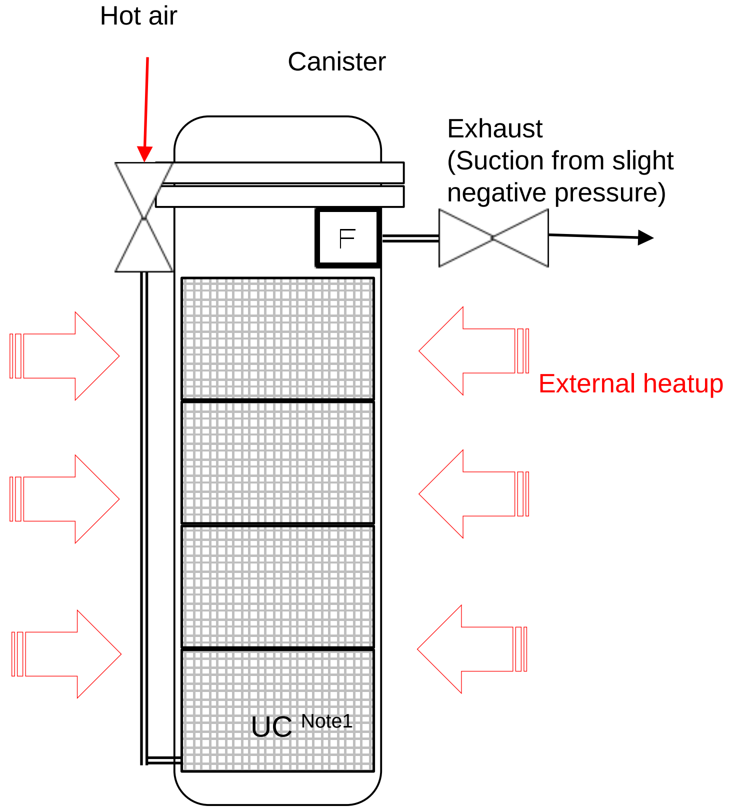
① The types of materials that can undergo the drying treatment were specified.

② Alternative countermeasure proposal for hydrogen generation

[Test policy]

i. The range of application for the current treatment concept with difficult-to-dry materials (moisture content rate at 24 hours (reference)) shall be verified.

ii. The necessary alternative countermeasures for hydrogen generation and their methods shall be proposed based on trends in acquired data.



Current treatment concept (FY2019-2020 examination results when drying in a canister Note 2)

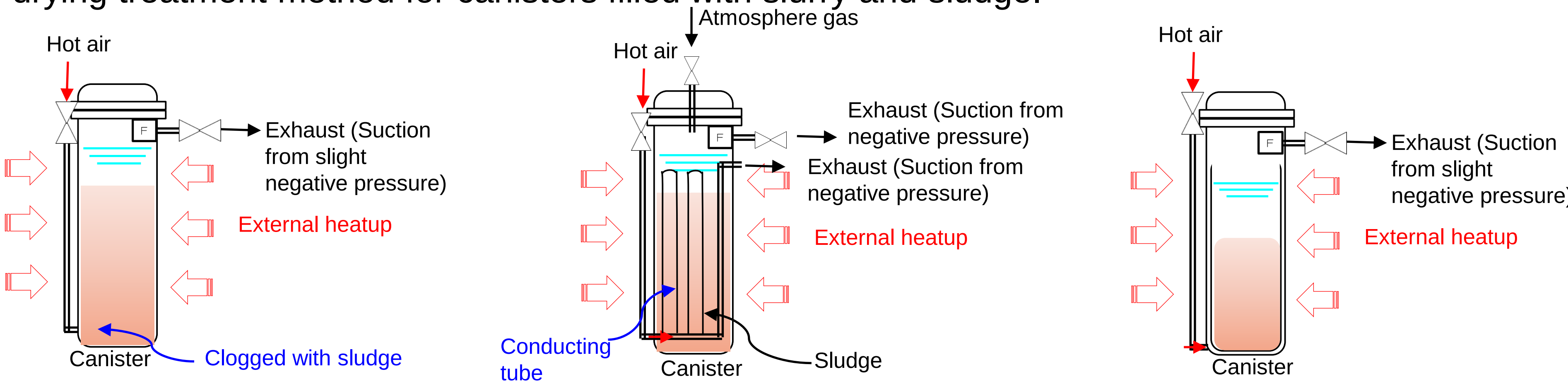
Note 1: "UC" represents unit can.
Note 2: Replace canister with drying chamber when drying in a drying chamber.

6.1 Element tests

③ Implementation items and results

(3) Study of test plan: Test items and objectives (1/3)

- The assumed drying conditions is applied to the current treatment concept and tests shall be planned.
- A method of the “Proposal ③ the inner container filled with slurry and sludge” was applied to the drying treatment method for canisters filled with slurry and sludge.



[Proposal ① Direct filling]
1. Assuming that current canister specifications using air supply and exhaust vents are applied. However, an internal filter is added to prevent the spread of contamination
2. There is a high possibility that airflow treatment cannot be conducted due to clogged the air supply vent with sludge.

⇒ X (Not applicable)

[Proposal ② Add conducting tubes]
1. Add conducting tubes and nozzles
2. Drying treatment can be available, but the canister will be very expensive. This proposal is unrealistic.

⇒ X (Not applicable)

[Proposal ③ Fill an inner container with slurry and sludge]
1. The container is doubled-walled and the inner container is filled with sludge
2. The risk of clogging pipes will be significantly reduced.

⇒ ○ (Applicable)

③ Implementation items and results

(3) Study of test plan: Test items and objectives (2/3)

Issues in element tests with an inner container filled with slurry and sludge

- The equipment in the FY2019-2020 beaker scale test assumed that both heat transfer and moisture transfer moved in the same direction. (Figure 1)

- When using an inner container filled with sludge and slurry, however, heat is transferred from the side and moisture moves three-dimensionally, evaporating from the open top. (Figure 2)

<Issues from the difference in direction between heat transfer and moisture transfer>

- ✓ The directions of movement for heat transfer and moisture transfer do not match. Therefore, the equipment from the FY2019-2020 beaker scale drying test cannot be used.
- ✓ Evaluation of actual scaled-up equipment after obtaining reduced-scale test data is difficult with three-dimensional drying behavior.
- ✓ In scaled-down models, heat capacity (volume) is relatively smaller than heat input (external surface area) and so the temperature of the test piece (thus its drying rate level) is higher than it would be in an actual equipment under the same heating conditions. (Figure 3)

Based on the above points, a full-scale test should be conducted to test an inner container filled with slurry and sludge.

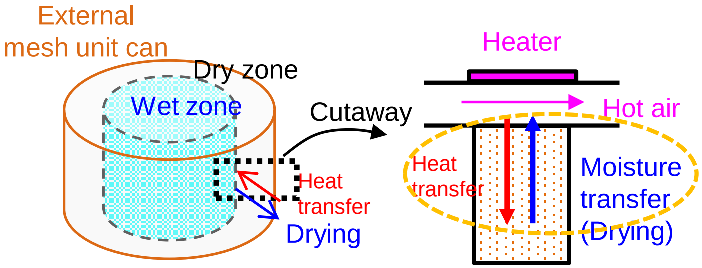


Figure 1: Beaker scale test

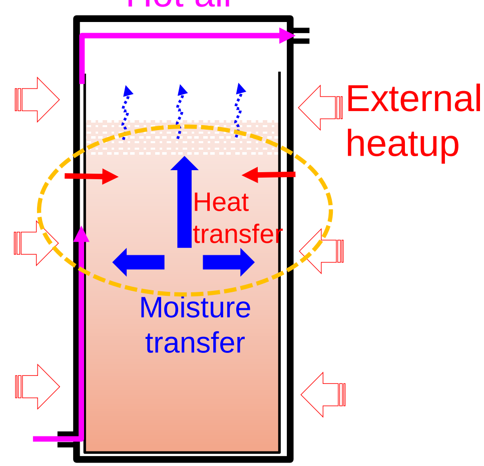


Figure 2: Slurry and sludge drying

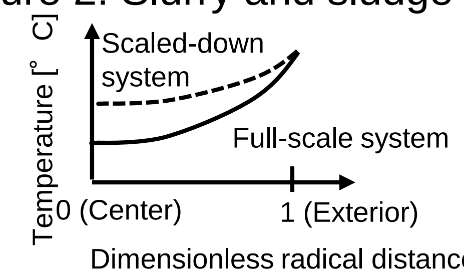


Figure 3: Schematic diagram of temperature distribution in scaled-down and full-scale systems

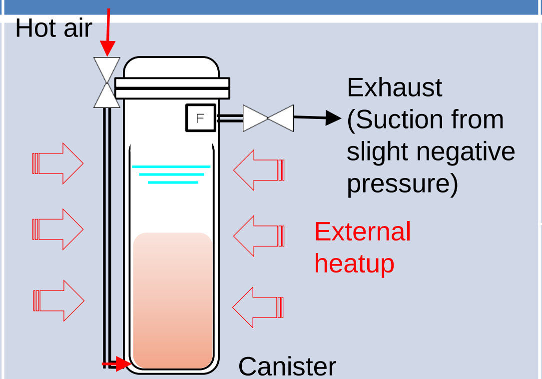
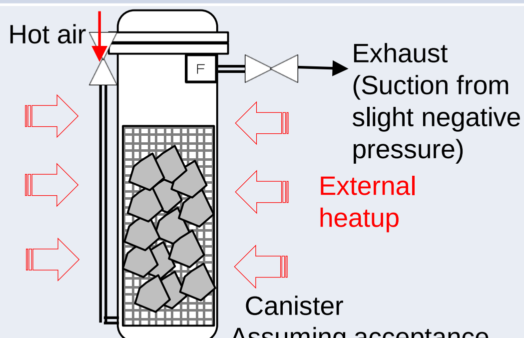
6.1 Element tests

③ Implementation items and results

(3) Study of test plan: Test items and objectives (3/3)

Note 1: See the figure on slide No. 20.
Note 2: The time from the heater turning ON and the start of airflow
Note 3: Wet/dry weight. Target: 0.1 wt% in terms of fuel debris

Data will be obtained as listed below to clarify the range of application for the existing concept.

Material to be dried	Assumed application of treatment concept Note1	Test type	Items	Objective and outline	Data and information to be obtained
Slurry and sludge		Full-scale	Drying characteristics of temperature	Using the currently assumed slurry and sludge, obtain data on drying characteristics with temperature and filling volume as parameters, and verify the range to which the existing treatment concept can be applied	Internal temperature/time Note 2 vs Moisture content rate Note 3
		Full-scale	Drying characteristics of filling volume		Filling volume/time Note2 vs Moisture content rate Note3
Concrete	 Assuming acceptance of the UC	Beaker scale	Drying characteristics of concrete	Study changes in moisture content rate over time and verify the drying time of external seepage water to evaluate the impact of hydrates inside the concrete	Time Note2 vs Moisture content rate Note 3
Filter media	Packed directly in a canister	Analysis	Range of dry material types	Use test data on slurry and sludge, etc. to verify whether filter media can be dried and the types of media that can be dried	Analysis results

6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 1 (full-scale slurry and sludge test plan (1/2))

〇 Test objective

- Use full-scale test equipment to verify whether the target moisture content rate via drying can be achieved (achievable treatment time) for slurry and sludge discharged from sedimentation equipment.
- Verify the impacts of drying temperature (heater surface temperature) and filling height in case it is not achievable or as a proposal for reducing drying time.

〇 Evaluation method

- Measure temperature distribution within the sample, the mass of the sample, and changes in the dew point of exhaust gas over time, and evaluate the degree of moisture content rate attained and the drying rate (moisture reduction rate).
- Collect particles in the exhaust gas.

〇 Slurry and sludge conditions

- Slurry and sludge: Silica sand [Note 1, 2] (1 condition)
- Flocculant : Aluminum sulfate [Note 1] (1 condition)
- Slurry and sludge particle size: 10 to 100 µm

〇 Treatment conditions

- Drying method: side heater + hot air heatup
- Heater surface/hot air temperature: 200° C, 300° C
- Filling height: 200 mm minimum (observe dispersion conditions and adjust test conditions to verify the impact of fill height)

Table: Proposed test conditions

Slurry and sludge material	Particle size [µm]	Filling height [mmH]	Heater surface/hot air temperature [°C]	Heater output [kW]	Flow velocity [Note 4] [m/s] (Flow rate [Nm³/h])
Silica sand	10 to 100	200/400	200	up to 10	3(37)
$Al_2(SO_4)_3$	—	200/400	200	up to 10	3(37)
Silica sand + $Al_2(SO_4)_3$	—	400	200	up to 10	3(37)
Representative condition 1 [Note 3]	—	200	300	up to 10	3(37)

Note 1: Only material discharged from the roughing system in the water treatment project is targeted and representative condition 1 is selected for slurry, sludge, and the flocculant
Note 2: Silica sand was selected from the components of simulated slurry and sludge (tungsten carbide, SUS316L, silica sand) in the water treatment project element tests as it has the highest moisture content rate and is considered to be difficult to dry
Note 3: Determined based on other test results Note 4: The chamber annulus section

6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 1 (full-scale slurry and sludge test plan (2/2))

- Data on the drying characteristics of the slurry and sludge in the inner container shall be obtained.

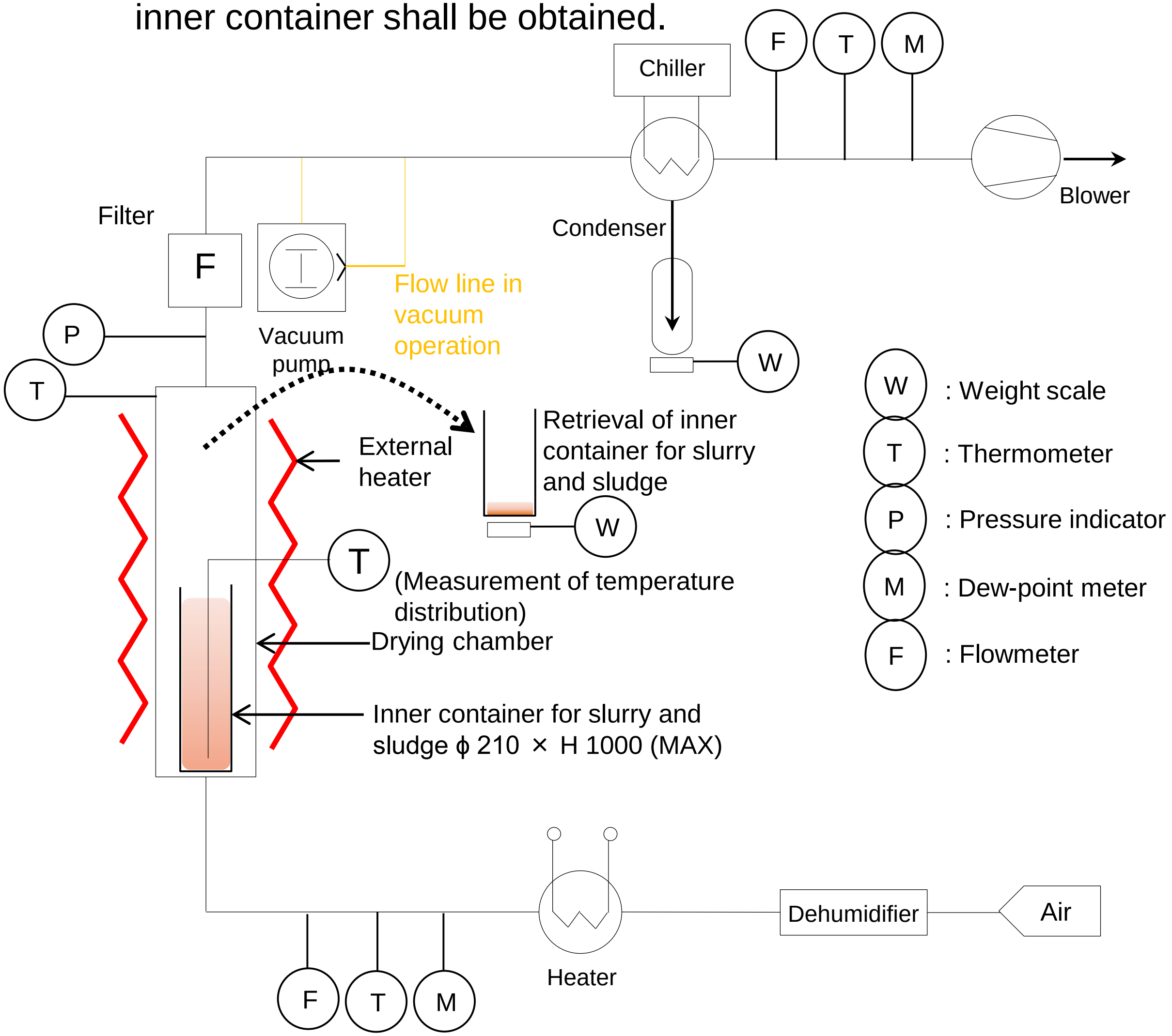
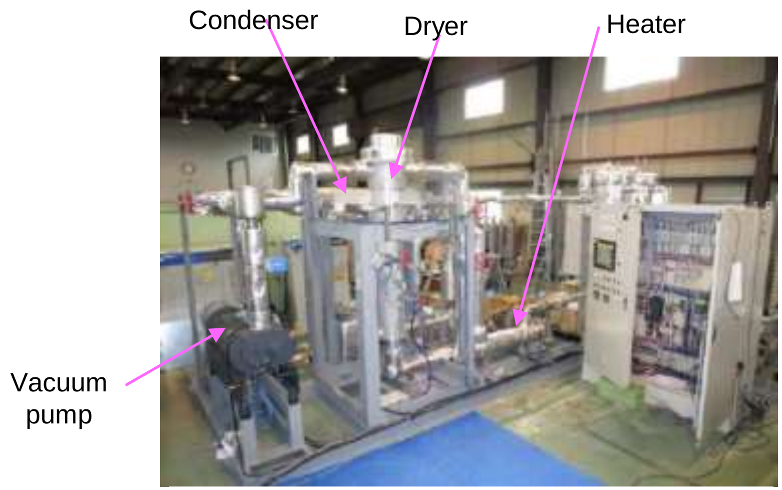


Figure: Schematic of the full-scale drying test system

(Test conditions and system)
- Hot air drying
- The inner container is filled with slurry and sludge, which is then dried in the drying chamber
- Material to be dried: Flocculated and sedimented slurry and sludge
  (Examined in the water treatment project)
- Measure the internal temperature of the slurry and sludge / Measure the weight of retrieved material (obtain data on drying characteristics)

(Test parameters)
- Sample material, temperature, slurry and sludge filling height

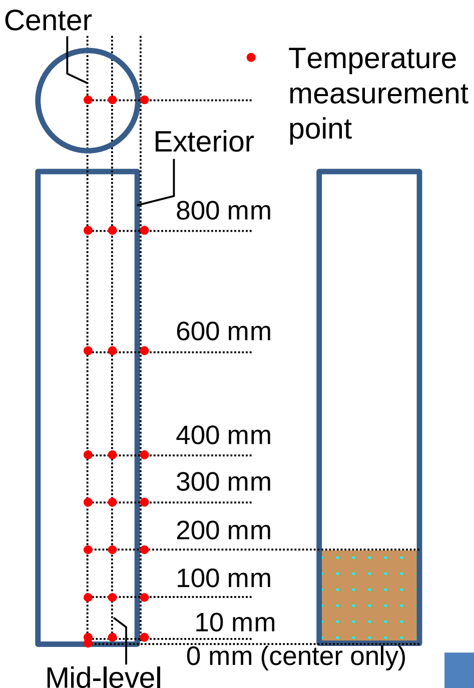


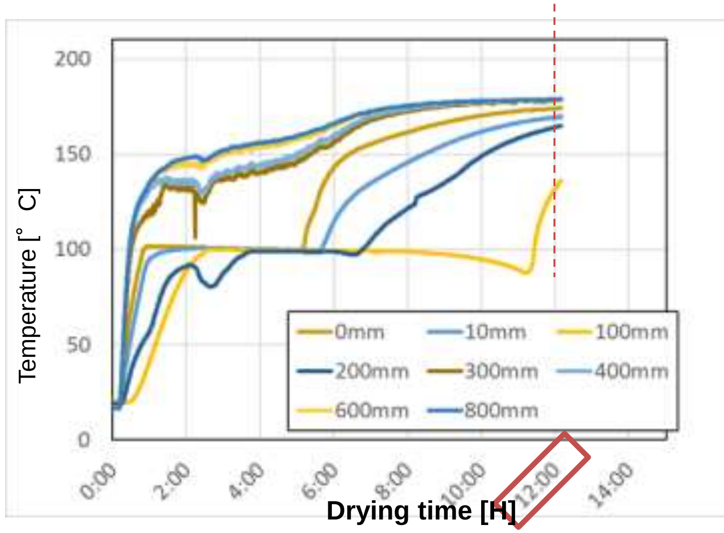
External appearance of the full-scale drying test system

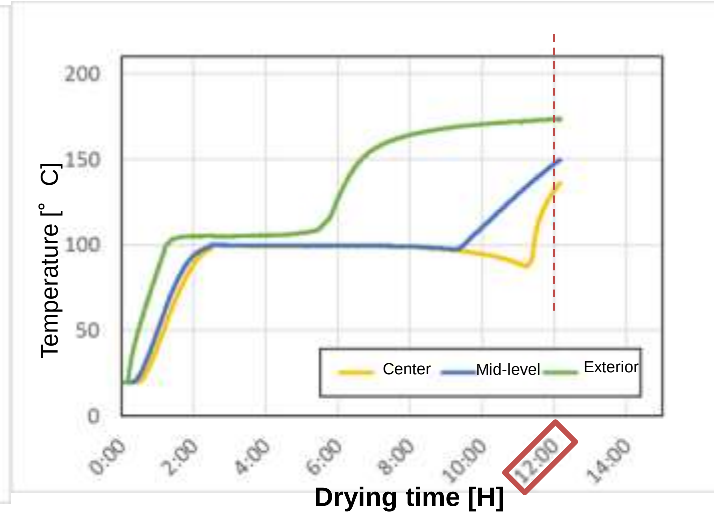
6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 1 (full-scale slurry and sludge test results (1/2)
• • • Silica sand 200 mm (20% height)



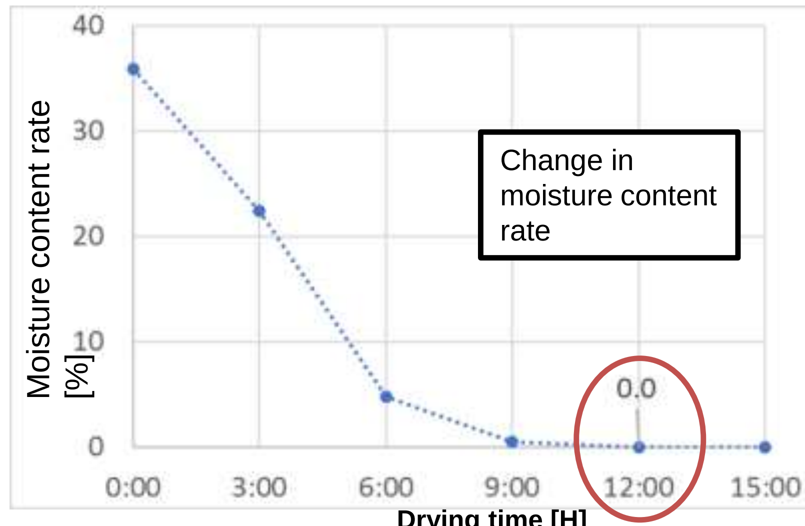




Temperature change at 200 mm (20% filling height) Left: Center (0 to 800 mm) / Right: Radical direction (100 mm)

State at beaker scale construction (However, the supernatant was removed before drying)

Weight measurement results	
Absolute dry weight Note 1	10280g
Initial moisture content rate Note 2	36%
Amount of residual moisture after 12 hours	≒ 0 Note3
Moisture content rate after 12 hours Note2	≒ 0 Note3



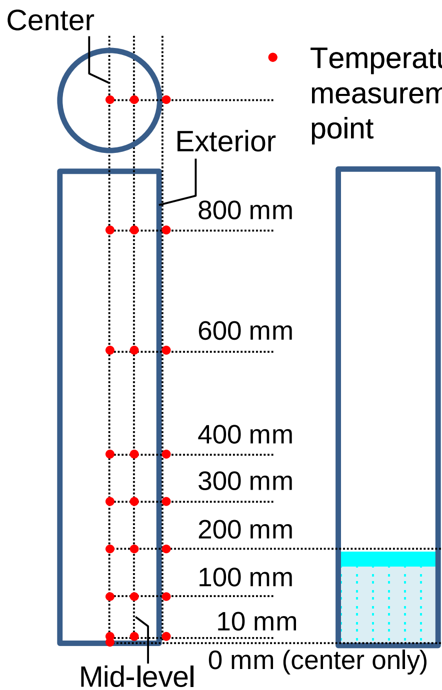
Note 1: Weight when heated at 300° C for 5 hours Note 2: Moisture content rate/Absolute dry weight (weight after holding at 300° C for minimum 5 hours). Drying target is 0.2 wt% (target moisture content rate in terms of fuel debris) Note 3: Including measurement error Error evaluation is in progress

6.1 Element tests

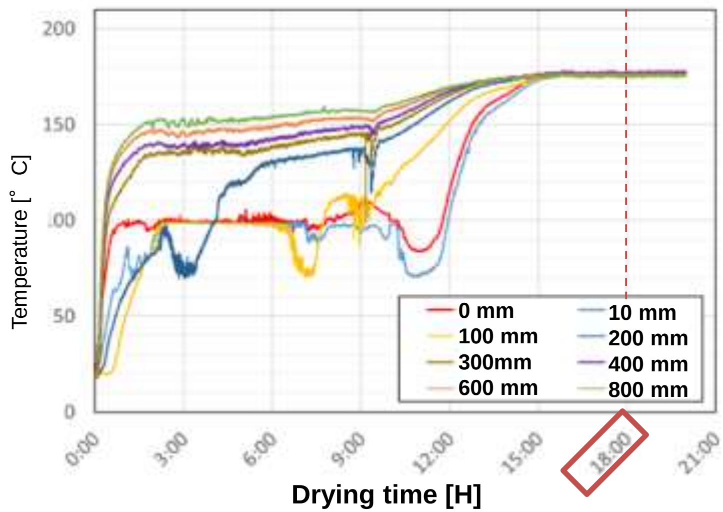
③ Implementation items and results

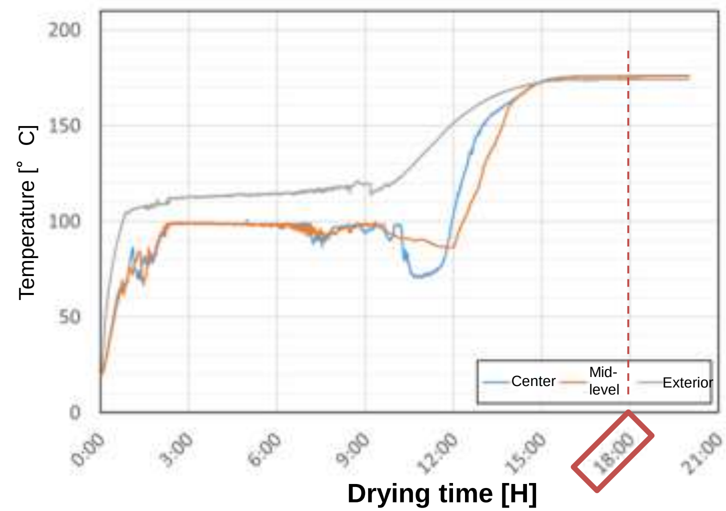
(4) Data expansion of element tests 1 (full-scale slurry and sludge test results (2/2)

• • • Flocculant (Floc) 200 mm (20% height)



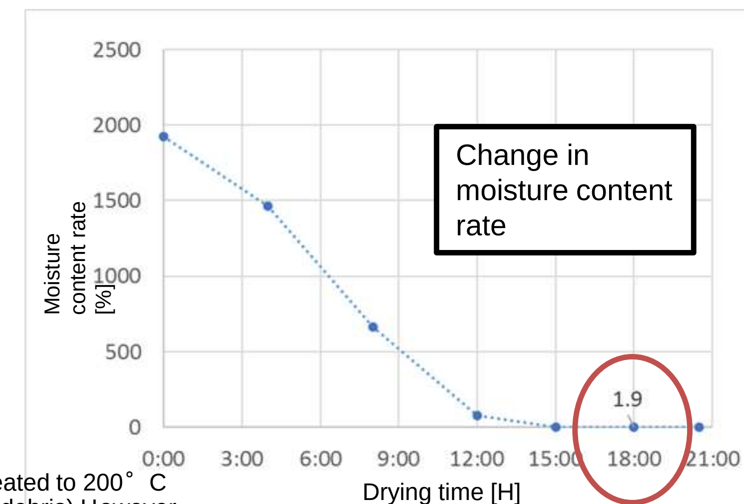
State at beaker scale construction





Temperature change at 200 mm (20% filling height) Left: Center (0 to 800 mm) / Right: Radical direction (10 mm)

Weight measurement results	
Absolute dry weight Note 1	363g
Initial moisture content rate Note 2	1927%
Amount of residual moisture after 18 hours	7g
Moisture content rate after 18 hours Note 2	1.9% Note 2



Note 1: Theoretical value calculated from the amount of input reagent for the mass of material generated when heated to 200° C
Note 2: Moisture content rate/Absolute dry weight. Target is 0.2 wt% (target moisture content rate in terms of fuel debris) However, absolute dry weight is currently being evaluated

6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 2 (concrete beaker scale test: overall plan)

- A beaker scale drying test shall be conducted to understand the effects of hydrates within concrete on drying characteristics.
- Concrete contains cement components (such as calcium), aggregates (such as silica), and additives (surfactants).
- Therefore, concrete composition parameter tests shall be conducted to verify the extent of influence on the drying behavior of concrete composition.
- In addition, the effects of concrete piece size and treatment conditions (gas temperature and gas flow velocity) shall be verified to reflect findings in actual equipment design and treatment conditions.

○ Concrete conditions

- Cement: Ordinary Portland cement (JIS R 5210)
- Fine aggregate: Sand (fineness modulus: 2.5 to 2.9)
- Coarse aggregate: Gravel (fineness modulus: 6.2 to 6.6)
- Chemical admixture: Water reducing agent, etc. (selected in accordance with JIS A 6204)

○ Test parameters:

- Concrete composition Note 1
  - Water/cement weight ratio
  - Aggregate/cement weight ratio
  - Fine aggregate/coarse aggregate weight ratio
- Diameter of concrete particle
- Gas temperature
- Gas flow rate

$$\text{Fineness modulus} = \frac{x_{40} + x_{20} + x_{10} + x_{5} + x_{2.5} + x_{1.2} + x_{0.6} + x_{0.3} + x_{0.15}}{100}$$

Xi: Ratio of aggregate mass retained in the imm sieve [%]

Note 1: Also plan to obtain the thermophysical properties in addition to the beaker scale test

6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 2 (concrete beaker scale test: physical properties measurement test plan)

○ Measurements of the physical properties of concrete material

- The physical properties that contribute to the drying behavior shall be measured in order to evaluate the drying behavior of concrete materials.
- The following items will be measured.
  - ✓ Thermophysical properties (thermal conductivity and specific heat) : Evaluate the correlation between concrete composition and impacts on drying behavior.
  - ✓ TG/DTA-MS Note 1 : Verify the thermal decomposition behavior during drying treatment.
  - ✓ Pore diameter distribution : Compare moisture adsorption characteristics with zeolites.
- The following table lists the measurement conditions for each physical property.

Run	Water/cement ratio	Aggregate/ cement ratio	Fine aggregate/total aggregate ratio	AE agent Note 2/cement ratio	Blending parameter evaluation items	Thermal conductivity	Specific heat	TG/DTA-MS	Pore diameter distribution
	[wt%]	[-]	[wt%]	[wt%]					
1	55	5.4	44	0.03	Base condition	Conducted	Conducted	Conducted	Conducted
2	45	5.4	44	0.03	① Water/cement weight ratio	Conducted	Conducted	Conducted	Conducted
3	70	5.4	44	0.03		Conducted	Conducted	Conducted	Conducted
4	55	3.0	44	0.03	② Cement/total aggregate weight ratio	Conducted	Conducted	—	—
5	55	6.0	44	0.03		Conducted	Conducted	—	—
6	55	5.4	60	0.03	③ Fine aggregate/total aggregate weight ratio	Conducted	Conducted	—	—
7	55	5.4	30	0.03		Conducted	Conducted	—	—
A	55	0	—	—	Presence of aggregate in Run 1	Conducted	Conducted	Conducted	Conducted
B	40	0	—	—	Presence of aggregate in Run 2 Note 3	Conducted	Conducted	Conducted	Conducted
C	70	0	—	—	Presence of aggregate in Run 3	Conducted	Conducted	Conducted	Conducted

Note 1: Simultaneous measurement of thermogravimetric/differential thermal analysis and gas mass spectrometry Note 2: Air Entraining Agent
Note 3: The water/cement ratio is slightly lower in Run 2 because water was added to address poor clumping during blending in Run 2.

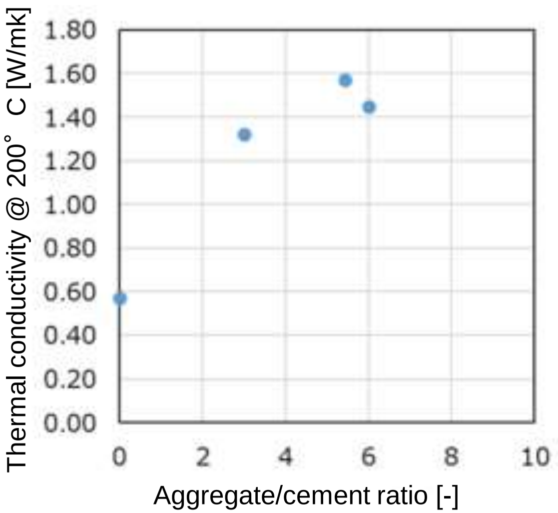
6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 2 (concrete beaker scale test: physical properties measurement test results (1/3))

○ Results of thermophysical property measurements (thermal conductivity and specific heat)

- Both thermal conductivity and specific heat were greatly affected by the aggregate/cement ratio (with or without aggregate), while other compositions showed relatively small impact.
- The higher aggregate/cement ratio, the lower the overall cement ratio and therefore the lower ratio of fine voids, etc., present in the cemented portion, which may have resulted in a tendency toward high thermal conductivity.
- Since the specific heat of aggregate is less than half that of cement, the significant differences in specific heat may have been the result of the presence or absence of aggregate.



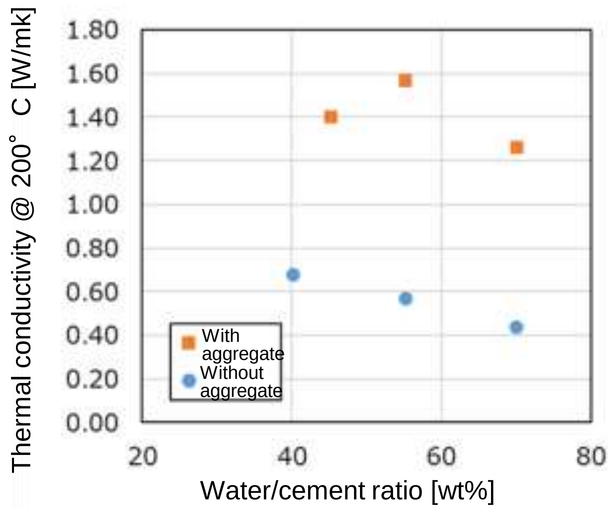


Figure: Thermal conductivity measurement results

Table: Specific heat measurement results

Run	Specific heat [J/K·g]/ measured temperature [°C]	
	207	297
1	1.4	1.3
2	1.4	1.3
3	1.4	1.4
4	1.4	1.3
5	1.3	1.2
6	1.4	1.3
7	1.4	1.3
A	2.8	2.2
B	2.7	2.2
C	2.9	2.3
Fine aggregate	1.1	1.2
Coarse aggregate	1.2	1.2

③ Implementation items and results

(4) Data expansion of element tests 2 (concrete beaker scale test: physical properties measurement test results (2/3))

○ TG/DTA-MS measurement results

- Samples without aggregate tended to have a high initial moisture content rate due to the large amount of cement, which absorbs moisture easily.
- Remarkable heat absorption and weight reductions were observed when the temperature was raised to 200° C, but very little was observed when held at 200° C.
- Therefore, although moisture desorption and thermal decomposition due to temperature rise is possible, it is believed to have little effect during drying treatment at 200° C.

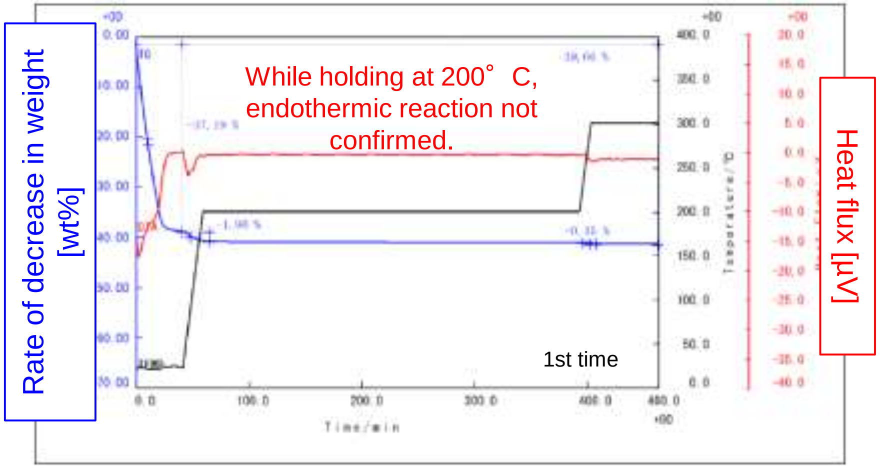


Figure: TG/DTA measurement results

Table: Moisture content rate evaluation

Run	Initial moisture content rate [wt%]	Moisture content rate attained [wt%]
1	4.2	0.3
2	6.8	0.3
3	3.3	0.3
A	16.8	1.3
B	17.8	1.2
C	18.3	1.2

* Run 1 to 3 are average values of N number 3
* Moisture content rate = Volume of water/Absolute dry weight × 100
Calculated based on the initial value at the start of temperature rise, the end point of drying after holding at 200° C for 5.5 hours, and the absolute dry weight after holding at 300° C for 1 hour

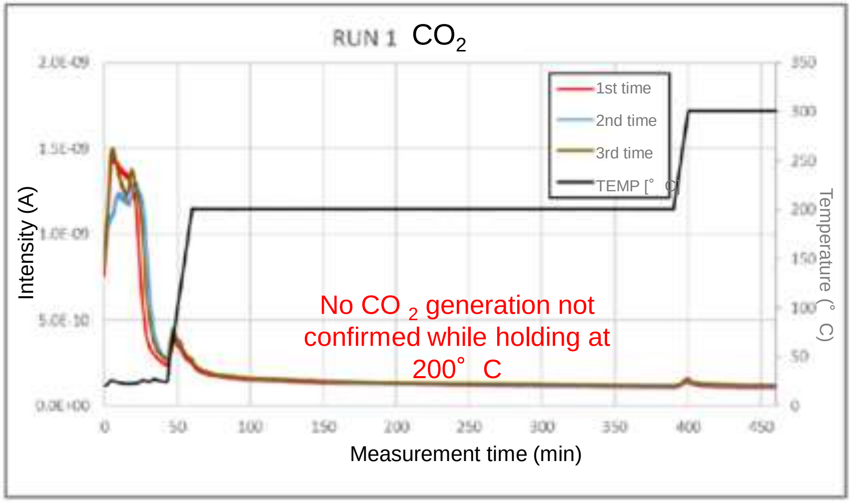


Figure: MS measurement results of generated gas

6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 2 (concrete beaker scale test: physical properties measurement test results (3/3))

〇 Pore diameter distribution measurement results

- It was verified that average pore diameter was almost the same regardless of the water/cement ratio and the presence or absence of aggregate.
- It was verified that samples without aggregate tended to have large pore volume and large specific surface area.
- Compared to zeolite, average pore diameter in the 0 to 4 nm range within concrete samples was verified to be slightly less than twice as large, and pore volume was also verified to be one order of magnitude smaller.
- Therefore, the effect on drying from water adsorption is believed to be less with concrete material than with zeolite.

Table: Results of measurements in pore diameter and pore volume

Run	Measurement range: 0 to 4 nm, Average pore diameter [nm]	Measurement range: 0 to 4 nm, Pore volume [cm³/g]	Measurement range: 1 to 200 nm, Average pore diameter [nm]	Measurement range: 1 to 200 nm, Pore volume [cm³/g]	Specific surface area [m²/g]
1	1.66	0.006	11.00	0.031	10.99
2	1.70	0.014	6.60	0.041	23.58
3	1.69	0.022	7.18	0.074	38.00
A	1.72	0.039	7.77	0.140	66.23
B	1.72	0.029	7.61	0.101	49.59
C	1.73	0.038	10.43	0.190	65.39
Zeolite	0.95	0.135	9.57	0.141	341.24

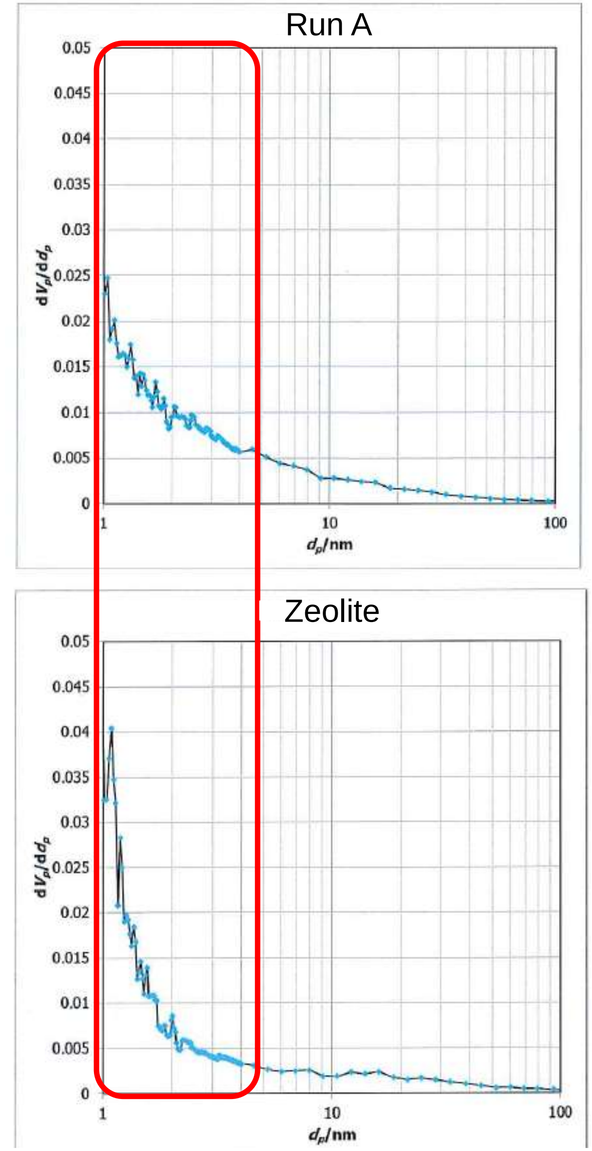


Figure: Pore diameter distribution measurement results

6.1 Element tests

③ Implementation items and results

(4) Data expansion of element tests 2 (concrete beaker scale results: drying test plan (1/2))

- The beaker scale test equipment manufactured in FY2020 will be used to conduct a drying test on concrete pieces to understand the correlation between concrete composition and drying characteristics.

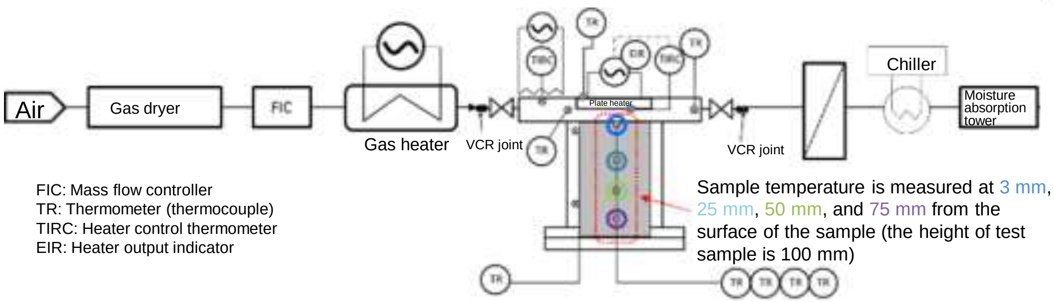


Figure: Simplified schematic of the hot air drying element test system

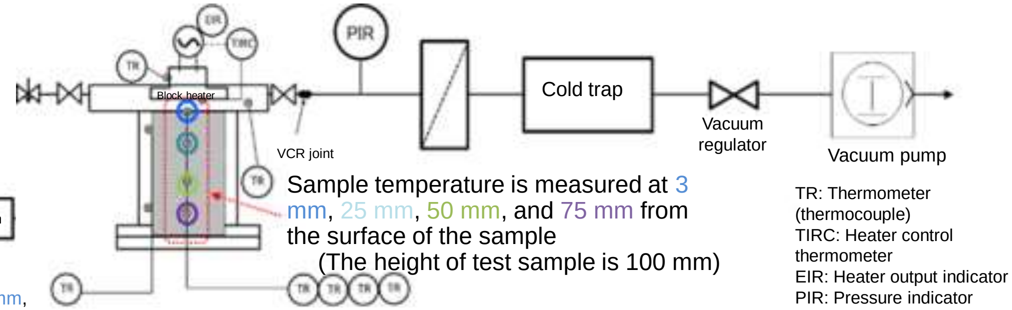
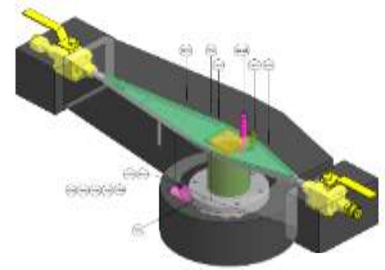
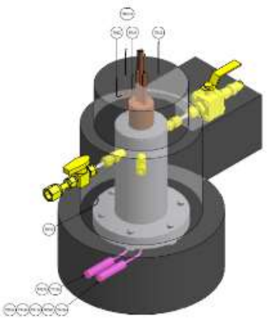


Figure: Simplified schematic of the decompression drying element test system



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



3D CAD drawing of a test container for decompression drying element test system

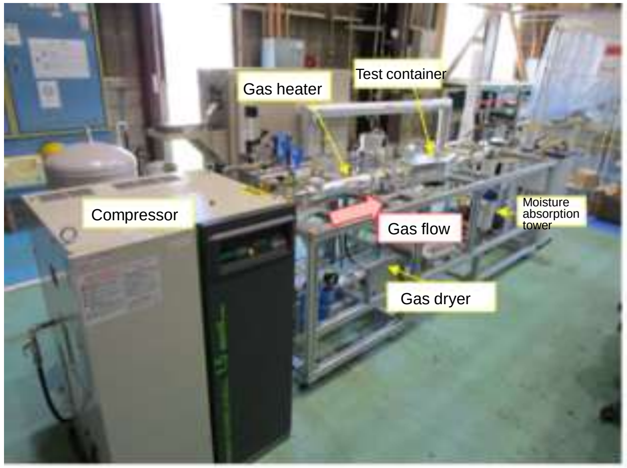


Figure: External appearance of the hot air drying element test system

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

(4) Data expansion of element tests2 (concrete beaker scale results: drying test plan (2/2))

〇 Test objective

- The objective of the test is to acquire data on the drying characteristics to formulate drying treatment conditions for concrete pieces.
- On the basis of the test data obtained, a quantitative evaluation of differences from zeolite and metal balls tested in FY2020 shall be performed to discover the applicable drying treatment conditions for each material to be dried.

〇 Evaluation method

- The evaluation shall be performed by measuring the temperature distribution of the sample and the change in mass of the sample over time to assess the moisture content rate attained and the drying rate (moisture reduction rate).

Table: List of test conditions

Run	Water/cement Note 1 [-]	Aggregate/cement Note 1 [-]	Coarse aggregate/fine aggregate Note 1 [-]	Diameter of concrete particle [mm]	Filling rate [vol%]	Gas temperature [°C]	Gas flow rate [m/s]
1	55	6	1.3	10	Resultant	200	1
2	55	6	1.3	5	Resultant	200	1
3	55	6	1.3	20	Resultant	200	1
4	55	0	—	10	Resultant	200	1
5	55	6	1.3	10	Resultant	200	3
6	55	6	1.3	10	Resultant	200	0.1
7	55	6	1.3	10	Resultant	300	1

Note 1: Concrete component conditions are set with reference to the 1F construction report (see Note 2) and thermophysical properties, etc., and added or changed as required.
Note 2: Nomura et al., "Construction report on the Fukushima Nuclear Power Station Unit 3," *Concrete Journal*, vol.12, No.6, 1974

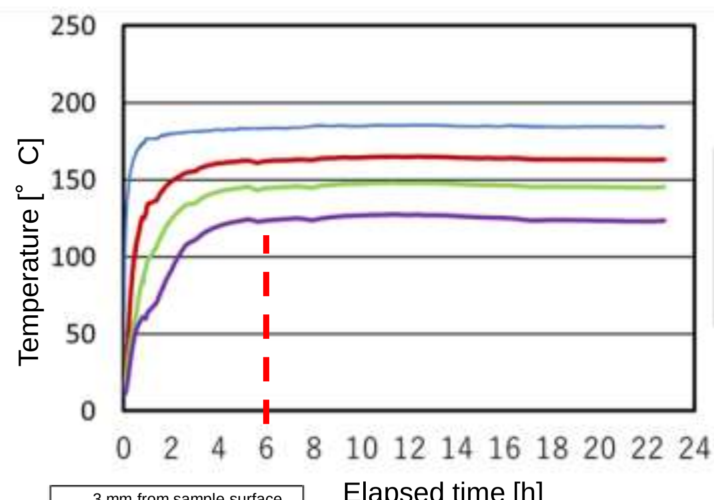
6.1 Element tests

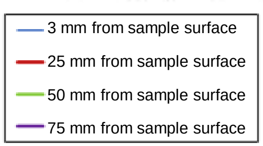
③ Implementation items and results

(4) Data expansion of element tests2 (concrete beaker scale results: drying test results)

○ Comparative evaluation versus zeolite samples

- Drying test was conducted on concrete samples under the same test conditions as the FY2020 zeolite samples.
- Compared to zeolite, concrete test pieces were verified to require less time to reach a constant internal sample temperature (completion of a constant drying rate).
- This is most likely because concrete samples have larger particle diameters and lower water absorption properties compared to zeolite, resulting in less moisture adhesion to the material and lower initial moisture content rate [Note 1].
- The end point of drying will be evaluated in the future by measuring the mass at the point where drying treatment time is 10 to 20 hours.





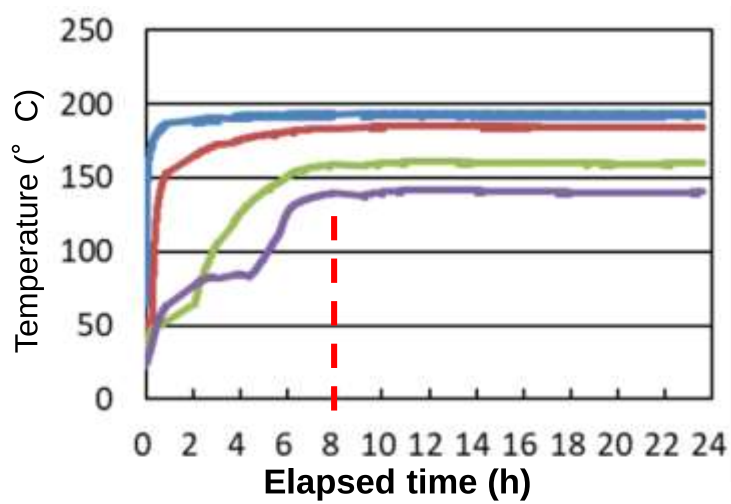


Figure: Change of internal sample temperature over time
(Left: Concrete, Right: Zeolite (FY2020))

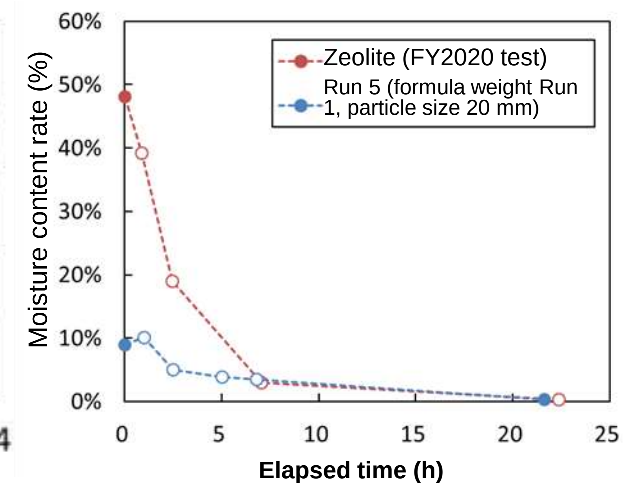


Figure: Change of moisture content rate over time

Note 1: Moisture content rate = Volume of water/Absolute dry weight × 100

Absolute dry weight is the weight when holding at 300° C for at least 5 hours

(5) Content of analysis

The following items were studied by using the analysis model.

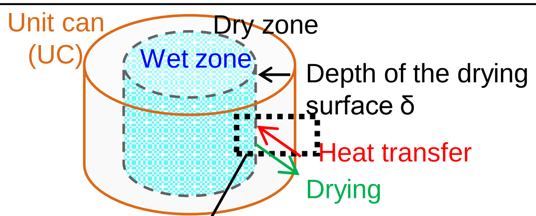
- Evaluation of concrete drying based on element tests, development to a full-scale system
- Sensitivity evaluation of drying time based on the type of material to be dried, such as filter media

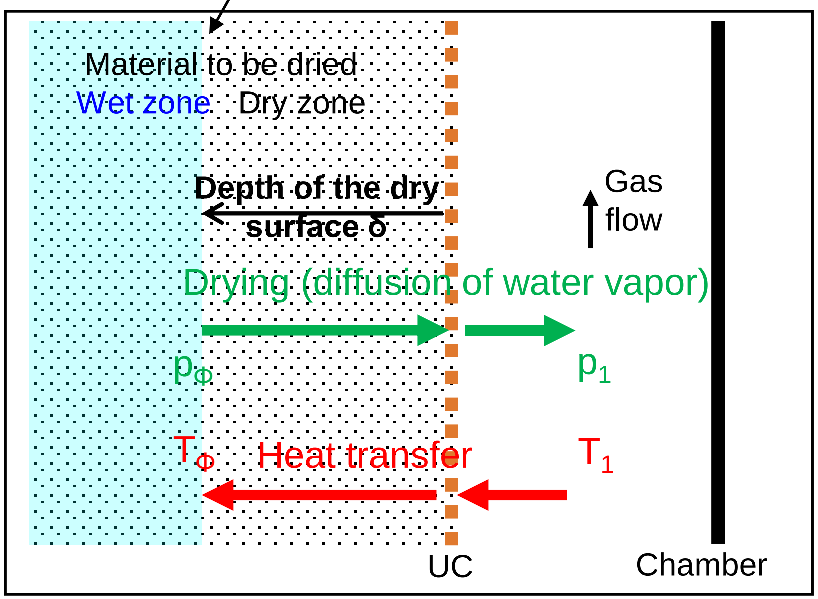
6.1 Element tests

③ Implementation items and results

(6) Analysis model

- Considering that the movement of heat and water vapor is predominantly perpendicular in heat transfer and drying, a one-dimensional model is considered.
- Regarding the dry and wet zones, drying causes the boundary surface (called the drying surface) to move inward. (One idea in the falling rate drying model)





Schematic diagram of drying and heat transfer (longitudinal section)

Drying and heat transfer rates are calculated from the resistance and drive force between the atmosphere and the drying surface (drying rate is the vapor pressure difference and heat transfer rate is the temperature difference).

Drying rate

$$W = \frac{A}{\frac{1}{h_D} + \frac{\delta}{\varepsilon_d D}} \left(\frac{p_\phi}{R_w T_\phi} - \frac{p_1}{R_w T_1} \right)$$

Heat transfer rate

$$Q = \frac{A}{\frac{1}{h} + \frac{\delta}{\varepsilon_\lambda \lambda}} (T_1 - T_\phi)$$

A: Area [m^2]
D: Diffusion coefficient of water vapor [m^2/s]
h: Heat transfer coefficient of the outer surface of the material to be dried (Radiation is considered separately) [$W/(m^2\text{-}K)$]
h_D: Mass transfer coefficient of the outer surface of the material to be dried [m/s]
h_{fg}: Latent heat [J/kg]
p_1: Partial pressure of steam in the atmosphere [Pa]
p_Φ: Partial pressure of water vapor in the drying surface [Pa] (= saturated vapor pressure at TΦ)
Q: Amount of heat transfer [W]
R_w: Gas constant of water vapor [J/(kg-K)]
T_1: Atmospheric temperature [K]
T_Φ: Temperature of the drying surface [K]
W: Drying rate [kg/s]
ε_d, ε_λ: Compensation coefficient regarding porosity, etc. [-]
δ: Depth of the dry zone [m]
λ: Thermal conductivity of the material to be dried [W/(m-K)]

Calculate T_Φ from the relationship between the drying rate and the heat transfer rate in the following equation.

$$W = Q/h_{fg}$$

Drying rate W causes the depth of the drying surface δ to increase with time (as drying progresses).
Adding W gives the average reduction in moisture content rate.

The atmosphere, water vapor partial pressure on the drying surface, and temperature are obtained from drying test measurement data and the depth of the drying surface δ is estimated from the measured temperature. The thermal conductivity of the sample is obtained separately. ε_d and ε_λ are adjusted from these data and the changes in moisture content rate in the test over time.
The difference in the type of material to be dried is reflected in λ, and the difference in shape is reflected in A and δ for evaluation.

6.1 Element tests

③ Implementation items and results

(7) Summary

- Data of objects to be dried, such as slurry, sludge, and concrete, and their storage forms which has not yet been obtained was organized. (No.18 to 19)

- Regarding objects to be dried which data has not yet been obtained, a method of applying drying concepts developed n FY2019/2020 objects was examined. Element test plan was developed depending on each storage form. (No.20 to 23)

- Currently element tests have been conducted to verify the drying characteristics of slurry, sludge and concrete, with their current status as follows. (No.24 to 35)
  - ① The slurry and sludge simulant silica sand and flocculant (filling height 200 mmH) completed drying in 12 to 18 hours
  - ② Results of TG/DTA-MS (simultaneous measurement of thermogravimetric/differential thermal analysis and gas mass spectrometry) show that temperature rises in concrete could potentially lead to moisture desorption and the thermal decomposition of water crystals, but the effect is minimal during drying treatment at 200° C
  - ③ Compared to the zeolite tested in FY2020, concrete pores are one magnitude smaller in pore volume and the effect of moisture adsorption on drying is small.

- Concrete drying evaluation is being planned based on analysis element tests and the sensitivity evaluation on drying time is also planned depending on the type of material to be dried, such as filter media expansion and applying to a full-scale system. (No.36 to 37)

6.1 Element tests

④ Contribution of outcomes to relevant study areas

- The expanded data on the materials to be dried will be organized to contribute to the countermeasures for hydrogen generation during transfer in future.

⑤ Analysis with respect to the on-site applicability

- Equipment specifications will be examined from the perspective of on-site operations, such as presenting optimum operating conditions.

⑥ Issues

- There are no issues in executing the current plan.

⑦ Goal achievement level

- Tests are currently ongoing and are expected to produce the desired results according to plan.

⑧ Future plans

- Element tests will be continued to verify the drying characteristics of slurry, sludge, and concrete.
- In FY2022, the continuation of element tests and the sensitivity evaluation of drying time via analysis will be conducted, and the applicability of the drying concept for each material to be dried will be evaluated.

6.2 Full-scale test

① Purposes and goals

Note 1: 0.1 wt% in terms of fuel debris (target moisture content rate is 0.1 wt% in terms of fuel debri

FY2019-2020
Conducted full-scale drying chamber test

Dried porous media for 16 hours to a moisture content rate of 0.3 wt%[Note 1]

Target: Rationalize the treatment

Canister method

Full-scale test

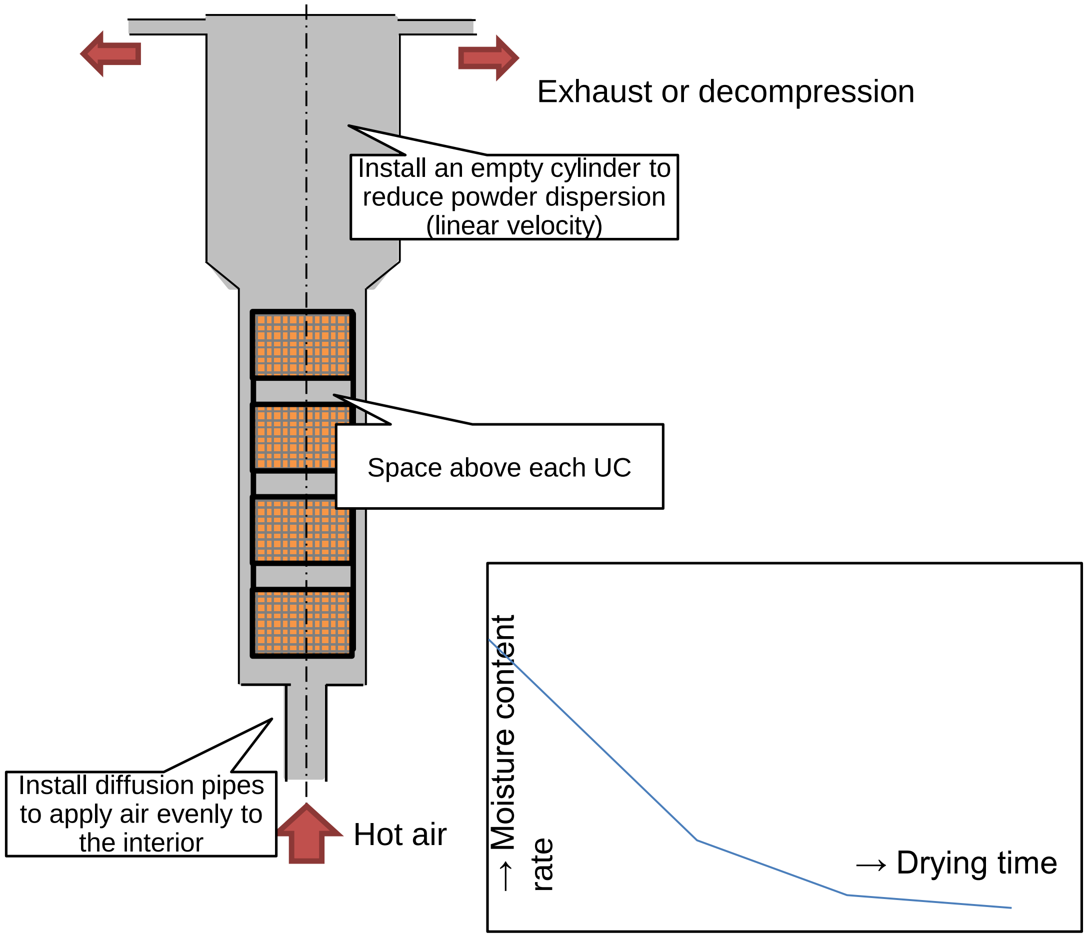
(Test objective) The test objective is to verify the feasibility of drying treatment using the canister method

(Results)

① Prevention of spreading contamination from the drying treatment

② Simplified the treatment procedures (reduce UC loading and unloading procedures)

Results from FY2019-2020 evaluations (chamber method)



Conceptual image of data obtained
Drying time and moisture content rate

6.2 Full-scale test

② Comparison with existing technology

Under the project the Development of Technologies for Containing, Transfer, and Storage of Fuel Debris until FY2020, technology for safely handling and storing lump-like or particulate fuel debris using the canisters was developed. Additionally, conceptual studies of drying methods for difficult-to-dry-materials, zeolite, and drying equipment of the unit cans were conducted.

On the other hand, compared to the chamber form drying method studied in FY2020, the applicability of the canister form drying method (which is considered effective in suppressing the spread of contamination) has not yet been verified. Therefore, it is necessary to obtain drying data on the canister form and compare its advantages and disadvantages with the results of the chamber test, and then to organize the requirements for the canister structure proposal from the viewpoint of drying treatment for fuel debris in slurry and sludge form, concrete pieces with fuel debris attached, filter media, etc.

6.2 Full-scale test

③ Implementation items and results

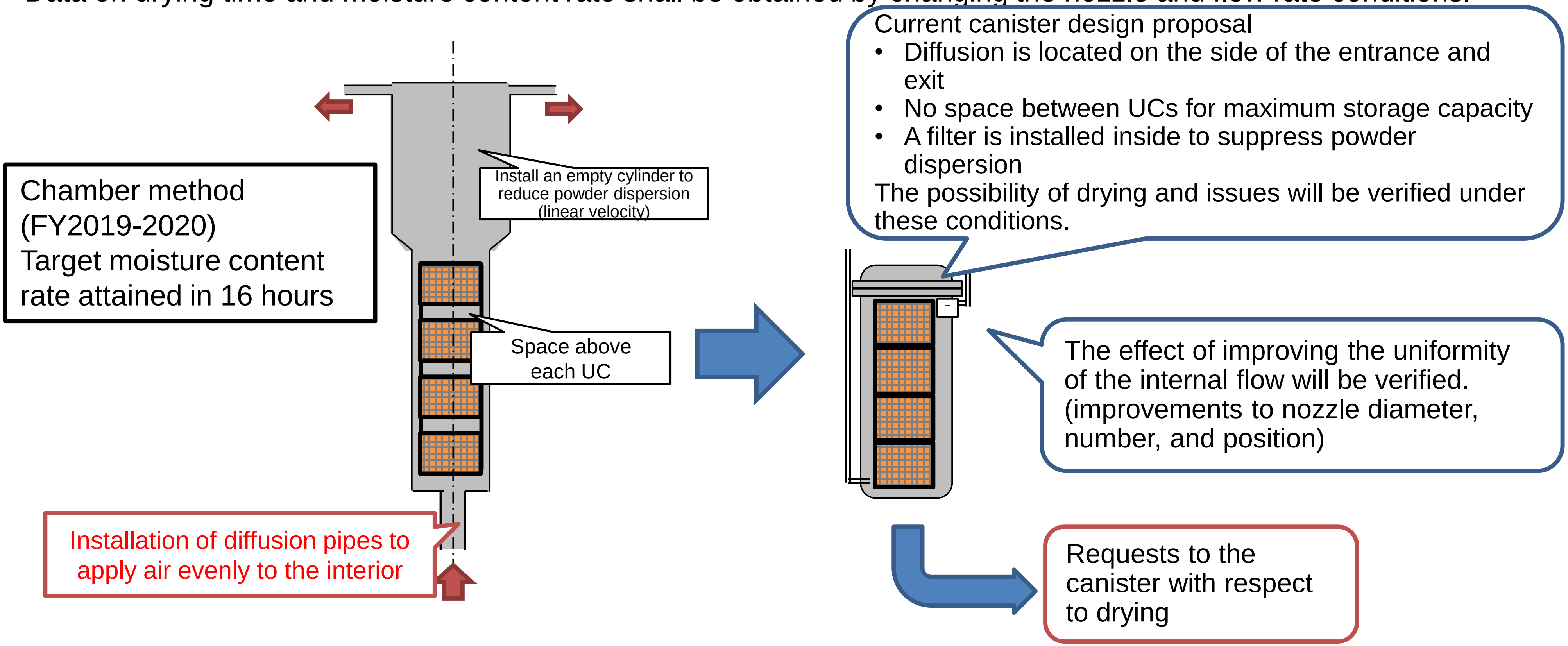
(1) Study of test plan: Test objectives

○ Test objective

- The test objective is to verify the feasibility of achieving (achievable treatment time) the drying target moisture content rate (0.1 wt% in terms of fuel debris) in order to examine the feasibility of drying treatment using a full-scale canister method.
- The requests for the current canister structure proposal shall be organized with respect to drying in case it is not achievable or as a proposal for reducing drying time.

○ Evaluation method

- Data on drying time and moisture content rate shall be obtained by changing the nozzle and flow rate conditions.



6.2 Full-scale test

③ Implementation items and results

(2) Study of test plan: Test equipment (1/2)

Chamber method full-scale test equipment (FY2019-2020) → Modified in the canister method

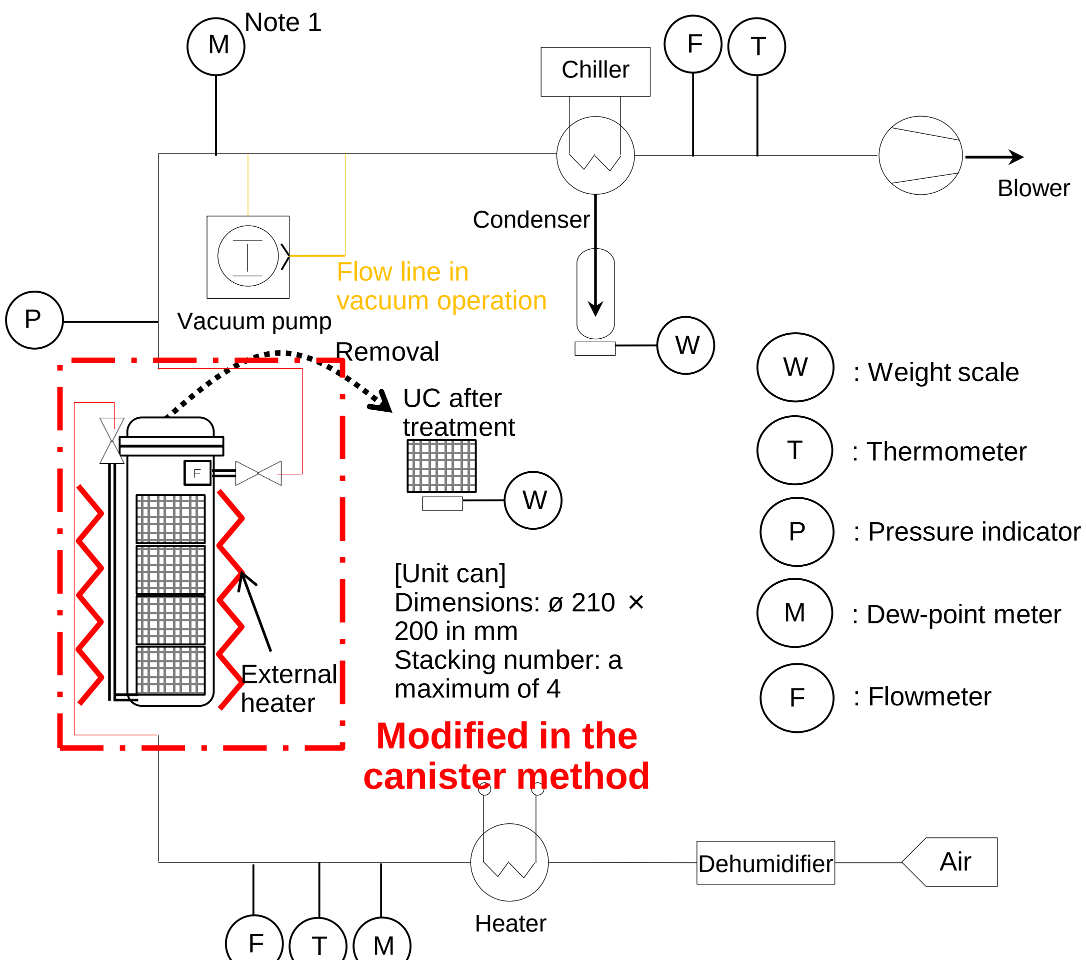


Figure: Schematic of the full-scale drying test system

(Test conditions and system)

- Hot air / periodic drying
- Connect the test equipment system to the canister nozzle
- A maximum of 4 unit cans (UC) inside the canister
- Drying target: Zeolite
- Measure weight after drying and obtain data on changes over time for the amount of condensation, dew point, gas flow rate, temperature, etc. Note 1

(Test parameters)

- Canister nozzle dimensions, number of nozzles, hot air flow rate

Note 1: Plan to change the installation position of the dew point meter from the FY2019-2020 equipment and verify improvements to the method for determining drying completion

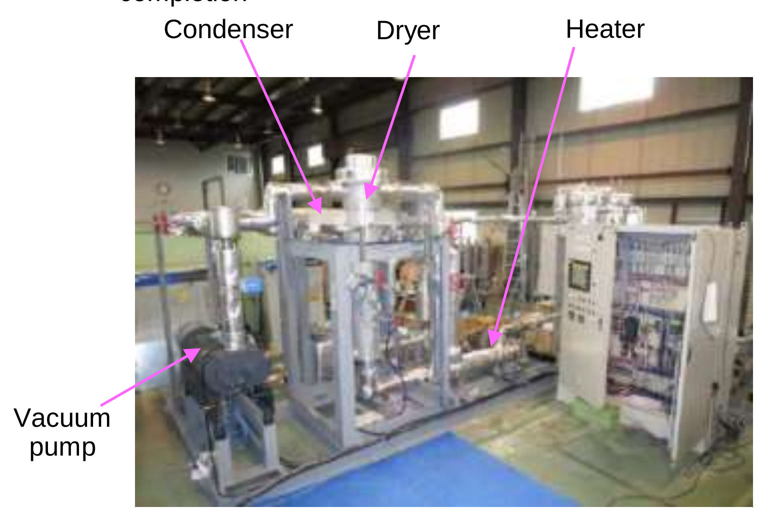


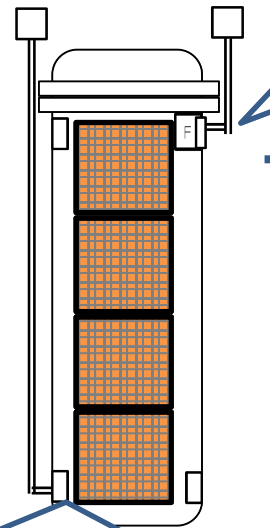
Figure: External appearance of the full-scale drying test system

6.2 Full-scale test

③ Implementation items and results

(2) Study of test plan: Test equipment (2/2)

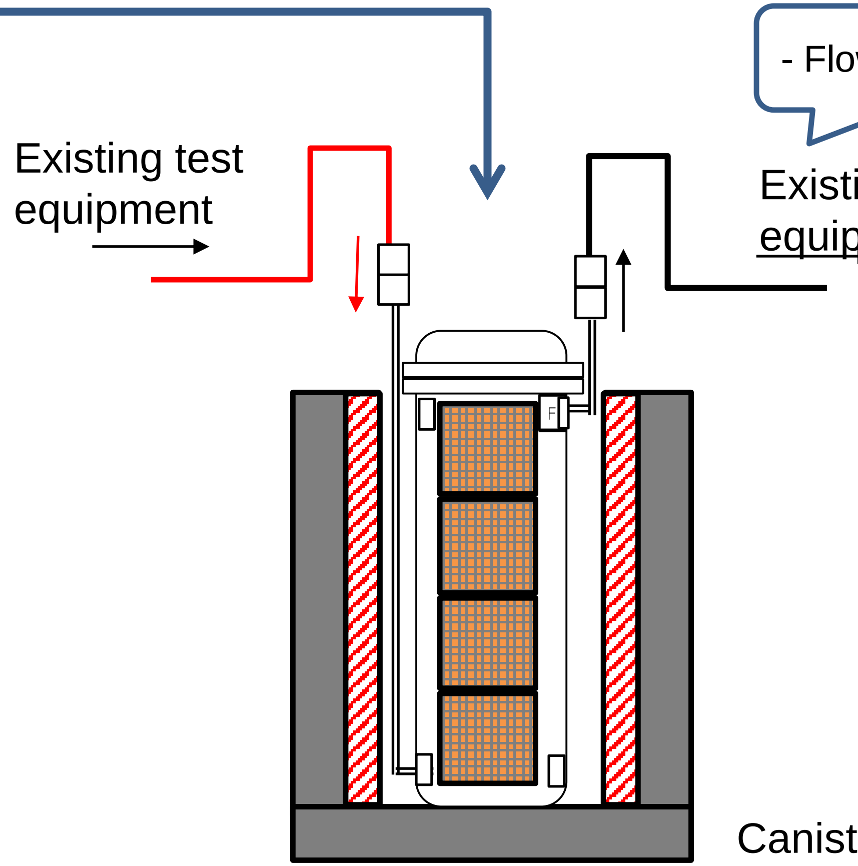
Illustration of drying in a canister



- Variable outlet nozzle diameter and number (connector)

- Variable inlet nozzle diameter and number (connector)

- Flow rate change



Drying target: Zeolite
- Filling height 100 vol%
- Initial moisture content rate approximately 40 to 45 wt%

(Equivalent to the FY2019-2020 chamber test)

6.2 Full-scale test

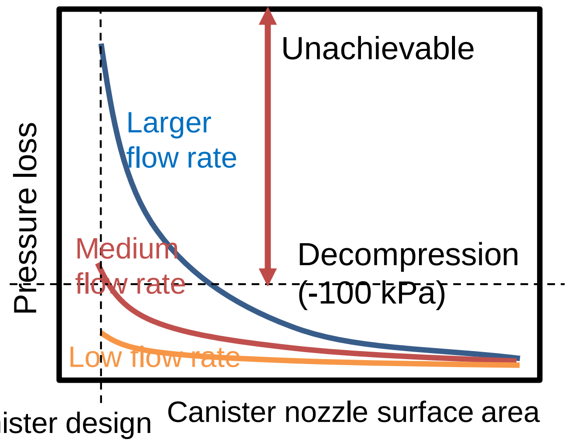
③ Implementation items and results

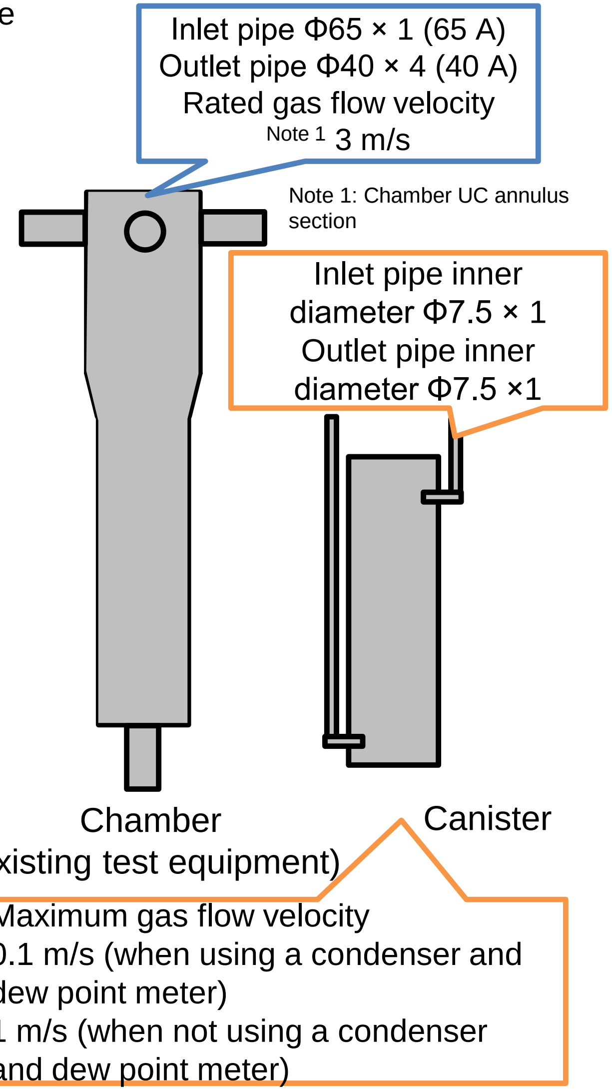
(3) Study of test plan: Modification issues and test content

<u>Issues based on the shape of the canister in the current plan</u>

- The diameter of the canister piping is smaller than that in the existing full-scale test equipment using the chamber method and there are fewer pipes, which results in excessive pressure loss.
- Since fuel debris drying equipment is assumed to control negative pressure, there is a limit to the pressure system that can be created.
- The condenser and dew point meter cannot function or conduct measurements because they fall outside the operating pressure range of the test equipment components and instruments.

Canister nozzle surface area - Pressure loss (Image)





[Test details]

There will be two tests with different items to be measured depending on test objective.

✓ <u>Canister dryability test</u>

Compare the drying time in the current canister design with the data from the chamber method without using a condenser or dew point meter

✓ <u>Acquisition of data on drying time using canister design conditions as parameters</u>

Drying trends (amount of condensation, dew point temperature) shall be measured when changing canister nozzle design and flow rate, and the result will be used as canister design data.

6.2 Full-scale test

③ Implementation items and results

Note 1: Time from heater ON and the start of airflow
Note 2: Moisture/dry weight. Target: 0.1 wt% in terms of fuel debris

(4) Study of test plan: Test content and objectives

Category	Items	Outlines	Data and information to be obtained
I. Verification of canister dryability	RUN⓪ Comparison with the chamber method	Collect RUN① comparison data (assume the same flow rate and gas temperature at the canister inlet)	Drying time Note 1 vs Moisture content rate Note 2
	RUN① Drying with the current canister design	Drying operations with the current canister plan shall be conducted to verify the possibility of drying treatment.	
II. Acquisition of data on changes in drying time	RUN② Increase nozzle diameter	Nozzle diameter shall be increased and drying treatment shall be conducted using the same flow rate and temperature as the chamber drying in FY2020. The drying performance and effects shall be verified when enlarging the nozzle diameter to increase the airflow cross-sectional area and creating the same hot air flow rate as the chamber method.	Drying time Note 1 vs Moisture content rate Note 2 Drying time Note 1 vs Condensation/dew point
	RUN③ Increase the number of nozzles	The number of nozzles shall be increased and drying treatment shall be conducted using the same flow rate and temperature as the chamber drying in FY2020. The drying performance and effects shall be verified when increasing the number of nozzles to increase the airflow cross-sectional area and creating the same hot air flow rate as the chamber method and further creating near-uniform air direction conditions.	
	RUN④ Periodic operation	The effect of periodic hot air and decompression drying shall be verified.	Drying time Note 1 vs Moisture content rate Note 2

Values for gas flow rate and heater current will be obtained as equipment design data

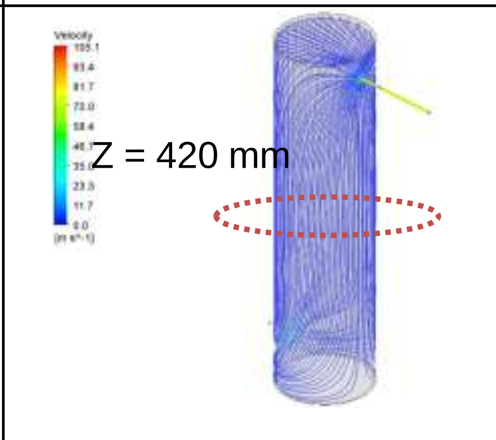
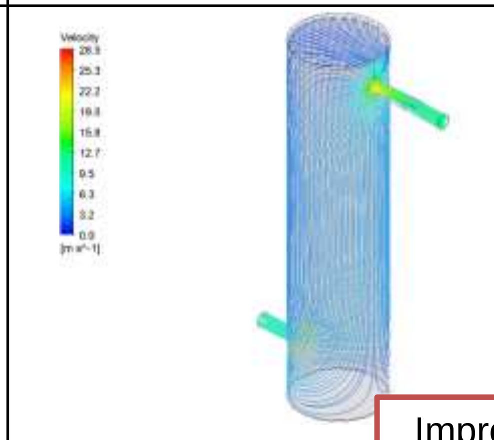
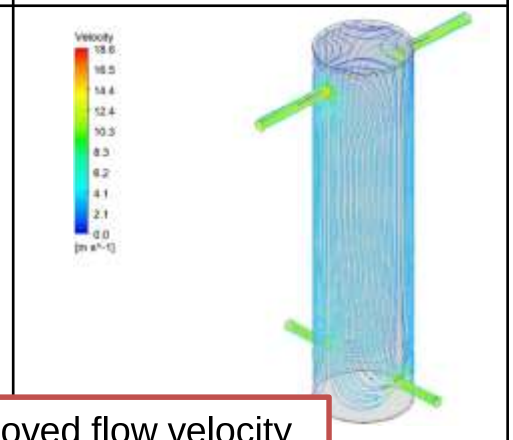
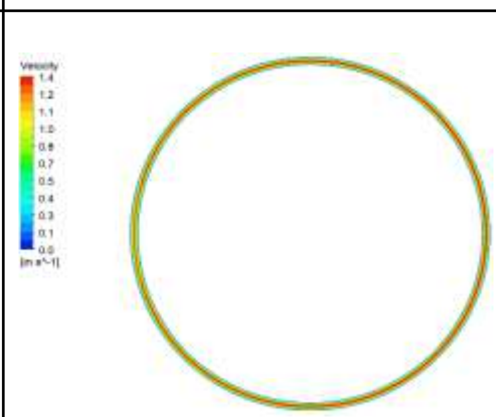
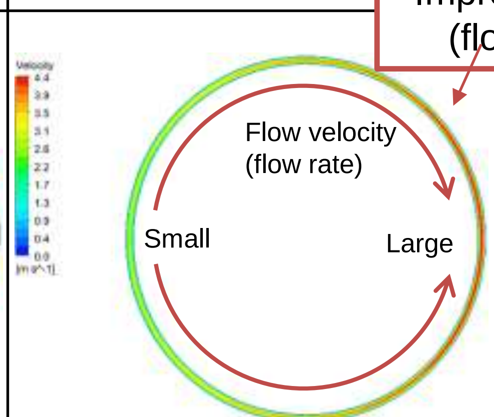
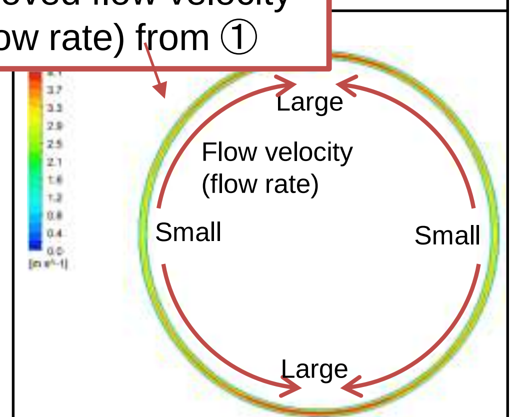
6.2 Full-scale test

③ Implementation items and results

(5) Study of test plan: Test case (1/2)

FY2019-2020 element test results showed that flow velocity affects the drying performance.

The improved canister proposal was examined to create the flow velocity equal to the chamber rating and to improve flow path uniformity, and CFD analysis (ANSYS FLUENT v17.2) verified the improved flow velocity and flow path conditions.

	① Current canister design (1 m/s) * Inlet and outlet pipe diameter Φ7.5	② Improved canister 1 (3 m/s) * Large diameter (Φ35)	③ Improved canister 2 (3 m/s) *Large diameter (Φ25) + increased number of nozzles
Flow diagram			
Flow velocity (Z = 420 mm)	 0.52 to 1.4 m/s	 1.4 to 4.4 m/s	 1.7 to 4.1 m/s

Improved flow velocity (flow rate) from ①

- Compared to the flow velocity in the central section of the current canister design in ① (cross-section of canister height 420 mm), improved canister 1 in ② and improved canister 2 in ③ show faster flow velocity throughout the entire canister and both designs are expected to improve the drying performance.
- Comparing ② and ③, ③ is expected to have a faster minimum flow velocity, improved qualitative uniformity, and to better facilitate drying.

CFD analysis results

6.2 Full-scale test

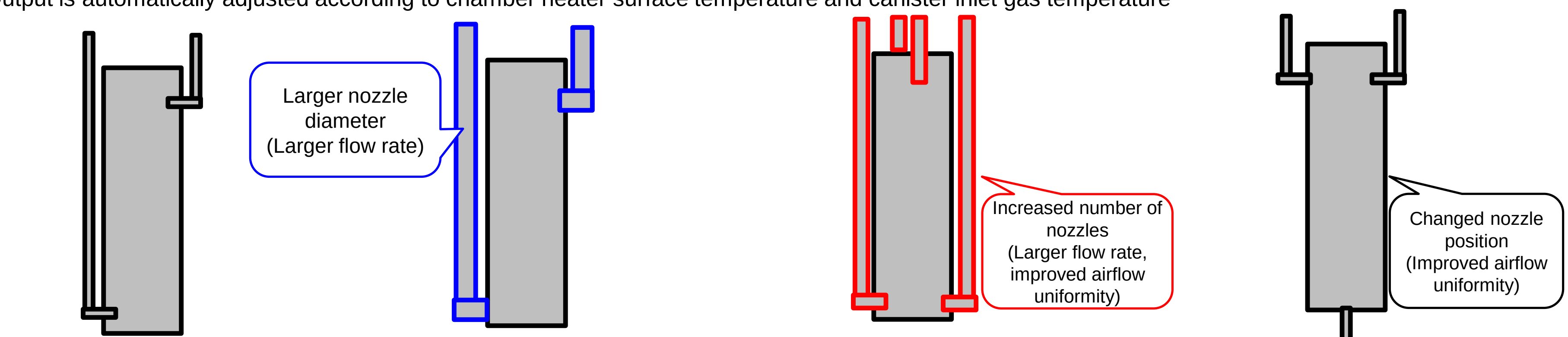
③ Implementation items and results

(5) Study of test plan: Test case (2/2)

Classification Note 1	RUN	Canister structure	Operating mode	Inlet/outlet pipe: Internal diameter (mm)	Inlet/outlet pipe: No. of each (nozzles)	Inlet/outlet pipe: Cross-sectional area (mm^2)	Heater surface/hot air temperature (°C)	Chamber/canister heater output (kW)	Flow velocity Note 2 (m/sec) (Flow rate (Nm^3/h))
I	⓪	Chamber	Hot air	—	—	—	200	up to 10 Note 3	1(12)
I	①	Current structure proposal	Hot air	7.5	1	44.2	200	up to 10 Note 3	1(12)
II	②	Modification 1 (larger nozzle diameter)	Hot air	35	1	962.1	200	up to 10 Note 3	3(37)
II	③	Modification 2 (Increased number of nozzles)	Hot air	25	2	981.7	200	up to 10 Note 3	3(37)
II	④	Current structure proposal	Periodic switching between heating and vacuum	7.5	1	44.2	200	up to 10 Note 3	1(12)

Note 1: I ••• Verification of canister dryability II ••• Acquisition of data on changes in drying time Note 2: Flow velocity between canister and UC annulus section

Note 3: Output is automatically adjusted according to chamber heater surface temperature and canister inlet gas temperature



Current structure proposal

Modification 1

Modification 2

Not applicable
(Dryability and drying performance with the same uniform airflow conditions were obtained in the FY2019-2020 chamber test)

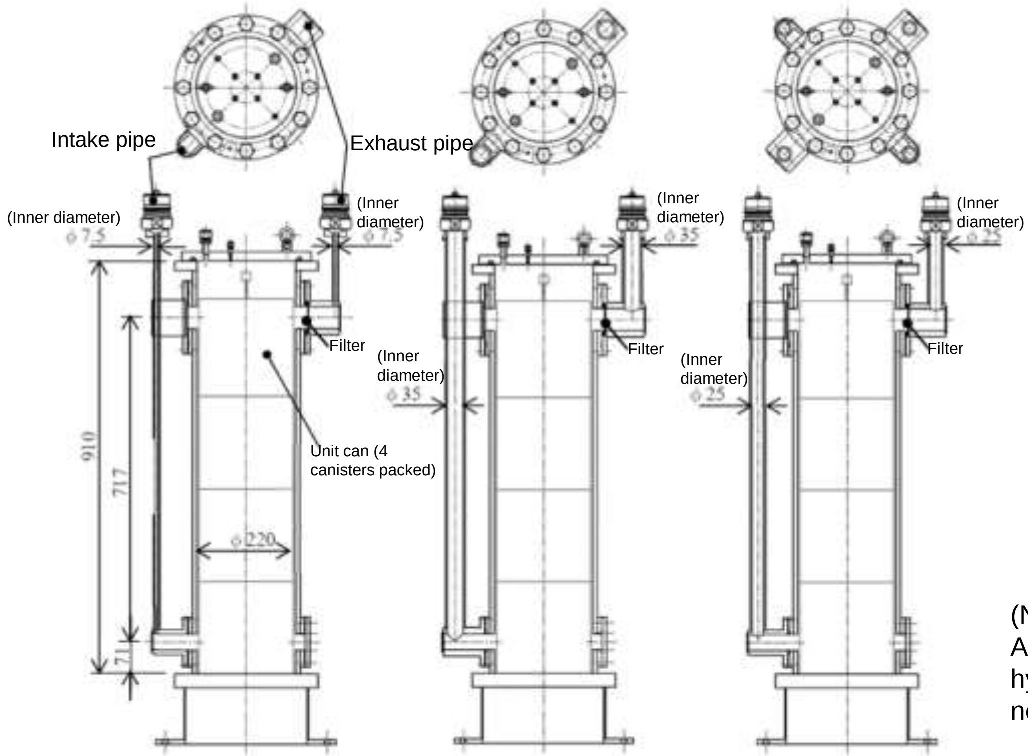
6.2 Full-scale test

③ Implementation items and results

Note 1: Hereafter, "② Design and manufacture of a canister for testing and design and modification of full-scale test equipment" described in the implementation schedule (No.13) will be abbreviated as "design, manufacture, and modification of test equipment"

(6) Design, manufacture, and modification of test equipment Note 1

- The drying issues in the canister form (No. 45) were organized and it was verified that, compared to the FY2019-2020 chamber method, there is a flow deflection in the way the air hits inside the canister and that there is a limit to hot air flow rate from increased pressure loss. To address these problems, a modification proposal that could be incorporated without drastically changing the current canister design was examined (see the figure below), and the improved canisters with different inner diameter of diffusion pipes (intake and exhaust pipes) and number of pipes were examined. The improved canisters are being manufactured for full-scale testing.
- The body of the test equipment is being modified according to the plan in No.43 to 44.



	Current canister design	Improved canister 1	Improved canister 2
Inner diameter of diffusion pipe	Φ7.5 mm	Φ35 mm	Φ25 mm
Number of diffusion pipes	1	1	2
Improvement	—	Improved to increase the inner diameter of diffusion pipes for a large flow rate.	Improved to increase the inner diameter of diffusion pipes and further to increase the number of pipes, which result in increased flow rate and improved flow deflection.

(Notes)
A hydrogen vent hole and a filter are installed in the canister lid, but because the hydrogen vent hole is closed during drying, the lid of a canister for the drying test will not include the hydrogen vent hole and filter.

Figure: Illustration of the shape of canisters for drying test

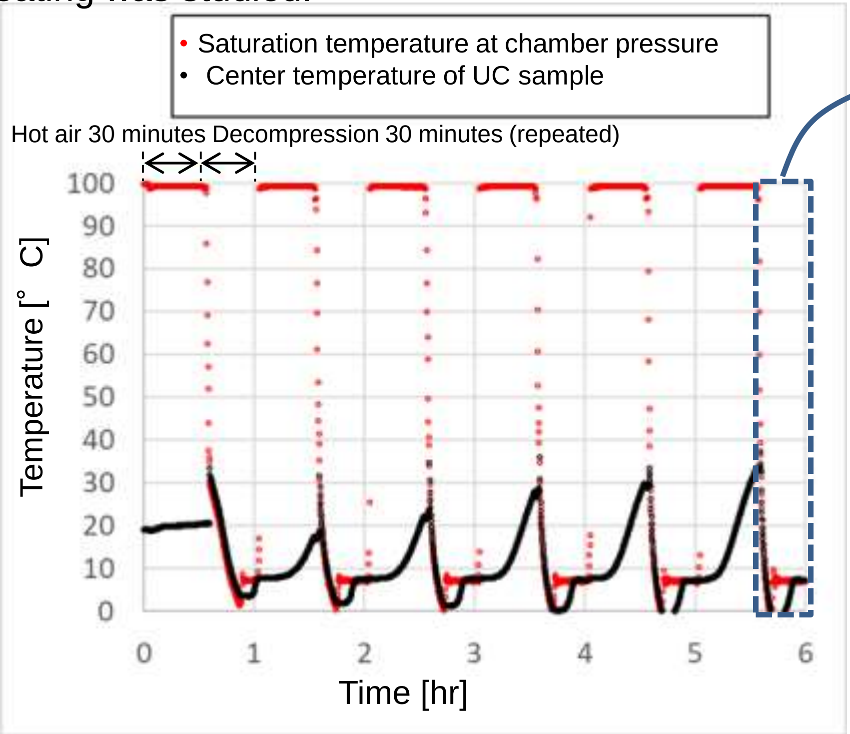
(6) Content of analysis (1/3)

The following items were studied by using the analysis model.

- Drying time sensitivity evaluation and optimization studies using hot air and decompression cycles in periodic drying

(6) Content of analysis (2/3)

- The periodic drying method aims to temporarily increase drying rate by storing heat in moisture-containing material during hot air and heater heatup and then suddenly converting that moisture into evaporation heat by rapidly reducing pressure.
- In the FY2020 test, the temperature at the center of the unit can (UC) was only raised about 30° C and the effect on increasing drying rate was not considered sufficient, so extending amount of time for hot air heating was studied.



FY2020 Periodic drying test
Figure 1: Change of saturation temperature and UC temperature at chamber pressure over time
(An expanded time scale of the first half of drying)

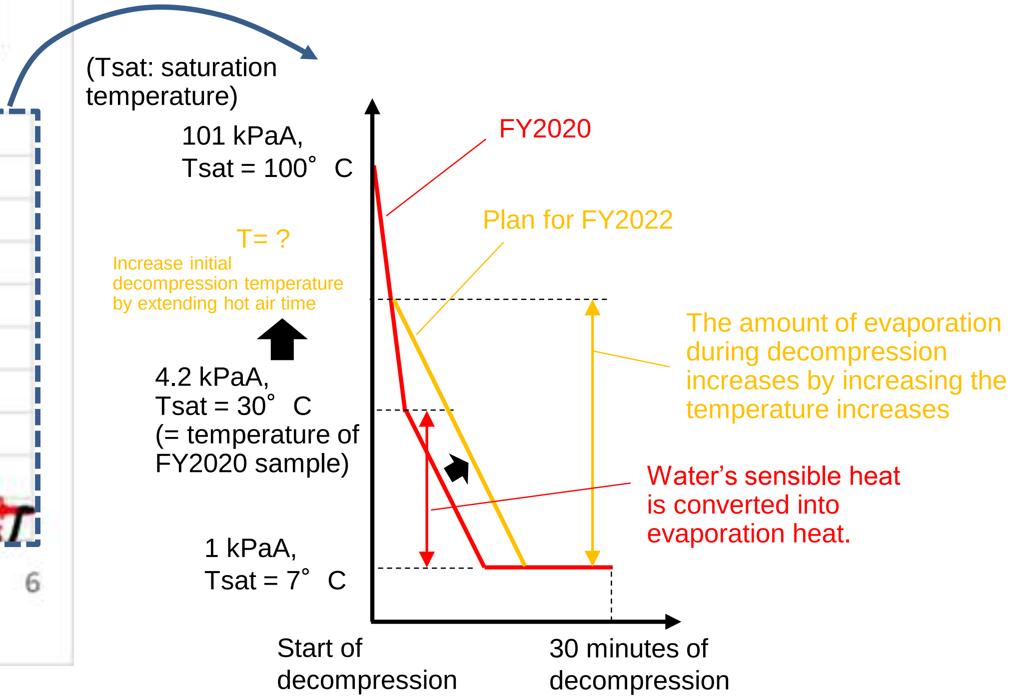
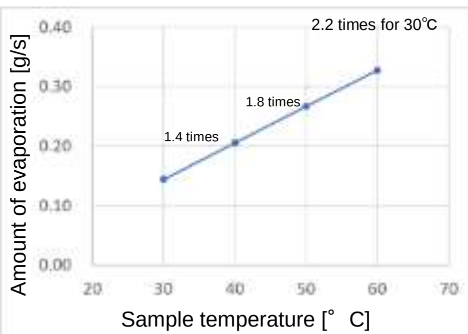


Figure 2: Schematic diagram of the relationship between pressure/temperature changes and evaporation

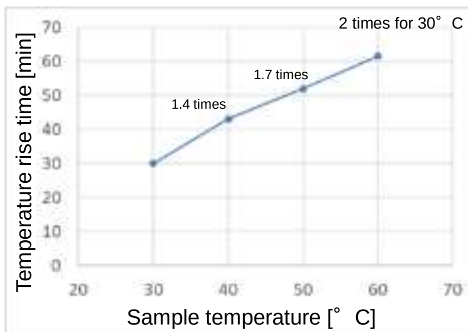
③ Implementation items and results

(6) Content of analysis (3/3)

- The objective is to increase the drying rate during decompression by raising the temperature of the sample. However, if it takes too long to preheat the sample, then there will be no reduction to the time required for the entire drying process.
- When raising the temperature of the sample to 60° C, the effect is doubled in the amount of evaporation, but twice as much time is required to raise the temperature (Figure 1). As it stands now, 0.5 hr temperature rise + 0.5 hr decompression = 1 hr/1 set ⇒ 1 hr temperate rise + 0.5 hr decompression = 1.5 hr/1 set. Considering the two together, doubling of the amount of evaporation for a 1.5 increase in time per set can be expected to increase the drying rate by 1.3 times. (There is an upper limit on water's boiling point during preheating, so there should be a limit to the effect of raising the temperature.)
- It is assumed that the above effect is small in the latter half of drying, when the influence of fine pores in zeolite is thought to be prominent. Applying the above effect to the data up to 9.5 hour mark (the assumed first half of drying), the time reduction of 9.5 - 9.5 / 1.3 = 2 hours can be expected. However, based on the drying end time in the test, drying time was shortened by about 1.5 hours (Figure 2).



Relationship between sample temperature and the amount of evaporation during periodic drying and decompression



Sample temperature and temperature rise time during periodic drying and heatup

Study of the amount of evaporation from the rate of decrease for water enthalpy Δh during decompression and cooling processes W [kg/s] = Δh [J/kg/s] × moisture content rate [kg]/latent heat [J/kg]

Study using one-dimensional unsteady state heat conduction calculations in the radial direction of a unit can

Figure 1: Estimated results based on FY2020 test

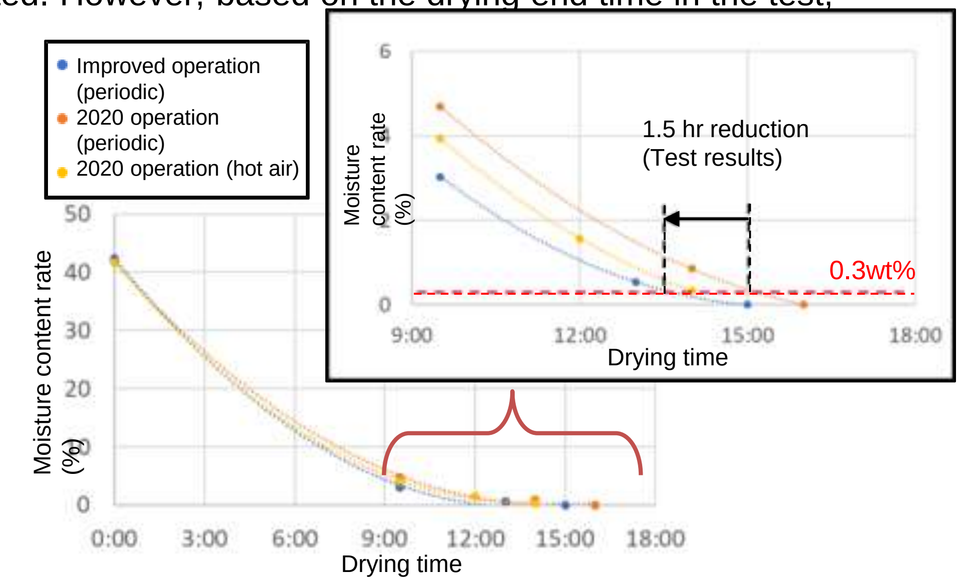


Figure 2: FY2022 Periodic drying test Change in moisture content rate over time Comparison with FY2020 test

6.2 Full-scale test

③ Implementation items and results

(7) Summary

- The concepts of canister drying, the details of test using full-scale test equipment, the range of necessary modifications and the test conditions for the canister were studied, and the canister drying test was planned. (No.40 to 48)
  ⇒ Pressure loss is large with the current canister structure and sufficient airflow rate cannot be secured.
  ⇒ The required canister structure will be organized for drying treatment in accordance with the guiding policy.

- Canisters for testing and full-scale test equipment are being designed and manufactured according to the canister drying test. (No.49)

- The improved operation proposal for periodic drying operations in FY2019-2020 was analyzed and studied. The verification operation test was conducted. (No.50 to 52)
  ⇒ The treatment time is expected to reduce by approximately 1.5 hours.

④ Contribution of outcomes to relevant study areas

- The requirements for canister specifications will be consolidated to contribute to the study of countermeasures for hydrogen generation during transfer of the container in future.

⑤ Analysis with respect to on-site applicability

- Equipment specifications will be examined from the perspective of on-site operations, such as presenting optimum operating conditions.

⑥ Issues

- There are no issues in executing the current plan.

⑦ Goal achievement level

- A specific test plan has been proposed and equipment and canisters for testing are being prepared. The desired results are expected to be achieved according to the plan.

⑧ Future plans

- In FY2022, the modification of full-scale test equipment, expansion of the data via full-scale test, sensitivity evaluation of drying time by analysis, and actualization of the drying concept based on the results of tests and analysis will be implemented.
- Based on the acquired data, the concept of canister drying equipment, the optimum operating conditions for canisters, and the evaluation for advantages and disadvantages compared to the chamber method, as well as issues when applying multiple treatments will be studied.

7. Summary

- Tests for the proposed results of element tests (data on the drying characteristics of slurry, sludge, and concrete) are being planned and implemented. Data on the sample temperature distribution and moisture content rate change in full-scale drying for slurry and sludge, and data on the physical characteristics and the sample temperature distribution and moisture content rate change in the beaker scale for concrete, are being obtained and studied on an ongoing basis.

- The proposed results of element tests (the range of application (the materials to be dried) for the drying concept and alternative methods and means for the materials that are difficult to dry) will be reviewed and the results will be obtained in FY2022 based on the above test results.

- Based on the proposed results of full-scale test (results of verification test in the canister form), issues in modifying test equipment were extracted and the studies of modified test equipment, canisters for testing, and test conditions were conducted. As a result, test conditions that factor in pressure loss were determined and the manufacturing of canisters and modification of test equipment are in progress. The test will be conducted in FY2022 to obtain these results.

- For the proposed results of full-scale test (the concept of canister drying equipment, the optimum operating conditions for canisters, the evaluation for advantages and disadvantages compared to the chamber method, issues when applying multiple treatments, and the requirements for canister design), the analytical evaluation and the verification test were conducted to review the cycle of periodic drying for the study of optimum operating conditions, and improvements from FY2020 operations were verified. The rest will be examined in FY2022 based on the above test results and results will be obtained.

Reference materials

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of basic specifications for drying equipment

③ Implementation items and results (estimated and actual)

a. Study of basic conditions (1/2)

i. Clarification of performance requirements

Reference material (target moisture content rate)
Excerpt from "Subsidy Project of Government-led R&D Program on Decommissioning and Contaminated Water Management in FY2018 Supplementary Budget (Development of Technologies for Containing, Transfer, and Storage of Fuel Debris)" Final Report FY2020 (June, 2021)

Objects to be dried and target process time and moisture content rate were set as described below as performance requirements for the drying system.

(Material to be dried) Porous media. Based on the fact that collected materials at TMI-2 were porous media.
Zeolites, known as representative porous media, are used for the test.

(Target process time) 24 hours from loading to unloading

(Target moisture content rate) 0.1 wt% Note 1

Note 1: Moisture content rate premised on fuel debris density.
It will be revised based on the density of the zeolite test sample used for the test.

Nov 11, 2021 postscript
In element tests, target moisture content rate is determined by converting the density of the material to be dried.
- Slurry and sludge (silica sand): 2.6 g/cm^3 → converted value of 0.2 wt%
- Concrete: 2.3 g/cm^3 → converted value of 0.2 wt%
(Could be revised depending on the sample used)

Table: Evaluation of performance requirements

Performance requirements		Description of target
Target items	It should deal with the properties of fuel debris collected at the retrieval side	The target object is porous media with small pores. Although slurry might be subject to drying, considering the fact that their current properties are unknown, the applicability of the drying technology to be considered in the main target will be examined through element tests, etc.
	It should be handled by a method allocated from the retrieval side	Considering their handling in unit cans or canisters
Target time	It should dry within the time corresponding to the throughput the fuel debris retrieved	The assumed target time from receiving to allocation is 24 hours.
Target moisture content rate	The volume of residual water should be reduced as much as possible after drying.	The target moisture content rate is set to 0.1 wt% estimating a margin on the moisture content rate (1.5 wt%) where the hydrogen concentration in the canister reaches the lower explosion limit (4 vol%) during the transfer period of 7 days.

6. Implementation details

6.4 Development of drying technology and systems

(1) Study of basic specifications for drying equipment

Reference materials (FY2019-20 Implementation details: element tests)
Excerpt from “Subsidy Project of Government-led R&D Program on Decommissioning and Contaminated Water Management in FY2018 Supplementary Budget (Development of Technologies for Containing, Transfer, and Storage of Fuel Debris)” Final Report FY2020 (June, 2021)

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

i. Element tests

[Test results] - Understand the sensitivity of the operation parameters during hot air and decompression drying ➡ Temperature, pressure, and gas flow velocity significantly affect drying performance

- The end point of drying is achieved in approximately 13 hours for both methods ➡ There is a possibility of achieving the 0.3 wt% target moisture content rate with airflow drying

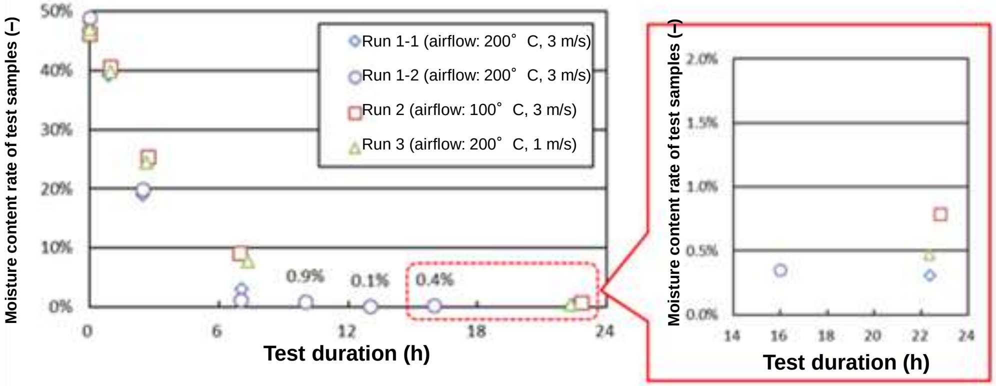


Figure: Decompression drying element test Change in moisture content rate over time

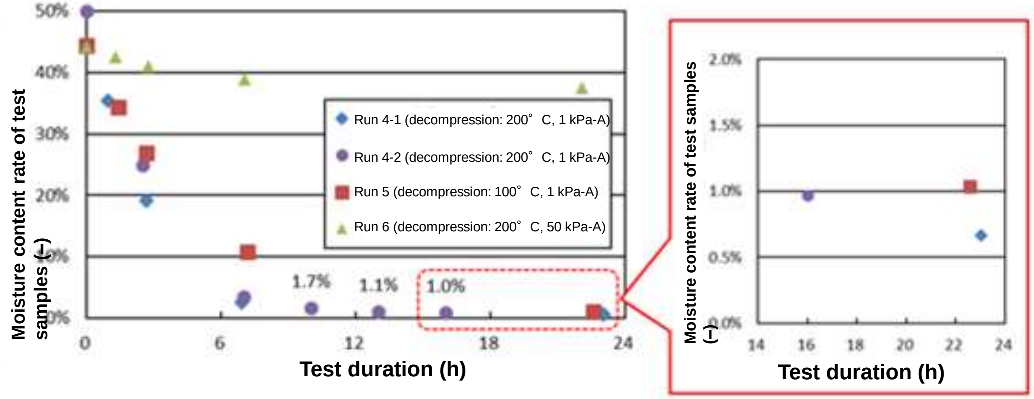


Figure: Decompression drying element test Change in moisture content rate over time

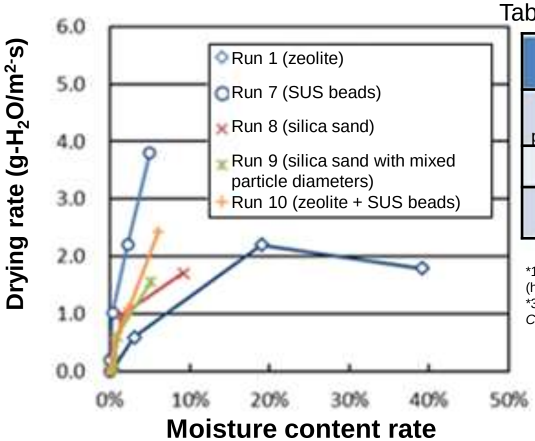


Figure: Drying characteristic curves from impact assessment of materials to be dried

Table: Physical properties of materials to be dried

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

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

[Test results]

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

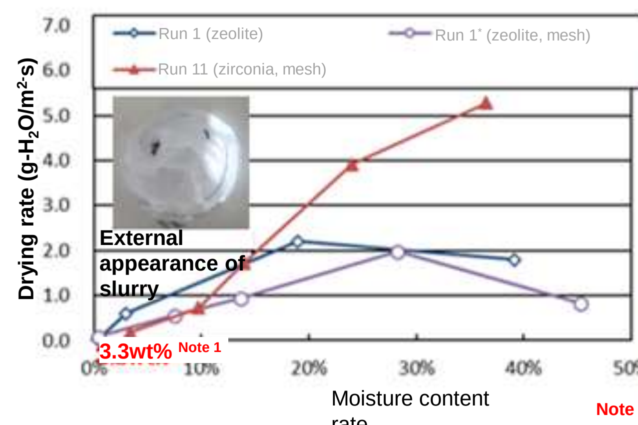


Figure: Drying characteristic curves from slurry hot air drying test

Table: Physical properties of slurry (zirconia)

Items	Value
Material	ZrO_2
Particle size	0.04 μm
Density	6.0 g/cm³*1
Thermal conductivity	3 W/m·K*1
Specific surface area	14±3m²/g
SS concentration	70wt%
Filling rate	27%

Note 1: Moisture content rate of zirconia and mesh at 24 hours from the start of the test

[Test results] Air layers were formed between particles after drying slurry with a low filling rate
➡The drying rate decreased due to decreased thermal conductivity of the test sample surface

6. Implementation details

6.4 Development of drying technology and systems
(1) Study of basic specifications for drying equipment
③ Implementation items and results (estimated and actual)
b. Collection of drying behavior data (3/6)
i. Element tests

Reference materials (FY2019-20 implementation details: analytical evaluation)
Excerpt from "Subsidy Project of Government-led R&D Program on Decommissioning and Contaminated Water Management in FY2018 Supplementary Budget (Development of Technologies for Containing, Transfer, and Storage of Fuel Debris)" Final Report FY2020 (June, 2021)

[Evaluation method]
① Reverse calculation of effective diffusion coefficients from test data using a drying process evaluation model (De′)
② Comparison of obtained De′ with the theoretical values of the steam diffusion coefficient in the layers concerned

○ Evaluation results (1/2)

(1) In the first half of the drying period: De′/De>1
- Drying rate was greater than water vapor diffusion rate
- It was inferred that liquid water diffused toward the surface and facilitated the drying process. (The diffusion coefficient was estimated higher in the model)

(2) In the second half of the drying period: De′/De<1
- Slow drying in fine pores was inferred to be a cause (based on the results of tests with SUS beads having no fine pores not indicating this tendency)
- This tendency was most prominent in decompression drying

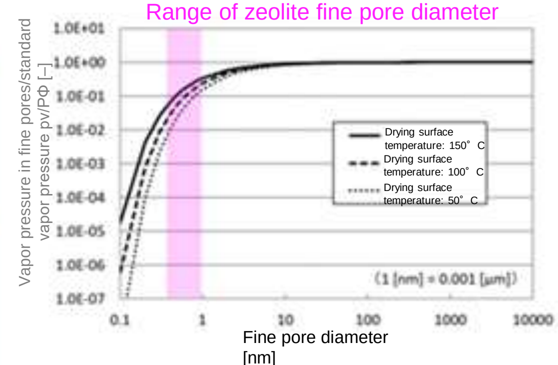


Figure: Relationship between fine pore diameter and vapor pressure

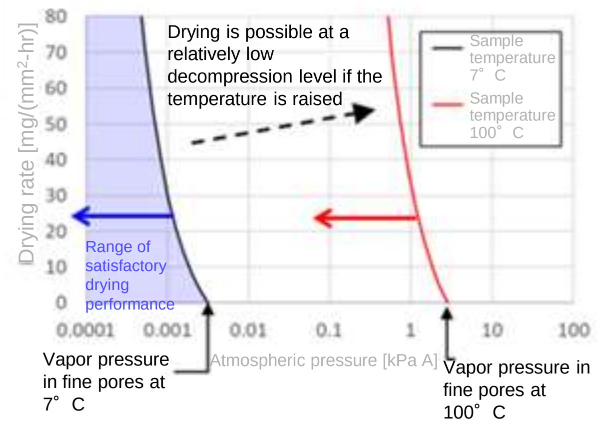


Figure: Relationship between atmospheric pressure and drying rate in decompression drying

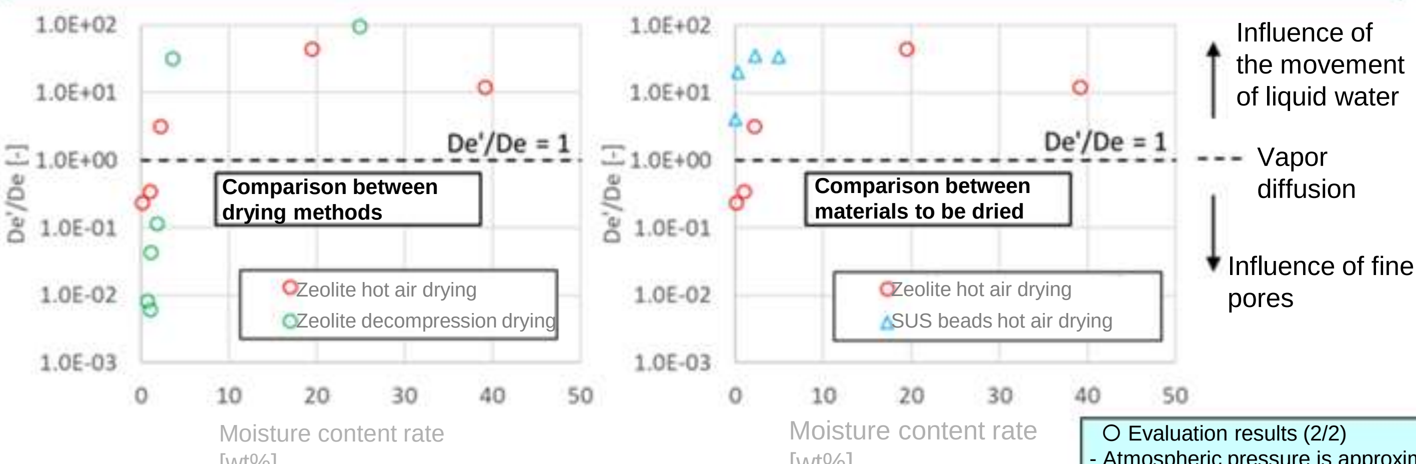


Figure: Results of estimations of effective diffusion coefficients based on element tests

○ Evaluation results (2/2)
- Atmospheric pressure is approximately 1/100 to 1/10 vapor pressure at a fine pore diameter of 0.4 to 1 nm
- Moisture in fine pores cannot be dried at low temperatures (approximately 7° C at drying surface) and 1 kPa A of pressure
- The treatment method of sufficiently heating the material to be dried and decompressing inside the drying chamber is effective

6. Implementation details

Reference materials (FY2019-20 Implementation details: full-scale test)
Excerpt from "Subsidy Project of Government-led R&D Program on Decommissioning and Contaminated Water Management in FY2018 Supplementary Budget (Development of Technologies for Containing, Transfer, and Storage of Fuel Debris)" Final Report FY2020 (June, 2021)

6.4 Development of drying technology and systems
(1) Study of basic specifications for drying equipment
③ Implementation items and results (estimated and actual)
b. Collection of drying behavior data (6/6)
iii. Collection of handleability and drying behavior data

Table Results of full-scale test

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

Note 1: Moisture content rate = Moisture content rate (g)/Absolute dry weight (g)
The absolute dry weight in the test was approximately 16 kg (total of 4 UCs with 100% filling rate)

- The target moisture content rate of 0.3 wt% or less was achieved in approximately 14 hours with 100% filling rate
- Comparing drying methods, about the same performance was obtained in hot air and periodic switching drying, whereas a longer drying time was required with decompression drying
- Roughly the same results were obtained even when the UCs were placed decentered → The influence of flow velocity distribution in the dryer chamber is small
- Decreased filling rate resulted in decreased drying time →This can be explained by a lower initial volume of water.Note 2

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

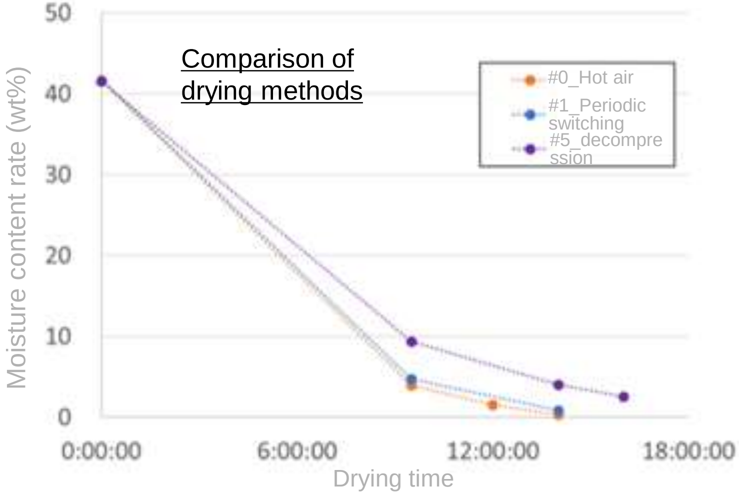


Figure Comparison of drying methods with respect to moisture content rate change over time

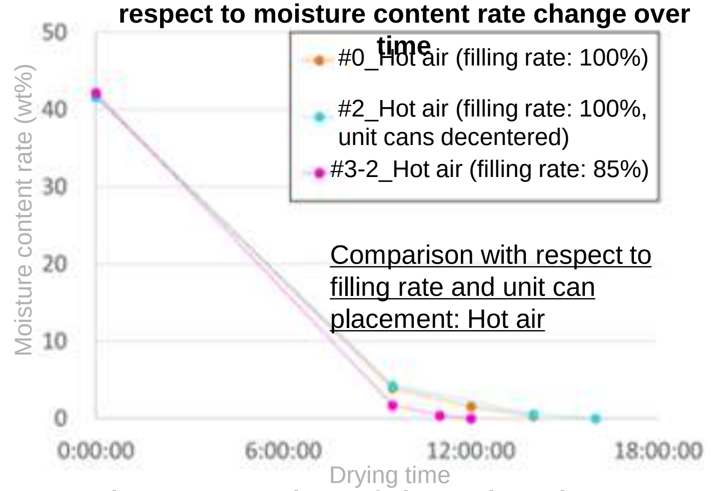


Figure: Comparison of change in moisture content rate over time in hot air drying with respect to filling rate and unit can placement

Reference: Definition of the absolute dry weight for each sample

Sample	Definition of absolute dry weight in this project	Absolute dry measurement method
Zeolite	Weight when heated to 300°C and held for at least 5 hours	Heat the test sample to 300°C for at least 5 hours and then measure the weight after simple isolation cooldown Note 1
Slurry and sludge (silica sand)		
Concrete		
Slurry and sludge (flocculant)	Theoretical value of product at test condition temperatures	Calculate the theoretical value of the product from the amount of reagents used in the test (200°C: $Al(OH)_3 + Na_2(SO_4)$, 300°C: $Al_2O_3 + Na_2(SO_4)$)

Note 1: Simple isolation cooldown: Cooldown in an isolation container with a desiccant like silica gel installed in the vent