Subsidy Project of Decommissioning and Contaminated Water Management

Development of Safety Systems
(Liquid/Gas Phase Systems and Criticality Control Technology)

Accomplishment Report for FY2021

(1) Liquid/Gas Phase Systems
(2) Criticality Control Technology

August 2022

International Research Institute for Nuclear Decommissioning
(IRID)

(1) Liquid/Gas Phase Systems

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1. Purposes and goals of subsidy projects

[Purpose of Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)]

It is assumed that nuclear fuel has melted along with the reactor internals at Tokyo Electric Power Company (TEPCO) Holdings, Inc. Fukushima Daiichi Nuclear Power Station (NPS) and exists in the form of molten fuel debris in the Reactor Pressure Vessel (RPV) and the Primary Containment Vessel (PCV).

The fuel debris accumulated inside the RPV and PCV is estimated to be currently in a sub-critical state; however the plant itself is in an unstable condition unlike its initial design, since the Reactor Building (R/B), RPV, PCV, etc. have been damaged due to the accident. Therefore, it is necessary to retrieve the fuel debris in order to maintain the sub-critical state, and to prevent diffusion of radioactive materials.

Against this background, this project is intended to conduct studies based on the "Mid-and-Long-Term Road-map Towards Decommissioning of TEPCO's Fukushima Daiichi NPS" (hereinafter "Mid-and-Long-Term Road-map"), aiming towards the implementation of large-scale fuel debris retrieval in coordination with the engineering and project management activities undertaken by TEPCO. The development results of this project will be used in TEPCO's engineering activities.

The purpose of this project is to advance the level of Japanese science and technology by supporting the development of technologies that contribute to the safe decommissioning of the Fukushima Daiichi NPS and handling of contaminated water, based on the Mid-and-Long-Term Roadmap and the "FY2021 Decommissioning Research and Development Plan" (the 86th Secretariat Team Meeting for Countermeasures for Decommissioning and Contaminated Water Treatment).

Specifically, technologies for removal of soluble α-nuclides that are considered to be eluted in circulating cooling water from fuel debris, treatment of RO-concentrated water (*), treatment of secondary waste, and on-site operating methods for criticality approach monitoring and neutron absorber will be developed.

***Liquid waste with a high impurity concentration generated by Reverse Osmosis filter (RO filter) removal of impurities from cooling water**

[Overall development goal]

Development goals are to develop element technology necessary for systems and to conduct tests for technology for ensuring safety for further increasing the scale of retrieval of fuel debris and the reactor internals based on the R&D results obtained so far.

1. Purposes and goals of subsidy projects

The material in this report deals with the following items.
The objective of each item's implementation is shown.

(1) Liquid/gas systems

① Development of soluble α-nuclide removal technology

- Element test assuming fuel debris retrieval work

  Selection of candidates for adsorbents that can remove α-nuclides (Pu, U, etc.) during fuel debris retrieval work, taking into account the gas phase environment inside the PCV (nitrogen atmosphere).

② Development of Reverse Osmosis (RO)-concentrated water treatment technology

- Selection of adsorbent and condensing agent

  Selection of powder adsorbents and flocculants needed to treat RO-concentrated water through element tests and devise a treatment method for RO-concentrated water.

③ Development of secondary waste treatment technology

- Investigation of pretreatment technologies

1) Characterization of liquid waste generated from particle removal system

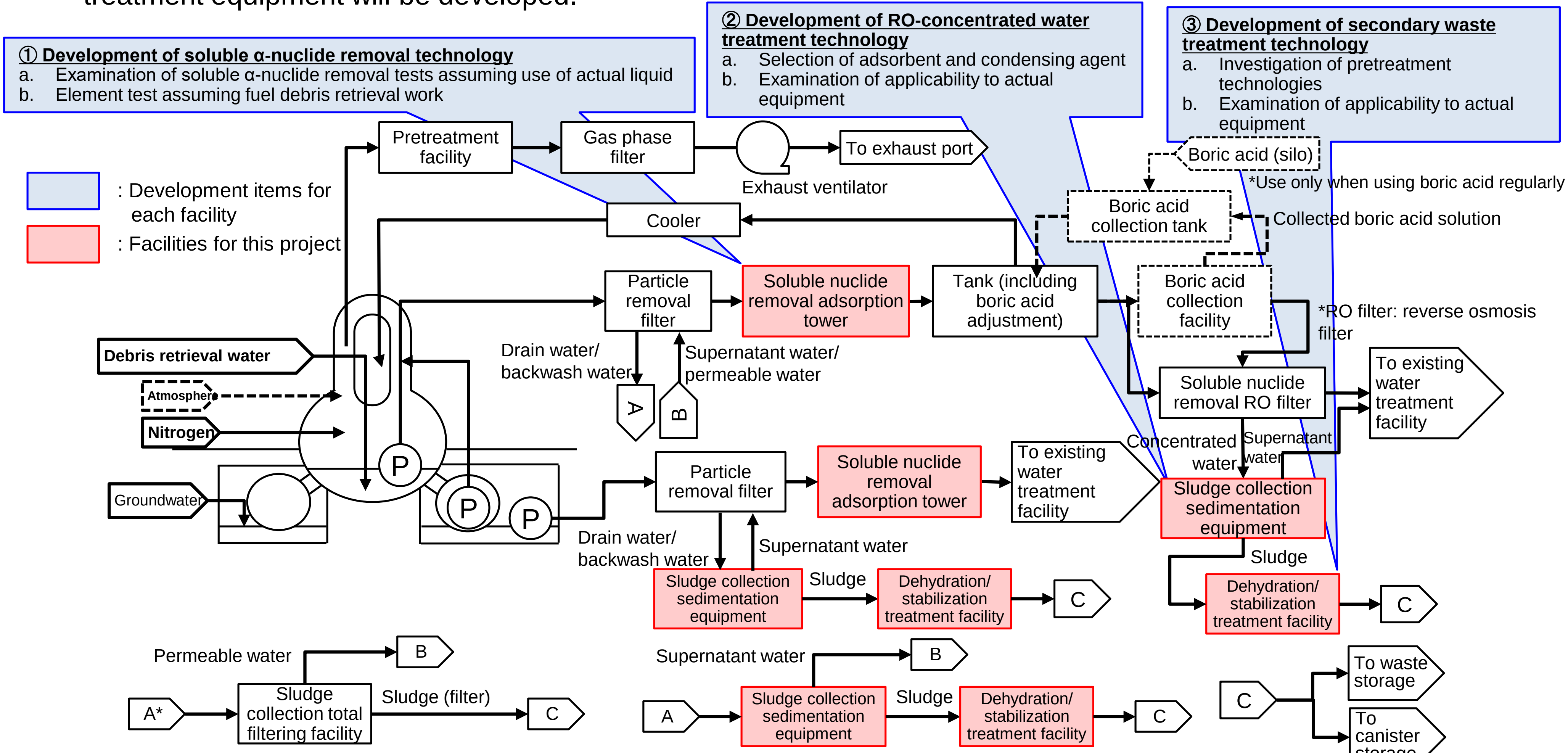
   Performance assessment tests on the filter components of the particle removal system are conducted. Then the properties of the filtered liquid waste discharged into the sludge collection system are consolidated.

2) Selection of dehydration technology for sedimentation sludge

   Applicable dehydration technologies for volume reduction treatment of sedimentation sludge from sludge collection equipment are selected from the literature research. Then a sludge treatment method is planned based on the results of the literature research and element tests.

2. Overview of subsidy projects

System configuration diagram of the liquid and gas systems under review for the subsidy project is shown.
In this year’s subsidy project, a soluble nuclide removal equipment and a sludge dehydration and stabilization treatment equipment will be developed.



① Development of soluble α-nuclide removal technology
a. Examination of soluble α-nuclide removal tests assuming use of actual liquid
b. Element test assuming fuel debris retrieval work

② Development of RO-concentrated water treatment technology
a. Selection of adsorbent and condensing agent
b. Examination of applicability to actual equipment

③ Development of secondary waste treatment technology
a. Investigation of pretreatment technologies
b. Examination of applicability to actual equipment

🟦 : Development items for each facility
🟥 : Facilities for this project

*: Particle removal; used as drainage water collection from roughing treatment.

Figure. Liquid and gas systems during fuel debris retrieval (based on subsidy projects)

Note: This conceptual diagram is an example of facility configuration (in the case of no leakage from PCV)

3. Previous fiscal year project results and remaining issues

① Development of soluble α-nuclide removal technology

🟨 : For examination in this project

No.	Items	Efforts and results of the previous project*	Remaining issues
1	Nuclides targeted for removal	The effects of powder generation for 15 nuclides of 5 elements (U, Np, Pu, Am, and Cm) were verified by tests. It was verified that the necessity of adsorption and removal of U is low because its solubility near neutral pH 5 to 9 under atmospheric conditions and the concentration in the PCV stagnant water are about two orders of magnitude lower than the announcement density.	Dissolution and adsorption behavior of α-nuclides for U, Np, Pu, Am, and Cm, respectively, assuming a nitrogen environment in the PCV
2	Quality of water to be treated	The evaluation was conducted assuming elution of seawater components, elution of concrete components, and injection of sodium pentaborate, a criticality inhibitor.	Effects of oil, coating, rust inhibitor, and non-soluble criticality inhibitor components
3	Treatment flow rate	If an adsorption/removal system is installed in the facility that circulates and cools the PCV stagnant water, a treatment flow rate of 10 m^3/h can be set to maintain a lower concentration of α-nuclides. If an adsorption/removal system is installed outside of the facility that circulates and cools the PCV stagnant water, only the volume of water increase from fuel debris retrieval work is treated so the water balance can be maintained if the treatment flow rate is 3.5 m^3/h or higher.	Setting of treatment flow rate considering facility operating schedule
4	Concentration of α-nuclides in assumed water quality	The dissolution behavior of each α-nuclide was determined based on the water quality that is assumed under conditions of elution of seawater components and the injection of sodium pentaborate, a criticality inhibitor. Regarding the effect of concrete elution, it was verified that evaluation in a nitrogen atmosphere similar to the PCV environment is necessary because in an atmospheric environment α-nuclides co-precipitate with the formation of calcium carbonate.	Dissolution and adsorption behavior of α-nuclides at high pH assuming elution of concrete components
5	Requirements for concentration reduction	The target DF for reduction of public exposure effects is 100, and the concentration reduction target for transferring to water treatment facility is the announcement density. (No progress)	Necessary DF setting accounting for the concentration of particulate α-nuclides
			Setting of concentration reduction targets for individual nuclides

* Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary budgets
“Development of Technology for Retrieval of Fuel Debris and Reactor Internals”
(2) (ii) Technical development of treatment of fuel debris and deposit
① Removal technology for soluble nuclides in circulating cooling water
② Treatment technology for deposits collected from inside PCV
Hereinafter referred to as “the previous project.”

3. Previous fiscal year project results and remaining issues

① Development of soluble α-nuclide removal technology

No.	Items	Efforts and results of the previous project	Remaining issues
6	Adsorbent application	As a result of the evaluation of α-nuclide adsorption performance by immersion tests, activated carbon, zirconium phosphate, and titanic acid were selected as candidate adsorbents for application. At this stage, since the adsorbent with a large equilibrium adsorption capacity was selected through immersion tests, it is necessary to verify its performance when applied to water flow treatment. In addition, since it is not possible to conduct high quantity α-nuclide circulation tests in a laboratory, the evaluation method is an issue.	Method for evaluating adsorption/removal performance when applied to water flow treatment
7	Adsorption tower configuration	Each tower has a series of activated carbon for removing colloidal α-nuclides, zirconium phosphate for adsorbing Pu, Am, Cm, Np, titanic acid for adsorbing Np, etc., with activated carbon at the top. Assuming merry-go-round operation, each tower is counted as two towers. The tower configuration should be reviewed taking into account the impact assessment of each nuclide simultaneously present in solution, as well as the removal performance and replacement frequency during the water flow treatment.	Interactive effects of multiple α-nuclides
			Effects of adsorption inhibitor components
			Review of tower configuration based on removal performance and replacement frequency during water flow treatment
8	Replacement timing /Replacement frequency	All of the adsorbents selected as candidates for application have low cesium (CS) adsorption performance, so the risk of replacement due to an increase in the tower surface dose is low. Although it is typical to conduct a circulation test to determine the replacement frequency due to the deterioration of adsorption performance, high α-nuclide quantity makes such a test impossible in a laboratory setting. Thus, the evaluation method remains an issue.	Evaluation method of adsorbent replacement frequency
9	Replacement method	Whether replacing the entire adsorption tower or only the adsorbent, in either case it is necessary to design equipment according to the treatment policy of the used adsorbent (long-term storage for the time being).	Operation at the time of replacement
			Handling of used adsorbents
10	Tower size	At a treatment flow rate of 10 m^3/h, the size is about the same as the adsorption tower of the multi-nuclide removal system (outside diameter: approx. 1 m, height: approx. 2.5 m).	Adsorption tower design with input of shielding policy, replacement method, etc.

3. Previous fiscal year project results and remaining issues

② Development of RO-concentrated water treatment technology
③ Development of secondary waste treatment technology

🟨 For examination in this project

No.	Items	Efforts and results of the previous project	Remaining issues
1	Water quality for treatment	The assumed water quality of the drain water and backwash water discharged from the particle removal system, which is the input water to the sludge collection system, was regulated based on the results of element tests and filter tests of the fuel debris retrieval method project. However, since the **intermediate filter of the particle removal system has not yet been selected**, it is necessary to select candidate components and evaluate the properties of the generated liquid waste. In addition, in the previous fiscal year's element tests, evaluation was only possible when spherical particles were passed through, and it is necessary to **evaluate the filter behavior and the properties of the generated liquid waste when non-spherical particles are passed through**.	Candidate components for the intermediate filter will be selected by literature research. Applicability will be verified through element tests and the properties of the generated liquid waste should be determined. Element tests will be conducted to assess the impacts on the particle removal system when treating non-spherical particles. If it is assessed that there is a predominating impact on the behavior of component differential pressure increase, recovery rate, or the amount of liquid waste generated, this will be reflected in the assumed input water quality of the sludge collection system.
2	Treatment flow rate	The treatment flow rate requirement of the sludge collection system was assessed based on the operating schedule of the fuel debris retrieval method, the filter test results, and the liquid system flow rates.	If the assumed input water quality of the liquid system changes as a result of future studies, this will be reflected in the treatment flow rate requirement of the sludge collection system.
3	Treatment method	Coagulation-precipitation treatment was selected as the treatment method for filtered liquid waste and RO-concentrated water, and usable flocculants were selected through element tests. The use of sedimentation tanks in the coagulation-precipitation treatment procedures were also examined. It is necessary to **examine the applicability to actual equipment for the flocculation sedimentation treatment of RO-concentrated water** in the case of sedimentation tank usage. In addition, it is necessary to investigate treatment procedures to simplify operations and reduce the amount of sludge generated.	Adsorption using powdered adsorbent and flocculation-precipitation using flocculant as treatment methods for RO-concentrated water will be selected. Usable powdered adsorbents and flocculants will be selected.
4	Sedimentation sludge properties and the amount generated	The amount of sedimentation sludge generated was estimated based on flocculation sedimentation test. The amount of sedimentation **sludge generated from RO-concentrated water was rated high** due to the high treatment flow rate and the high moisture content of sedimentation sludge, and there were concerns about the complexity of the discharge process and the load increase at the discharge point. Therefore, it is necessary to **reduce the amount of the sedimentation sludge**.	In order to reduce the amount of sedimentation sludge generated, each step of the RO-concentrated water treatment procedures will be reviewed. Through element tests, the effects of reducing the quantity of flocculant and powder adsorbent, and optimization of stirring conditions, etc. will be examined. The application of dehydration treatment to sedimentation sludge will be analyzed, applicable dehydration technology will be selected via literature research, and the applicability to actual equipment will be assessed through element tests.

3. Previous fiscal year project results and remaining issues

② Development of RO-concentrated water treatment technology
③ Development of secondary waste treatment technology

No.	Items	Efforts and results of the previous project	Remaining issues
5	Supernatant liquid properties	The quantity of suspended solids (SS) and other components remaining in the supernatant after solid-liquid separation were sorted.	The required acceptance conditions of the soluble nuclide removal equipment and the existing water treatment facility will be sorted out, and the necessity of neutralization treatment and removal of neutralized salt and trace amounts of residual SS components will be examined.
6	Operating methods	The process of coagulation-precipitation treatment of filtered liquid waste and RO-concentrated water using a sedimentation tank was examined based on the operating schedule of fuel debris retrieval method and element test results. An operating cycle in which one batch process is completed per day was examined.	The results of this year's element tests will be applied to the coagulation-precipitation treatment process studied in the previous project.
7	Equipment specifications	Equipment tests verified the operability of the sedimentation tank and each component. Since large particles were caught when opening and closing the gate valve, it is necessary to reconsider the specifications of the gate valve.	In element tests using RO-concentrated water treatment test equipment to be conducted from this fiscal year onwards, each mechanism of the sedimentation tank will be re-evaluated. In addition, valves that can be applied to sedimentation tanks will be examined.
8	Methods for discharge of sedimentation sludge	The discharge method of sedimentation sludge using a sludge collection container was examined, and through an equipment test confirmed that this method can be applied to actual equipment. It was verified that it is possible to insert piping from the top of the sediment tank and remove sedimentation sludge by suction pump. In the future, the required acceptance conditions of the sedimentation sludge discharge point will be sorted out and sludge canister size and applicability of dehydration treatment will be examined.	When the sedimentation sludge is treated and disposed of as waste, it is discharged to the waste line, so it is necessary to consider the final disposal of sedimentation sludge and apply pretreatment. In the future, if a policy for the final disposal of sludge is presented, the necessary pretreatment within the liquid system will be examined and applied to the sedimentation sludge discharge method. When sedimentation sludge is stored in canisters, it is discharged to the canister line, so it is necessary to apply pretreatment to satisfy the requirements of long-term storage. The requirements for long-term storage of sedimentation sludge will be sorted out and the shape and moisture content of the sludge collection container will be examined.
9	Handling of sedimentation sludge	Assumed properties of sedimentation sludge and the amount generated were arranged based on the results of element tests and the liquid system requirements.	Assumed properties of sedimentation sludge will be shared to both the waste project and the canister project. Issues will be identified respectively to each project.

4. Input/output information

No.9

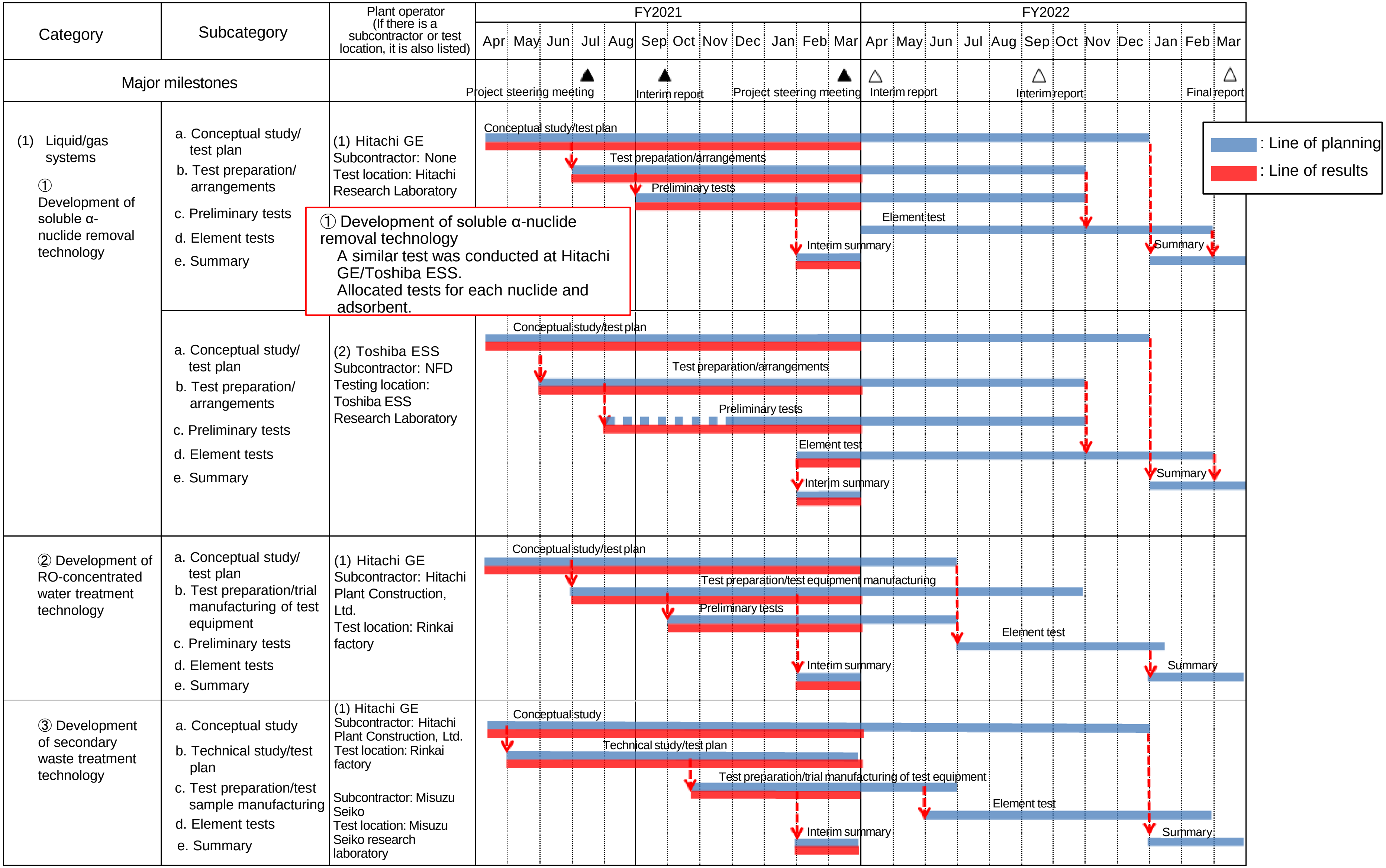
This project will be proceeded in collaboration with related projects such as the Development of Technologies for Containing, Transfer and Storage of Fuel Debris project and the R&D for Treatment and Disposal of Solid Waste project.

ID	Demand-side project	Provider-side project	Contents (overview)	Information use
1	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	Development of Technologies for Containing, Transfer and Storage of Fuel Debris	Acceptance conditions for canisters	Examination of stabilization treatment technology for secondary waste
2	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	R&D for treatment and disposal of solid waste	Acceptance conditions for waste storage containers	Examination of stabilization treatment technology for secondary waste
3	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	Development of Analysis and Estimation Technology for Fuel Debris Characterization	Results of examination on formation behavior of fuel debris particles	Examination of properties of particles in circulating cooling water
4	Development of Technologies for Containing, Transfer and Storage of Fuel Debris	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	Properties of sedimentation sludge generated from liquid gas system	Identification of issues in the handling of fuel debris in slurry or sludge form
5	R&D for treatment and disposal of solid waste	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	Properties of sedimentation sludge generated from liquid gas system	Identification of issues in the treatment and disposal of radioactive waste in slurry or sludge form

*Also planned to discuss collaboration with TEPCO in the future.

5. Implementation schedule

No.10



Category	Subcategory	Plant operator (If there is a subcontractor or test location, it is also listed)	FY2021 Apr–Mar	FY2022 Apr–Mar
Major milestones			▲ Project steering meeting (Jul) ▲ Interim report (Sep) ▲ Project steering meeting (Mar)	△ Interim report (Apr) △ Interim report (Oct) △ Final report (Mar)
(1) Liquid/gas systems ① Development of soluble α-nuclide removal technology	a. Conceptual study/ test plan b. Test preparation/ arrangements c. Preliminary tests d. Element tests e. Summary	(1) Hitachi GE Subcontractor: None Test location: Hitachi Research Laboratory		
	a. Conceptual study/ test plan b. Test preparation/ arrangements c. Preliminary tests d. Element tests e. Summary	(2) Toshiba ESS Subcontractor: NFD Testing location: Toshiba ESS Research Laboratory		
② Development of RO-concentrated water treatment technology	a. Conceptual study/ test plan b. Test preparation/trial manufacturing of test equipment c. Preliminary tests d. Element tests e. Summary	(1) Hitachi GE Subcontractor: Hitachi Plant Construction, Ltd. Test location: Rinkai factory		
③ Development of secondary waste treatment technology	a. Conceptual study b. Technical study/test plan c. Test preparation/test sample manufacturing d. Element tests e. Summary	(1) Hitachi GE Subcontractor: Hitachi Plant Construction, Ltd. Test location: Rinkai factory Subcontractor: Misuzu Seiko Test location: Misuzu Seiko research laboratory		

① Development of soluble α-nuclide removal technology
A similar test was conducted at Hitachi GE/Toshiba ESS.
Allocated tests for each nuclide and adsorbent.

*Hitachi GE: Hitachi-GE Nuclear Energy, Ltd.
*Toshiba ESS: Toshiba Energy Systems & Solutions Corporation

6. Project organization

Tokyo Electric Power Company Holdings, Inc.

- Coordination for on-site applicability

International Research Institute for Nuclear Decommissioning (IRID)

- Coordination of general planning and overall technology management
- Coordination of technology administration including technology development progress management

Hitachi-GE Nuclear Energy, Ltd.

[Element test, technical development]
(1) Liquid/gas system development
① Development of soluble α-nuclide removal technology
  - Examination of soluble α-nuclide removal test assuming the use of actual liquid (stagnant water in the reactor building)
  - Element test assuming fuel debris retrieval work
② Development of RO-concentrated water treatment technology
  - Selection of adsorbents and flocculants
  - Examination of applicability to actual equipment
③ Development of secondary waste treatment technology
  - Investigation of stabilization treatment technology
  - Examination of applicability to actual equipment

(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology
  - Formulation of criticality approach monitoring procedures

Toshiba Energy Systems & Solutions Corporation

[Element test, technical development]
(1) Liquid/gas system development
① Development of soluble α-nuclide removal technology
  - Examination of soluble α-nuclide removal test assuming the use of actual liquid (stagnant water in the reactor building)
  - Element test assuming fuel debris retrieval work

(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology
  - Formulation of criticality approach monitoring procedures
  - Performance assessment of neutron detector sub-criticality measurement
  - Formulation of operating procedures for usage of absorbers
  - Examination of the impacts of the fuel debris on drying process

Mitsubishi Heavy Industries, Ltd.

[Element test, technical development]
(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology
  - Formulation of criticality approach monitoring procedures
  - Performance assessment of neutron detector sub-criticality measurement

Japan Atomic Energy Agency

[Element test, technical development]
(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology
  - Development of solidified absorber technology

Development project teams in cooperation with this project

- Development of Fuel Debris Retrieval Method
- Development of Technologies for Containing, Transfer and Storage of Fuel Debris
- R&D on Solid Waste Treatment and Disposal
- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Development of Technology for Detailed Investigation inside PCV
- Development of Technology for Investigation inside the RPV
- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Development of Technology for Sorting of Fuel Debris and Radioactive Waste

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Development history

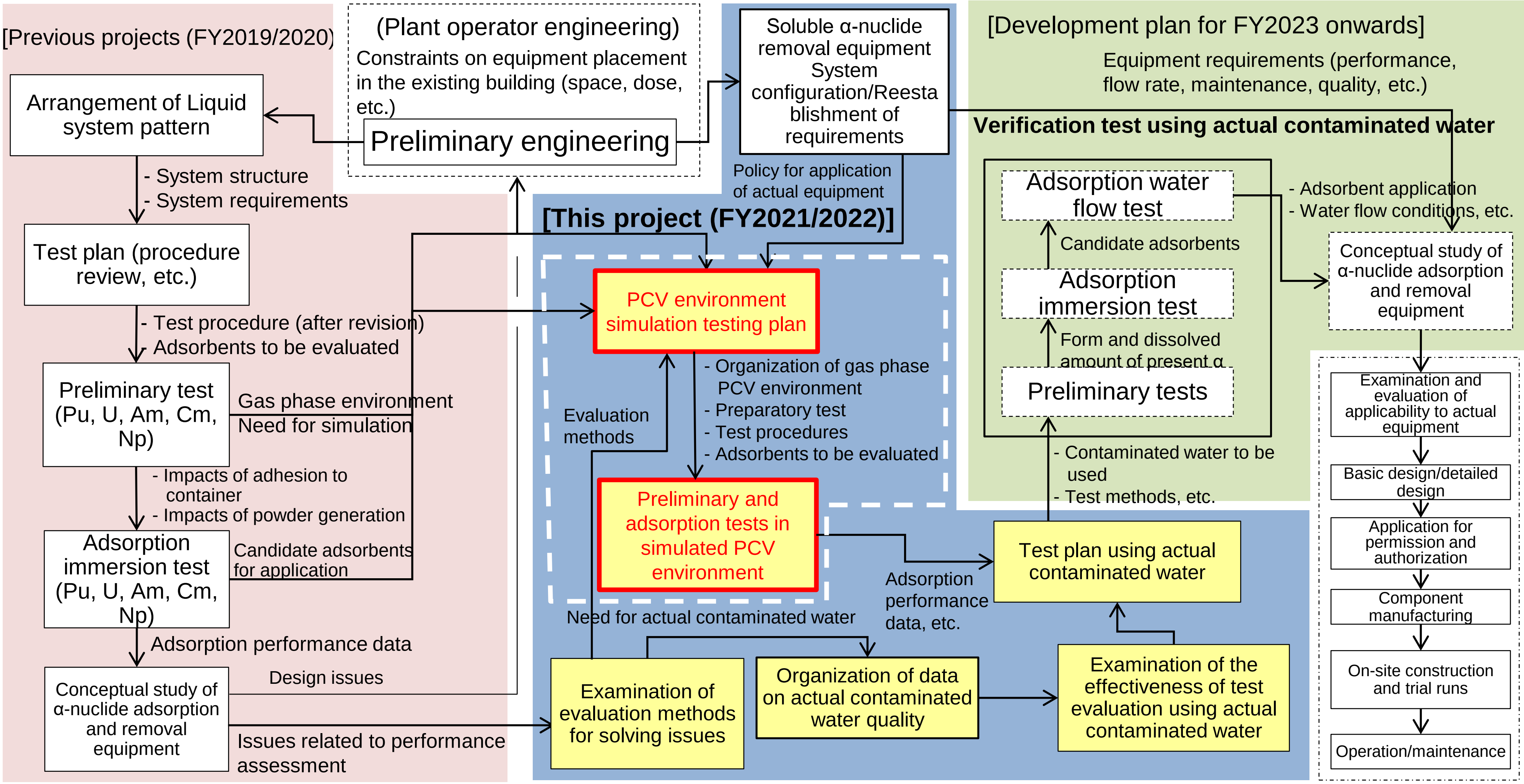
- In the FY2016 subsidy project, “Upgrading of Methods and Systems for Retrieval of Fuel Debris and Reactor Internals,” site boundary exposure doses for liquid system during normal and accident conditions were evaluated. The site boundary exposure dose was below the threshold value in both normal and accident conditions, but in both cases the effects of Pu-based nuclides and daughter product (Pu-238, Pu-241, Am-241) were significant.
- Alpha-emitting nuclides (hereinafter referred to as α-nuclides) at existing nuclear facilities are not nuclides that are discharged into the environment and the exposure due to α-nuclides should be as low as reasonably achievable. Therefore, from the subsidy projects (FY2017/2018) “Upgrading of Methods and Systems for Retrieval of Fuel Debris and Reactor Internals,” examination and evaluation of the effectiveness of removing α-nuclides in liquid system have started. Candidate technologies are selected for each type of α-nuclide (non-soluble α-nuclides and soluble α-nuclides), and element tests are conducted to evaluate the feasibility of the selected technologies.
- Adsorption removal and RO filters have been selected as candidate technologies for removal of soluble α-nuclides; RO filters are capable of removing α-nuclides in principle. On the other hand, although adsorption removal is a proven technology for the Fukushima Daiichi NPS contaminated water treatment, its applicability depends on the adsorbent selected and the form of α-nuclides present in solution.
- The previous project (subsidy project for FY2019 to 2020) dealt with the development of adsorption removal technology and adsorption tests under open-atmospheric conditions were conducted on Pu, U, Am, Cm, and Np α-nuclides (the 5 nuclides targeted for removal). Candidate adsorbents were selected, but their actual effectiveness in the event of PCV water quality fluctuation has not yet been evaluated.
- In addition, in order to verify the adsorption removal technology’s efficacy in removing α-nuclides, a verification test using actual contaminated water is required, but plans for such a test are still under discussion.

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Mapping out of this project

End of FY2021 Subject of report



[Previous projects (FY2019/2020)]

Arrangement of Liquid system pattern

- System structure
- System requirements

Test plan (procedure review, etc.)

- Test procedure (after revision)
- Adsorbents to be evaluated

Preliminary test (Pu, U, Am, Cm, Np)

Gas phase environment
Need for simulation

- Impacts of adhesion to container
- Impacts of powder generation

Adsorption immersion test (Pu, U, Am, Cm, Np)

Candidate adsorbents for application

Adsorption performance data

Conceptual study of α-nuclide adsorption and removal equipment

Design issues

Issues related to performance assessment

(Plant operator engineering)

Constraints on equipment placement in the existing building (space, dose, etc.)

Preliminary engineering

Soluble α-nuclide removal equipment System configuration/Reestablishment of requirements

Policy for application of actual equipment

[This project (FY2021/2022)]

PCV environment simulation testing plan

Evaluation methods

- Organization of gas phase PCV environment
- Preparatory test
- Test procedures
- Adsorbents to be evaluated

Preliminary and adsorption tests in simulated PCV environment

Need for actual contaminated water

Adsorption performance data, etc.

Test plan using actual contaminated water

Examination of evaluation methods for solving issues

Organization of data on actual contaminated water quality

Examination of the effectiveness of test evaluation using actual contaminated water

[Development plan for FY2023 onwards]

Equipment requirements (performance, flow rate, maintenance, quality, etc.)

Verification test using actual contaminated water

Adsorption water flow test

Candidate adsorbents

Adsorption immersion test

Form and dissolved amount of present α

Preliminary tests

- Contaminated water to be used
- Test methods, etc.

- Adsorbent application
- Water flow conditions, etc.

Conceptual study of α-nuclide adsorption and removal equipment

Examination and evaluation of applicability to actual equipment

Basic design/detailed design

Application for permission and authorization

Component manufacturing

On-site construction and trial runs

Operation/maintenance

Figure Overall flow of development of soluble α-nuclide removal technology

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Issues, implementation details and goals to be addressed in this project

[Issues]

- The behavior of α-nuclides in solution under conditions simulating the PCV environment during fuel debris retrieval work has not been verified.
- The impacts of changes in solution water quality on the soluble α-nuclide removal performance has not yet been evaluated.

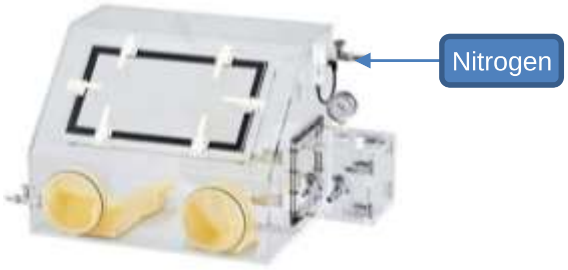
[Implementation details]

- A test equipment was manufactured to simulate the environment during fuel debris retrieval work.
- Preliminary tests were conducted to verify the dissolution behavior of α-nuclides under conditions simulating the environment during fuel debris retrieval work.
- Adsorption tests were conducted to verify the α-nuclide removal performance under conditions simulating the environment during fuel debris retrieval work, and applicable adsorbents are selected.

[Goals]

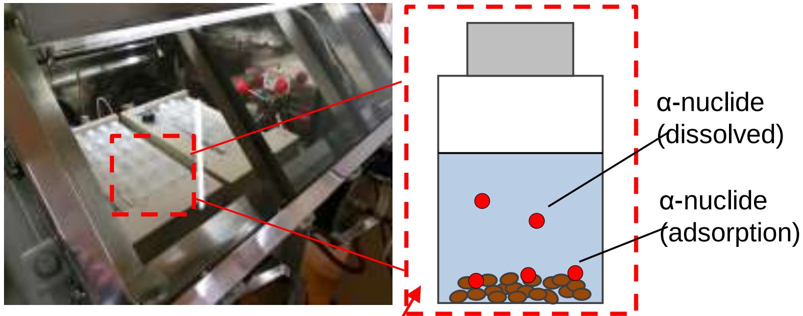
- Data acquisition on α-nuclide adsorption performance in the environment assuming fuel debris retrieval work, and select candidate adsorbents.
- Establishment of a water quality adjustment policy for soluble α-nuclide removal equipment.

<Illustration of test equipment for simulating a nitrogenous environment during fuel debris retrieval work>



Simple glove box

<Adsorption test>



View of glove box interior

Container for adsorption testing

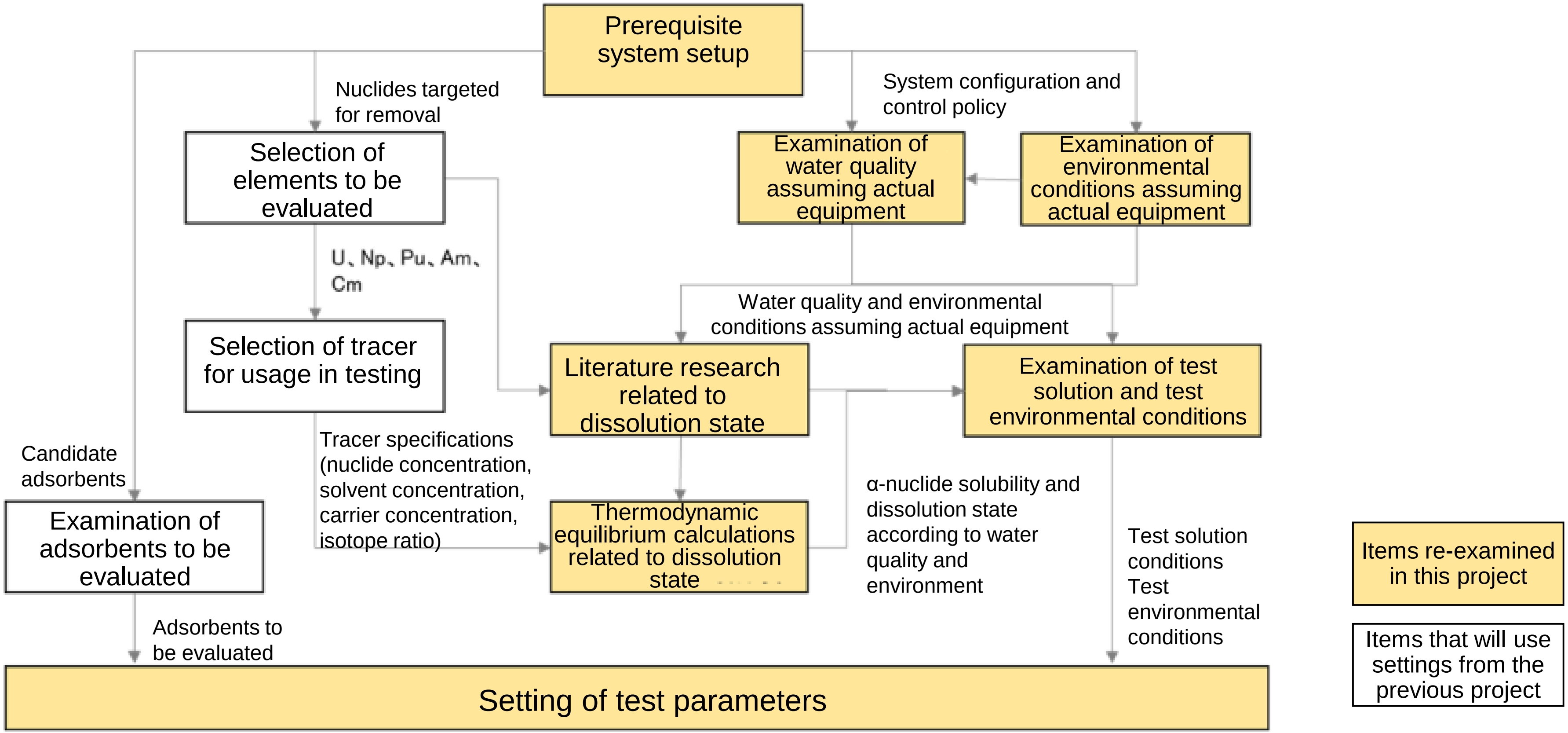
Measure the nuclide concentration in the liquid before and after the test and assess the adsorption amount

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Response flow up to element test parameter setting

After setting up the prerequisite system, the environmental and water quality conditions in the actual equipment were examined. The test environment and test solution conditions were also examined based on the literature research and calculation of thermodynamic equilibrium related to the dissolution state of α-nuclides. Then the test parameters were set according to the adsorbent to be evaluated.



Prerequisite system setup

Nuclides targeted for removal

System configuration and control policy

Selection of elements to be evaluated

Examination of water quality assuming actual equipment

Examination of environmental conditions assuming actual equipment

U、Np、Pu、Am、Cm

Water quality and environmental conditions assuming actual equipment

Selection of tracer for usage in testing

Literature research related to dissolution state

Examination of test solution and test environmental conditions

Candidate adsorbents

Tracer specifications (nuclide concentration, solvent concentration, carrier concentration, isotope ratio)

α-nuclide solubility and dissolution state according to water quality and environment

Examination of adsorbents to be evaluated

Thermodynamic equilibrium calculations related to dissolution state

Test solution conditions
Test environmental conditions

Items re-examined in this project

Items that will use settings from the previous project

Adsorbents to be evaluated

Setting of test parameters

Figure Response flow up to element test planning

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Setting of prerequisite system (liquid/gas systems)

- In the liquid system, in order to control water level and confine the contaminated water in the PCV, water is taken from the D/W (dry well) or S/C (PCV suppression chamber) and fuel debris is cooled by injecting and circulating water taken from D/W or S/C after cooling.
- The gas system manages negative pressure to confine dust and other substances in the PCV, and fills the PCV with nitrogen for hydrogen scavenging and other purposes.
- Although air flows in due to negative pressure control, the gas phase inside the PCV becomes mostly nitrogenous.
- Up until 2020 α-nuclide adsorption tests had been conducted in an atmospheric environment. Testing in a nitrogen environment is necessary in order to further investigate application to actual equipment.

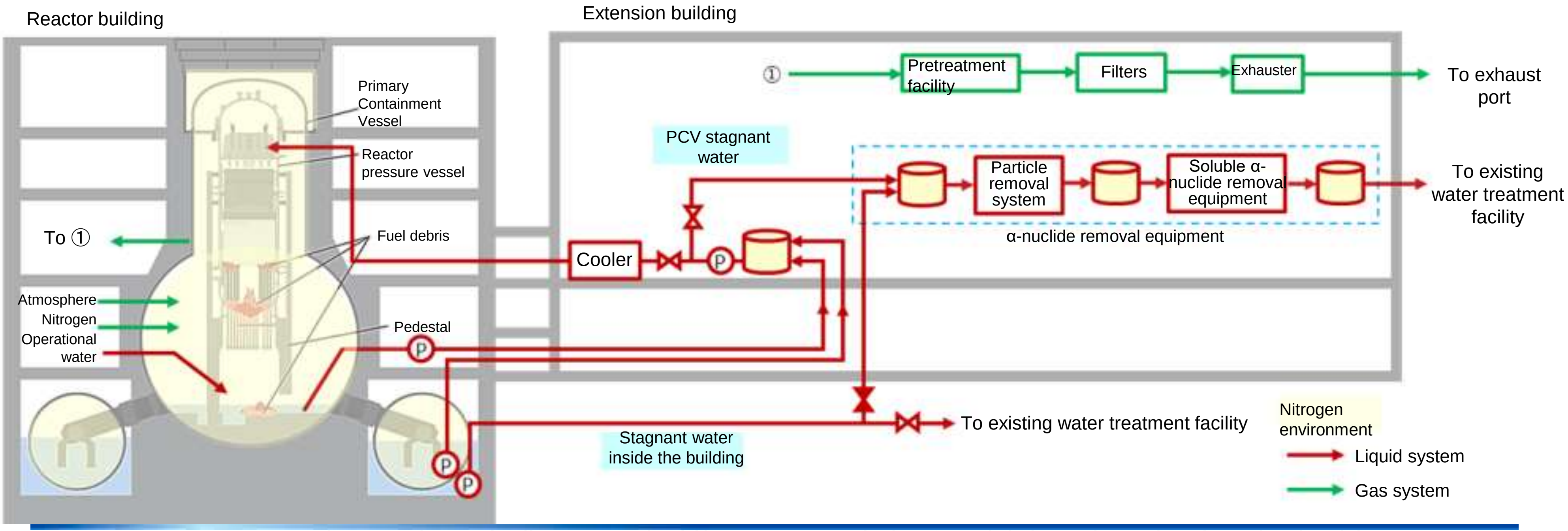


Figure Schematic diagram of liquid/gas systems during fuel debris retrieval (engineering basis)

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Setting of prerequisite system (soluble α-nuclide removal system)

- In the previous project, to study soluble α-nuclide removal system when adsorption/removal is applied, a facility configuration consisting of receiving tank, adsorption tower, monitoring tank, sampling equipment, etc. was examined.
- Adsorption tests were conducted under atmospheric conditions using α-nuclides elements (the nuclides targeted for removal). A tower configuration with attached activated carbon on top and zirconium phosphate/titanic acid in the second stage was proposed. The former is assumed to remove mainly colloidal α-nuclides while the latter is assumed to remove dissolved α-nuclides.
- In this project, similar adsorption tests under a nitrogen atmosphere (simulating the gas phase environment in the PCV) were conducted to evaluate the impacts on the solubility of α-nuclides and adsorption performance, and to investigate whether the tower configuration and adsorbent used in the previous project need to be altered.

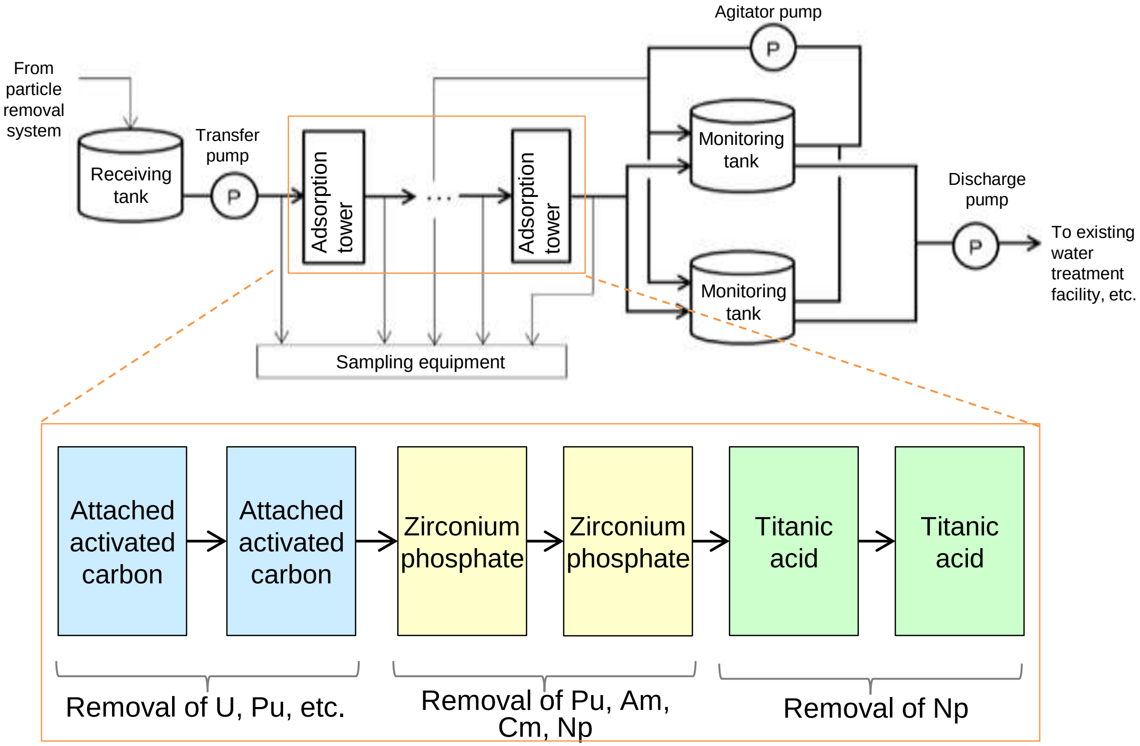


Figure Schematic diagram of soluble α-nuclide removal system and proposed tower configuration*

*Supplementary information on the tower configuration

- The number of towers in each adsorption tower is provisionally set at 2 to enable merry-go-round operation. The number of required towers for each adsorption tower needs to be evaluated in the future.
- In order to reduce the number of adsorption towers as much as possible, attached activated carbon adsorption towers (which have high removal performance for colloidal α-nuclides in addition to soluble α-nuclides) and zirconium phosphate adsorption towers (which have high adsorption performance for multiple soluble α-nuclides) are installed. However, since the Np adsorption performance of the attached activated carbon and zirconium phosphate is only relatively high and the concentration reduction during water flow treatment may be insufficient, a titanic acid adsorption tower should be installed at the post zirconium phosphate stage.

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Examination of environmental conditions assuming actual equipment and policy for applying these conditions to the test environmental conditions

- The following table summarizes the proposed control policy and control values for the gas phase environment of the PCV, based on the analysis status in the plant operator engineering.
- Oxygen concentration is related to the degree of air inflow, and since it is under consideration to set the control value less than 4%, this will be reflected in the conditions in the test evaluation. (Note, however, that the 4% figure is tentative, and not a definite value.)
- The atmospheric component in the PCV gas phase is estimated to be at a concentration less than 1/5 that of the atmosphere, which has an oxygen concentration of about 20%. (Carbon dioxide concentration in the PCV is assumed to be 70 to 80 ppm or less)

Table Proposed control policy and values for environmental items during fuel debris retrieval (gas system)

No.	Environmental item		Control requirements	Proposed control policy	Proposed control value	Remarks
1	Gas phase environment	PCV gas phase pressure	Gas phase confinement (leakage prevention)	Negative pressure is managed by controlling the exhaust flow rate	TBD	If negative pressure control is not feasible, the alternatives are positive pressure control or equalization pressure control.
2		Nitrogen concentration	No	(Nitrogen supply control)	—	Nitrogen concentration itself is not a control target.
3		Hydrogen concentration	Gas phase confinement (fire/explosion prevention)	Nitrogen supply and exhaust flow rate are controlled to keep hydrogen below the lower explosive limit	Less than 2%	This is tentative, not a definite value.
4		Oxygen concentration	Gas phase confinement (fire/explosion prevention)	Nitrogen supply and exhaust flow rate are controlled to prevent the conditions of Zr fire outbreak.	Less than 4%	Concentration increase due to air inflow during negative pressure control. This is tentative, not a definite value.
5		Carbon dioxide concentration	No	Course of events	—	Concentration increase due to air inflow during negative pressure control.
6		Dust concentration	Gas phase confinement (leakage prevention)	Exhaust flow rate is controlled to keep the activity concentration below the specified level	TBD	At the time of full discharge, the concentration is less than or equal to the public exposure dose of 5 mSv.

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Examination of water quality conditions assuming actual equipment and policy for applying these conditions to the test solution conditions (1/3)

- By the start of fuel debris retrieval work, incremental changes in water quality are assumed due to circulation cooling operations in the liquid system and PCV negative pressure control in the gas system.
- Once fuel debris retrieval work begins, it is anticipated that the pH of the liquid phase will increase due to elution of concrete during cutting.
- The increase in pH is also assumed to increase the amount of gas phase carbon dioxide that dissolves into the liquid phase.

Table Evaluation status of water quality of PCV stagnant water and α-nuclide adsorption performance under liquid/gas systems and fuel debris retrieval operating conditions

Operating conditions		STEP1	STEP2	STEP3	STEP4
Circulation cooling		Not conducted	Conducted	Conducted	Conducted
PCV negative pressure control		Not conducted	Not conducted	Conducted	Conducted
Fuel debris retrieval work		Not conducted	Not conducted	Not conducted	Conducted
Quality of PCV stagnant water	Overview	RO-treated water is injected from the outside the PCV and then leaks out, so the water quality is basically the same as RO-treated water.	Circulation of RO-treated water may cause elution of concrete, etc. Since the gas phase is in a nitrogen atmosphere, there is no atmospheric impacts.	By managing the PCV with negative pressure, the carbonic acid concentration underwater increases due to gas phase carbon dioxide concentration increase from air inflow into the PCV.	Increased elution of concrete due to fuel debris retrieval work causes a pH increase. Carbonic acid concentration is positively correlated with pH. Injection of boric acid solution as criticality prevention is also hypothesized.
	Estimated pH	Approx. 7	7 to 9	5 to 9	5 to 12
	Inorganic carbon* concentration (estimated)	Approx. 1 ppm	Approx. 1 ppm	Several ppm (Impacts of air inflow)	Several dozen ppm (Air inflow + impacts of pH increase)
α-nuclide adsorption performance evaluation status		(Not applicable)	(Not applicable)	Selection of candidate adsorbents through adsorption tests up to FY2020	Not yet evaluated

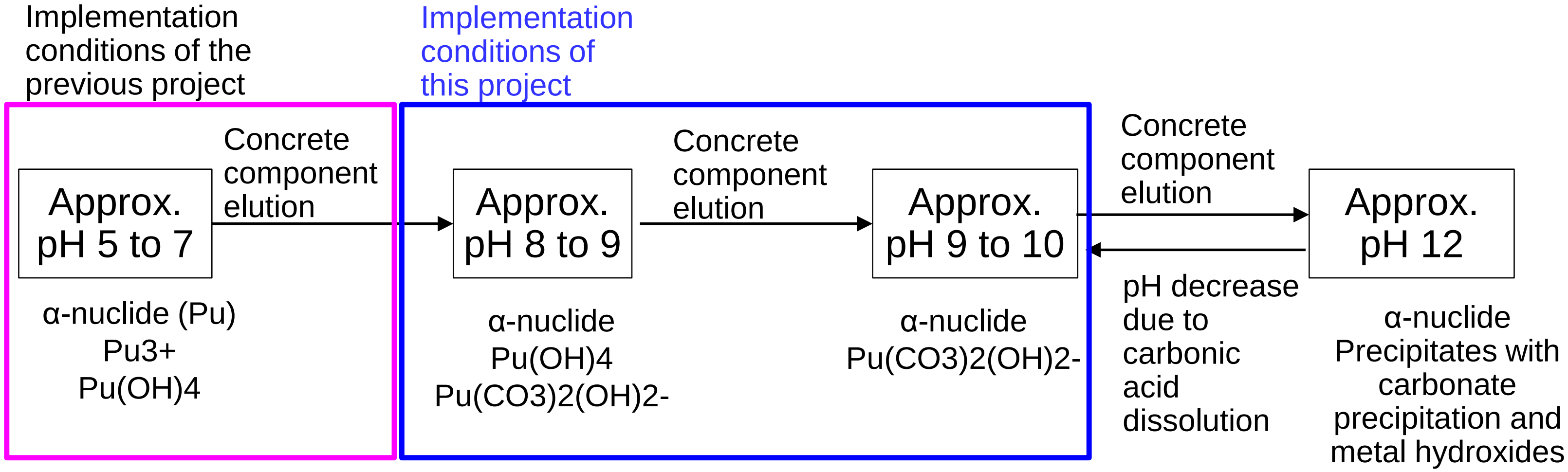
*Collective term for CO_2, HCO_3^- and CO_3^{2-}. The abundance ratio varies with the pH of the solution.

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Examination of water quality conditions assuming actual equipment and policy for applying these conditions to the test solution conditions (2/3)

- The pH range required for estimation was studied because the amount of pH and carbon dioxide elution into the liquid phase are assumed to increase due to elution of concrete components during fuel debris retrieval.
- When calcium from concrete is eluted, the pH of a saturated solution of calcium hydroxide is approximately 12.4, but in the high pH region, carbon dioxide in the gas phase is more soluble, and over time the pH drops to about 9 to 10 due to carbonic acid dissolution.
- When the pH decreases due to carbonic acid dissolution, calcium carbonate precipitates and α-nuclide concentration is assumed to decrease due to coprecipitation, in which case the need for adsorption removal is reduced.
- In order to verify the dissolved α-nuclide adsorption performance, adsorption tests under alkaline conditions (pH 8 to 10) are planned under this project, in which the α-nuclide concentration in the liquid phase is not assumed to decrease significantly.



Implementation conditions of the previous project

Implementation conditions of this project

Approx. pH 5 to 7

Concrete component elution

Approx. pH 8 to 9

Concrete component elution

Approx. pH 9 to 10

Concrete component elution

Approx. pH 12

pH decrease due to carbonic acid dissolution

α-nuclide (Pu)
Pu^{3+}
$Pu(OH)_4$

α-nuclide
$Pu(OH)_4$
$Pu(CO_3)_2(OH)_2^-$

α-nuclide
$Pu(CO_3)_2(OH)_2^-$

α-nuclide
Precipitates with carbonate precipitation and metal hydroxides

Figure Water quality fluctuation scenario in case of concrete component elution

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Examination of water quality conditions assuming actual equipment and policy for applying these conditions to the test solution conditions (3/3)

- There are three factors that contribute to changes in PCV stagnant water quality: elution of seawater components, elution of concrete components, and injection of boric acid solution (sodium pentaborate). The water quality conditions assuming actual equipment with each condition as a parameter are summarized below.
- Concrete component elution-mediated pH increase is assumed to alter the form of α-nuclides. Since it is necessary to understand the impacts of pH on adsorption performance, implementation under two conditions is planned.

Table List of PCV stagnant water quality conditions assuming actual equipment

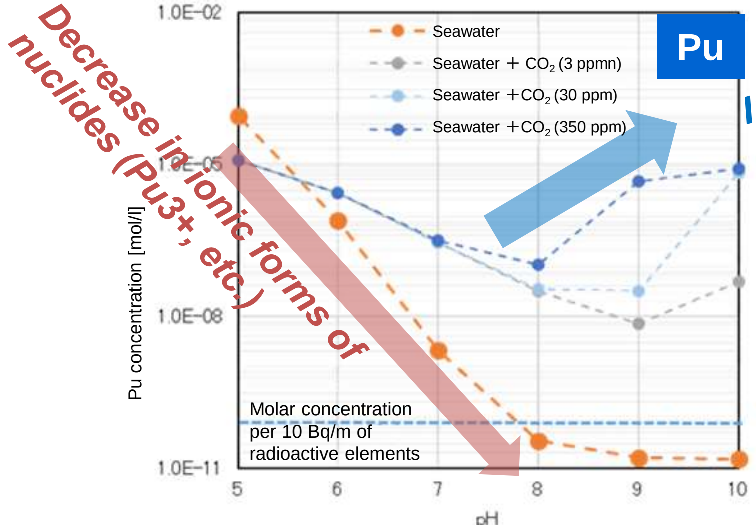
Type of test water	Expected conditions	Seawater component	Concrete component	Boric acid solution component	Conditions						
					Temperature [°C]	Cl ion concentration [ppm]	Ca ion concentration [ppm]	Boron concentration [ppm]	pH	Inorganic carbon concentration [ppm]	SS concentration [ppm]
1	Circulation with water of similar quality to RO-treated water	No	No	No	10 to 40	0	<1	<1	6 to 7	Approx. 1	<1
2-1	Small amount of seawater components eluted into the circulating cooling water	Yes	No	No	10 to 40	20	<1	<1	6 to 7	Approx. 1	<1
2-2	Large amount of seawater components eluted into the circulating cooling water	Yes	No	No	10 to 40	100	Approx. 1	<1	6 to 7	Approx. 1	<1
3-1	Small amount of concrete component eluted into water quality 2-1	Yes	Yes	No	10 to 40	20	Low	<1	8 to 9	Low	<1
3-2	Large amount of concrete component eluted into water quality 2-1	Yes	Yes	No	10 to 40	20	High	<1	9 to 10	High	<1
4-1	Small amount of concrete component eluted into water quality 2-2	Yes	Yes	No	10 to 40	100	Low	<1	8 to 9	Low	<1
4-2	Large amount of concrete component eluted into water quality 2-2	Yes	Yes	No	10 to 40	100	High	<1	9 to 10	High	<1
5	Boric acid solution injected into water quality 2-1 to prevent criticality	Yes	Yes	Yes	10 to 40	20	Low	7000	8 to 9	High	<1

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Investigation and evaluation related to dissolution state

- In the previous project, thermodynamic equilibrium calculations were performed for a system in which carbon dioxide exists in the gas phase. It was evaluated that the solubility form of coordinated carbonate ions (carbonate complexes) as the dissolved form of α-nuclides increases in alkaline conditions.
- The increase in carbonate ion concentration accompanying the rise in pH may cause precipitation formation with Ca (Ca carbonate), a concrete component, accompanied by a decrease in concentration due to coprecipitation of α-nuclides. However, this coprecipitation phenomenon cannot be evaluated by equilibrium calculations, so verification through test evaluation under simulated environment assuming actual equipment is required.

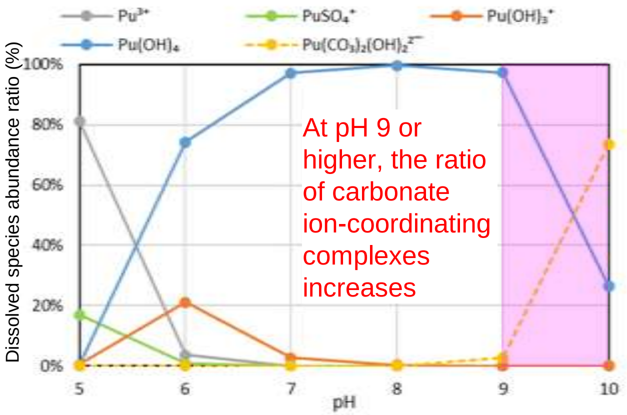


Decrease in ionic forms of nuclides (Pu3+, etc.)

Increase in carbonic acid-coordinating nuclides (Pu(CO3)2(OH$_3^{2-}$))

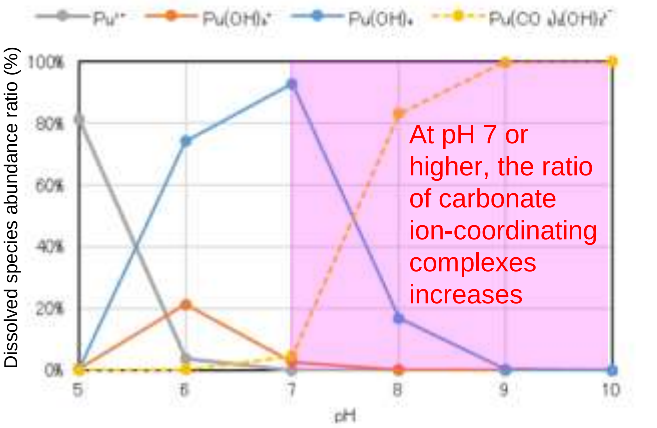
Figure Results of evaluating Pu solubility based on thermodynamic equilibrium calculation with condition of carbon dioxide concentration in gas phase as a parameter (50-fold diluted seawater)

(1) Carbon dioxide concentration in gas phase: 3 ppm



At pH 9 or higher, the ratio of carbonate ion-coordinating complexes increases

(2) Carbon dioxide concentration in gas phase: 350 ppm



At pH 7 or higher, the ratio of carbonate ion-coordinating complexes increases

Figure Results of evaluating dissolved form of Pu based on thermodynamic equilibrium calculation with condition of carbon dioxide concentration in gas phase as a parameter (50-fold diluted seawater)

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Overall test plan

- In the previous project, the soluble α removal test was conducted in an environment simulating the air atmosphere inside the R/B, whereas in this project the test simulated the nitrogen atmosphere environment inside the PCV.
- The adsorption test was conducted after completing the preparatory and preliminary tests. The outline and objectives of each test are as follows.
  - ① Preparatory test: Verification of feasibility of controlling the nitrogen atmosphere in the simple glove box (verification of feasibility of maintaining an oxygen concentration of 4% or less)
  - ② Preliminary test: Verification of the impacts of α-nuclide in the liquid phase adhering to containers as well as the impacts of precipitation formation (verification of concentration reduction factors other than adsorbents)
  - ③ Adsorption test: Verification of soluble α-nuclide adsorption performance by immersion testing

[This project] Simulation of PCV environment (nitrogen atmosphere)

Comparison of nitrogen atmosphere/air atmosphere

① Preparatory test

↓

② Preliminary test

↓

③ Adsorption test

Use of a simple glove box (under a nitrogen atmosphere) to simulate the PCV gas phase environment

[Previous project] Simulation of R/B environment (air atmosphere)

Test in air atmosphere

① Preliminary test

↓

② Adsorption test

Figure Overall test implementation flow

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Test system and preparatory test results

- The diagram below (Figure A) shows the test system for evaluating simulation of the internal PCV environment (nitrogen atmosphere).
- In order to investigate radiation control, a simple glove box (simple GB) was installed in the hood of the laboratory, and a nitrogen-filled line from an N2 cylinder is connected to create a nitrogen atmosphere inside the simple GB.
- By verifying the impacts of air inflow into the simple GB, it was confirmed that it takes about 10 days to exceed the 4% oxygen concentration control target, and that the atmosphere can be maintained even when human work is unavailable (e.g., nights and holidays). (Figure B)
- In addition to periodically checking the oxygen concentration in the simple GB and filling it with nitrogen as appropriate, it was also decided to adopt a policy of adding nitrogen prior to collecting liquid from test samples, since the GB atmosphere is strongly affected each time the lid of the test sample container is opened.
- Temperature control in the simple GB is difficult due to space constraints. Therefore, temperature was measured and recorded during the test and data necessary to investigate any impacts from temperature difference was collected.

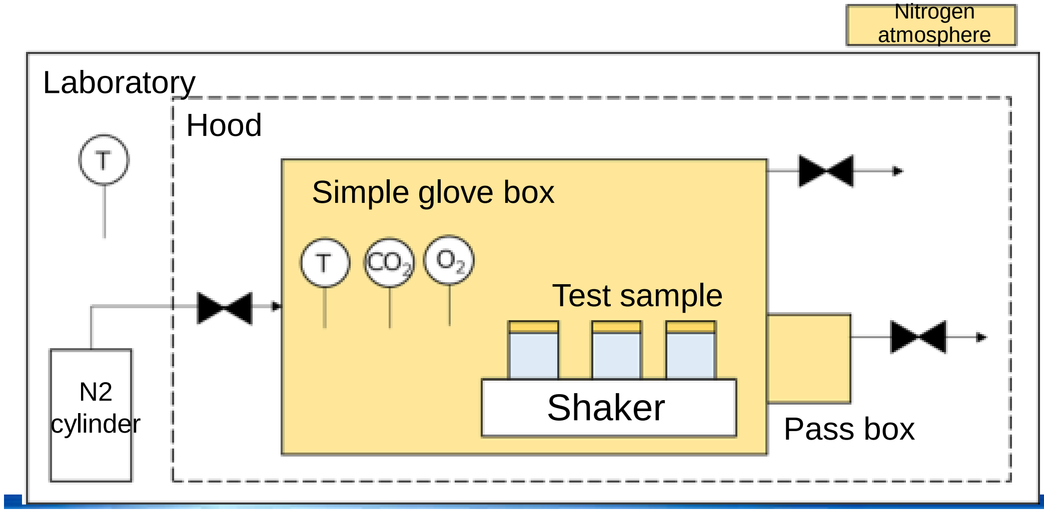


Figure A Test system simulating a nitrogen atmosphere

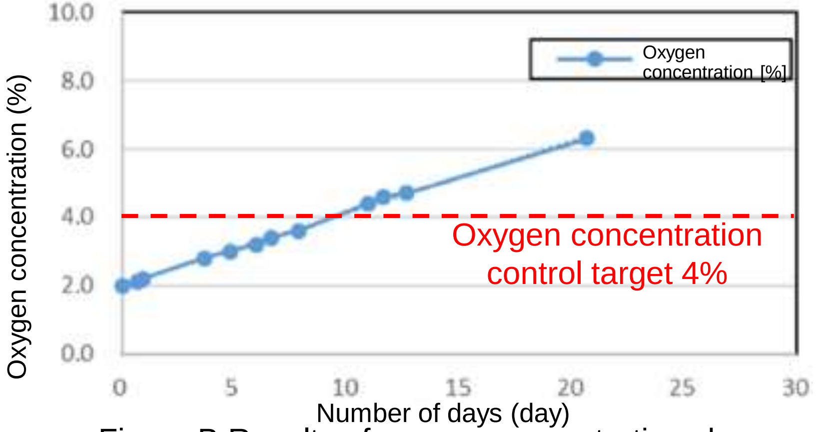


Figure B Results of oxygen concentration changes verified in a simple GB

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Preliminary test procedures

The preliminary test procedures, established based on the preparatory test results, are shown below.
The test procedures are the same as in the previous project, and the test environment was performed under a nitrogen atmosphere.

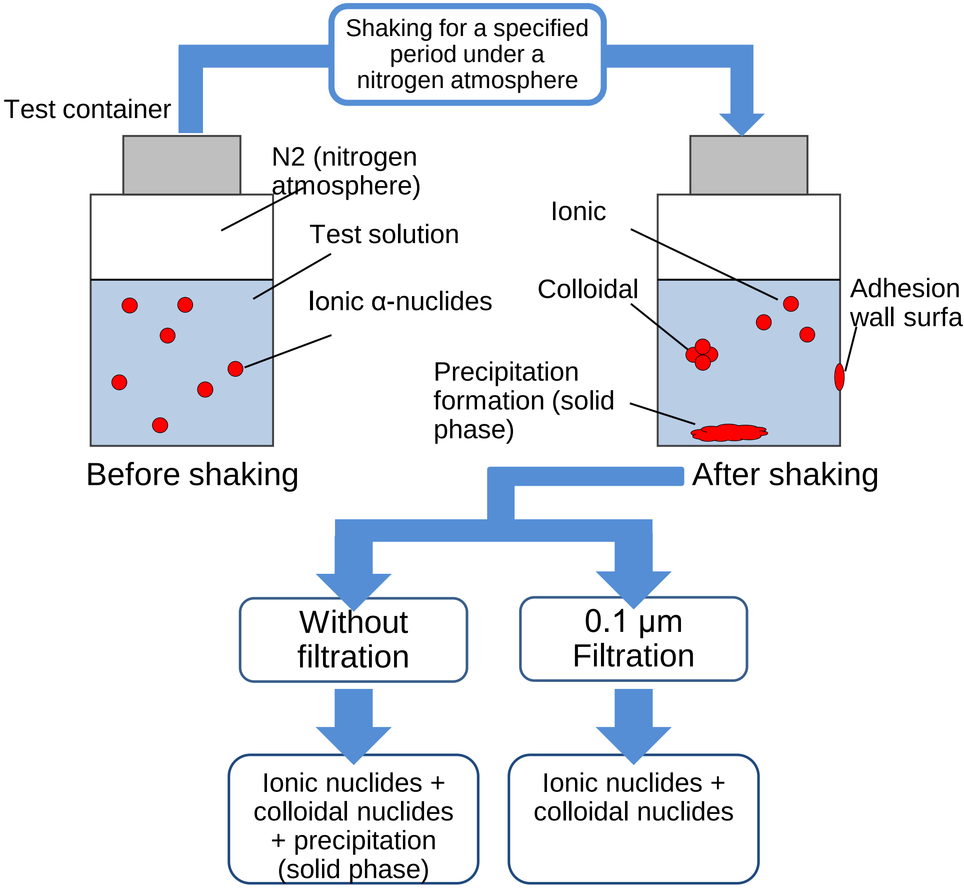


Figure Diagram of preliminary test

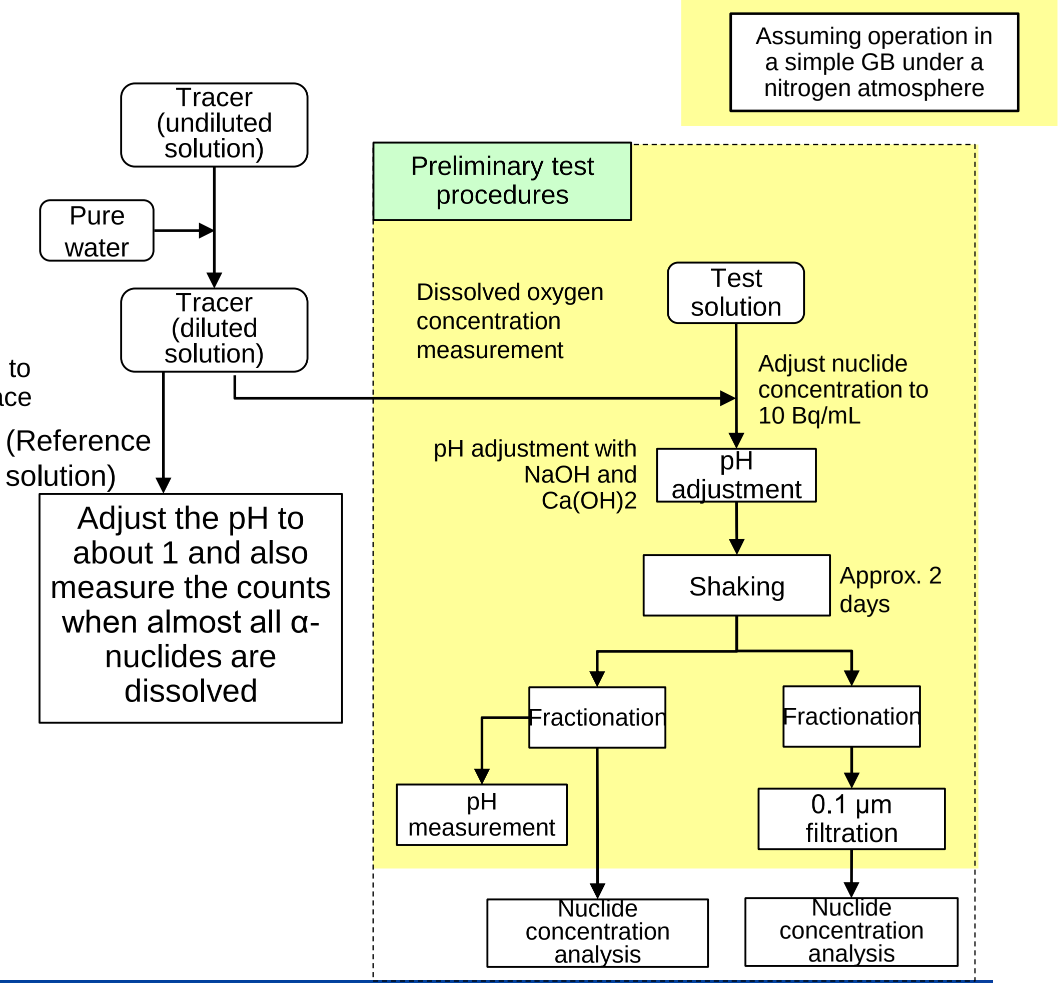


Figure Preliminary test procedures

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Adsorption test procedures

The adsorption test procedures, established based on the preparatory test results, are shown below.

The test procedures are the same as in the previous project, and the test environment was performed under a nitrogen atmosphere.

Assuming operation in a simple GB under a nitrogen atmosphere

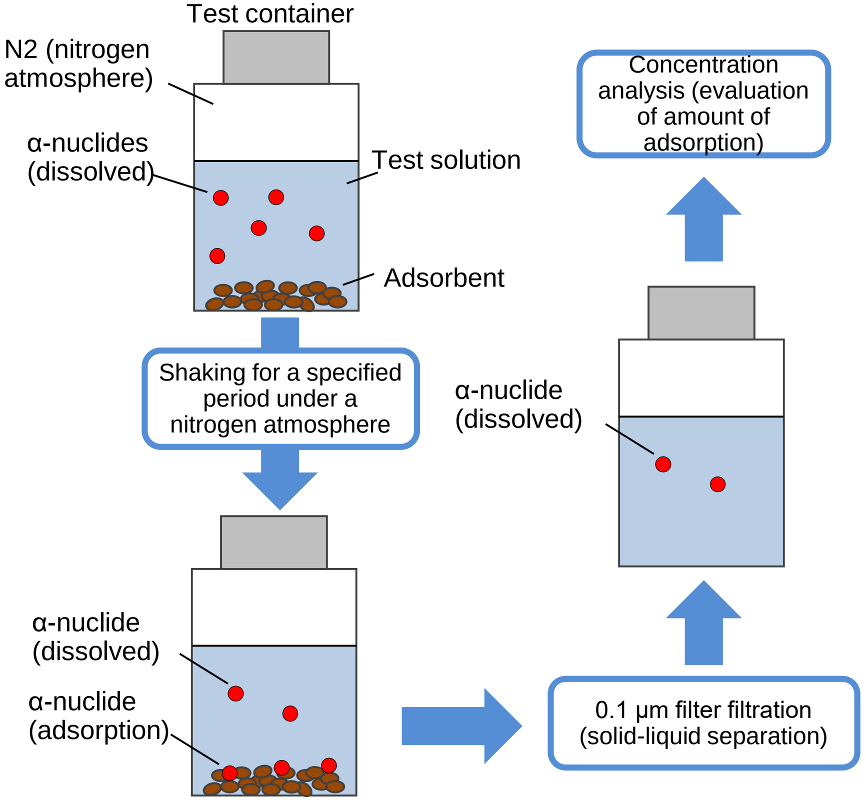


Figure Diagram of adsorption test

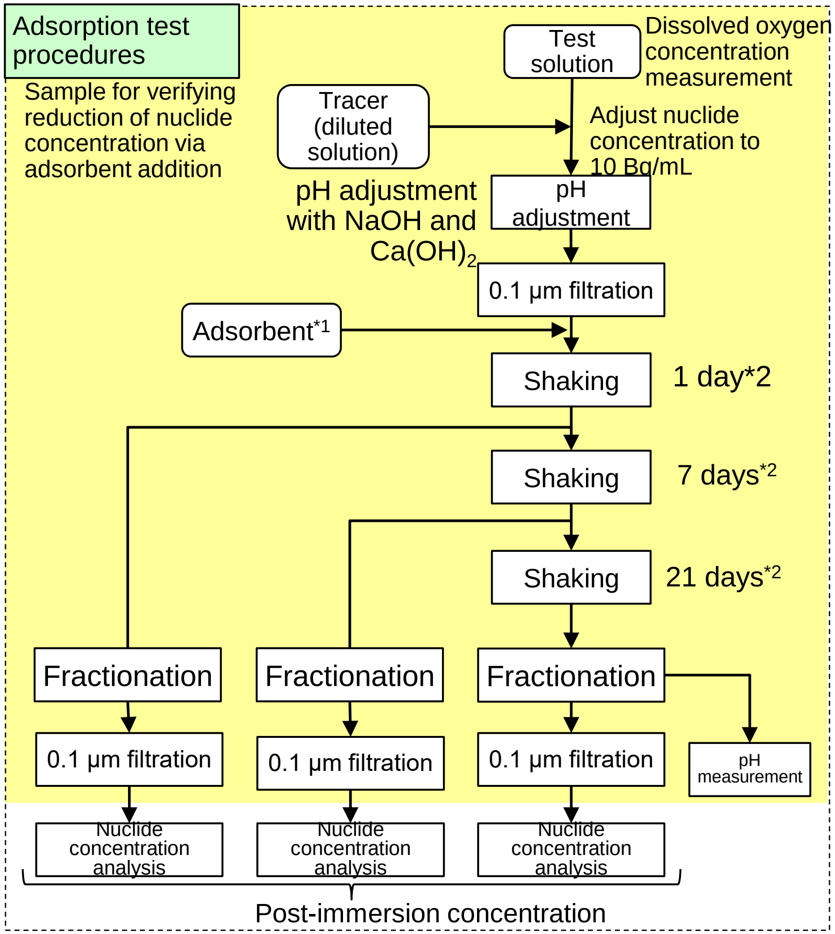


Figure Adsorption test procedures

*1: Some adsorbents are pre-washed to reduce pH fluctuations from addition of adsorbents.

*2: Equilibrium attainment is ensured by setting a 3-pattern shaking period.

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Preliminary test parameters

Considering the PCV gas phase environmental conditions (nitrogen environment) and the alkaline conditions during concrete cutting, the following test conditions were set.

Table Test parameters for preliminary test

No.	Test parameters	Setting requirements	Remarks
1	Nuclide	Am, Cm, Pu, Np, U	Based on the results of exposure assessment at the site boundary, it is highly necessary to remove these particular α-nuclides
2	Nuclide concentration	10 Bq/mL	Particular concentrations that can be handled by the test facility and that allow for analysis of removal rates
3	Gas phase environment	Nitrogen atmosphere	Required conditions given the anticipated gas phase environment inside the PCV during fuel debris retrieval Based on preparatory test results, the atmosphere is controlled using a simple GB with an oxygen concentration of 4% as the reference value
4	Material of test container	PP, PFA	Adsorption tests are conducted under two conditions, containers with a low container adhesion impacts are used PP: Polypropylene, PFA: Fluoropolymer.
5	Water quality conditions	See the table below	

Table Water quality conditions for preliminary test

No.	Water quality conditions	pH	Remarks
1	1000-fold diluted seawater	6 to 7	The policy is to use the results of condition implementation from the previous project, and to utilize as-yet unimplemented conditions.
2	200-fold diluted seawater	6 to 7	
3	1000-fold diluted seawater ＋Ca(OH)2	Approx. 9	- Assumed to be operated near the analysis value of the chloride ion concentration in the stagnant water up to the present (19 ppm) due to the low elution of seawater components - Assuming a rise in pH due to elution of concrete components
4		Approx. 10	
5	200-fold diluted seawater ＋Ca(OH)2	Approx. 9	- Assumed to be operated near the upper control limit (100 ppm) due to high elution of seawater components - Assuming a rise in pH due to elution of concrete components
6		Approx. 10	
7	Sodium pentaborate water (7000 ppm as B)	8 to 9	Conditions for evaluating the impacts of sodium pentaborate injection

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Adsorption test parameters

The proposed adsorption test conditions are shown in the table below. Based on the results of the preliminary tests to be conducted in the future, water quality conditions, adsorbent conditions, and shaking period conditions to be implemented will be selected.

Table Test parameters for adsorption test

No.	Test parameters	Setting requirements	Remarks
1	Nuclide	Am, Cm, Pu, Np, U	Based on the results of exposure assessment at the site boundary, it is highly necessary to remove these particular α-nuclides
2	Nuclide concentration	10 Bq/mL	Particular concentrations that can be handled by the test facility and that allow for analysis of removal rates
3	Gas phase environment	Nitrogen atmosphere	Required conditions given the anticipated gas phase environment inside the PCV during fuel debris retrieval Based on preparatory test results, the atmosphere is controlled using a simple GB with an oxygen concentration of 4% as the reference value
4	Shaking period	1, 7, and 21 days	Evaluation of near-equilibrium state by shaking for 7 and 21 days. Judgment whether the adsorption rate is remarkably low by shaking for a short time.
5	Material of test container	PP or PFA	Based on the preliminary test results, the type of container to be used is selected. PP: Polypropylene, PFA: Fluoropolymer.
6	Adsorbent	see remarks	Adsorbents (attached activated carbon, activated carbon, titanic acid, silicic titanic acid, zirconium phosphate) that have obtained high adsorption performance in the evaluation under atmospheric environmental conditions up to the previous project are targeted.
7	Water quality conditions	See the table below	

Table Water quality conditions for adsorption test*

No.	Water quality conditions	pH	Remarks
1	1000-fold diluted seawater ＋Ca(OH)2	Approx. 9	- Assumed to be operated near the analysis value of the chloride ion concentration in the stagnant water up to the present (19 ppm) due to the low elution of seawater components - Assuming a rise in pH due to elution of concrete components
2		Approx. 10	
3	200-fold diluted seawater ＋Ca(OH)2	Approx. 9	- Assumed to be operated near the upper control limit (100 ppm) due to high elution of seawater components - Assuming a rise in pH due to elution of concrete components
4		Approx. 10	
5	Sodium pentaborate water (7000 ppm as B)	8 to 9	Conditions for evaluating the impacts of sodium pentaborate injection

*Since all conditions cannot be implemented due to restrictions in the test process, the plan is to narrow down the water quality conditions to be implemented based on the preliminary test results.

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Preliminary test progress

- Using Cm, 1000-fold diluted seawater and 200-fold diluted seawater were adjusted to pH 9 and 10 with calcium hydroxide, and shaken for 2 days in two types of containers (PP, PFA).
- Since the counts are reduced by 10 to 30% without filtration, it is estimated that part of Cm adheres to the container.
- In addition, it is estimated that part of the Cm changed into particles from the decrease in the count after 0.1 μm filtration.
- Adhesion to containers and formation of particles were verified, but since Cm exists in a dissolved state to some extent, it was verified that an adsorption test was required. Since there is no big difference in the results between PP and PFA, PP containers will be used in the adsorption test.

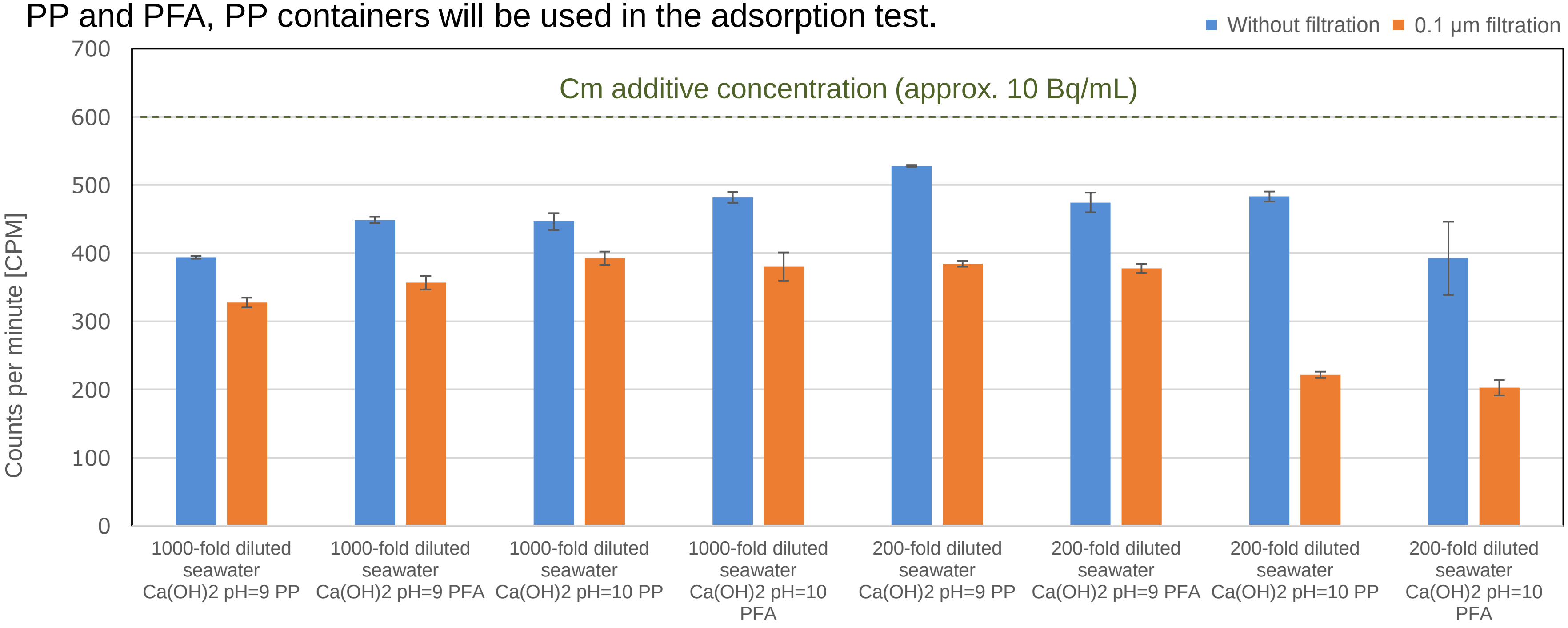


Figure Preliminary test results using Cm

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Preliminary test progress (2)

- Based on 1000-fold diluted seawater and 200-fold diluted seawater, Am was used to prepare solutions adjusted to pH 9 and 10 with calcium hydroxide and B=7000 ppm with sodium pentaborate, and shaken for 2 days.
- The counts were lower than that of the reference solution under the unfiltered conditions of 1000-fold diluted seawater pH 9,10 and 200-fold diluted seawater pH 10, and it is estimated that part of Am adheres to the container. In addition, it is estimated that part of Am changed into particles from the decrease in the count after 0.1 μm filtration.
- Adhesion to containers and formation of particles were verified for some liquids, but since Am exists in a dissolved state to some extent, it was verified that an adsorption test was required.

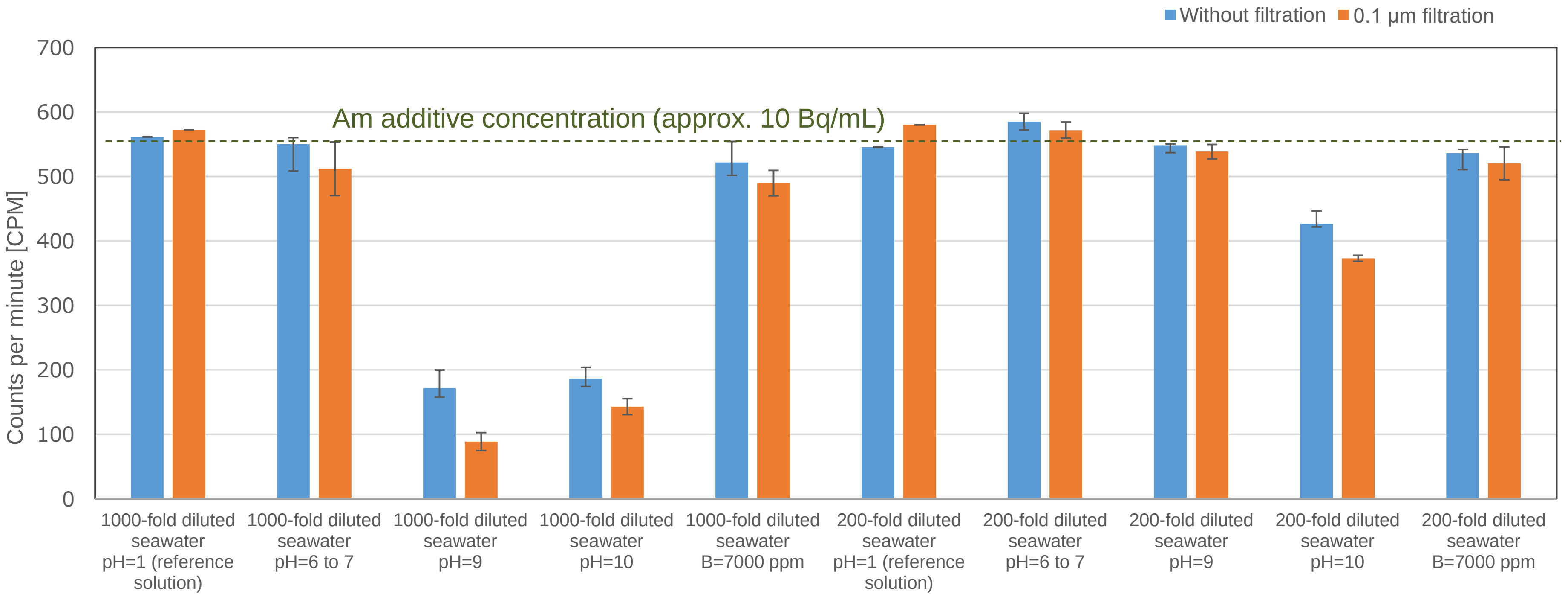


Figure Preliminary test results using Am

7. Implementation details

① Development of soluble α-nuclide removal technology (element test assuming fuel debris retrieval work)

- Summary

[Results for this year]

- ✓ Based on the control policy for the gas phase environment inside the PCV during fuel debris retrieval, a policy was determined to control the oxygen concentration at 4% or less as a simulation of the test environment, and it was verified that is possible to control the atmosphere inside the simple glove box during the preparatory test.
- ✓ Based on the gas-phase atmosphere control policy verified in the preparatory test, the test procedures for the preliminary test and the adsorption test were devised in the simple glove box with nitrogen atmosphere.
- ✓ Some preliminary tests have been started, and Am and Cm exist in a dissolved state to some extent in a nitrogen atmosphere and alkaline conditions (pH 9, 10), so it was verified that there is a high need for nuclide removal and an adsorption test.

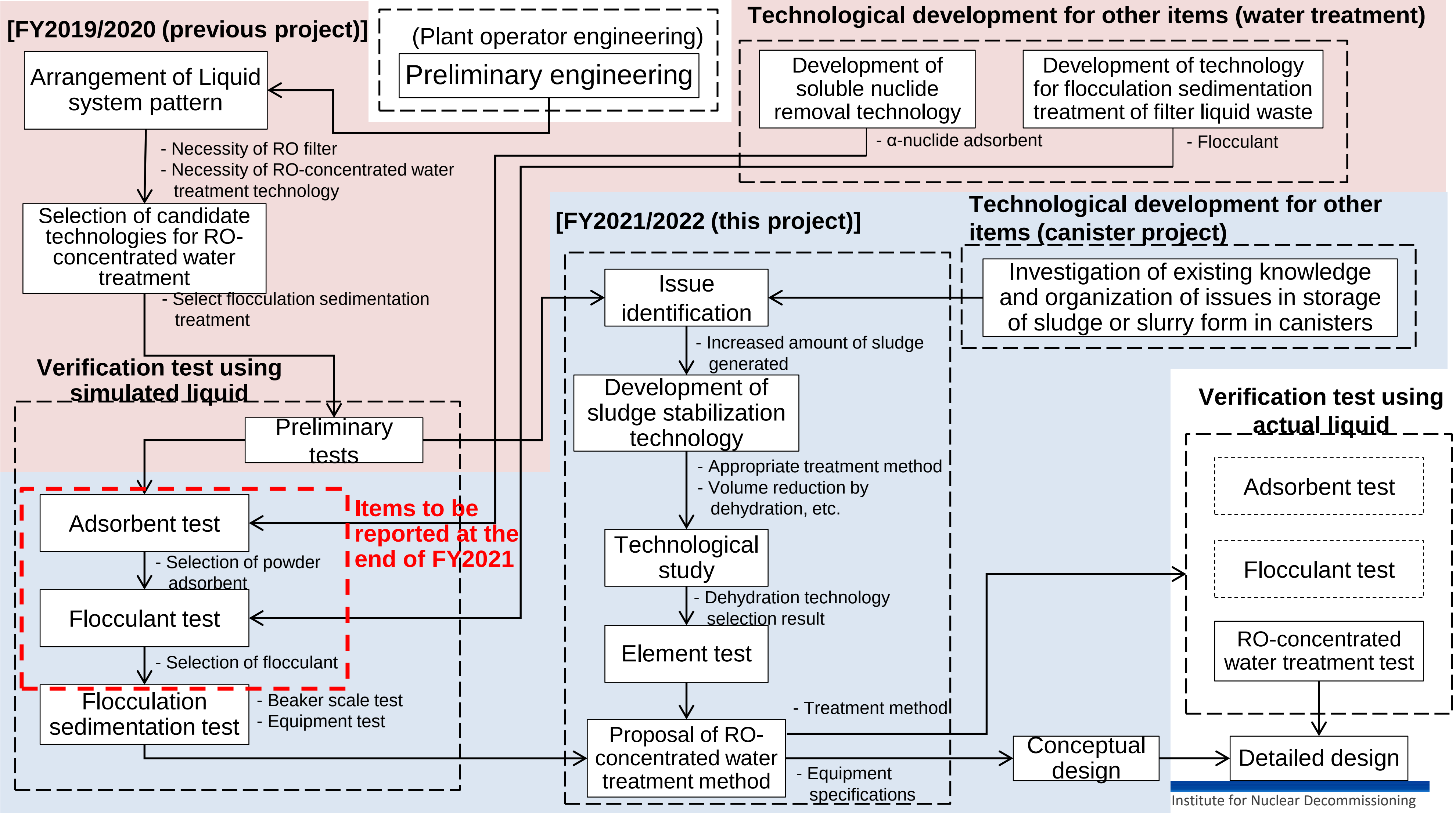
[Future plans]

- ✓ Preliminary tests for Pu, U, and Np will be implemented using the proposed test procedures to verify the behavior of α-nuclides under each water quality condition.
- ✓ Based on the results of the preparatory and preliminary tests, conditions for adsorption tests will be examined.
- ✓ An adsorption test will be conducted to evaluate the adsorption performance of each candidate adsorbent for α-nuclides.
- ✓ Based on the results of the adsorption test, the conceptual system design will be reviewed and a test plan using actual contaminated water will be devised.

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Flowchart of examination



[FY2019/2020 (previous project)]

(Plant operator engineering)

Preliminary engineering

Technological development for other items (water treatment)

Arrangement of Liquid system pattern

- Necessity of RO filter
- Necessity of RO-concentrated water treatment technology

Development of soluble nuclide removal technology

- α-nuclide adsorbent

Development of technology for flocculation sedimentation treatment of filter liquid waste

- Flocculant

Selection of candidate technologies for RO-concentrated water treatment

- Select flocculation sedimentation treatment

[FY2021/2022 (this project)]

Technological development for other items (canister project)

Investigation of existing knowledge and organization of issues in storage of sludge or slurry form in canisters

Verification test using simulated liquid

Preliminary tests

Issue identification

- Increased amount of sludge generated

Development of sludge stabilization technology

- Appropriate treatment method
- Volume reduction by dehydration, etc.

Technological study

- Dehydration technology selection result

Element test

Adsorbent test

- Selection of powder adsorbent

Flocculant test

- Selection of flocculant

Items to be reported at the end of FY2021

Flocculation sedimentation test

- Beaker scale test
- Equipment test

Proposal of RO-concentrated water treatment method

- Treatment method
- Equipment specifications

Verification test using actual liquid

Adsorbent test

Flocculant test

RO-concentrated water treatment test

Conceptual design

Detailed design

7. Implementation details

② Development of RO-concentrated water treatment technology

[Issues]

- As a treatment method for RO-concentrated water generated from RO filters, flocculation sedimentation is being examined, and it is necessary to establish treatment procedures.
- Powder adsorbents and flocculants that can be used for RO- concentrated water treatment have not been selected, and data on their nuclide adsorption performance and flocculation sedimentation performance are insufficient.

[Implementation details]

- Candidates for powder adsorbents and flocculants were selected based on literature research and past results of use in the existing water treatment facility.
- The nuclide removal performance of the powder adsorbent was evaluated by adsorption test.
- A beaker scale flocculation sedimentation test evaluates the flocculant performance of a flocculant on a powder adsorbent.

[Goals]

- Evaluation on the nuclide removal performance of the powder adsorbent and the flocculation sedimentation performance of the flocculant.
- Selection of applicable powder adsorbent and flocculant candidates.
- Development of treatment procedures for RO-concentrated water.

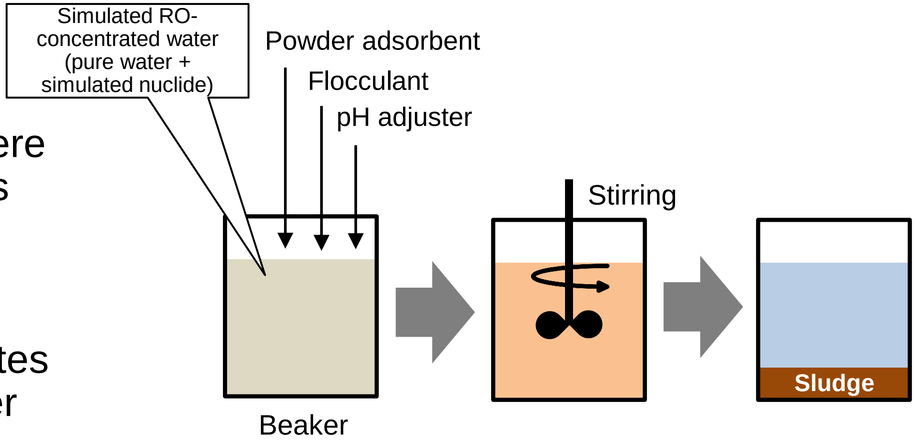


Figure RO-concentrated water treatment element test image

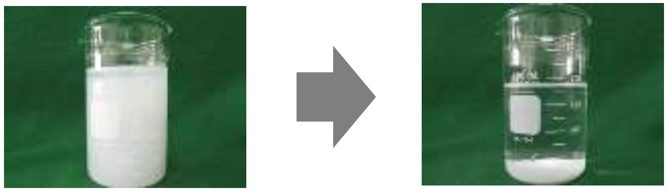

Before flocculation sedimentation treatment
After flocculation sedimentation treatment

Figure RO-concentrated water treatment element test

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ System configuration of sludge collection system

Solid components were collected from liquid waste generated from non-soluble nuclide removal equipment and RO filter equipment.

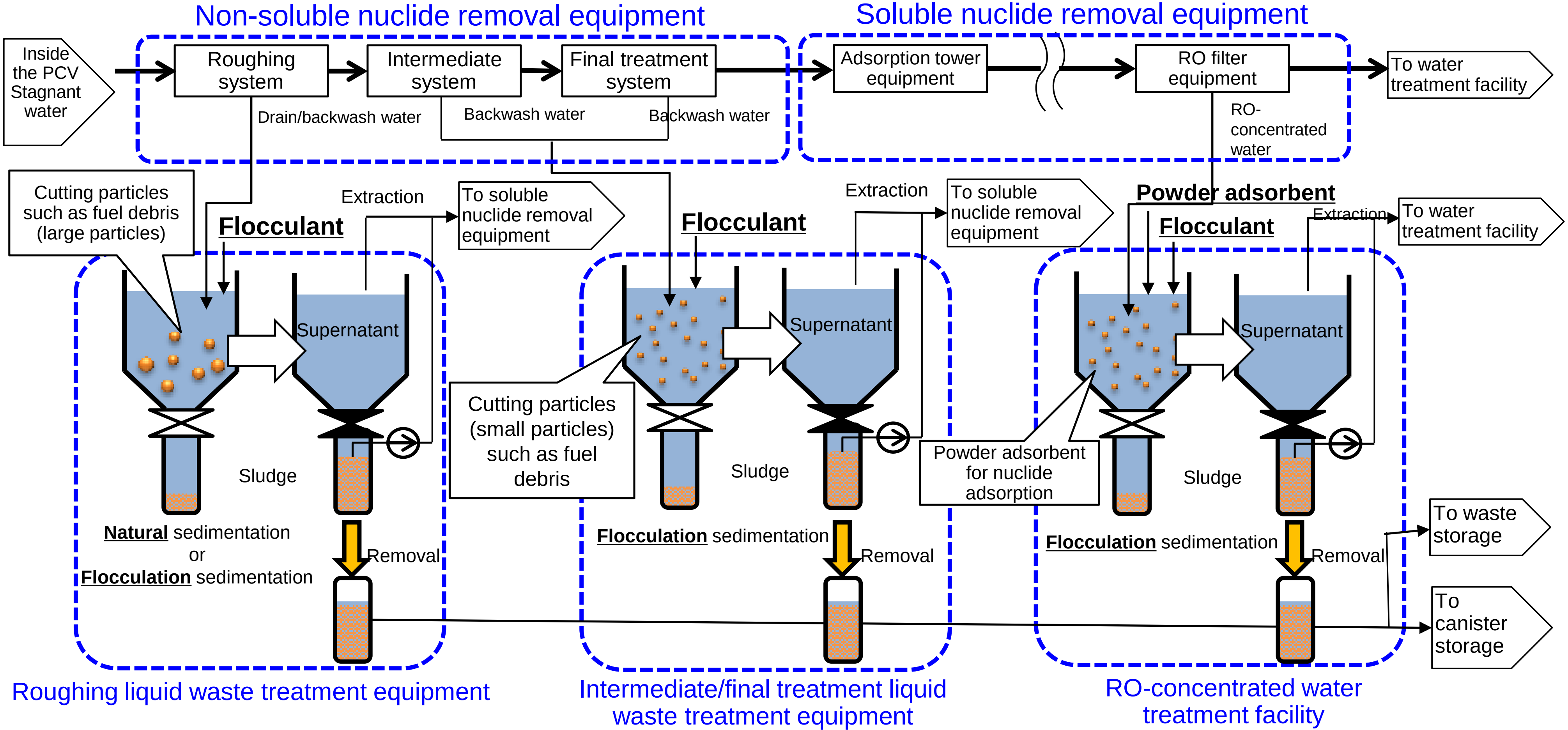


Figure System configuration concept of sludge collection system

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Sludge collection system requirements

The liquid to be treated and treatment requirements for each sedimentation equipment are shown below.

Table System requirements for each sedimentation equipment

*Trial calculation based on the water quality conditions set in the subsidy project

No.	Items	Roughing liquid waste treatment equipment	Intermediate/final treatment liquid waste treatment equipment	RO-concentrated water treatment facility
1	Water to be treated	Drain water and backwash water generated from roughing components	Backwash water generated from intermediate components and final treatment components (It is assumed that the intermediate system will be in bypass operation during fuel debris retrieval work)	RO-concentrated water generated from RO filter equipment
2	Contained particle component (for flocculation sedimentation)	Molten fuel, core structures, concrete components, other solids (Particle size 100 to several tens of μm)	Molten fuel, core structures, concrete components, other solids (Particle size several tens to 0.1 μm)	Powder adsorbent for nuclide adsorption
3	Particle concentration	Thousands to 10000 ppm From filter element test results	Thousands to 10000 ppm From filter element test results	Hundreds to 10000 ppm From adsorbent element test results
4	Treatment flow rate	Intermittent drain: 100 m^3/year Regular drain: 1300 m^3/year From filter element test results	0.1 μm UF filter: 10 m^3/year 0.05 μm UF filter: 100 m^3/year From filter element test results	8 to 11 m^3/day Fuel debris retrieval water Calculated assuming an RO filter concentration ratio of 2 to 3 times at (22 m^3/day)
5	Treatment flow rate requirements	Intermittent drain: 1.0 m^3/day or more Regular drain: 8.2 m^3/day or more Flow rate to enable treatment at 80% equipment availability	0.1 μm UF filter: 0.063 m^3/day or more 0.05 μm UF filter: 0.63 m^3/day or more Flow rate to enable treatment at 80% equipment availability	14 m^3/day or more Flow rate to enable treatment at 80% equipment availability
6	Operating method	Batch treatment Assuming completion of 1 batch treatment in 1 day		

7. Implementation details

② Development of RO-concentrated water treatment technology

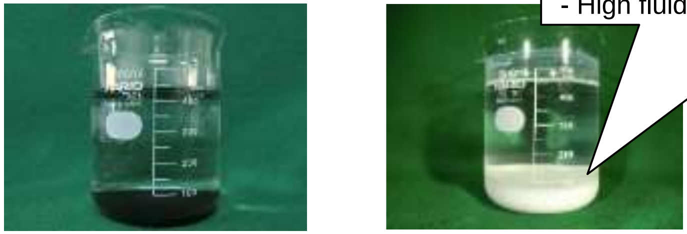
[Issue] A large amount of flocculated sediment (hereinafter referred to as sedimentation sludge) are generated from a sedimentation tank.

Assuming that the sludge collection container is a unit can size (Φ200 x H400 mm), the required number of times of discharging is calculated as shown in the table below

Sedimentation sludge properties
- The amount generated is about 10 to 15 vol% of the initial liquid volume
- The moisture content is about 90%
- High fluidity

Table Number of discharge of sludge collection container

Liquid waste to be treated	Number of collection containers [pieces/day]
Roughing liquid waste	1
Final treatment liquid waste	8
RO-concentrated water	111



RO-concentrated water treatment test
*Magnetite 1000 ppm

Filter liquid waste flocculation sedimentation test
*SiO_2 10000 ppm

Figure Appearance of liquid waste after flocculation sedimentation treatment

- ➢ The amount of sedimentation sludge generated from the sedimentation tank for filter liquid waste treatment is relatively small, and it is estimated that the number of times it is discharged is on the order that can be applied to the actual equipment
- ➢ The amount of sedimentation sludge generated from the sedimentation tank for RO-concentrated water treatment is enormous and needs to be discharged an enormous number of times, so improvement is necessary

Proposed plan

① Selection of adsorbent with higher removal performance
② Examination of optimizing the amount of powder adsorbent to be added
③ Examination of optimizing the amount of flocculant to be added
④ Review of sedimentation treatment procedures and equipment
⑤ Examination of volume reduction treatment of sedimentation sludge by dehydration

① to ④ ⇒ Examine via element tests
⑤ ⇒ Perform element tests after literature research and theoretical study
*Examined in Item ③

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Adsorbent test

[Purpose] Selection of adsorbents applicable to RO-concentrated water treatment

[Implementation details] The adsorption performance of the powder adsorbent was evaluated by an agitated batch test.

<u>Examination of test system</u>

When evaluating the adsorption performance of adsorbents, it is common to conduct an immersion batch test, but since RO-concentrated water is agitated and treated in a sedimentation tank, a test system that simulates the actual equipment was adopted.

<u>Selection of powder adsorbent</u>

The adsorbents used in this test were selected as shown in the table below, referring to the results of literature research, the results of use in the Fukushima Daiichi NPS, and the adsorption rate data obtained in tests up to fiscal 2020. Adsorbents reported to have high removal performance against α-nuclides (Pu, Am, etc.) were selected.

Table Selection results of powder adsorbent*

No.	Adsorbent type	Particle size	Remarks
1	Titanic acid	4.08 μm	There is the use results at the Savannah River Site in the United States (batch treatment)
2	Titanium silicate	8.55 μm	There are the use results in the Fukushima Daiichi NPS
3	Activated carbon	Several μm	There are the use results in the Fukushima Daiichi NPS
4	Hematite	1.32 μm	Iron oxide-based adsorbent. There is a report of high Kd (partition coefficient) for α-nuclides such as Pu.
5	Magnetite	1.96 μm	An iron oxide-based adsorbent similar to hematite.

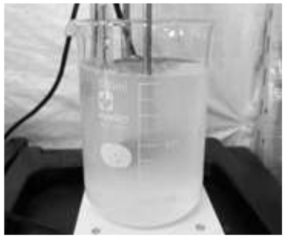


Figure Adsorbent test (titanic acid)

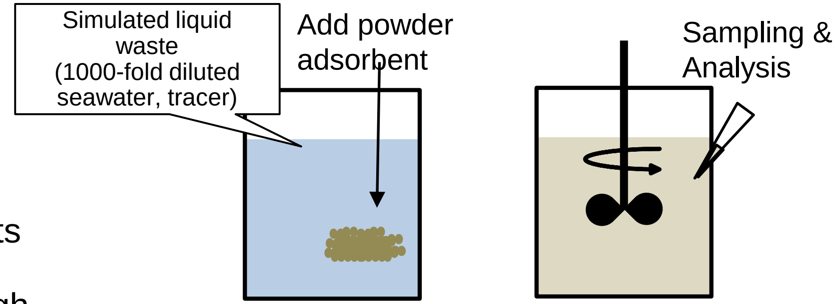


Figure Stirring type adsorption test Image

*Since HOT test is difficult with this test method, all tests are performed as COLD test.
For α-nuclides (Pu, etc.) that are difficult to simulate with a COLD tracer, item ① soluble adsorption rate data is referred.

*Selected from α-nuclide adsorbents
Selected from adsorbents that cannot be formed into granules and are difficult to fill in adsorption towers

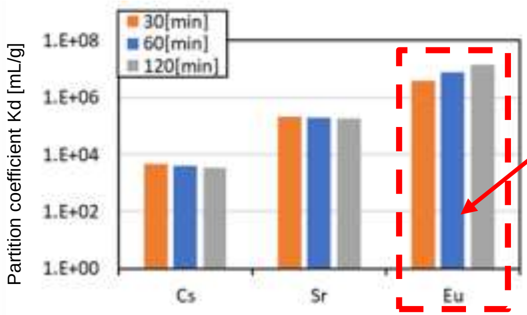
*Particle size of activated carbon not yet measured (to be implemented in the future)

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Adsorbent test results

Test conditions
Test solution: 1000-fold diluted seawater, pH: 7
Tracer: Cs (0.1 ppm), Sr (0.1 ppm), Eu (0.5 ppm)
Adsorbents: right figure (particle size: several tens to several μm)
Concentration of adsorbent added: 20 to 500 ppm
Stirring conditions: 150 rpm × 30, 60, 120 min



Verified decrease in tracer concentration even after 30 minutes under the condition that the amount of adsorbent added was small

However, in almost all test cases, verified that adsorption equilibrium was reached within 30 minutes

Figure Adsorbent test results (titanic acid 20 ppm) Change in partition coefficient over time

Eu removal performance of Kd=1E6 to 7 was verified by titanic acid and titanium silicate.

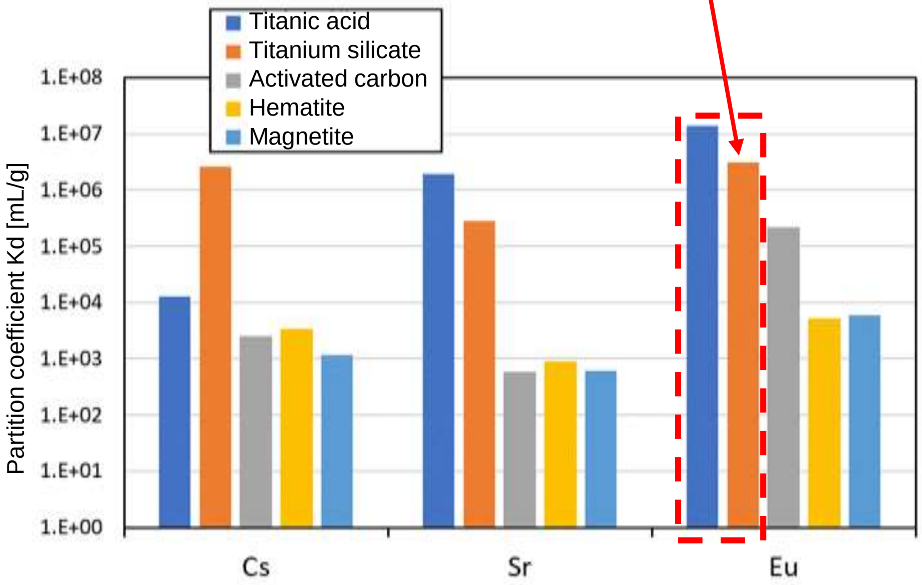


Figure Adsorbent test results: Partition coefficient

Titanic acid has a Kd of about 1E+7 and has the highest Eu removal performance.
Titanium silicate has a Kd of 1E+6 to 7 and has the second highest Eu removal performance after titanic acid.
Activated carbon has a Kd of about 1E+5 to 6, and hematite and magnetite both have a relatively low Kd of about 1E+3 to 4.

In addition, the Kd of titanic acid with respect to Sr and the titanium silicate with respect to Cs and Sr are comparable (compared to the Kd of Eu), and the Kd with respect to Cs and Sr of activated carbon, hematite and magnetite are relatively low.

The adsorption rate is fast and it is assumed that the adsorption equilibrium will be reached within 30 minutes.

7. Implementation details

② Development of RO-concentrated water treatment technology

- **Adsorbent test results**

The additive amount required to satisfy the removal requirement (DF100) was evaluated.

Evaluation of required additive amount of powder adsorbent

No.	Adsorbent	Partition coefficient [mL/g] *1			Additive amount*2	Treatment time *3
		Cs	Sr	Eu (Am)		
1	Titanic acid	1.3.E+04	1.9.E+06	1.4.E+07	<50 ppm	<30 min
2	Titanium silicate	2.6.E+06	2.8.E+05	3.2.E+06	50ppm	
3	Activated carbon	2.5.E+03	5.8.E+02	2.2.E+05	200 ppm<	
4	Hematite	3.5.E+03	9.1.E+02	5.2.E+03	1000 ppm<	
5	Magnetite	1.1.E+03	6.0.E+02	5.9.E+03	1000 ppm<	

*1 Results with relatively high removal performance are shown in red. No.3 is a relatively high result, but is inferior to No.1 and 2, so it is shown in light red.

*2 In this test, the tracer concentration was set to be higher than the actual water quality, so it is possible that the amount of adsorbent added can be reduced for liquid waste with lower concentration. It is necessary to evaluate the adsorption isotherm separately and evaluate the partition coefficient in each concentration region.

*3 If the solution can be uniformly agitated, the treatment time is assumed to be short (approximately 30 min) because the adsorption rate in the initial stage is fast.

Titanic acid (No. 1) and titanium silicate (No. 2) have high removal performance against Eu, and the required additive amount was evaluated as several tens of ppm.
Since it is possible to reduce it from the 1000 ppm that was assumed in the past, it is thought that the amount of sludge generated can be reduced accordingly.

It was verified that the iron oxide-based (No. 4, 5) have a relatively low Eu removal rate.
→ Compared to titanic acid, etc., the amount to be added must be increased (several thousand ppm or more).

Since the removal rate for Cs and Sr is low, it is possible to selectively remove only α-nuclides

When selectively removing only α-nuclides → Select activated carbon (magnetite)
When removing total activity including α-nuclides → Select titanic acid and titanium silicate

7. Implementation details

② Development of RO-concentrated water treatment technology

- **Adsorbent selection policy**

  In addition to the removal performance of α-nuclides, the removal performance of Cs and Sr is considered to select the adsorbent.

Liquid system configuration plan 1

The liquid system shall be a system capable of selectively removing only α-nuclides and not removing Cs and Sr as much as possible

- The α-activity concentration shall be reduced to a level that can be discharged to the existing water treatment facility
- β and γ nuclides such as Cs and Sr are removed by the existing water treatment facility
- If only α-nuclides are sludged and captured, the dose of sludge can be kept low
- The shielding function required for sedimentation equipment and sedimentation sludge treatment equipment can be kept low, contributing to the reduction of worker exposure

Candidate powder adsorbents: activated carbon, (titanic acid, magnetite)

Adsorbents with high removal rate of α-nuclide (Eu) and low removal rate of Cs and Sr are selected
Considering the Eu removal rate, there is a concern that the additive amount must be increased (several hundred ppm)
→The amount of sludge generated increases

Even when retrieving fuel debris, if the Cs and Sr concentrations are at a level that can be treated with the existing water treatment facility, the only activity that needs to be reduced in the liquid system is α-nuclides. If a powder adsorbent capable of adsorbing and removing Cs and Sr is used for RO-concentrated water treatment, a strong shielding function will be required for the equipment itself, leading to an increase in the scale of the equipment. For the above reasons, it is assumed that it is necessary to select a powder adsorbent capable of selectively removing only α-nuclides. As the powder adsorbent for selective removal of α-nuclides, select a powder adsorbent that has high Eu removal performance and low adsorption performance for Cs and Sr.

7. Implementation details

② Development of RO-concentrated water treatment technology

- **Adsorbent selection policy**

  In addition to the removal performance of α-nuclides, the removal performance of Cs and Sr are considered to select the adsorbent

Liquid system configuration plan 2

The liquid system shall be a system capable of reducing the concentration of total activity, including α-activity

- The total activity concentration including α-activity concentration shall be reduced to a level that can be discharged to the existing water treatment facility
- Since Cs and Sr, which are dominant as activity, are also sludged and captured, the dose of the sedimentation sludge will be high
- From the viewpoint of worker exposure prevention, the level of shielding function required for sedimentation equipment and sedimentation sludge treatment equipment will increase

Candidate powder adsorbents: Titanic acid *, titanium silicate

*Titanic acid has a low Cs removal rate

Adsorbents with high removal rates for α-nuclides (Eu), Cs, and Sr are selected
Due to the high Eu removal rate, the additive amount is evaluated to be relatively small (<several tens of ppm)

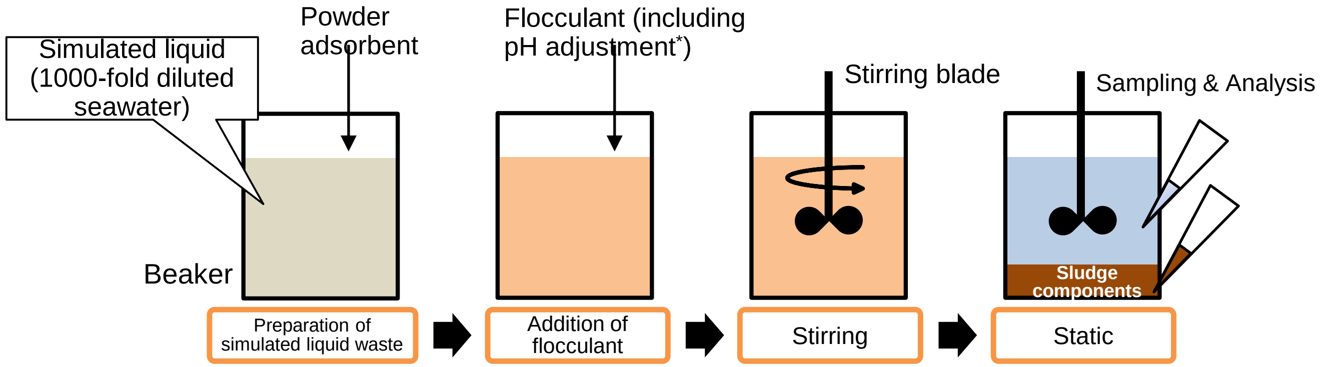
If the total activity concentration is set as a system requirement for being discharged to the existing water treatment facility, it will be necessary to reduce the concentrations of Cs and Sr, which are assumed to be predominantly radioactive, in addition to α-nuclides. Therefore, it is assumed that it is necessary to select a powder adsorbent that can reduce the total activity. As a powder adsorbent for total activity removal, select a powder adsorbent with high removal performance for all of Cs, Sr, and Eu.

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Flocculant test

[Purpose] Selection of flocculants applicable to RO-concentrated water treatment
[Implementation details] Flocculation sedimentation treatment for the simulated liquid to which the powder adsorbent is added was performed.



Preparation of simulated liquid waste ➡ Addition of flocculant ➡ Stirring ➡ Static

Figure Flocculant test Image

Figure Flocculant test Appearance of equipment

*The tracer removal rate is not evaluated because the main item to be verified is whether the powder adsorbent flocculates and settles. Therefore, no tracer is added.

*All of the flocculants selected this time are acidic reagents, and it is necessary to adjust to the neutral region after addition, so sodium hydroxide solution is used.

<u>Examination of test system</u>

A stirring jar test similar to the adsorbent test is adopted.
It simulates a scaled-down system of treatment in an actual flocculation sedimentation tank.

<u>Selection of flocculant</u>

Flocculant was selected as shown in the table on the right based on the results of the literature research and the results of FY2020 test.
In addition to the flocculation sedimentation performance, redundancy with respect to the ionic strength of liquid waste was also considered.

Table Results of flocculant selection

No.	Flocculant	Remarks
1	High base PAC	There are reports of high treatment performance for liquid waste with low ionic strength
2	Sulfuric acid Aluminum	Preliminary project test verifies high treatment performance for liquid waste containing boric acid

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Flocculant test results

The amount of sedimentation sludge generated after the flocculation sedimentation treatment was less dependent on the type of flocculant, and largely dependent on the type of powder adsorbent.

Amount of sedimentation sludge generated

Conventionally, when the amount of powder adsorbent added was 1000 ppm, the amount of sludge generated was assumed to be about 10 vol%

Titanic acid, activated carbon, magnetite → All results were found in 0.2 to 0.3 vol%.

Titanium silicate, hematite →The results of order of several vol% were frequently found(varies depending on test conditions).

Table Flocculant test conditions (adsorbent/flocculant)

Powder adsorbent*1		Flocculant*2			
Types	Concentration [ppm]	Types	Concentration [ppm]	Types	Concentration [ppm]
Titanic acid	50	High base PAC	100	Aluminum sulfate	20
Titanium silicate	50		1000		200
Activated carbon	200		1000		50
Hematite	500		1000		1000
Magnetite	500		1000		50

*1 Conditions set based on adsorbent test results

*2 Conditions set based on the preparatory test

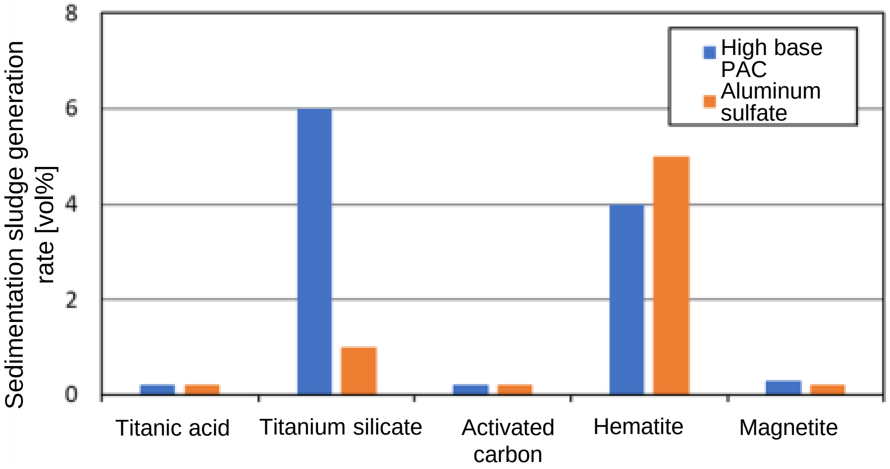


Figure Flocculant test results Sedimentation sludge volume

There was no significant difference between high-base PAC and aluminum sulfate in terms of the amount of sedimentation sludge generated.

7. Implementation details

② Development of RO-concentrated water treatment technology

Flocculant test results

- A large percentage of particles settle within 10 minutes after flocculation sedimentation treatment
- It was evaluated that it is possible to reduce the SS concentration to about 10 ppm by adding a flocculant.
- It was difficult to reduce the SS concentration to 1 ppm or less without depending on the amount of powder adsorbent added.

  *Because the turbidity measurement results were converted to SS concentration, there is a possibility that the region of 10 ppm or less could not be evaluated appropriately

- It was verified that the less the SS components, the narrower the adjustment range of the flocculant concentration.

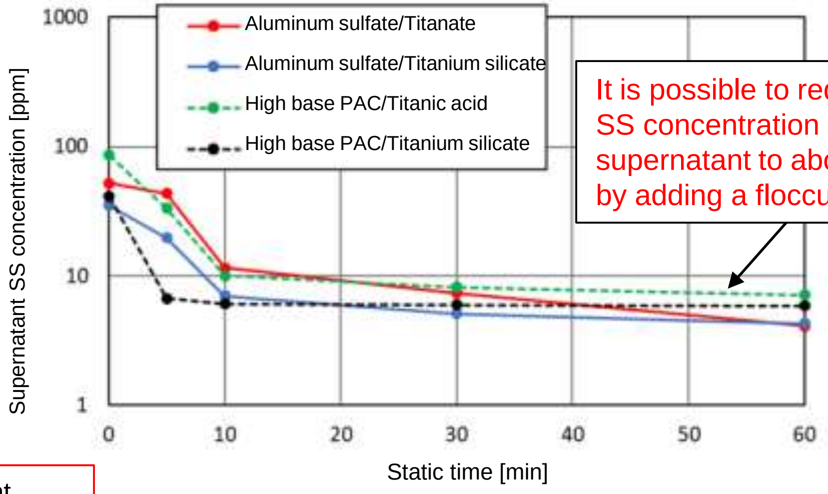
→ It will be difficult to adjust the amount of flocculant added in actual equipment operation.

Table Flocculant test conditions (adsorbent/flocculant)

Powder adsorbent*[1]		Flocculant*[2]			
Types	Concentration [ppm]	Types	Concentration [ppm]	Types	Concentration [ppm]
Titanic acid	50	High base PAC	100	Aluminum sulfate	20
Titanium silicate	50		1000		200
Activated carbon	200		1000		50
Hematite	500		1000		1000
Magnetite	500		1000		50

*1 Conditions set based on adsorbent test results
*2 Conditions set based on the preparatory test

The figure on the right shows the transition of SS concentration



It is possible to reduce the SS concentration of the supernatant to about 10 ppm by adding a flocculant

Figure Flocculant test results Transition of SS concentration (titanic acid, titanium silicate)

No difference was observed in sedimentation behavior of particles between high base PAC and aluminum sulfate. Aluminum sulfate was selected as the flocculant because it was verified to have high flocculation and sedimentation properties in the previous project, even when water quality fluctuated due to boric acid solution conditions.

7. Implementation details

② Development of RO-concentrated water treatment technology

➢ Examination on the discharge of supernatant to the existing water treatment facility

Acceptance requirements for the existing water treatment facility were examined mainly based on the past results of accepting stagnant water in the process main building (PMB).

*Primarily set based on the past results of accepting PMB stagnant water in FY2018.
Acceptance requirements for the existing water treatment facility during the fuel debris retrieval work is an issue for future study

Table Tentative set values for acceptance requirements for the existing water treatment facility*

Items	Set value	Test results	Remarks
Cl	<700 ppm	<17 ppm	It is assumed that if the concentration of each ion in the circulating cooling water is below the assumed water quality conditions, the concentration in the supernatant water will not exceed this item. However, regarding the Cl concentration, it is necessary to examine the possibility of treating high Cl concentration stagnant water such as torus room water.
Ca	<50 ppm	-	
Mg	<30 ppm	-	
SO_4	-	Scheduled to acquire data	When aluminum sulfate is used, most of the sulfate ions remain in the supernatant.
pH	7 to 8.5	6.7 to 7.2	In the process of flocculation sedimentation treatment, the pH of the supernatant is adjusted to about pH 7, so it is assumed that this item will be satisfied.
SS concentration	<20 ppm	<10 ppm	Since it is assumed that the SS concentration can be reduced to about 10 ppm or less by flocculation sedimentation treatment, the SS concentration reference is assumed to satisfy the acceptance requirements. However, since the particles remaining in the supernatant have a high amount of activity, it is necessary to separately evaluate whether they meet the requirements for acceptance based on the activity concentration.
Total α concentration	<7.4E+0 Bq/L	99% removal rate against initial concentration (after 0.45 μm filtration)	Set from the maximum α concentration of the inlet water of the existing water treatment facility. Issues for future study. It is assumed that it can be evaluated from the total α concentration of the input water and the removal performance and additive amount of the powder adsorbent. Evaluation is also necessary from the viewpoint of public exposure dose (DF100) and announcement density.

It is estimated that the supernatant water after the flocculation sedimentation treatment can be discharged to the existing water treatment facility, considering the assumed treatment results of the existing water treatment facility. However, removal of residual particles in the supernatant water, such as by filtration, may be necessary.

7. Implementation details

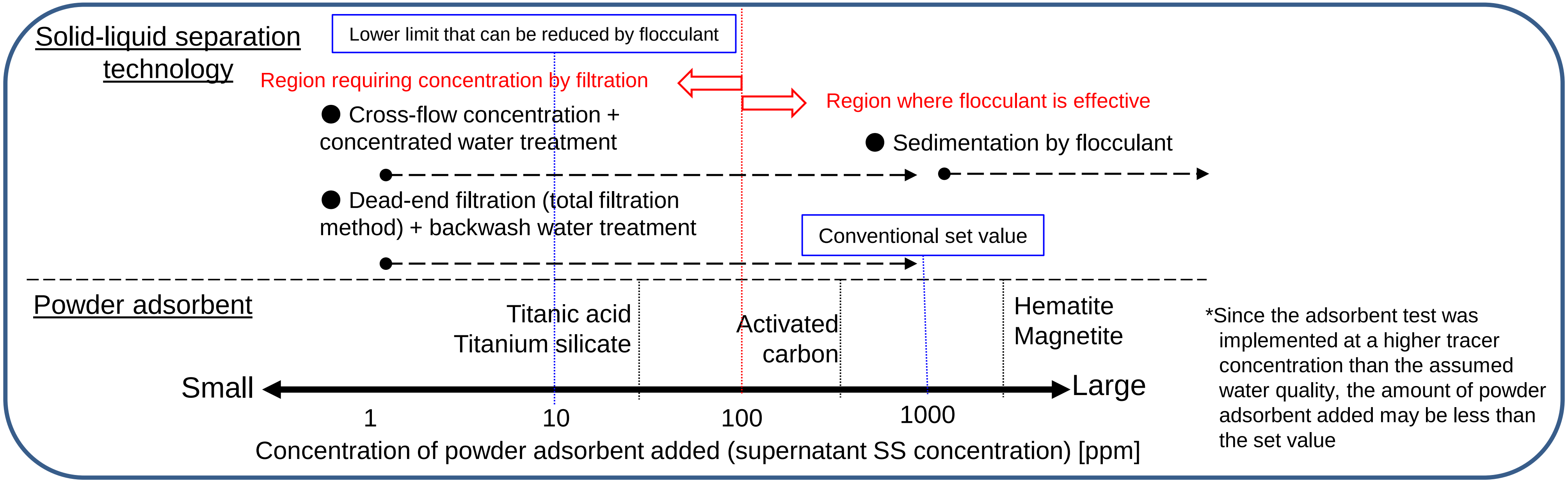
② Development of RO-concentrated water treatment technology

➢ Examination of solid-liquid separation of powder adsorbent when the amount added is small

It was suggested that the amount of powder adsorbent added could be reduced from the conventional set value (1000 ppm). Since flocculants are not applicable to the treatment of liquid waste with a small amount of SS, a system that concentrates the SS components as a pretreatment was examined.

Concentration of powder adsorbent added	Solid-liquid separation technology
Thousands to hundreds of ppm	→ Solid-liquid separation by flocculant is effective
Hundreds to several tens of ppm	→ Solid-liquid separation by flocculant (concentration treatment if necessary)
Several tens of ppm or less	→ Concentration treatment + flocculant

*It is assumed that cross-flow filtration and dead-end filtration are effective for concentration treatment



Solid-liquid separation technology

Lower limit that can be reduced by flocculant

Region requiring concentration by filtration

Region where flocculant is effective

● Cross-flow concentration + concentrated water treatment

● Sedimentation by flocculant

● Dead-end filtration (total filtration method) + backwash water treatment

Conventional set value

Powder adsorbent

Concentration of powder adsorbent added (supernatant SS concentration) [ppm]

*Since the adsorbent test was implemented at a higher tracer concentration than the assumed water quality, the amount of powder adsorbent added may be less than the set value

By concentrating the SS components through concentration treatment, solid-liquid separation using a flocculant is possible while reducing the amount of liquid waste

7. Implementation details

② Development of RO-concentrated water treatment technology

- **Examination of solid-liquid separation of powder adsorbent when the amount added is small**

Application of concentration treatment to RO-concentrated water treatment

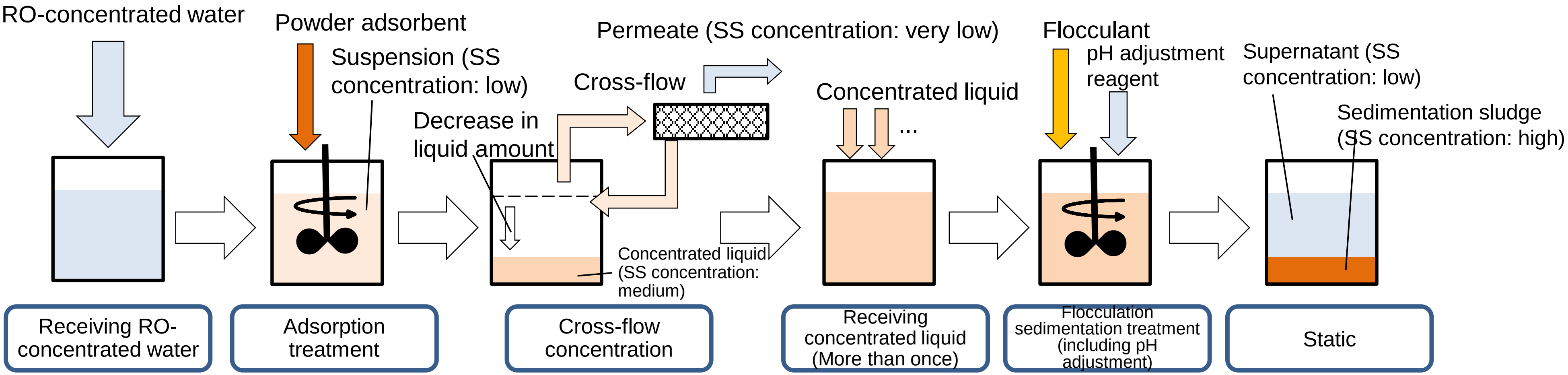


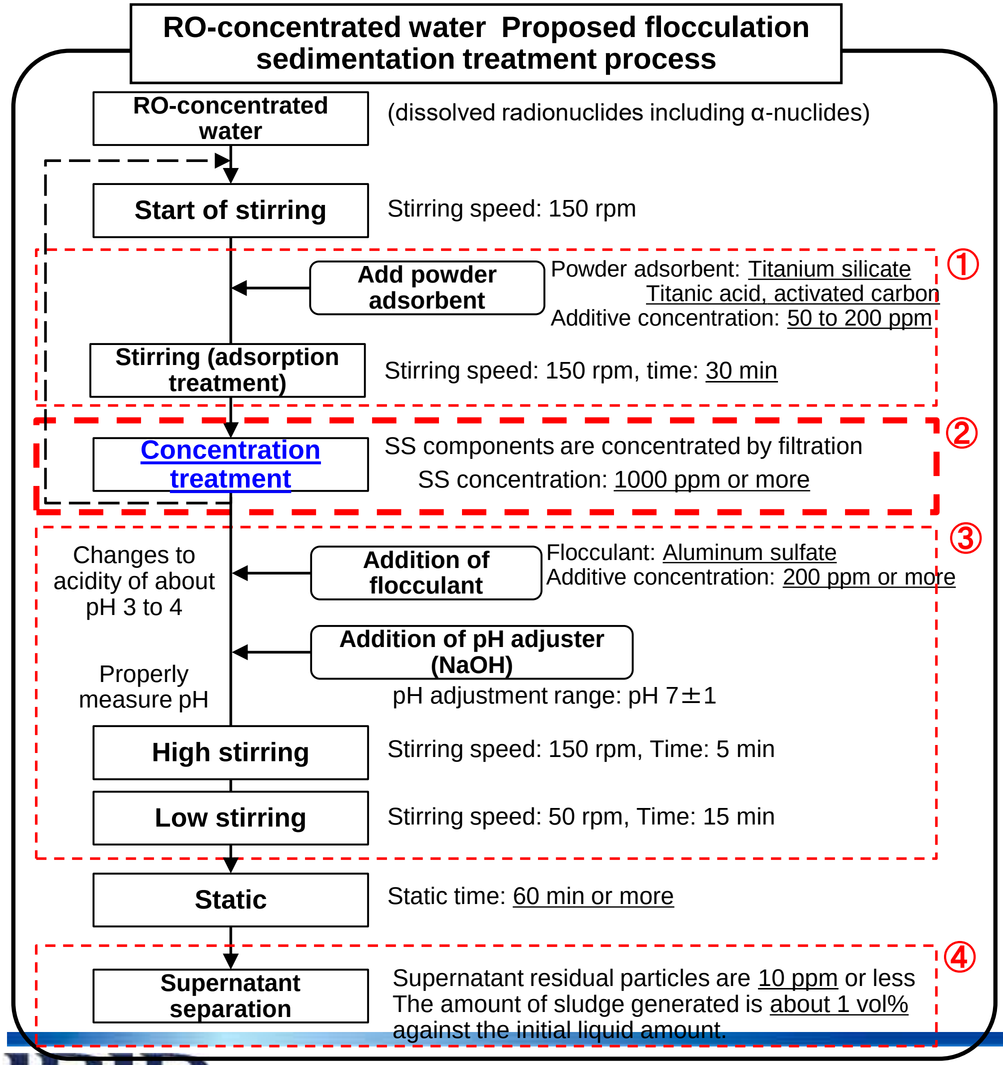
Figure Proposed procedures for RO-concentrated water treatment method when cross-flow concentration is applied

If the concentration of powder adsorbent added is low (dozens of ppm or less), cross-flow filtration is performed after adsorption treatment to separate moisture to reduce the liquid amount and concentrate SS components (approx. 1000 ppm or more).
After that, the concentrated liquid is subjected to flocculation sedimentation treatment to separate into supernatant and sedimentation sludge.
In addition, since the liquid amount is reduced by the concentration treatment, it can be assumed that the concentrated liquid for multiple times can be subjected to the flocculation sedimentation treatment at once. Therefore, the concentrated liquid is discharged into a tank for flocculation sedimentation treatment, and the treatment is performed after securing a certain amount of liquid.

Mass balance (water volume, sludge volume) in the system using each concentration treatment will be evaluated in the future.

7. Implementation details

② Development of RO-concentrated water treatment technology



RO-concentrated water Proposed flocculation sedimentation treatment process

RO-concentrated water (dissolved radionuclides including α-nuclides)

Start of stirring Stirring speed: 150 rpm

①

Add powder adsorbent Powder adsorbent: Titanium silicate, Titanic acid, activated carbon
Additive concentration: 50 to 200 ppm

Stirring (adsorption treatment) Stirring speed: 150 rpm, time: 30 min

②

Concentration treatment SS components are concentrated by filtration
SS concentration: 1000 ppm or more

③

Changes to acidity of about pH 3 to 4

Addition of flocculant Flocculant: Aluminum sulfate
Additive concentration: 200 ppm or more

Properly measure pH

Addition of pH adjuster (NaOH) pH adjustment range: pH 7±1

High stirring Stirring speed: 150 rpm, Time: 5 min

Low stirring Stirring speed: 50 rpm, Time: 15 min

Static Static time: 60 min or more

④

Supernatant separation Supernatant residual particles are 10 ppm or less
The amount of sludge generated is about 1 vol% against the initial liquid amount.

(1) Adsorption treatment
Soluble nuclides are adsorbed by adding a powder adsorbent and stirring for a certain period of time.

(2) **Concentration treatment** (adding reflecting the examination results)
Powder adsorbents are concentrated, such as by cross-flow filtration or dead-end filtration.
* Receiving RO-concentrated water → ① → ② are repeated to secure a certain amount of concentrated liquid.

(3) Flocculation sedimentation treatment
A flocculant is added to the concentrated liquid, adjusted to a neutral region with a pH adjusting reagent, and agitated for a certain period of time to cause flocculation and sedimentation of the powder adsorbent. (RO-concentrated water sedimentation sludge generation)

(4) Discharge of supernatant and sedimentation sludge
Supernatant: Filtration to remove residual particles after extraction.
Sedimentation sludge: Extracted by pump or discharged in a collection container.

The volume reduction of sedimentation sludge by applying dehydration treatment will be examined in the development item 3 "Development of secondary waste treatment technology."

7. Implementation details

② Development of RO-concentrated water treatment technology

- Summary

[Results for this year]

- ✓ Adsorbent tests were implemented, and powder adsorbents with high removal performance against α-nuclides were selected. Activated carbon was evaluated as highly applicable for selective removal of α-nuclides, and titanic acid and titanium silicate were evaluated as highly applicable for removing total activity including α-nuclides.
- ✓ A flocculant test was implemented, and aluminum sulfate was selected as a flocculant for flocculation and sedimentation of the powder adsorbent. In addition, data on the supernatant and the amount of sedimentation sludge generated and its properties were obtained.
- ✓ The water quality conditions under which solid-liquid separation by flocculant is effective were organized. As a treatment method for low SS concentration liquid waste, which is difficult to separate solid-liquid using flocculant, a system applying concentration treatment was devised.
- ✓ Based on the results of this fiscal year, treatment procedures for RO-concentrated water were devised.

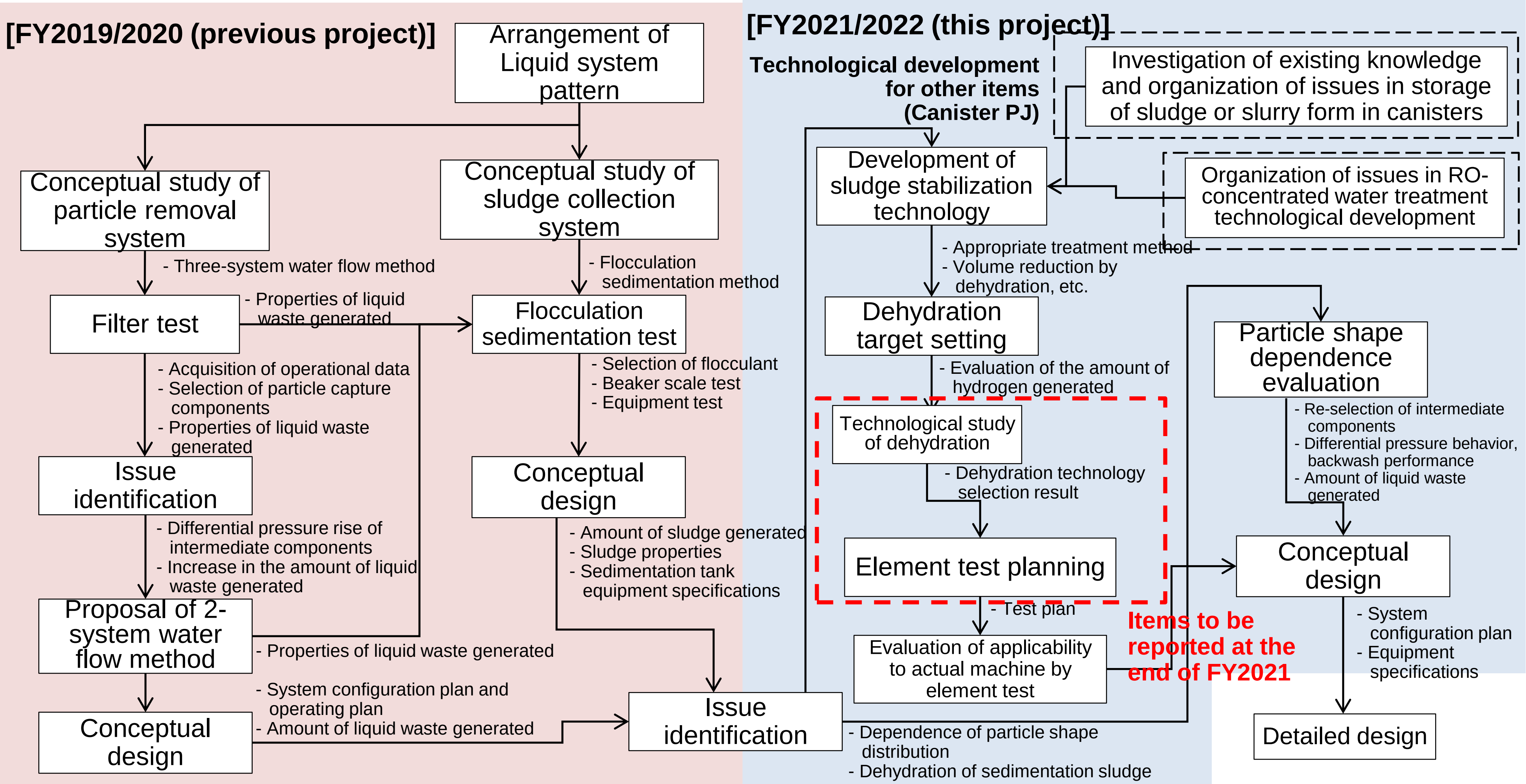
[Future plans]

- ✓ Beaker-scale RO-concentrated water treatment tests and equipment tests will be implemented to obtain test data.
- ✓ Based on the results of each test, a method for treating RO concentrated water will be devised, and a conceptual system design for the system will be implemented.

7. Implementation details

③ Development of secondary waste treatment technology

- Flowchart of examination



[FY2019/2020 (previous project)]

Arrangement of Liquid system pattern

Conceptual study of particle removal system

- Three-system water flow method

Filter test

- Properties of liquid waste generated

- Acquisition of operational data
- Selection of particle capture components
- Properties of liquid waste generated

Issue identification

- Differential pressure rise of intermediate components
- Increase in the amount of liquid waste generated

Proposal of 2-system water flow method

- Properties of liquid waste generated

- System configuration plan and operating plan
- Amount of liquid waste generated

Conceptual design

Conceptual study of sludge collection system

- Flocculation sedimentation method

Flocculation sedimentation test

- Selection of flocculant
- Beaker scale test
- Equipment test

Conceptual design

- Amount of sludge generated
- Sludge properties
- Sedimentation tank equipment specifications

Issue identification

- Dependence of particle shape distribution
- Dehydration of sedimentation sludge

[FY2021/2022 (this project)]

Technological development for other items (Canister PJ)

Investigation of existing knowledge and organization of issues in storage of sludge or slurry form in canisters

Organization of issues in RO-concentrated water treatment technological development

Development of sludge stabilization technology

- Appropriate treatment method
- Volume reduction by dehydration, etc.

Dehydration target setting

- Evaluation of the amount of hydrogen generated

Technological study of dehydration

- Dehydration technology selection result

Element test planning

- Test plan

Evaluation of applicability to actual machine by element test

Items to be reported at the end of FY2021

Particle shape dependence evaluation

- Re-selection of intermediate components
- Differential pressure behavior, backwash performance
- Amount of liquid waste generated

Conceptual design

- System configuration plan
- Equipment specifications

Detailed design

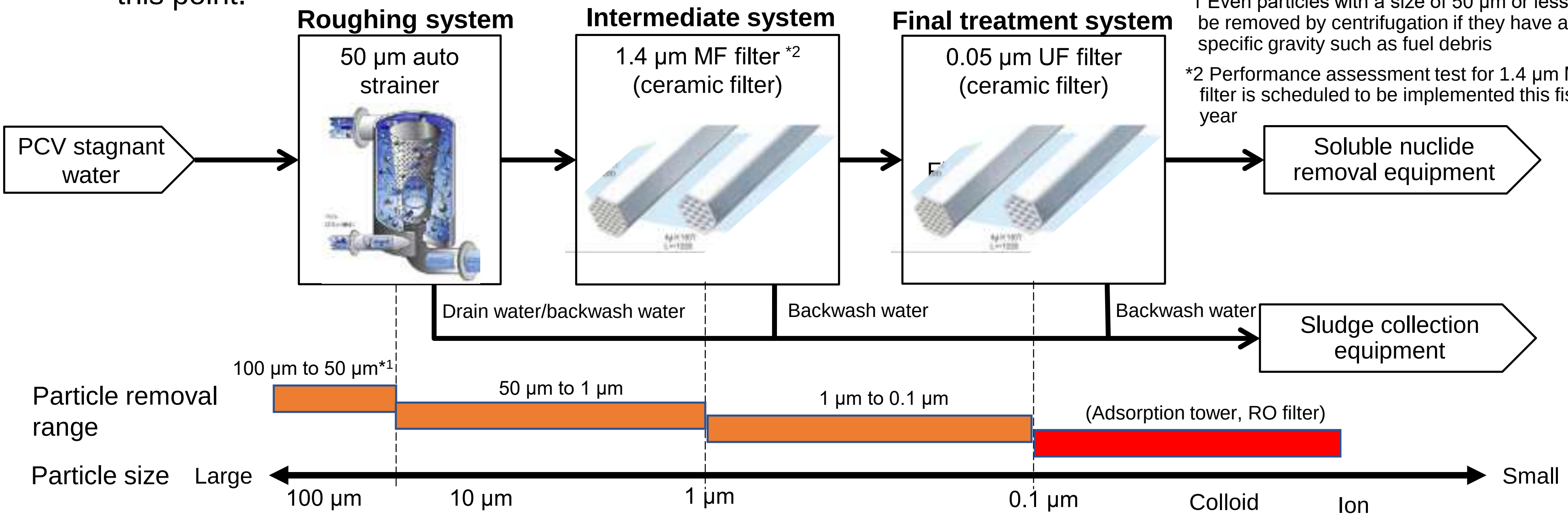
7. Implementation details

③ Development of secondary waste treatment technology

1) Characterization of liquid waste generated from particle removal system

- **System configuration of particle removal system**

The system configuration of particle removal system was examined based on the results of development up to this point.



PCV stagnant water

Roughing system

50 μm auto strainer

Intermediate system

1.4 μm MF filter [*2] (ceramic filter)

Final treatment system

0.05 μm UF filter (ceramic filter)

Soluble nuclide removal equipment

Drain water/backwash water

Backwash water

Backwash water

Sludge collection equipment

Particle removal range

100 μm to 50 μm[*1]

50 μm to 1 μm

1 μm to 0.1 μm

(Adsorption tower, RO filter)

Particle size Large 100 μm 10 μm 1 μm 0.1 μm Colloid Ion Small

[*1] Even particles with a size of 50 μm or less can be removed by centrifugation if they have a large specific gravity such as fuel debris

[*2] Performance assessment test for 1.4 μm MF filter is scheduled to be implemented this fiscal year

Figure Conceptual diagram of the particle removal equipment system configuration

It is assumed that the fuel debris processing work performed in the PCV will atomize the processed matter, and particles of approximately 100 μm or less will float in the liquid and migrate to the liquid system.
Particles of 50 μm or larger are removed by the auto strainer in the roughing system. Particles with a high specific gravity (e.g., fuel debris, core structures) are also removed, where their centrifugal separation effect is significant. Small particles that have passed through the roughing system are removed by the MF and UF filters in the intermediate and final treatment systems, with the entire system removing particles down to 0.1 μm.
Captured particles are discharged by drain/backwash, and the liquid waste is treated in the sludge collection equipment.

7. Implementation details

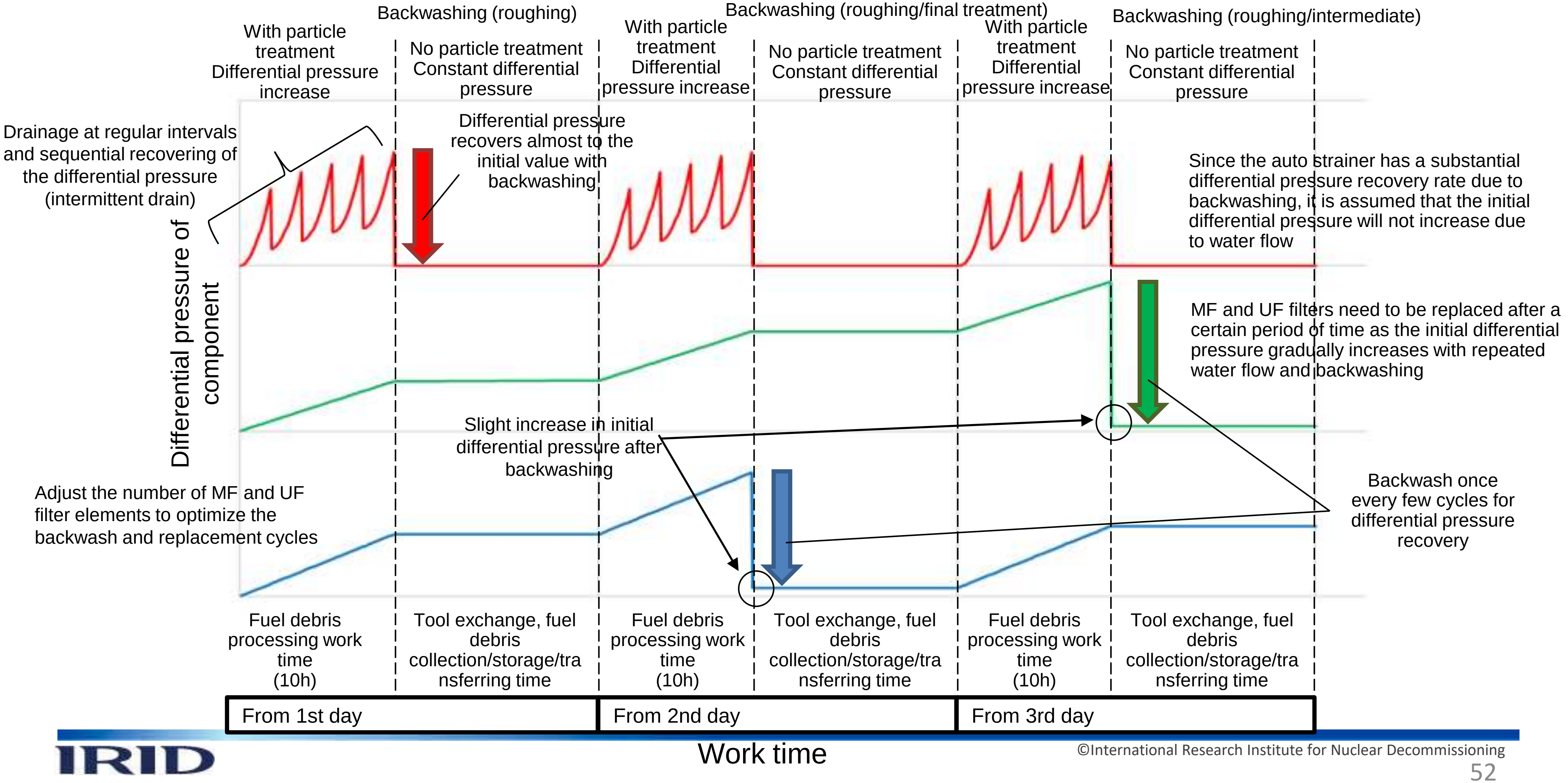
③ Development of secondary waste treatment technology

1) Characterization of liquid waste generated from particle removal system

- **Examination of water flow cycle during fuel debris retrieval work**

3-system configuration (Roughing→ Intermediate → Final treatment)

🟥 : Roughing; 50 μm auto strainer
🟩 : intermediate; 1.4 μm MF filter
🟦 : Final treatment; 0.05 μm UF filter



With particle treatment Differential pressure increase

Backwashing (roughing)

No particle treatment Constant differential pressure

With particle treatment Differential pressure increase

Backwashing (roughing/final treatment)

No particle treatment Constant differential pressure

With particle treatment Differential pressure increase

Backwashing (roughing/intermediate)

No particle treatment Constant differential pressure

Drainage at regular intervals and sequential recovering of the differential pressure (intermittent drain)

Differential pressure recovers almost to the initial value with backwashing

Since the auto strainer has a substantial differential pressure recovery rate due to backwashing, it is assumed that the initial differential pressure will not increase due to water flow

MF and UF filters need to be replaced after a certain period of time as the initial differential pressure gradually increases with repeated water flow and backwashing

Slight increase in initial differential pressure after backwashing

Adjust the number of MF and UF filter elements to optimize the backwash and replacement cycles

Backwash once every few cycles for differential pressure recovery

7. Implementation details

③ Development of secondary waste treatment technology

1) Characterization of liquid waste generated from particle removal system

➢ MF filter water flow test

[Issue]

The intermediate filters such as an auto strainer, a sintered metal filter, and a bag filter were selected and their applicability was evaluated by filter tests. However, both resulted in a significant increase in the component differential pressure during water flow due to the small effective filtration area and the small contribution of centrifugal separation effect to particles of only a few μm. As such, a highly applicable intermediate filter component has not yet been selected at this time.

[Purpose]

Evaluation of the applicability of a MF filter with pore size of 1.4 μm (ceramic filter) as an intermediate filter.

[Implementation details]

Implement a filter water flow test using a 1.4 μm MF filter to obtain operational data.

1.4 μm MF filter

- It was verified that the UF filter selected as the final treatment filter has a very large effective filtration area, leading to a gentle increase in differential pressure
- It is assumed that off-the-shelf identical ceramic filters with pore size of up to 1.4 μm can remove particles in the intermediate filter range
- The investigation confirmed that ceramic filters with pore sizes of 1.4 μm or larger are not available, or that only tube types with a small filtration area are available

7. Implementation details

③ Development of secondary waste treatment technology

1) Characterization of liquid waste generated from particle removal system

- **Particle shape dependence evaluation test**

[Issue]

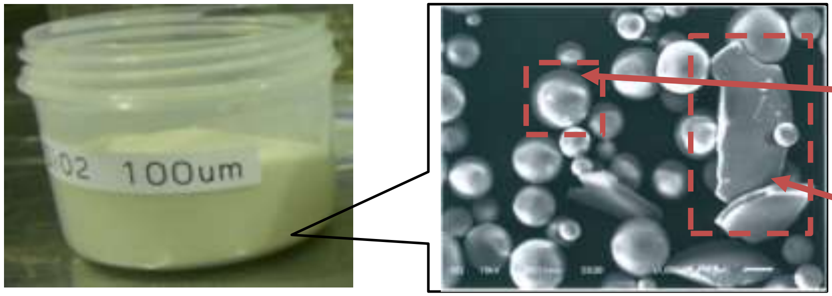
The effect of particle shape on filter performance has not been evaluated for the selected filter components in each system. All filter tests conducted up to the previous project used spherical particles, and there is a possibility that the filter performance was not evaluated in a conservative manner.

[Purpose]

Evaluation of the particle shape dependence of the filter performance for the selected filter components in each system.

[Implementation details]

A filter water flow test using spherical particles and non-spherical particles was conducted to evaluate particle size dependence by comparative examination.
In addition, properties of the backwash water, which are the input conditions to the sludge collection equipment were examined.



Dominated by spherical particles

Flat particles were also observed, but the abundance ratio was insignificant

Figure Particles used in the filter test of the previous project

7. Implementation details

③ Development of secondary waste treatment technology

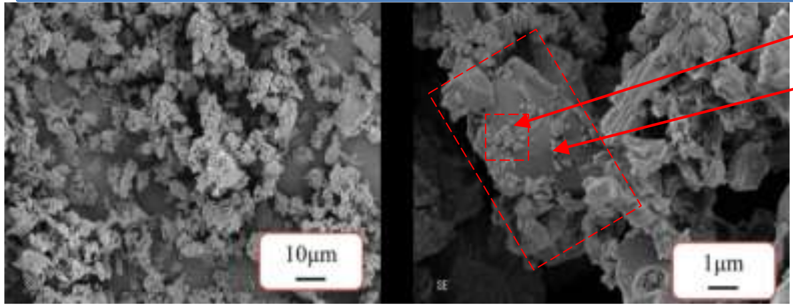
1) Characterization of liquid waste generated from particle removal system

➢ **Non-spherical particles used in filter test**

Simulant particles were selected based on the assumption that the cutting debris generated by machining process is passed through a filter.

Simulant target

Powders generated by machining process test of simulant fuel debris in the implementation of the characterization project*



Relatively small particles: <1 μm

Relatively large particles: several μm

Figure. SEM image of a sample after cutting test of simulant fuel debris implemented in the characterization project (excerpt)

Particle size distribution

Formation of agglomerates of <1 μm powders on the surface of a large particle of the order of several to 10 μm

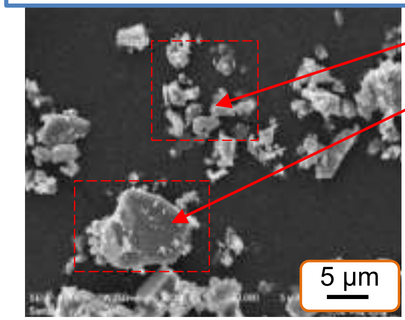
Particle Shape

Dominated by Block-like particles

*FY2018 Subsidy Project of “Development of Analysis and Estimation Technology for Fuel Debris Characterization”

Simulant particles

Non-spherical particles used in this study



Relatively small particles: <1 μm

Relatively large particles: several μm

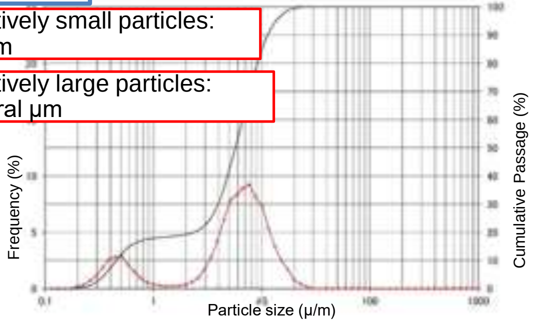


Figure Simulant particles SEM image

Figure Simulant particles Particle size distribution

Particle size distribution and shape are simulated based on the test report of the characterization project

Silica sand particles with a shape and particle size that are relatively similar to those used by particle manufacturers are used

Sizing to be performed as necessary

7. Implementation details

③ Development of secondary waste treatment technology

1) Characterization of liquid waste generated from particle removal system

- **Test system for water flow test**

For filter components, particle capture components of each system selected up to the previous project were used.

The 1.4 μm MF filter, which has been evaluated as having high applicability based on literature research, was only be used for the intermediate filter.

Table list of particle capture components used

No.	System	Particle capture component	Filter mesh size
1	Roughing	Auto strainer	50 μm
2	Intermediate	MF filter (ceramic filter)	1.4 μm
3	Final treatment	UF filter (ceramic filter)	0.05 μm

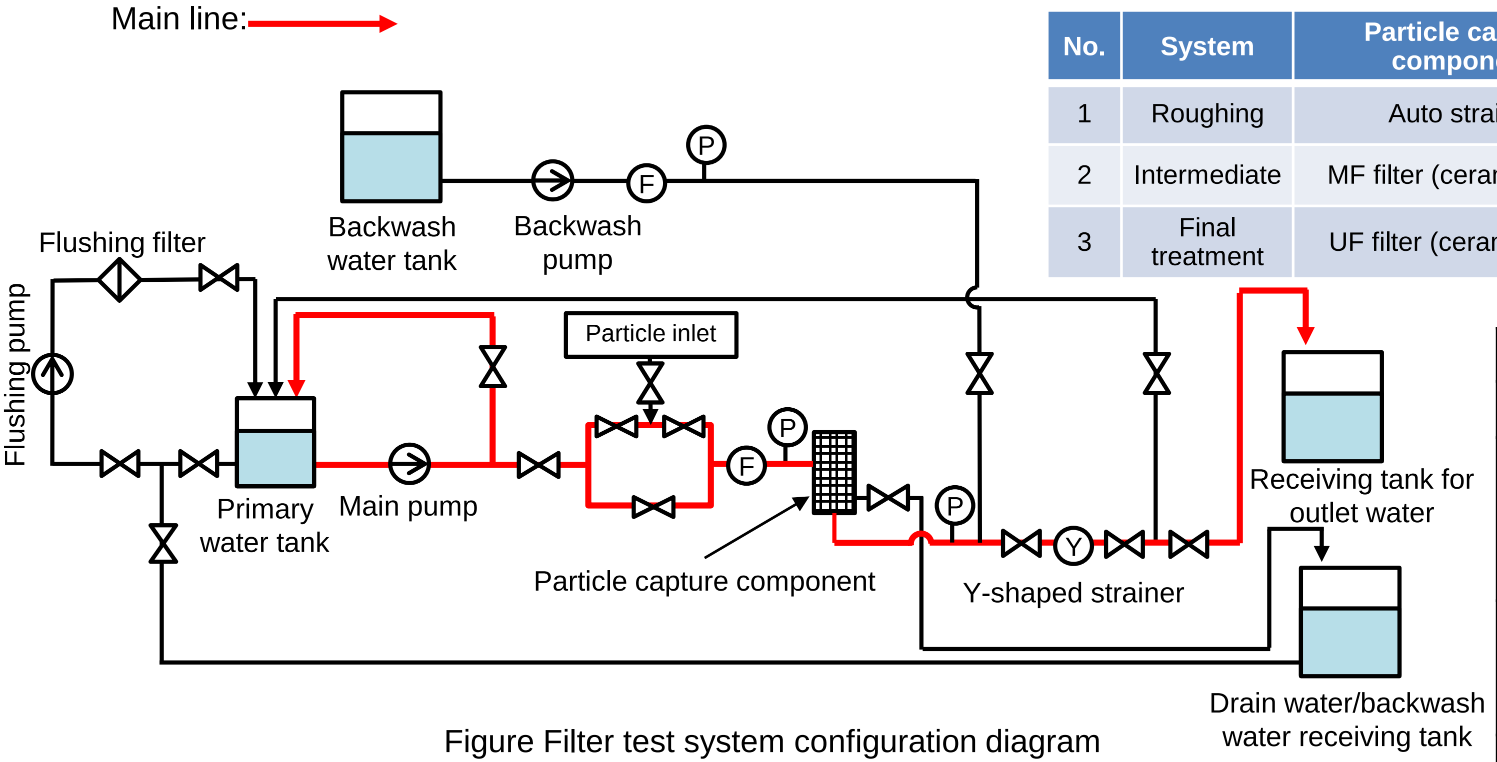


Figure Filter test system configuration diagram

Table Evaluation Items

No.	Items
1	Particle capture rate
2	Time of water flow until backwash pressure is reached (Differential pressure rising trend)
3	Backwashing performance (Differential pressure recovery performance)
4	Backwash water properties

In this test, the performance of each filter was evaluated, and property data on the liquid waste was obtained.

7. Implementation details

③ Development of secondary waste treatment technology

1) Characterization of liquid waste generated from particle removal system

- **Filter element replacement cycles**

  Replacement cycles for the particle capture components are assumed to be as follows

  Roughing system components: 2 times/year → Rate-limiting corrosion of materials due to chlorine

  Intermediate system components: Evaluation for this year* → Rate-limiting increase in initial differential pressure

  Final treatment system components: 5 to 8 times/year → Rate-limiting increase in initial differential pressure

  *It is assumed that it can be operated for a longer period of time because the pore size is larger than that of the final treatment system components

- **Filter element replacement**

  It is necessary to evaluate worker exposure due to residual particles in the housing during the replacement

  Fundamentally, a cartridge system will be adopted, and it is assumed that the entire housing will be replaced.

  The housing should be sufficiently shielded to prevent exposure to workers.

  Another possible method is to replace the elements remotely, but the feasibility of full remote control processing needs to be studied.

- **Examination of the amount of filter liquid waste and secondary waste generated**

  This shows the filter specifications and approximate results of the amount of liquid waste and secondary waste generated which was evaluated from the test results up to FY2020

Summary of filter performance assessment results based on previous element test results

System	Particle capture component		Number of required base	Number of elements required	Rated flow	Filtering accuracy	Removal efficiency	Approximate dimensions (per reactor)	Required area dimensions (per reactor)	Replacement frequency	Amount of secondary waste generated	Number of times drained/back washed	Amount of liquid waste generated
			Base/1 system	Number	m^3/h	µm or more	% or higher	Φ__ m × __ mH	__ mL × __ mW	times/year	kg/year	times/day	m^3/year
Roughing	Auto strainer	Intermittent drain	1	1	10 to 30	50	99	Φ0.5 m × 1.0 mH	1.4 mL × 1.4 mW	2	11	2.5	167
		Continuous drain	1	1	10 to 30	50	99	Φ0.5 m × 1.0 mH	1.4 mL × 1.4 mW	2	11	Continuous drain	1300
	Liquid cyclone		1	1	10	40	80	Φ0.4 m × 1.1 mH	1.6 mL × 1.6 mW	-	-	Continuous drain	2000
Intermediate	MF filter	1.4 µm				Scheduled to be tested in FY2022							
Final treatment	UF filter	0.1 µm	2	33	6.5	0.1	99	Φ0.21 m × 1.3 mH	3.0 mL × 1.6 mW	8	314	0.34	11
		0.05 µm	3	46	<23	0.05	99	Φ0.3 m × 1.4 mH	1.4 mL × 1.4 mW	5	253	0.23	98.6

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Issues]

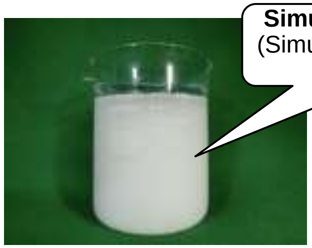
- The amount of sedimentation sludge generated from the sludge collection equipment is high due to the high moisture content, etc., so it is necessary to reduce the volume by dehydration.
- Since dehydration technology applicable to sedimentation sludge has not yet been selected, it is necessary to select a candidate technology.

[Implementation details]

- Assumed properties of sedimentation sludge and supernatant were organized to select an applicable dehydration treatment technology through literature research, etc.
- An element test plan was developed to evaluate the applicability of the selected candidate technology for actual equipment.

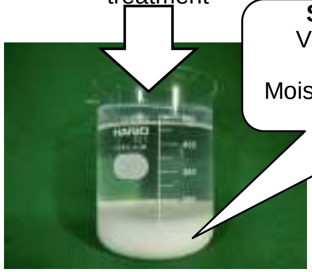
[Goals]

- Selection of candidates for the sedimentation sludge dehydration treatment technology.
- Planning of an element test for evaluation of applicability to actual equipment.



Simulated liquid waste
(Simulant particles + pure water)

Before flocculation sedimentation treatment



Sedimentation sludge
Volume after flocculation: Approx. 15 to 20%
Moisture Content: Approx. 90% to 95%

After flocculation sedimentation treatment

Simulant drain water and backwash water flocculation sedimentation test

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Implementation details]

Dehydration technologies that can be applied to sedimentation sludge were selected through literature research and element tests.
The applicability of the selected dehydration technologies for actual equipment was examined through element tests.

The sedimentation sludge for the dehydration technology to be developed shall be the sedimentation sludge generated from the sedimentation tank for RO-concentrated water treatment, where the amount generated is enormous.

Implementation items

1. Coordination with the canister project (connection conditions, etc.)
2. Consolidation of assumed properties of sedimentation sludge based on the previous project results
3. Evaluation of the amount of hydrogen generated based on sedimentation sludge properties
4. Setting dehydration target (moisture content after dehydration)
5. Investigation of existing dehydration technologies and theoretical study of their applicability
6. Proposal of test plan that can evaluate the applicability to the actual equipment
7. Implementation of applicability evaluation test on the actual equipment

The following items were coordinated among project teams: Project of Development of Technology for Containing, Transfer and Storage of Fuel Debris*1 and project of Development of Safety Systems (liquid and gas systems)*2.

○ Liquid system - Canister storage line interface requirements
○ Sharing of development results
  *Canister PJ: Control policy for collection, transfer, and storage
  Safety system (liquid and gas systems) PJ: Properties of sedimentation sludge at the time of discharge, etc.
○ Classification of the future development contents of both projects

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∗1 Project of Development of Technology for Containing, Transfer and Storage of Fuel Debris: Canister PJ
∗2 Project of Development of Safety Systems (liquid and gas systems: Safety System PJ

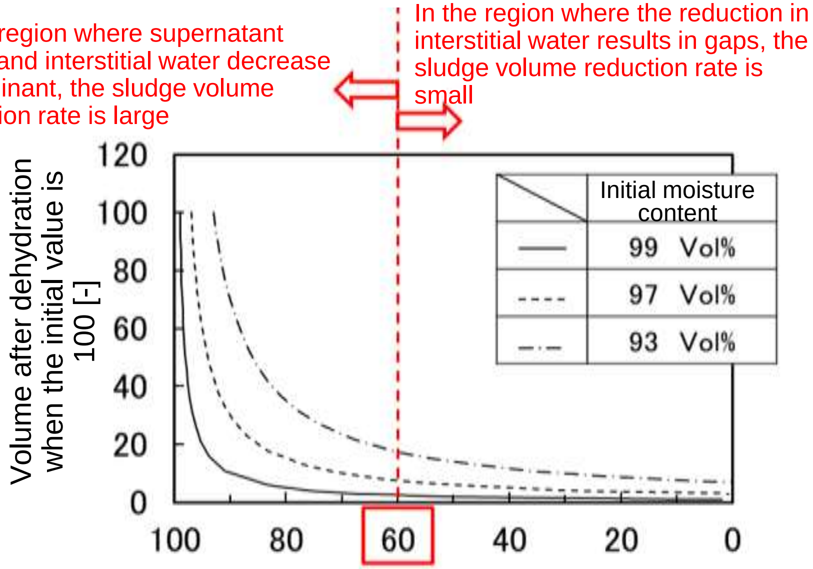
7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Implementation details] The volume reduction of sedimentation sludge due to dehydration was evaluated.

The volume reduction behavior of sedimentation sludge was evaluated when moisture was removed from the assumed moisture content of approximately 90%.

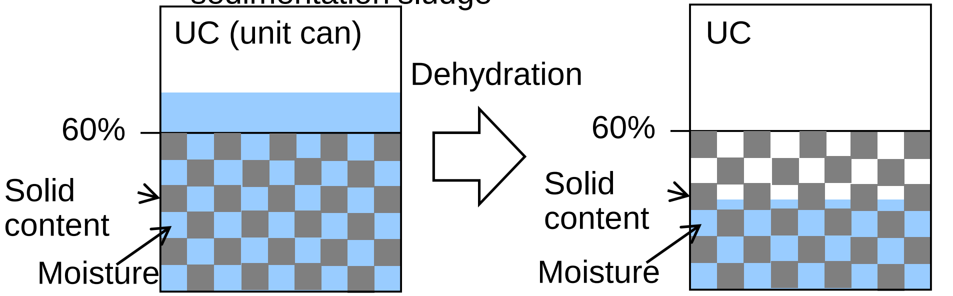


Water content ratio [vol%]

Figure Relationship between moisture content and volume of sludge

Appearance of sedimentation sludge

Water content ratio below 60% is unlikely to contribute much to the sludge volume reduction, as the space occupied by moisture results in gaps



(a) Water content ratio of 60% or more

(b) Water content ratio of 60% or less

Figure Illustration of sludge volume reduction behavior

If the initial moisture content is 90 vol% or more, the volume can be reduced to nearly 20 vol% by dehydration treatment to a moisture content of 60 vol%.
Volume reduction by dehydration has a small effect in the region where the water content is 60 vol% or less, because the volume reduction reaches its limit.

➡ Tentatively set the target value for the water content after dehydration treatment at 60 vol%*, and examine dehydration treatment technology.

*Sludge content rate of 40 vol%

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Implementation details] The amount of hydrogen generated from sedimentation sludge during the transferring period was evaluated.

The amount of hydrogen generated was evaluated based on the collection, transfer, and storage conditions set in the canister PJ.
⇒ The results are shown on the next page

■ Collection, transfer, and storage conditions

(1) Fuel debris: 100% UO^2 with maximum burnup in the Fukushima Daiichi NPS
(2) Waste filling rate: 30 vol% of fuel debris
(3) During transferring
  - Transferring period: 1 week
  - Gas vent (opening the coupler of the canister)
    Case 1 Canister: Vent, Transfer cask: Sealed
    Case 2 Canister: Sealed, Transferring cask: Sealed
(4) During storage
  - Gas Vent Canister: Vent

■ Assumed properties of sedimentation sludge

(a) Sedimentation sludge generated from the sedimentation tank for filter liquid waste treatment: fuel debris content 100%
(b) Sedimentation sludge generated from the sedimentation tank for RO-concentrated water treatment: fuel debris content 0.1%*

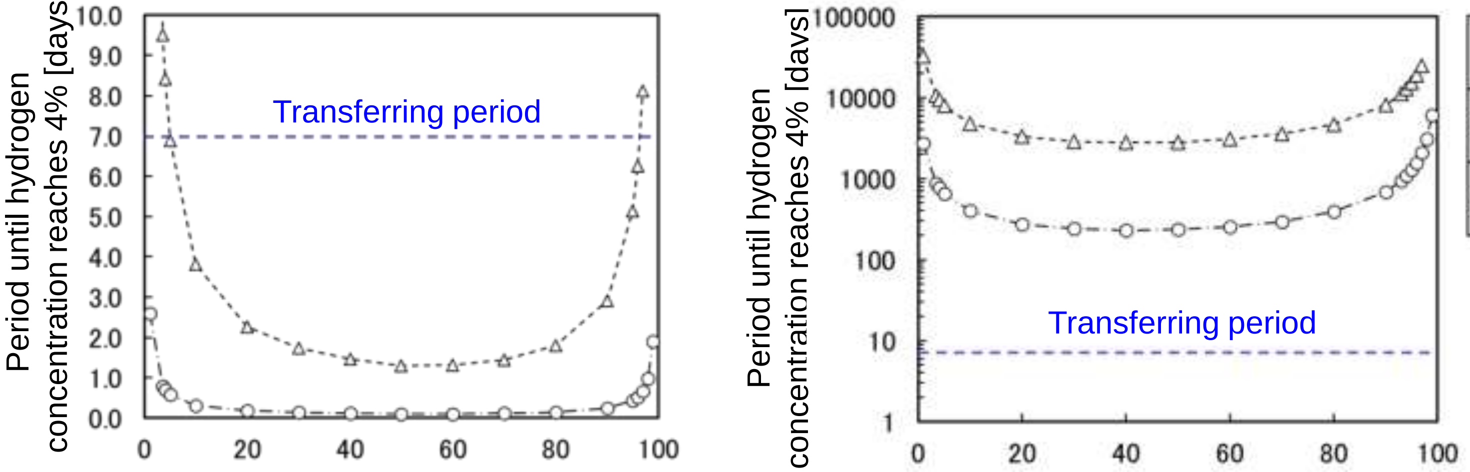
*Rate setting based on the removal rate of nuclides (DF100) in the particle removal equipment and soluble nuclide removal equipment, the assumed concentration rate (2 to 4 times) in the RO filter, etc.

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Implementation details] The amount of hydrogen generated from sedimentation sludge during the transferring period was evaluated.



		Canister	Transfer cask
○	Period required for canister to reach 4% hydrogen concentration	Closed	Closed
△	Period required for transfer cask to reach 4% hydrogen concentration	Opened	Closed

Canister
Gas phase: 0.0133 m^3
Sludge: 0.0115 m^3
Transfer cask
Gas phase: 1.82 m^3
Sludge: 0.16 m^3

Water content ratio [vol%]
(a) Filter liquid waste sedimentation sludge

Water content ratio [vol%]
(b) RO-concentrated water sedimentation sludge

Figure. Evaluation of sludge moisture content and amount of hydrogen generated

In both cases, it was verified that the amount of hydrogen generated was the largest when the amount of water and fuel debris content were around 40% to 60%.
If the filter liquid waste sedimentation sludge is dehydrated from the initial moisture content of about 90%, there is a concern that the risk of hydrogen explosion will increase unless the water content is reduced to a few percent or less.
It is unlikely that the RO-concentrated water sedimentation sludge will reach the explosive limit of hydrogen concentration during the transferring period regardless of the water content.

Even if RO-concentrated water sedimentation sludge is stored for a long period, the amount of hydrogen generated would not reach the explosion limit, so the need for dehydration treatment is low from the viewpoint of the amount of hydrogen generated.

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Implementation details] Proven technologies were selected as the sludge collection treatment technology for overseas nuclear facilities.

Table Results of sludge dehydration technological study at overseas nuclear power sites

No.	Treatment method	Advantages	Disadvantages	Examples/Ready-made products
1	MF, UF filters (DE) filtration	High DF, low cost.	Requires Backwash and backwash water treatment.	-
2	Cross-flow (CF) filtration	Suitable for radioactive colloid removal.	Clogging due to fouling. Requires concentrated water treatment.	Used in recent PWR liquid waste treatment. Equipment available for treatment at 300 GPM
3	RO concentration	Suitable for concentration of CF filtered water.	Clogging due to fouling.	Used in recent PWR liquid waste treatment.
4	Evaporator	High DF.	Requires scaling treatment, high equipment cost.	-
5	Cartridge filter	Space-saving, low cost.	Low waste collection efficiency.	Solids Collection Filter (SCF) with shielding function for treating large volumes, is used to remove S/P pool sludge, etc.
6	Decompression/thermal dehydration (In-Drum dryer)	Waste can be reduced by 85 to 95%.	Treatment speed depends on drying level.	Mobile equipment

Cartridge filters, which are assumed to be able to dehydrate sedimentation sludge to the target moisture content of 60%, as well as decompression and thermal dehydration will be selected as the dehydration technology for sedimentation sludge.

For other candidate technologies, applicability as concentration treatment technology and secondary nuclide removal technology, which are assumed to have high applicability for each technology, will be examined.

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

[Implementation details] Proven technologies were selected as the sludge collection treatment technology for overseas nuclear facilities.
For sludge collection in accident reactors and weapon legacy systems, the technology used is selected according to the sludge content.

*UK: Atomic Weapons Establishment (AWE), US: TMI, Hanford Site, etc.

Table Investigation of cases of dehydration technologies applied by sludge content

No.	Amount of sludge	Target case	Sludge removal, dehydration, and drying methods
1	Miniscule amount	SNF pool water	Cartridge filter filtration
2	Miniscule amount	Radioactive liquid waste	Cartridge filter filtration + evaporator, RO concentration
3	Small amount (sub-percent)	Sludge during reprocessing, saltcake	Cross-flow filter filtration
4	Medium amount (a few percent)	Long-term corroded SNF pool	Dehydration through filters
5	Large amount (several tens of percent)	Research reactor waste Concentrates No. 2 to 4	(Solidified as is)

When the sludge content is small, there are many cases where filtration with a cartridge filter is adopted. If the sludge content is slightly low, cross-flow filtration is used to concentrate it to a few percent. However, raising the concentration to several tens of percent is difficult.
If the sludge content is high, instead of dehydration treatment, solidification treatment such as cement solidification or vitrification is adopted depending on the activity level and final disposal method. If the treatment/disposal method is undecided, it is stored for a long period of time, making use of facilities such as underwater storage.
In many cases of overseas sites, the sludge content is increased by cross-flow concentration, drying treatment, etc., and then solidified.

7. Implementation details

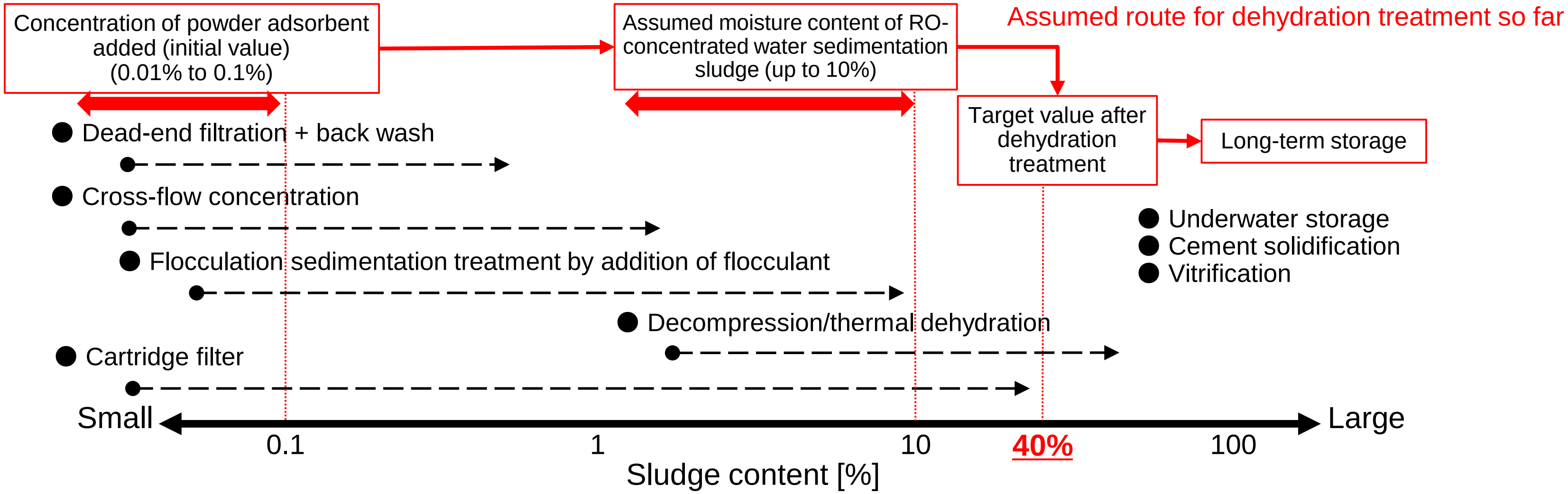
③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

➢ Examination of RO-concentrated water treatment system

The case results show that in many cases, appropriate dehydration methods have been adopted for each sludge content region, and the sludge content has been concentrated to the target sludge content.

<u>Selection of RO-concentrated water sedimentation sludge dehydration technology</u>



Concentration of powder adsorbent added (initial value) (0.01% to 0.1%)

Assumed moisture content of RO-concentrated water sedimentation sludge (up to 10%)

Assumed route for dehydration treatment so far

Target value after dehydration treatment

Long-term storage

- Dead-end filtration + back wash
- Cross-flow concentration
- Flocculation sedimentation treatment by addition of flocculant
- Decompression/thermal dehydration
- Cartridge filter

- Underwater storage
- Cement solidification
- Vitrification

Small ◀ 0.1 1 10 **40%** 100 ▶ Large

Sludge content [%]

The following two proposals were examined as treatment processes for RO-concentrated water.

Plan 1:	① Flocculation sedimentation treatment	→	② Cartridge filter filtration	→	③ Long-term storage
Plan 2:	① Flocculation sedimentation treatment	→	② Decompression/thermal dehydration	→	③ Long-term storage

* For plan 2, since it is difficult to treat large volumes with decompression/thermal dehydration equipment, a system that reduces the amount of liquid by concentration treatment (cross-flow, etc.) as a pretreatment was also examined.

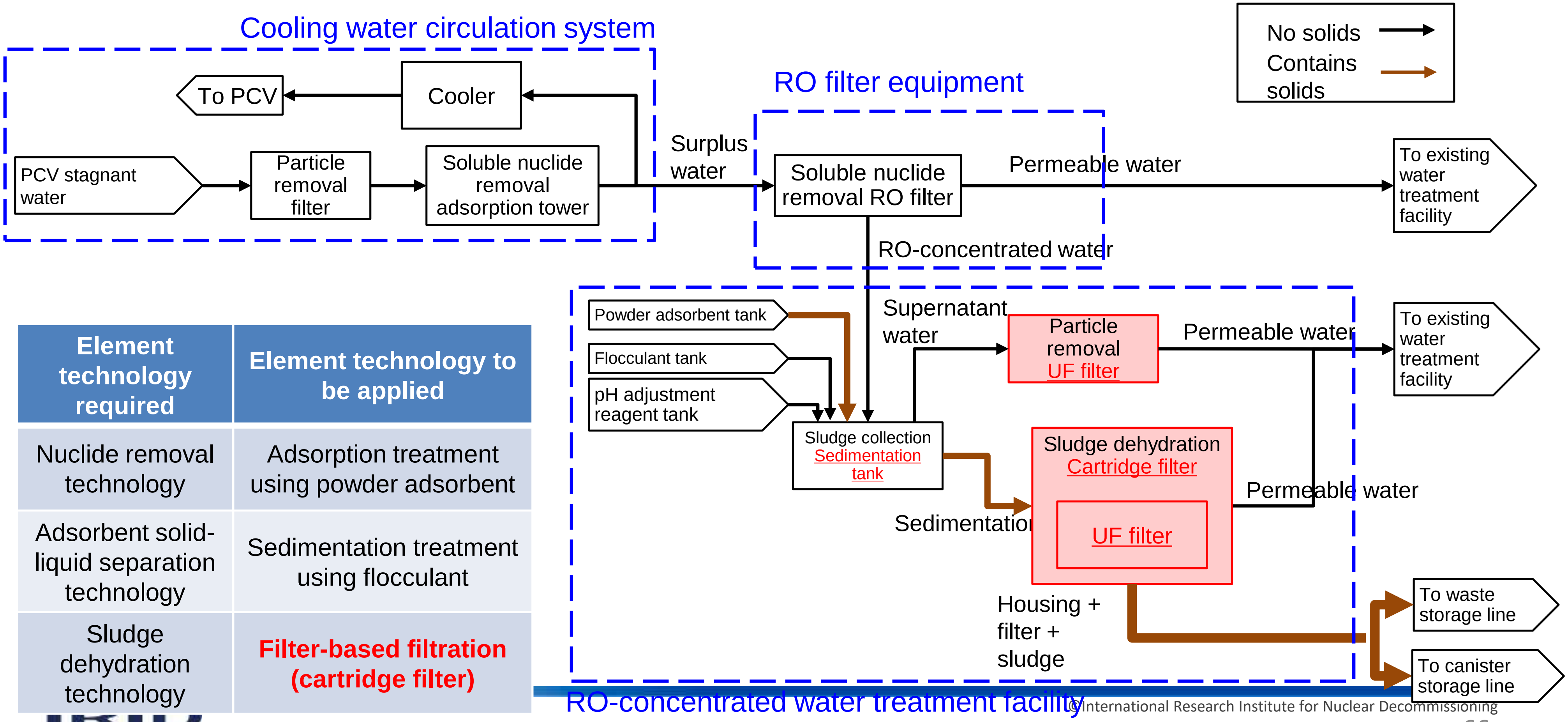
7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

- **Examination of RO-concentrated water treatment system**

Plan 1: ① Flocculation sedimentation treatment → ② Cartridge filter filtration → ③ Long-term storage



Element technology required	Element technology to be applied
Nuclide removal technology	Adsorption treatment using powder adsorbent
Adsorbent solid-liquid separation technology	Sedimentation treatment using flocculant
Sludge dehydration technology	**Filter-based filtration (cartridge filter)**

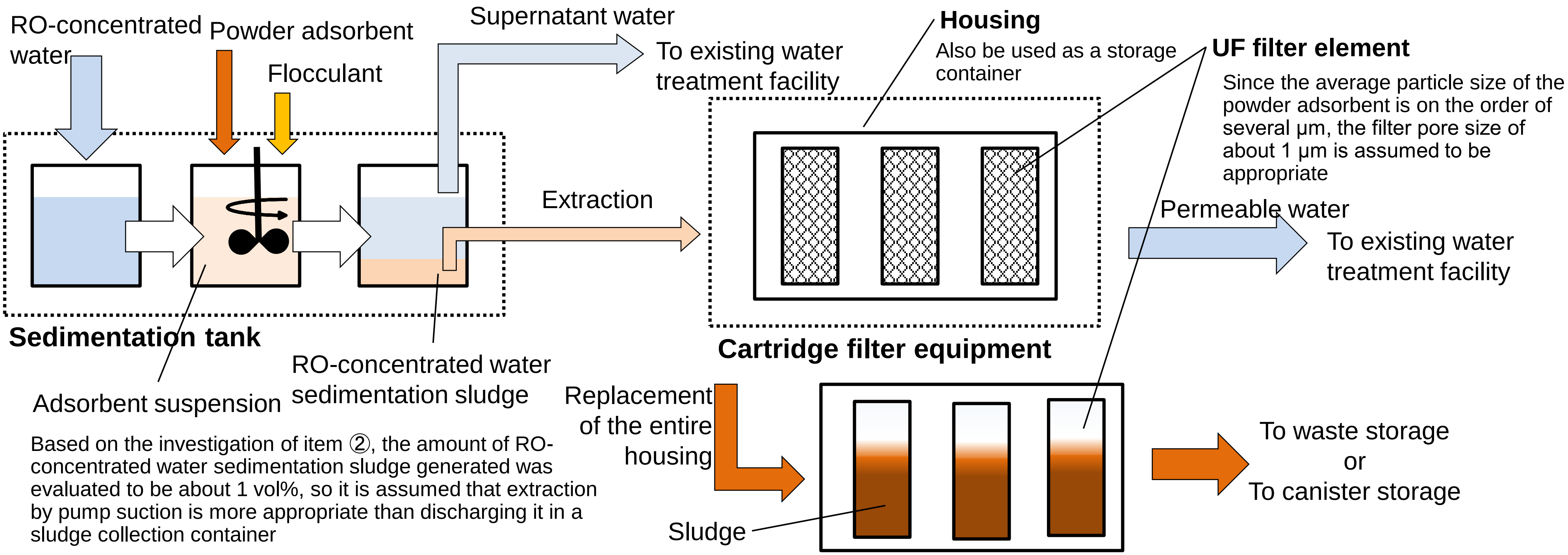
7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

➢ Examination of RO-concentrated water treatment system

Plan 1: ① Flocculation sedimentation treatment → ② Cartridge filter filtration → ③ Long-term storage



RO-concentrated water

Powder adsorbent

Flocculant

Supernatant water

To existing water treatment facility

Housing

Also be used as a storage container

UF filter element

Since the average particle size of the powder adsorbent is on the order of several μm, the filter pore size of about 1 μm is assumed to be appropriate

Extraction

Permeable water

To existing water treatment facility

Sedimentation tank

Cartridge filter equipment

RO-concentrated water sedimentation sludge

Adsorbent suspension

Replacement of the entire housing

To waste storage or To canister storage

Sludge

Based on the investigation of item ②, the amount of RO-concentrated water sedimentation sludge generated was evaluated to be about 1 vol%, so it is assumed that extraction by pump suction is more appropriate than discharging it in a sludge collection container

*Verified in the FY2020 test that it has fluidity due to its high moisture content of about 90% and can be extracted with a pump

The structure of cartridge filters can be designed to be replaced as a module.
By handling the housing as a storage container, long-term storage is possible as it is.
Since it is not necessary to retrieve the element, worker exposure can be reduced if the housing has a shielding function.
It is also simpler to operate than element replacement and can therefore be expected to be operated remotely.

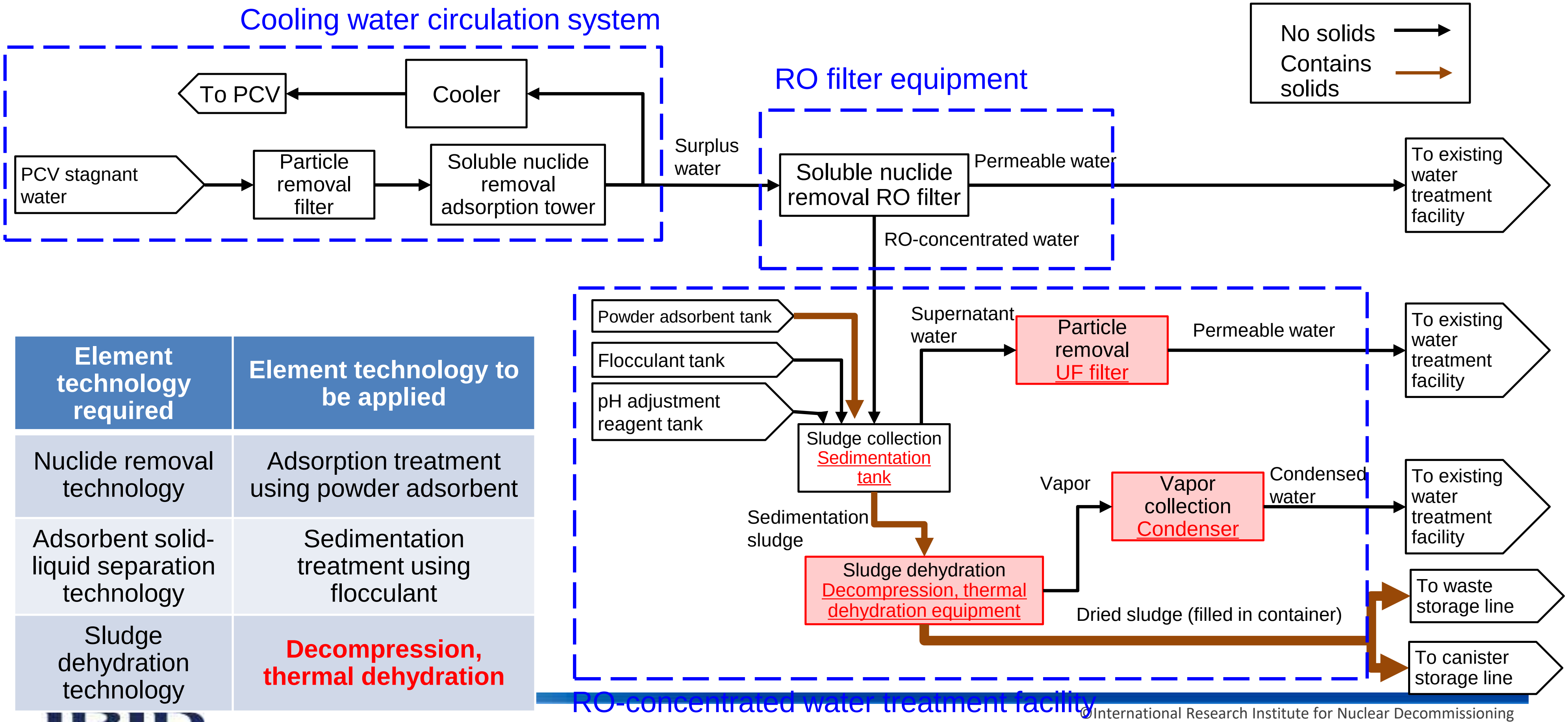
7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

- **Examination of RO-concentrated water treatment system**

Plan 2: ① Flocculation sedimentation treatment → ② Decompression/thermal dehydration → ③ Long-term storage



Element technology required	**Element technology to be applied**
Nuclide removal technology	Adsorption treatment using powder adsorbent
Adsorbent solid-liquid separation technology	Sedimentation treatment using flocculant
Sludge dehydration technology	**Decompression, thermal dehydration**

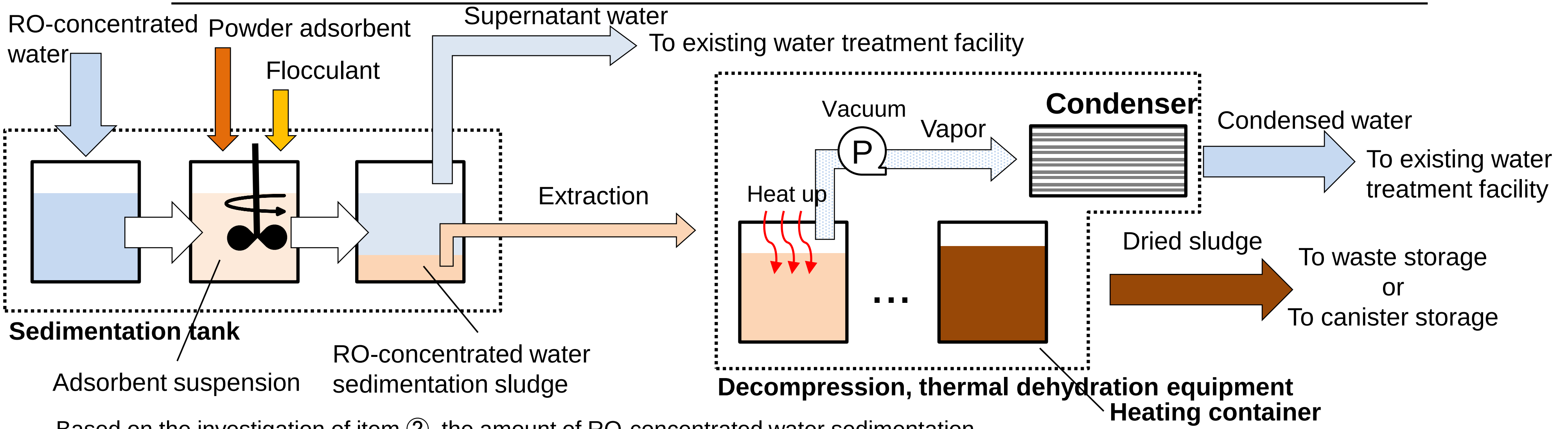
7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

➢ Examination of RO-concentrated water treatment system

Plan 2: ① Flocculation sedimentation treatment → ② Decompression/thermal dehydration → ③ Long-term storage



RO-concentrated water

Powder adsorbent

Flocculant

Supernatant water

To existing water treatment facility

Extraction

Sedimentation tank

Adsorbent suspension

RO-concentrated water sedimentation sludge

Vacuum

P

Vapor

Condenser

Condensed water

To existing water treatment facility

Heat up

…

Dried sludge

To waste storage
or
To canister storage

Decompression, thermal dehydration equipment

Heating container

Also be used as a storage container

Based on the investigation of item ②, the amount of RO-concentrated water sedimentation sludge generated was evaluated to be about 1 vol%, so it is assumed that extraction by pump suction is more appropriate than discharging it in a sludge collection container

*Verified in the FY2020 test that it has fluidity due to its high moisture content of about 90% and can be extracted with a pump

RO-concentrated water sedimentation sludge is transferred to the container for dehydration treatment, and the water is evaporated by decompression and heating.
The generated vapor is collected and condensed in the condenser and discharged to the existing water treatment facility.
Although dried sludge remains on the container side, it is assumed that the dead space inside the container is large due to the volume reduction.
Therefore, the cycle of receiving sedimentation sludge→ dehydration treatment→ residual dried sludge is repeated to increase the filling rate of dried sludge in the container. After it is filled to a certain level, the entire container is discharged and stored for a long period of time.
By giving the container a shielding function, worker exposure can be reduced.

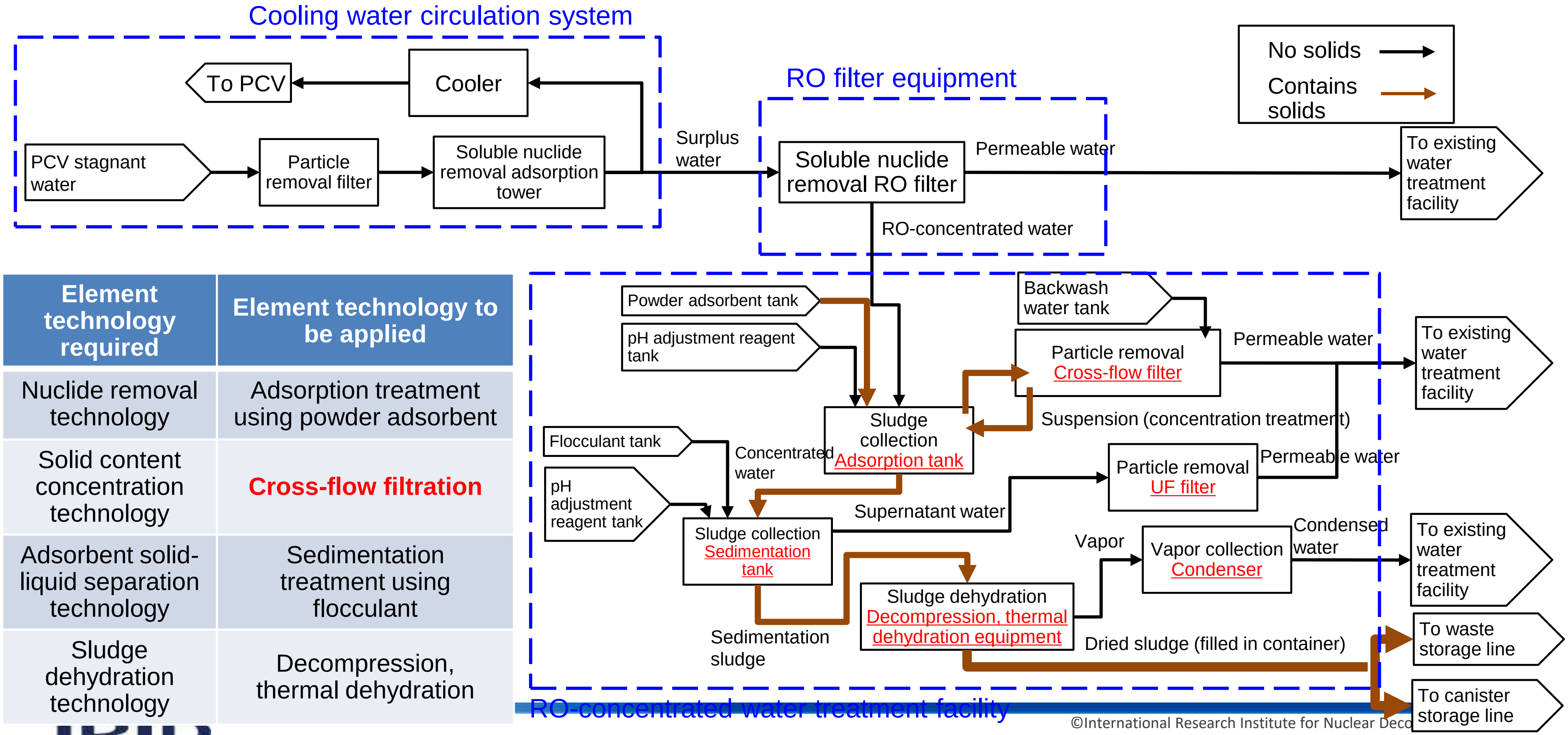
7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

- **Examination of RO-concentrated water treatment system (when adopting cross-flow concentration)**

① Cross-flow concentration → ② Flocculation sedimentation treatment → ③ Decompression, thermal dehydration → ④ Long-term storage



Element technology required	Element technology to be applied
Nuclide removal technology	Adsorption treatment using powder adsorbent
Solid content concentration technology	**Cross-flow filtration**
Adsorbent solid-liquid separation technology	Sedimentation treatment using flocculant
Sludge dehydration technology	Decompression, thermal dehydration

7. Implementation details

③ Development of secondary waste treatment technology

2) Selection of dehydration technology for sedimentation sludge

- **Examination on element test of sludge dehydration technology**

  The applicability of candidate technologies that were selected by the literature research was verified through element test.

Sludge dehydration technology	Concept	Items to be verified in element test	Possibility of dehydration up to the target value of 60%	Element test Necessity
Cartridge filter	Depending on the sludge properties (particle size distribution, moisture content, etc.), it is necessary to select an appropriate filter element (pore size, filtration area), filtration conditions, etc.	- Selection of filtration method and conditions - Dependence of dehydration performance on sedimentation sludge properties	Possible	Required
Decompression, thermal dehydration	It is assumed that the dehydration treatment can be performed up to the target value without greatly depending on the sludge properties (particle size distribution, particle properties)	—	Possible	Not required
(Solidification treatment)	Solidification treatment is considered to be effective from the viewpoint of stabilization of sludge type waste, but the concept of final disposal of waste in the Fukushima Daiichi NPS is currently under examination. Since solidification treatment should be performed according to the burial requirements, it is not examined in this development, and long-term storage after dehydration treatment is estimated.	—	—	—

➡ Element tests for cartridge filters were conducted to obtain operational data.

*System using decompression and thermal dehydration will also be examined with reference to literature data, etc.

- **Small-scale test (assuming 0.1 to 1L scale)**

  A filtration method which the sedimentation sludge moisture content after dehydration treatment satisfies the target value of 60 vol% and the amount generated is at a level that can be discharged to a later stage equipment was selected.

  Tests for Vacuum filtration and pressure filtration using RO-concentrated water sedimentation sludge simulants were conducted. Information on average cake resistance, wet-dry mass ratio, etc. to evaluate whether the requirements for throughput and dehydration effect can be satisfied. (Test content under consideration)

7. Implementation details

③ Development of secondary waste treatment technology

- Summary

1) Characterization of liquid waste generated from the particle removal system

[Results for this year]

- ✓ A 1.4 μm MF filter was adopted as the intermediate filter. Non-spherical particles were selected to evaluate particle shape dependence of filter apparatus for each system. A test method of filter test was devised to evaluate the performance of each filter.

[Future plans]

- ✓ A filter water flow test (both scheduled for FY2022) will be conducted to evaluate the applicability of the 1.4 μm MF filter (intermediate component) and the particle shape dependence of each filter apparatus.

2) Selection of dehydration technology for sedimentation sludge

[Results for this year]

- ✓ The required dehydration performance was examined from the viewpoint of the amount of hydrogen generated and volume reduction, and the sludge dehydration target was tentatively set at a moisture content of 60 vol%.
- ✓ Based on literature research, cartridge filters and decompression and thermal dehydration were selected as dehydration treatment methods applicable to sedimentation sludge.

[Future plans]

- ✓ Element tests will be planned and conducted to examine the applicability of cartridge filters.
- ✓ The sludge dehydration treatment system that was selected candidate technologies (cartridge filters, decompression, thermal dehydration) through literature research will be studied.

8. Specific objectives for achieving the purposes of technological developments

(1) Liquid/gas systems	
① Development of soluble α-nuclide removal technology - Examination of soluble α-nuclide removal test assuming use of actual liquid	In order to verify the effectiveness and feasibility of the soluble α- nuclide removal equipment, the test method, test equipment and test plan that assume the use of actual liquid shall be specified. (TRL at the end of the project: Level 3)
- Element test assuming fuel debris retrieval work	Regarding the soluble α-nuclide removal equipment, the α-nuclide adsorption performance data in the environment assumed during fuel debris retrieval work shall be obtained, and candidate adsorbents shall be selected. At that time, a water quality adjustment policy shall be established. (TRL at the end of the project: Level 4)
② Development of RO-concentrated water treatment technology - Selection of adsorbent and condensing agent	Regarding the RO-concentrated water treatment facility, the nuclide removal performance of the powder adsorbent and the flocculation sedimentation performance of the flocculant shall be evaluated and the powder adsorbent and flocculant shall be selected. (TRL at the end of the project: Level 4)
- Examination of applicability to actual equipment	Regarding the RO-concentrated water treatment facility, the conceptual design of the treatment method and equipment shall be implemented from the test using the sedimentation tank. (TRL at the end of the project: Level 4)
③ Development of secondary waste treatment technology - Investigation of pretreatment technologies	A candidate stabilization treatment technology shall be selected for the sludge generated from the flocculation sedimentation tank. At that time, pretreatment technology for liquid waste such as supernatant water shall also be selected. (TRL at the end of the project: Level 3)
- Examination of applicability to actual equipment	The applicability of the pretreatment technology to the actual equipment shall be verified based on the results of element tests. In addition, the conceptual design of the pretreatment equipment shall be established. (TRL at the end of the project: Level 4)

*TRL: Technology readiness levels

End

Supplementary Budget for Government-Led R&D Program on Decommissioning and Contaminated Water Management “Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)”

Accomplishment Report for FY2021

(2) Criticality Control Technology

August 2022

International Research Institute for Nuclear Decommissioning (IRID)

Table of Contents

1. Purposes and goals of "Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)"

[Purpose of Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)]

At the Fukushima Daiichi Nuclear Power Station (NPS) of Tokyo Electric Power Company Holdings, Inc. (TEPCO), it is believed that nuclear fuel melted together with the reactor internals and remains as fuel debris inside the Reactor Pressure Vessel (RPV) and the Primary Containment Vessel (PCV).

The fuel debris in the RPV and PCV is likely present in a sub-criticality state. However, due to damage to the Reactor Building (R/B), RPV, PCV and other structures, the entire nuclear power plant is in an unstable condition deviant to the original design. In order to stabilize the plant, the fuel debris must be retrieved while maintaining its sub-criticality state and preventing radioactive material diffusion.

This project will be examined within the above-stated background context and based on the "Mid-and-Long Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station" (hereinafter referred to as the "Mid-and-Long-Term Roadmap"), with the goal of realizing large-scale fuel debris retrieval work under TEPCO engineering and project management. The development results of this project will be utilized in the engineering conducted by TEPCO.

The purpose of this project is to advance the level of Japanese science and technology by supporting the development of technologies that contribute to the safe decommissioning of the Fukushima Daiichi NPS and handling of contaminated water, based on the Mid-and-Long-Term Roadmap and the "FY2021 Decommissioning Research and Development Plan" (the 86th Secretariat Team Meeting for Countermeasures for Decommissioning and Contaminated Water Treatment).

Specifically, development will be implemented on the technology to remove soluble α-nuclides that are considered to be eluted in circulating cooling water from fuel debris, treatment technology of RO-concentrated water, treatment technology of secondary waste, and on-site operating methods for criticality approach monitoring and neutron absorber technologies.

1. Purposes and goals of "Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)"

[Overall development goal]

Applying the R&D results obtained thus far, the element technologies necessary for systems and safety assurance technologies for further increasing the scale of retrieval of fuel debris and the reactor internals will be developed and tested.

[Specific goals of development items]

① Development of on-site operating procedures

- Development of on-site operating procedures for criticality approach monitoring using neutron detectors to share among the fuel debris retrieval method team.
- Evaluation of the sub-criticality measurement performance of the three new types of neutron detectors to reflect it in the on-site operating procedures.
- Development of on-site operating procedures for non-soluble neutron absorbers to share among the fuel debris retrieval method team.

② Development of solidified absorber technology

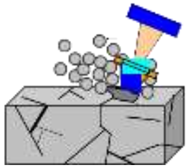
- Acquisition of data on the impacts of fuel debris with solidified absorbers (water glass) on the drying process to utilize it for ① Development of on-site operating procedures as well as examination of equipment operation such as fuel debris drying time.

2. Overview of subsidy projects

Development of on-site operating methods for criticality approach monitoring and neutron absorber technologies

As for the criticality control technology, each element of criticality prevention, criticality approach monitoring, criticality detection, and impact mitigation has been developed in the Project of Decommissioning and Contaminated Water Management by the previous fiscal year. Of these, criticality prevention and criticality approach monitoring, which are still the issues, will be examined and specified based on the results of technological development up to the previous fiscal year.

a. Restrict and control procedures to prevent criticality



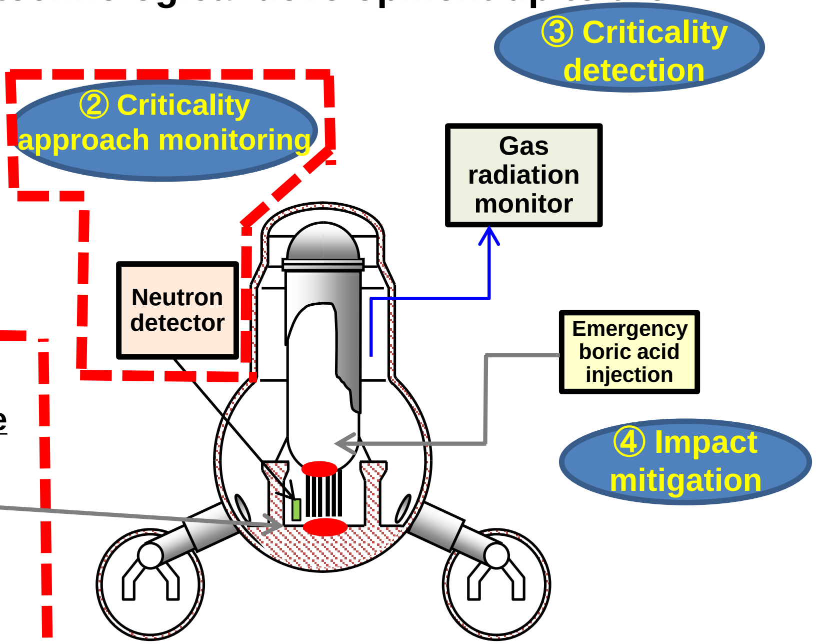
① Criticality prevention

b. Injection of neutron absorbers

Solid type

Solidified type

Target range of this project



Overview of technological development for criticality control

3. Previous fiscal year project results and remaining issues

Development results of criticality approach monitoring technology and details of this project

Final target	Goals to be achieved until application to actual equipment	Status	Remaining Issues/Details of this Project
Establishment of sub-criticality measurement technology	① Establishment of measurement method	- A method that combines the reactor noise method and the neutron source multiplication method was selected. - Detector sensitivity and placement to reduce measurement errors	
	② Development of system specifications	- System specifications for detectors, measurement circuits, etc. were developed.	
	③ Specifications for neutron detectors	- Specifications for neutron detectors were developed and a detector for prototype was selected.	
	④ System design and test manufacturing	- A system consisting of a neutron detector, measurement circuit, and an analysis PC was manufactured as a test system.	
	⑤ Verification of feasibility of sub-criticality measurement	- The feasibility was verified under simulated conditions of homogeneous fuel debris (KUCA test #1/#2). - The feasibility was verified under large-scale fuel debris simulated conditions (KUCA test #3) - The feasibility was verified under simulated conditions of non-homogeneous fuel debris / neutron absorber (KUCA test #4).	**Applicability verification test for alternative neutron detectors (corona-type, SiC-type, multi-cell He-3 based) (KUCA test #5)** **(→ Section 7.1.2)** KUCA: Kyoto University Critical Assembly
Incorporation into fuel debris retrieval system	① Verification of applicability of neutron detectors to the on-site	- The specifications of the neutron detector that will be transferred by the robot arm were organized. - Cable handling concept was developed. - Alternative neutron detector prototype (corona-type, SiC- based, multicell He-3 type) was manufactured and the basic performance was confirmed. - Neutron detector units were designed and test-manufactured. - Radiation resistance of preamplifier was evaluated.	
	② Electromagnetic noise reduction method	The impacts of simulated noise were evaluated and countermeasures for the noise impact were examined.	
	③ Examination of criticality approach control procedures	The time required for measurement was evaluated. Procedures for criticality approach monitoring at each step of the fuel debris retrieval method	**Measurement procedures before and after processing, determination of measurement targets, measurement time, daily work procedures for sub-criticality maintenance control, repair/maintenance requirements, and organization of requirements to the processing side** **(→ Section 7.1.1)**

3. Previous fiscal year project results and remaining issues

Development results of non-soluble neutron absorbers and details of this project

Final target	Goals to be achieved until application to actual equipment	Status	Remaining Issues/Details of this Project
Establishment of criticality prevention technology	① Selection of candidate materials	- Candidate materials for non-soluble neutron absorbers were selected after verification of basic characteristics, irradiation characteristics, and nuclear characteristics (4 types of candidate materials were selected).	
	② Verification of constructability and specifications of sub-criticality maintenance conditions	- The required amount of input was estimated according to the assumed usage. - Workability of chisel for crushed fuel debris was verified. The distribution of absorber was confirmed and sub-criticality maintenance was evaluated (solid absorber).	
	③ Evaluation of corrosion effects	- From the long-term irradiation test, the hydrogen generation G value (*) was less than the design value, and the diluted seawater with eluted absorbent components had a pH of 6 or higher - The impacts of irradiation on rust inhibitor effect were evaluated.	
	③ Evaluation of secondary impacts	- The number of canisters and the amount of waste increased by up to about 10% for solid absorbers and up to about 40% for solidified absorbers	**Impacts of water glass on fuel debris drying (→ Section 7.2)**
Incorporation into fuel debris retrieval system	① Examination of injecting equipment for non-soluble neutron absorbers and operating methods	- A method for inserting absorbers was developed. - Impacts of chisel processing was verified. - Availability of underwater insertion was confirmed.	**Amount of solidified absorbers used** **Applicable conditions for processing scenes Level 2→ Level 1 return procedures** **Effectiveness of pre-insertion (→ Section 7.1.3)**
	② Design of absorber injecting equipment	- The concept of the absorbent injecting equipment was developed based on the weight and size restrictions of the absorbent injecting equipment and the absorbent transportation path restrictions.	**Downsizing and weight reduction of the equipment (→ Section 7.1.3)**
	③ Verification of combination with retrieval equipment	- Applicable absorbers for fuel debris processing methods for each fuel debris location were examined.	

(*) Hydrogen generation G value: Number of molecules of hydrogen generated when absorbing 100 eV energy

4. Input/output

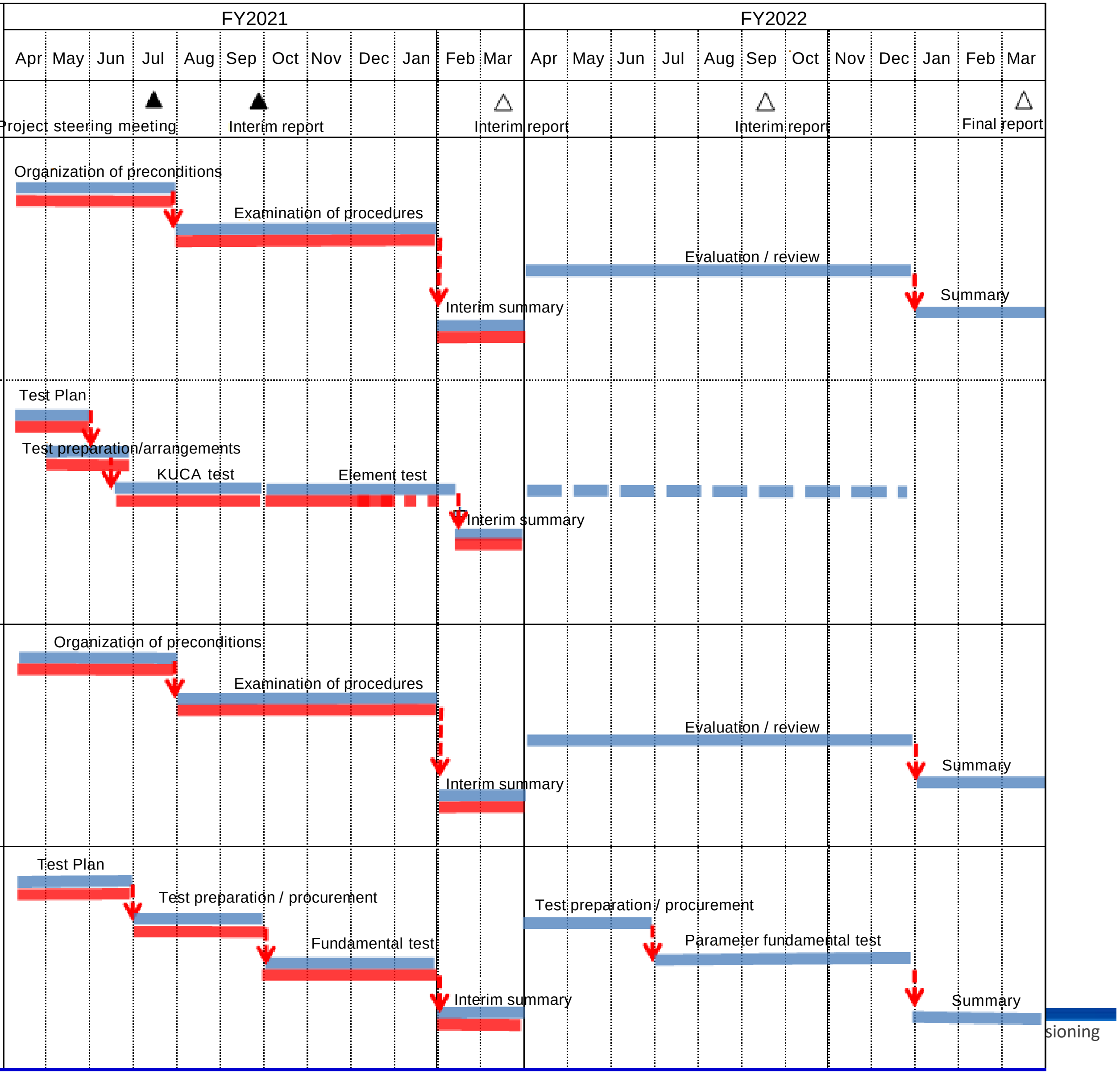
This project is being conducted in collaboration with the Project of Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals, and the Project of Development of Technologies for Containing, Transfer and Storage of Fuel Debris.

ID	Demand-side project	Provider-side project	Contents (overview)	Timing	Information use
1	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals	Methods of removing interfering objects, methods of accessing fuel debris, methods of processing and collecting fuel debris and the reactor internals	June 2021	Examination of on-site operating procedures for criticality approach monitoring and absorbent dispersion
2	Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	On-site operating procedures for criticality approach monitoring using neutron detectors, on-site operating procedures for non-soluble neutron absorbers	March 2023	Examination of throughput of fuel debris retrieval method
3	Development of Technologies for Containing, Transfer and Storage of Fuel Debris	Development of Safety Systems (Liquid/Gas Systems, Criticality Control Technology)	Data on the impacts of fuel debris with water glass (non-soluble neutron absorber) on the drying process	March 2023	Examination of the drying process of canisters

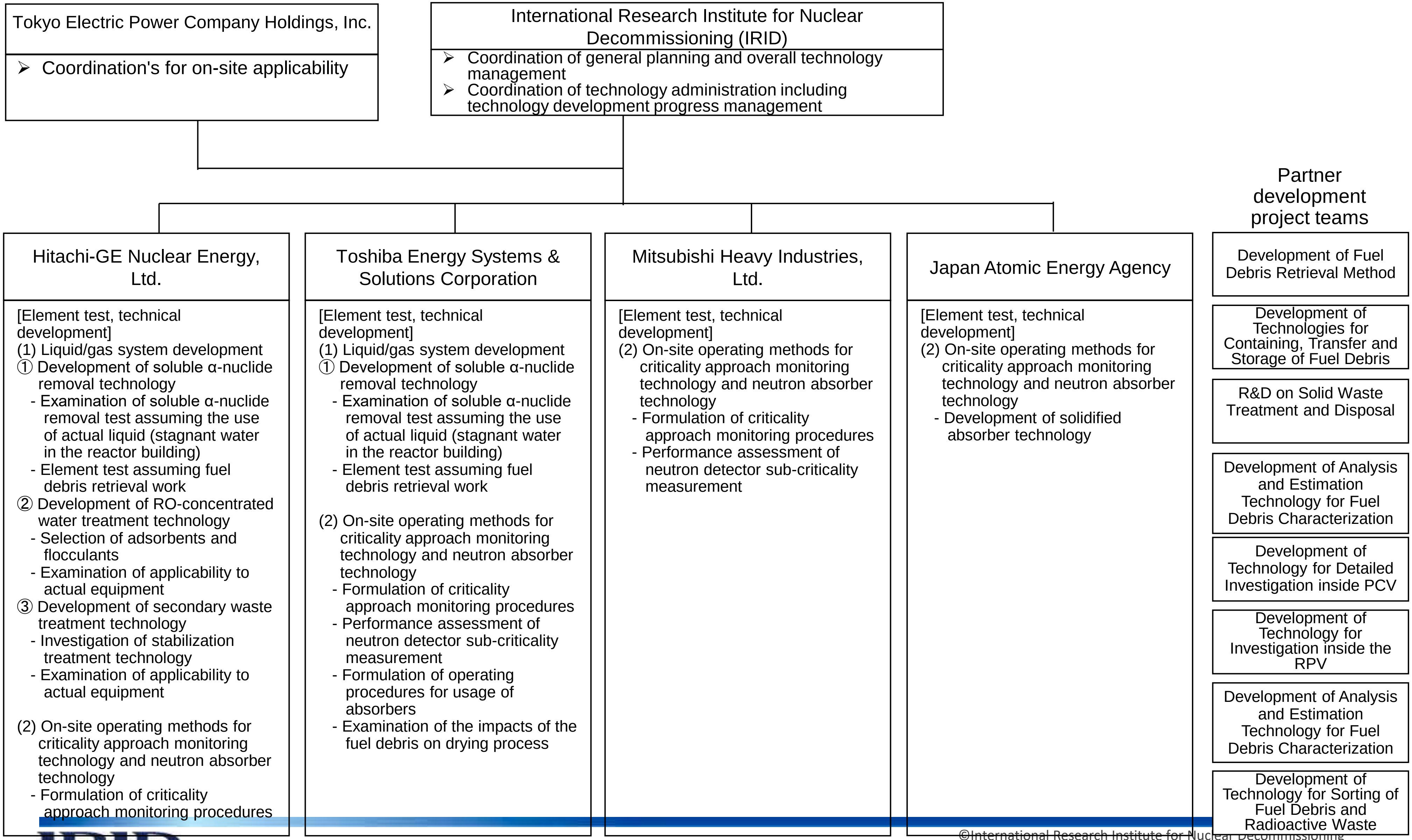
5. Implementation schedule

Criticality control technology

Category	Subcategory	Plant operator (If there is a subcontractor or test location, it is also listed)
Major milestones		
(2) On-site operating methods of criticality approach monitoring technology and neutron absorber technology ① Development of on-site operating procedures (i) Formulation of operating procedures for criticality approach monitoring	a. Organization of preconditions b. Examination of procedures c. Evaluation / review d. Summary	(1) Hitachi GE (2) Toshiba ESS (3) Mitsubishi Heavy Industries
(ii) Neutron detector sub-criticality measurement test	a. Test plan b. Test preparation/ arrangements c. Element test d. Summary	(1) Toshiba ESS Subcontractor: FEO / CETD Test location: KUCA Nagoya University (2) Mitsubishi Heavy Industries Subcontractor: IPL Test location: KUCA
(iii) Formulation of operating procedures for non-soluble absorbers	a. Organization of preconditions b. Examination of procedures c. Evaluation / review d. Summary	(1) Hitachi GE (2) Toshiba ESS (3) Mitsubishi Heavy Industries
② Development of solidified absorber technology	a. Test plan b . Test preparation/ material procurement c. Element test d. Summary	(1) JAEA Subcontractor: Inspection Development Company Ltd. Test location: JAEA



6. Project organization



Tokyo Electric Power Company Holdings, Inc.

- Coordination's for on-site applicability

International Research Institute for Nuclear Decommissioning (IRID)

- Coordination of general planning and overall technology management
- Coordination of technology administration including technology development progress management

Hitachi-GE Nuclear Energy, Ltd.

[Element test, technical development]

(1) Liquid/gas system development

① Development of soluble α-nuclide removal technology

- Examination of soluble α-nuclide removal test assuming the use of actual liquid (stagnant water in the reactor building)
- Element test assuming fuel debris retrieval work

② Development of RO-concentrated water treatment technology

- Selection of adsorbents and flocculants
- Examination of applicability to actual equipment

③ Development of secondary waste treatment technology

- Investigation of stabilization treatment technology
- Examination of applicability to actual equipment

(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology

- Formulation of criticality approach monitoring procedures

Toshiba Energy Systems & Solutions Corporation

[Element test, technical development]

(1) Liquid/gas system development

① Development of soluble α-nuclide removal technology

- Examination of soluble α-nuclide removal test assuming the use of actual liquid (stagnant water in the reactor building)
- Element test assuming fuel debris retrieval work

(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology

- Formulation of criticality approach monitoring procedures
- Performance assessment of neutron detector sub-criticality measurement
- Formulation of operating procedures for usage of absorbers
- Examination of the impacts of the fuel debris on drying process

Mitsubishi Heavy Industries, Ltd.

[Element test, technical development]

(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology

- Formulation of criticality approach monitoring procedures
- Performance assessment of neutron detector sub-criticality measurement

Japan Atomic Energy Agency

[Element test, technical development]

(2) On-site operating methods for criticality approach monitoring technology and neutron absorber technology

- Development of solidified absorber technology

Partner development project teams

- Development of Fuel Debris Retrieval Method
- Development of Technologies for Containing, Transfer and Storage of Fuel Debris
- R&D on Solid Waste Treatment and Disposal
- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Development of Technology for Detailed Investigation inside PCV
- Development of Technology for Investigation inside the RPV
- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Development of Technology for Sorting of Fuel Debris and Radioactive Waste

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

[Issues]

In the related project (*), a method of criticality approach monitoring in the rough work steps of the top/side-entry method is being examined. (Figure 1) In order to discuss the operating procedures and throughput with the fuel debris retrieval method team, it is necessary to further refine the work steps and materialize the criticality approach monitoring procedures.

[Implementation details]

- Organization of the procedures for criticality approach monitoring using neutron detectors in a step diagram for the fuel debris retrieval method and processing/collection equipment studied in the related project (*).
- Study on the neutron response when approaching criticality during fuel debris processing, and the procedures for determining criticality approaching.
- Study on the measurement procedures before and after processing, determination of measurement targets, measurement time, daily work procedures for sub-criticality maintenance control, repair/maintenance requirements, and organization of requirements to the processing side.

[Goals]

- Development of the on-site operating procedures for criticality approach monitoring using neutron detectors to share them with the fuel debris retrieval method team.

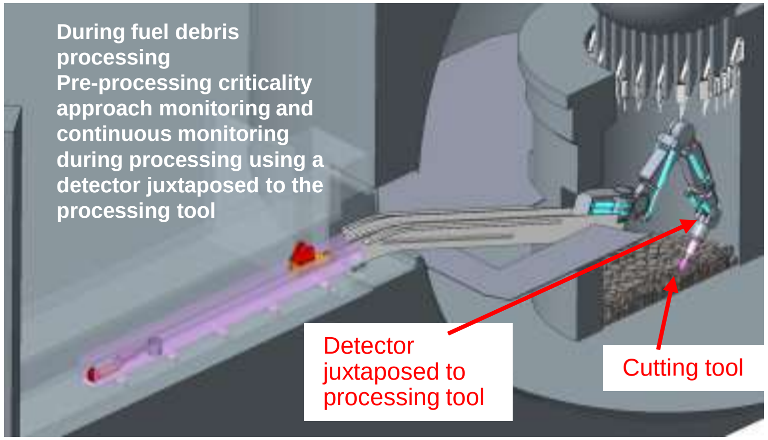

During fuel debris processing
Pre-processing criticality approach monitoring and continuous monitoring during processing using a detector juxtaposed to the processing tool

Figure 1 Criticality approach monitoring during fuel debris retrieval (example of side-entry)

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

a. Organization of preconditions

Development of criticality control involving the retrieval step

Step	Sub-step	Arm maximum loading weight	Processing restrictions/criticality control methods	Possibility of pre-insertion of absorbers	Criticality approach monitoring			Other criticality prevention measures	Remarks (*2)
					Sub-criticality measurement	Criticality approach monitoring for each constant amount of processing	Continuous monitoring during processing		
2. Removal of interfering objects in the PCV/preparation for fuel debris removal									
③ Removal of interfering objects in the PCV	4) Processing/ cutting of interfering objects	(Loading into PCV) up to 100 kg (Mounted on arm) up to 30 kg	No deposits presumed to be fuel debris: No restrictions	— (*1)	—	—	—	- Prevention of cut pieces from falling onto sediments inside the pedestal - Prevention of heavy weight objects from falling onto the top sediments in the pedestal (measures to prevent contact with CRD, etc.) - Measures to prevent the cutting tool from falling)	
			With deposits (small amount of deformation): Restrictions on the amount of cutting powder falling onto the bottom sediments	—	—	—	—		Deformation criterion is minimum critical weight (30 to 60 kg)
			With deposits (large amount of deformation): - Processing while performing criticality approach monitoring - Restrictions on the amount of cutting powder falling onto the bottom sediments	Possible When approaching criticality	—	Neutron flux measurement/criticality approach monitoring before and after processing/cutting	Continuous monitoring during processing may be required as a backup		

Step division of retrieval method (Insert sub-step on criticality side)

Constraints of detectors and non-soluble absorbent injecting equipment

Criticality control methods, processing restrictions, etc.

Potential step to apply non-soluble absorbers

Discuss specific procedures for criticality approach monitoring.

Points to note from criticality control (mainly countermeasures to prevent the occurrence of accompanying events)

*1 "—" means not applicable.
*2 Left blank if there are no special notes.

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

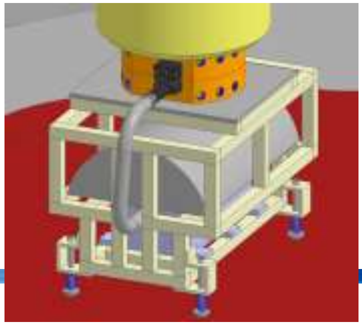
a. Organization of preconditions

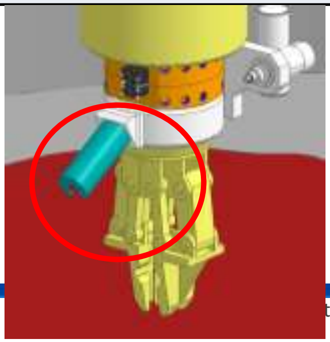
Functions to configure criticality approach monitoring

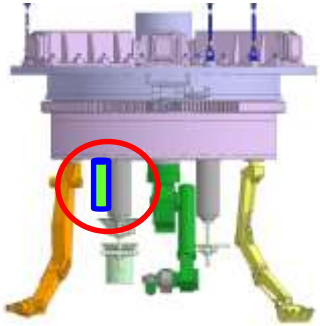
Name	**Detector for sub-criticality measurement**	**Criticality approach monitoring detector (Note 1)**	**Continuous monitoring detector (Note 1)**
Intended use	Understanding the state before work	Decision to start processing	Detection of unexpected changes
Function	Sub-criticality measurement	Criticality approach monitoring before and after processing	Continuous monitoring of neutron flux during processing
	Absolute value measurement of neutron multiplication factor	Measurement of relative change in neutron multiplication factor	
Form	Mounted on arm	Juxtaposed to processing tool	Installed on platform /juxtaposed to processing tool
Weight	30 kg to 100 kg	30 to 50 kg	30 kg or less
Measurement time	From several hours to a week (depending on-site environment)	Approx. 10 min	Continuous
Measuring position(Note 2)	One point near the retrieval start position	Moves appropriately according to the processing position	Same as left/a place that can be viewed from a distance from the processing position

(Note 1) Depending on the conditions such as weak gamma rays at on-site and strong neutrons in the fuel debris, it is possible that both “criticality approach monitoring” and “continuous monitoring” can be used.

(Note 2) It is not fixed and may be changed from time to time.







Installed on platform

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures

Outline of implementation of 7.1.1.b

While discussing the operating procedures and throughput with the fuel debris retrieval method team, examination of 10 items that were raised as issues was implemented.

- - Top access retrieval method - -

① Criticality monitoring method during top-access retrieval (→ No. 14)

- - - - - - - - - - - - Side access retrieval method - - - - - - - - - - -

② Criticality monitoring method during side-access retrieval (→ No. 15)

③ Criticality monitoring method for side-entry PLAN-B method (→ No. 16 to 18)

- Method for transferring the integrated unit -

③ Criticality monitoring method for top-entry integral transfer plan (→ No. 16 to 18)

④ Monitoring range of three types of criticality approach monitoring (→ No. 19)

⑤ Organization of measurement procedures during fuel debris processing and retrieval work (→ No. 20)

⑥ Organization of the roles of criticality approach monitoring (→ No. 21)

⑦ Basic concept of criticality monitoring based on environmental conditions for aerial and underwater processing (→ No. 22)

⑧ Organization of criticality risks in underwater processing (→ No. 23,24)

⑨ Monitoring procedures in typical processing example (laser processing) (→ No. 25)

⑩ Monitoring system maintenance (→ No. 26)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures ① Criticality monitoring method during top-access retrieval

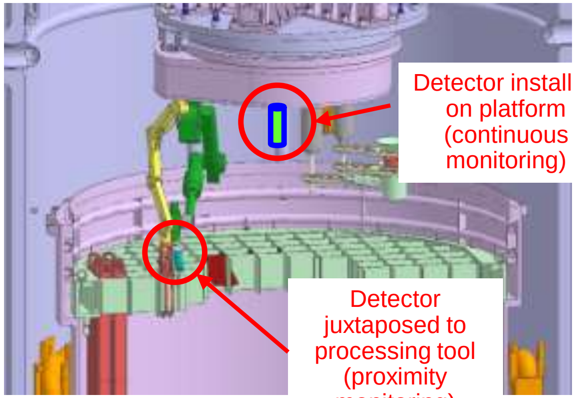
[Results of the study so far]

Taking the top-access retrieval method as a typical example, the method of criticality approach monitoring in the fuel debris retrieval step was investigated.

Criticality approach monitoring consists of three kinds of neutron measurements (← No.12), but it is not necessary to perform three types of monitoring in all work steps. (← No. 11)

Depending on the assumed criticality risk, use the necessary monitoring function properly.

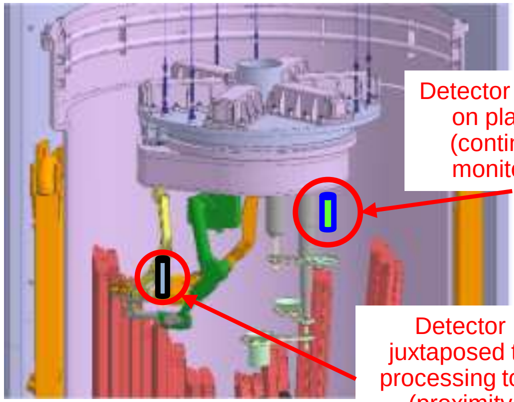
(3 kinds or 2 kinds of measurements;)



Detector installed on platform (continuous monitoring)

Detector juxtaposed to processing tool (proximity monitoring)

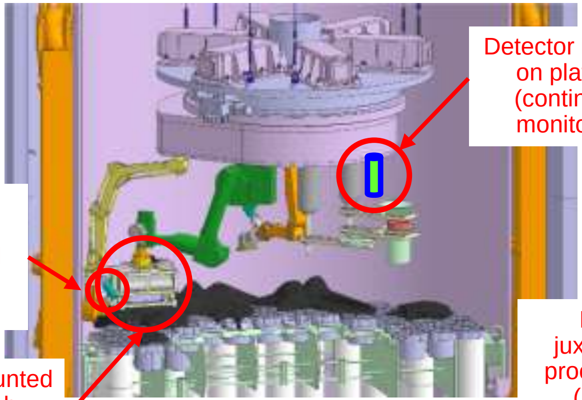
Upper grid plate



Detector installed on platform (continuous monitoring)

Detector juxtaposed to processing tool (proximity monitoring)

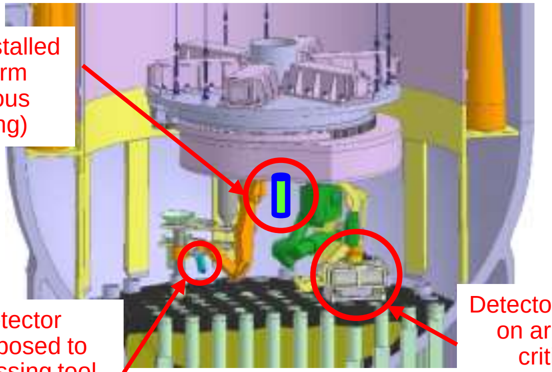
Remaining fuel ir



Detector juxtaposed to processing tool (proximity monitoring)

Detector mounted on arm (sub-criticality measurement)

Core support plate



Detector installed on platform (continuous monitoring)

Detector juxtaposed to processing tool (proximity monitoring)

Detector mounted on arm (sub-criticality measurement)

RPV bottom

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

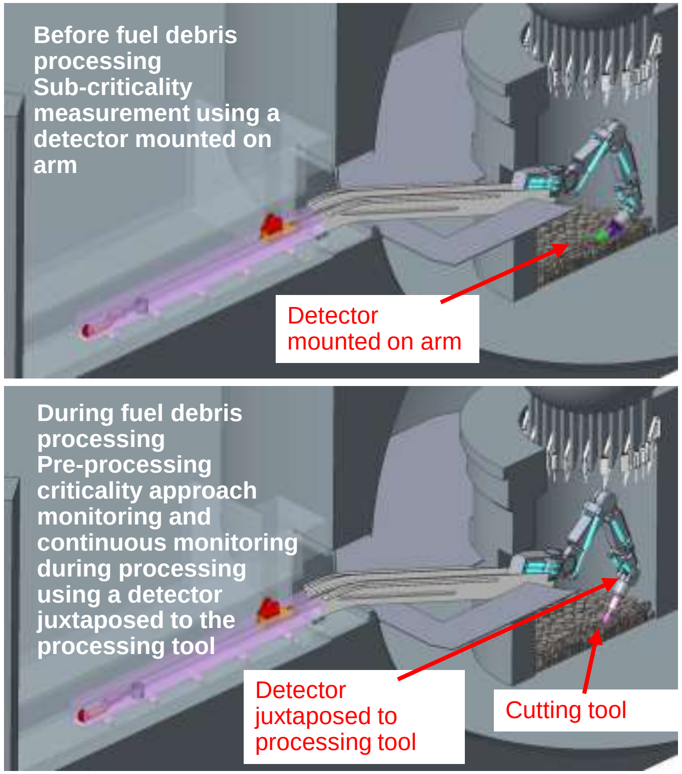
b. Examination of procedures② Criticality monitoring method during side-access retrieval

[Results of the study so far]

A criticality approach monitoring method was examined for the side-access retrieval method.

Of the three criticality monitoring functions, sub-criticality measurement is performed by a detector mounted on the arm, while criticality approach monitoring and continuous monitoring during processing are performed by a detector juxtaposed to the processing tool, thereby reducing the frequency of processing tool and detector replacement and minimizing the impacts on the fuel debris retrieval work throughput.

Criticality monitoring method during side-access retrieval



Before fuel debris processing
Sub-criticality measurement using a detector mounted on arm

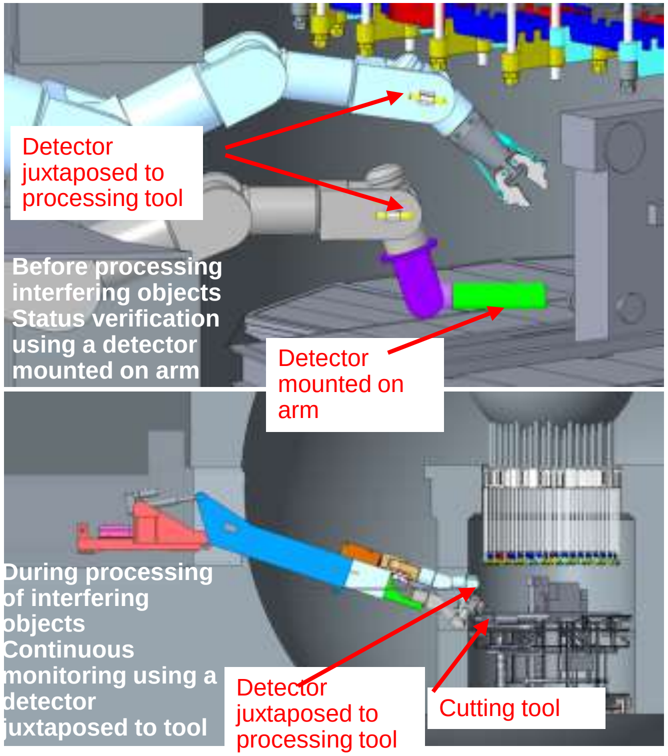
Detector mounted on arm

During fuel debris processing
Pre-processing criticality approach monitoring and continuous monitoring during processing using a detector juxtaposed to the processing tool

Detector juxtaposed to processing tool

Cutting tool

Figure Criticality monitoring during fuel debris retrieval (excerpt)



Detector juxtaposed to processing tool

Before processing interfering objects
Status verification using a detector mounted on arm

Detector mounted on arm

During processing of interfering objects
Continuous monitoring using a detector juxtaposed to tool

Detector juxtaposed to processing tool

Cutting tool

Figure Criticality monitoring during removal of interfering objects (excerpt)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring b. Examination of procedures

③ Criticality monitoring methods for side-entry PLAN-B method/top-entry integral transfer plan

[Details of study]

- For the work steps of the side-entry PLAN-B method and the modified method 2 for top-entry integral transfer plan B , the criticality approach monitoring procedures when applying the processing and collection methods using the following equipment were examined, and issues and risks were identified.

Loading and moving a neutron detector unit (simulant) using a heavy weight object transportation equipment (Side-entry PLAN-B method)

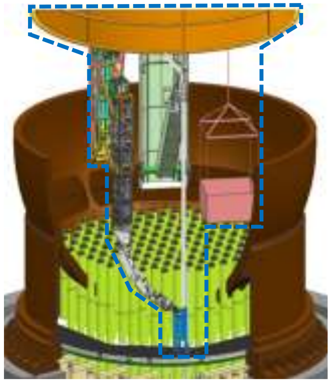


Illustration of removal of interfering objects at the bottom of the reactor (Modified method 2 for top-entry integral transfer plan B)

Loading and moving crushing and suction equipment by heavy weight object transportation equipment (Side-entry PLAN-B method)

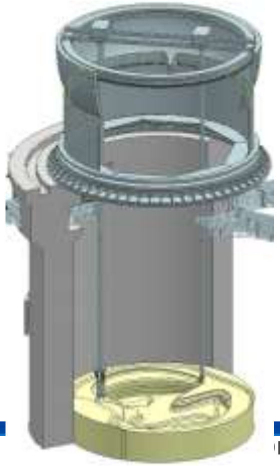


Illustration of fuel debris retrieval from the bottom of the pedestal after transferring the RPV bottom head and CRD housing (Modified method 2 for top-entry integral transfer plan B)

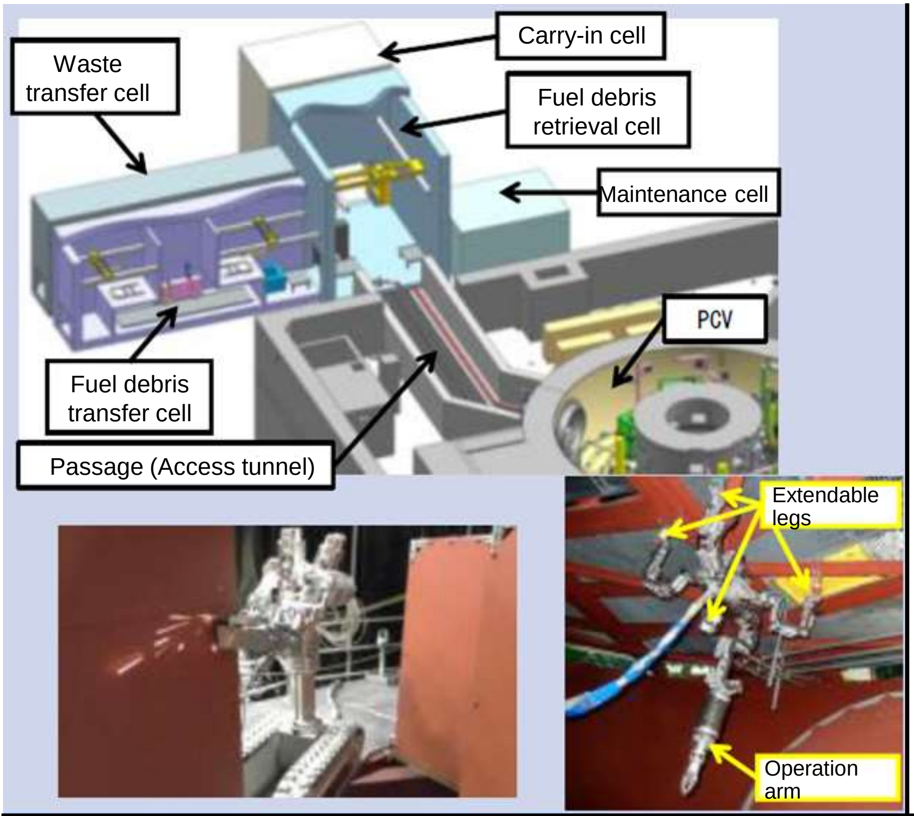
7. Implementation details

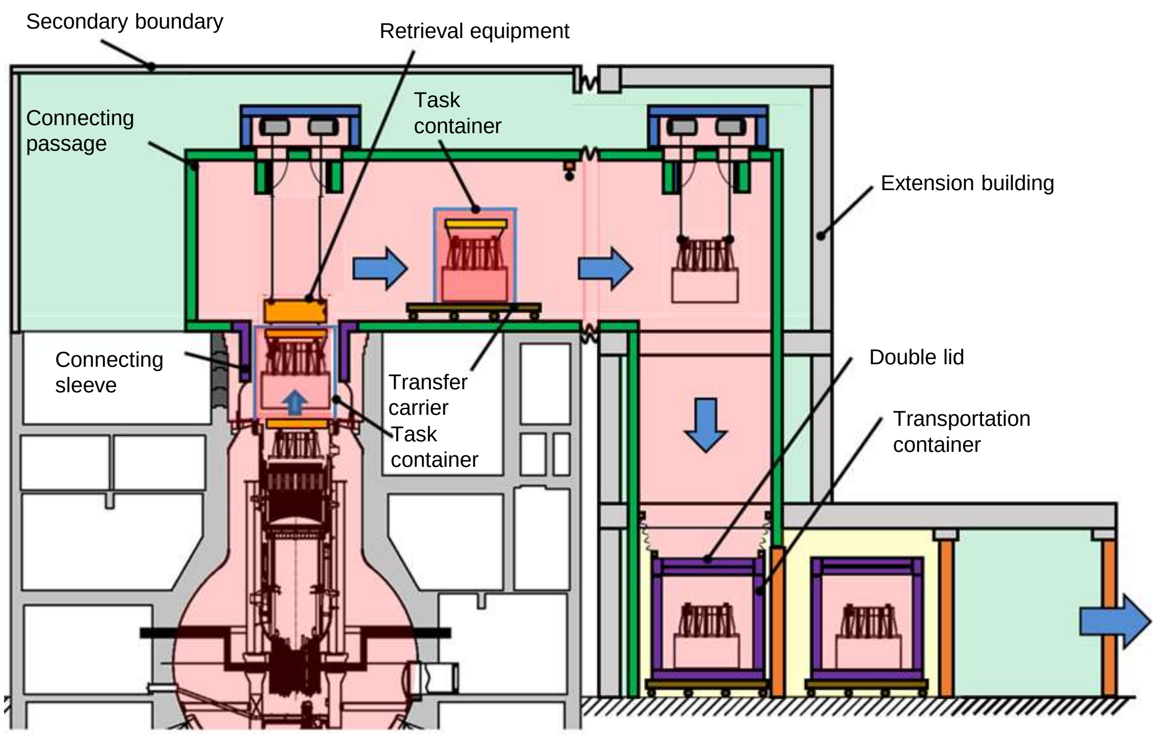
7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring b. Examination of procedures

③ Criticality monitoring methods for side-entry PLAN-B method/top-entry integral transfer plan

- Outline of the side-entry PLAN-B method and the modified method 2 for top-entry integral transfer plan B





- Access from the equipment hatch
- Use multiple operation equipment (some equipment are assembled in the PCV)

- Reactor internals including fuel debris are integrated with solidified material containing neutron absorbers and transferred
- Fuel debris at the bottom of the pedestal is retrieved by top-entry (lower right on the previous page)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring b. Examination of procedures

③ Criticality monitoring methods for side-entry PLAN-B method/top-entry integral transfer plan

[Study results]

- Issues and risks were identified in the table on the right for the work steps of the side-entry PLAN-B method and the modified method 2 for top-entry integral transfer plan B.

[Future study]

- The optimum criticality monitoring procedures for the identified issues and risks will be examined in collaboration with the project of Development of Fuel Debris Retrieval Method.

No.	Issue
1	Can the presence and amount of fuel debris be confirmed from camera images, neutron flux distribution, and characteristic gamma- ray distribution?
2	Is it possible to install neutron detectors with appropriate positional relationship and distance from the heavy weight object transportation equipment used to transport neutron detectors?
3	Is it possible to measure the degree of sub-criticality for fuel debris with a critical mass or more and several tens of kilograms?
4	Is it possible to install neutron detectors when the fuel debris has an inclined surface?
5	Is it possible to transport a neutron detector on the platform and install the neutron detector with appropriate positional relationship and distance?
6	By installing the equipment directly on the fuel debris, is there any reactivity input due to crack growth or water intrusion?
7	When processing and collecting sediments by lowering the water level, how to manage lumps that cannot be collected or accumulation of water in depressions?
8	It is assumed that the cutting surface will be lower than the bottom of the pedestal when retrieving bottom concrete-mixed fuel debris. Therefore, it is considered necessary to take measures to prevent stagnation of cooling water that had been discharged from the worker access tunnel.
9	Can neutron detectors be transported between the outer periphery of the shroud and the RPV, and installed at an appropriate positional relationship and distance?
10	Measures to prevent the outflow of the filling solidifying agent may prevent the cooling water from being discharged, causing reactivity input (transitional state until the solidifying agent is injected).

No.	Risk
1	Reactivity input due to falling of equipment onto fuel debris, crack growth due to impact, and water intrusion into the crack.
2	During processing, crack growth due to falling fuel debris, etc., exceeding critical mass.
3	Detachment of fuel debris from the solidified part, fall, crack growth due to impact, and reactivity input by water intrusion into the crack.

7. Implementation details

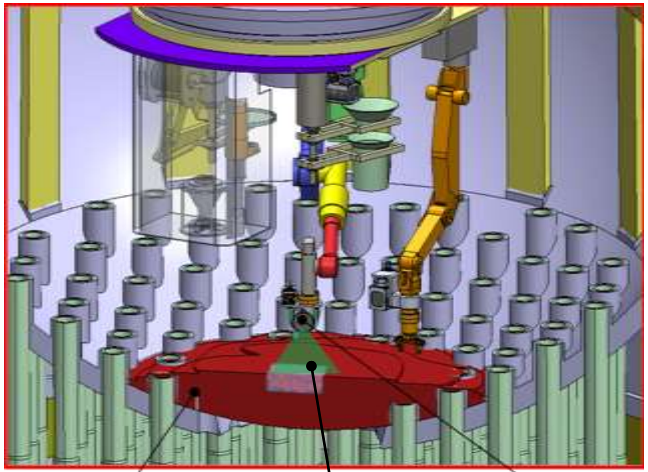
7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

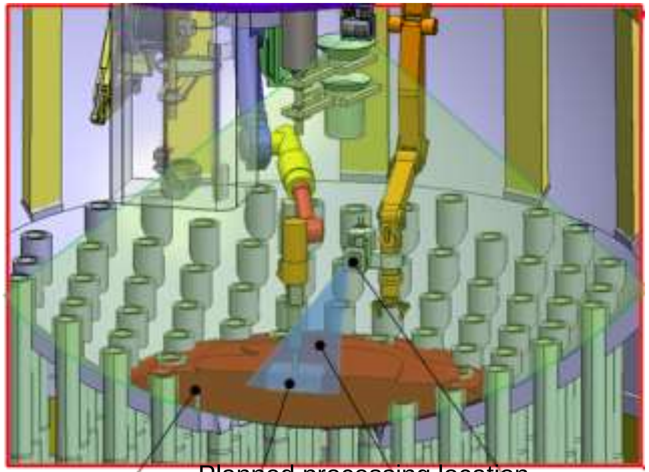
b. Examination of procedures ④ Monitoring range of three types of criticality approach monitoring

- **The monitoring ranges for each of the three types of criticality approach monitoring functions were organized. (The figure shows an example of top-access retrieval)**

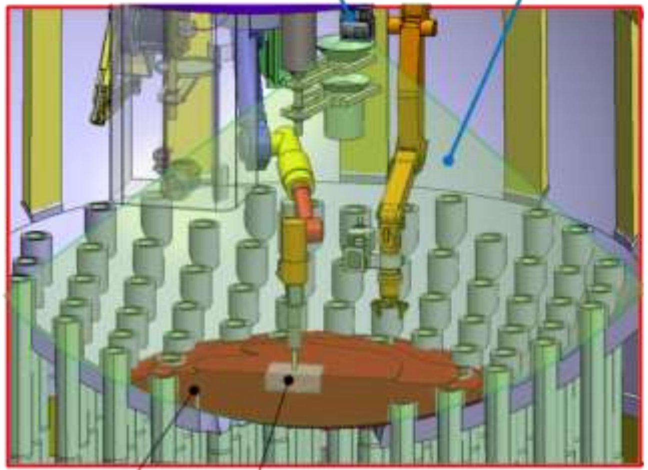
Function: **Sub-criticality measurement**
Measurement point: One point near the retrieval start position
Intended use: Grasping the state before work



Function: **Criticality approach monitoring before and after processing**
Measuring point: Moves appropriately according to processing position
Intended use: Decision to start processing



Function: **Continuous monitoring of neutron flux during processing**
Measurement point: A place that can be viewed from a distance from the processing position
Intended use: Detection of unexpected changes



7. Implementation details

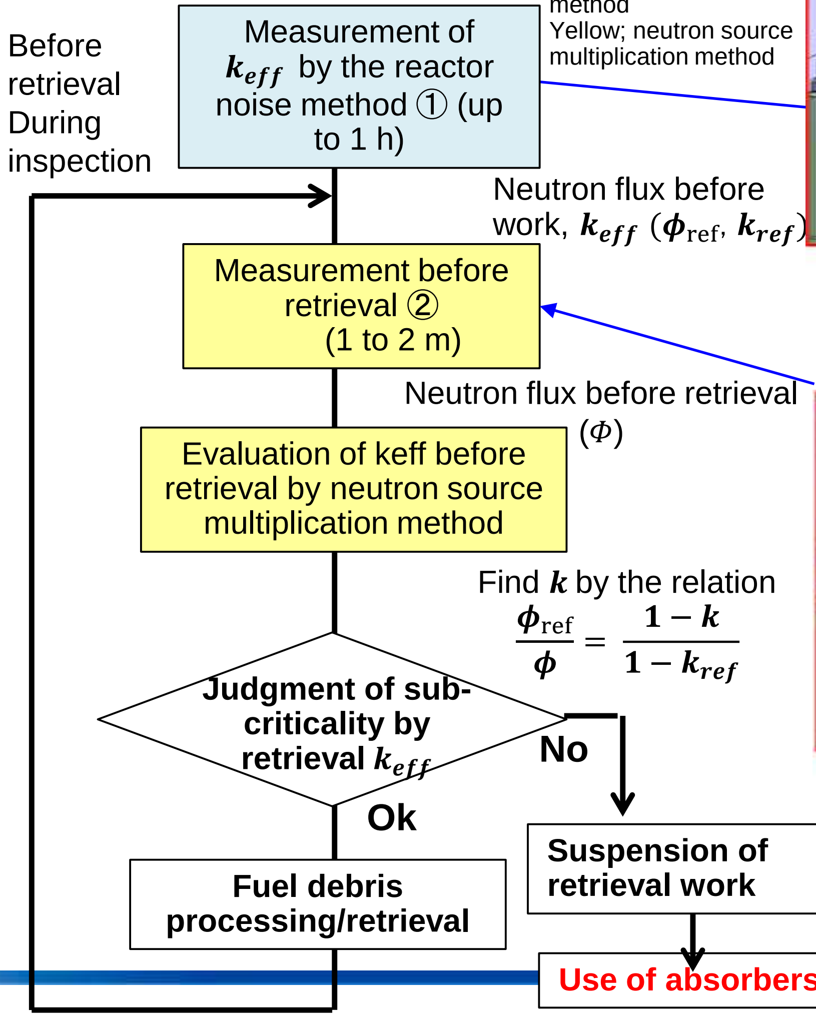
7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures ⑤ Organization of measurement procedures during fuel debris processing and retrieval work

- **The procedures for measurement during fuel debris processing and retrieval work was examined.**

- Tthe neutron multiplication factor (keff) is measured by reactor noise method before starting fuel debris retrieval work ①
  This is the criterion for the neutron source multiplication method.
- The neutron count rate is measured before and after fuel debris processing. ②
- Neutron count rate is continuously monitored during fuel debris retrieval processing.
- The neutron multiplication factor is evaluated (keff) by the neutron source multiplication method when the neutron count rate changes.
- The work is suspended when the neutron multiplication factor reaches the criterion
- Use absorbers.
- The neutron multiplication factor is measured (keff) by reactor noise method after using absorbers. ①
  This is a re-measurement of the neutron source multiplication criterion.



Before retrieval
During inspection

Measurement of k_{eff} by the reactor noise method ① (up to 1 h)

Light blue; reactor noise method
Yellow; neutron source multiplication method

Neutron flux before work, k_{eff} (ϕ_{ref}, k_{ref})

Measurement before retrieval ② (1 to 2 m)

Neutron flux before retrieval (Φ)

Evaluation of keff before retrieval by neutron source multiplication method

Find k by the relation

$$\frac{\phi_{\text{ref}}}{\phi}=\frac{1-k}{1-k_{ref}}$$

Judgment of sub-criticality by retrieval k_{eff}

No

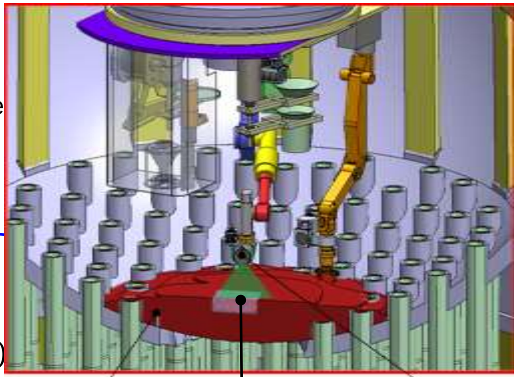
Ok

Fuel debris processing/retrieval

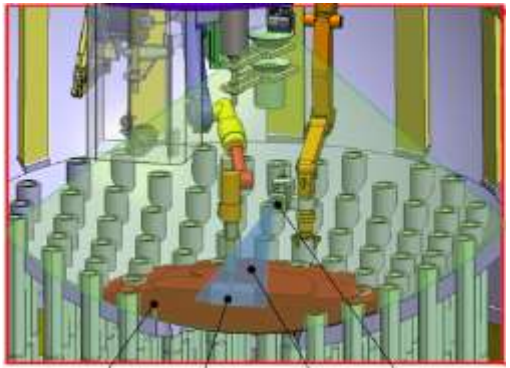
Suspension of retrieval work

Use of absorbers

Sub-criticality measurement



Criticality approach monitoring before and after processing



Continuous monitoring of neutron flux during processing
(always on, apart from the above diagram)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

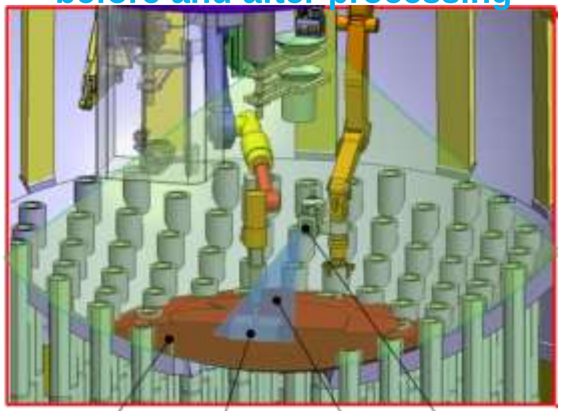
b. Examination of procedures ⑥ Organization of the roles of criticality approach monitoring

- **The role of the three monitoring functions during criticality approach was examined.**

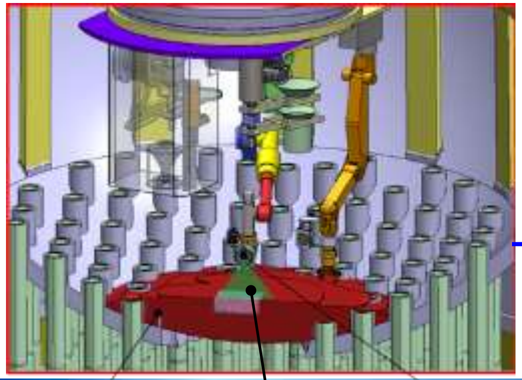
- The neutron multiplication factor (keff) is measured by reactor noise method before starting fuel debris retrieval work. ①
This is the criterion for the neutron source multiplication method.
- The neutron count rate is measured before and after fuel debris processing. ②
- The neutron count rate is continuously monitored during fuel debris retrieval processing
- The neutron multiplication factor (keff) is evaluated by the neutron source multiplication method when the neutron count rate changes
- The work is suspended when the neutron multiplication factor reaches the criterion
- Use absorbers
- The neutron multiplication factor (keff) is measured by reactor noise method after using absorbers ①
- Decision to resume work - resumption of work

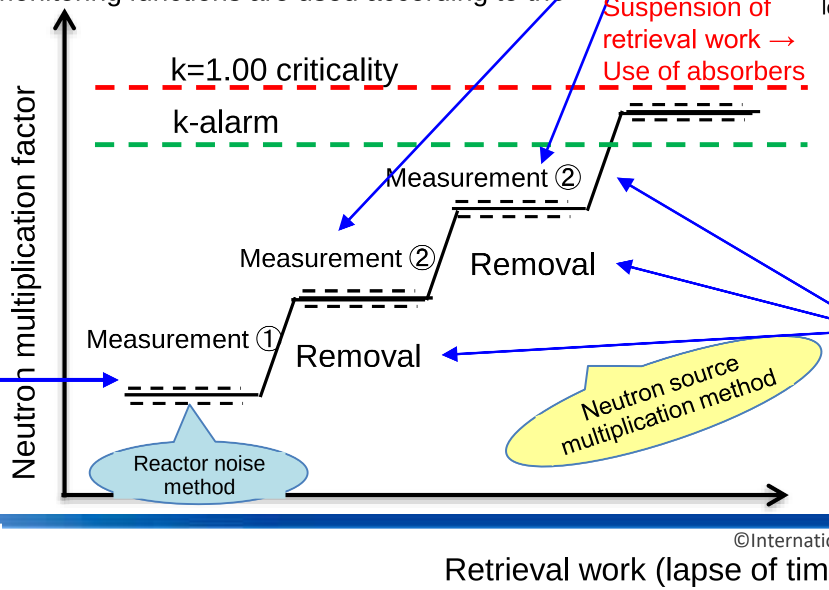
As described in No.14 to 15 sheets, the above monitoring functions are used according to the situation of on-site.

Criticality approach monitoring before and after processing

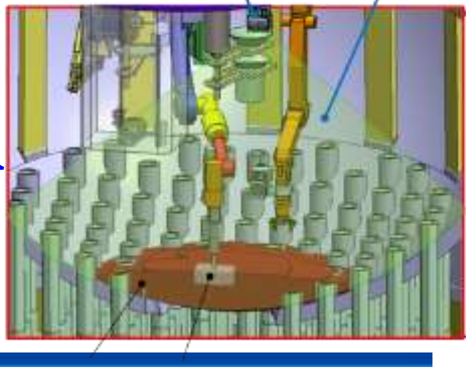


Sub-criticality measurement





Continuous monitoring of neutron flux during processing



7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures ⑦ Basic concepts of criticality monitoring based on the environmental conditions for aerial and underwater processing

- The environmental conditions for aerial processing and underwater processing, which are prerequisites for criticality control, were organized.
- The risk of criticality in the air is small, and the same control as underwater is not required, but local attention such as accumulation of water is required.

Aerial processing	Underwater processing
- There is no water level above fuel debris. - There is a possibility of accumulation of water under fuel debris. - Cooling water is flowing. - Water droplets are falling. - Processing is performed while water is sprinkled around the processing area to prevent dust from being dispersed.	- Water level is formed above fuel debris. - From the start of processing to collection, the process is performed underwater.

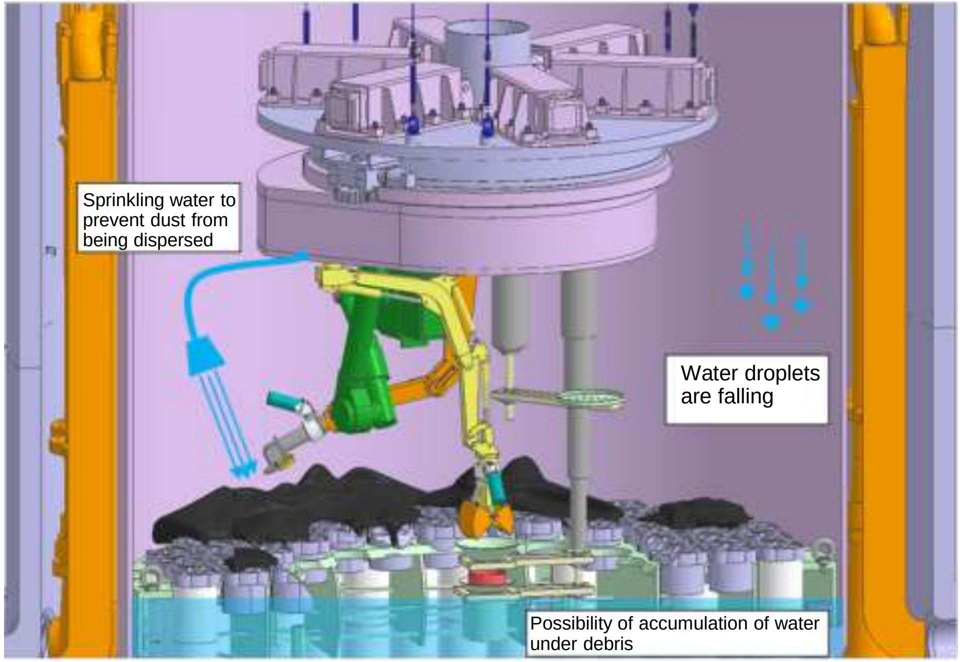


Figure 1 Environmental conditions for aerial processing

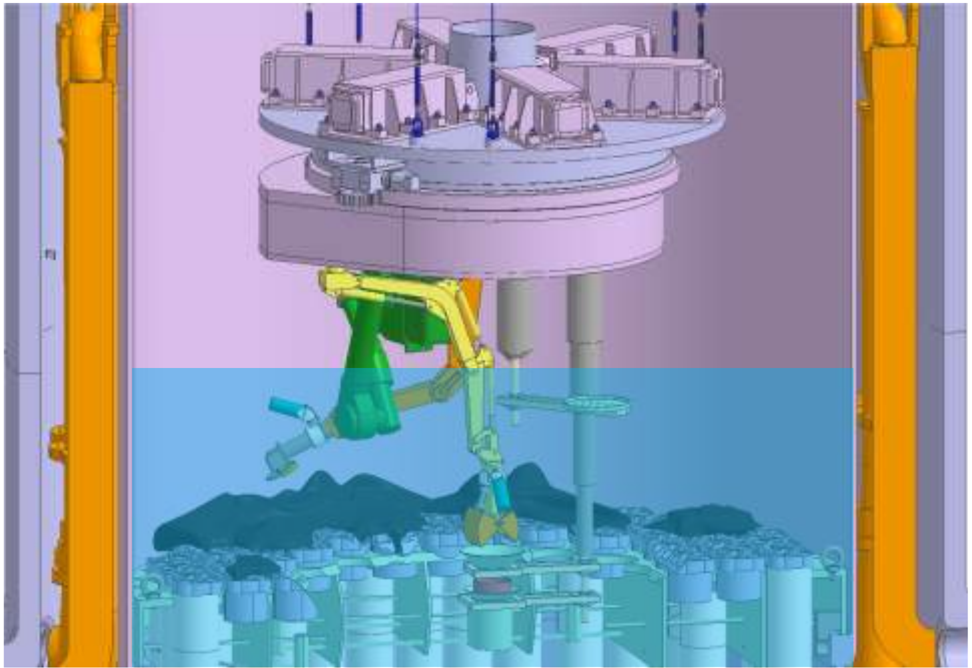


Figure 2 Environmental conditions for underwater processing

7. Implementation details

7.1 Development of on-site operating procedures

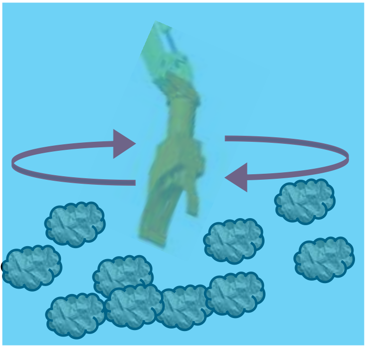
7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures

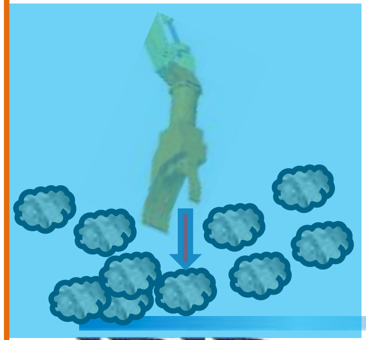
⑧ Organization of criticality risks in underwater processing

- The criticality risks of the processing method examined in the related project (*) was evaluated based on the analysis, etc.

Use other than intended method

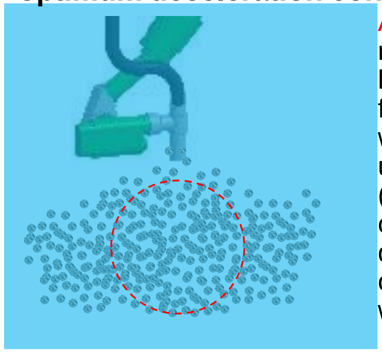


There is no criticality risk in picking up small pieces of fuel debris with a size of up to 200 mm (size that fits in a canister) underwater. However, attention is required when fuel debris retrieval work by using the robot arm including stirring and crushing small pieces of fuel debris.



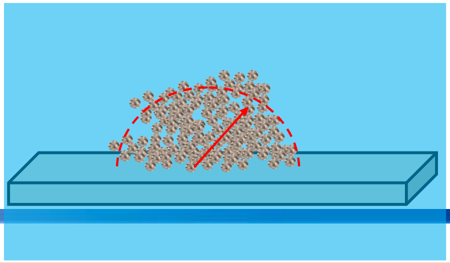
Attention is required when falling small pieces of fuel debris and collapsing the deposited small pieces of fuel debris.

Processing that may exceed the minimum critical mass under the optimum deceleration condition

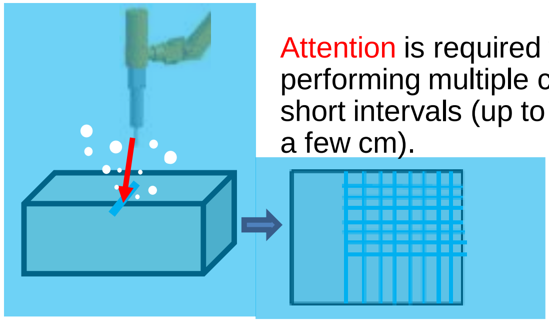


Attention is required when hoisting powdery fuel debris over a wide area underwater. (Indication: 46 cm or more in diameter, 71 kg or more in weight)

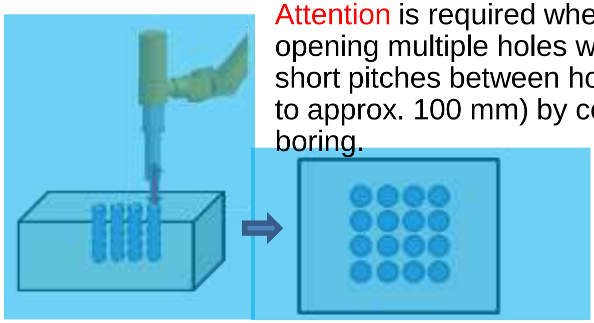
Attention is required when a large amount of powdery fuel debris are accumulated underwater. (Indication: radius of 35 cm or more, weight of 499 kg or more)



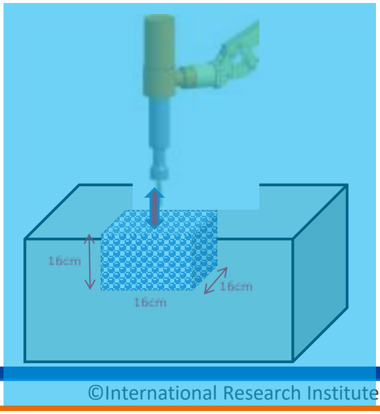
Processing where reactivity input may exceed 0.5% dk



Attention is required when performing multiple cuts at short intervals (up to approx. a few cm).



Attention is required when opening multiple holes with short pitches between holes (up to approx. 100 mm) by core boring.



When crushing fuel debris with a chisel, there is a risk of criticality if the processing area exceeds 16 x 16 x 16 cm.

(*) Related project "Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals" (FY2019/2020)

7. Implementation details

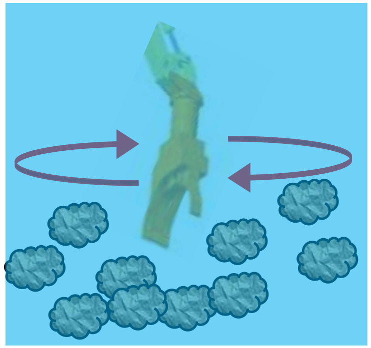
7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

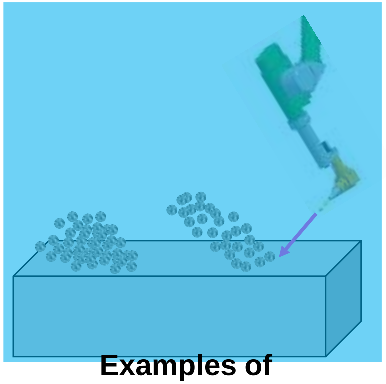
b. Examination of procedures

⑧ Organization of criticality risks in underwater processing

- The criticality risk for each processing method was organized separately for aerial processing and underwater processing.
- Even if there is no risk of criticality in the processing method itself, it is necessary to pay attention to unexpected usage and secondary effects other than the processing point.



Examples of unexpected usage



Examples of secondary effects

Table Criticality risk for each processing method

From the previous seat No.23

Classification	Processing methods	Properties/outlines (*)	Criticality risks	
			Aerial processing	Underwater processing
Picking up	Grabbing	Pinch small pieces of fuel debris	No	Caution
	Clamshell bucket	Scoop up small pieces of fuel debris	No	Caution
Suction	Suction	Suction/collection of fuel debris in powder form	No	Caution
Cutting	Laser gouging	Laser cutting of fuel debris surface	No	Caution
Opening holes	Core boring	- Sampling process with a hole saw - Separate cutting of the core is required - Water is required to discharge chips and cool blades	Be careful if there is accumulation of water	Caution
	Ultrasonic core drill	Capable of simultaneous processing of ceramics and metals		Caution
Cutting	Circular saw	Ceramics can be processed, but tool damage is severe. The cutting edge is serrated.		Caution
	Cutting wheel	Capable of simultaneous processing of ceramics and metals		Caution
	Hydraulic cutter	Hydraulic-driven scissors		Caution
	AWJ	Cutting with high-pressure water mixed with abrasives Cutting width is dispersed to the surrounding environment		Caution
	Laser cutting	Thermal cutting with laser heat		Caution
Crushing	Hammer (chisel)	Press the chisel against the object and crush it by hitting it with the up-and-down movement of the piston		Yes

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

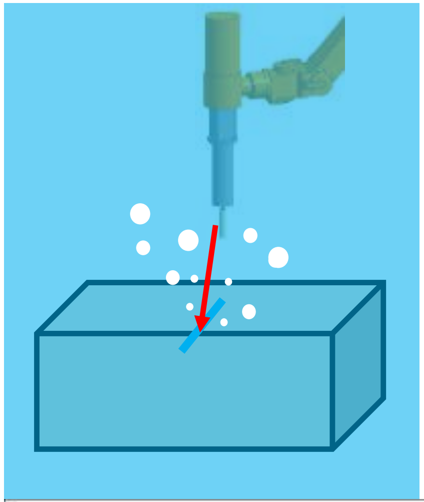
7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures

⑨ Monitoring procedures in typical processing example (laser processing)

- The procedure of measurement during fuel debris processing was examined using easy-to-understand laser cutting as a typical example.
- A condition was assumed in which a straight cut line generated in the fuel debris, and water entered the cut line, causing it to approach criticality.
- It is assumed that the neutron multiplication factor of the fuel debris before processing is around keff=0.95, which does not exceed the criterion.
- **The neutron count rate before processing should be measured.**
- When processing starts, the reactivity of Δk=0.016 is added in 10 minutes of processing, and the neutrons discharged from the fuel debris increase by a factor of 1.5. (Figure)
- **The neutron count rate was measured after processing**, and it was observed that the neutron count rate increased by a factor of 1.5. The neutron multiplication factor is estimated to have increased from 0.95 to 0.967 by neutron source multiplication method. (→ Sheet No. 20)
- It is judged that the neutron multiplication factor has exceeded the criterion, and the retrieval work is suspended (sheet No. 21).
- Procedures for other processing methods will also be examined in the future.

(Note) Although there is no risk of criticality due to a single cut, extreme condition was set as an easy-to-understand example.



[Evaluation conditions]
Fuel debris composition: 4 wt% enriched uranium structural material, no FP, Gd
The air cavities in the fuel debris are filled with water, and keff=0.95 in the initial condition before processing.
Assuming processing to insert a cutting line with a width of 2 cm, a depth of up to 60 cm, and a length of up to 60 cm. (Note)
The processing speed of laser cutting is 1 [mm/sec], and processing is performed for 10 minutes.
The MVP code was used to calculate the effective multiplication factor, and the one-point reactor kinetics analysis was used to calculate the neutron response.
Neutron source intensity 1 [n/sec]
Neutron detector detection efficiency 100 [%]

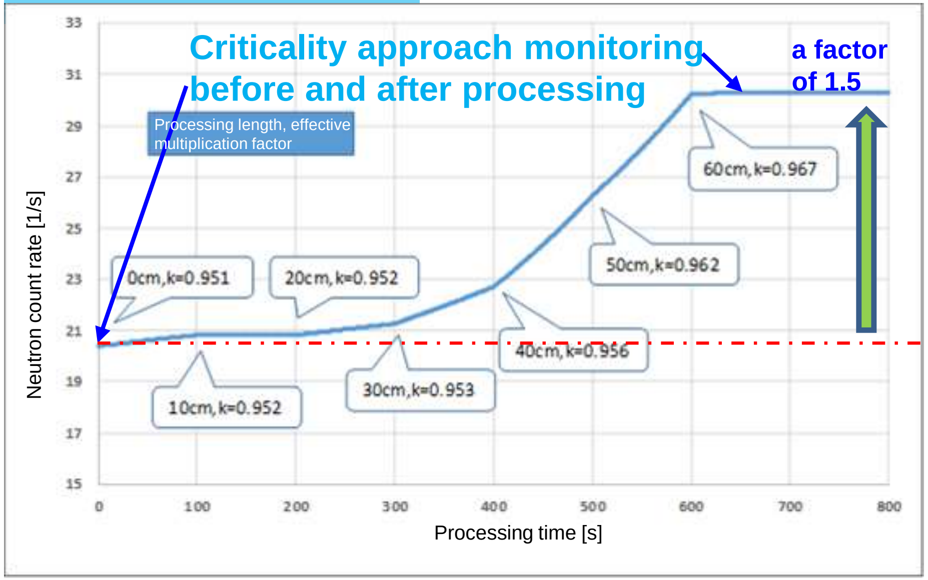


Figure Neutron response simulation assuming laser cutting

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

b. Examination of procedures

⑩ Monitoring system maintenance

- Regarding the maintenance of the criticality approach monitoring system, the concept of daily inspection, periodic inspection, and corrective maintenance was organized (Table).
- Daily inspections are performed by moving the detector unit to a maintenance area (assuming SFP, etc. (*)) in the building (Note 1) and by remote control (Note 2). (Figure)
- Part of the periodic inspection and corrective maintenance in the event of a problem are decontaminated and transferred out of the building, where workers carry out the work.

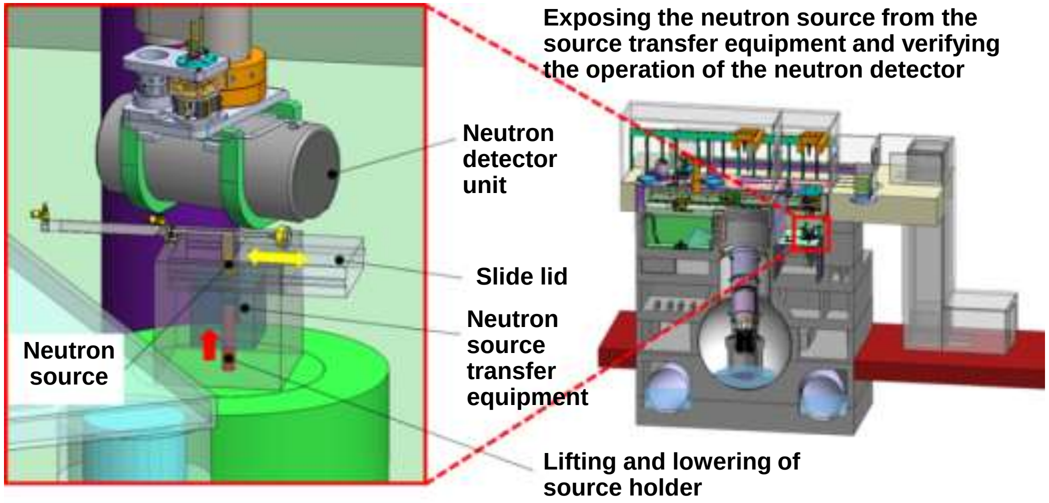


Figure Maintenance area inside the building

Table. Maintenance items of the criticality approach monitoring system

Goal	Frequency	Inspection details	Inspection items	Method
Preventive maintenance	Daily check	System integrity, noise impacts	Operation verification by neutron source, background measurement	The detector unit will be moved to the remote maintenance area, and the neutron source equipment installed there will be used to perform indirect maintenance of the fuel debris processing/collection equipment by remote control. (It takes about 1 hour)
	Periodic inspection 1 to 2 times/year	Detector/connector/cable integrity, detector sensitivity	Discriminator, insulation resistance, capacitance, cable characteristics, source calibration	If remote maintenance in the maintenance area is difficult, remove the detector unit from the fuel debris processing/collection equipment, lift it out of the PCV, decontaminate it, and then perform maintenance directly. (It takes several days)
Corrective maintenance	Irregular	Overhaul, repair, replacement,	Gas leak, insulation deterioration, poor contact, disconnection, circuit diagnosis, etc.	If a system malfunction occurs and the detector cannot be restored in the PCV, remove the detector unit from the fuel debris processing/collection equipment, lift it out of the PCV, decontaminate it, and then perform maintenance directly. (one week or more if disassembly/assembly is required)

(Note 1) It is a routine operation for the fuel debris retrieval equipment with the detector unit to move to the maintenance area and wait.

(Note 2) It is necessary to develop a method for remotely calibrating neutron detectors using neutron source.

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.1 Operating procedures for criticality approach monitoring

d. Interim Summary

[Results of this year]

While discussing operating procedures and throughput with the fuel debris retrieval method team (top-access retrieval/side-access retrieval/integral transfer), the following items were specified and shared.

- Three types of criticality approach monitoring roles and monitoring range
- Measurement procedures during fuel debris processing and retrieval work
- Concept of criticality monitoring in aerial processing and underwater processing
- Criticality risks in underwater processing
- Monitoring procedures when approaching criticality, using laser processing as a typical example
- Monitoring system maintenance

These will be the preconditions to be considered when the fuel debris retrieval method is to be implemented in the future.

[Future plans]

Based on the above procedures, the range of study will be expanded, such as development of processing methods other than laser, to evaluate the impacts on the throughput of fuel debris retrieval, aiming to optimize the operating procedures.

7. Implementation details

7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

[Issues]

Three types of neutron detectors (corona-type, SiC-type, and multicell He-3 type) have been developed in the related project (*) from the viewpoint of sub-criticality measurement (Figure 1). To verify the on-site applicability of these detectors, it is necessary to validate the ability to measure sub-criticality and evaluate the performance of criticality approach monitoring.

[Implementation details]

A sub-criticality system simulating fuel debris at the Kyoto University Critical Assembly (KUCA) was established. A sub-criticality measurement test using the developed neutron detectors was conducted. (Figure 2)

In addition, the neutron measurement performance was evaluated under gamma-ray environment.

[Goals]

- Evaluation of sub-criticality measurement performance of neutron detectors
- Reflection in operating procedures for neutron detectors assuming on-site conditions

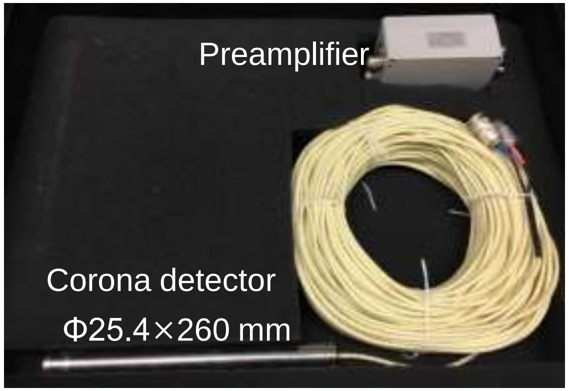


Figure 1 Appearance of Corona-based detector (^{10} B)

Figure 2 Kyoto University Critical Assembly

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

a. Test plan

Table. Summary of KUCA tests conducted in related projects up to the previous fiscal year and test items

Test 6	Neutron detector	Goal	Results
KUCA tests (1st, 2nd)	B10 proportional counter	Verify that sub-criticality can be measured in a small system using uranium fuel	- Measurement error (2% to 10%) for different degrees of sub-criticality, from near-criticality with neutron multiplication factor=0.95 to deep sub-criticality with 0.7 - Uncertainty of the mixing state of fuel debris and water (neutron energy spectrum) has little impacts on measurement errors - The measurable distance between the fuel debris and the detector is within 20 cm underwater and within 35 cm in air
KUCA tests (3rd)	B10 proportional counter	Verify that sub-criticality can be measured in a large (uniform) system using uranium fuel	Verified that local sub-criticality near the detector can be monitored (Monitoring of the entire system is difficult)
KUCA tests (4th)	B10 proportional counter	Verify the effects of large, non-uniform systems and neutron absorber placement	Measured sub-criticality in a system simulating non-uniform fuel debris, and verified position dependence. Verified that the sub-criticality can be measured by conducting a test in a state simulating the surface application of non-soluble neutron absorbers. (-15 to +14%)
KUCA tests (5th)	Corona-based SiC-type Multicell He-3 based	Verify that alternative candidates for neutron detectors can measure sub-criticality	June 28–July 9, 2021 Implemented

Target of this test

7. Implementation details

7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

a. Test plan

Table. Neutron detector candidates for sub-criticality measurement

No.	Detector name	Provider	Classification	Remarks
1	Fission ionization chamber	Photonis	Fission ionization chamber	Neutron detectors being considered for use in the investigation inside the PCV (considered in the related project (*))
Tested 2	Improved small-sized B-10 proportional counter	IRID/ Hitachi-GE	Gas Detector	
3	B-10 proportional counter	CETD		Neutron detectors that have been investigated for the criticality project (verified that these can be used for sub-criticality measurement by the Feynman-α method)
Target of this test 4	He-3 proportional counter (Multicell-based He-3 proportional counter)	CETD		
5	B-10 corona detector	RosRAO		Neutron detectors being considered for use in the investigation inside the PCV (highly radiation-resistant neutron detectors being considered in the related project*)
6	He-3 corona detector	RosRAO		
7	SiC detector	IPL	Semiconductor detector	
8	CMOS detector	IRID/Hitachi-GE		

(*) Related project "Development of Fundamental Technology for Retrieval of Fuel Debris and Reactor Internals (Development of Small Neutron Detectors)"

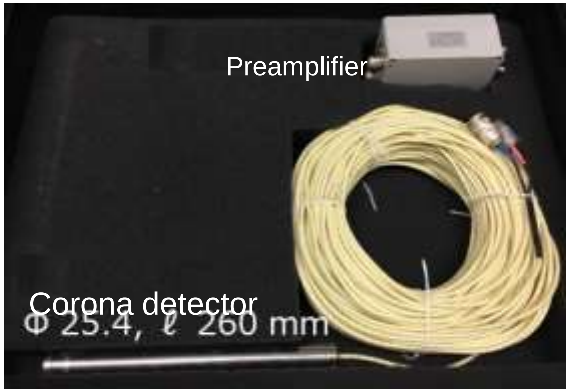
7. Implementation details

7.1 Development of on-site operating procedures

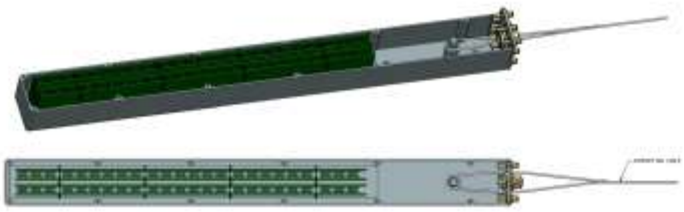
7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

b. Test preparation/arrangements

Appearance of neutron detectors whose performance was evaluated in the KUCA* test



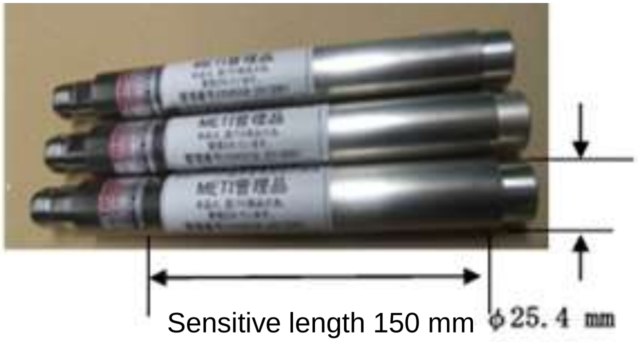
Corona-based neutron detector (B-10/He-3)



50×50×540 mm

SiC semiconductor-type neutron detector

Multicell-based He-3 proportional counter



Conventional B-10 proportional counter
(Reference; not used for testing this time)

*KUCA: Kyoto University Critical Assembly

7. Implementation details

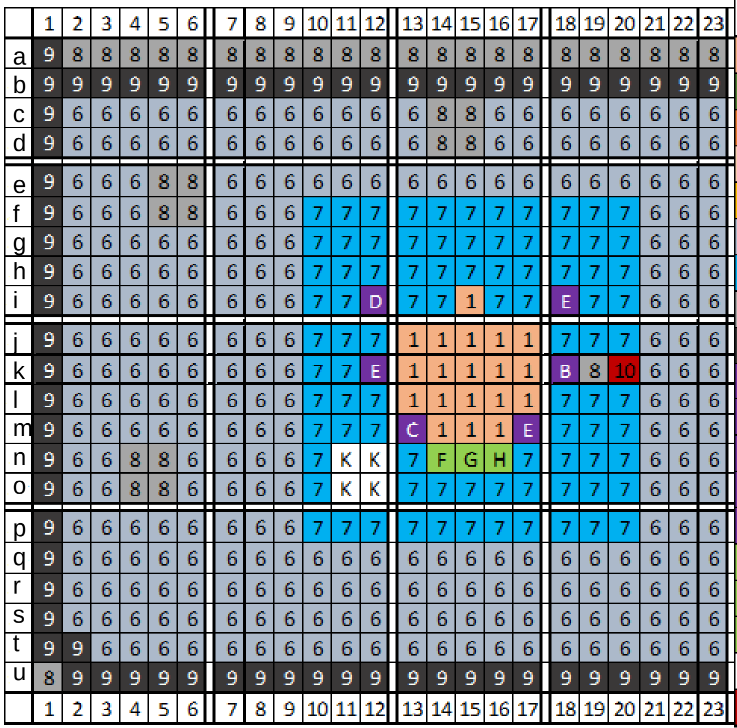
7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

c. Element test

KUCA* test system

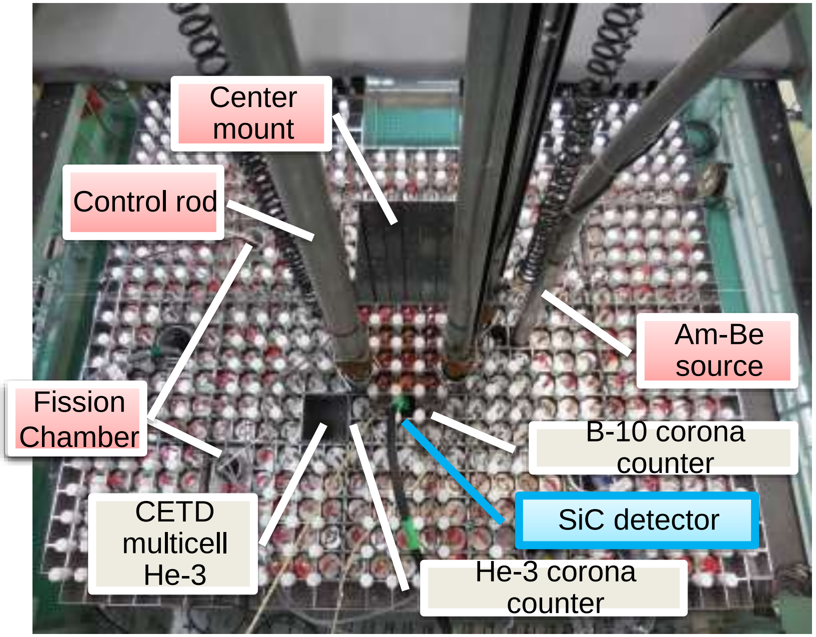
- The test core was composed of a fuel assembly combining enriched uranium and polyethylene (solid moderator)
- Neutron detectors to be tested were placed adjacent to the fuel assembly, time-series data of neutron counts is collected, and analysis was performed by the Feynman-α method



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
a	9	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
b	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
c	9	6	6	6	6	6	6	6	6	6	6	6	6	8	8	6	6	6	6	6	6	6	6
d	9	6	6	6	6	6	6	6	6	6	6	6	6	8	8	6	6	6	6	6	6	6	6
e	9	6	6	6	8	8	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
f	9	6	6	6	8	8	6	6	6	7	7	7	7	7	7	7	7	7	7	7	6	6	6
g	9	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	6	6	6
h	9	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	6	6	6
i	9	6	6	6	6	6	6	6	6	7	7	D	7	7	1	7	7	E	7	7	6	6	6
j	9	6	6	6	6	6	6	6	6	7	7	7	1	1	1	1	1	7	7	7	6	6	6
k	9	6	6	6	6	6	6	6	6	7	7	E	1	1	1	1	1	B	8	10	6	6	6
l	9	6	6	6	6	6	6	6	6	7	7	7	1	1	1	1	1	7	7	7	6	6	6
m	9	6	6	6	6	6	6	6	6	7	7	7	C	1	1	1	E	7	7	7	6	6	6
n	9	6	6	8	8	6	6	6	6	7	K	K	7	F	G	H	7	7	7	7	6	6	6
o	9	6	6	8	8	6	6	6	6	7	K	K	7	7	7	7	7	7	7	7	6	6	6
p	9	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	6	6	6
q	9	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
r	9	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
s	9	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
t	9	9	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
u	8	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

ID	Description
1	3/8” p32 EU fuel assembly
2	1/8” p72 EU fuel assembly
3	1/8” p54 EUEU fuel assembly
4	3/8” p10 EU fuel assembly
5	Absorbent sample cell
6	Old PE block cell
7	New PE block cell
8	Void, KUCA instrumentation cell
9	Graphite cell
A	Control rod full stroke
B	C1 rod cell (adjustment rod)
C	C2 rod cell (adjustment rod)
D	C3 rod cell (adjustment rod)
E	Safety bar cell (S4 to S5)
F	He-3 corona counter
G	IPL SiC detector
H	B-10 corona counter
K	CETD multicell He-3
10	AmBe source

The KUCA test core and detector layout (keff=0.95)



Actual test

*KUCA: Kyoto University Critical Assembly

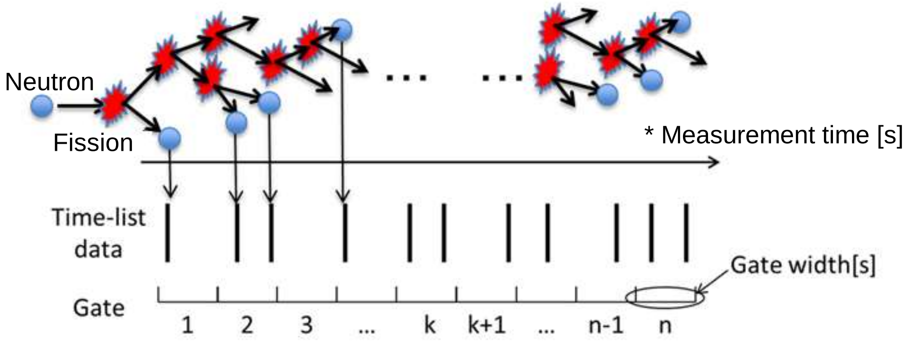
7. Implementation details

7.1 Development of on-site operating procedures

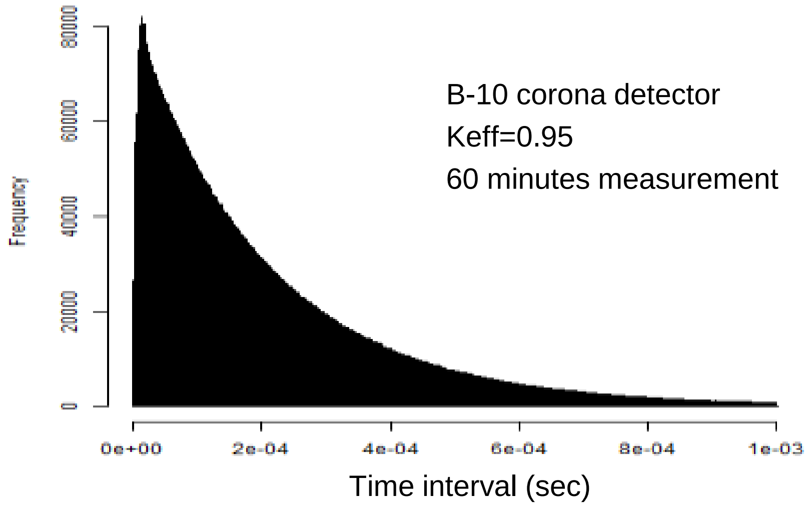
7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

c. Element test

Evaluation procedure for sub-criticality measurement (Feynman-α method)



Conceptual image of data to be acquired

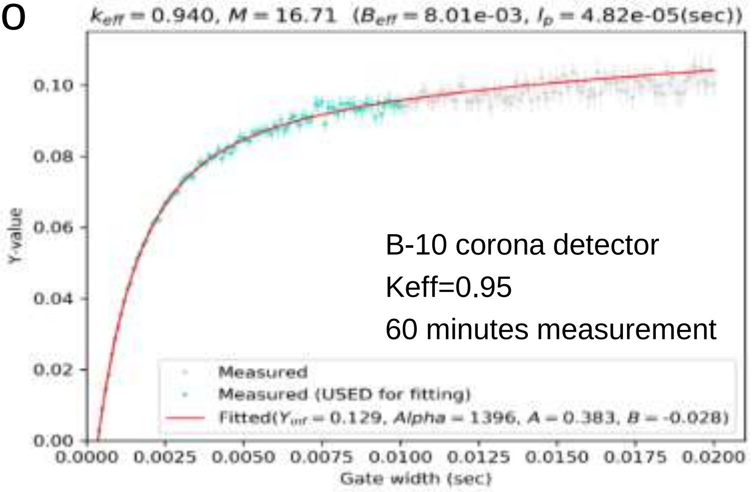


B-10 corona detector

Keff=0.95

60 minutes measurement

Frequency distribution of time-list data



B-10 corona detector

Keff=0.95

60 minutes measurement

Plot the variance-to-mean ratio (Y value)

$$Y(\Delta T) = Y\infty\left(1 - \frac{1 - \exp(-\alpha \Delta T)}{\alpha \Delta T}\right)$$

α (prompt neutron attenuation constant) is determined by fitting (red line) with a theoretical formula.

$$k_{eff} = \frac{1 - \alpha \ell}{1 - \beta}$$

Keff is determined from the measured α and pre-calculated l and β.

The keff obtained above was compared with the keff calculated by the analysis code (reference solution).

7. Implementation details

7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

c. Element test

Results of KUCA* test (Corona-based, Multi-cell based)

- The availability of corona-type and multicell He-3 type detectors was verified to measure sub-criticality with the same level of accuracy as the conventional B-10 proportional counter (Figure and Table).
- Regarding the multi-cell He-3 type detector, the event in which the counting value fluctuated and the operation became unstable was verified.

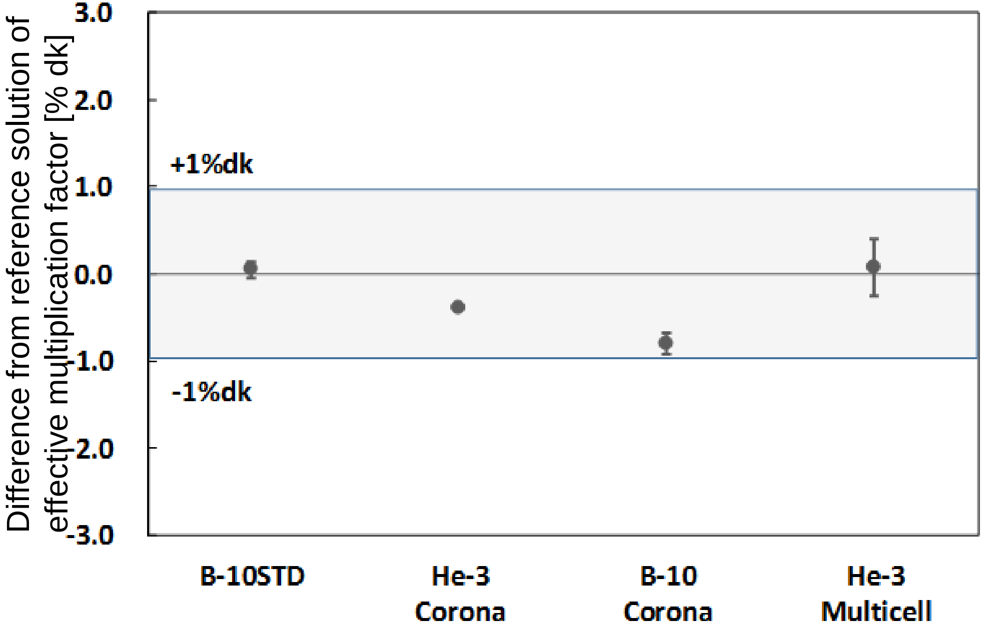


Figure Difference between measured value and reference solution (keff=0.95)

	B-10 proportional counter	He-3 corona detector	B-10 corona detector	Multicell-based He-3 proportional counter
Difference from reference solution	+0.05%dk	-0.39%dk	-0.80%dk	+0.08%dk
Uncertainty	±0.09% dk	±0.03% dk	±0.12% dk	±0.32% dk
Measurement time (min)	30, 30	10, 10, 12, 33, 60	10, 10, 12, 30, 60	10
Number of data	2	5	5	1

Table Measurement results for each detector (keff=0.95)

Since the keff calculation of the KUCA test system by the MVP code tends to overestimate by about 0.5% dk in the criticality state, this is corrected

*KUCA: Kyoto University Critical Assembly

7. Implementation details

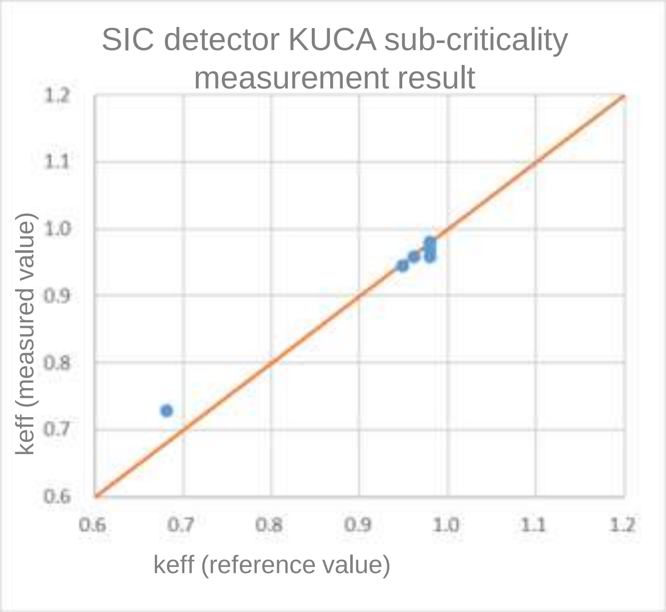
7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

c. Element test

Results of KUCA* test (SiC-type semiconductor)

- The degree of sub-criticality was evaluated after the data obtained by the SiC semiconductor-type detector was processed by the Feynman-α method. As shown in the table below, it was verified that sub-criticality can be measured with a difference of about 1% when keff is around 0.9. When the sub-criticality is deep, the difference from the reference value increases to approximately 7%, but it was verified that the sub-criticality can be measured with the same accuracy as the conventional B-10 proportional counter.



Reference value: Core analysis value by MVP

Figure Difference between measured and reference values (SiC semiconductor-type neutron detector)

Table Measurement results for each test system

Test core	Reference value	Measured value	Difference (%)	Remarks
Case1-1 (keff=0.95)	0.948	0.944	-0.4	
Case1-2 (keff=0.97)	0.962	0.958	-0.4	
Case1-3 (keff=0.98)	0.979	0.968	-1.1	Measurements with different pulse shape discrimination parameters
	0.979	0.958	-2.1	
	0.979	0.981	0.2	
Case1-4 (keff=0.70)	0.681	0.729	7.0	

*KUCA: Kyoto University Critical Assembly

7. Implementation details

7.1 Development of on-site operating procedures

7.1.2 Verification of applicability of neutron detectors to sub-criticality measurement

Summary of results

[Results of this year]

- ✓ Sub-criticality measurement tests for three types of new neutron detectors (corona-type, SiC-type, and multicell He-3 type) were conducted at the Kyoto University Critical Assembly (KUCA).
- ✓ It was verified that sub-criticality can be measured by using corona-type, multicell He-3 type, and SiC semiconductor-type detectors with the same accuracy as the conventional B-10 proportional counter.

[Future plans]

- ✓ Neutron measurement tests for the corona-type and multicell He-3 type detectors will be conducted under gamma-ray environment.
- ✓ The sub-criticality measurement performance will be comprehensively evaluated, taking into account the effects of the assumed on-site gamma-ray environment.

As of the middle of March 2022

7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

[Issues]
In the related project (*), a method of inserting non-soluble neutron absorbers into fuel debris is being examined. (Figure 1) In order to discuss operating procedures and throughput with the debris retrieval method team, it is necessary to specify the procedures for neutron absorber dispersion and injecting equipment operation.

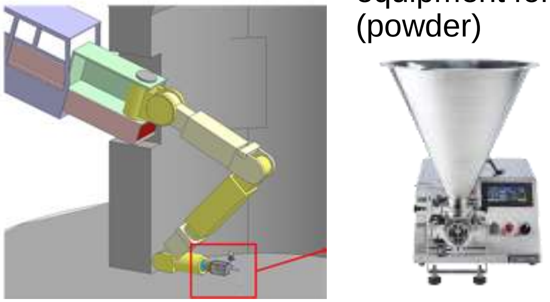
[Implementation details]

- For the fuel debris retrieval method and processing/collection equipment examined in the related project (*), the procedures for dispersing non-soluble neutron absorbers to fuel debris were consolidated in a step diagram.
- Study of applicable conditions for fuel debris processing scenes, proper use of absorbers, effectiveness of pre-insertion, and reduction in size and weight of the injecting equipment.
- Evaluation of the operability and feasibility of the entire procedures together with the criticality approach monitoring operating procedures (item 7.1.1).

[Goals]

- Development of on-site operation procedures for non-soluble neutron absorbers and sharing them with the fuel debris retrieval method team.

Glass material containing B/Gd | Gd2O3 particles | Water glass/Gd2O3 granulated powder



Example of injecting equipment for solids (powder)

Figure 1 Illustration of inserting absorbers into fuel debris

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

a. Organization of preconditions

Appropriate use of absorbers

- Various shapes such as rods and particles are assumed for fuel debris. So far, it has been shown that the optimum type of neutron absorber should be used according to the shape of fuel debris.
- Non-soluble neutron absorbers are classified into solid type and type that solidifies from liquid to solid over time (water glass type). Since the water glass type has fluidity and viscosity immediately after insertion, the type is effective when the residual fuel (stump fuel) stands vertically (Figure 5), when the gap between fuel debris is small (Figures 3 and 4), or when the debris surface has large unevenness (Figure 6).

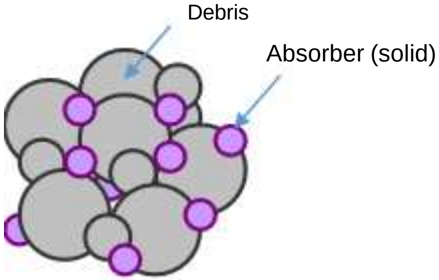


Figure 1 Using a solid type absorber for pebble-like fuel debris

Figure 3 Using a liquid → solidification type absorber for pebble-like fuel debris

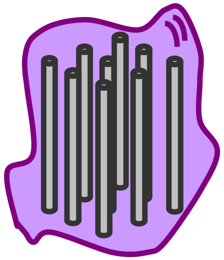


Figure 5 Using liquid → solidification type absorber for rod-shaped fuel debris

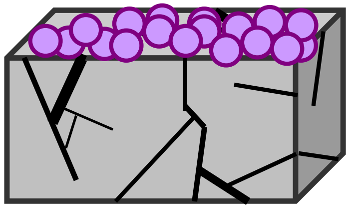


Figure 2 Using a solid type absorber for bedrock-like fuel debris

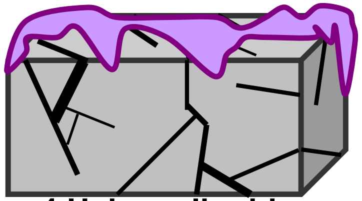


Figure 4 Using a liquid → solidification type absorber for bedrock-like fuel debris

Figure 6 Using a liquid → solidification type absorber for fuel debris with large unevenness

7. Implementation details

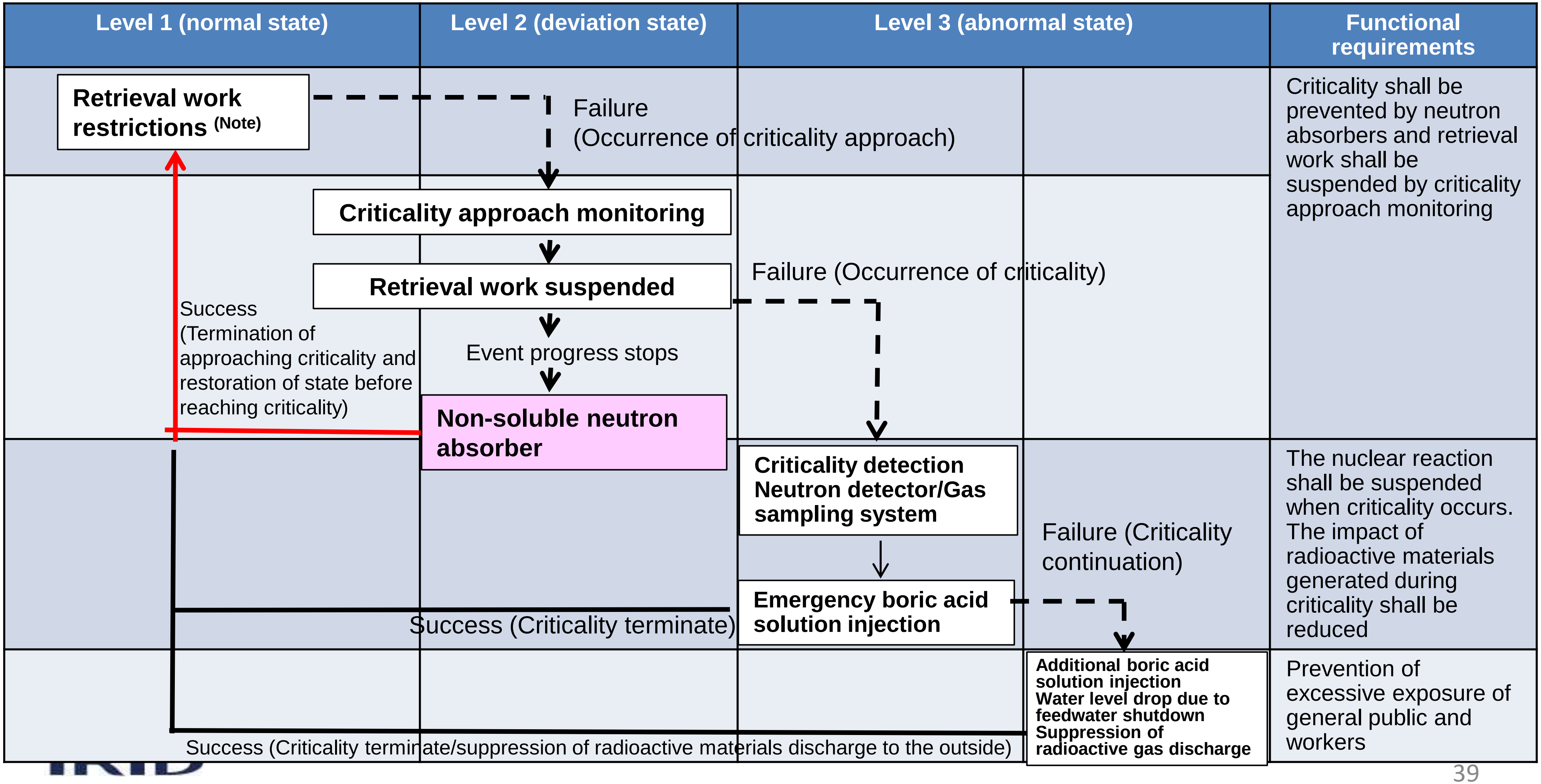
7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

a. Organization of preconditions **Positioning of defense in depth**

- Since the use of non-soluble neutron absorbers affects the throughput of fuel debris retrieval, the policy is to use them at level 2 for the retrieval processing position.

(Note) This table covers events that become criticality due to fuel debris retrieval work when boric acid solution is not used at all times. See No. 46 for events caused by falling fuel debris, etc.



Level 1 (normal state)	Level 2 (deviation state)	Level 3 (abnormal state)	Functional requirements

Retrieval work restrictions (Note)

Failure (Occurrence of criticality approach)

Criticality approach monitoring

Retrieval work suspended

Event progress stops

Non-soluble neutron absorber

Success (Termination of approaching criticality and restoration of state before reaching criticality)

Failure (Occurrence of criticality)

Criticality detection Neutron detector/Gas sampling system

Emergency boric acid solution injection

Success (Criticality terminate)

Failure (Criticality continuation)

Additional boric acid solution injection Water level drop due to feedwater shutdown Suppression of radioactive gas discharge

Success (Criticality terminate/suppression of radioactive materials discharge to the outside)

Criticality shall be prevented by neutron absorbers and retrieval work shall be suspended by criticality approach monitoring

The nuclear reaction shall be suspended when criticality occurs. The impact of radioactive materials generated during criticality shall be reduced

Prevention of excessive exposure of general public and workers

7. Implementation details

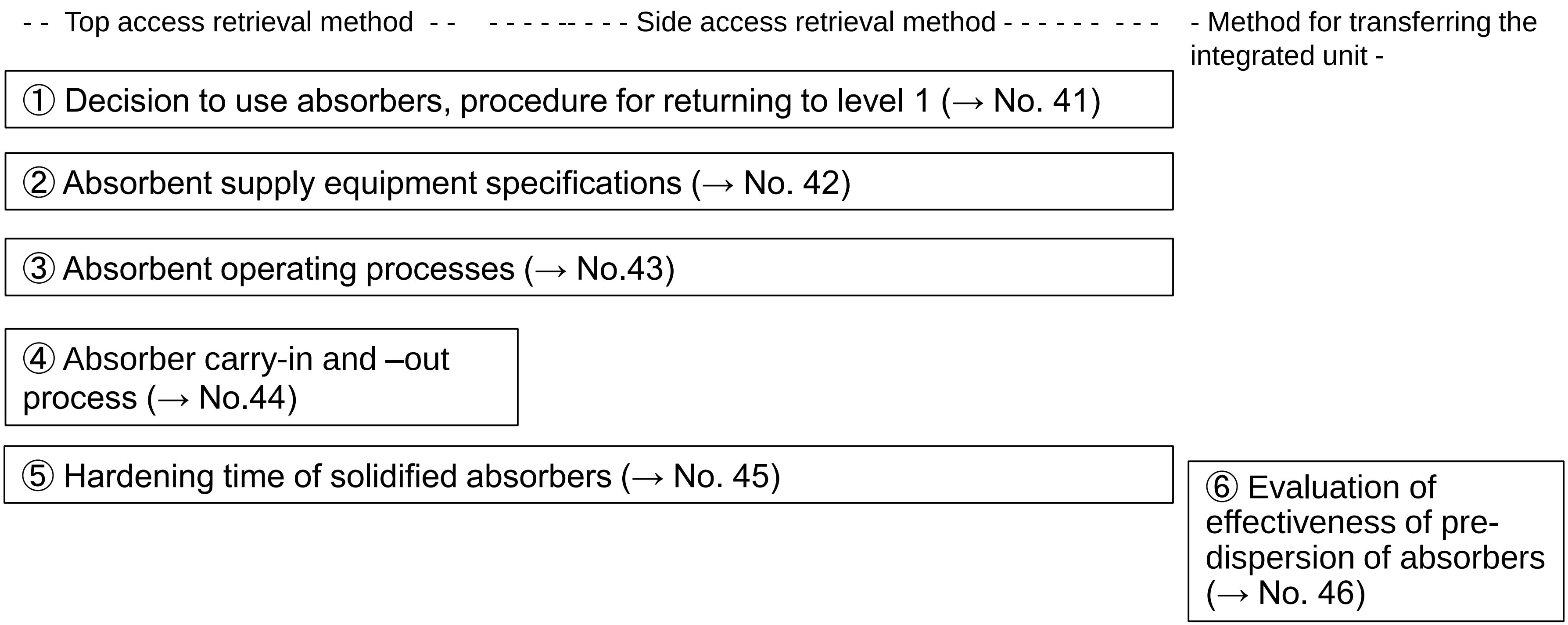
7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

b. Examination of procedures

Outline of implementation details of 7.1.3.b

While discussing the operating procedures and throughput with the fuel debris retrieval method team, six items identified as issues were examined.



- - Top access retrieval method - -

- - - - - -- - - - Side access retrieval method - - - - - - - - - -

- Method for transferring the integrated unit -

① Decision to use absorbers, procedure for returning to level 1 (→ No. 41)

② Absorbent supply equipment specifications (→ No. 42)

③ Absorbent operating processes (→ No.43)

④ Absorber carry-in and –out process (→ No.44)

⑤ Hardening time of solidified absorbers (→ No. 45)

⑥ Evaluation of effectiveness of pre-dispersion of absorbers (→ No. 46)

7. Implementation details

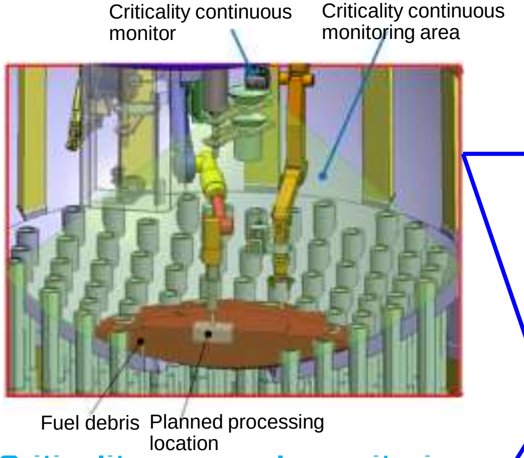
7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

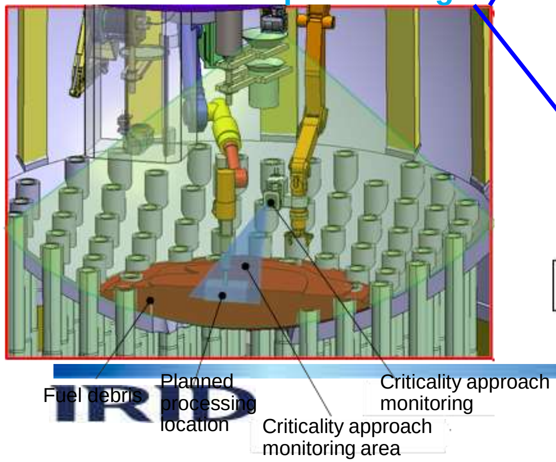
b. Examination of procedures ① Decision to use absorbers, procedures for returning to Level 1

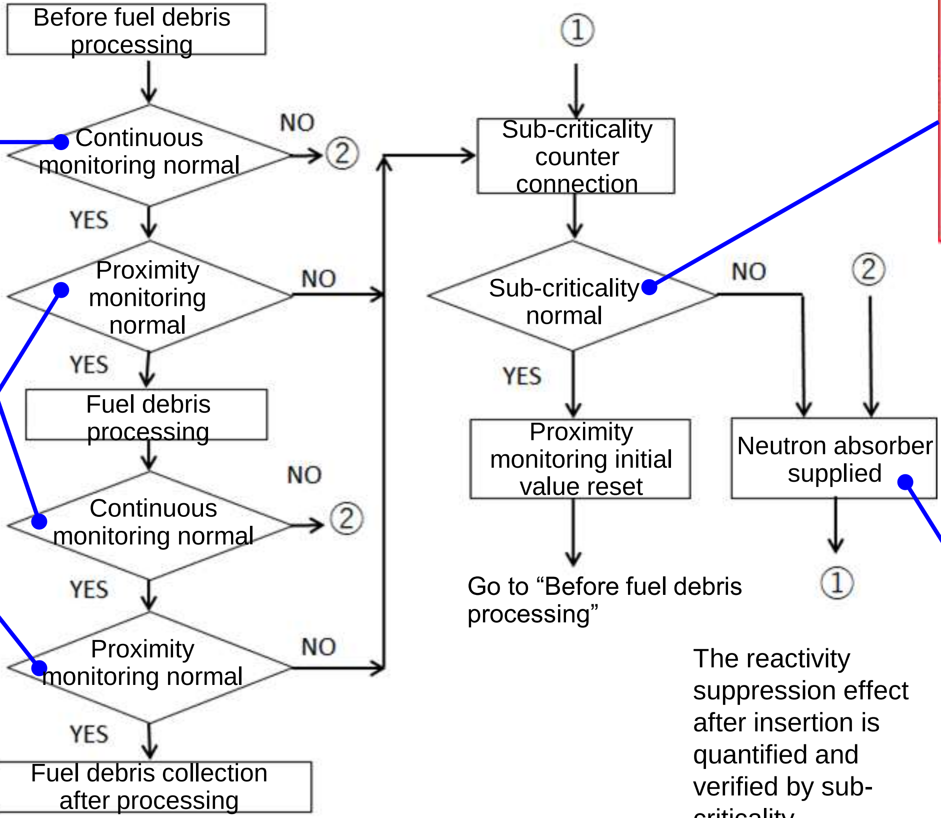
- Organized the decision to use absorbers and the procedures for returning to level 1

Continuous monitoring of neutron flux during processing



Criticality approach monitoring before and after processing




Before fuel debris processing

Continuous monitoring normal — NO → ② / YES ↓

Proximity monitoring normal — NO → Sub-criticality counter connection / YES ↓

Fuel debris processing

Continuous monitoring normal — NO → ② / YES ↓

Proximity monitoring normal — NO → Sub-criticality counter connection / YES ↓

Fuel debris collection after processing

① ↓

Sub-criticality counter connection

Sub-criticality normal — NO → Neutron absorber supplied / YES ↓

Proximity monitoring initial value reset

Go to "Before fuel debris processing"

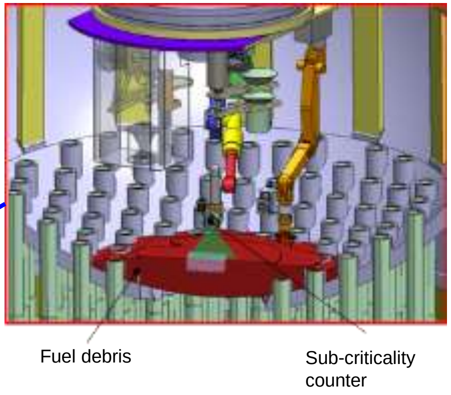
② ↓

Neutron absorber supplied

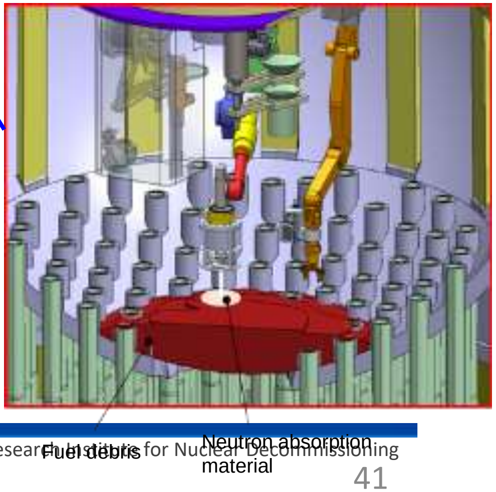
↓ ①

The reactivity suppression effect after insertion is quantified and verified by sub-criticality measurement.

Sub-criticality measurement



Neutron absorber insertion



7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

b. Examination of procedures ② Absorbent supply equipment specifications

- Based on the required amount of absorber (Table) reviewed in the related project (*), the specifications of the absorbent supply equipment was reviewed and the volume was reduced to about half. (Figures 1 and 2)

Table Required amount of absorber

Non-soluble neutron absorber	Absorbent weight (Note 1) (kg/day)	Absorbent capacity (liters/day)
Gd_2O_3 particles	6.4	1.5
Water glass/Gd_2O_3 granulated powder	6.3	3.0

Note 1: It is assumed that the fuel debris retrieval target per day is 300 kg.
Assume that 50% of the inserted absorber functions effectively (safety factor doubled)

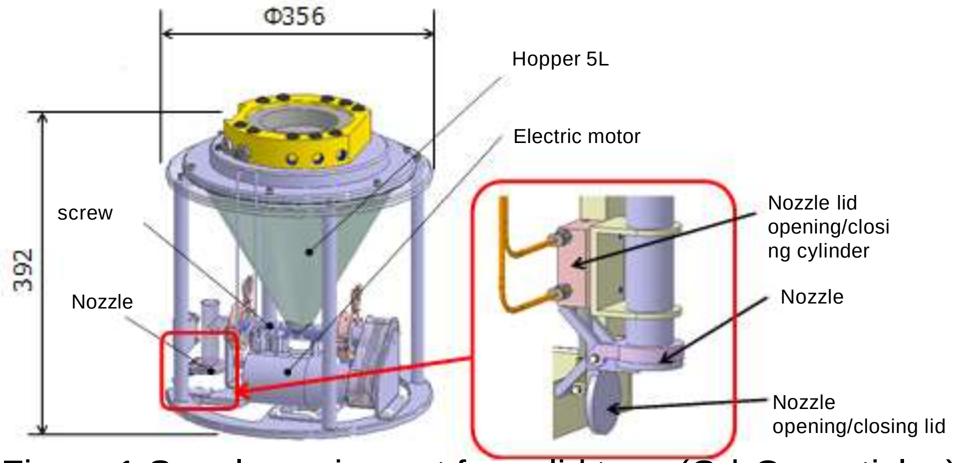
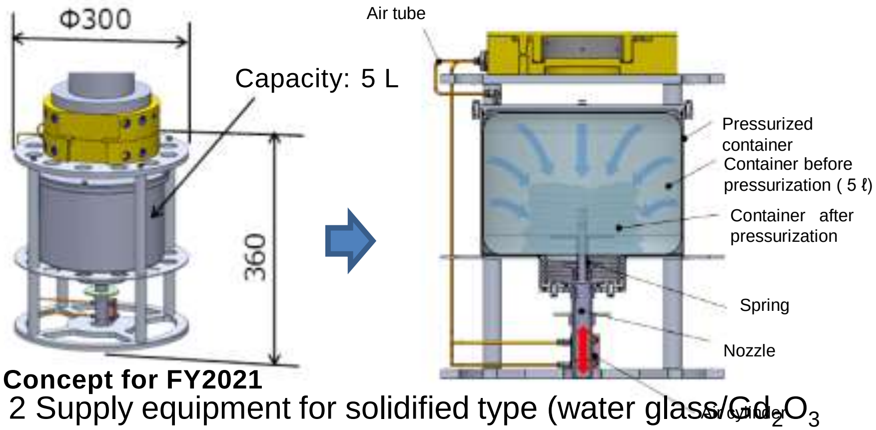


Figure 1 Supply equipment for solid type (Gd_2O_3 particles)



Concept for FY2021

Figure 2 Supply equipment for solidified type (water glass/Gd_2O_3 granulated powder)

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

b. Examination of procedures ③ Absorbent operating procedures

- The assuming processes when using absorbers at the site was considered (Tables 1 and 2).
- In the case of the solidified type absorber(water glass), since it is necessary to knead the raw materials and to wash the injecting equipment with water after use, the operating process is more complicated than that of the solid type.

Table 1 Operating process of solid type (Gd_2O_3 particles, glass material containing B/Gd)

No.	Operating process	Description
1	Storage of absorbers	Glass material containing B/Gd or Gd2O3 particles are stored ready for use as absorbers.
2	Weighing of absorber	Weigh the amount of absorber needed for the work.
3	Loading absorber into injecting equipment	Load the absorber into the hopper of the injecting equipment.
4	Transferring injecting equipment to the site	Connect the injecting equipment loaded with absorber to the manipulator and transfer it to directly above the fuel debris retrieval site.
5	Inserting absorber into fuel debris	Drop the absorber from directly above the fuel debris retrieval site to be applied to the surface of fuel debris.
6	Return of injecting equipment	After the completion of insertion, return the injecting equipment to the predetermined position from the fuel debris retrieval site.

Table 2 Operating process of solidified type (water glass/Gd_2O_3 granulated powder)

No.	Operating process	Description
1	Storage of raw materials	The five raw materials for the water glass neutron absorber are ① water glass, ② gadolinia granulated powder, ③ cement, ④ monosodium phosphate, and ⑤ water. Temporarily store these at the production site. ④ and ⑤ can be mixed and stored as an aqueous solution.
2	Weighing of raw materials	Weigh each of the raw materials required for the amount of absorber to be applied. There is also a method of inserting a predetermined amount of raw material stored in tanks into a kneader using a dedicated squeeze feeder.
3	Kneading of raw materials (*)	Knead the raw materials in a kneader to produce a water glass neutron absorber.
4	Loading absorber into injecting equipment	Load the water glass neutron absorber prepared by the kneader into the hopper of the injecting equipment.
5	Transferring injecting equipment to the site	Connect the injecting equipment loaded with water glass neutron absorber to the manipulator and transfer it to directly above the fuel debris retrieval site.
6	Inserting absorber into fuel debris	Drop water glass absorber from directly above the fuel debris retrieval site to be applied to the surface of fuel debris.
7	Return of injecting equipment	After the completion of application, return the injecting equipment to the predetermined position from the fuel debris retrieval site.
8	Cleaning of injecting equipment (*)	Wash the used kneader and injecting equipment with water to wash off adhering water glass absorbers. Collect and store the wash water.

(*) Processes in red are specific to the solidified type and are unnecessary for the solid type

7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

b. Examination of procedures

④ Absorber carry-in and -out process

Example of solidified type (water glass/Gd2O3 granulated powder) for top-access retrieval method (mobile cell method)

- For the solidified type, which has many operating processes, the transfer procedures from storage to use and collection were examined (Figures 1 and 2)
- To save the limited space in the R/B, the absorber will be stored and prepared in a separate maintenance building. In order to transfer the contaminated absorbent injecting equipment between buildings, the transportation equipment (mobile cell) developed in the related project (*) will be used. The mobile cell is for transferring unit cans collecting fuel debris.
- The time required for transportation from preparing the water glass absorber, inserting it into fuel debris, and collecting the injecting equipment is about 2 hours for the outward trip + about 4 hours for the return trip (for cleaning and exchanging air in the transfer area) = Estimated 6 hours total.
- The reactivity suppression effect after insertion will be verified by sub-criticality measurement using neutron detectors. (No. 41)

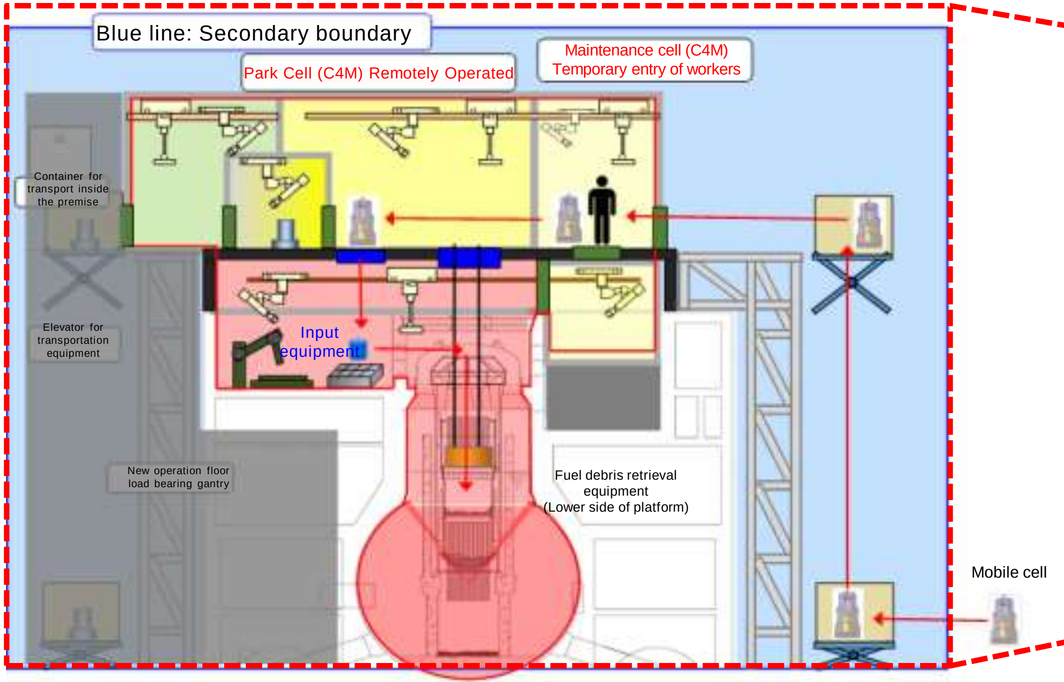
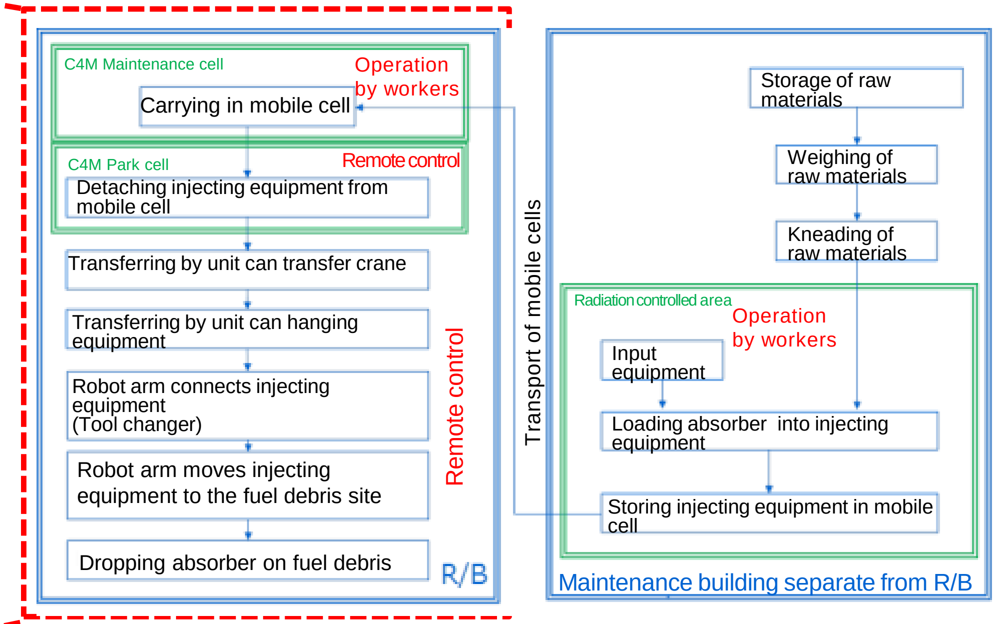


Figure 2 Carry-in route of supply equipment


C4M Maintenance cell — Operation by workers
Carrying in mobile cell

C4M Park cell — Remote control
Detaching injecting equipment from mobile cell

Transferring by unit can transfer crane

Transferring by unit can hanging equipment

Robot arm connects injecting equipment (Tool changer)

Robot arm moves injecting equipment to the fuel debris site

Dropping absorber on fuel debris

Remote control

R/B

Transport of mobile cells

Storage of raw materials

Weighing of raw materials

Kneading of raw materials

Radiation controlled area — Operation by workers

Input equipment

Loading absorber into injecting equipment

Storing injecting equipment in mobile cell

Maintenance building separate from R/B

Figure 1 Operating process flow up to insertion of absorber (water glass/Gd_2O_3 granulated powder)

(The process of collecting injecting equipment and mobile cell after insertion is separate)

(*) Related project “Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals” (FY2019/2020)

7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

b. Examination of procedures ⑤ Hardening time of solidified absorbers

- The issue of the solidified type absorber (water glass / Gd_2O_3 granulated powder) was clarified with respect to the transportation time.
- It is necessary to adjust the water glass absorber so that it does not solidify before insertion (up to 2 hours). In addition, it is necessary to adjust so that the residue remaining inside the container after insertion does not harden before cleaning. (Approx. 3 hours for cleaning in the dryer separator pit (DSP), approx. 6 hours for cleaning in the maintenance building)
- The range of viscosity that can be inserted and cleaned is 0 to 5000 [mPa·s].
- The test was performed by changing the concentration of the retardant (Table) (0.95 to 1.87 wt%), and the time to reach 5000 [mPa·s] was measured.
- As a result of the test, the prospect of delaying the hardening time by more than 5 hours was obtained (Figure). Although it is a little short of 6 hours, it is thought that there is a possibility that it will be established if the transportation process is examined in detail in the future.

Table Raw materials of water glass/ Gd_2O_3 granulated powder

Raw material	Classification
Main material	No. 1 Sodium Silicate (Baume specific gravity 55)
Hardener	Ordinary Portland cement
Retardant	Monosodium phosphate
Water	Ion-exchange water
Neutron absorption material	Gadolinium oxide

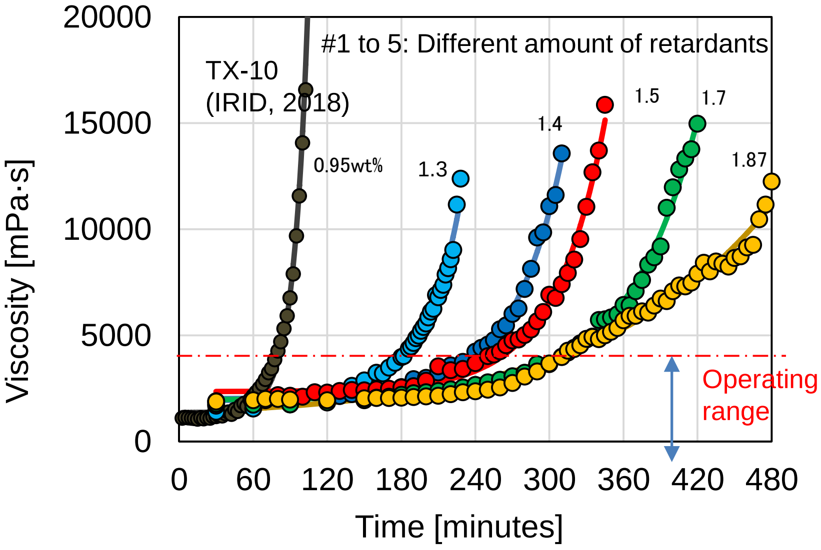


Figure Elapsed time and viscosity test results after mixing water glass/Gd_2O_3 granulated powder

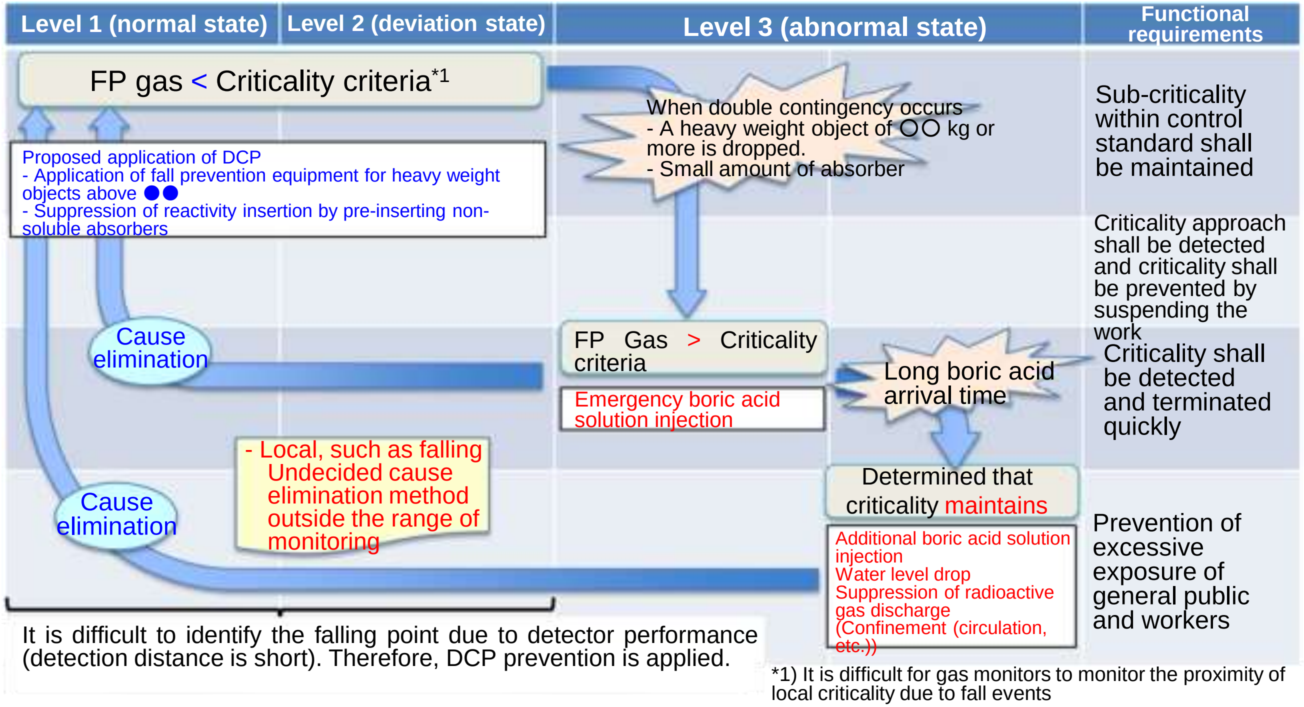
7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

b. Examination of procedures ⑥ Evaluation of effectiveness of pre-dispersion of absorbers

- The applicability of non-soluble absorbers were examined to response to a criticality risk outside of fuel debris processing locations. Specific criticality risks include the fall of equipment and fuel debris
- Absorbers should be inserted in advance since the local sub-criticality cannot be measured.
- The effectiveness of preventing the criticality risk associated with falling fuel inside a large transport cask was examined as a reference.
- The necessity and applicability of measures against falling during work inside the pedestal will be examined.



Level 1 (normal state) | **Level 2 (deviation state)** | **Level 3 (abnormal state)** | **Functional requirements**

FP gas < Criticality criteria[*1]

Proposed application of DCP
- Application of fall prevention equipment for heavy weight objects above ●●
- Suppression of reactivity insertion by pre-inserting non-soluble absorbers

When double contingency occurs
- A heavy weight object of ○○ kg or more is dropped.
- Small amount of absorber

Sub-criticality within control standard shall be maintained

Criticality approach shall be detected and criticality shall be prevented by suspending the work

Cause elimination

FP Gas > Criticality criteria

Emergency boric acid solution injection

Long boric acid arrival time

Criticality shall be detected and terminated quickly

- Local, such as falling
Undecided cause elimination method outside the range of monitoring

Cause elimination

Determined that criticality maintains

Additional boric acid solution injection
Water level drop
Suppression of radioactive gas discharge
(Confinement (circulation, etc.))

Prevention of excessive exposure of general public and workers

It is difficult to identify the falling point due to detector performance (detection distance is short). Therefore, DCP prevention is applied.

*1) It is difficult for gas monitors to monitor the proximity of local criticality due to fall events

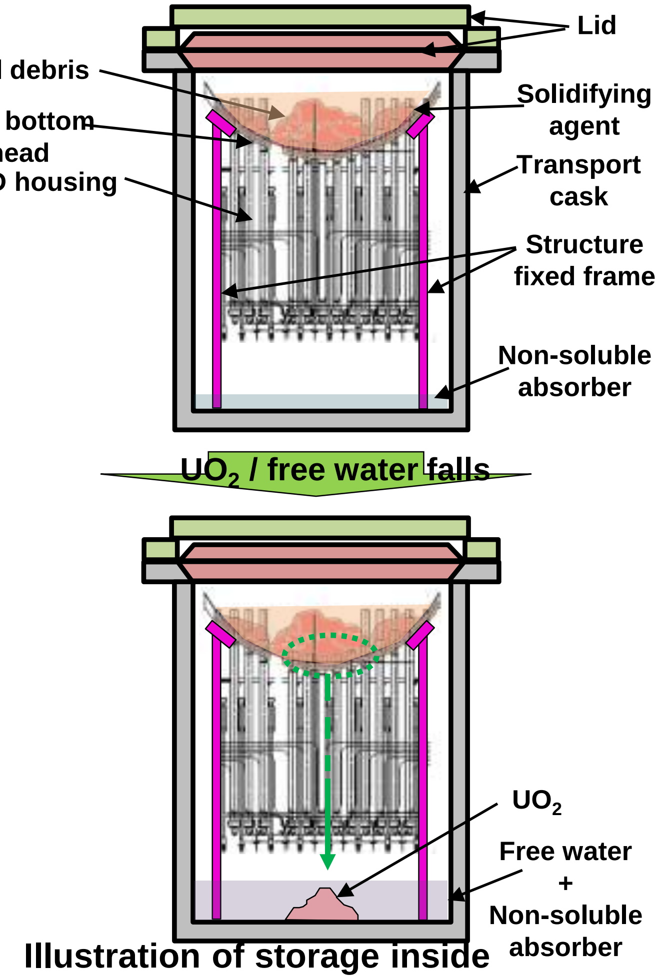


Illustration of storage inside the transport cask

Criticality control method for reactivity input due to events other than fuel debris processing locations

7. Implementation details

7.1 Development of on-site operating procedures

7.1.3 Operating procedures for neutron absorbers

d. Interim Summary

[Results of this year]

While discussing operating procedures and throughput with the fuel debris retrieval method team (top-access retrieval/side-access retrieval/integral transfer), the following items were specified and shared.

- Procedures for deciding necessity of use of absorber by criticality approach monitoring
- Procedures for returning to Level 1 after using absorber
- Size reduction of absorbent supply equipment specifications
- Transfer procedures of absorber into core and time required for transfer
- Effectiveness of pre-dispersion of absorber as a measure against criticality caused by fall of fuel

These items will be the preconditions to be considered when the fuel debris retrieval method is specified in the future.

[Future plans]

Based on the above procedures, study of the impacts on fuel debris retrieval throughput will be expanded, aiming to optimize the operating procedures.

As of the middle of March 2022

7. Implementation details

7.2 Development of solidified absorber technology (water glass)

[Issues]
Among the non-soluble neutron absorbers developed in the related project(*1), the water glass type absorbent (hereafter referred to as water glass material) is a viscous solidified material that covers and adheres to the fuel debris surface (Figure 1).

- ➢ If the surface of the fuel debris is covered with water glass material (Figure 2), concerns have been pointed out that it will hinder the drying of the fuel debris.

Figure 1 Insertion of water glass type neutron absorber into simulant fuel debris

[Implementation details]

- With reference to the conditions in the fuel debris drying process obtained in the related project(*2), the change in the water content of the test sample covered with water glass material was measured.
  - ➢ For the test sample, a porous ceramic of Al_2O_3 that had the same drying behavior as UO_2 was adopted.
  - ➢ In this year's test, the test was conducted under the condition that the surface in contact with the outside air was completely coated.
  - ➢ Set the dry state target value to 0.54 vol% moisture content (equivalent to 0.3 wt% hydrous-bearing zeolite)

[Goals]

- Acquisition of data on the impacts of fuel debris coated with water glass material on the drying process

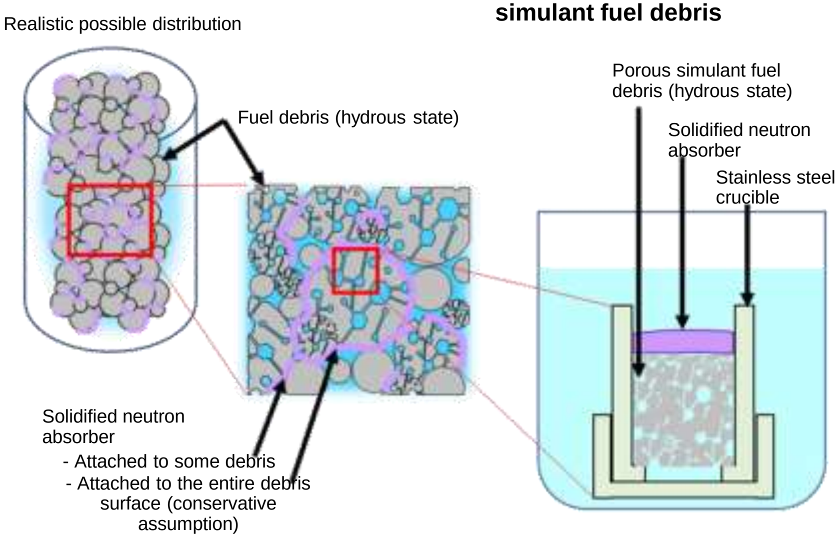


Figure 2 Estimation of fuel debris state in canister and simulated sample

Major achievements:

- Acquisition of quantitative data on the impacts of fuel debris with water glass on the drying process.
- Coordination with the current projects (retrieval work and drying treatment related) enables cooperation in studies for on-site applicability, which are necessary for understanding the impacts of the retrieval work process and setting drying conditions.
  - ➢ By setting the target moisture content of the test sample to 0.3 wt% (in terms of zeolite), the evaluation is equivalent to the fuel debris drying test conducted in the canister project, and the results of this research can be fed back.

(*1) Related project "Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals" (FY2019/2020)
(*2) Related projects "Development of Technology for Fuel Debris Characterization and Treatment (FY2014)", "Fuel Debris Characterization" (FY2015/2016)

7. Implementation details

7.2 Development of solidified absorber technology (water glass) a. Test plan

Outline of solidified Absorber

- **No. 1 sodium silicate (water glass) mixed with Gd_2O_3 granulated powder, which is a neutron absorbing material (Table 1).**
- **It is a viscous liquid that solidifies over time.**
- **It can be applied to uneven surfaces and slopes that are different from flat surfaces. It can be attached to fuel debris.**
- **Various shapes such as rods and particles are assumed for fuel debris, and neutron absorbers are used accordingly.**

Table 1 Components of water glass type neutron absorber

Component	Chemical formula
No. 1 Sodium Silicate	$Na_2O \cdot nSiO_2 \cdot xH_2O$
Cement	SiO_2, CaO, Al_2O_3, Fe_2O_3, $CaSO_4$
Monosodium phosphate	$NaH_2PO_4 \cdot 2H_2O$
Water	H_2O
Gadolinium oxide	Gd_2O_3

Figure An example of covering uneven surface with water glass absorber

Water glass material can be used regardless of debris shape

Figure 1 Example of application of solid type absorber to pebble-like debris

Figure 2 Example of application of solidified type absorber to pebble-like debris

Figure 3 Example of application of solidified type absorber to rod-shaped debris

Figure 4 Example of applying solid type absorber to bedrock-like debris

Figure 5 Example of application of solidified type absorber to bedrock-like debris

Figure 6 Example of application of solidified type absorber to debris with large unevenness

Figure Examples of proper use of neutron absorbers

It has been pointed out that if the surface of fuel debris is covered with absorber, it may hinder the drying of the fuel debris.

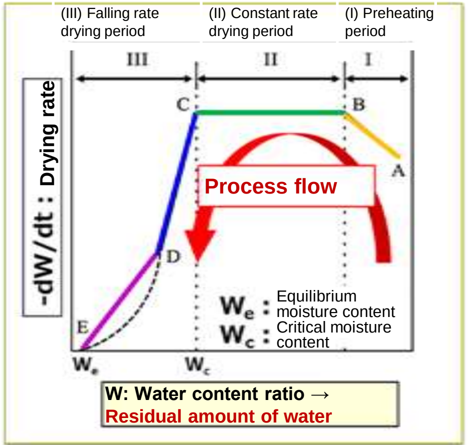
7. Implementation details

7.2 Development of solidified absorber technology (water glass) a. Test plan

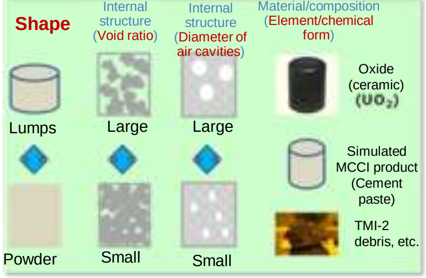
Impact assessment of solidified neutron absorbers on fuel debris drying characteristics

Outline of implementation

Result of basic characteristics grasp test
Evaluation of drying behavior of porous media in the case of fuel debris
- **Establishment of evaluation method by drying characteristic curve**



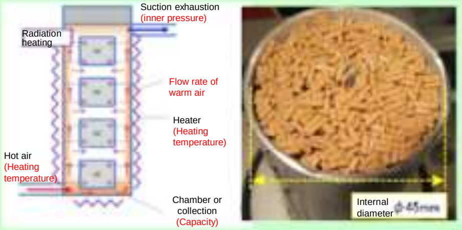
Basic characteristics grasp test



Bench scale

Al_2O_3 powder

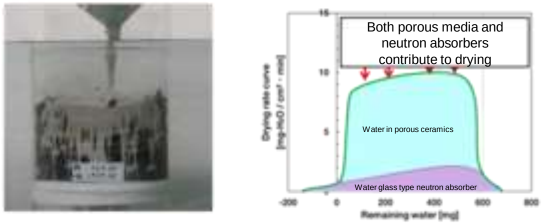
Pilot scale



Conceptual study of drying equipment

Practical application

Fundamental test based on proven porous media



Standardization of the impacts of water glass materials i.e., Amount of change in drying rate (time)

Bench scale

The test conditions were determined with reference to test conditions of past projects (*1). Drying tests were conducted in an experimental system that can be compared with the results of the past projects to understand the differences in drying behavior. The impacts of water glass material on drying were clarified.

- Small-scale tests using proven porous media as a base material were conducted.

(*1) Related projects "Development of Technology for Fuel Debris Characterization and Treatment (FY2014)", "Fuel Debris Characterization" (FY2015/2016)

7. Implementation details

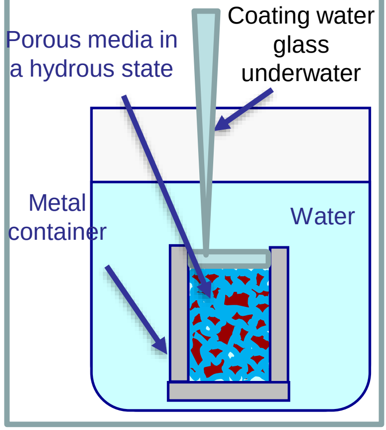
7.2 Development of solidified absorbent technology (water glass) b. Test preparation

Impact assessment of solidified neutron absorbers on fuel debris drying characteristics Outline of implementation

(1) Hydrous state porous media
(Used as simulant fuel debris in past tests)

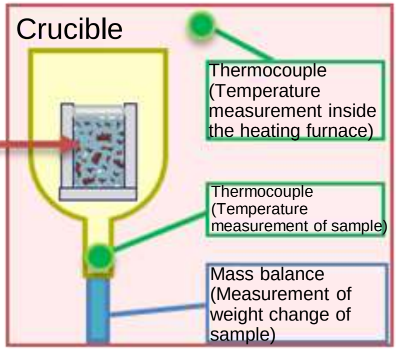
(2) Water glass material (single material)

(3) Water glass-coated porous media

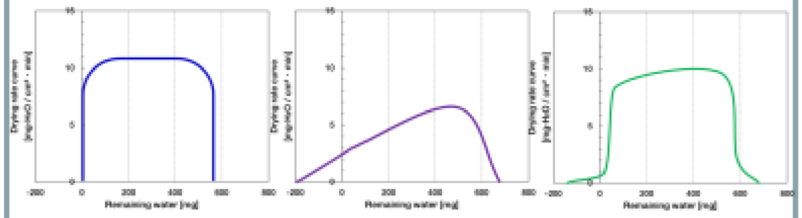


Thermal analysis

Image inside equipment



Drying characteristic curve (image)



Porous media

Water glass material

Water glass material + porous media

Appearance observation using a microscope, etc.

In order to obtain test data that can prove that the water contained in the porous media coated with the water glass material evaporates and dries,

① Manufacture a test sample in which the route during evaporation of water is restricted to one direction so that the evaporated water from the porous media would be discharged after passing through the water glass material

② In order to understand the impacts of the presence of water glass material on the drying behavior, obtain data on the drying of three types of test samples and compare with each other

- ➢ Data required for the drying characteristic curve (drying rate, etc.), change in moisture content of the test sample over time

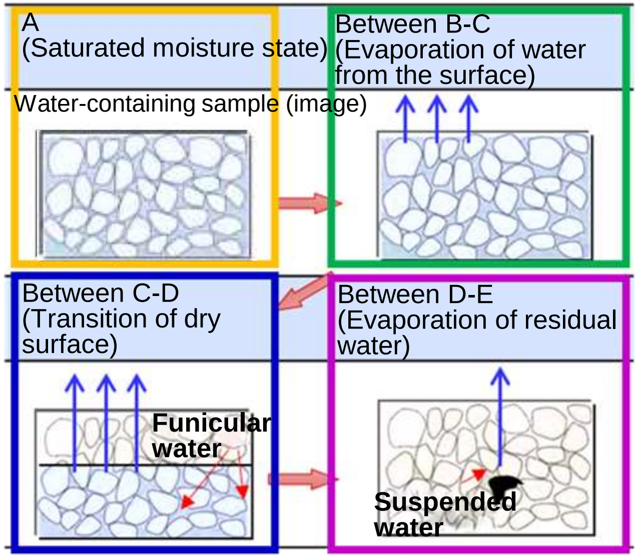
③ Observe changes in water glass material coating conditions before and after drying treatment

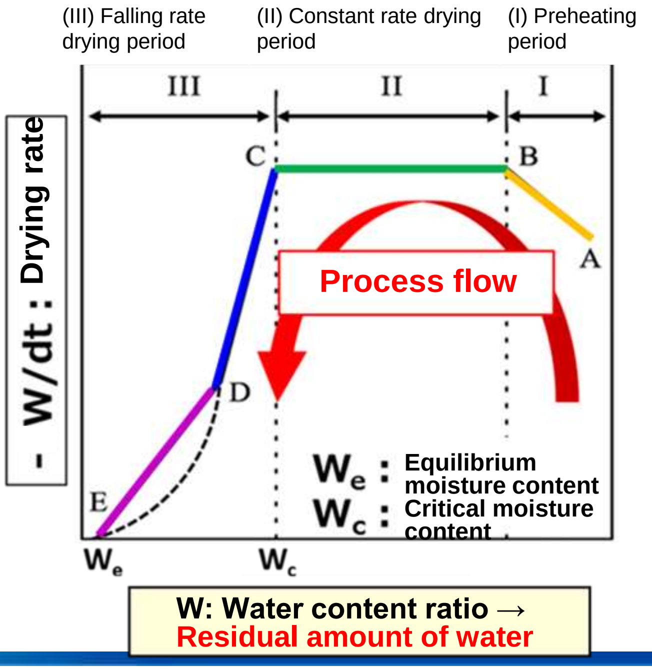
7.2 Development of solidified absorber technology (water glass)

Reference: Past knowledge (investigation of drying behavior of fuel debris) (*1)

- In the past, in cooperation with the collection & storage project, fundamental research was conducted on the evaluation of the drying behavior of fuel debris
- In the case of fuel debris, many parameters (shape, material, drying temperature, etc.) were assumed to affect the drying behavior, so the drying characteristic curve, which allows unified expression and comparison was focused on
- In order to apply it to fuel debris with various specific gravities that cannot be compared by moisture content, a new evaluation method was devised based on the relationship between drying rate and residual water, and an optimum diagram method was studied
- Although the mechanisms leading to the drying of water glass material and porous media are different, by clarifying the degree of impact on the drying rate, it is possible to infer the impacts on the drying treatment

◆ Drying characteristic curve and drying theory





Water content ratio

$$W = \frac{(W_2 - W_1)}{W_1} \times 100\ [\%]$$

Dry weight: W_1
Wet weight: W_2

Equilibrium moisture content: W_e

Water content ratio at which drying does not proceed any further

Critical moisture content: W_c

Water content ratio when transitioning from constant rate drying period to falling rate drying period

(*1) Related projects "Development of Technology for Fuel Debris Characterization and Treatment (FY2014)", "Fuel Debris Characterization" (FY2015/2016)

7.2 Development of solidified absorbent technology (water glass) b. Test preparation
Fundamental test conditions and parameters

- Test under basic conditions (FY2021)

  Test setting based on the fuel debris drying test[*1] conducted in the past in the fuel debris property project
  - ✓ Simulated material: Al_2O_3 (Reference conditions for past tests)
  - ✓ Drying conditions
    - Temperature: 200°C[*2] (reference conditions for past tests, basic conditions for drying equipment)
    - Atmosphere: inert gas (gas flow) (reference conditions for past tests)
  - ✓ Hydrous state: Saturated moisture state (reference conditions for past tests)
  - ✓ Coating method of water glass: fixed or no coating

  ⇒ The drying behavior for the above test and the water glass material alone were investigated and determine **the possibility effect on the water glass material was the drying treatment**

- Test with changing parameters (FY2022)
  - ✓ Examination of changing the simulated material: Zeolite (currently used for examination of the drying process) + Al_2O_3 for comparison
  - ✓ Coating method of water glass material
    - Change the quantity of coating: Change the thickness of the coating by changing the quantity of coating
    - Change the coating area: Change the coating ratio for the surface
  - ✓ In addition, **treatment conditions such as drying temperature can be changed according to requirements from other projects and decommissioning operators**

Fiscal year	Simulated material	Sample size	Water glass material	Hydrous state	Drying conditions
2021	Al_2O_3	Φ10×h10 mm	No coating	Saturated moisture state	200°C[*2] Ar gas atmosphere
			Amount of coating, coating area: fixed		
2022	Al_2O_3, Zeolite		Amount of coating, coating area: parameters	Examine based on the results of the previous year	

*1 Related projects "Development of Technology for Fuel Debris Characterization and Treatment (FY2014)", "Fuel Debris Characterization" (FY2015/2016)

*2 The temperature for the drying treatment when examining the drying process in the collection & storage project

7. Implementation details

7.2 Development of solidified absorbent technology (water glass) c. Element test

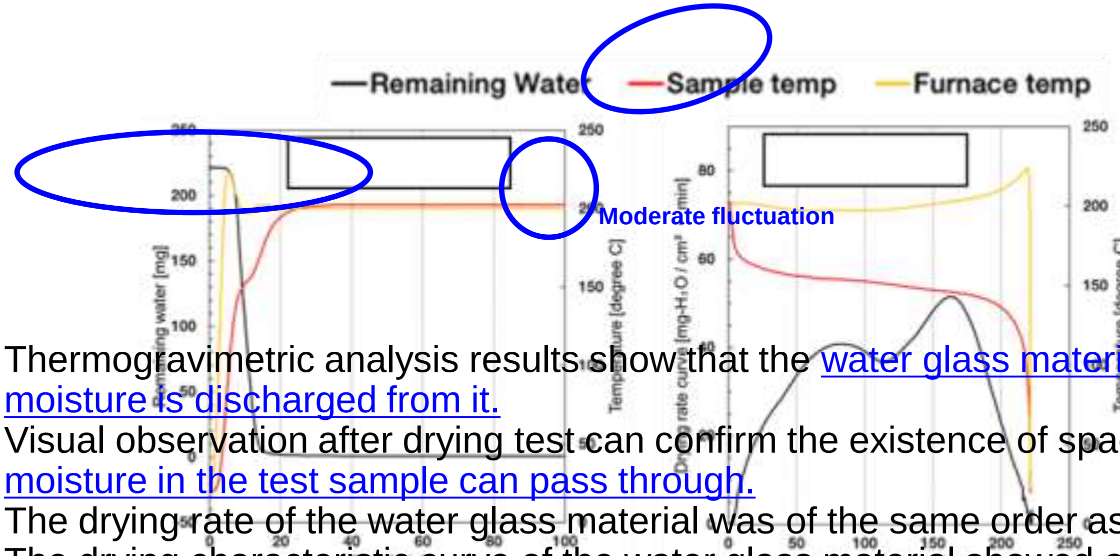
Drying test of water glass material alone

Thickness of water glass material: 1 mm, Underwater curing: 24 hours

Reference: Drying characteristic curve of hydrate-bearing porous media

Thermogravimetric analysis result

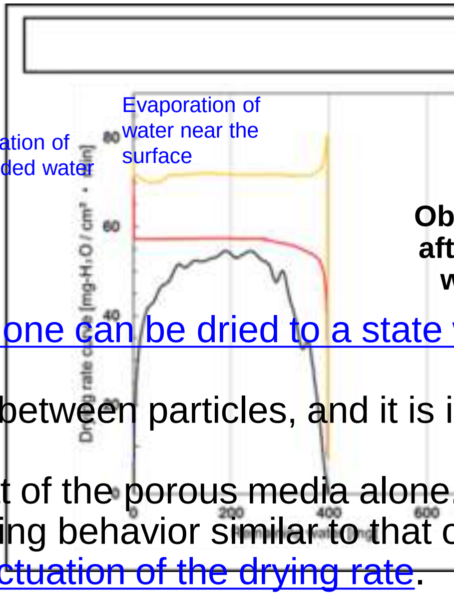
Drying characteristic curve



High fluctuation

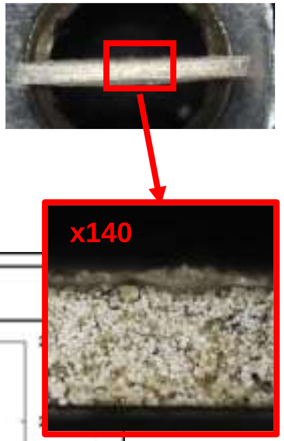
Moderate fluctuation

Evaporation of water from surface to center



Evaporation of suspended water

Evaporation of water near the surface



Observation photograph after drying test (side of water glass material)

- Thermogravimetric analysis results show that the water glass material alone can be dried to a state where no moisture is discharged from it.
- Visual observation after drying test can confirm the existence of spaces between particles, and it is inferred that the moisture in the test sample can pass through.
- The drying rate of the water glass material was of the same order as that of the porous media alone.
- The drying characteristic curve of the water glass material showed a drying behavior similar to that of the hydrate-bearing porous media as a whole, but showed a different trend in the fluctuation of the drying rate.
  - ➢ It was suggested that the bound water of water glass material and the stagnant water (free water) existing between the particles of water glass material may have different drying rates.
  - ➢ Future studies will also focus on the changes in the crystal structure of the water glass material and proceed with the investigation.

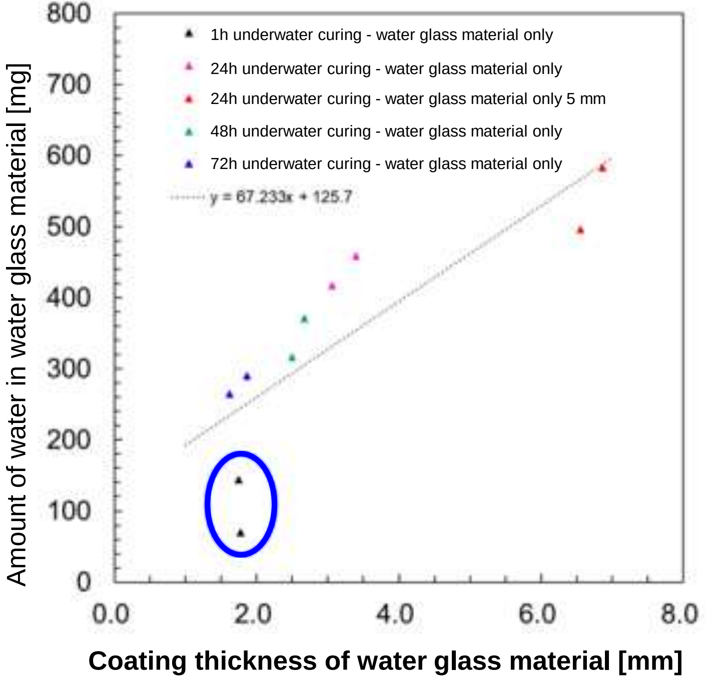
7. Implementation details

7.2 Development of solidified absorbent technology (water glass) c. Element test

Correlation between water glass material thickness and amount of water

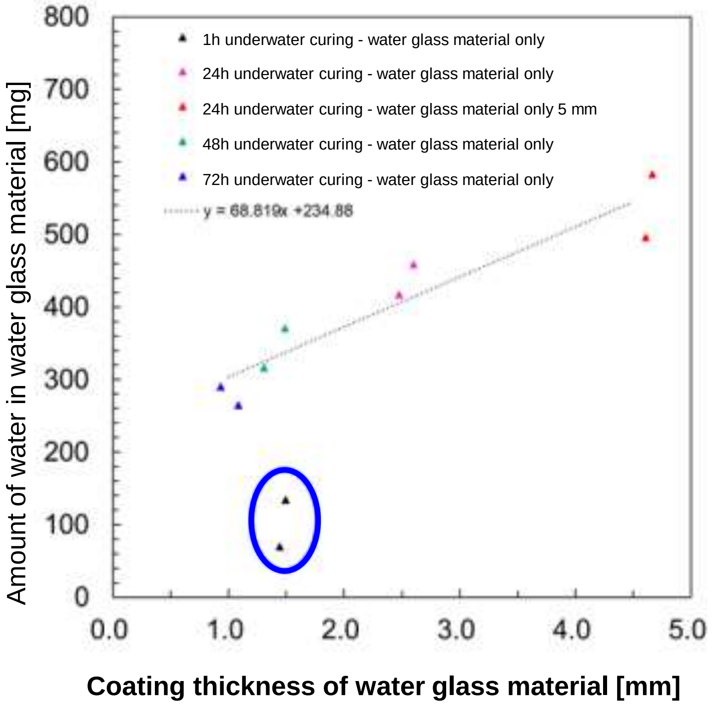
- The thickness of the water glass material was calculated from the input amount and density of the water glass material and the crucible diameter

(Evaluation of coating thickness before drying test)



- The thickness of the water glass material was measured with a microscope after the drying test

(Evaluation of coating thickness after drying test)



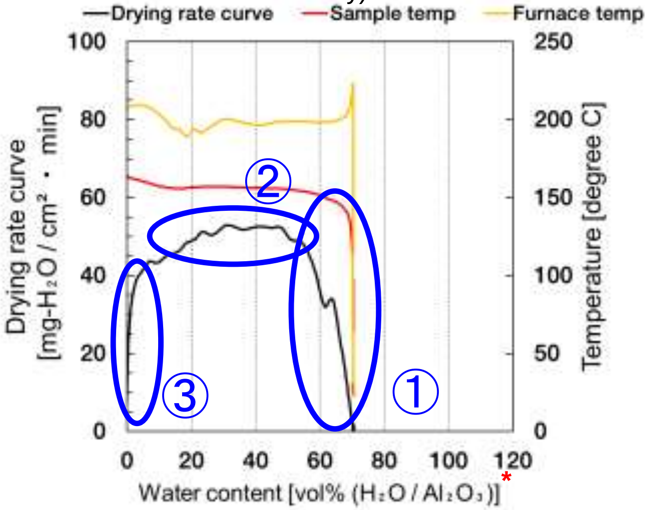
- The change in weight determined by thermal analysis was evaluated as the amount of water.
- Both methods clarified a correlation between coating thickness (mean value) and amount of water.
  - ➢ Accuracy needs to be improved by accumulating data, but it is possible to quantitatively evaluate the amount of water in water glass materials
- In underwater curing for 1 hour, it was judged that it was difficult to accurately evaluate the amount of water, and was excluded from the quantitative evaluation.

7. Implementation details

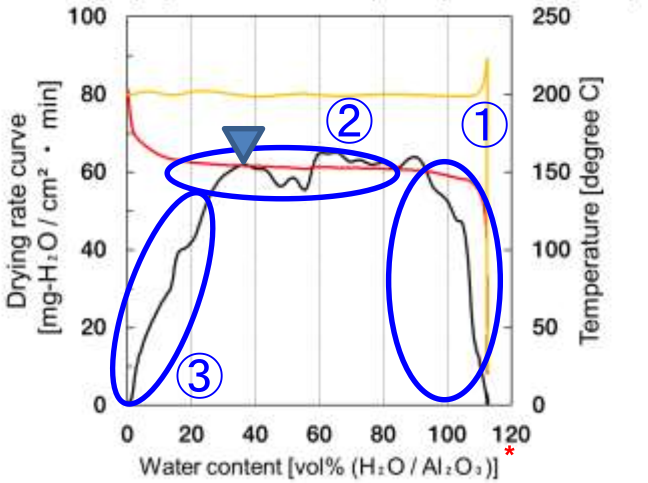
7.2 Development of solidified absorbent technology (water glass) c. Element test

Drying characteristic curve (Coating thickness 1 mm, Underwater curing 24 hours)

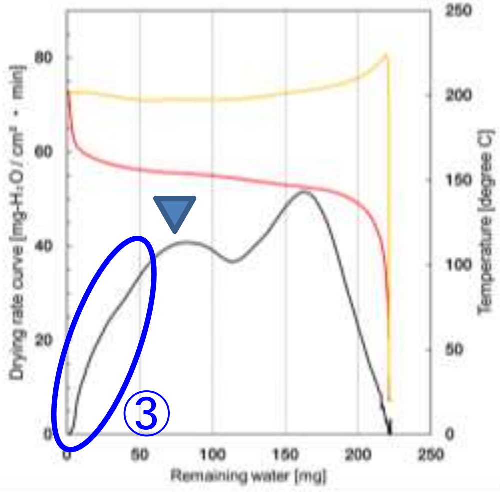
Drying characteristic curve (porous media only)



Drying characteristic curve (porous media + water glass material)



Reference: Drying characteristic curve (water glass material)



- Comparison of drying characteristic curves

① The sample coated with water glass tend to dry faster during the preheating period.

② The drying rate of the sample coated with the water glass material is slightly faster than that of the porous media alone.

- ➢ ① and ② suggest the possibility that the moisture in the water glass material (bound water) and the free water that has moved from the porous media into the water glass material evaporate at the same time

③ The sample coated with the water glass material shows a slight decrease in the drying rate near the drying end point.

- ➢ It is inferred to be dominated by the effect of moisture generated by the intermittent thermal decomposition of the water glass material

Overall, the change in drying rate showed behavior similar to the combination of porous media and water glass material.

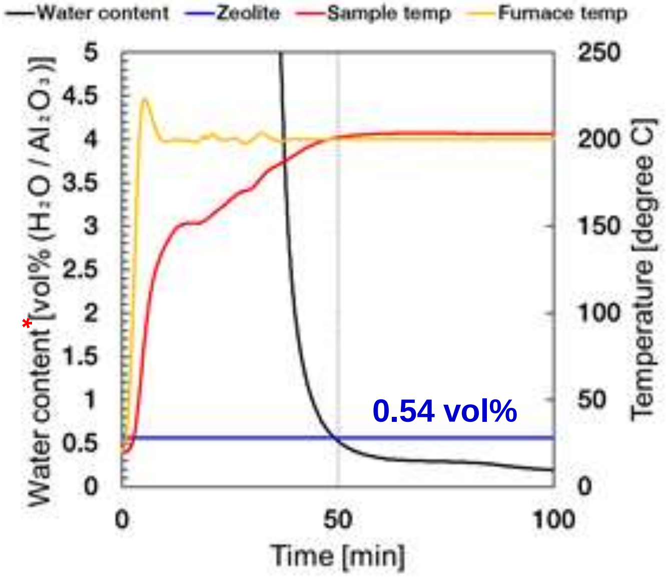
*Water content ratio: A value obtained by calculating the volume ratio of “the amount of water present in the test sample” to “the volume of the porous media.”
The amount of water in the water glass material is the value obtained by the calibration curve added to the “the amount of water present in the test sample”

7. Implementation details

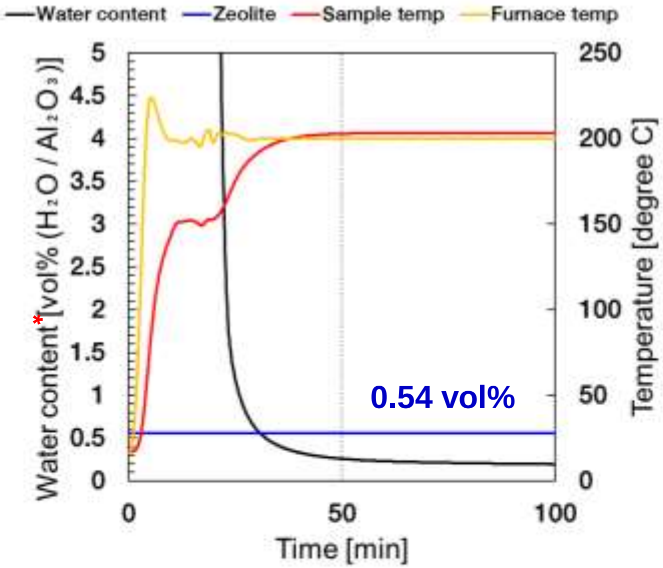
7.2 Development of solidified absorbent technology (water glass) c. Element test

Water content ratio change curve over time

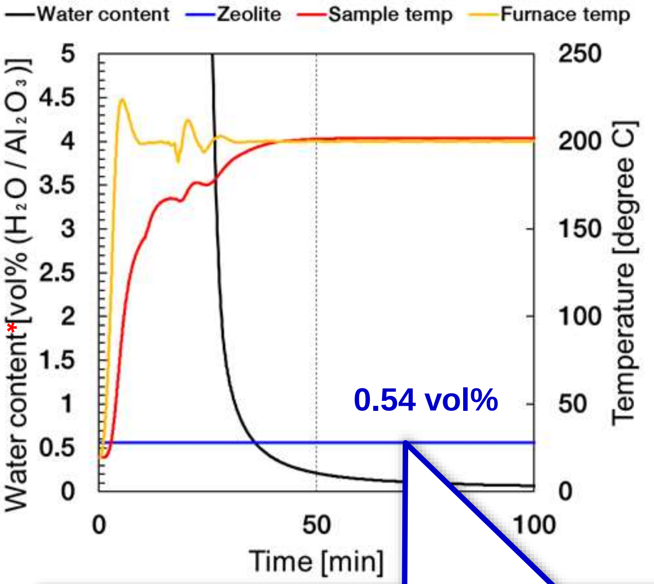
Porous media + water glass material
Coating thickness 5 mm, Underwater curing
24 hours



Porous media + water glass material
Coating thickness 1 mm, Underwater
curing 24 hours



Porous media + water glass material
Coating thickness 1 mm, Underwater
curing 72 hours



Target moisture content of the canister project (drying test of hydrous-bearing zeolite on actual scale)
⇓
0.3 wt% ≒ 0.54 vol% in terms of zeolite
Target moisture content: less than 0.54 vol%

It was possible to dry the porous media until the water content was less than the target even for the sample with the coating thickness of the water glass material of 5 mm.
It was also verified that curing time underwater does not affect drying behavior within the range of 24 to 72 hours.

*Water content ratio: A value obtained by calculating the volume ratio of “the amount of water present in the test sample” to “the volume of the porous media.”
The amount of water in the water glass material is the value obtained by the calibration curve added to the “the amount of water present in the test sample”

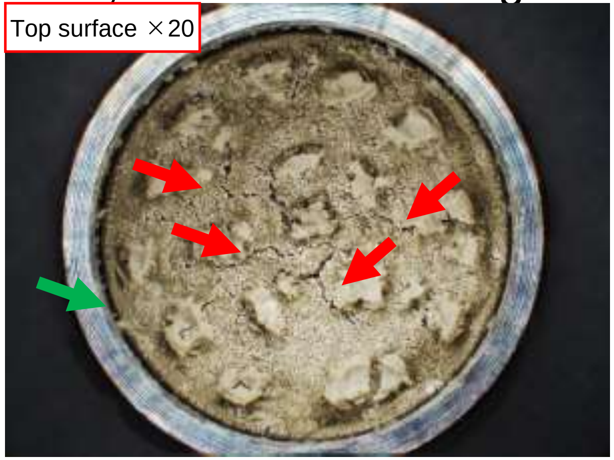
7. Implementation details

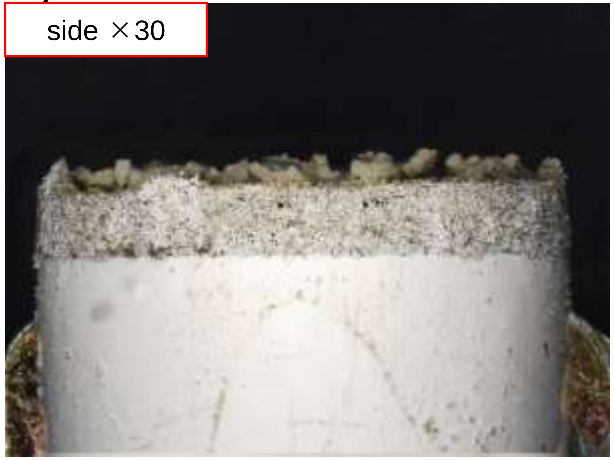
7.2 Development of solidified absorbent technology (water glass) c. Element test

Observation of water glass material-coated porous media after the test (Coating thickness: 1 mm, Underwater curing 24 hours)

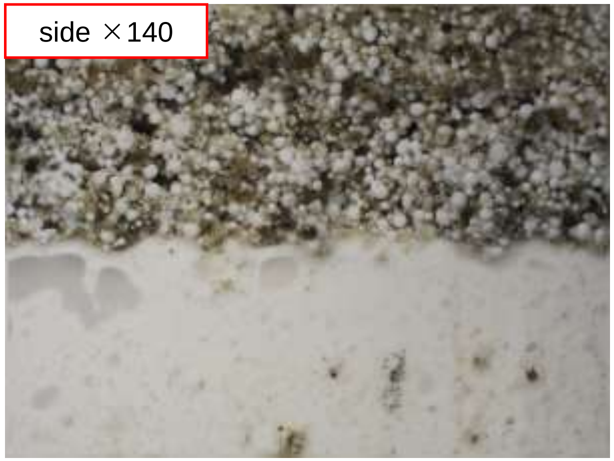
Cracks were confirmed on the top surface.

Overall shrinkage, gaps around the perimeter


Top surface ×20


side ×30


Top surface ×140


side ×140

Verified gaps between particles

- It was observed that the water glass material itself shrank due to the heating and cracks were generated.

➢ Investigation of the behavior changes until dry, such as composition analysis focusing on amorphous materials, is under consideration.

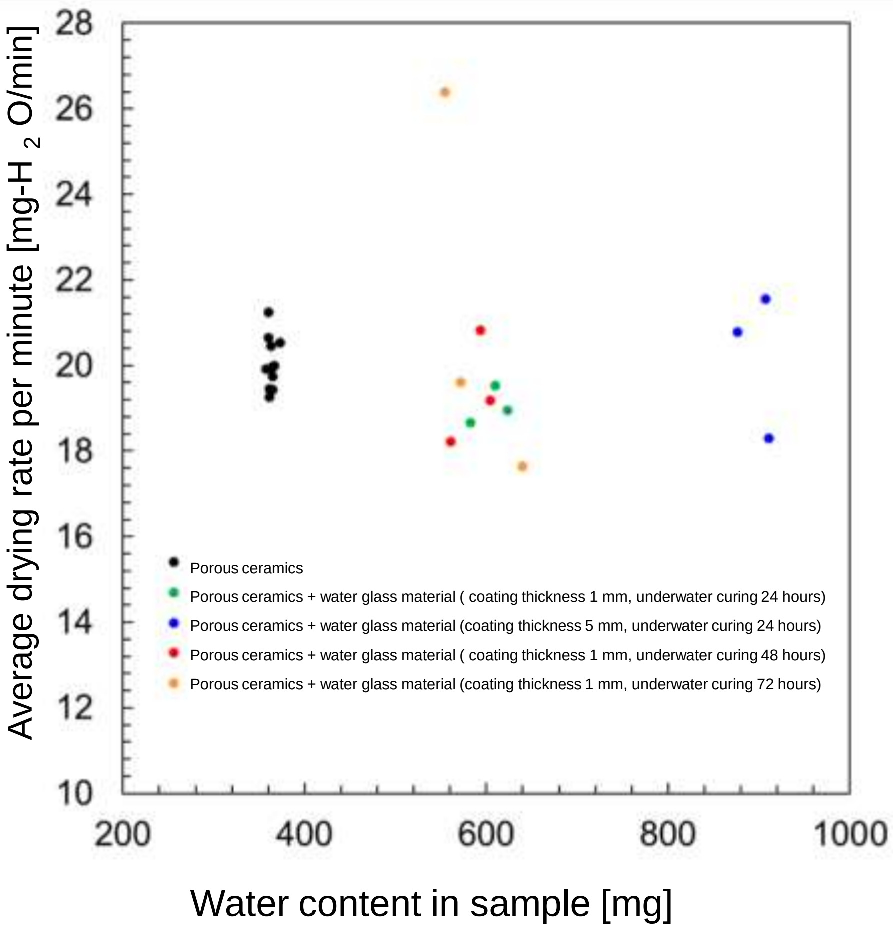
7. Implementation details

7.2 Development of solidified absorbent technology (water glass) c. Element test

Comparison of drying rate for each sample

In order to specify the impacts of the presence of water glass material on the drying operation, the drying rate for each sample prepared in this test was compared.

- The time when the target moisture content (less than 0.54 vol%) was reached was defined as the drying end time, and the average drying rate per unit time was obtained.
- The drying rate under each test condition was compared with respect to the total volume of water content in the porous media and the water glass material of the test samples.



The drying rate (amount of evaporation per unit time) does not change with or without the water glass material.

- ➢ It is inferred that when the coating thickness of the water glass material is in the range of 1 to 5 mm, the bound water in the water glass material and the moisture retained in the porous media can be treated equally.
- ➢ The time required to complete drying tends to depend on the total amount of water derived from each of the porous media and the water glass material.

7. Implementation details

7.2 Development of solidified absorber technology (water glass)

d. Interim Summary

In order to evaluate whether the porous media would reach a dry state even with the water glass material attached, and to evaluate the effect of the drying treatment, a drying test was conducted 結合水using porous Al_2O_3 as simulant fuel debris.

- The preparation method of test samples and the test procedures were examined, and a basic evaluation method for the drying of the water glass materials was established.
- Drying characteristics of water glass material alone

  It was suggested that heating at a temperature of 200° C would dry to a state where no moisture is discharged.
- Drying characteristics of porous media coated with water glass material

  The water glass material had cracks during the drying process, and no events that interfered with the evaporation of water in the simulant fuel debris were confirmed.

➢ It was verified that even when covered with a water glass material, the volumetric moisture content of less than 0.54 [vol%] (≒ moisture content by weight of 0.3 wt% (converted to zeolite)), which is the target for achieving the drying treatment, was reached.

➢ There was no significant change in the drying rate of simulant fuel debris before and after coating with water glass material.

➢ It is possible to treat the bound water in the water glass material in the same way as the water retained in the porous media.

[Future plans]

Tests in the next fiscal year will be conducted based on parameters such as the material of the porous media and the coating amount of the water glass material.

Quantitative evaluation on the degree of impact of drying caused by water glass material will be performed by comparing the obtained results with the test results of this year.

➢ The test results including the result of next fiscal year will be shared with the project of “Development of Technology for Drying Fuel Debris” , to cooperate in considering how to reflect them in the drying process conditions.

As of the middle of March 2022

8. Specific objectives for achieving the purposes of technological developments

(2) On-site operating methods for criticality approach monitoring technology and neutron absorbent technology	
① Development of on-site operating procedures	On-site operating procedures for criticality approach monitoring with neutron detectors shall be formulated. The sub-criticality measurement performance of neutron detectors shall be evaluated and reflected in on-site operating procedures. On-site operating procedures for non-soluble neutron absorbers shall be formulated. (TRL at the end of the project(*): Level 4)
② Development of solidified absorber technology	Data on the impacts on the drying process of fuel debris attached with solidified absorber (water glass) shall be obtained. (TRL at the end of the project(*): Level 4)

(*) TRL; Technology readiness levels

End