Subsidy Project of Decommissioning, Contaminated Water and Treated Waste Management commenced in FY2022
"Project for Development of Analysis and Estimation Technology for Fuel Debris Characterization
(Development of non-destructive technologies for measurement of fuel debris, etc. required for sorting fuel debris)"

Final Report

October 2023

International Research Institute for Nuclear Decommissioning (IRID)

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1. Introduction

1.1 Research Background and Purpose

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1.1 Research Background and Purpose (1/2)

[Purpose]

- During reactor decommissioning at the Fukushima Daiichi Nuclear Power Station, it is not necessarily logical to handle all objects retrieved from inside the Primary Containment Vessel as fuel debris.
- **The work from retrieving fuel debris to storing it can possibly be streamlined if a distinction can be made between fuel debris and radioactive waste** using the results of measuring the quantity of nuclear fuel material contained in the retrieved objects as a guideline.
- **Prospective measurement technologies** that are likely to be able to measure the quantity of nuclear fuel material were selected during the previous Decommissioning and Contaminated Water Management projects, and the impact of factors leading to measurement errors arising from the quantity of material other than nuclear fuel material contained in the objects retrieved from inside the Primary Containment Vessel, the status of filling inside the canisters, etc., were analyzed and evaluated by means of simulation.
- However, characteristics of the measuring equipment such as detector response, etc. were not simulated, and studies on the method of estimating and evaluating the quantity of nuclear fuel material based on the quantity measured by the measuring equipment have not been started.
- Hence, **conceptualizing the equipment** by analyzing detector response keeping in mind the measurement technologies (*1 below) that were studied during the Decommissioning and Contaminated Water Management Project, and studying the **method of evaluating the quantity of nuclear fuel material** based on the measured quantity are essential for establishing the sorting technology in the future.

  (*1) **Active neutron method, passive neutron method, muon scattering method, x-ray CT method, passive gamma rays method**
- Moreover, since it is not possible to reproduce all phenomenon occurring during measurement and to actualize all the issues related to measurement through only analysis and evaluation by simulation, it is important to carry out verification by conducting experiments, and the **elemental technology verification test plan** for that needs to be studied.
- Further, in addition to conducting these studies, it is important to keep in mind the final goal to be achieved through R&D or the ideal application of the outcome of R&D. And in order to accomplish this, it is essential to study **the target performance values** required for sorting and the **sorting scenarios** from the perspective of both the latest needs and seeds.
- Technology pertaining to the following items will be developed.

  ① Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment

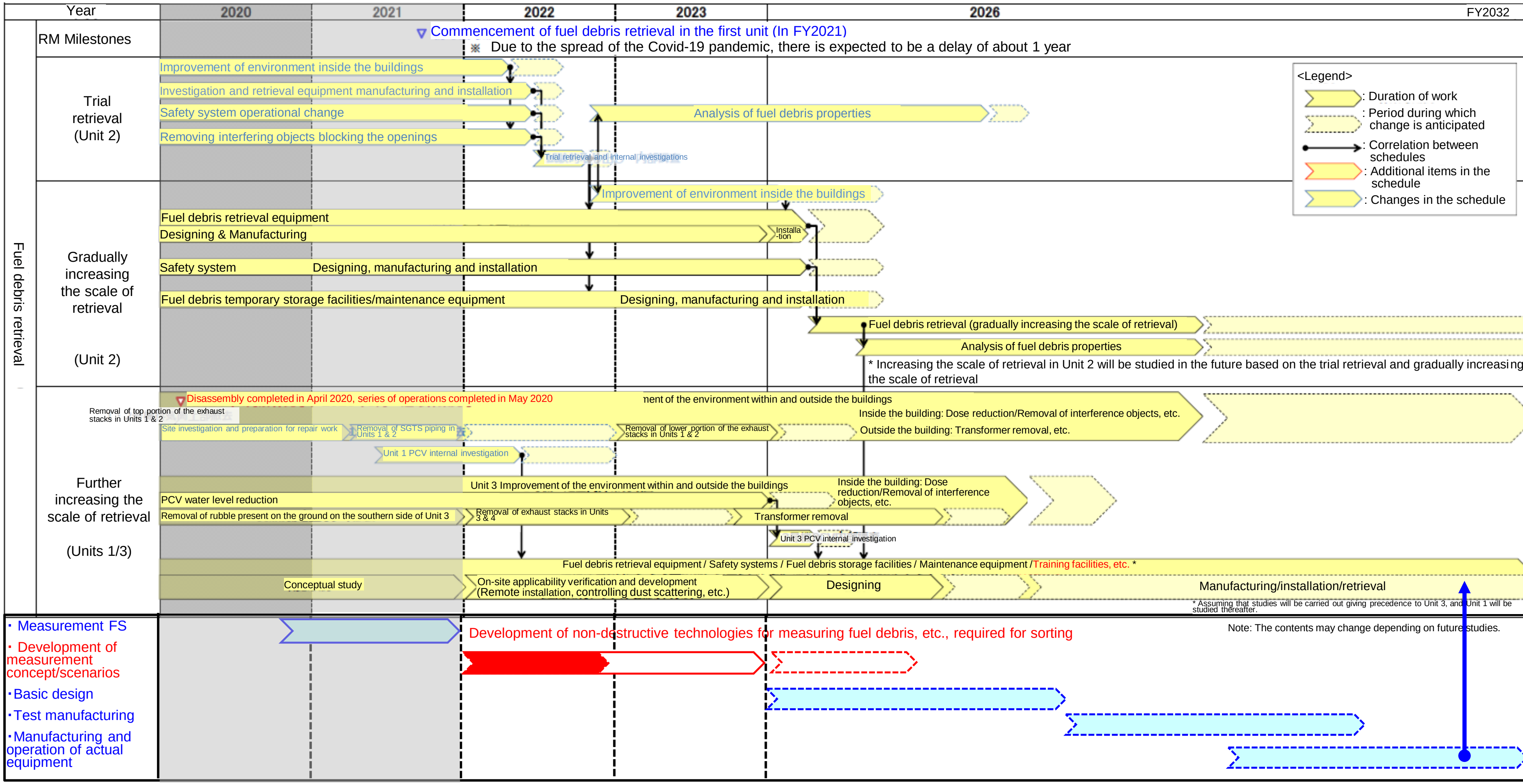
  ② Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios

  ③ Study of elemental technology verification test methods using existing equipment, etc.

[Purpose of overall development] **Development of non-destructive technologies for measuring the fuel debris, etc. which is required for sorting** the objects retrieved from the Primary Containment Vessel during fuel debris retrieval into **fuel debris and radioactive waste**, for the purpose of further increasing the scale of fuel debris retrieval.

1.1 Research Background and Purpose (2/2)

Non-destructive technology for measuring fuel debris, etc. which is required for sorting into fuel and radioactive waste will be developed according to the following schedule for further increasing the scale of fuel debris retrieval.
("Schedule for development of non-destructive technologies for measuring fuel debris, etc." is added to the lower section of the Decommissioning R&D Plan*1)



*1 Cited from Document 3-4 Preparation for fuel debris retrieval from the 98th Decommissioning, Contaminated Water and Treated Water Management Team Management Office Meeting

1.2 Objectives

Implementation items and objectives of this project are given below.
(The section numbers have been used for numbering the implementation items. An overview of the implementation items is provided in No. 8 to 10.)

4.1 Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment	
4.1.1 Study of the target performance values required for sorting	**・The equipment performances that influence the feasibility of sorting should be consolidated and based on that the target performance values of the non-destructive measuring equipment used for sorting and distinction between fuel debris and waste should be established. (*1)**
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis	**・The concept of non-destructive measuring equipment should be established using 5 types of prospective technologies (*2) (Target TRL at completion: Level 3)**
4.2 Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios	
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity	**・The primary proposal pertaining to the techniques for evaluating nuclear fuel material, etc. based on the quantity measured using 5 types of prospective technologies (*2) (including combinations as required) should be studied, and the evaluation efficiency of the said proposal should be evaluated. (Target TRL at completion: Level 3)**
4.2.2 Study of sorting scenarios	**・Sorting scenarios using 5 types pf prospective technologies (*2) (including combinations as required) should be proposed.（*1）**
4.3 Study of elemental technology verification test methods using existing equipment, etc.	
4.3.1 Active neutron method	**・In the future, in order to verify the feasibility of sorting using 5 types of prospective technologies (*2), testing methods should be planned for issues that need to be verified by conducting experiments, based on the results of simulation tests or simple tests. (Target TRL at completion: Level 2)**
4.3.2 Passive neutron method	
4.3.3 Muon scattering method	
4.3.4 X-ray CT method	
4.3.5 Passive gamma rays method	

***1: TRL will not be set for the study of target performance values required for sorting and the study of sorting scenarios as they are not development items.**
***2: Active neutron method, passive neutron method, muon scattering method, x-ray CT method, passive gamma rays method**

2. Research Planning

2.1 Implementation Items, their Correlations, and Relations with Other Research

2.2 Project Organization

2.1 Implementation Items, their Correlations, and Relations with Other Research (1/4)

[Overview]

The following development challenges having **greater importance and higher priority** will be studied keeping in mind the measurement technologies studied as part of Government-led R&D Program on Decommissioning and Contaminated Water Management, with the purpose of developing the technology for sorting objects retrieved from the PCV into fuel debris and radioactive waste.

[Pending issues]

(Issues that have particularly greater importance and higher priority from among the issues identified and consolidated during the Government-led R&D Program on Decommissioning and Contaminated Water Management)

- Study of the **target performance values** required for sorting
- Development of the **concept of the equipment** by means of detector response analysis
- Study of the **techniques for evaluating** the quantity of nuclear fuel material, etc. based on the measured quantity
- Re-examination of **sorting scenarios**
- **Elemental technology verification** tests using existing equipment, etc.

[Implementation details]

It is important to always bear in mind the final goal to be achieved through R&D or the ideal application of the outcome of R&D. Hence, in parallel with **developing the concept of the equipment and studying techniques for evaluation**, **the target performance values** required for sorting and **the sorting scenarios** will be studied from the perspective of the latest needs and seeds. Issues that cannot be verified through simulation will be verified through simple tests and **the elemental technology verification test plan** for the future will be studied. The implementation items and their positioning (flow of study) are indicated from the next page onwards.

It is difficult to determine applicability through technical studies focusing on public information and reference literature. It is important to conduct studies pertaining to development by changing opinions with vendors for the meeasuring instruments, data analysis technology, etc.

2.1 Implementation Items, their Correlations, and Relations with Other Research (2/4)

4.1 Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment

4.1.1 Study of the target performance values required for sorting

The **performance indicators** contributing to the determination of feasibility of the sorting technology will be **consolidated**, and their **target values will be studied**. The target performance will be **studied based on the needs**, and thereafter **will be reviewed as necessary based on the outcome of this project (seeds),**

↓

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

The **concept of the measuring equipment** applicable to sorting will **be developed** by **simulating the structure of the measuring equipment** such as the detector, etc. and obtaining **detector response data** to be used for studying the concept of the measuring equipment.

4.2 Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

The method for deriving the quantity or properties to be evaluated from the measured quantity, in the case of the measuring equipment concept studied in ②, **will be studied**, and **a tentative plan pertaining to the techniques for evaluating the quantity of nuclear fuel material based on the measured quantity will be created**.

↓

4.2.2 Study of sorting scenarios

Considering the policy for managing the fuel debris and waste and the characteristics/feasibility of the potential measurement technology, **the physical quantity used for sorting and the type of measurement technology that will be applied (including a combination of multiple technologies) will be studied**.

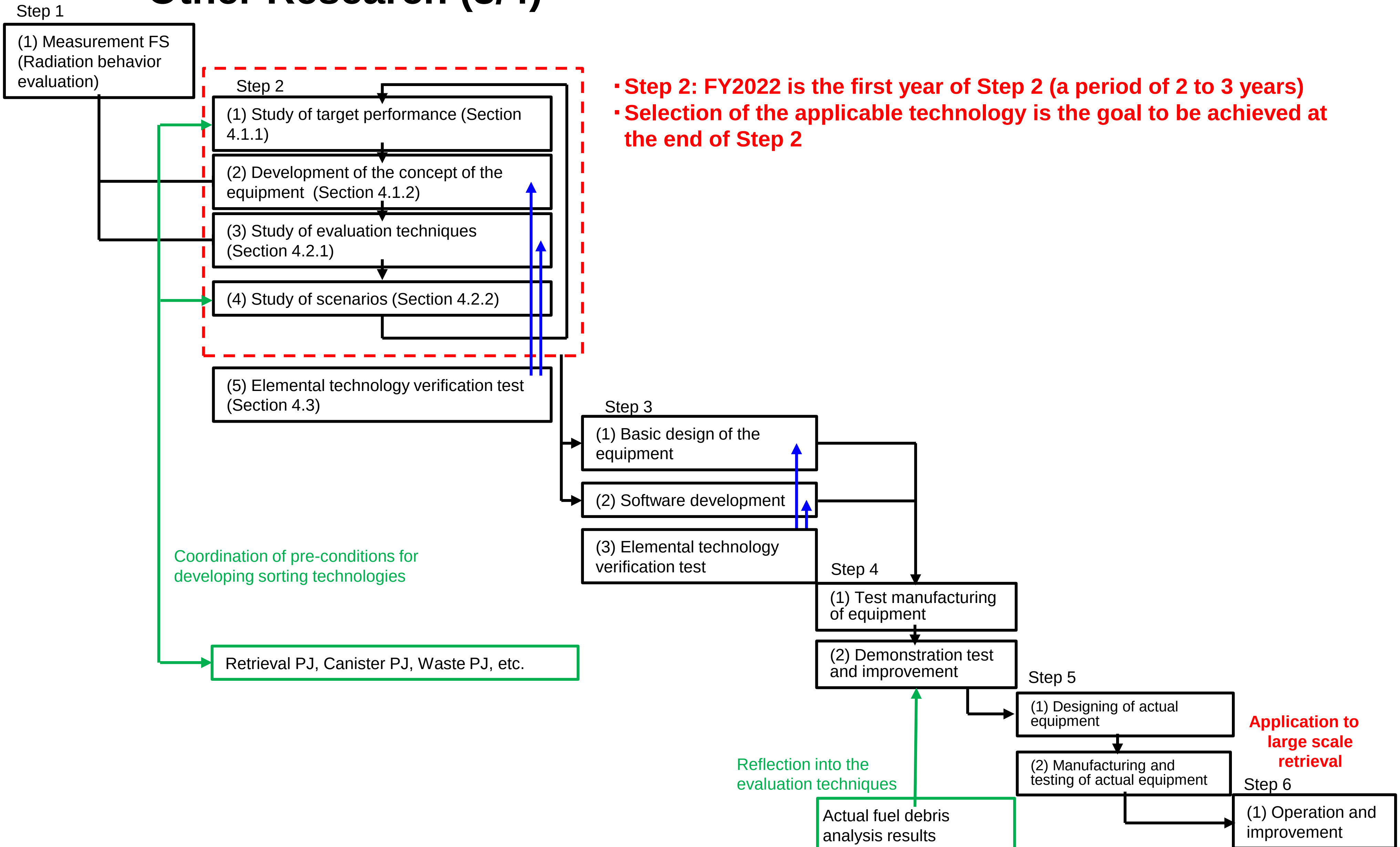
4.3 Study of elemental technology verification test methods using existing equipment, etc.

- **① Active neutron method**
- **② Passive neutron method**
- **③ Muon scattering method**
- **④ X-ray CT method**
- **⑤ Passive gamma rays method**

In order to verify the feasibility of sorting using measurement technologies ① to ⑤ mentioned on the left, in the future, based on the results of simulation or simple tests, **testing methods will be studied for issues that needs to be verified through experiments, and plans will be created**.

2.1 Implementation Items, their Correlations, and Relations with Other Research (3/4)

- Step 2: FY2022 is the first year of Step 2 (a period of 2 to 3 years)
- Selection of the applicable technology is the goal to be achieved at the end of Step 2



2.1 Implementation Items, their Correlations, and Relations with Other Research (4/4)

① Study of target performance (Common) (Section 4.1.1)

① Active neutron method
- ② Development of the concept of the equipment (Section 4.1.2)
- ③ Study of evaluation techniques (Section 4.2.1)
- ⑤ Elemental technology verification test (Section 4.3)

② Passive neutron method
- ② Development of the concept of the equipment (Section 4.1.2)
- ③ Study of evaluation techniques (Section 4.2.1)
- ⑤ Elemental technology verification test (Section 4.3)

③ Muon scattering method
- ② Development of the concept of the equipment (Section 4.1.2)
- ③ Study of evaluation techniques (Section 4.2.1)
- ⑤ Elemental technology verification test (Section 4.3)

④ X-ray CT method
- ② Development of the concept of the equipment (Section 4.1.2)
- ③ Study of evaluation techniques (Section 4.2.1)
- ⑤ Elemental technology verification test (Section 4.3)

⑤ Passive gamma rays method
- ② Development of the concept of the equipment (Section 4.1.2)
- ③ Study of evaluation techniques (Section 4.2.1)
- ⑤ Elemental technology verification test (Section 4.3)

③ Study of evaluation techniques (Combination) (Section 4.2.1)

④ Study of scenarios (Combination) (Section 4.2.2)

- The sorting reference value or the measurement time, etc. will be studied keeping the **target performance the same.**
- **The concept of the equipment will be developed, evaluation techniques will be studied and elemental technology verification tests will be conducted for each measurement technology**.
- **Combinations of measurement technologies** will be studied mainly for **the evaluation techniques**.
- **Scenarios that consider combination** of measurement technologies will be studied.
- The accuracy of the studies will be enhanced by **mutually reflecting the results of flows ① to ⑤ (Sections 4.1.1 to 4.3)** in Step 2 (a period of 2 to 3 years), **and repeating the studies.**
- FY2022 is the first year of Step 2 and corresponds to the first cycle of repeated studies.
- Selection of the applicable technology is the goal to be achieved at the end of Step 2.

IRID

2.2 Project Organization

International Research Institute for Nuclear Decommissioning (Headquarters)

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

Tokyo Electric Power Company Holdings, Inc.

- ○ Various coordination from the viewpoint of site applicability

Mitsubishi Heavy Industries, Ltd.

(1) Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment, review of items implemented by other companies

(2) Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios, review of items implemented by other companies

(3) Assistance in studying elemental technology verification test methods using existing equipment, etc. (① Active neutron method, ② Passive neutron method, ⑤ Passive gamma rays method) and review of items implemented by other companies

Toshiba Energy Systems and Solutions Corporation

(1) Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment, review of items implemented by other companies

(2) Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios, review of items implemented by other companies

(3) Study of elemental technology verification test methods using existing equipment, etc. (③ Muon scattering method) and review of items implemented by other companies

Hitachi-GE Nuclear Energy, Ltd.

(1) Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment, review of items implemented by other companies

(2) Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios, review of items implemented by other companies

(3) Study of elemental technology verification test methods using existing equipment, etc. (④ X-ray CT method) and review of items implemented by other companies

Japan Atomic Energy Agency

(1) Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment, review of items implemented by other companies

(2) Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios, review of items implemented by other companies

(3) Study of elemental technology verification test methods using existing equipment, etc. (① Active neutron method, ② Passive neutron method, ⑤ Passive gamma rays method) and review of items implemented by other companies

Project teams to cooperate for technological development

- Development of analysis and estimation technology for characterization of fuel debris
- Research and development for treatment and disposal of solid waste
- Development of technology for collection, transfer and storage of fuel debris

MHI NS Engineering Co., Ltd.
Assistance in the study of analytical simulation using simulated detectors related to non-destructive measurement technologies for measuring fuel debris and waste, and the overall development

Mirion Technologies (Canberra)
・Study of techniques for evaluating non-destructive measurement concepts pertaining to fuel debris and waste, and quantity of nuclear fuel

Los Alamos National Laboratory
・Evaluation by simple tests using existing equipment, etc. for "Cosmic rays scattering measurement method (muon scattering method)" related to the study of elemental technology verification test methods

Hitachi Industry and Control Solutions, Ltd.
・Analysis of parameters having an impact on measurement errors (Creation of input output conditions, actual analysis, organization and consolidation of analytical data)

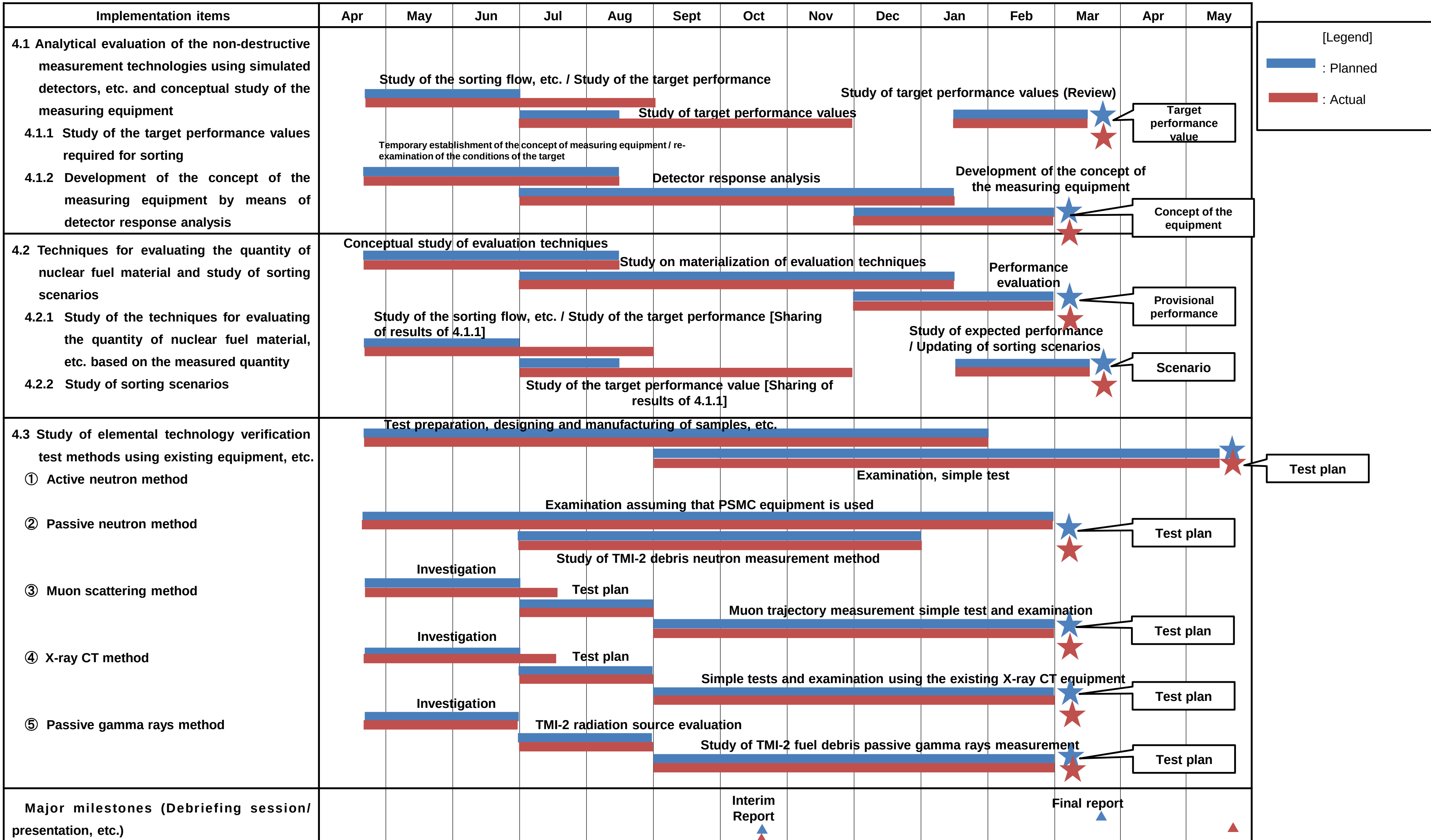
Central Research Institute of Electric Power Industry
・Study of TMI-2 fuel debris radiation measurement method

3. Implementation Schedule

3. Implementation Schedule

No.13

・The study of target performance values and sorting scenarios, as also the study of the elemental technology verification test method using the active neutron method required a longer time than what was allocated in the initial plan, but eventually the planned items were completed.



4. Research Details and Results

4.1 Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment

4.2 Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios

4.3 Study of elemental technology verification test methods using existing equipment, etc.

4.1 Analytical evaluation of the non-destructive measurement technologies using simulated detectors, etc. and conceptual study of the measuring equipment

4.1.1 Study of the target performance values required for sorting

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

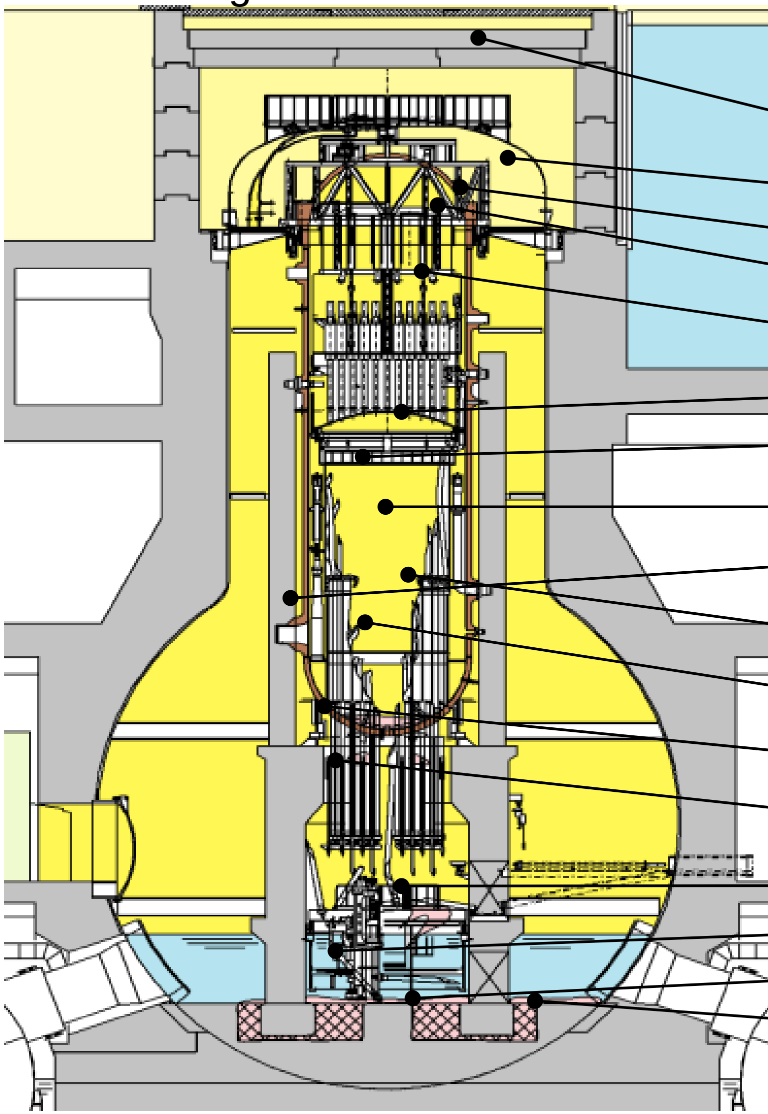
4.1.1 Study of the target performance values required for sorting

[Objective]
- The equipment performances that influence the feasibility of sorting should be consolidated and based on that the target performance values of the non-destructive measuring equipment used for sorting and distinction between fuel debris and waste should be established.
- Technology Readiness Level (TRL) will not be set for the study of target performance values required for sorting as the study is not a development item.

4.1.1 Study of the target performance values required for sorting (1/19)

Target of measurement

・The target of measurement is set according to the figure below.



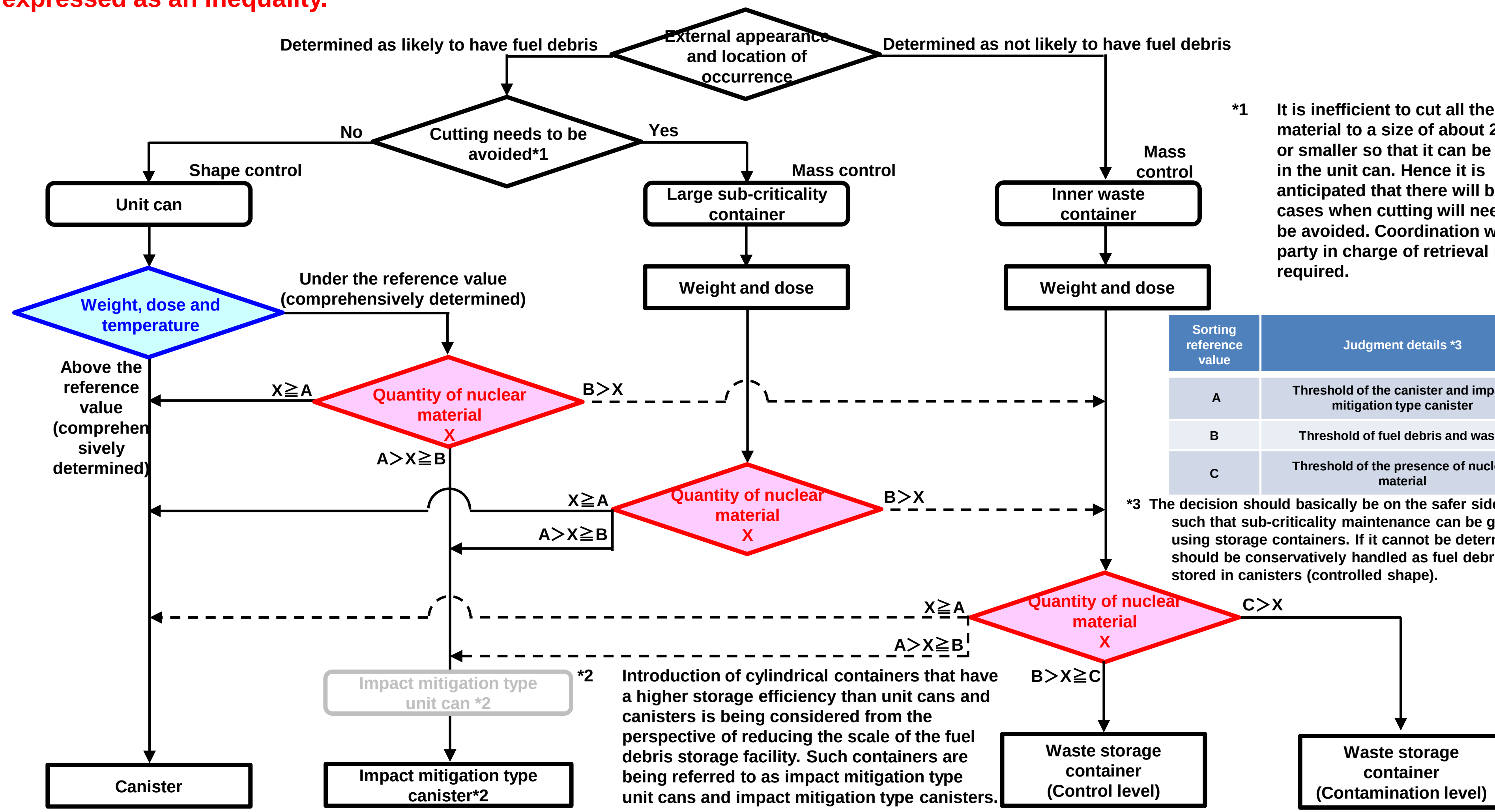
Target	Expected sorting
Shield plug	Structures to which nuclear fuel has not adhered ↓ Radioactive waste
PCV head	
RPV insulation material	
RPV head	
Steam dryer	
Shroud head	
Upper grid plate	Structures to which little nuclear fuel has adhered ↓ Radioactive waste
Shroud	
Jet pump	
Core support plate	Structures in which nuclear fuel is mixed Structures to which a lot of nuclear fuel has adhered ↓ Fuel debris
Core fuel debris	
Fuel debris at RPV bottom	
Fuel debris adhering to RPV lower part/CRV housing	
Pedestal internal structures	
CRD exchanger	
Fuel debris inside the pedestal	
Fuel debris outside the pedestal	

Expected to be removed in the form of large structures
↓
Not to be measured with the sorting equipment

Expected to be cut and removed
↓
To be measured with the sorting equipment

Approach towards sorting (sorting flow)

- **The approach towards sorting** is set as shown below.
- The sorting reference values A and B, C have different units, and since the specifications and use of containers to be handled other than unit cans and canisters have not been finalized (Refer to No. 19-20), it is difficult to simply compare their relationship in terms of size, but **the concept of the method of determination based on the results of measuring the quantity of nuclear material is expressed as an inequality.**



*1 It is inefficient to cut all the material to a size of about 20cm or smaller so that it can be stored in the unit can. Hence it is anticipated that there will be cases when cutting will need to be avoided. Coordination with the party in charge of retrieval is required.

Sorting reference value	Judgment details *3
A	Threshold of the canister and impact mitigation type canister
B	Threshold of fuel debris and waste
C	Threshold of the presence of nuclear material

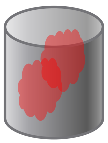
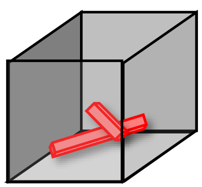
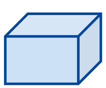
*3 The decision should basically be on the safer side. A value such that sub-criticality maintenance can be guaranteed using storage containers. If it cannot be determined, it should be conservatively handled as fuel debris and stored in canisters (controlled shape).

*2 Introduction of cylindrical containers that have a higher storage efficiency than unit cans and canisters is being considered from the perspective of reducing the scale of the fuel debris storage facility. Such containers are being referred to as impact mitigation type unit cans and impact mitigation type canisters.

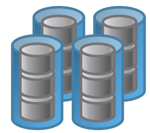
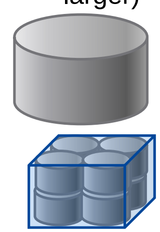
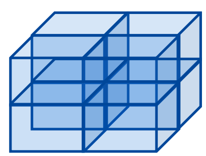
Containers to be handled

- Consolidation of specifications of containers to be handled (Specifications have been roughly finalized for 2 types of containers, namely unit cans and canisters.)
- **Coordination with related PJs (Retrieval PJ, Canister PJ, Waste PJ, etc.) needs to be carried out** for containers for which specifications have not yet been finalized.

Retrieval containers

Container	Target	Limit value	Management criteria
Unit can  <Φ210	• Fuel debris with an indefinite shape such as gravel • Tiny structures	• <Φ210	• A radius such that UO_2 with 5wt% concentration does not become critical
Large sub-criticality container 	• Structures such as the control rods, etc. which are difficult to cut to small pieces on site	• <30kg(5wt%) • <45kg(4wt%) • <80kg(3wt%)	• A mass that does not lead to criticality even if the stored contents are all UO_2 • Neutron absorption material, etc.
Inner waste container  500x300H	• Does not contain nuclear fuel	• No	• No

Storage containers

Storage methods	Nuclear fuel	Concentration/reactivity	Management criteria
Canister (Φ210) 	• Is likely to contain	• Is likely to be high	• Controlled shape • Shape such that storing any type of fuel debris does not lead to criticality
Impact mitigation type canister (Φ400 or larger) 	• Is likely to contain	• Less concentration of 1.5wt% enriched U-235 (equivalent reactivity)	• Reactivity management • Only fuel debris with reactivity that does not lead to criticality is stored in homogeneous infinite systems
Waste storage container 	• No	• No	• Does not contain nuclear fuel

Target performance value (needs): Measurement accuracy (1/3)

・The target performance value of the nuclear fuel quantity measurement accuracy is presumed to be **the accuracy with which the following judgment criteria can be determined**.

Sorting categories and sorting criteria (Tentative proposal consolidating the approaches when the quantity to be evaluated is the quantity of U)

Sorting category	Main purpose of sorting	Criteria (tentative)			
		(None of the conditions mentioned on the right are met)	*1 Concentration of U in the entire stored contents: 1.5wt% or less	*2 Quantity of U is 3.7kg/container or less	Quantity of nuclear material is equal to or lower than the quantity (to be determined) in the case of which physical protection and safeguards end
a: Canister (Inner diameter 220mm, height approx. 1m)		○	–	–	–
b: Impact mitigation type canister (Inner diameter 400mm)	Reducing the scale of fuel debris storage facilities	–	○	–	–
c: Waste storage container (Control level)	Reducing the scale of fuel debris storage facilities Ensuring criticality safety of waste	–	–	○	–
d: Waste storage container (Contamination level)	Streamlining of storage and management of waste	–	–	○	○

Approach towards the judgment criteria

*1: [Canister PJ] According to results of past evaluations conducted during the Canister PJ, **if it is assumed that fuel debris consists of UO_2 and H_2O made up of 4.9w/o concentration U (composed of U-235 and U-238)**, as long as **weight percent of U-235 in fuel debris is about 1.7wt% or lower**, **canisters with inner diameter 400mm** can be used.

[Sorting PJ] In the Sorting PJ, **1.5wt%** was assumed **after leaving some margin in** 1.7wt% which was the result of the Canister PJ. Further, **considering the quantity that can be verified at the site of sorting, 1.5wt% or lower weight percent of U-235 in the entire stored contents was assumed to be the judgment criteria**.

*2: Considering accumulation type arrangement and stacking type arrangement at the time of storage, **the minimum critical quantity (approx. 30Kg) of U (Not UO_2) with 5wt% concentration was set by equally dividing it amongst 8 waste storage containers** .

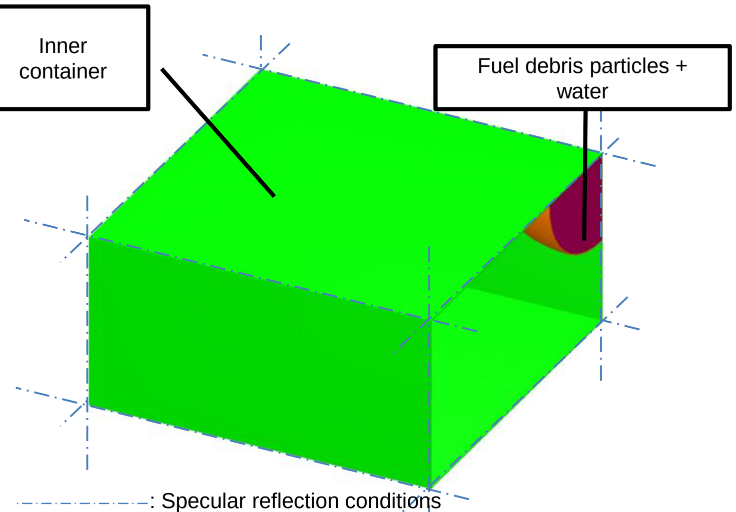
Target performance value (needs): Measurement accuracy (2/3)

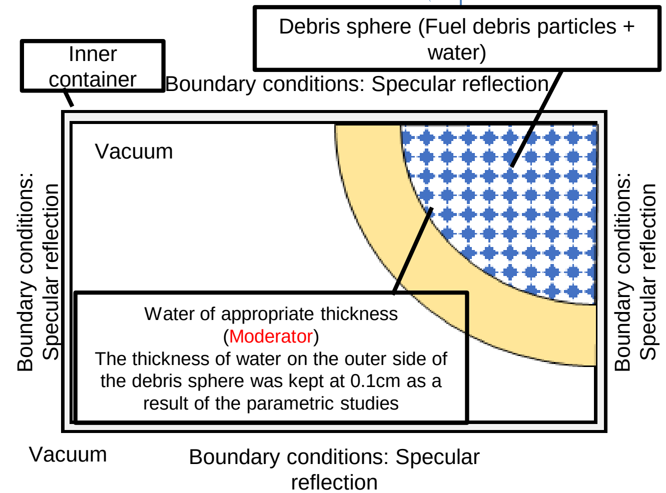
Weight of fuel debris that can be stored in 1 waste storage container is evaluated for the waste storage area.

- In the past, the weight was considered to be approx. 3.7kg (dividing the minimum critical mass of approx. 30kg specified in the criticality and safety handbook into 8 equal parts, and assuming that the fuel debris is disproportionately placed in the corner of the 8 inner waste containers) if the inner waste containers (☐500mmx300mmH, plate thickness t6mm, made of SUS) are stored side by side in the waste storage area.
- Here, the validity of the tentatively set value of approx. 3.7kg is verified. The figure on the right shows the evaluation model. Here evaluation is performed based on a system in which inner waste containers are arranged infinitely. Further, water is set up outside the "debris sphere" that is made up of fuel debris particles + water with a thickness based on parametric studies such that the mutual interactions between the neutrons and the fuel debris that they approach becomes the maximum.
- The Monte-Carlo code MVP3.0 (Cross-section library JENDL-04) is used as the computational code for the evaluation.

	Basis for "Approx. 30Kg" in the past (*1)	Current assessment
Criteria (Keff: Effective multiplication factor)	0.98	keff+3σ≦0.95
Fuel specifications	5wt% New fuel	4.9wt% New fuel
Gd consideration	None	None
Analysis system	A 30cm water reflector is set up around heterogeneous fuel.	A neutron moderator (water) of appropriate thickness is set up around heterogeneous fuel to maximize the mutual interaction between neutrons and the inner container that the neutrons approach.

(*1) JAEA-Date/Code 2009-010 Nuclear Criticality Safety Handbook and Data Collection Version 2





Criticality evaluation model for the storage container infinite arrangement system

Target performance value (needs): Measurement accuracy (3/3)

Weight of fuel debris that can be stored in 1 waste storage container is evaluated for the waste storage area.

Evaluation of the weight of fuel debris that can be stored in the inner container

- Based on the evaluation results (figure on the right), the weight of fuel debris that can be stored in 1 inner container is approx. 3.8kg (thickness of water on the outside of the debris sphere is 0.1cm). With the past set value (3.7kg) as the target, it is believed that it would be reasonable to develop the sorting equipment.

- Points to be noted
- If the external environment of the inner waste container (moisture conditions, neutron reflection effect conditions, necessity to evaluate the facility as multiple units, etc.), shape of the container, plate thickness, deformation of the container due to corrosion, etc. can be predicted, these need to be reflected appropriately into the criticality evaluation model.

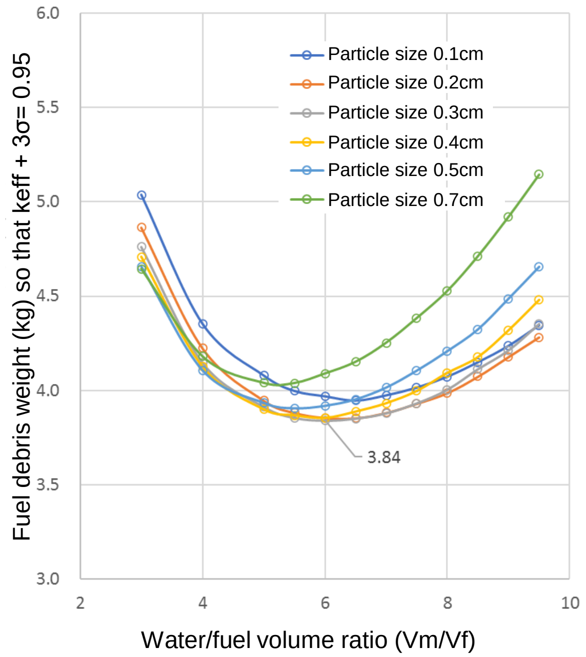


Figure Weight of fuel debris that can be stored in 1 inner container

Issues in establishing the criteria for sorting (items for which needs need to be clearly specified)

Issues in establishing the criteria for sorting

Criteria (tentative)	Issues	Details
Concentration of U of the entire stored contents: 1.5wt% or less*	Establishment of the specifications of the impact mitigation type unit can/canister	Sub-criticality maintenance conditions (criteria) change depending on the specifications of the impact mitigation type unit can/canister. Container shape, dimensions and material, etc. need to be specified.
	Establishment of the method of operating the impact mitigation type unit can/canister	Sub-criticality maintenance conditions (criteria) change depending on the method of operating the impact mitigation type unit can/canister. In order to study the interaction during storage the placement and surrounding conditions (the conditions of the structures that serve as neutron absorbers and reflectors), etc. of the impact mitigation type unit can/canister need to be specified.
	Criticality analysis	Based on the establishment (tentative) of specifications and operating method of the impact mitigation type unit can/canister, criticality analysis is performed to verify sub-criticality maintenance conditions (criteria). Based on the analysis results, specifications and operating method of the impact mitigation type unit can/canister are adjusted.
Quantity of U is 3.7kg/container or less*	Establishment of inner waste container/storage container specifications	Sub-criticality maintenance conditions (criteria) change depending on the specifications of the inner waste container/storage container. Container shape, dimensions and material, etc. need to be specified.
	Establishment of operating method of inner waste container/storage container	Sub-criticality maintenance conditions (criteria) change depending on the operating method of the inner waste container/storage container. In order to study the interaction during storage the placement and surrounding conditions (the conditions of the structures that serve as neutron absorbers and reflectors), etc. of the inner waste container/storage container need to be specified.
	Criticality analysis	Based on the establishment (tentative) of specifications and operating method of the inner waste container/storage container, criticality analysis is performed to verify sub-criticality maintenance conditions (criteria). Based on the analysis results, the inner waste container/storage container specifications and operating methods are adjusted.

* Refer to No. 20 for the approach towards the criteria

Target performance value (needs): Measurement time (Processing capability) (1/4)

- Preliminary calculation of the target measurement time per unit can in which fuel debris is stored is performed. (Targeting the stage when retrieval scale is increased.)
- It is presumed that the entire quantity of material categorized as fuel debris in No. 17 "Target of measurement" is measured.

	Item		Unit 1	Unit 2	Unit 3	Remarks
①	Quantity stored in unit can	kg/unit can	10			Tentative value
②	Total quantity of fuel debris	ton	465	613	592	Cited from the FY2018 Subsidy Project Results
③	Retrieval period	years	10	10	10	Tentative value
④	Quantity of yearly retrieval	ton/year	46.5	61.3	59.2	④=②÷③
-	<When measuring equipment is installed in every unit>	-	-	-	-	
⑤	Number of days of operation of the measuring equipment	days/year	200	200	200	Considering maintenance period, etc.
⑥	Quantity (mass) measured per day	kg/day	233	307	296	⑥=④÷⑤
⑦	Quantity (number of unit cans) measured per day	unit cans/day	24	31	30	⑦=⑥÷①
⑧	Operating time per day	hours/day	20	20	20	Assuming 4 hours for detector calibration
⑨	Measurement time per unit can	minutes/unit can	50.0	38.7	40.0	⑨=⑧÷⑦ x 60
-	<When measuring equipment is used in common>	-	-			
⑩	Quantity (mass) measured per day	kg/day	835			Sum of ⑥
⑪	Quantity (Number of unit cans) measured per day	unit cans/day	84			⑪=⑩÷①
⑫	Operating time per day	hours/day	20			Assuming 4 hours for detector calibration
⑬	Measurement time per unit can	minutes/unit can	14.3			⑬=⑫÷⑪ x 60

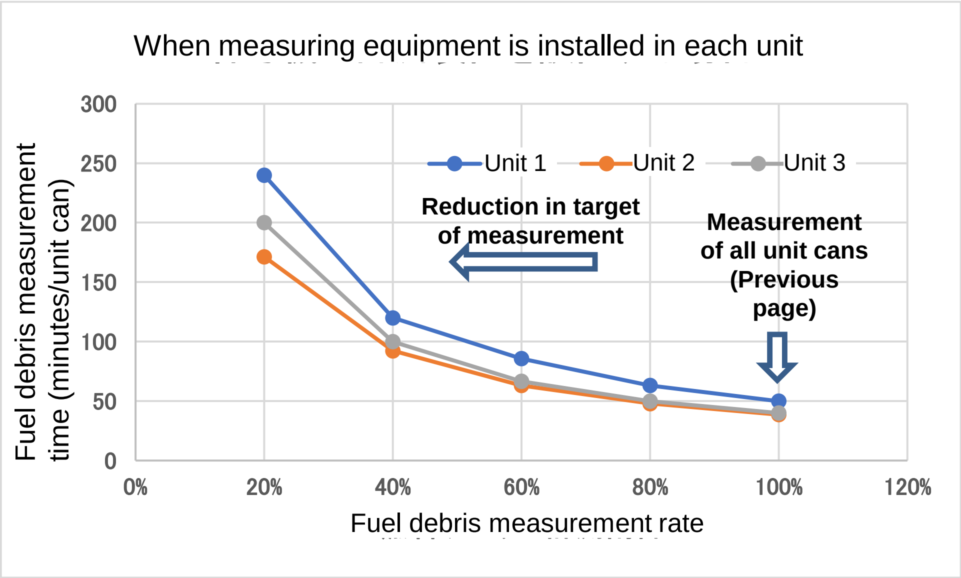
Prospective scenario ③-1 (Refer to No. 245)

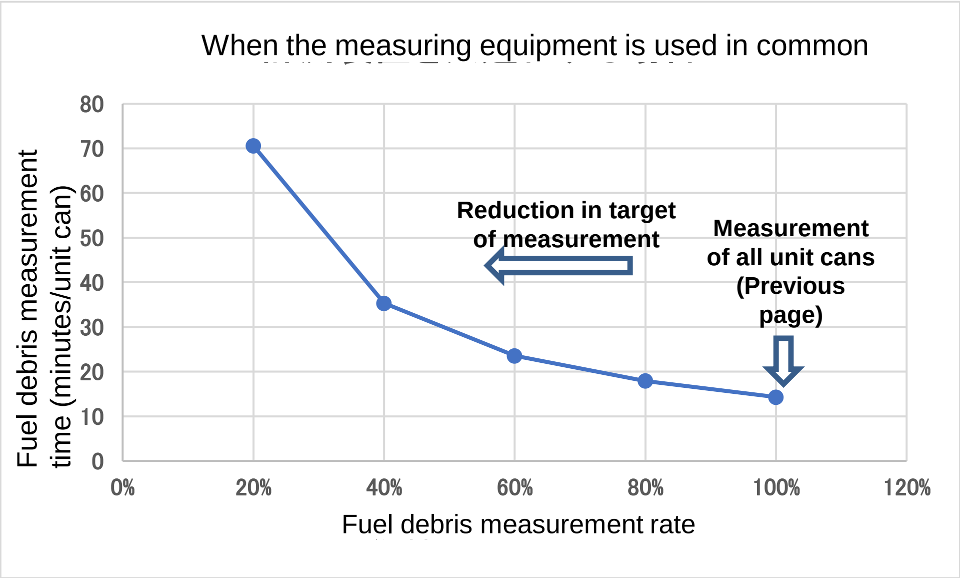
Prospective scenario ③-2 (Refer to No. 246)

- ✓ If the number of installed measuring equipment is increased, the measurement time per unit can increases proportional to the number of installed equipment.
- ✓ If the proportion of unit cans stored in the canister increases based on the indicators other than the quantity of nuclear material, the measurement time per unit can increases. (Parameter survey results are indicated on the following page.)

Target performance value (needs): Measurement time (Processing capability) (2/4)

- **The results of preliminary calculation of the time required for measuring fuel debris (unit can) to be sorted, with the fuel debris measurement rate (defined as the percentage of unit cans from among all unit cans, for which measurement is performed) as the parameter, when the proportion of unit cans stored in the canister increases based on indicators other than the quantity of nuclear material, are indicated below.**





Prospective scenario ③-1: Assumes that the Technology Readiness Level is high in the latter part of retrieval, and that sorting is carried out in the additional building (Refer to No. 245)

Prospective scenario ③-2: Assumes that the Technology Readiness Level is high in the latter part of retrieval, and that sorting is carried out at the storage pre-treatment facility (Refer to No. 246)

Target performance value (needs): Measurement time (Processing capability) (3/4)

- **Preliminary calculation of the target measurement time per inner waste container in which waste is stored is performed. (Targeting the stage when retrieval scale is increased.)**
- **It is presumed that the entire quantity of material categorized as waste in No. 17 “Target of measurement” is measured.**

Item			Unit 1	Unit 2	Unit 3	Remarks
①	Quantity stored in inner container	kg/container	30			Established from the perspective of mass control of critical quantity
②	Total quantity of waste	ton	57.3	64.1	64.1	Cited from the FY2018 Subsidy Project Results
③	Retrieval period	years	10	10	10	Tenatative value
④	Quantity of yearly retrieval	ton/year	5.73	6.41	6.41	④=②÷③
-	<When measuring equipment is installed in every unit>	-	-	-	-	
⑤	Number of days of operation of the measuring equipment	days/year	200	200	200	Considering maintenance period, etc.
⑥	Quantity (mass) measured per day	kg/day	29	32	32	⑥=④÷⑤
⑦	Quantity (number of inner containers) measured per day	containers/day	1	2	2	⑦=⑥÷①
⑧	Operating time per day	hours/day	20	20	20	Assuming 4 hours for detector calibration
⑨	Measurement time per inner container	minutes/container	1200	600	600	⑨=⑧÷⑦ x 60
-	<When measuring equipment is used in common>	-	-			
⑩	Quantity (mass) measured per day	kg/day	92.8			Sum of ⑥
⑪	Quantity (number of inner containers) measured per day	containers/day	4			⑪=⑩÷①
⑫	Operating time per day	hours/day	20			Assuming 4 hours for detector calibration
⑬	Measurement time per inner container	minutes/container	300			⑬=⑫÷⑪ x 60

Prospective scenario ③-1 (Refer to No. 245)

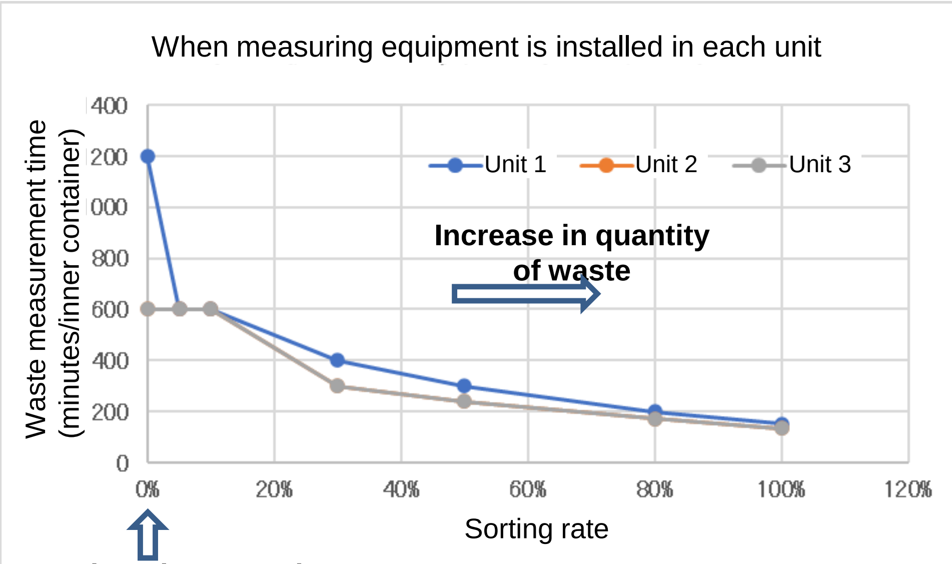
Prospective scenario ③-2 (Refer to No. 246)

- ✓ **If the number of installed measuring equipment is increased, the measurement time per inner container increases proportional to the number of installed equipment.**
- ✓ **When fuel debris is sorted, the quantity of waste increases as a result of which the number of inner containers for which the quantity of nuclear material is measured increases thereby reducing the measurement time per inner container. (Parameter survey results are indicated on the following page.)**

4.1.1 Study of the target performance values required for sorting (11/19)

Target performance value (needs): Measurement time (Processing capability) (4/4)

- **The waste measurement time mentioned on the previous page presumes that only the waste before sorting and categorizing radioactive waste is measured. When fuel debris is sorted, the quantity of waste increases as a result of which the number of inner containers for which the quantity of nuclear material is measured increases thereby reducing the measurement time per inner container.**
- **The results of preliminary calculation of the waste (inner container) measurement time considering sorting rate（defined as the percentage of material other than nuclear fuel from fuel debris that becomes waste）as a parameter are indicated below.**



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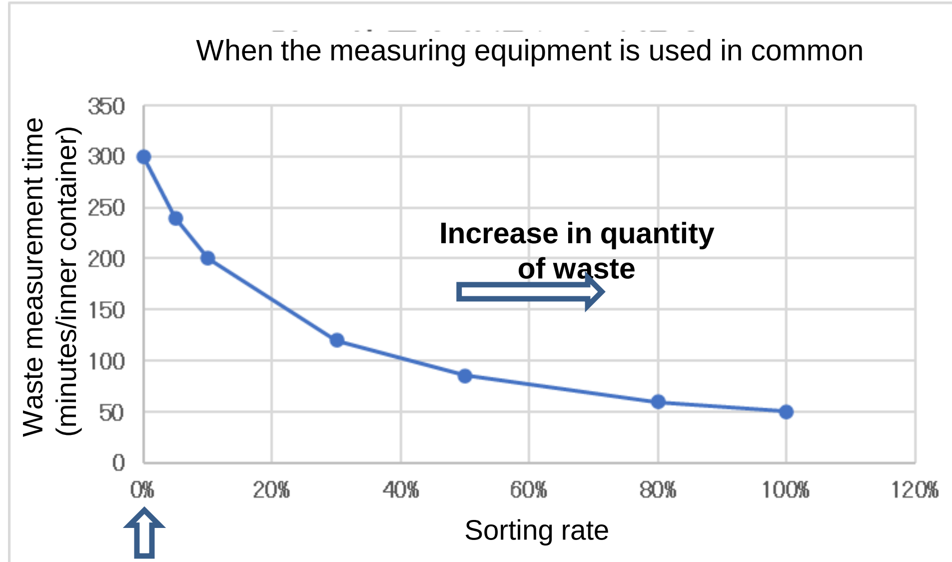

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Prospective scenario ③-1: Assumes that the Technology Readiness Level is high in the latter part of retrieval, and that sorting is carried out in the additional building (Refer to No. 245)

Prospective scenario ③-2: Assumes that the Technology Readiness Level is high in the latter part of retrieval, and that sorting is carried out at the storage pre-treatment facility (Refer to No. 246)

Method of determining sorting besides the method using the quantity of nuclear fuel material (1/7)

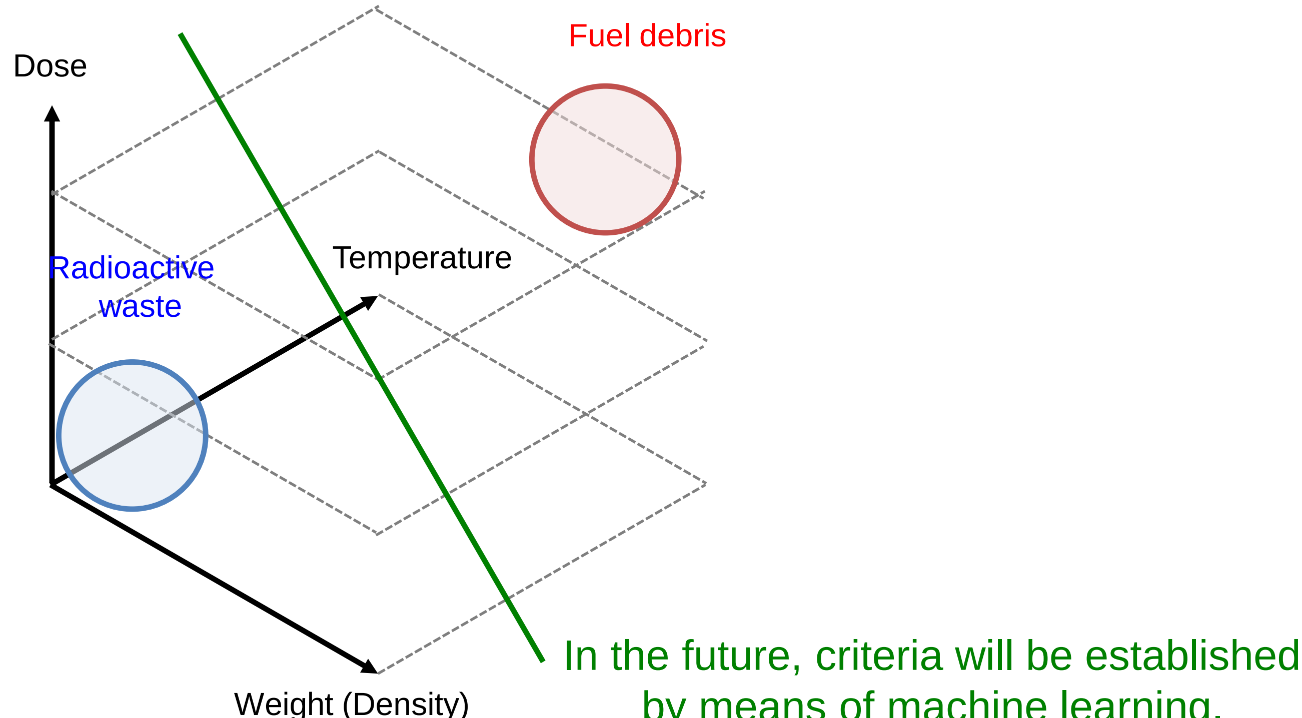
・Methods that could potentially be used for determining sorting other than the quantity of nuclear fuel material are studied.

Propective methods for determining sorting other than the quantity of nuclear fuel material

No.	Physical quantity	Measurement and evaluation method	Remarks
1	Weight	・Weighing scale	・Items that are obviously heavy are considered as fuel debris
2	Density	・Weighing scale + inner volume of container ・X-ray CT method	・Items that are obviously highly dense are considered as fuel debris
3	Temperature	・Radiation thermometer	・Items that are obviously hot are considered as fuel debris
4	Surface dose	・Passive measurement method (gamma, neutrons)	・Items that obviously have high radiation are considered as fuel debris
5	Effective multiplication factor	・Sub-criticality measurement using the neutron detector and the Feynman-alpha method	・Sub-criticality maintenance that is not based on measurement of the quantity of nuclear fuel material

Method of determining sorting besides the method using the quantity of nuclear fuel material (2/7)

- It is believed that weight (bulk density), temperature, radiation dose are related to the quantity of nuclear fuel material. The physical quantity is such that it can be measured **easily in a short time** . However, **there are major fluctuations in these parameters due to storage conditions,** and hence it is difficult to apply these as is for sorting.
- **Combining** weight (bulk density), temperature and radiation dose, is expected to **enhance determination accuracy for sorting**.
- In order to develop a system for determining sorting by combining weight (bulk density), temperature and radiation dose, the method of **simulating a huge number of cases of storage conditions** and **using machine learning to understand the correlation of these conditions with the quantity of nuclear fuel material** in order to **establish criteria** is conceivable in the future.



Method of determining sorting besides the method using the quantity of nuclear fuel material (3/7)

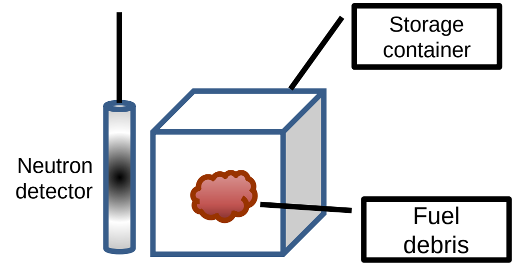
Study of the applicability of the sub-criticality measurement method for maintaining sub-criticality

① Purpose of the study and proposed study procedures

1. Purpose of the study

The applicability of sub-criticality measurement method was studied as a technology that could potentially be used for determining sorting apart from the method of using the quantity of nuclear fuel material.

Note) It is difficult to estimate the weight of fissile material from the sub-criticality measurement results.
It is difficult to estimate sub-criticality from the quantity of nuclear fuel material obtained by nuclear instrumentation.



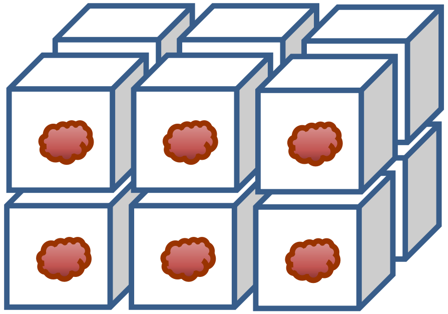
2. Proposed study procedures

2.1 The maximum weight of fissile material per container should be evaluated for keeping the Effective multiplication factor (keff) under 0.95 in the storage area (right bottom figure: Infinite arrangement system for the containers).

2.2 It should be studied whether or not it is possible to measure sub-criticality using the neutron detector when fuel debris with maximum fissile material weight is stored in each container.

2.3 Example arrangements of neutron detectors required for monitoring sub-criticality in the storage area should be studied.

2.4 Applicability and issues pertaining to sub-criticality measurement methods as a back-up (ensuring criticality safety in the storage area) for sorting using nuclear instrumentation should be studied.



Example of infinite arrangement system for the containers

Figure illustrating the concept of evaluation

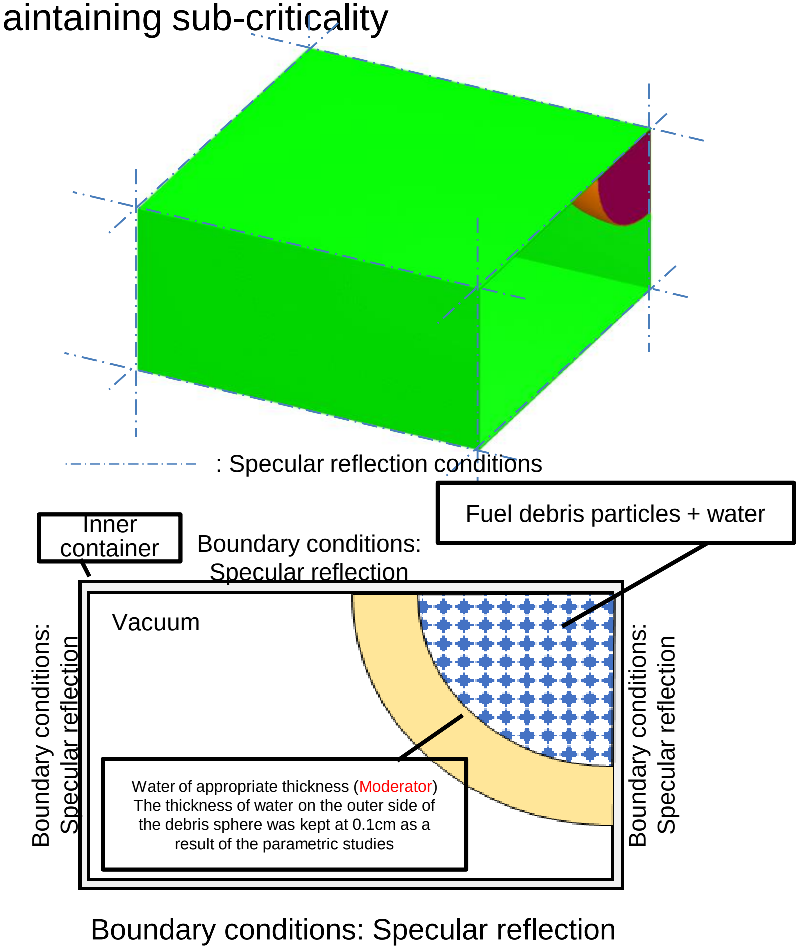
4.1.1 Study of the target performance values required for sorting (15/19)

Method of determining sorting besides the method using the quantity of nuclear fuel material (4/7)

Study of the applicability of the sub-criticality measurement method for maintaining sub-criticality

② Study conditions, study details

1. Computational code
   The sub-criticality measurement method (Feynman-α method) included in the Monte Carlo Computational Code (MVP3 code, cross-section library: JENDL-4.0) was used as the study tool.
2. Fuel debris specifications
   - The fuel debris had an unirradiated fuel composition with 4.9wt% concentration of U-235 (not considering Gd/neutron absorption material).
   - Fuel debris was a heterogeneous system consisting of fuel and water and a fuel/water volume ratio that facilitated optimal deceleration was used.
   - Moderator (water) was set up outside the heterogeneous fuel debris region such that the mutual interactions between the neutrons and the fuel debris that they approach becomes the maximum.
3. Storage container specifications
   The storage container was □500mmx300mmH, made of SUS and had a plate thickness of t6mm.
4. Neutron detector specifications
   Assuming several types of neutron detectors with varied thermal neutron sensitivity, it was assumed that neutrons within the system would be measured by the passive neutron method.
   It was studied whether or not the sub-criticality can be measured for the container in which fuel debris with a weight that can be stored in 1 inner container as evaluated using the evaluation system (infinite arrangement system) shown in the figure on the right, is stored.



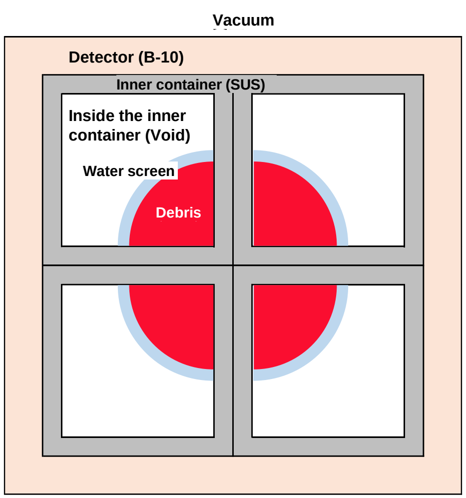
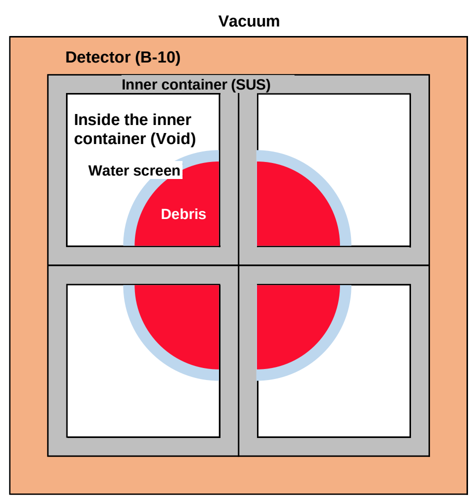
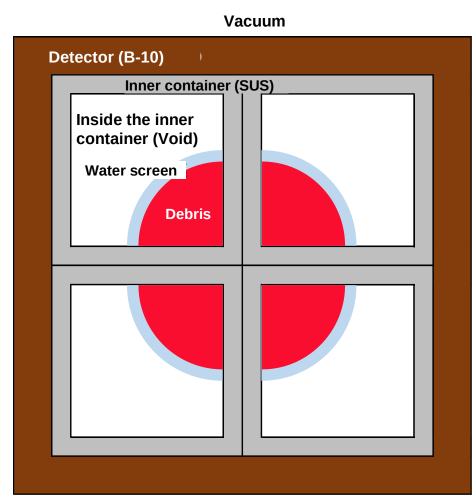
Criticality evaluation model for the storage container infinite arrangement system

Method of determining sorting besides the method using the quantity of nuclear fuel material (5/7)

Study of the applicability of the sub-criticality measurement method for maintaining sub-criticality

Feynman-α method simulation model

- Based on the criticality evaluation using the infinite arrangement system for inner containers, it was estimated that the weight of fuel debris that can be stored in 1 inner container would be approx. 3.84kg and thus a deeper sub-criticality was expected. Hence sub-criticality measurement was simulated with a system of 8 containers.
- In the analysis model, the entire outer surface of the 8 containers was covered by the neutron detector (B-10 detector), and whether or not sub-criticality can be measured was studied by measuring the neutrons leaking outside the containers.

<table>
<tr><th>Analysis model 1</th><th>Analysis model 2</th><th>Analysis model 3</th></tr>
<tr><td>A model in which the B-10 content in the B-10 detector was equivalent to the B-10 content in the B-10 detector that is commercially available.</td><td>A model in which the B-10 content in the B-10 detector was increased about 200 times of the B-10 content in the B-10 detector that is commercially available.</td><td>A model in which all neutrons leaking outside is measured.</td></tr>
<tr><td>
</td><td>
</td><td>
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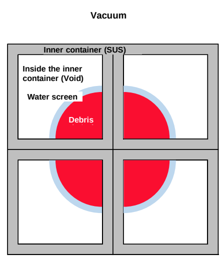
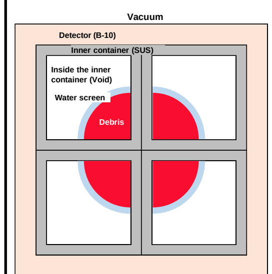
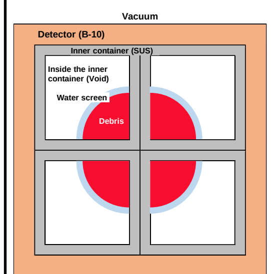
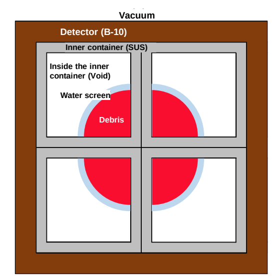
</table>

Method of determining sorting besides the method using the quantity of nuclear fuel material (6/7)

Study of the applicability of the sub-criticality measurement method for maintaining sub-criticality

Feynman-α method simulation model results

- Results of sub-criticality measurement simulation from each of the models are consolidated in the table below.

	Reference solutions	Analysis model 1	Analysis model 2	Analysis model 3
Obtained effective multiplication factor (keff)	0.643	0.880	0.781	0.614
Absolute value of the gap with the reference solutions	–	0.237	0.138	0.029
Neutron detection efficiency	–	0.3%	11.6%	100%
Analysis model figure				

Method of determining sorting besides the method using the quantity of nuclear fuel material (7/7)

Study of the applicability of the sub-criticality measurement method for maintaining sub-criticality

- Summary
  - The control methods involving monitoring of sub-criticality of the container for maintaining sub-criticality in the waste storage facilities were tested and studied through simulation.
  - **In order to place the containers in an infinite arrangement and keep keff ≦0.95, it becomes essential to keep keff at 0.643 or lower in a system containing 8 containers.** However, even in the case of an ideal detection system in which the outer surface of the containers is completely covered by the neutron detector, measurement needs to be performed using a neutron detector (detector with 40 times the sensitivity is used in this test analysis) with a detection efficiency higher than the commercially available B-10 detector (sensitivity of about 10cps/nv).
  - **Even if a neutron detector with high detection efficiency is used,**, it is believed that **detection becomes even more difficult** since the limit value of the keff obtained by means of neutron measurement becomes 0.505(=0.643-0.138) considering the error (Δkeff=0.138 in model 2) in the keff obtained by means of neutron measurement.
  - In order to maintain sub-criticality at the storage facility after performing measurement with an 8 container system, **it becomes necessary to maintain an environment that is the same as the environment in which measurement was performed (moisture environment, condition of fuel debris inside the container, etc**.)
  - Also, so far there are no instances of a control method involving maintenance of sub-criticality in a fuel handling and storage facility by measuring sub-criticality. (It may be used as a backup for the usual sub-criticality maintenance method involving mass control and shape control)
  - Therefore, it is believed that **it would be difficult to use the control method involving monitoring of sub-criticality of the container for maintaining sub-criticality in a waste storage facility**.

Summary of the study of the target performance values required for sorting

[Results / Contribution to development]

・The **objects to be sorted** were set up to be retrieved from the lower grid plate rather than the upper grid plate. As a result, **crystallization of pre-conditions (properties and quantity of target objects)** made progress.

・As the **approach towards sorting, a sorting flow** was established in which the objects were stored in retrieval containers (unit can, large sub-criticality container, inner waste container) depending on their external appearance and location of occurrence, and sorted into storage containers (canister, impact mitigation type canister, waste container (control level) and waste container (contamination level)) **based on the results of measuring the quantity of nuclear fuel material**. As a result, **crystallization of pre-conditions (dimensions of the target objects, criteria that must be established)** made progress.

・Amongst the target performance values, **the criteria for sorting** was assumed to be **the threshold of the canister and impact mitigation type canister** (1.5wt% of U-235 in the entire quantity stored), **threshold of the fuel debris and waste** (quantity of nuclear fuel material 3.7kg/container), **the quantity of nuclear material such that the physical protection and safeguards end** (To be determined).

・Amongst the target performance values, **the measurement time** was calculated as **40 to 50 minutes/unit can and 600 to 1200 minutes/inner waste container** when **measured for each unit,** and **14 minutes/unit can and 300 minutes/inner waste container** when objects retrieved from Units 1 to 3 were **all measured with a single measuring equipment** .

・**Introducing the method of screening measurement (comprehensive determination based on weight, radiation dose, temperature, etc.)** was proposed as a determination method besides the method using the quantity of nuclear fuel material. This is likely to reduce the quantity to be measured using the non-destructive measuring equipment and is likely to extend the measurement time per unit of measurement.

・**The application of the control method involving monitoring of sub-criticality of the container** is believed to be **difficult** as a result of the studies based on simulation, however, its applicability to criticality approach monitoring by **installing neutron detectors as a back-up for criticality monitoring at the waste storage facility** will be studied in the future.

[Issues]

・Since sorting criteria needs to consider criticality safety during storage, **the specifications and operating methods of the containers to be handled need to be coordinated with related projects and the criteria need to be established by conducting criticality analysis**. Also, the threshold of the control level and contamination level of the radioactive waste needs to be studied based on the approach towards the control level and contamination level in collaboration with the concerned parties such as the operators, etc.

・If all the objects retrieved from Units 1 to 3 are measured using a single measuring equipment, the target measurement time is extremely short. **The quantity processed by a single measuring equipment needs to be reduced by introducing multiple units of equipment and by introducing the method of screening measurement**.

・**Crystallization of the method and criteria pertaining to screening measurement** (comprehensive determination based on weight, radiation dose, temperature, etc.) **needs to be considered**.

・**Applicability of** installation of neutron detectors as a backup for criticality control at the waste storage facility **for criticality approach monitoring needs to be studied through simulation.**

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

[Objective]
・The concept of non-destructive measuring equipment using the active neutron method, passive neutron method, muon scattering method, x-ray CT method and passive gamma rays method should be established.
(Target TRL at completion: Level 3)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(Items that are common to the measurement technologies)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

Items common to the measurement technologies (1/5)

➢ **The concept of the measuring equipment applicable to sorting is developed by simulating the structure of the measuring equipment such as the detector, etc. and obtaining detector response data to be used for developing the concept of the measuring equipment.**

Analytical simulation (Overall flow)

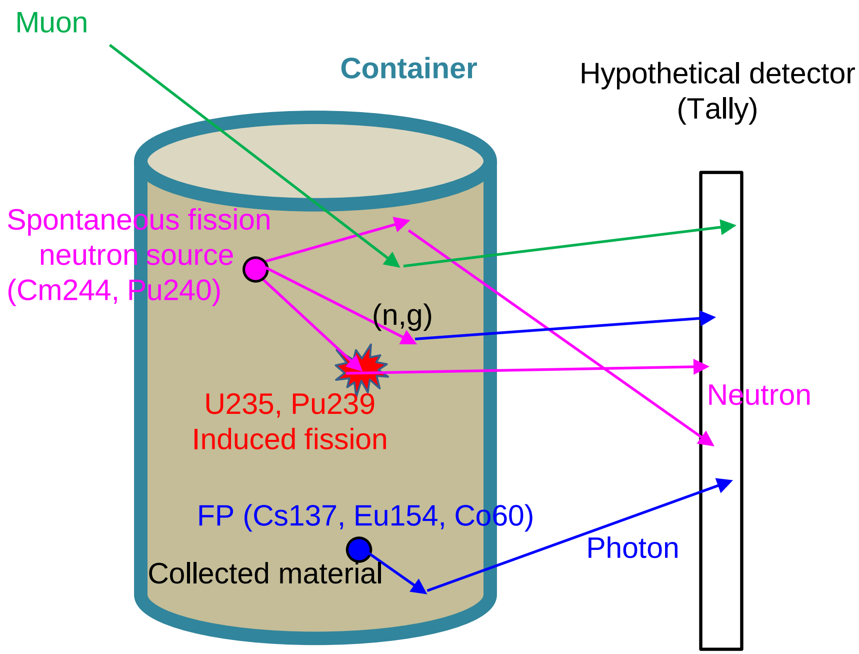
Creation of fuel debris radiation source model (data on each material)

Development of model for the fuel debris stored in containers considering the influencing factors (material mixing conditions, type of container, etc.)

Implementation of particle transport simulation with the Monte Carlo method (MCNP, PHITS code) for every measurement technology

Analysis of detector response for each case of sensitivity analysis

Particle transport simulation (Neutron / photon / electron /muon)

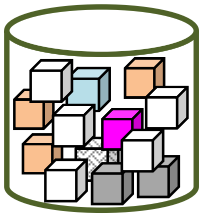


4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

Items common to the measurement technologies (2/5)

Development of voxel-based mixed fuel debris model for simulation

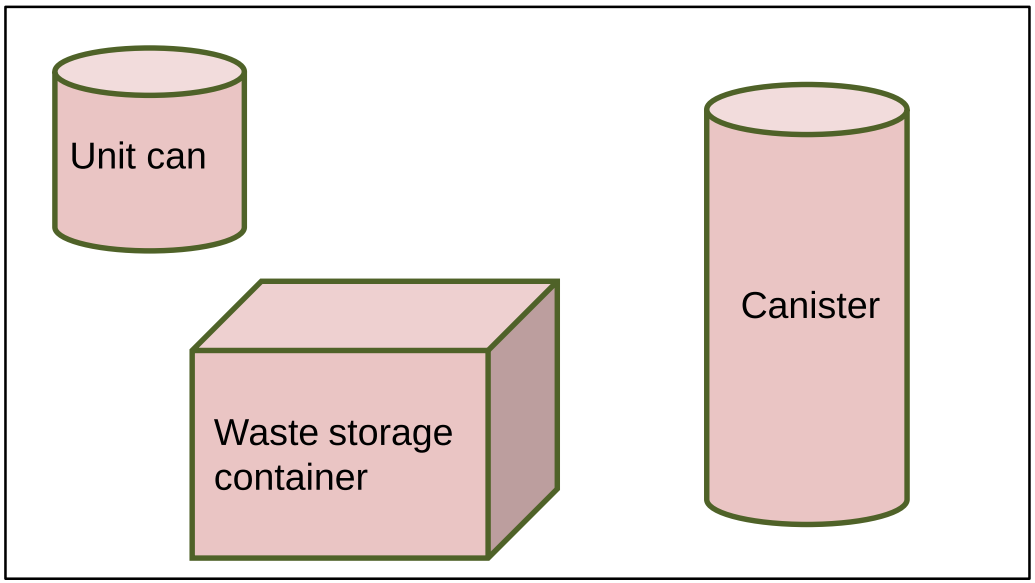
- Unitary handling of a great number of sensitivity analysis cases
- Avoiding unrealistic models by using correlated parameters
  (Example of correlation: The average density of fuel debris with a higher uranium concentration tends to be high.)



A variety of fuel debris is simulated by adjusting the number of voxels for each material stored in the container.

(The radiation source is proportionate to the number of voxels.)

Mixed uniformly and stored in various containers (simulation model)



Fuel debris material (voxel)

- UO_2 **(contains BP)** ★
- MOX **(contains BP)** ★
- ZrO_2 ★
- B_4C — **Control rods / criticality prevention material**
- SUS ★
- Gd_2O_3 — **Criticality prevention material**
- H_2O — **For adjusting the moisture content**
- Concrete
- Empty — **For adjusting the filling factor and bulk density**

Size: $1 cm^3$
Weight: Material density
★: Radiation source is present

18 types of voxel data are created including the difference in the radiation source model
➡ A variety of fuel debris is simulated by using various combinations

- Molten debris: $(U_{0.5}, Zr_{0.5})O_2$
- Uranium-rich debris
- MCCI debris
- Metallic debris

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

Items common to the measurement technologies (3/5)

Additional information related to “burn-up”

At the time of the accident, Units 1 to 3 of the Fukushima Daiichi Nuclear Power Station were all operating in an equilibrium cycle. Hence right before the accident, fuel of around 1 to 50 [GWd/t] was distributed in the reactors depending on the location of the reactor. As a result of the accident, this fuel is believed to have fused and mixed. However, the proportion of the types of fuel that got mixed to form fuel debris and their respective burn-ups are not known.

In this project, the following 3 types of fuel have been considered as typical fuel based on operation management data of a 3 dimensional reactor core, considering Unit 2 which has the widest range of burn-up as the target reactor.

1) Average composition of the reactor core region
2) Composition of the reactor core region with the least burn-up
3) Composition of the reactor core region with the largest burn-up

These combustion fuel compositions and the radiation source data calculated from the compositions were assigned to the “UO_2” voxels. The burn-up cannot be defined for fuel debris that is formed as a result of fusion and mixing wherein the burn-up of the source and the mixing ratio are unknown. However, in this project, since based on the average composition of the respective core regions mentioned in 1), 2) and 3) above, their burn-ups are equivalent to 23 [Gwd/t], 1.3 [GWd/t] and 51 [Gwd/t], these are referred to as “Burn-up”. These 3 types of “UO_2” voxels respectively refer to the following characteristic fuel debris materials.

1) Fuel containing lot of U-235 but little Eu-154 and Cm-244 which are measured when the passive gamma rays method or the passive neutrons method are used.
2) Fuel that is mixed uniformly in the entire reactor core region (standard case)
3) Fuel in which U-235 has decreased, Pu element is formed due to conversion, and Eu-154 and Cm-244 are present in the largest quantities.

However, when fuel debris formed as a result of mixing of fuels having varying burn-ups is considered, it is necessary to note that the quantity of nuclides corresponding to each burn-up is not necessarily proportional to the burn-up.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

Items common to the measurement technologies (4/5)

➢The concept of the measuring equipment that uses the technologies indicated in the red frame, which have been selected so far as the feasible technologies for measuring nuclear material, will be studied.
With respect to the technologies that were selected with the precondition of being used in combination as well, the stand-alone equipment will be studied and thereafter, the combination will be studied using the evaluation technique.

○: Technology expected to be used
△: Technology that is likely to be feasible
×: No feasible technology at this stage

No.	Determination (Measurement) technology	Location of application		
		Inside PCV	Additional building	Storage pre-treatment facility
1	Visual (image) determination	△ Image determination	△ Image determination	△ Image determination
2	Estimation of nuclear material distribution inside PCV	△ Passive α rays measurement △ Passive γ rays measurement △ Passive neutron measurement		
3	Measurement of nuclear material (nuclides, concentration)			
	① For measuring concentration of fissile material	x	△ X-ray CT method △ Muon scattering method	△ X-ray CT method △ Muon scattering method
	② For criticality and safety control	△ Passive α rays measurement △ Passive γ rays measurement △ Passive neutron measurement	△ Passive γ rays measurement △ Passive neutron measurement △ X-ray CT method △ Muon scattering method △ Active neutron measurement △ Passive neutron measurement + γ rays measurement △ Passive/active neutron measurement+ γ rays measurement	△ Passive γ rays measurement △ Passive neutron measurement △ X-ray CT method △ Muon scattering method △ Active neutron measurement △ Passive neutron measurement + γ rays measurement △ Passive/active neutron measurement+ γ rays measurement
	③ For determining end of physical protection, safeguards	—	△ Active neutron measurement △ Passive/active neutron measurement+ γ rays measurement	△ Active neutron measurement △ Passive/active neutron measurement+ γ rays measurement

"Subsidy Project of Decommissioning and Contaminated Water Management" in the FY2018 Supplementary Budget
"Development of technology for further increasing the scale of retrieval of fuel debris and reactor internal structures"
No. 700 cited from the FY2020 Final Report (July 2021) and expressions simplified.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

Items common to the measurement technologies (5/5)

➢ The study cases of the measuring equipment

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191
②-1	Passive neutron method A	He-3	None	None	Mass of spontaneous fission nuclides (Cm-244, etc.)	Same as above	MHI	81-93 192-203
②-2	Passive neutron method B	B-10	None	None	Same as above	Same as above	Hitachi-GE	94-101 204-207
③	Muon scattering method	Muon trajectory detector	None	None	Atomic weight	Same as above	Toshiba ESS	102-116 208-214
④	X-ray CT method	X-ray detector	Accelerator based x-ray source	From the lateral side	Density	Same as above	Hitachi-GE	117-127 215-220
⑤-1	Passive gamma rays method A	Ge	None	None	Mass of fission product nuclides (Eu-154, etc.)	Same as above	MHI	128-140 221-233
⑤-2	Passive gamma rays method B	CZT, $LaBr_3$ etc.	None	None	Same as above	Same as above	Hitachi-GE	141-154 234-237

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(①-1 Active neutron method A)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191

[Characteristics]

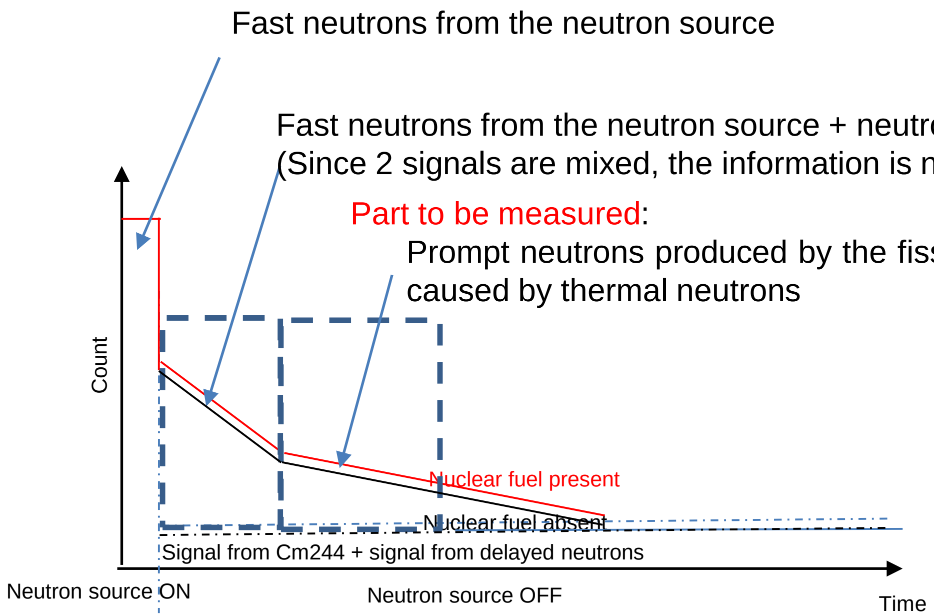
- The He-3 detector was selected based on its track record.
- D-T neutron source was selected as the irradiation source based on its neutron generation efficiency and past track record.
- Irradiation from the lateral side of the target object was selected as the neutron irradiation direction based on past track record.

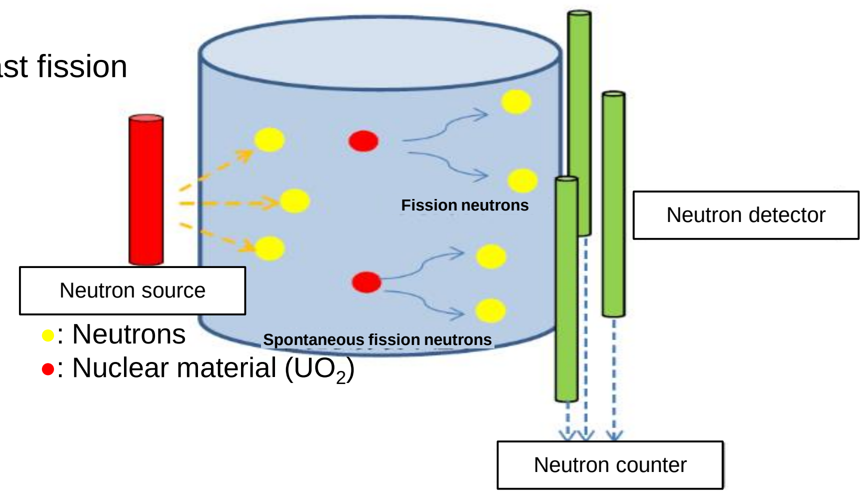
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

① Items common to the active neutron method

Measurement concept

- Pulsed neutrons are repeatedly irradiated from the neutron source to the fuel debris, and neutrons produced by fissile nuclides (U-235, Pu-239, etc.) contained in fuel debris are measured.

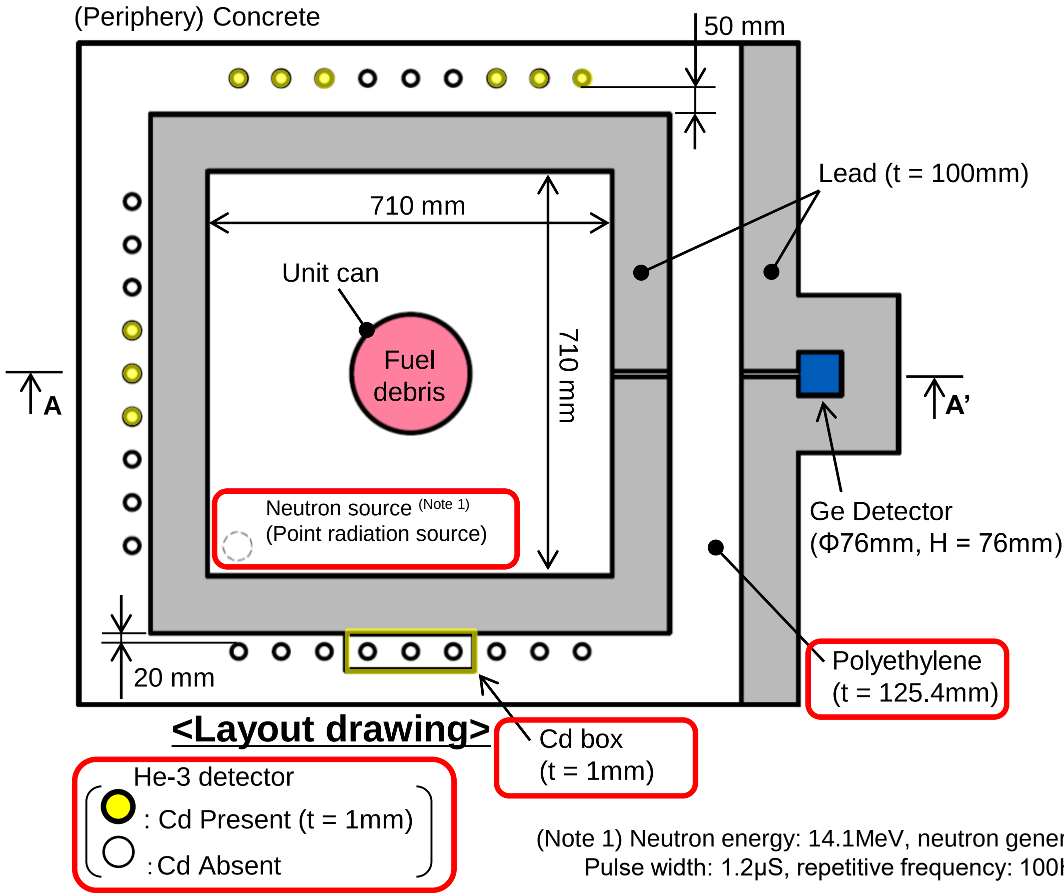




4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (1/11)

<Study of the concept of the measuring equipment>･･･Concepts of the equipment that support the active n, passive n and γ measurement methods were studied using stand-alone measuring equipment.



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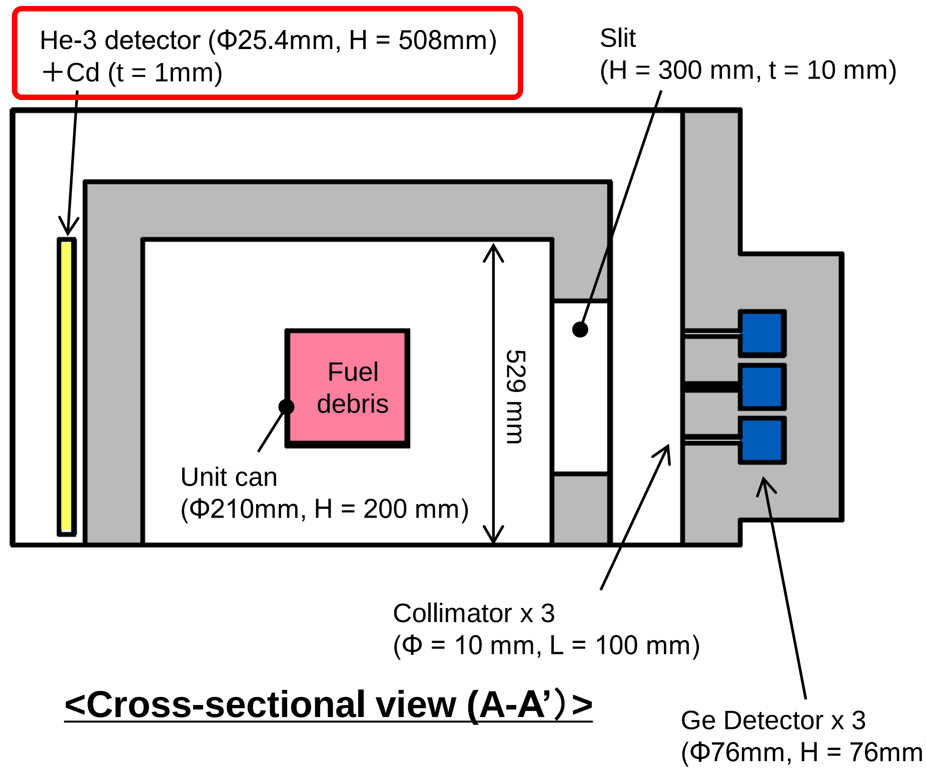


<Cross-sectional view (A-A')>

(Note 1) Neutron energy: 14.1MeV, neutron generation rate: $2x10^8$n/s,
Pulse width: 1.2μS, repetitive frequency: 100Hz, neutron generation direction: Isotropic

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (2/11)

<Study of conditions of the target object>

- Conditions of the target object: **It was assumed that "molten debris", "MCCI debris" and "Metallic debris"** (Note 1) are measured.
- The following was assumed regarding the containers to be evaluated based on the cases evaluated in FY2021.

Debris properties	Container/Shape of container	Remarks
Molten debris MCCI debris	**Unit can/**Φ210mm × H200mm	Smallest single container. Area contributing to the dose rate, represented by H200mm wherein the quantity of radiation source becomes smaller.
Metallic debris	**Waste storage container (inner container)** / □500mm×300mmH	Represented by an inner container that does not have any shielding and which is smaller than the storage container, since the thickness of the shielding of the waste storage container is yet to be determined. (From amongst the multiple options for inner (collection) containers, the typical option from the Treatment & Disposal PJ was used)

Based on the influencing factors consolidated as results until FY2021, detector response analysis cases focusing on the parameters (**self-shielding**(Note 2) **(composition)**, **burn-up**, **presence of neutron absorption material)** identified as technical issues were set up for the study.

[Number of analysis cases]

A: Molten debris ⇒ Total 12 cases

(Composition: 2 cases) x (Burn-up: 3 cases) x (Presence/absence of neutron absorption material)

B: MCCI debris ⇒ Total 12 cases

(Composition: 2 cases) x (Burn-up: 3 cases) x (Presence/absence of neutron absorption material)

C: Metallic debris ⇒ Total 3 cases

(Composition: 3 cases) x (Burn-up: 1 cases) x (Absence of neutron absorption material)

Total 27 cases

⇒ Conditions of each case are listed from the next page onwards.

(Note 1) Subsidy Project of Decommissioning and Contaminated Water Management Development of technology for fuel debris characterization and analysis FY2016 Supplementary Budget Research Report (Interim report) March FY2018
(Note 2) In the future, cases with uneven distribution also are planned to be studied depending on the progress of work, for analyzing the impact of self shielding.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (3/11)

Table indicating analysis cases (Molten debris)

Case No.	Composition inside the container				Burn-up	Neutron Absorption material	FP Emission rate*1	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
A-1	Molten debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-2		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-3		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-4		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-5		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-6		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-7		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-8		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-9		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-10		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-11		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-12		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)

*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (4/11)

Table indicating analysis cases (MCCI debris)

Case No.	Composition inside the container				Burn-up	Neutron Absorption material	FP Emission rate*1	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
B-1	MCCI Debris	UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-2				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-3				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-4		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	**60 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-5				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-6				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-7		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-8				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-9				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-10		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	**60 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-11				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-12				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

①-1 Active neutron method A (5/11)

Table indicating analysis cases (Metallic debris)

Case No.	Composition inside the container				Burn-up	Neutron Absorption material	FP Emission rate*1	Cooling period	Uneven distribution	Container*2	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
C-1	Metal Debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 29.85 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)	D-T reaction (14.1MeV)
C-2	Metal Debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 44.85 vol%	**45 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)	D-T reaction (14.1MeV)
C-3	Metal Debris	UO_2 : 0.48vol% ZrO_2: 0vol% SUS: 10 vol%	**10.48 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)	D-T reaction (14.1MeV)

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)
*2 Mainly made of SUS, it is assumed to be sorted as inner container during the initial stage of retrieval
*3 Overview of each case is indicated below.

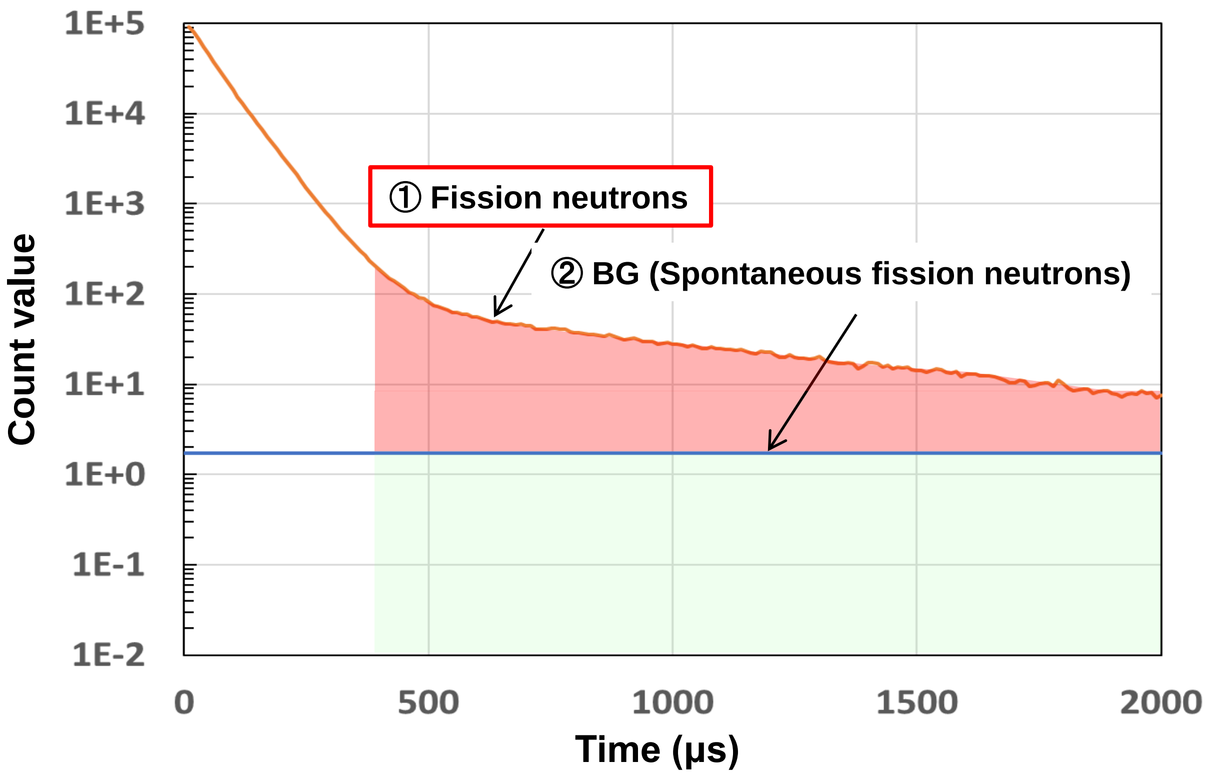
C-1: Base case
C-2: Case of sensitivity with respect to SUS composition
C-3: Case of sensitivity in which UO_2 has a volume percent equivalent to 3.7kg

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (6/11)

<Molten debris Detector response in the base case>

Case No.	Composition inside the container				Burn-up	Neutron Absorption material	FP Emission rate	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
A-1	Molten debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)



✓ The detectability of ① was verified through the analysis performed by creating a model of the concept of the measuring equipment.

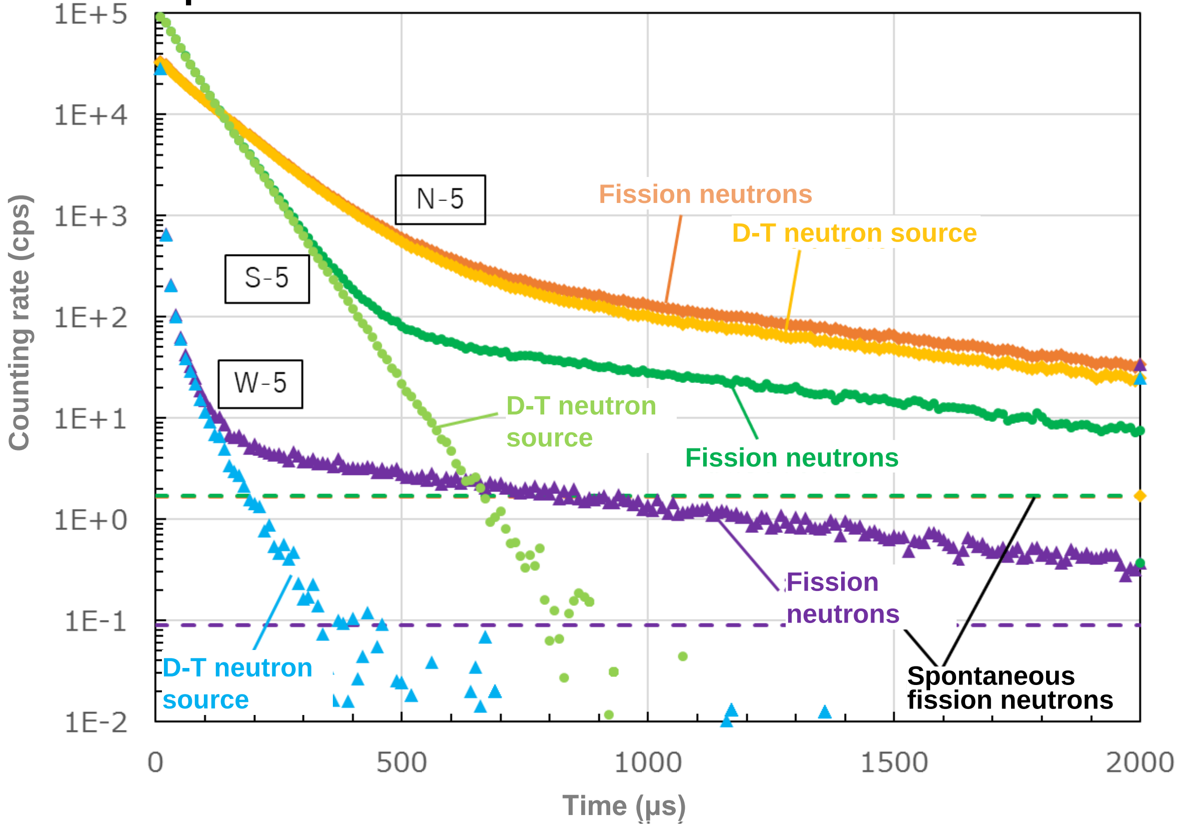
⇩

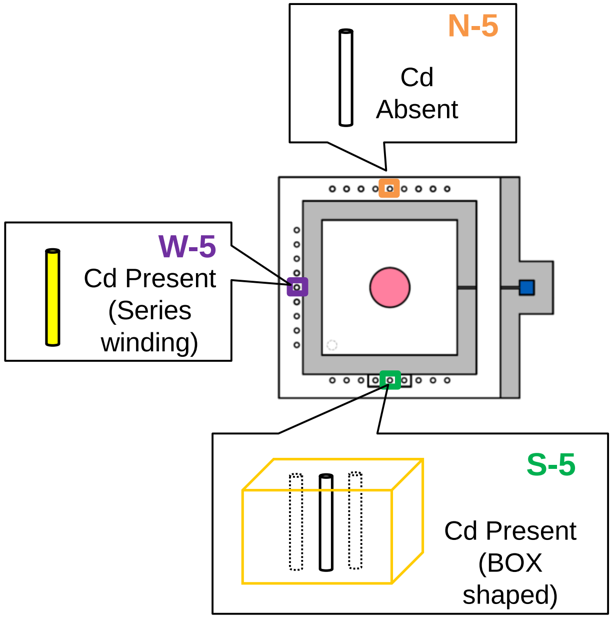
The integrated counting rate of the fission neutrons induced by the irradiated neutrons was focused on.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (7/11)

<Comparison of the response for each detector specification and selection of the detector to be used>





(He-3 detector position and Cd specifications)

- Comparison (molten debris base case) of the detectability for each specification (N-5: Cd Absent, W-5: Cd series winding, S-5: Cd BOX shaped) of the He-3 detector

  - N-5: It was difficult to differentiate between the neutrons originating from the D-T neutron source and the fission neutrons originating from fuel debris.
  - W-5: Not only the neutrons originating from the D-T neutron source but also the fission neutrons originating from fuel debris were absorbed.
  - S-5: The number of detections of neutrons originating from the D-T neutron source were efficiently reduced.

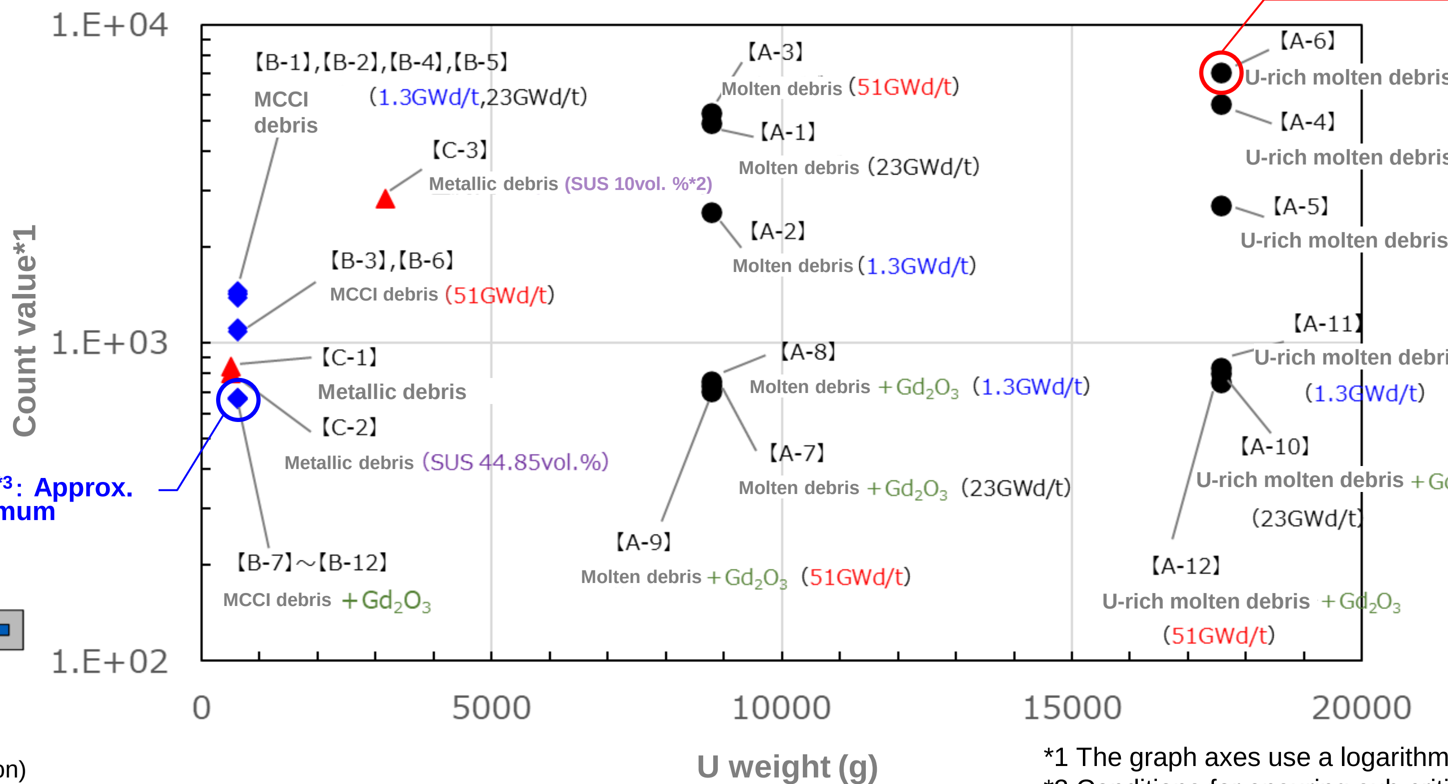
⇒ Results and considerations focusing on the He-3 detector position S-5 using the active neutron method A are consolidated hereinafter.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

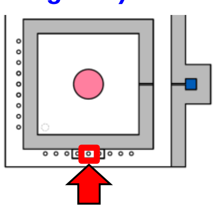
①-1 Active neutron method A (8/11)

- ✓ Molten debris : The counting rate was high in the order of high burn-up > average burn-up > low burn-up
  (It is believed that the relationship between the counting values in terms of magnitude was a result of the quantity of burnable poison Gd (Gd-155, 157) present in UO_2.)
- ✓ MCCI debris : Unaffected by burn-up in comparison with molten debris
- ✓ Metallic debris : Comparatively less sensitive to the quantity of SUS
  The fact that the detectability was verified in case C-3 suggests the applicability of this measurement method to ensuring sub-criticality
- ✓ Common : Presence/absence of neutron absorption material had a significant impact

Measurement time*3 : Approx. 3 seconds (maximum counting rate)



Measurement time*3 : Approx. 120 seconds (minimum counting rate)



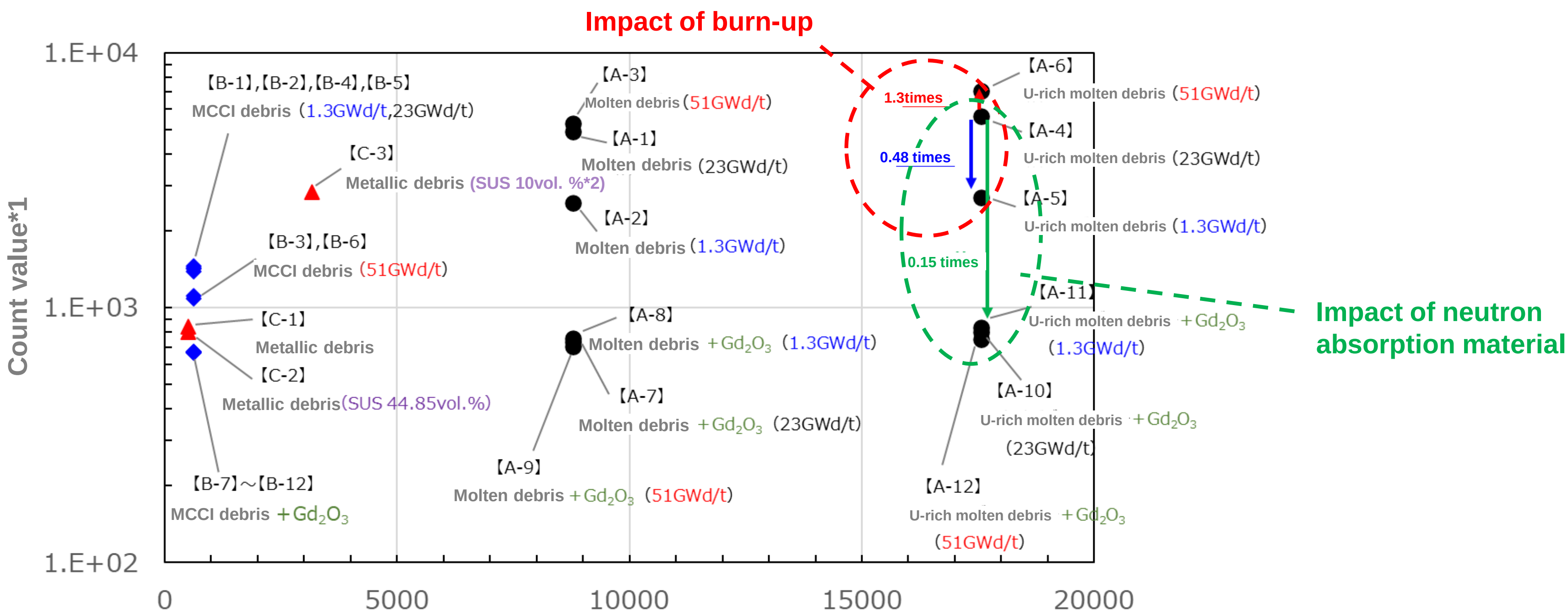
(He-3 detector position)

*1 The graph axes use a logarithmic scale
*2 Conditions for ensuring sub-criticality
*3 Measurement time with a 1% (10,000 count) statistical error

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (9/11)

<Analysis of the extent of impact of the influencing factors being focused on>



*1 The graph axes use a logarithmic scale
*2 Conditions for ensuring sub-criticality

Analysis of uranium rich fuel debris that has the highest impact

- ✓ Impact of burn-up: The count value of high burn-up (51Gwd/t) increased to approx. 1.3 times of the base case (burn-up 23GWd/t)
  The count value of low burn-up (1.3GWd/t) decreased to approx. 0.48 times of the base case (burn-up 23GWd/t)
- ✓ Impact of neutron absorption material: The count value of Gd content 3vol% decreased approx. 0.15 times of the base case (Gd content 0vol%)

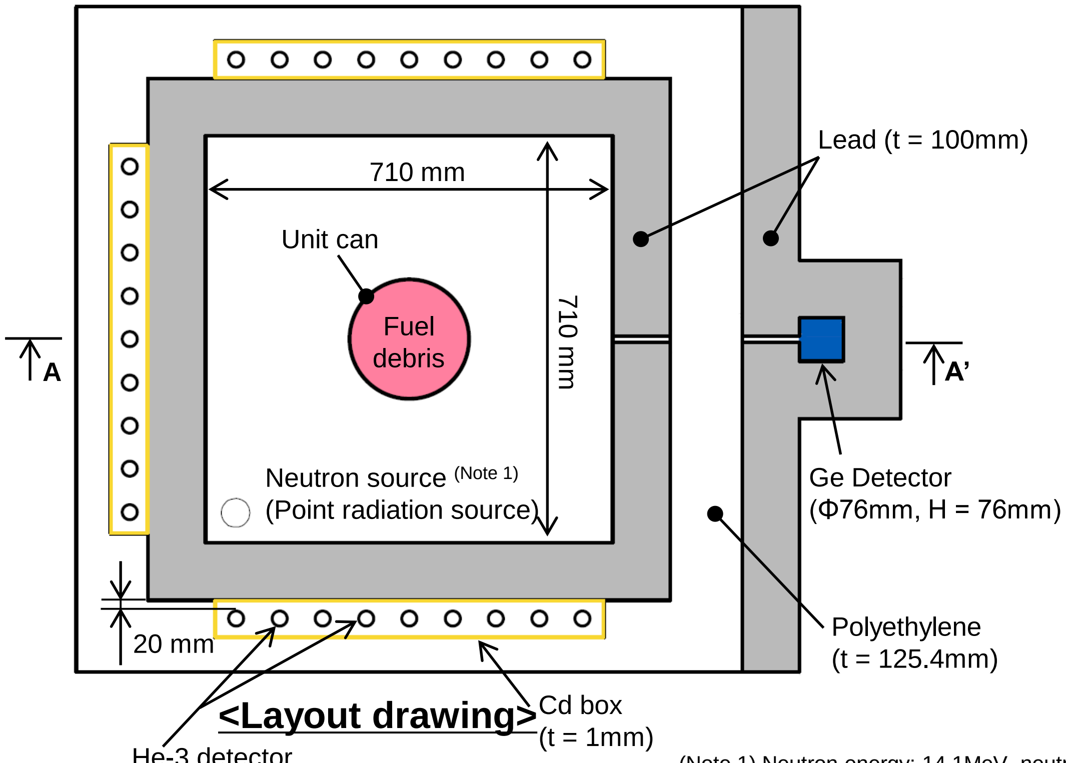
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (10/11)

<Primary proposal of the concept of the measuring equipment>

- ✓ Cd absent: It is difficult to differentiate between the neutrons originating from the D-T neutron source and the fission neutrons originating from fuel debris
- ✓ Cd Present (Series winding): Not only the neutrons originating from the D-T neutron source but also the fission neutrons originating from fuel debris are absorbed.
- ✓ Cd Present (BOX shaped) The number of detections of neutrons originating from the D-T neutron source can be efficiently reduced.

⇒ The measurement system using Cd present (BOX shaped) was set as the primary proposal



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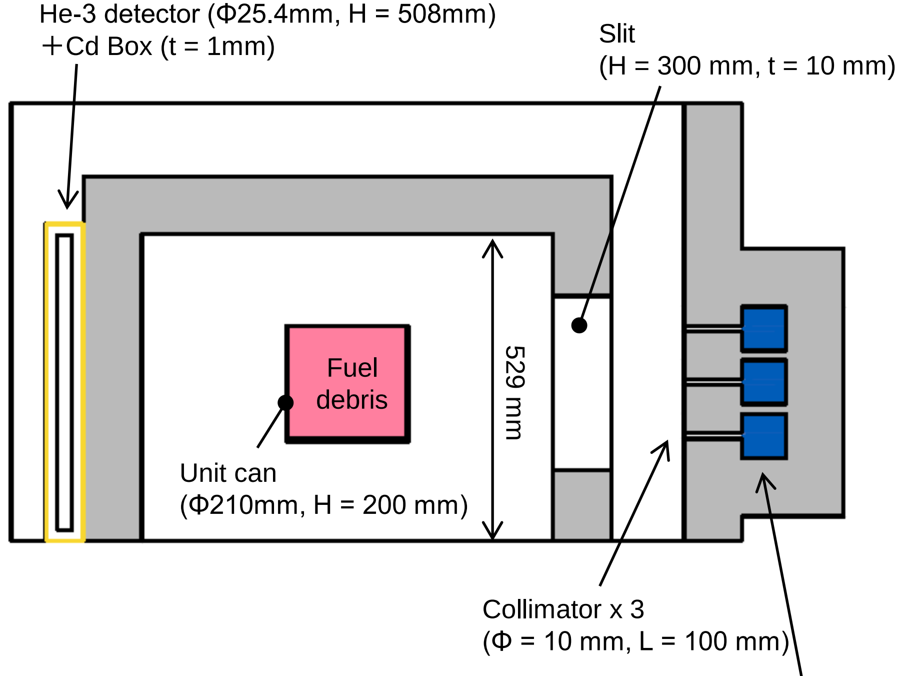


<Cross-sectional view (A-A')>

(Note 1) Neutron energy: 14.1MeV, neutron generation rate: 2×10^8n/s,
Pulse width: 1.2μS, repetitive frequency: 100Hz, neutron generation direction: Isotropic

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-1 Active neutron method A (11/11)

<Summary and future issues>

[Implementation details]

1) An analysis model using the active neutron method was studied.
2) Detector response was analyzed focusing on composition, burn-up and neutron absorption material.
3) The concept of the measuring equipment used for sorting fuel debris was studied.

[Results/Contribution to development]

1) An analysis model using a combination of active neutron method, passive neutron method and passive gamma rays method was created.
2) Results of analyzing 27 cases of detector response were acquired.
- Impact of the composition: The suggested applicability of the active neutron measurement method for ensuring sub-criticality of the inner waste container (metallic debris) was verified.
- Impact of burn-up: The burn-up increased approx. 2.2 times (23→51GWd/t) and the count value increased approx. 1.3 times.
  Burn-up decreased approx. 0.06 times (23→1.3GWd/t) and the count value decreased approx. 0.48 times.
- Impact of neutron absorption material: The Gd content increased from 0vol% to 3vol%, and the count value decreased approx. 0.15 times.

3) The concept of measuring equipment using a combination of the active neutron method, passive neutron method and the passive gamma rays method was developed.
- Detector specifications: He-3 detector enclosed in a Cd box (The number of detections of neutrons originating from the D-T neutron source can be efficiently reduced)
- Equipment dimensions: About W5mxD4mxH3m (Compatible with unit cans and inner waste containers)
- Measurement time: Approx. 3 seconds (Molten debris, 17.6kg of U, high burn-up (51GWd/t), neutron absorption material absent)
  Approx. 120 minutes (MCCI debris, 0.6kg of U, high burn-up (51GWd/t), neutron absorption material present)

[Issues and response measures]

1) Issue: Reduction of errors due to burn-up, neutron absorption material
   Response measure: Study of optimization of the correction method based on neutron die-away time, detailed study of correction method based on the Cm-244 and Eu-154 ratio, and study of application of the PGA method, etc.
2) Issue: Lack of data contributing to the optimization of the equipment structure
   Response measures: Parameter study on equipment structure should be enhanced by means of analysis, elemental technology verification test results should be reflected.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(①-2 Active neutron method B)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191

[Characteristics]

- The B-10 detector was selected since it can be used in locations with high gamma rays.
- D-T neutron source or accelerator based neutron source was selected as the irradiation source based on its neutron generation efficiency.
- Irradiation from the top of the target object was selected as the neutron irradiation direction due to higher extent of symmetry.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (1/13)

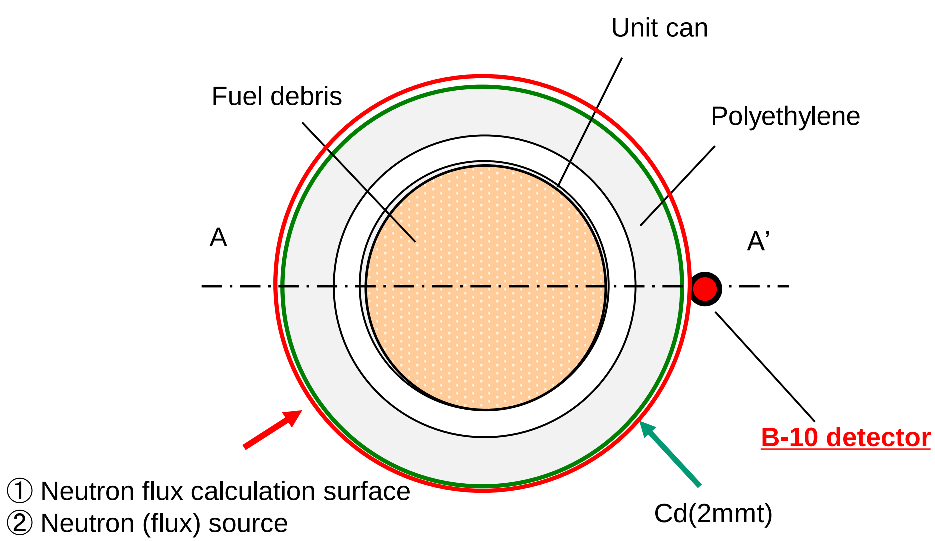
<Detector response analysis model>

- System: **B-10 detector** response was analyzed using the same system as the one used in FY2021 (Cd: 2mm thick, Polyethylene: 50mm thick)
- Neutron source: (Refer to conditions of a standard neutron tube)

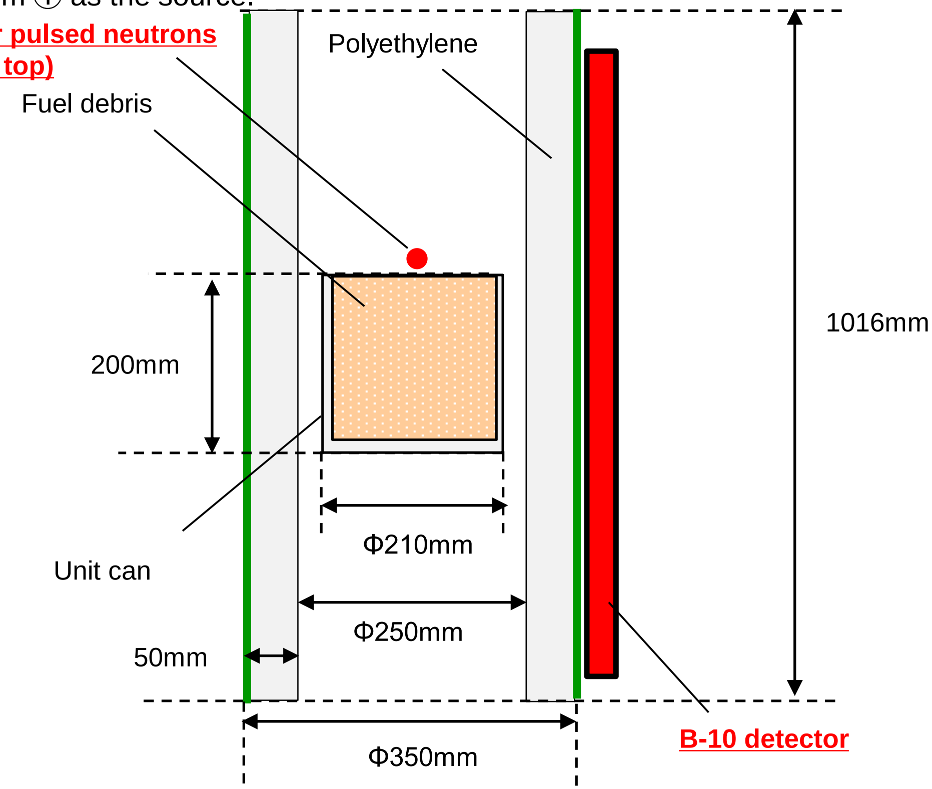
  Neutron energy: 14.1MeV, Neutron generation rate: 2×10^8n/s, Neutron generation direction: Isotropic, Pulse width: 1.2μs, Repetitive frequency: 100H
- Evaluation method

  ① **Neutrons were irradiated from the top** and neutron flux on the inside of the detector was calculated.

  ② The energy deposited in the detector was calculated with the flux from ① as the source.



Analysis model top view



Cross-sectional view A-A'

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (2/13)

<Detector response analysis cases>

◆ Analysis condition 1 (Cases with 3.7kg U)

Analyzed cases			UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Other than filling factor	Burn-up (GWd/t)	Source of irradiated neutrons	Cooling period (Years)	Amount of U (kg)
Molten debris	3-1	base	6.3	6.3	0	0	12.6	H_2O: 1wt%	23.0	D-T reaction	20	3.7
	3-2	Molten debris (small quantity of U)	6.3	19	0	0	25.3	H_2O: 1wt%	23.0	D-T reaction	20	3.7
	3-3	Gd content	6.3	6.3	0	0	12.6	Gd_2O_3: 3vol% H_2O:1wt%	23.0	D-T reaction	20	3.7
	3-4	Gd content	6.3	6.3	0	0	12.6	Gd_2O_3:30vol% H_2O:1wt%	23.0	D-T reaction	20	3.7
	3-5	B content	6.3	6.3	0	0	12.6	B_4C:0.51vol% H_2O:1wt%	23.0	D-T reaction	20	3.7
	3-6	B content	6.3	6.3	0	0	12.6	B_4C:10vol% H_2O:1wt%	23.0	D-T reaction	20	3.7
	3-7	Moisture content	6.3	6.3	0	0	12.6	H_2O:0.1wt%	23.0	D-T reaction	20	3.7
	3-8	Moisture content	6.3	6.3	0	0	12.6	H_2O:70vol%	23.0	D-T reaction	20	3.7
	3-9	Burn-up (low)	6.2	6.2	0	0	12.4	H_2O: 1wt%	1.3	D-T reaction	20	3.7
	3-10	Burn-up (high)	6.5	6.5	0	0	13.0	H_2O: 1wt%	51.0	D-T reaction	20	3.7
	3-12	Accelerator based neutron source	6.3	6.3	0	0	12.6	H_2O: 1wt%	23.0	Accelerator	20	3.7
MCCI	3-14	base	6.3	6.3	4.5	12.9	30	H_2O: 1wt%	23.0	D-T reaction	20	3.7
	3-15	Filling factor (high)	6.3	6.3	9.6	27.7	50	H_2O: 1wt%	23.0	D-T reaction	20	3.7

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (3/13)

◆ Analysis condition 2 (Cases of evaluating the margin of error in amount of U)

Analyzed cases				UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Other than filling factor	Burn-up (GWd/t)	Source of irradiated neutrons	Cooling period (Years)	Amount of U (kg)
Molten debris	3-18	Base case	Filling factor (low)	3.00	3.00	0	0	6.00	H_2O: 1wt%	23.0	D-T reaction	20	1.76
	3-19		Filling factor (medium)	10.00	10.00	0	0	20.00	H_2O: 1wt%	23.0	D-T reaction	20	5.86
	3-20		Filling factor (high)	15.00	15.00	0	0	30.00	H_2O: 1wt%	23.0	D-T reaction	20	8.79
	3-21	Gd content (low)	Filling factor (low)	3.00	3.00	0	0	6.00	Gd_2O_3: 3vol% H_2O:1wt%	23.0	D-T reaction	20	1.76
	3-22		Filling factor (medium)	10.00	10.00	0	0	20.00	Gd_2O_3: 3vol% H_2O:1wt%	23.0	D-T reaction	20	5.85
	3-23		Filling factor (high)	15.00	15.00	0	0	30.00	Gd_2O_3: 3vol% H_2O:1wt%	23.0	D-T reaction	20	8.78
	3-24	B content (low)	Filling factor (low)	3.00	3.00	0	0	6.00	B_4C:0.51vol% H_2O:1wt%	23.0	D-T reaction	20	1.76
	3-25		Filling factor (medium)	10.00	10.00	0	0	20.00	B_4C:0.51vol% H_2O:1wt%	23.0	D-T reaction	20	5.86
	3-26		Filling factor (high)	15.00	15.00	0	0	30.00	B4C:0.51vol% H_2O:1wt%	23.0	D-T reaction	20	8.79
	3-27	Moisture content (High)	Filling factor (low)	3.00	3.00	0	0	6.00	H_2O:70wt%	23.0	D-T reaction	20	1.76
	3-28		Filling factor (medium)	10.00	10.00	0	0	20.00	H_2O:70vol%	23.0	D-T reaction	20	5.86
	3-29		Filling factor (high)	15.00	15.00	0	0	30.00	H_2O:70wt%	23.0	D-T reaction	20	8.79
	3-30	Burn-up (low)	Filling factor (low)	3.00	3.00	0	0	6.00	H_2O: 1wt%	1.3	D-T reaction	20	1.80
	3-31		Filling factor (medium)	10.00	10.00	0	0	20.00	H_2O: 1wt%	1.3	D-T reaction	20	5.99
	3-32		Filling factor (high)	15.00	15.00	0	0	30.00	H_2O: 1wt%	1.3	D-T reaction	20	8.98

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (4/13)

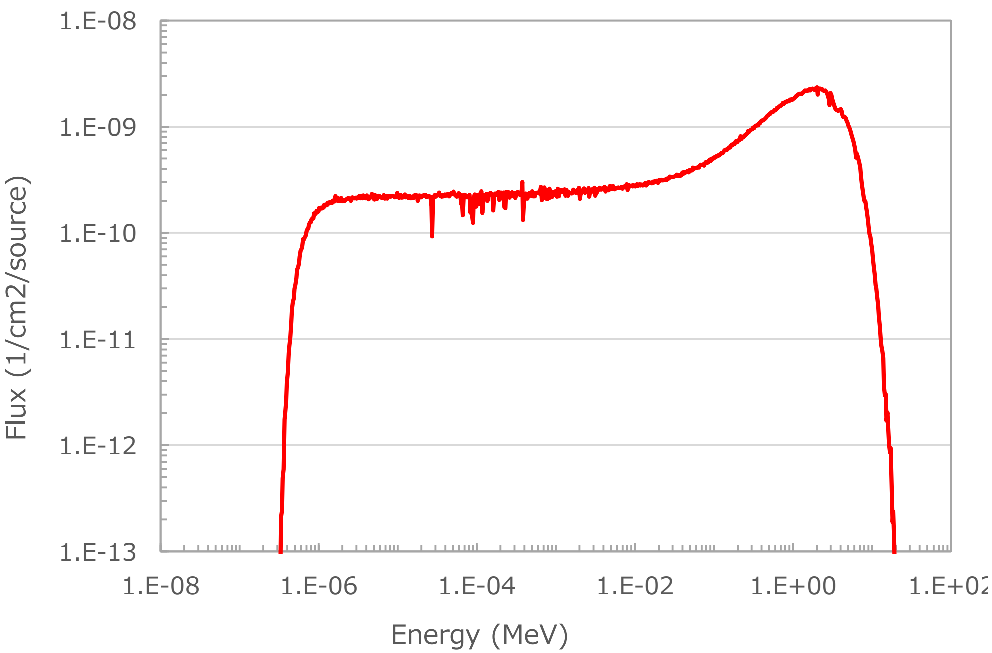
<Detector response analysis results>

◆ Results of calculating the neutron flux and the detector response spectrum for the base case [3-1 Molten debris]

➢ Neutron flux (Lateral side of the cylinder outside Cd)

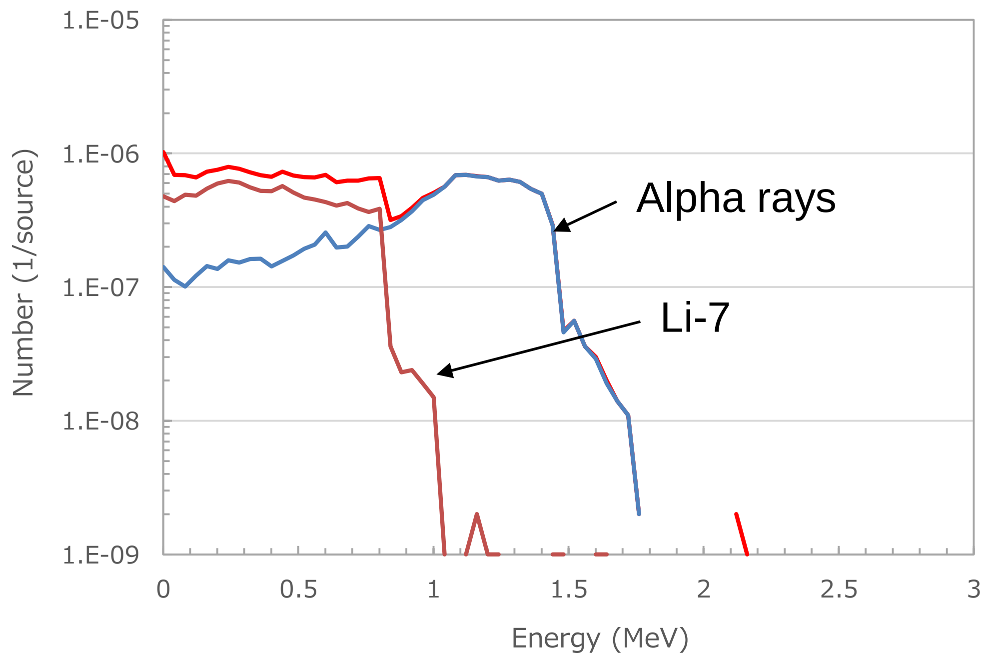
・Integrated value from 50μs to 2,000μs

(Neutron source: Pulse width 1.2μs, repetitive frequency: 100Hz)



➢ Detector response spectrum (B-10 detector)

・B-10 detector specifications: Diameter (inner diameter) 25.4mm, Effective length 1000 mm, housing thickness 0.5mm (SUS304) B-10 thickness 0.8547μm (=0.2mg/cm^2), Ar gas pressure 0.3atm



➢ Counting rate

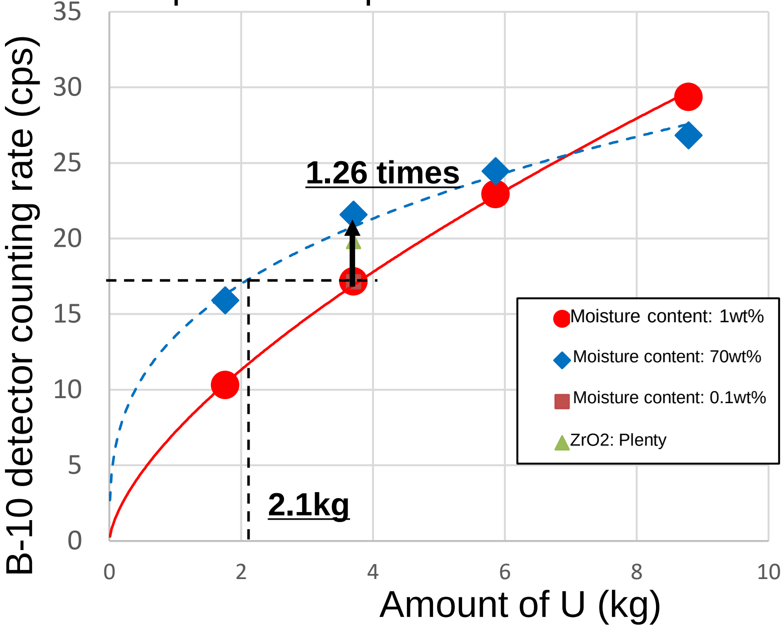
Alpha rays and Li-7 that impart 80keV or more energy in the detector response were measured.

⇒ 17.2cps(＋0.7cps(BG:Cm-244))

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (5/13)

◆ Molten debris
Impact of composition/moisture content



◆ Dependency on amount of U

① Base case (**Moisture content: 1wt%**)

Case No.	Amount of U [kg]	Counting rate [cps]	H2O content	
			wt%	vol%
3-1	3.70	1.72E+01	1wt%	1.0vol%
3-18	1.76	1.03E+01	1wt%	0.5vol%
3-19	5.86	2.29E+01	1wt%	1.6vol%
3-20	8.79	2.94E+01	1wt%	2.4vol%

② Large moisture content (**Moisture content: 70vol%**)

Case No.	Amount of U [kg]	Counting rate [cps]	H2O content	
			wt%	vol%
3-27	1.76	1.59E+01	59wt%	70vol%
3-8	3.70	2.16E+01	41wt%	70vol%
3-28	5.86	2.45E+01	30wt%	70vol%
3-29	8.79	2.68E+01	22wt%	70vol%

◆ Moisture content dependency (Amount of U 3.7kg)

Case No.	Amount of U [kg]	Counting rate [cps]	H2O content	
			wt%	vol%
3-1	3.70	1.72E+01	1wt%	1vol%
3-7	3.70	1.71E+01	0.1wt%	0.1vol%
3-8	3.70	2.16E+01	41wt%	70vol%

◆ Molten debris composition

Case No.	Amount of U [kg]	Counting rate [cps]	Remarks
3-2	3.70	1.98E+01	Molten debris: ZrO2: Plenty

➢ Comparison with the counting rate (1.72E+1cps) of the base case (moisture content 1wt%) when weight of U is 3.7kg
- Moisture content 0.1wt%: Counting rate (1.71E+1cps) did not change
- Moisture content 41wt%: Increase in counting rate (2.16E+1cps, 1.26 times)
- Composition (Increase in ZrO_2): Increase in counting rate (1.98E+1cps, 1.15 times)

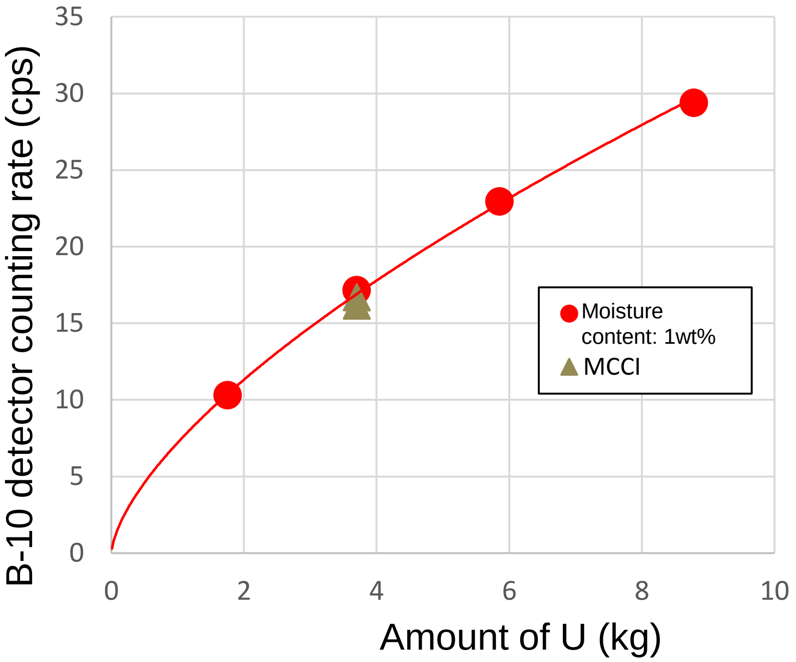
➢ Weight of U that results in counting rate (1.72E+1cps) of the base case (Weight of U 3.7kg)
- Moisture content 70vol%: 2.1kg (0.57 times)

Note) BG(Cm-244 count) not included in the counting rate

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (6/13)

◆ MCCI debris



◆Dependency on amount of U

① Base case (**Molten debris**)

Case No.	Amount of U [kg]	Counting rate [cps]	Remarks
3−1	3.70	1.72E+01	Molten debris
3−18	1.76	1.03E+01	
3−19	5.86	2.29E+01	
3−20	8.79	2.94E+01	

◆MCCI (Amount of U 3.7kg)

Case No.	Amount of U [kg]	Counting rate [cps]	Remarks
3−14	3.70	1.67E+01	MCCI
3−15	3.70	1.62E+01	

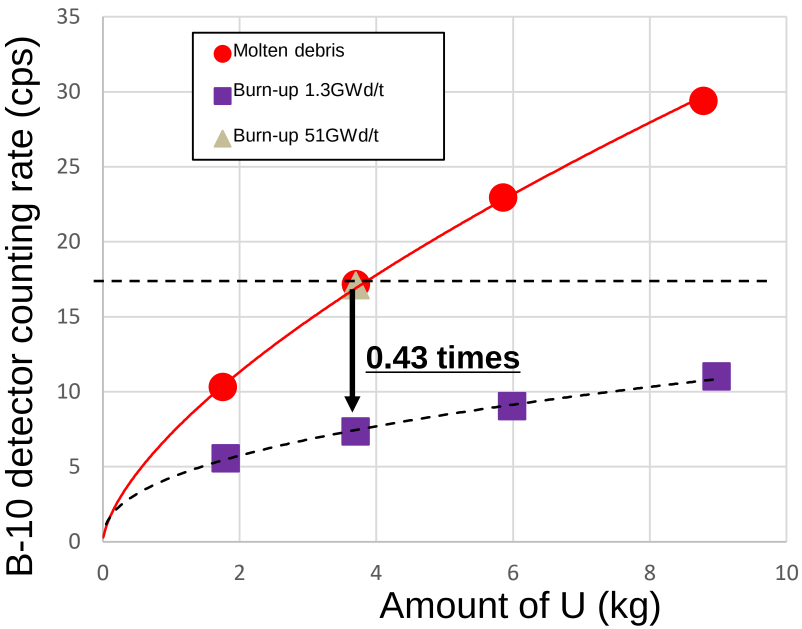
➢ Comparison with the counting rate (1.72E+1cps) of the base case (molten debris) when weight of U is 3.7kg
・In the case of MCCI: Roughly equivalent to the counting rate (1.62E+1cps, 0.94 times) to (1.67E+1cps, 0.97 times)

Note) BG(Cm-244 count) not included in the counting rate

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (7/13)

◆ Impact of burn-up



◆Dependency on amount of U

① Base case (**Burn-up: 23GWd/t**)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
3−1	3.70	1.72E+01	23.0
3−18	1.76	1.03E+01	23.0
3−19	5.86	2.29E+01	23.0
3−20	8.79	2.94E+01	23.0

② Small burn-up (**Burn-up: 1.3GWd/t**)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
3−30	1.80	5.55E+00	1.3
3−9	3.70	7.34E+00	1.3
3−31	5.99	9.02E+00	1.3
3−32	8.98	1.10E+01	1.3

◆Burn-up dependency (Amount of U 3.7kg)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
3−1	3.70	1.72E+01	23.0
3−9	3.70	7.34E+00	1.3
3−10	3.70	1.71E+01	51.0

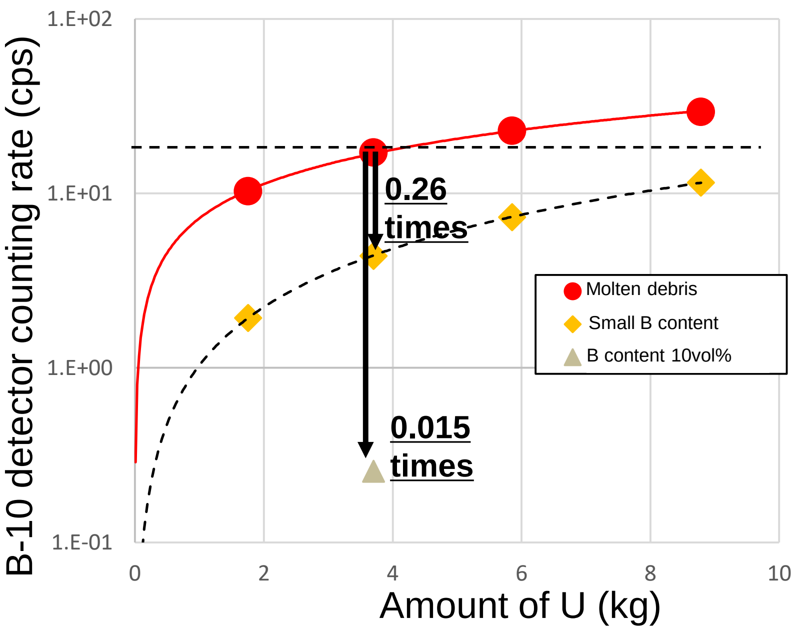
- Comparison with the counting rate (1.72E+1cps) of the base case (Burn-up 23GWd/t) when weight of U is 3.7kg
  - ・Burn-up 51GWd/t: Counting rate (1.71E+1cps) did not change (Cm-244 counting rate 4.1cps)
  - ・Burn-up 1.3GWd/t: Counting rate reduced to (7.34E+0cps, 0.43 times)(Cm-244 counting rate 2.6E-4)

- Weight of U that results in counting rate (1.72E+1cps)of the base case (Weight of U 3.7kg)
  - ・Burn-up 1.3GWd/t: 10kg or more

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (8/13)

◆ Impact of B content



◆ Dependency on amount of U

① Base case (**B content: 0vol%)**

Case No.	Amount of U [kg]	Counting rate [cps]	B content
3−1	3.70	1.72E+01	0vol%
3−18	1.76	1.03E+01	0vol%
3−19	5.86	2.29E+01	0vol%
3−20	8.79	2.94E+01	0vol%

② Small B content (**B content: 0.51vol%)**

Case No.	Amount of U [kg]	Counting rate [cps]	B content
3−24	1.76	1.94E+00	0.51vol%
3−5	3.70	4.40E+00	0.51vol%
3−25	5.86	7.33E+00	0.51vol%
3−26	8.79	1.16E+01	0.51vol%

◆ Dependency on B content (Amount of U 3.7kg)

Case No.	Amount of U [kg]	Counting rate [cps]	B content
3−1	3.70	1.72E+01	0vol%
3−5	3.70	4.40E+00	0.51vol%
3−6	3.70	2.56E−01	10vol%

➢ Comparison with the counting rate (1.72E+1cps) of the base case (Moisture content 0vol%) when weight of U is 3.7kg
 ・Increase in B content (0.51vol% to 10vol%): Counting rate reduced to (4.40E+0cps, 0.26 times) to (2.56E-1cps, 1.5E-2 times)

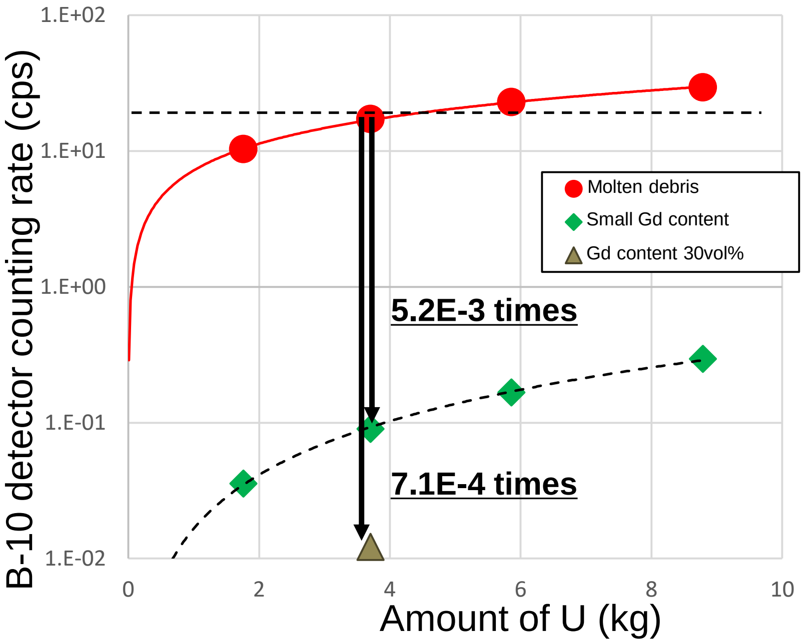
⇒ When B content increases, the BG counting rate is 0.7cps（Cm-244 counting rate）or less

➢ Weight of U that results in counting rate (1.72E+1cps) of the base case (Weight of U 3.7kg)
 ・B content 0.51vol%: 9kg or more

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (9/13)

◆ Impact of Gd content



◆Dependency on amount of U

① Base case (**Gd content: 0vol%)**

Case No.	Amount of U [kg]	Counting rate [cps]	Gd content
3−1	3.70	1.72E+01	0vol%
3−18	1.76	1.03E+01	0vol%
3−19	5.86	2.29E+01	0vol%
3−20	8.79	2.94E+01	0vol%

② Small Gd content (**Gd content: 3vol%)**

Case No.	Amount of U [kg]	Counting rate [cps]	Gd content
3−21	1.76	3.55E−02	3vol%
3−3	3.70	8.98E−02	3vol%
3−22	5.86	1.67E−01	3vol%
3−23	8.79	2.95E−01	3vol%

◆Dependency on Gd content (Amount of U 3.7kg)

Case No.	Amount of U [kg]	Counting rate [cps]	Gd content
3−1	3.70	1.72E+01	0vol%
3−3	3.70	8.98E−02	3vol%
3−4	3.70	1.22E−02	30vol%

➢ Comparison with the counting rate (1.72E+1cps) of the base case (Gd content 0vol%) when weight of U is 3.7kg
・Increase in Gd content (3vol% to 30vol%): Counting rate reduced to (8.98E-2cps, 5.2E-3 times) to (1.22E-2cps, 7.1E-4 times)

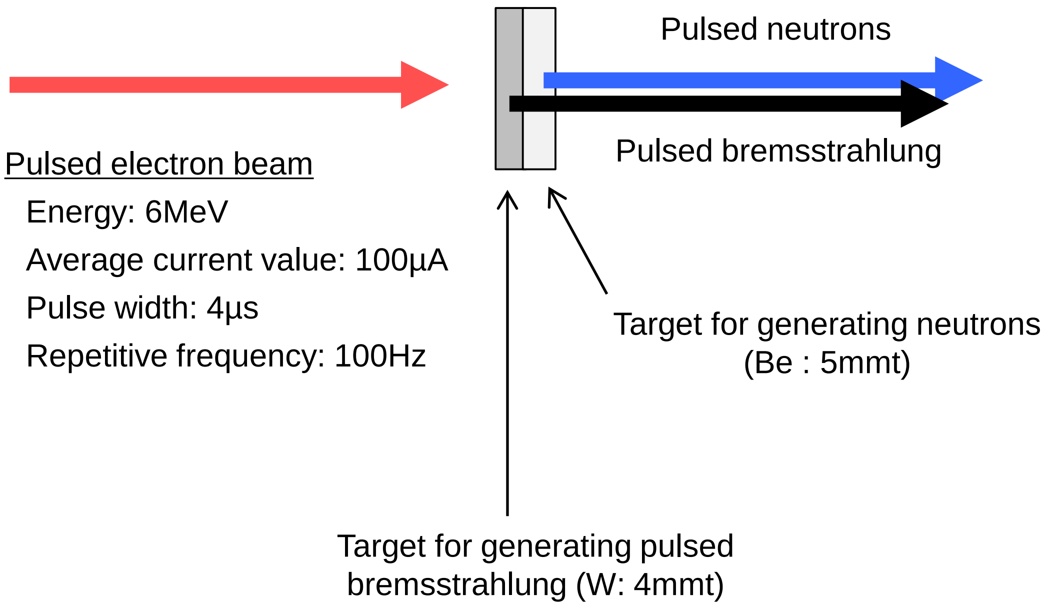
⇒ Gd content 3vol% and BG counting rate at 0.7cps（Cm-244 counting rate）or less

➢ Weight of U that results in counting rate (1.72E+1cps) of the base case (Weight of U 3.7kg)
・Gd content 3vol%： 10kg or more

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (10/13)

◆ Accelerator based neutron source [Case No. 3-12]



Pulsed electron beam

Energy: 6MeV

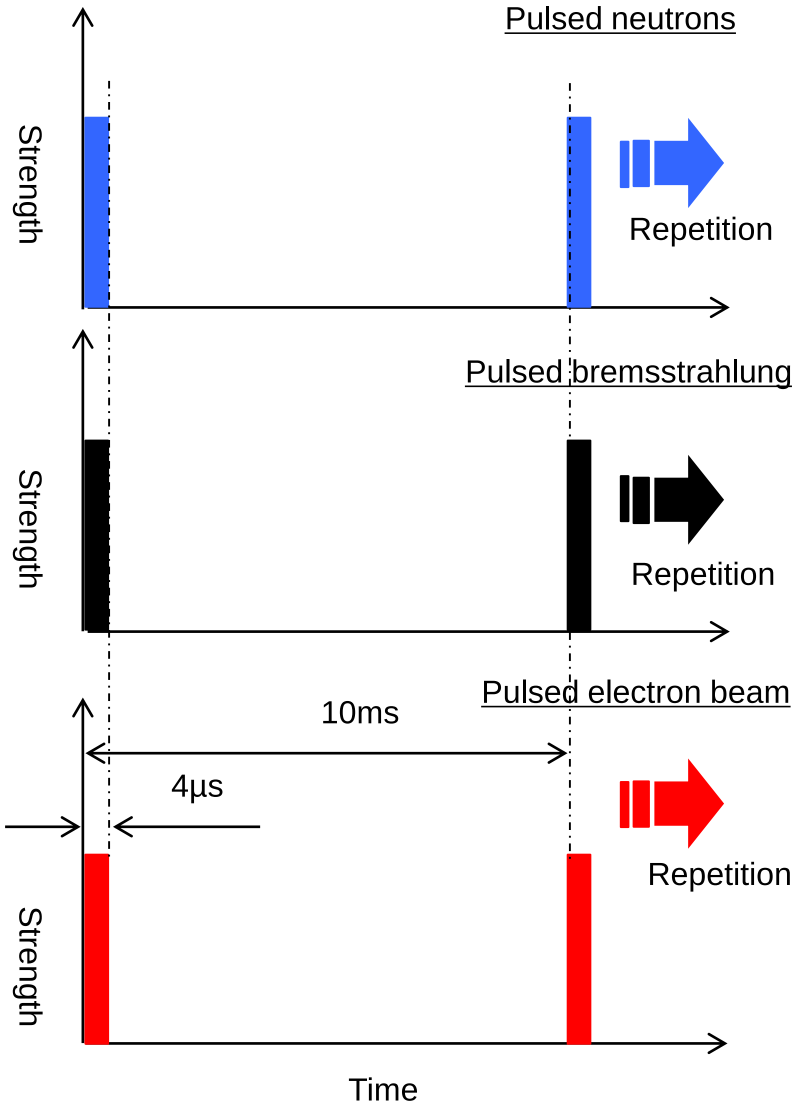
Average current value: 100μA

Pulse width: 4μs

Repetitive frequency: 100Hz

Rate of neutron generation: 4.5×10^8 neutrons/second

Average neutron energy: 1.13MeV



4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

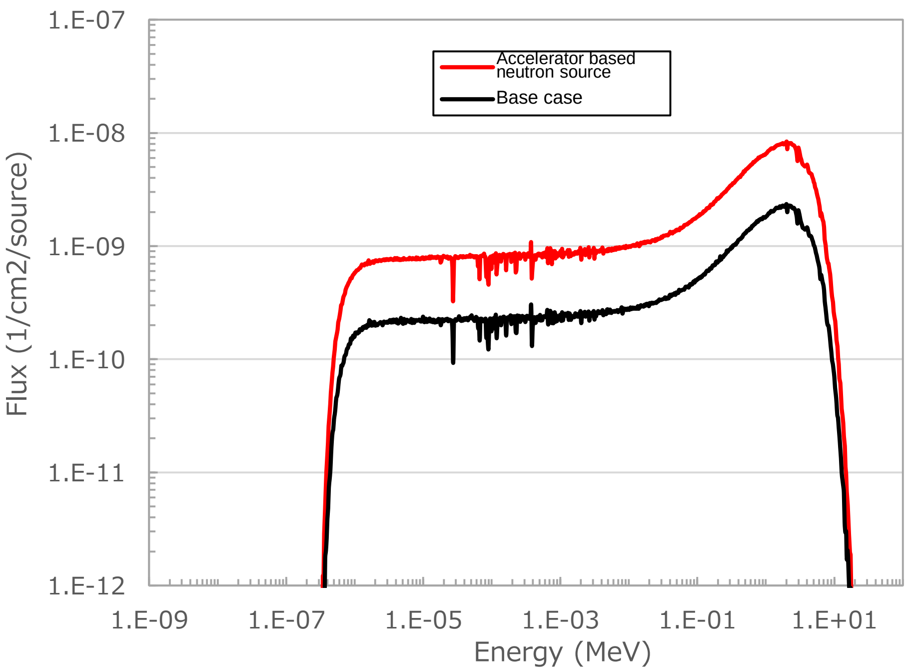
①-2 Active neutron method B (11/13)

◆ Accelerator based neutron source [Case No. 3-12]

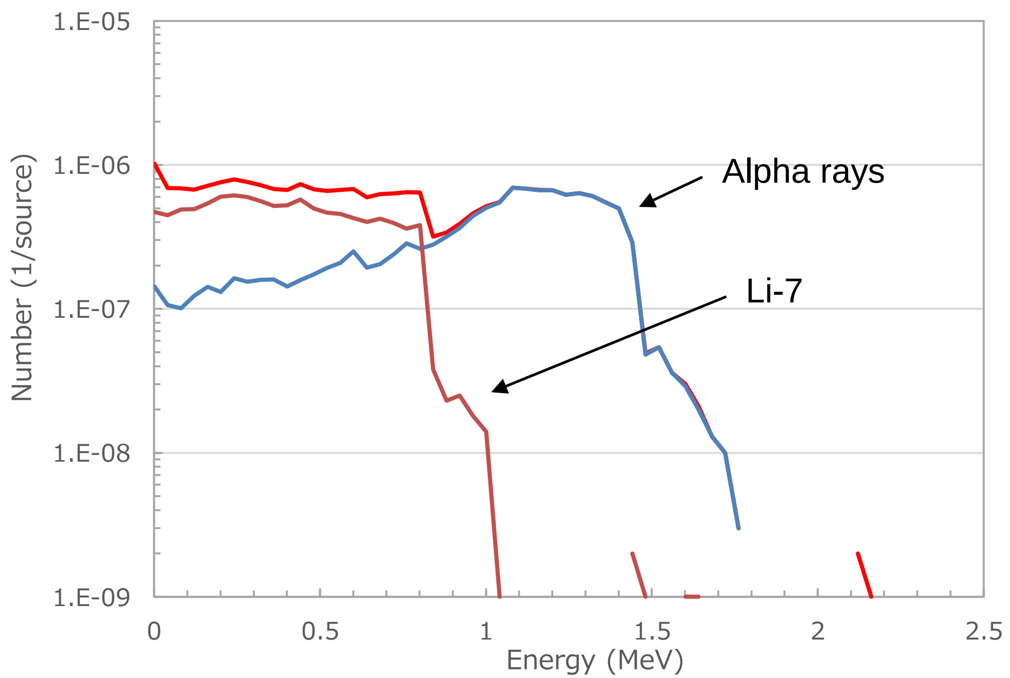
➢ Neutron flux (Lateral side of the cylinder outside Cd)

・Integrated value from 50μs to 2,000μs

(Neutron source: Pulse width 1.2μs, repetitive frequency: 100Hz)



➢ Detector response spectrum (B-10 detector)



➢ Counting rate

Alpha rays and Li-7 that impart 80keV or more energy in the detector response were measured.

⇒ 137Cps (8.0 times of the base case)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (12/13)

<Concept of the equipment>

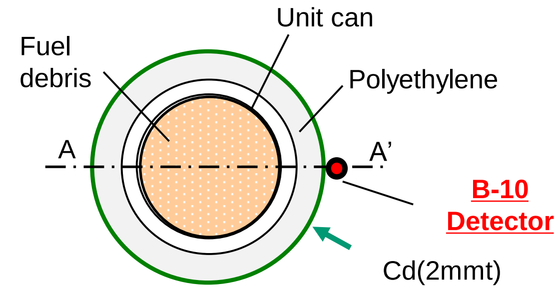
Analysis cases		Counting rate [cps]	Time required for a 10,000 count		
			[sec]	[min]	[hour]
3−1	Base (Unit can)	1.72E+01	5.8E+02	9.7E+00	1.6E−01
3−5	B content 0.51vol%	4.40E+00	2.3E+03	3.8E+01	6.3E−01
3−6	B content (10vol%)	2.56E−01	NG		
3−3	Gd content (3vol%)	8.98E−02	NG		
3−4	Gd content (30vol%)	1.22E−02	NG		

- **Measurement time**
  - The required measurement time in the base case is about 10 minutes and is sufficient.
  - **<u>If the amount contained by the neutron absorption material is several vol% or more, the counting rate becomes equal to or lower than the BG counting rate（0.7cps）</u>**

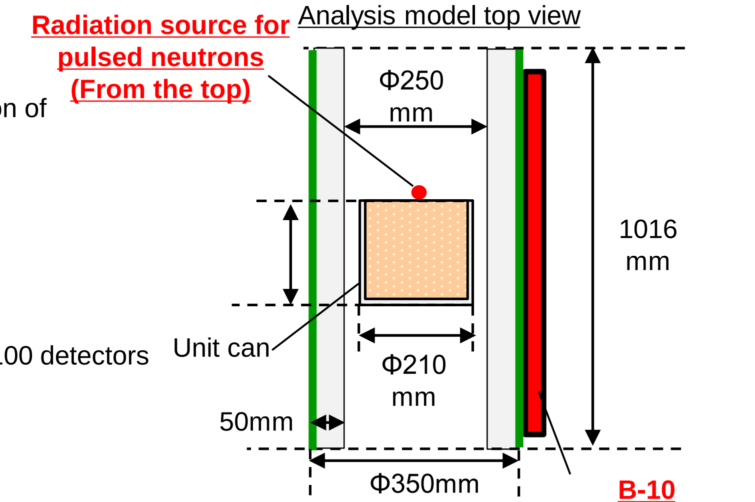
⇒**<u>Issue 1</u>**: **<u>Enhancing the counting rate of induced fission neutrons</u>**

<u>Issue 2</u>: **<u>Enhancing neutron detection efficiency</u>** (Measurement of about BG 0.7cps ⇒ Required measurement time: 4 hours)

- **Proposed countermeasure 1 (Issue 1)**
  - ① Increasing the neutron flux from the neutron source
    - Issue: Dependency on neutron source manufacturer
  - ② **<u>Reducing the energy of the irradiated neutrons</u>**
    - Deceleration due to polyethylene, etc.
    - **<u>Neutron source: D-T（14.1MeV）⇒ D-D（2.45MeV）⇒ Accelerator（1.1MeV）</u>**
    - Issue: Optimization of the placement of neutron moderator, selection of neutron source (selection of neutron radiation source that can actually be used)
  - ③ **<u>Accelerator based neutron source (8 times the sensitivity）</u>**
    - Issue: Demonstration of performance
- **Proposed countermeasure 2 (Issue 2)**
  - ① **<u>Increasing the number of detectors</u>**: 1 detector ⇒ about 45 detectors (Stage 1) ⇒ about 100 detectors (in multiple tiers)
    - Issue: Optimization of the placement of detector, detector cost
  - ② **<u>Optimization of the placement of polyethylene moderator</u>**
    - Installing polyethylene in all directions of the canister, installing polyethylene on the outer side of the detector



Analysis model top view



Cross-sectional view A-A'

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-2 Active neutron method B (13/13)

<Summary and future issues>

[Implementation details]

1) Study of the error in evaluating the amount of U by detector response analysis (B-10 neutron detector, D-T neutron source or accelerator based neutron source) in which the amount of U is set to 3.7kg which is the standard for sorting

2) Study of the concept of the equipment by estimating the required measurement time (10000 Counts (1% error)) based on the above results.

[Results/Contribution to development]

1) The following results were obtained upon comparison with the counting rate (1.72E+1cps) of the base case (molten debris with 3.7kg of U) .

① Impact of neutron absorption material:

- Increase in B content (0.51vol% to 10vol%): Decrease in counting rate (4.40E+0cps, 0.26 times) to (2.56E-1cps, 1.5E-2 times)
- Increase in Gd content (3vol% to 30vol): Decrease in counting rate (8.98E-2cps, 5.2E-3 times) to (1.22E-2cps, 7.1E-4 times)

② Impact of moisture content and fuel debris composition:

- Moisture content (0.1wt% to 41wt%): Increase in counting rate (1.71E+1cps, 1.00 times) to (2.16E+1cps, 1.26 times)
- Composition (Increase in ZrO_2): Increase in counting rate (1.98E+1cps, 1.15 times)
- In the case of MCCI: Roughly equivalent to the counting rate (1.62E+1cps to 1.67E+1cps)

③ Impact of burn-up (1.3GWd/t to 51GWd/t): Fluctuation in counting rate (7.34E+0cps, 0.43 times) to (1.71E+1cps, 1.00 times)

④ Accelerator based neutron source [Specifications: Energy 6MeV, Average current value: 100μA, Pulse width: 4μs, Repetitive frequency: 100Hz, W target & Be converter]

- The counting rate is (1.37E+2cps) which has increased 8 times of the base case (D-T neutron source)

2) Required measurement time:

- Base case (Molten debris 3.7kg of U): approx. 10 minutes
- With an increase in the quantity contained in the neutron absorption material (several vol%) the counting rate becomes equal to or lower than BG (Cannot be measured).

[Issues and response measures]

1) Issue: The neutron absorption material has a major impact and hence correction is essential. ⇒ Response measure: Evaluation of effectiveness of the CT or PGA methods as a prospective method for correcting the neutron absorption material

2) Issue: Improvement in the induced fission neutron counting rate ⇒ Response measure: Reducing the energy of the irradiated neutrons with the help of moderators, etc., selection of accelerator based neutron source

3) Issue: Enhancement of the neutron measurement sensitivity (4 hours required for BG measurement) ⇒ Response measure: Increasing the number of detectors (placed in multiple tiers), optimization of the placement of the moderator

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(①-3 Active neutron method C)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191

[Characteristics]

- In order to eliminate the variations in detector response brought about by the influencing factors, the Fast Neutron Direct Interrogation Method (FNDI method) was introduced which has been approved by IAEA for uranium waste (JAEA/Ningyo-toge).
- In order to correct the impact of neutron absorption material, the Prompt Gamma Analysis Method (PGA method) was introduced.
- The B-10 straw detector was introduced for ensuring compatibility in high gamma irradiation locations.
- In order to enhance sensitivity of the detector when the quantity of Uranium is small, etc., the high speed neutron detector bank was introduced.

The method in which the FNDI method and the PGA method are used in combination is an improvement for resolving the issues in the conventional active neutron method, considering the diversity of fuel debris and other radioactive waste.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (1/10)

<Study of the concept of the measuring equipment>･･･Study of the concept of the equipment with which **the active neutron method (FNDI) and the Prompt Gamma Analysis method (PGA method) can be implemented, using a stand-alone measuring equipment.**

PGA method is a technique for identifying and measuring the quantity of substances contained in the samples, by measuring gamma rays that are characteristic to the nuclides generated as a result of the nuclear reaction brought about by irradiating the samples to be measured with neutrons.

FNDI method enables accurate measurements regardless of the contents of the samples to be measured, but can easily get influenced by the neutron absorption material (Boron or Gadolinium). (Measurement cannot be performed if these neutron absorption materials are present in extreme abundance.)

Hence, by introducing the PGA method, the neutron absorption material is measured, thus enhancing the accuracy of the FNDI method (Enhancement of sorting accuracy).

Also, depending on the conditions, moisture, iron, chromium present in the samples can be expected to be measured by the PGA method.

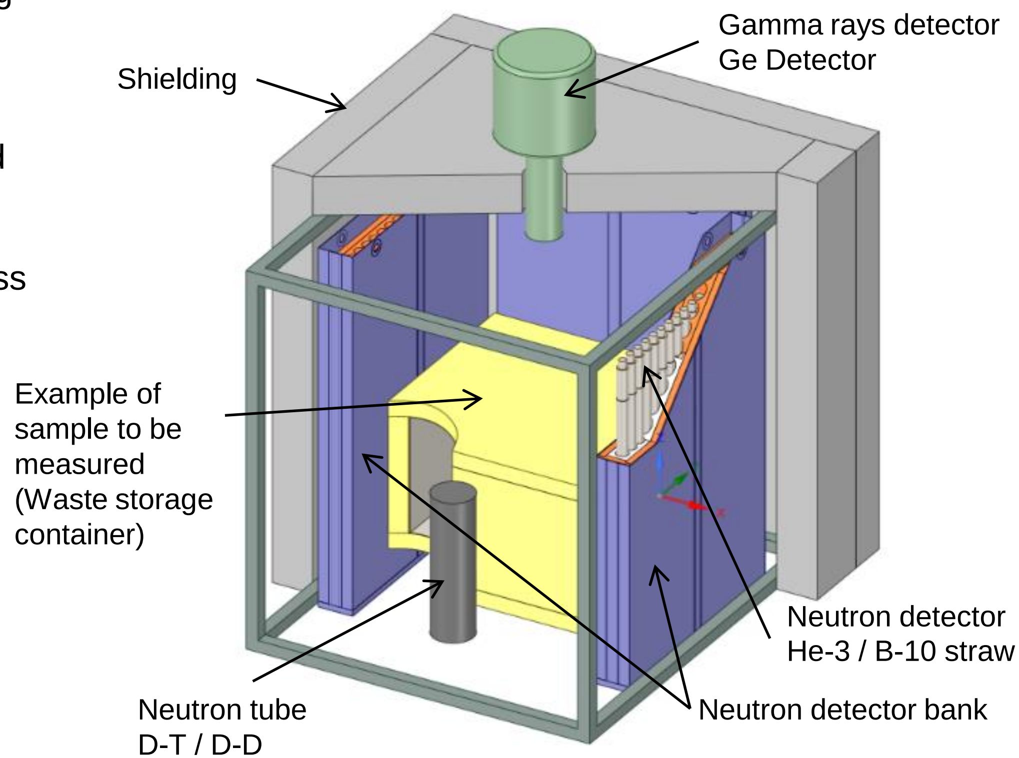


Illustration of the concept of the equipment for performing measurement using the FNDI + PGA method

(Dimensions: 1.5 x 1.5 x 2.0 m)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (2/10)

<Study of conditions of the target object>

- Conditions of the target object: **It was assumed that "molten debris", "MCCI debris" and "Metallic debris"** (Note 1) are measured.
- The following was assumed regarding the containers to be evaluated based on the cases evaluated in FY2021.

Debris properties	Container/Shape of container	Remarks
Molten debris MCCI debris	**Unit can/**Φ210mm × H200mm	Smallest single container. Area contributing to the dose rate, represented by H200mm wherein the quantity of radiation source becomes smaller.
Metallic debris	**Waste storage container (inner container)** / □500mm×300mmH	Represented by an inner container that does not have any shielding and which is smaller than the storage container, since the thickness of the shielding of the waste storage container is yet to be determined. (From amongst the multiple options for inner (collection) containers, the typical option from the Treatment & Disposal PJ was used)

- Detector response analysis cases focusing on the parameters **(Composition, burn-up, presence/absence of neutron absorption material**) identified as technical issues were set up for the study.

[Number of analysis cases]

A: Molten debris ⇒ Total 17 cases
(Composition: 3 cases) x (Burn-up: 3 cases) x (Neutron absorption material: 5 cases)

B: MCCI debris ⇒ Total 15 cases
(Composition: 2 cases) x (Burn-up: 3 cases) x (Neutron absorption material: 5 cases)

C: Metallic debris ⇒ Total 3 cases
(Composition: 3 cases) x (Burn-up: 1 case) x (Absence of neutron absorption material)

Total 35 cases

(Note 1) Classification based on the "Subsidy Project of Decommissioning and Contaminated Water Management Development of technology for fuel debris characterization and analysis FY2016 Supplementary Budget Research Report (Interim Report) March 2018". Specific information on composition is indicated from next page onwards.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (3/10)

Case No.	Debris properties	Case overview	Sensitivity analysis parameters			
			Composition	Moisture content	Burn-up	Neutron absorption material
A-1	Molten debris	Base case	UO_2: 15.0 ZrO_2: 15.0	1wt%	23	None
A-2		Low burn-up			1.3	
A-3		High burn-up			51	
A-4		Uranium-rich	UO_2: 30.0		23	
A-5		Uranium-rich Low burn-up			1.3	
A-6		Uranium-rich High burn-up			51	
A-7-1		Base case Neutron absorption material 1	UO_2: 15.0 ZrO_2: 15.0		23	Gd_2O_3 3vol%
A-7-2		Base case Neutron absorption material 2				Gd_2O_3 30vol%
A-7-3		Base case Neutron absorption material 3				B_4C 0.51vol%
A-7-4		Base case Neutron absorption material 4				B_4C 10vol%
A-8		Low burn-up Neutron absorption material			1.3	Gd_2O_3 3vol%
A-9		High burn-up Neutron absorption material			51	
A-10		A-4 + Neutron absorption material	UO_2: 30.0		23	
A-11		A-5 + Neutron absorption material			1.3	
A-12		A-6 + Neutron absorption material			51	
A-13		Base case Low moisture content	UO_2: 6.3 ZrO_2: 6.3	0.1wt%	23	None
A-14		Base case High moisture content		70vol%		

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (4/10)

Case No.	Debris properties	Case overview	Sensitivity analysis parameters			
			Composition (vol%)	Moisture content	Burn-up	Neutron absorption material
B-1	MCCI debris	Base case	UO_2: 1.05 ZrO_2: 1.05 SUS: 7.2 Conc: 20.7	1wt%	23	None
B-2		Low burn-up			1.3	
B-3		High burn-up			51	
B-4		Conc composition sensitivity	UO_2: 1.05 ZrO_2: 1.05 SUS: 7.2 Conc: 50.7		23	
B-5		Conc composition sensitivity Low burn-up			1.3	
B-6		Conc composition sensitivity High burn-up			51	
B-7-1		Base case Neutron absorption material 1	UO_2: 1.05 ZrO_2: 1.05 SUS: 7.2 Conc: 20.7		23	Gd_2O_3 3vol%
B-7-2		Base case Neutron absorption material 2				Gd_2O_3 30vol%
B-7-3		Base case Neutron absorption material 3				B_4C 0.51vol%
B-7-4		Base case Neutron absorption material 4				B_4C 10vol%
B-8		Low burn-up Neutron absorption material			1.3	Gd_2O_3 3vol%
B-9		High burn-up Neutron absorption material			51	
B-10		B-4 + Neutron absorption material	UO_2: 1.05 ZrO_2: 1.05 SUS: 7.2 Conc: 50.7		23	
B-11		B-5 + Neutron absorption material			1.3	
B-12		B-6 + Neutron absorption material			51	

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

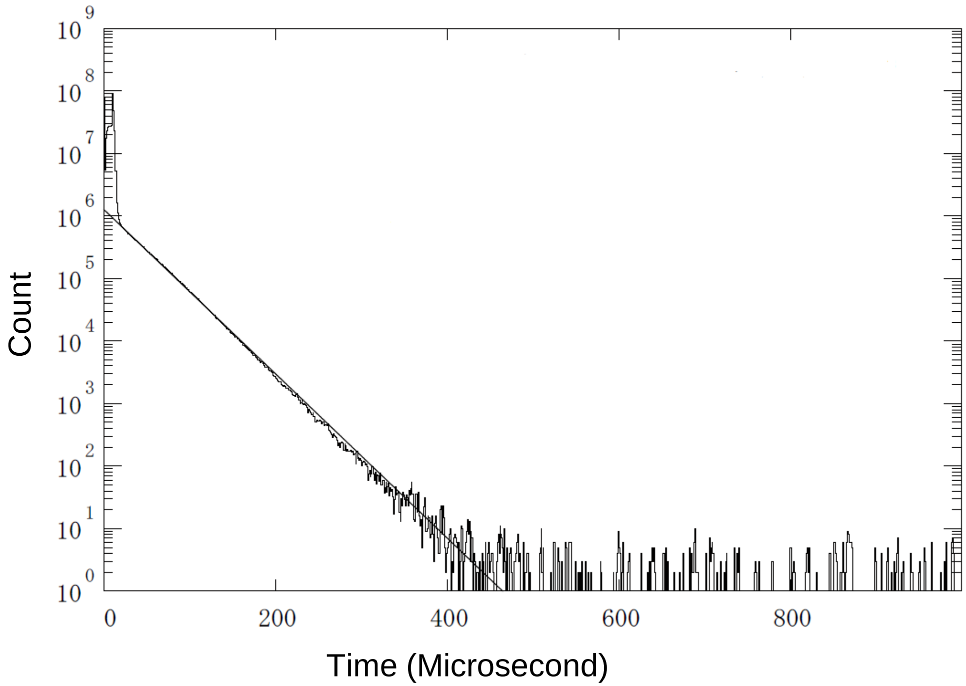
①-3 Active neutron method C (5/10)

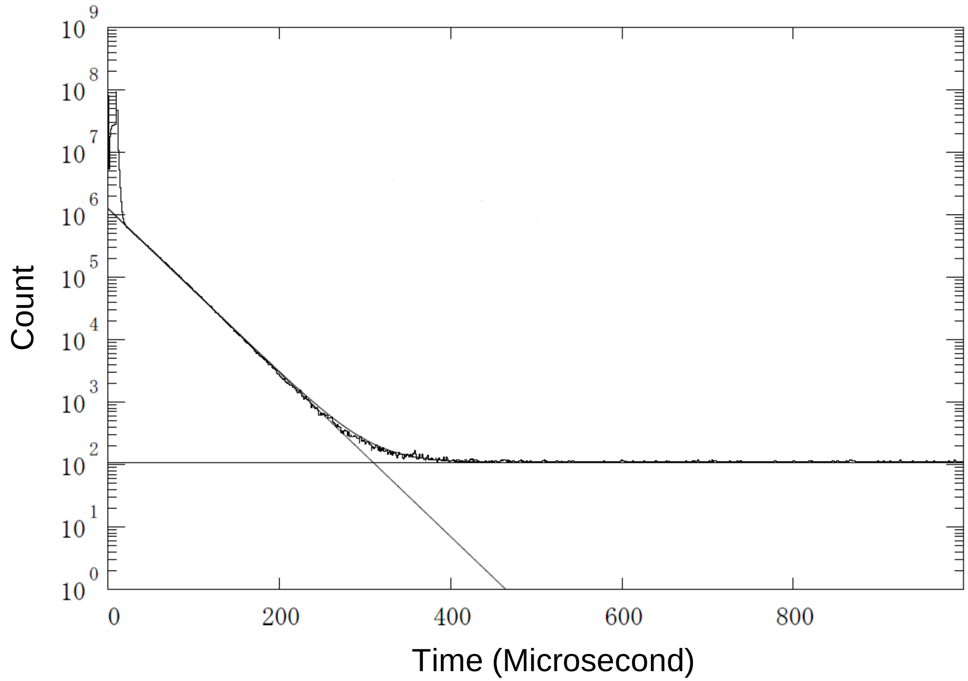
Case No.	Debris properties	Case overview	Sensitivity analysis parameters			
			Composition (vol%)	Moisture content	Burn-up	Neutron absorption material
C-1	Metallic debris	Base case	UO_2: 0.0075 ZrO_2: 0.0075 SUS: 29.85	1wt%	23	None
C-2		Composition sensitivity (SUS)	UO_2: 0.0075 ZrO_2: 0.0075 SUS: 44.85			
C-3		Composition sensitivity (UO_2, ZrO_2)	UO_2: 0.48 ZrO_2: 0.0 SUS: 10.0			

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (6/10)

<Example of detector response analysis>





Example of the calculation (Figure on the left：Cm-244 Absent, Figure on the right：Cm-244 Present)
(The straight line is a result of curve fitting)

It was verified that nuclear material can be measured, based on the analysis results obtained by creating a model.

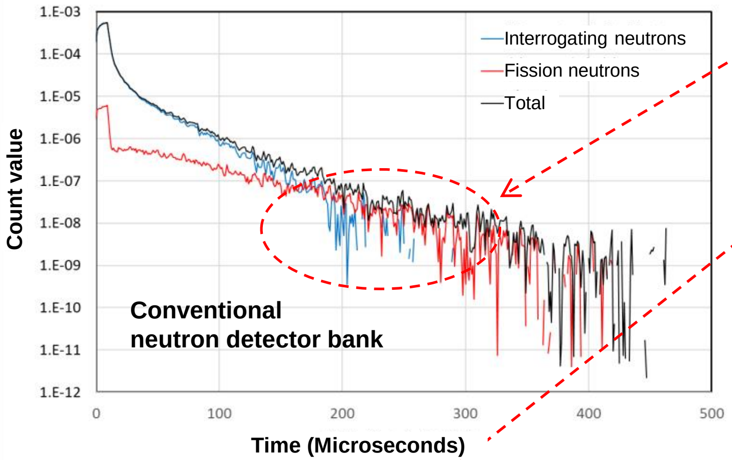
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

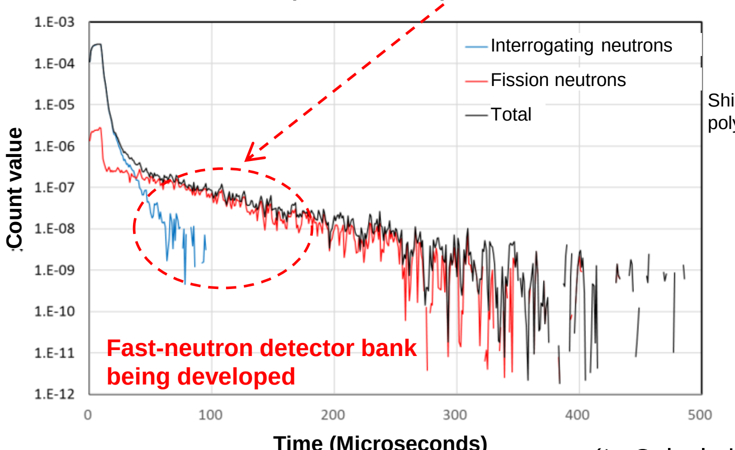
①-3 Active neutron method C (7/10)

The nuclear fuel material detection sensitivity was improved by developing a neutron detector bank.

Reduction of interrogating neutrons that hinder measurement

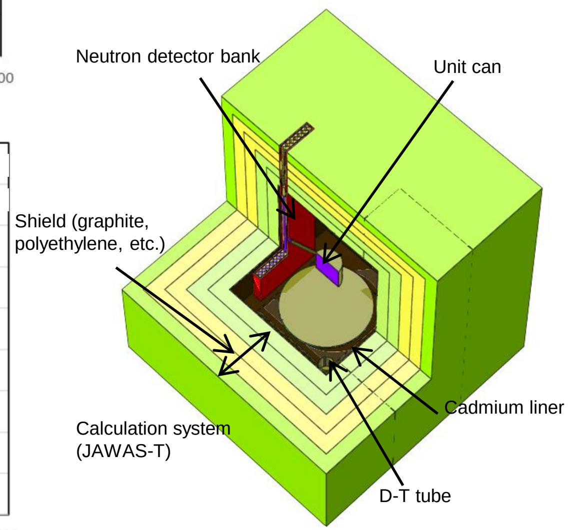
An example of measurement results*

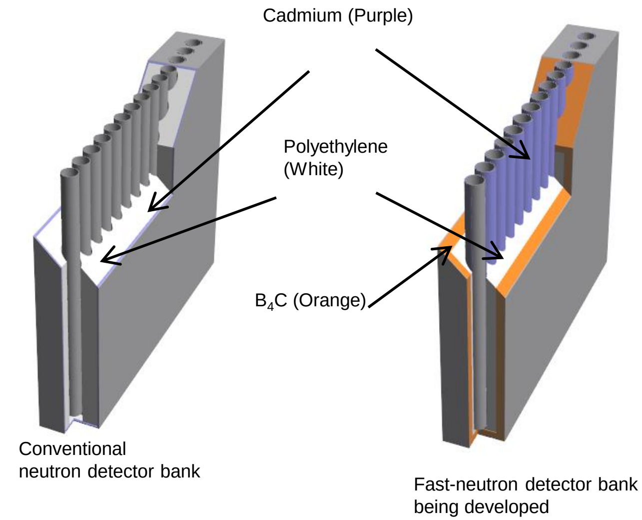




Conventional neutron detector bank：
The difference between interrogating nuclides (blue line) and fission neutrons (red line) is small.
＝ Nuclear fuel material detection sensitivity is bad

Fast-neutron bank being developed:
The difference between interrogating nuclides (blue line) and fission neutrons (red line) is big.
＝ Nuclear fuel material detection sensitivity is good





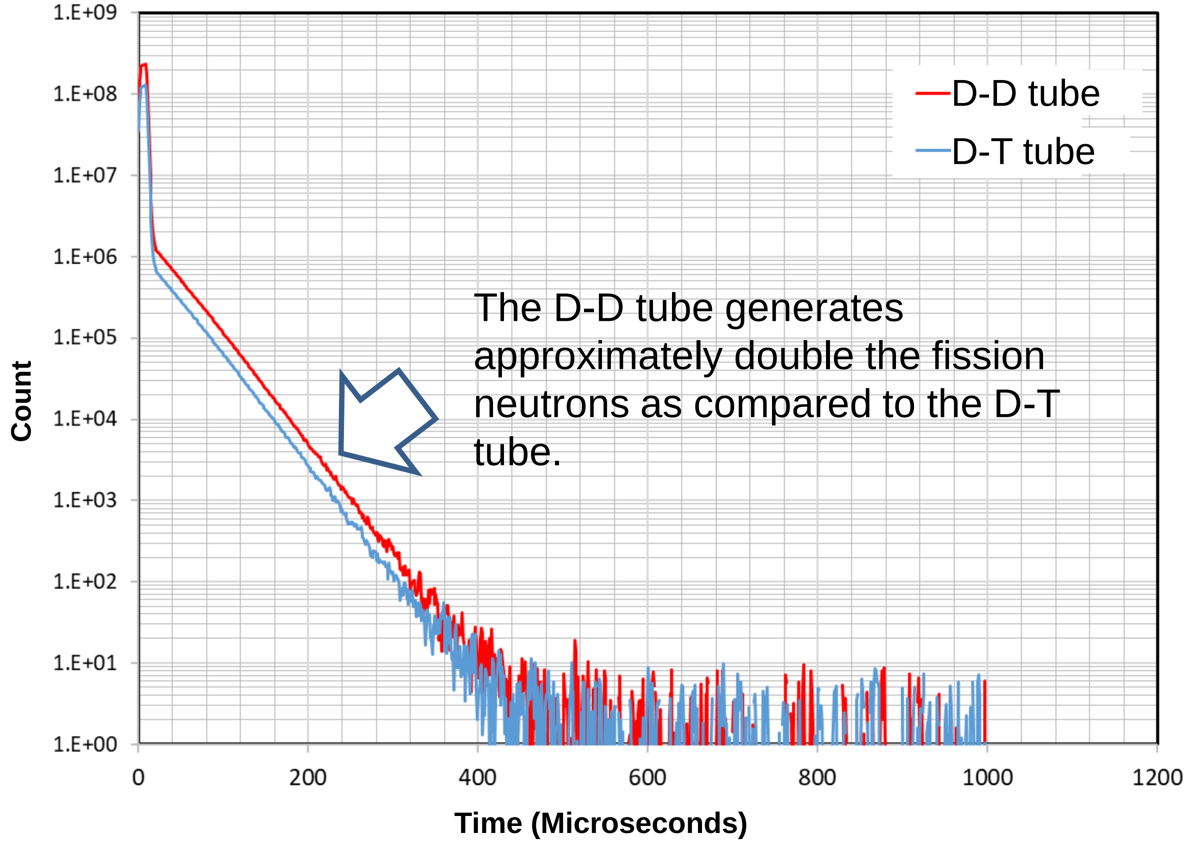
(*: Calculation system: JAWAS-T(Dimensions: Width 1.9 m, Depth 1.9 m, Height 2.1 m), Object to be measured: Unit can containing 2.8 kg UO_2, 4 kg water and 2.7g of boric acid.)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (8/10)

Use of D-D tube in the FNDI method

By using neutrons with lower energy (2.45 MeV) than neutrons generated from D-T tube (14MeV), the number of nuclear fission reactions increases and thereby measurement performance is expected to improve.



Example of the comparative calculation of the D-T tube and D-D tube

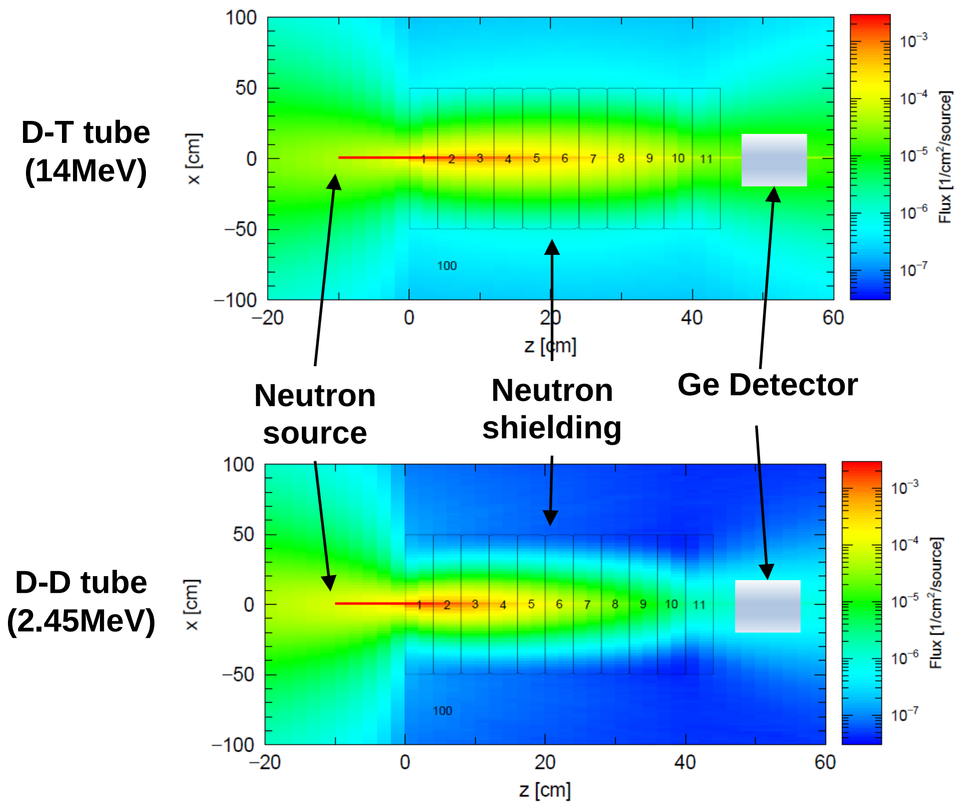
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

①-3 Active neutron method C (9/10)

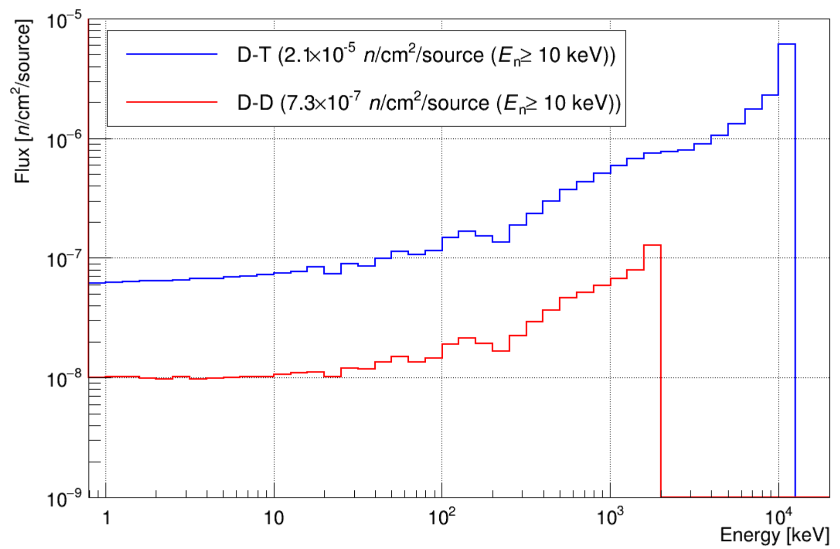
If the FNDI method and the PGA method are present together in a single unit of equipment, as there is limited space available for the neutron shield, etc., the interrogating neutrons enter the gamma rays detector (Ge detector), leading to worsening of the measurement accuracy of the PGA method and deterioration of the Ge detector, etc.

Using the D-D tube (2.45MeV) instead of the D-T tube (14MeV) that was used in the conventional FNDI method is likely to reduce the impact.

Calculation of the neutron shielding effect



Comparison of the neurton strength at various Ge Detector locations



The strength of the interfering neutrons can be reduced by about 1 digit by using the D-D tube.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

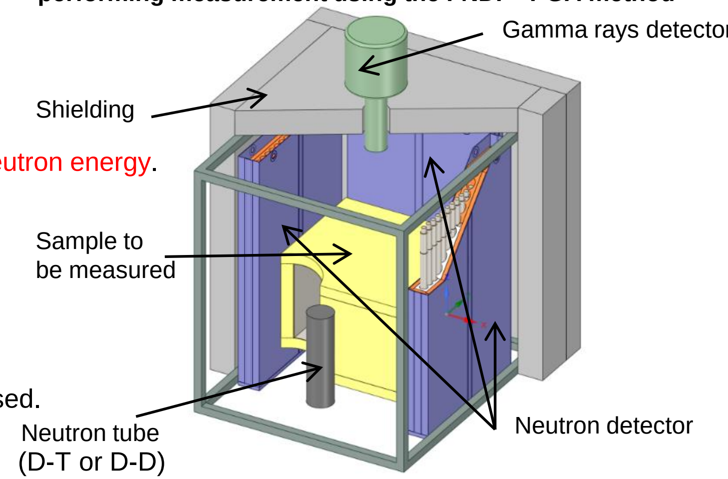
①-3 Active neutron method C (10/10)

<Summary and future issues>

[Implementation details]

1) A simulation model of the FNDI method (combination with the PGA method) was created.
2) Detector response was analyzed focusing on composition, burn-up, neutron absorption material and neutron energy.
3) The concept of the measuring equipment used for sorting fuel debris was studied.

Illustration of the concept of the equipment for performing measurement using the FNDI + PGA method



[Results/Contribution to development]

1) A simulation model of the detector was created for studying the background when the PGA method is used and the equipment used for performing measurement using the FNDI method for ascertaining the correlation between the neutron die-away time and the amount of uranium when the FNDI method is used.

2)

・ The calculation results by simulating 35 cases in which the FNDI method was used were obtained (Refer to "Study of techniques for evaluating the quantity of nuclear fuel material 4.2.1①-3" for the results.)

・ Nuclides from the D-T tube have greater energy (14MeV), due to which shielding is difficult. As a result, the impact on Ge detector, etc. used for the PGA method increased about 1 digit.

・ As the D-D tube does not have any radioactive material, its handling and management is easy, the generated neutrons have less energy (2.45MeV) as well and hence shielding is easy (about 1 digit smaller impact). Results suggesting about double performance improvement with the FNDI method were obtained.

3) Development of the concept of the equipment for performing measurement using the FNDI + PGA methods

・ Equipment dimensions: About 1.5m × 1.5m × 2.0m

・ Measurement time: about 10-20 minutes

[Issues and response measures]

1) Issue: The difference in energy of neutrons generated using the D-T tube and the D-D tube has an impact on the measurement accuracy of the FNDI method and the PGA method.

Response measure: The impact on the measurement accuracy needs to be evaluated by conducting the elemental technology verification test using the D-D tube.

2) Issue: There is lack of basic data in preparation for the basic design of the structure of the detector and the shield.

Response measure: Basic data on the detector and shield should be acquired by means of simulation calculation.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(②-1 Passive neutron method A)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
②-1	Passive neutron method A	He-3	None	None	Mass of spontaneous fission nuclides (Cm-244, etc.)	Fissile nuclide mass	MHI	81-93 192-203
②-2	Active neutron method B	B-10	None	None	Same as above	Same as above	Hitachi-GE	94-101 204-207

[Characteristics]

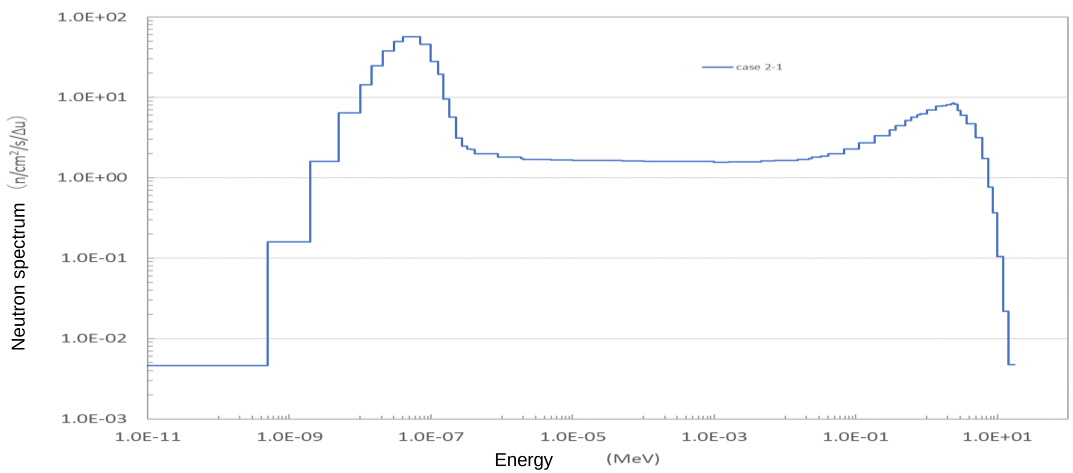
- The He-3 detector was selected based on its track record.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

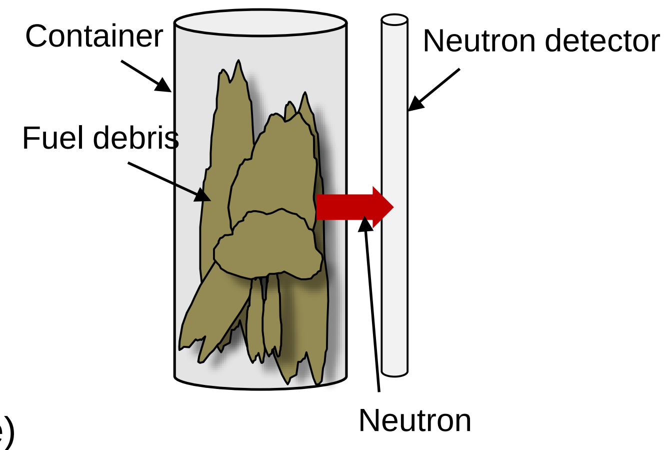
② Items common to the passive neutron methods

Measurement concept

- Fuel debris contains nuclides (Cm-244, etc.) that originate from fuel that emits neutrons due to spontaneous fission.
- In particular, since Cm-224 predominantly becomes a neutron generating nuclide as combustion progresses, it is assumed to become a nuclide that gets measured.



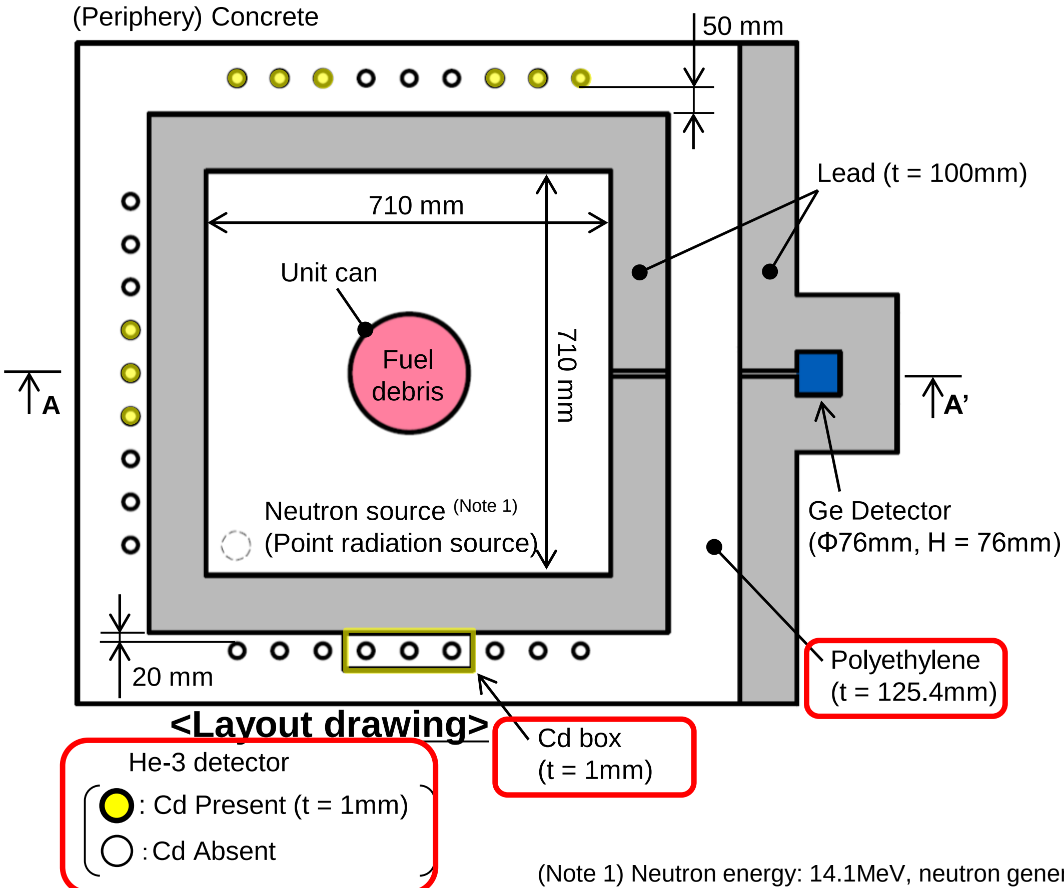
Example of analysis output (Moderator: Polyethylene)



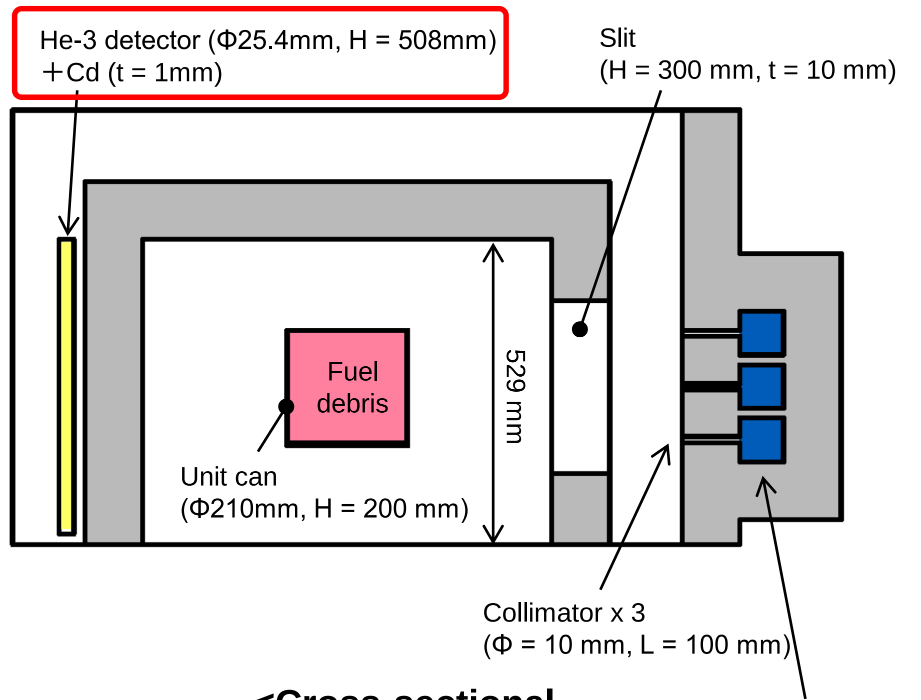
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (1/11)

<Study of the concept of the measuring equipment>･･･Concepts of the equipment that support the active n, **passive** n and γ measurement methods were studied using a single unit of measuring equipment.



<Layout drawing>



<Cross-sectional view (A-A')>

(Note 1) Neutron energy: 14.1MeV, neutron generation rate: 2×10^{8} n/s,
Pulse width: 1.2μS, repetitive frequency: 100Hz, neutron generation direction: Isotropic

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (2/11)

<Study of conditions of the target object>

- Conditions of the target object: **It was assumed that "molten debris", "MCCI debris" and "Metallic debris"** (Note 1) are measured.

- The following was assumed regarding the containers to be evaluated based on the cases evaluated in FY2021.

Debris properties	Container/Shape of container	Remarks
Molten debris **MCCI debris**	**Unit can/**Φ210mm × H200mm	Smallest single container. Area contributing to the dose rate, represented by H200mm wherein the quantity of radiation source becomes smaller.
Metallic debris	**Waste storage container (inner container)** / □500mm×300mmH	Represented by an inner container that does not have any shielding and which is smaller than the storage container, since the thickness of the shielding of the waste storage container is yet to be determined. (From amongst the multiple options for inner (collection) containers, the typical option from the Treatment & Disposal PJ was used)

- Based on the influencing factors consolidated as results until FY2021, detector response analysis cases focusing on the parameters (**self-shielding**(Note 2) **(composition)**, **burn-up**, **presence of neutron absorption material**) identified as technical issues were set up for the study.

[Number of analysis cases]

A: Molten debris ⇒ Total 6 cases
(Composition: 2 cases) x (Burn-up: 3 case)

B: MCCI debris ⇒ Total 6 cases
(Composition: 2 cases) x (Burn-up: 3 case)

C: Metallic debris ⇒ Total 3 cases
(Composition: 3 cases) x (Burn-up: 1 case)

Total 15 cases

⇒ Conditions of each case are listed from the next page onwards.

(Note 1) "Subsidy Project of Decommissioning and Contaminated Water Management Development of technology for fuel debris characterization and analysis FY2016 Supplementary Budget Research Report (Interim report) March FY2018

(Note 2) In the future, cases with uneven distribution also need to be studied as impact analysis of self shielding.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (3/11)

Table indicating analysis cases (Molten debris)

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate[*1]	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
A-1	Molten Debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-2		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-3		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can
A-4		**UO_2 : 30 vol%** **ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-5		**UO_2 : 30 vol%** **ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-6		**UO_2 : 30 vol%** **ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can

*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (4/11)

Table indicating analyzed cases (MCCI debris)

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
B-1	MCCI Debris	UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-2				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
B-3				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can
B-4		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	**60 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-5				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
B-6				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (5/11)

Table indicating analyzed cases (Metallic debris)

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container*2
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
C-1	Metallic Debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 29.85 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-2	Metallic Debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 44.85 vol%	**45 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-3	Metallic Debris	UO_2 : 0.48vol% ZrO_2: 0vol% SUS: 10 vol%	**10.48 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)

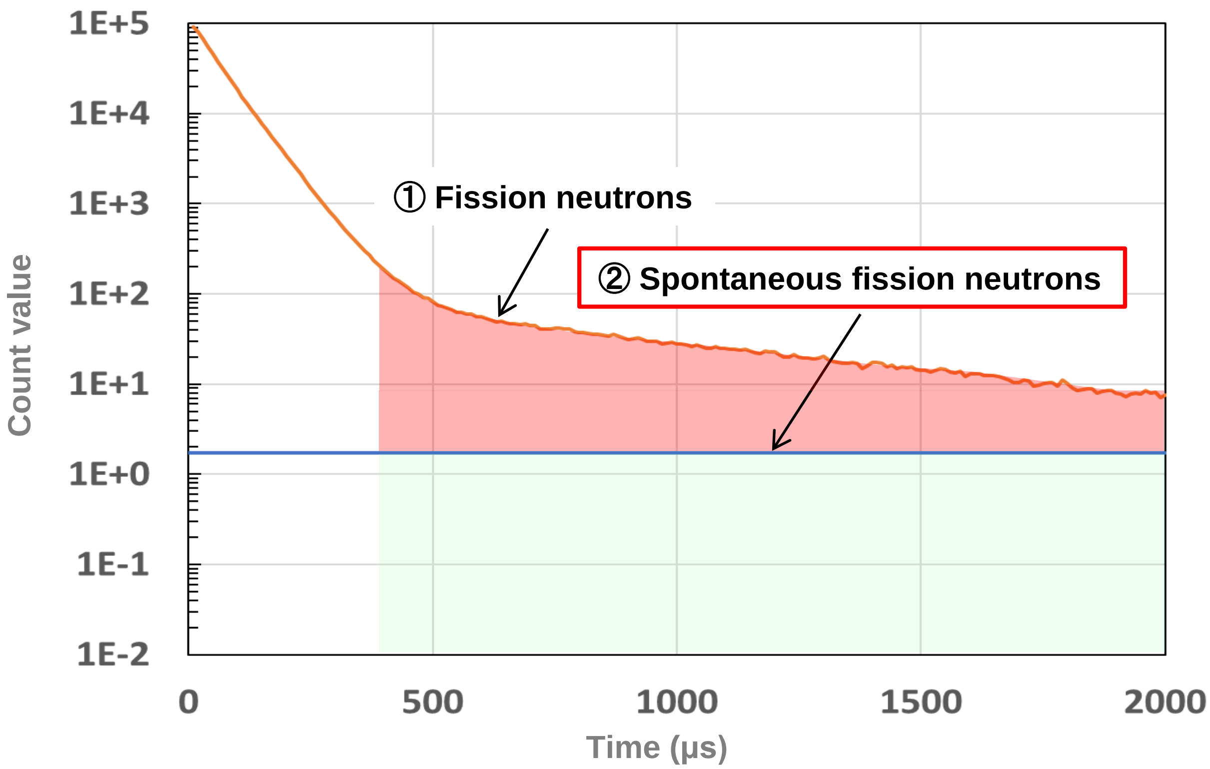
*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)
*2 Mainly made of SUS, it is assumed to be sorted as inner container during the initial stage of retrieval
*3 Overview of each case is indicated below.
C-1: Base case
C-2: Case of sensitivity with respect to SUS composition
C-3: Case of sensitivity in which UO_2 has a volume percent equivalent to 3.7kg

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (6/11)

<Molten debris Detector response in the base case>

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
A-1	Molten Debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	—

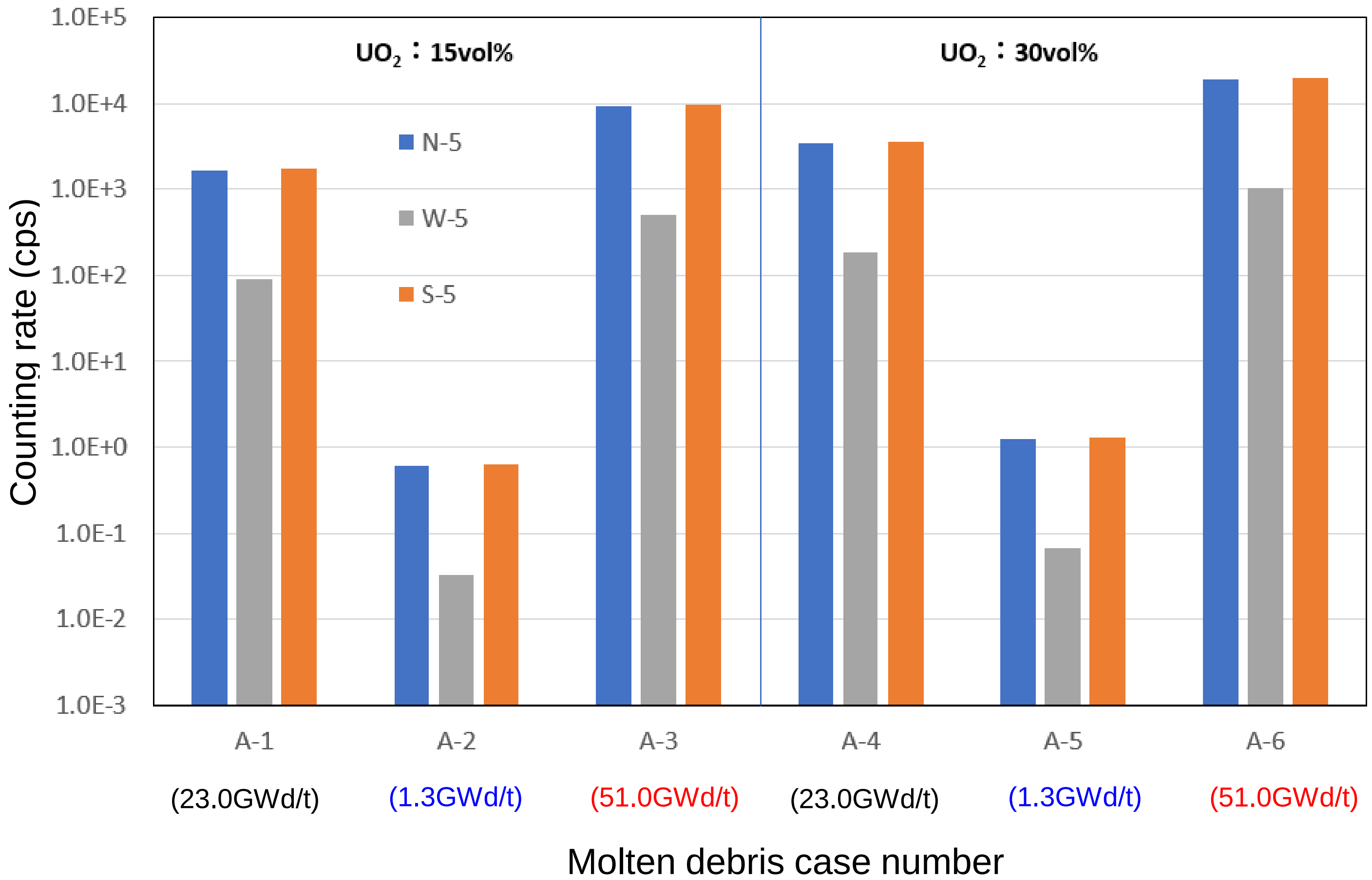


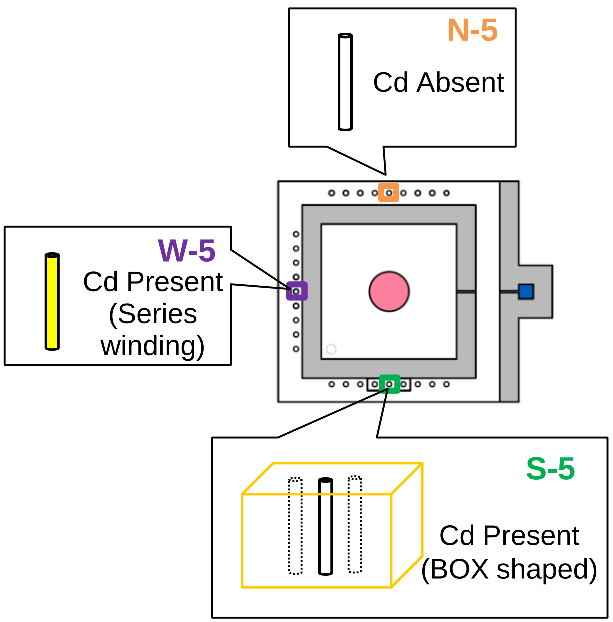
✓ The detectability of ② was verified through the analysis performed by creating a model of the concept of the measuring equipment.

Focusing on the counting rate of spontaneous fission neutrons

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (7/11)





(He-3 detector position and Cd specifications)

- Comparison (molten debris base case) of the detectability for each specification (N-5: Cd Absent, W-5: Cd series winding, S-5: Cd BOX shaped) of the He-3 detector
  - ➢ It was verified that except W-5 there was no major difference in the counting rates of each specification, and the couting rate of W-5 was smaller than the counting rates of other specifications.

⇒ Results and deliberations focusing on the He-3 detector position S-5 along with the active neutron method A are consolidated below.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

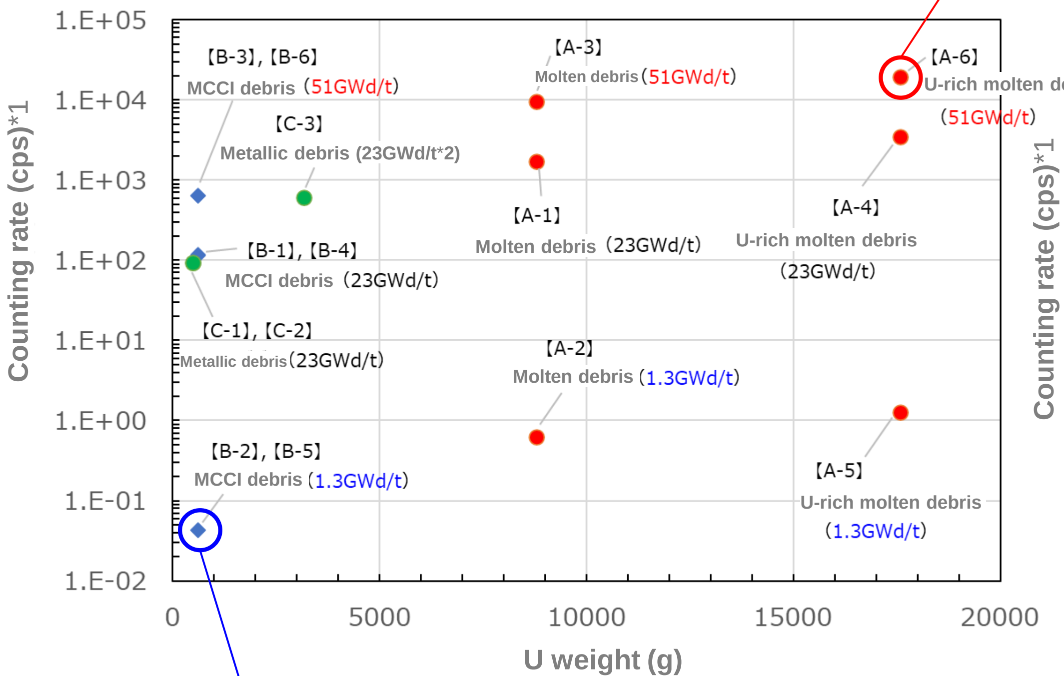
②-1 Passive neutron method A (8/11)

- ✓ Molten debris and MCCI debris: Weight of U and counting rate bear a roughly proportionate relationship when the burn-up is the same (the magnitude relationship between the burn-up and counting rate matches).
- ✓ Common: It was verified that there is a correlation between the weight of Cm-244 and the counting rate without any impact of bulk density and shape of the container.

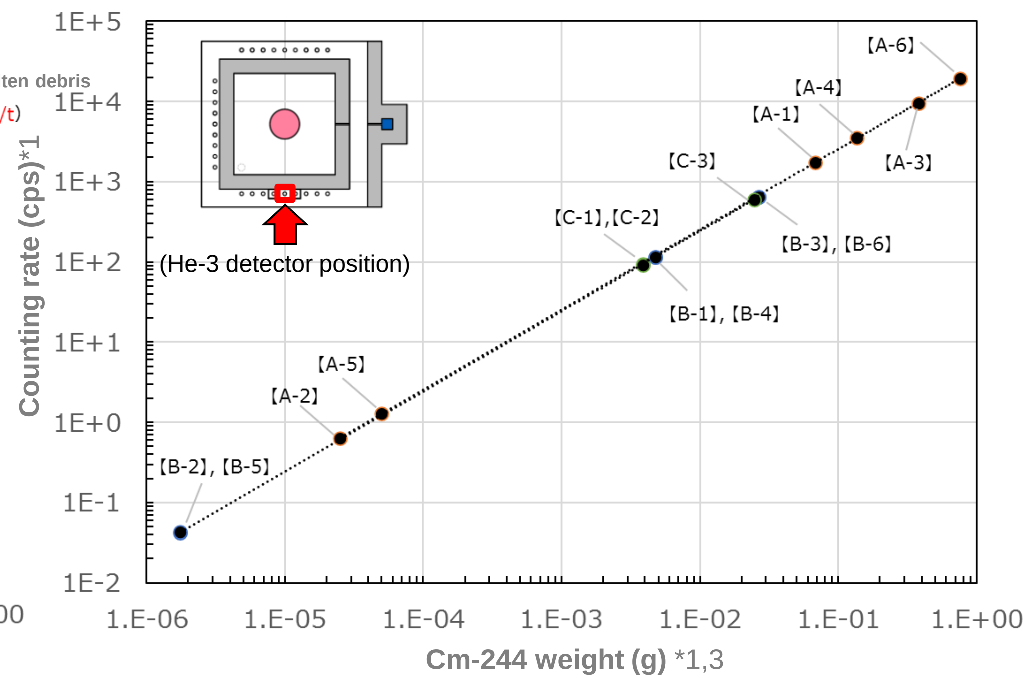
  If the carrying performance of Cm and U can be proved, it implies that there is a possibility that the burn-up impact correction method (conceptual study completed in FY2021) using the value obtained by evaluating the mass of Cm-244 by the passive neutron method and the value obtained by evaluating the mass of Eu-154 by the passive gamma rays method can be used.

There was significant impact depending on the magnitude of burn-up

Measurement time*4: Approx. 1 second (maximum counting rate)



Measurement time*4: Approx. 65 hours (minimum counting rate)



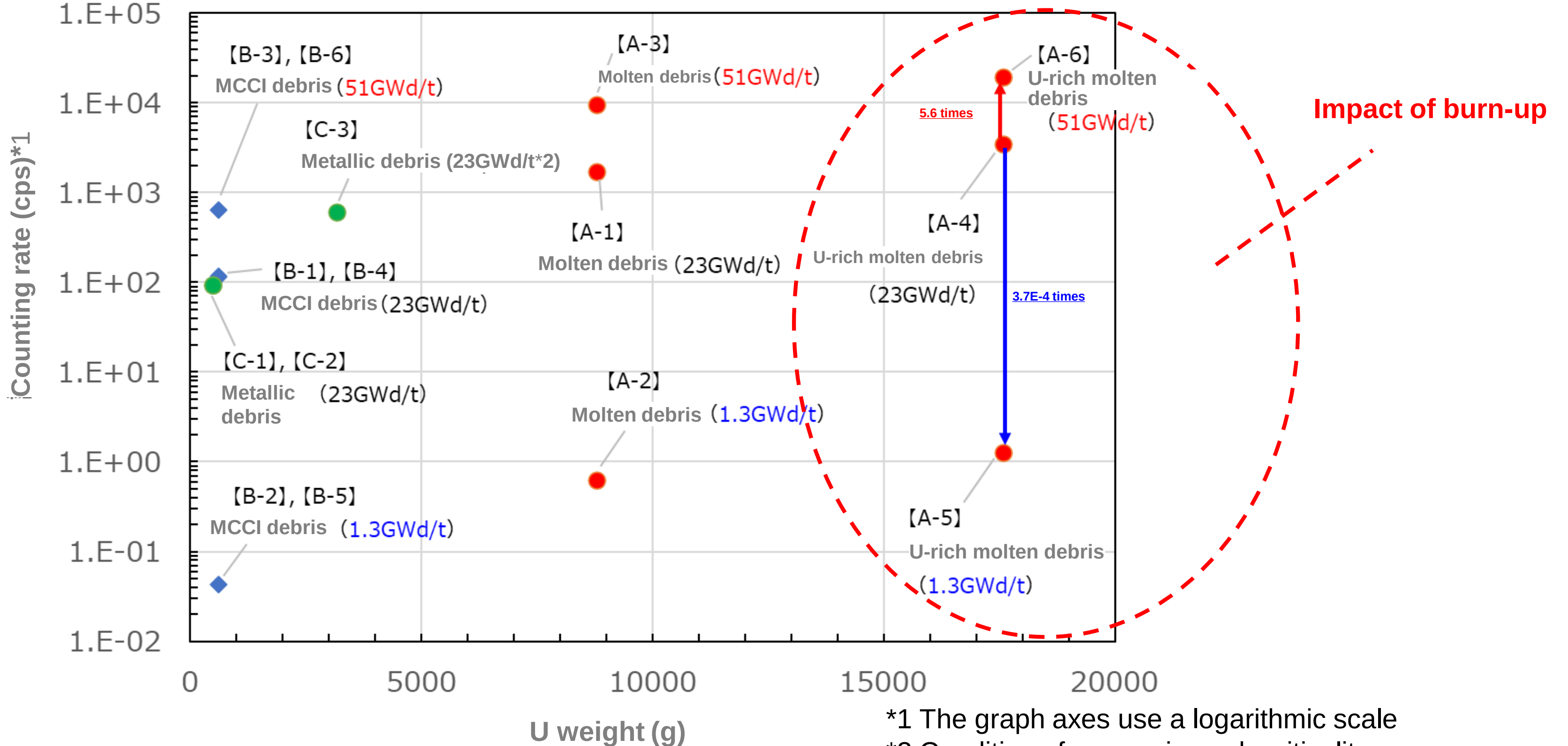
*1,3

*1 The graph axes use a logarithmic scale
*2 Conditions for ensuring sub-criticality
*3 The weight when the number of neutrons produced as a result of spontaneous fission is represented by Cm-244
*4 Measurement time with a 1% (10,000 count) statistical error

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (9/11)

<Analysis of the extent of impact of the influencing factors being focused on>



*1 The graph axes use a logarithmic scale
*2 Conditions for ensuring sub-criticality

Analysis of uranium rich fuel debris that has the highest impact

✓ Impact of burn-up: The count value of high burn-up (51Gwd/t) increased to approx. 5.6 times of the base case (burn-up 23GWd/t)
The count value of low burn-up (1.3GWd/t) decreased to approx. 3.7E-4 times of the base case (burn-up 23GWd/t)

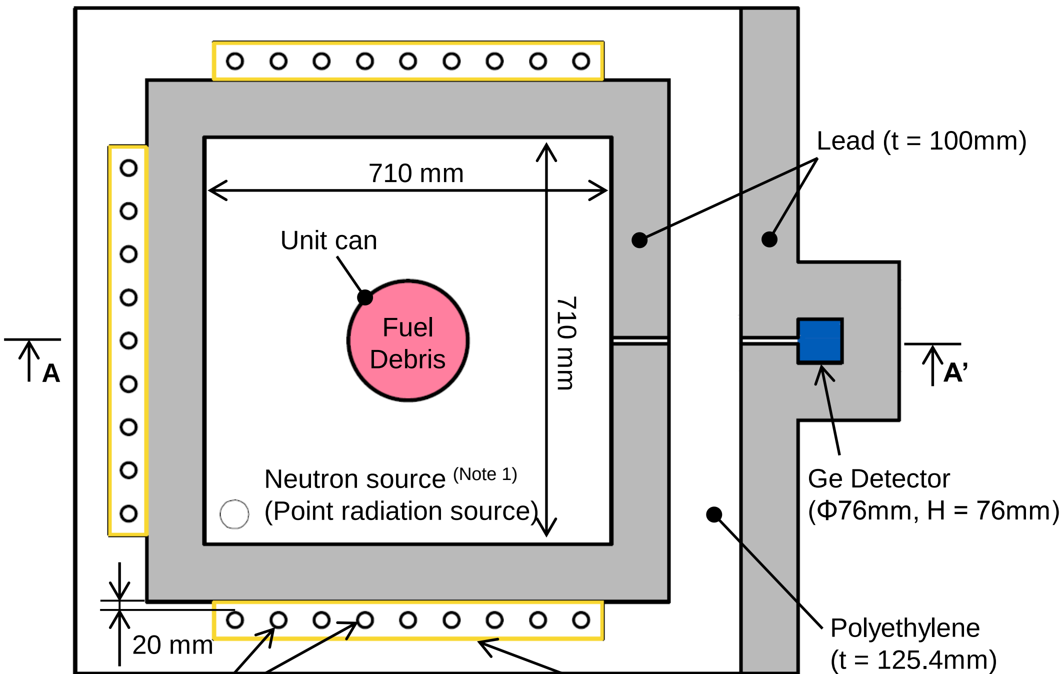
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (10/11)

<Primary proposal of the concept of the measuring equipment>

- ✓ Cd Present (Series winding): The neutrons that are thermalized by polyethylene are absorbed by Cd due to which the count reduces.
- ✓ Cd Absent and Cd Present (Box shaped)：The count of the detector is about the same

⇒ The measurement system using Cd present (BOX shaped) was set as the primary proposal (Similar to the active neutron method A).



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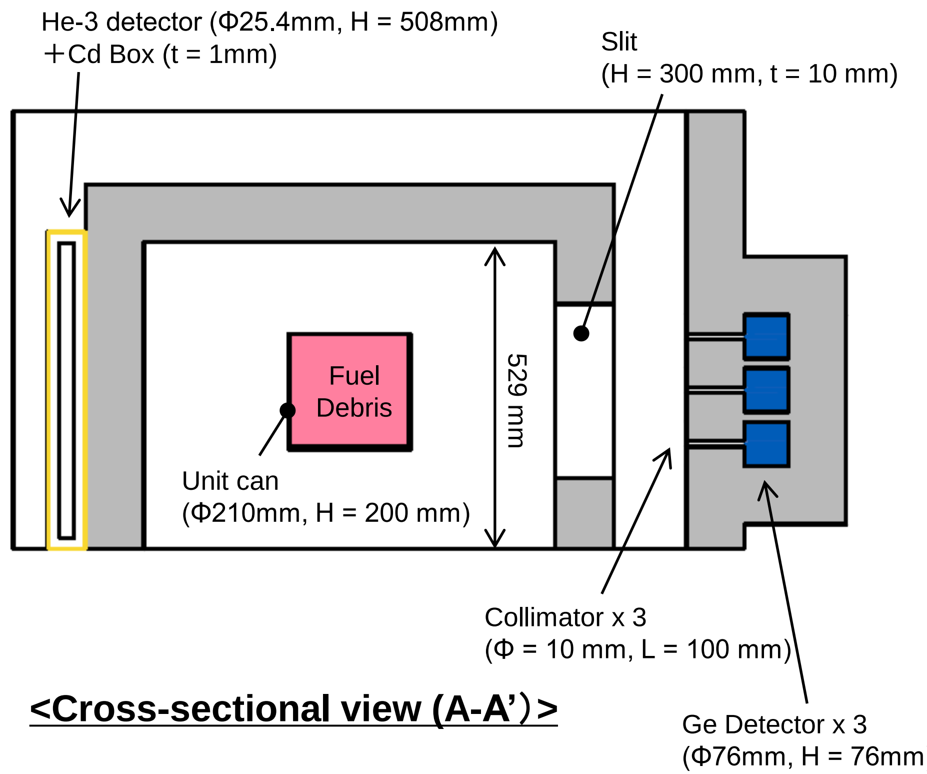


<Cross-sectional view (A-A')>

(Note 1) Neutron energy: 14.1MeV, neutron generation rate: 2×10^8 n/s,
Pulse width: 1.2μS, repetitive frequency: 100Hz, neutron generation direction: Isotropic

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-1 Passive neutron method A (11/11)

<Summary and future issues>

[Implementation details]

1) An analysis model using the passive neutron method was studied.
2) Detector response was analyzed focusing on composition and burn-up.
3) The concept of the measuring equipment used for sorting fuel debris was studied.

[Results/Contribution to development]

1) An analysis model using a combination of active neutron method, passive neutron method and passive gamma rays method was created.

2) Results of analyzing 15 cases of detector response were acquired.

- Impact of burn-up: The burn-up increased approx. 2.2 times (23→51GWd/t) and the count value increased approx. 5.6 times.
  Burn-up decreased approx. 0.06 times (23→1.3GWd/t) and the count value decreased approx. 3.7E-4 times.
- It is verified that there is a correlation between the weight of Cm-244 and the counting rate.

3) The concept of measuring equipment using a combination of the active neutron method, passive neutron method and the passive gamma rays method was developed.

- Detector specifications: He-3 detector placed in a Cd box (used in common with the active neutron method)
- Equipment dimensions: About W5m x D4m x H3m (Compatible with unit cans and inner waste containers)
- Measurement time: Approx. 1 second (Molten debris, 17.6kg U, high burn-up (51Gwd/t), neutron absorption material absent)
  Approx. 65 hours (MCCI debris, U 0.6kg U, low burn-up (1.3GWd/t), neutron absorption material absent)

[Issues and response measures]

1) Issue: Reduction of errors due to burn-up

Response measure: The correction method based on the ratio of Cm-244 and Eu-154 should be studied in detail.
The logic for explaining the carrying performance of Cm-244 & Eu-154 and U needs to be established.

2) Issue: Lack of data contributing to the optimization of the equipment structure

Response measures: Parameter study on equipment structure should be enhanced by means of analysis, elemental technology verification test results should be reflected.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(②-2 Passive neutron method B)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
②-1	Passive neutron method A	He-3	None	None	Mass of spontaneous fission nuclides (Cm-244, etc.)	Fissile nuclide mass	MHI	81-93 192-203
②-2	Passive neutron method B	B-10	None	None	Same as above	Same as above	Hitachi-GE	94-101 204-207

[Characteristics]

- The B-10 detector was selected since it can be used in locations with high gamma rays.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

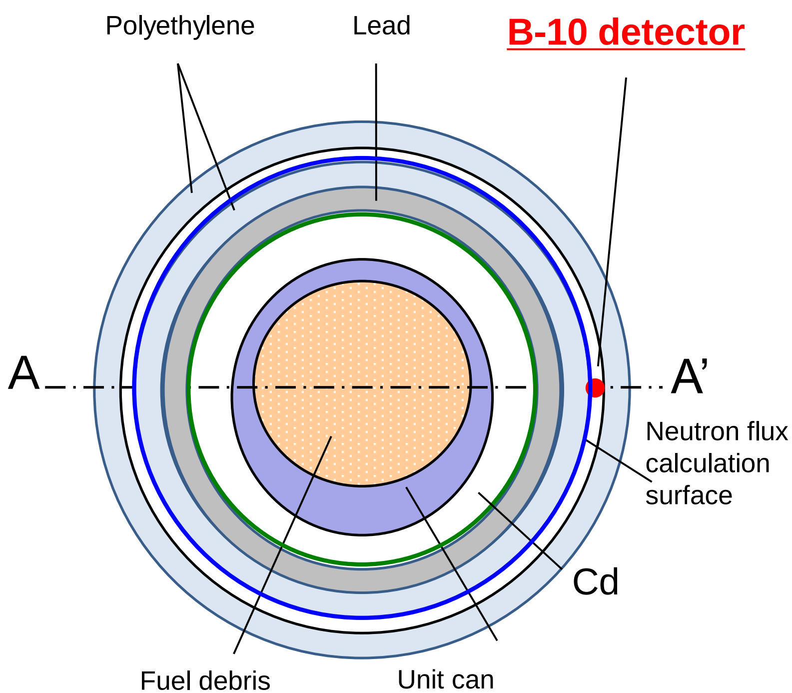
②-2 Passive neutron method B (1/7)

<Detector response analysis model>

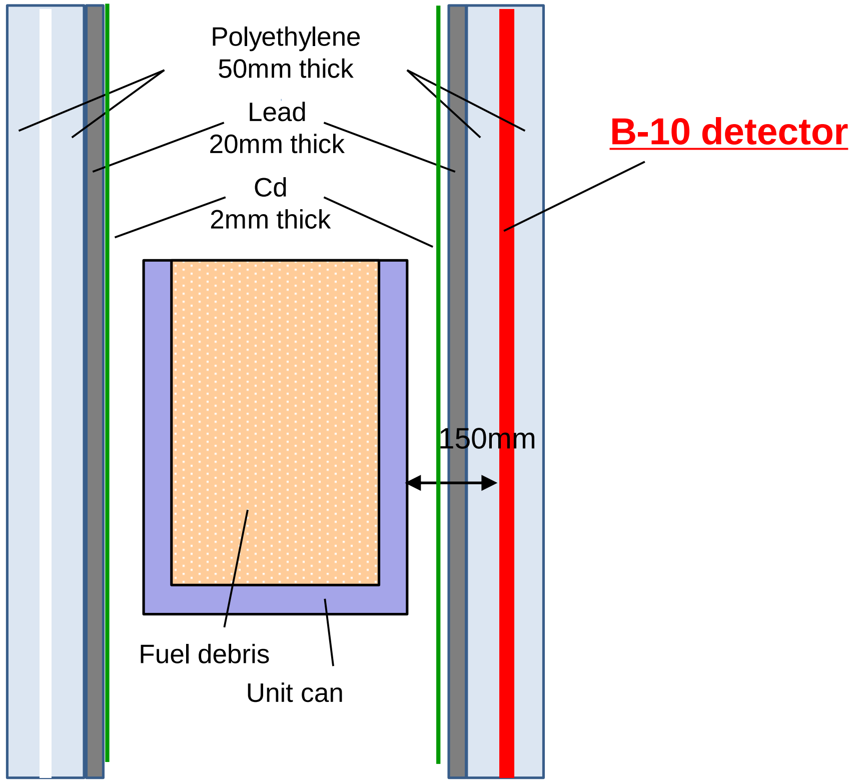
- System: **B-10 detector** response was analyzed using the results of studies conducted in FY2021 (Cd: 2mm thick, Pb: 20mm thick, polyethylene: 50mm thick)
- Evaluation method

① Neutron flux on the inner side of the detector was calculated

② The energy deposited in the detector was calculated with the flux from ① as the source.



Analysis model top view



Cross-sectional view A-A'

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-2 Passive neutron method B (2/7)

<Detector response analysis cases>

◆ Analysis condition (Cases with 3.7kg of U)

Analyzed cases			UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Other than filling factor	Burn-up (GWd/t)	Cooling period (Years)	Amount of U (kg)
Molten debris	2-1	Base	6.3	6.3	0	0	12.6	H_2O: 1wt%	23.0	20	3.7
	2-4	Moisture content	6.3	6.3	0	0	12.6	H_2O:0.1wt%	23.0	20	3.7
	2-5	Moisture content	6.3	6.3	0	0	12.6	H_2O:70vol%	23.0	20	3.7
	2-6	Burn-up (low)	6.2	6.2	0	0	12.4	H_2O: 1wt%	1.3	20	3.7
	2-7	Burn-up (high)	6.5	6.5	0	0	13.0	H_2O: 1wt%	51.0	20	3.7
MCCI	2-9	base	6.3	6.3	4.5	12.9	30	H_2O: 1wt%	23.0	20	3.7
	2-10	Filling factor (high)	6.3	6.3	9.6	27.7	50	H_2O: 1wt%	23.0	20	3.7

◆ Analysis condition (Cases of evaluating the margin of error in amount of U)

Analyzed cases			UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Other than filling factor	Burn-up (GWd/t)	Cooling period (Years)	Amount of U (kg)
Molten debris	2-13	Base (Small quantity of U)	3.0	3.0	0	0	6.0	H_2O: 1wt%	23.0	20	1.76
	2-14	Base (Medium quantity of U)	10.0	10.0	0	0	20.0	H_2O: 1wt%	23.0	20	5.86
	2-15	Base (Large quantity of U)	15.0	15.0	0	0	30.0	H_2O: 1wt%	23.0	20	8.79
	2-16	Low burn-up (Small quantity of U)	3.0	3.0	0	0	6.0	H_2O: 1wt%	1.3	20	1.80
	2-17	Low burn-up (Medium quantity of U)	10.0	10.0	0	0	20.0	H_2O: 1wt%	1.3	20	5.99
	2-18	Low burn-up (Large quantity of U)	15.0	15.0	0	0	30.0	H_2O: 1wt%	1.3	20	8.98
	2-19	High burn-up (Small quantity of U)	3.0	3.0	0	0	6.0	H_2O: 1wt%	51.0	20	1.72
	2-20	High burn-up (Medium quantity of U)	10.0	10.0	0	0	20.0	H_2O: 1wt%	51.0	20	5.72
	2-21	High burn-up (Large quantity of U)	15.0	15.0	0	0	30.0	H_2O: 1wt%	51.0	20	8.58

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

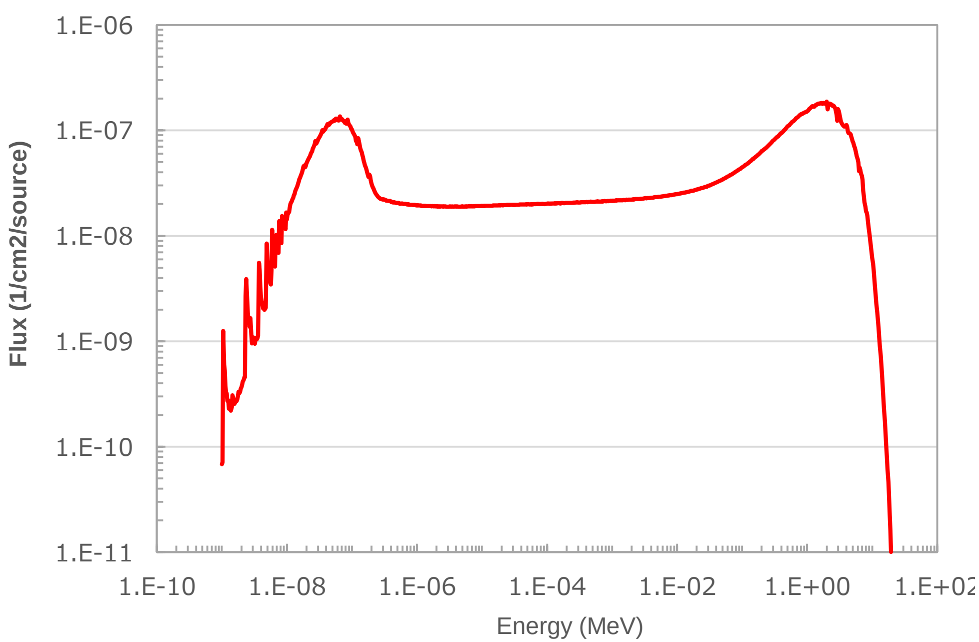
②-2 Passive neutron method B (3/7)

<Detector response analysis results>

◆ Results of calculating the neutron flux and the detector response spectrum for the base case [2-1 Molten debris]

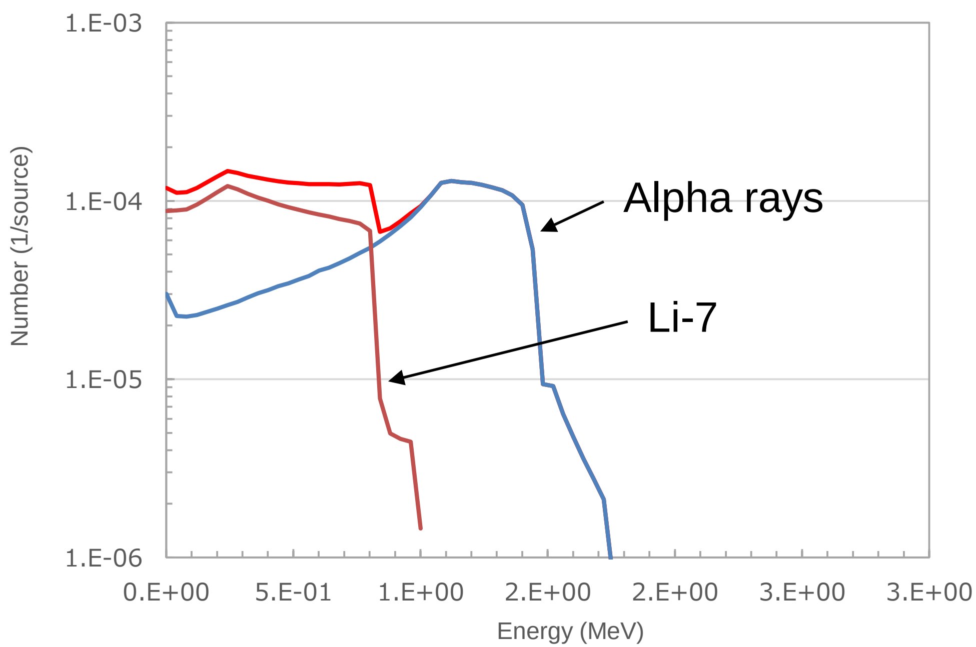
➢ Neutron flux

- Lateral side of the cylinder on the inner side of the detector (outer side of the polyethylene on the inner side)



➢ Detector response spectrum (B-10 detector)

・B-10 detector specifications: Diameter (inner diameter) 25.4mm, effective length 1000 mm, housing thickness 0.5mm (SUS304) B-10 thickness 0.8547μm (=0.2mg/cm^2), Ar gas pressure 0.3atm



➢ Counting rate

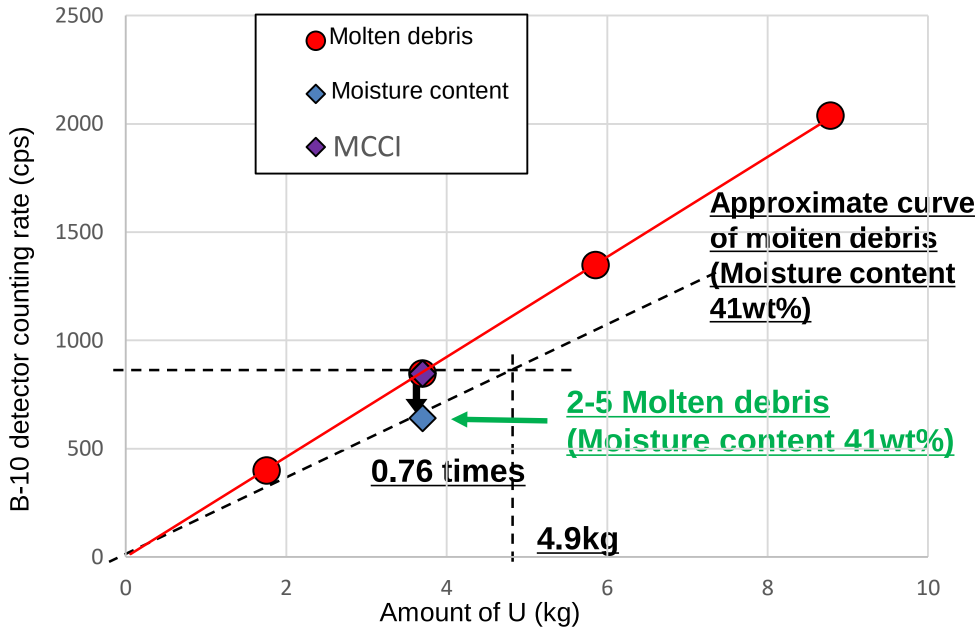
Alpha rays and Li-7 that impart 80keV or more energy in the detector response were measured.

⇒ 8.47E+2cps

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-2 Passive neutron method B (4/7)

◆ Moisture content impact, MCCI debris



◆ Dependency on amount of U (Base case)

Case No.	Amount of U [kg]	Counting rate [cps]	Moisture content
2−1	3.70	8.47E+02	1wt%
2−13	1.76	3.99E+02	1wt%
2−14	5.86	1.35E+03	1wt%
2−15	8.79	2.04E+03	1wt%

◆ Moisture content dependency (3.7kg of U)

Case No.	Amount of U [kg]	Counting rate [cps]	Moisture content
2−1	3.70	8.47E+02	1wt%
2−4	3.70	8.47E+02	0.1wt%
2−5	3.70	6.41E+02	41wt%

◆ MCCI debris (3.7kg of U)

Case No.	Amount of U [kg]	Counting rate [cps]	SUS [vol%]	Conc [vol%]	Filling factor [vol%]
2−1	3.70	8.47E+02	0	0	12.6
2−9	3.70	8.48E+02	4.5	12.9	30
2−10	3.70	8.47E+02	9.6	27.7	50

➢ In the base case (moisture content 1wt%), the counting rate was directly proportional to the amount of U (quantity of Cm-244)

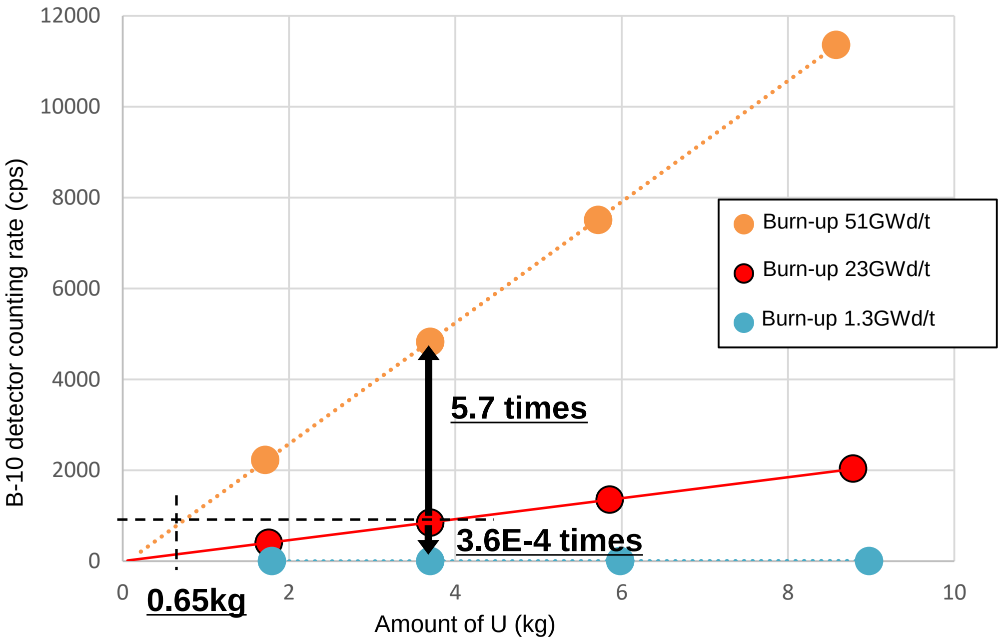
➢ Comparison with the counting rate (8.47E+2cps) of the base case (moisture content 1wt%) when weight of U is 3.7kg
・Moisture content 0.1wt%: Counting rate (8.47E+2cps) did not change
・Moisture content 41wt%: Decrease in counting rate (6.41E+2cps, 0.76 times)
・In the case of MCCI debris: Counting rate (8.47E+2cps to 8.48E+2cps) did not change

➢ Weight of U that results in counting rate (8.47E+2cps) of the base case (Weight of U 3.7kg)
・Moisture content 41wt%: 4.9kg (1.32 times)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-2 Passive neutron method B (5/7)

◆ Impact of burn-up



◆ Dependency on amount of U

① Base case (23GWd/t)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
2-1	3.70	8.47E+02	23.0
2-13	1.76	3.99E+02	23.0
2-14	5.86	1.35E+03	23.0
2-15	8.79	2.04E+03	23.0

② Low burn-up (1.3GWd/t)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
2-16	1.80	1.47E-01	1.3
2-6	3.70	3.04E-01	1.3
2-17	5.99	4.96E-01	1.3
2-18	8.98	7.53E-01	1.3

③ High burn-up (51GWd/t)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
2-19	1.72	2.23E+03	51.0
2-7	3.70	4.82E+03	51.0
2-20	5.72	7.50E+03	51.0
2-21	8.58	1.14E+04	51.0

◆ Burn-up dependency (3.7kg of U)

Case No.	Amount of U [kg]	Counting rate [cps]	Burn-up (GWd/t)
2-1	3.70	8.47E+02	23.0
2-6	3.70	3.04E-01	1.3
2-7	3.70	4.82E+03	51.0

➢ Comparison with the counting rate (8.47E+2cps) of the base case (Burn-up 23GWd/t) when weight of U is 3.7kg
- Burn-up 1.3GWd/t: Decrease in counting rate (3.04E-1cps, 3.6E-4 times)
- Burn-up 51GWd/t: Increase in counting rate (4.82E+3cps, 5.7 times)

➢ Weight of U that results in counting rate (8.47E+2cps) of the molten debris base case (Weight of U 3.7kg)
- Burn-up 1.3GWd/t: 10kg or more
- Burn-up 51GWd/t: 0.65kg (0.18 times)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-2 Passive neutron method B (6/7)

<Concept of the equipment>

◆ **Measurement time**

・The required measurement time in the base case is about 10 seconds and is sufficient.

・**<u>The required measurement time is about 9 hours in the case of low burn-up (1.3GWd/t)</u>**

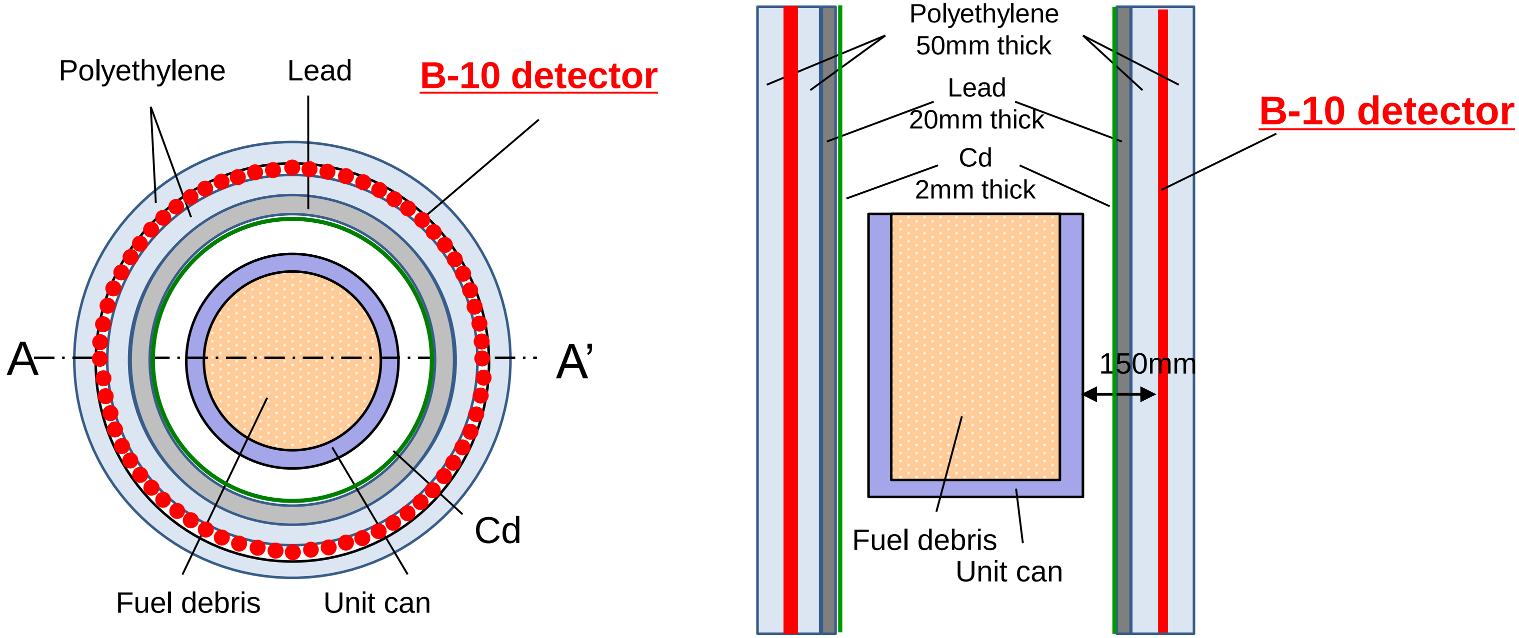
⇒**<u>Issue</u>**: **<u>Enhancement of sensitivity</u>**

Analysis cases		Counting rate [cps]	Time required for a 10,000 count		
			[sec]	[min]	[hour]
2−1	Base case (Unit can)	8.47E+02	1.18E+01	1.97E−01	3.28E−03
2−6	Burn-up 1.3GWd/t	3.04E−01	3.28E+04	5.47E+02	9.12E+00

◆ **Proposed countermeasures (Enhancement of sensitivity)**

①**<u>Increasing the number of detectors</u>**: 1 detector ⇒ about 60 detectors (Tier 1) ⇒ about 100 detectors (multiple tiers)

Issue: Optimization of the number of detectors and their placement, detector cost



Analysis model top view

Cross-sectional view A-A'

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

②-2 Passive neutron method B (7/7)

<Summary and future issues>

[Implementation details]

1) Study of the error in evaluating the amount of U by detector response analysis (B-10 neutron detector) in which the amount of U is set to 3.7kg which is the standard for sorting

2) Study of the concept of the equipment by estimating the measurement time based on the above results

[Results/Contribution to development]

1) The following results were obtained upon comparison with the counting rate (8.47E+2cps) of the base case (molten debris).

① Impact of burn-up:

- Burn-up 1.3GWd/t: Decrease in counting rate (3.04E-1cps, 3.6E-4 times)
- Burn-up 51GWd/t: Increase in counting rate (4.82E+3cps, 5.7E+0 times)

② Impact of moisture content and fuel debris composition:

- Moisture content 0.1wt%: Counting rate (8.47E+2cps) does not change
- Moisture content 41wt%: Decrease in counting rate (6.41E+2cps, 0.76 times)
- In the case of MCCI debris: Counting rate (8.47E+2cps to 8.48E+2cps) does not change

2) Required measurement time:

- Base case (Molten debris 3.7kg of U): approx. 10 seconds
- Low burn-up (1.3GWd/t): Approx. 9 hour

[Issues and response measures]

1) Issue: As burn-up impact is large, it is essential to correct burn-up.

⇒ Response measure: The effectiveness of the method of burn-up correction by means of PG/PN should be evaluated and the effectiveness of using the CT method for improving the accuracy of the method should be evaluated.

2) Issue: Enhancement of the neutron measurement sensitivity (9 hours required in the case of low burn-up) ⇒ Response measure: The number of detectors should be increased (placed in multiple tiers), the placement of the moderator should be optimized.

3) Issue: Carrying performance of Cm-244 with the nuclear fuel material ⇒ Response measure: Evidence should be accumulated in cooperation with other projects and the logic for explaining the phenomenon should be established.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(③ Muon scattering method)

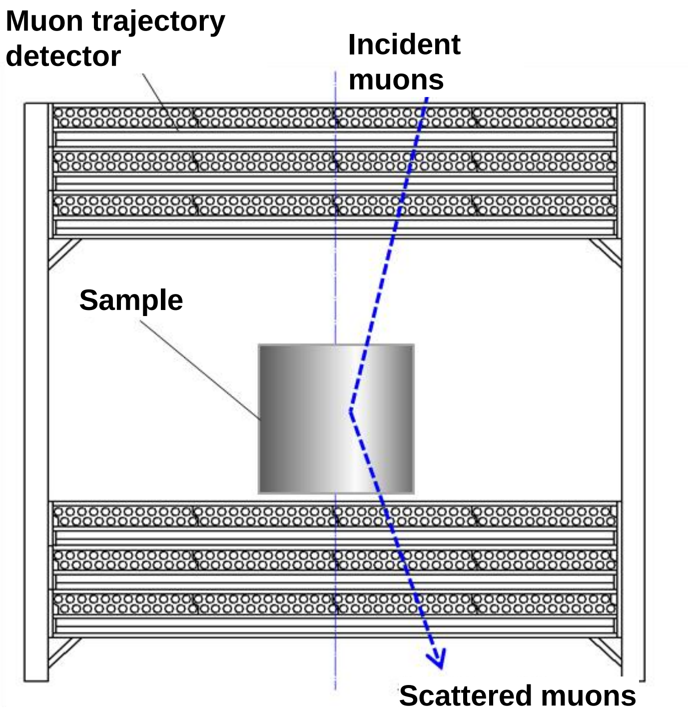
No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
③	Muon scattering method	Muon trajectory detector	None	None	Atomic weight	Fissile nuclide mass	Toshiba ESS	102-116 208-214

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

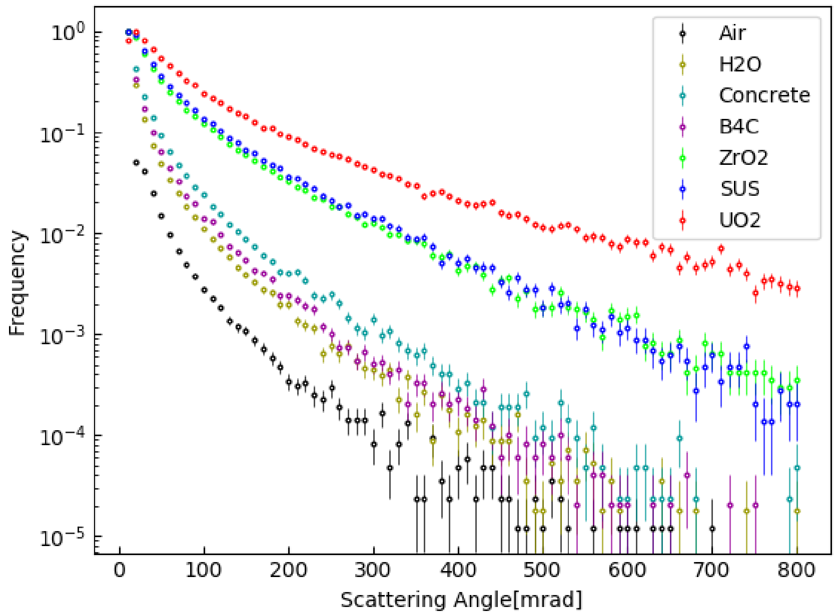
③ Muon scattering method (1/14)

(1) Detector response analysis model (Overview)

- Principle of measurement: Changes in the trajectory of muons passing through the sample were measured.
- Measurement system: Muon trajectory detectors were placed above and below the sample.
- Detector response: Spectrum of muon scattering angles (Frequency distribution for each angle)
- Measurement time: Assumed to be 1 to 2 hours (*Presumed value: varies depending on the detector specifications, size, placement, etc.)



Measurement system



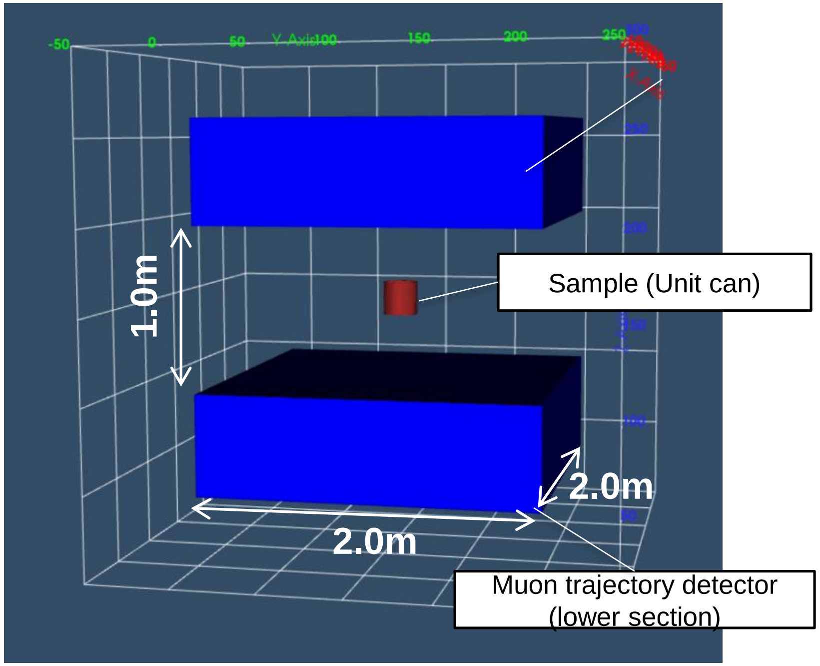
Measured value (Muon scattering spectrum)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

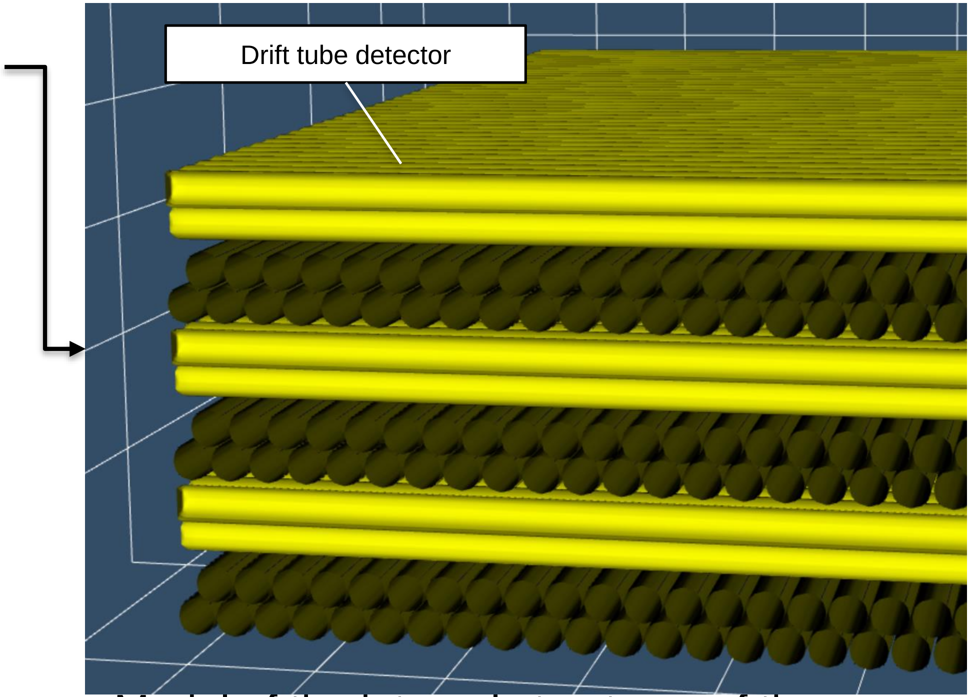
③ Muon scattering method (2/14)

(1) Detector response analysis model (Reproduction of the structure of measuring equipment)

- The measured value was evaluated under conditions such that ideal muon trajectory can be measured using the conventional model.
  - During actual measurement, muon scattering due to the structure of the detector became a cause of errors.
- The internal structure of the detector (shape, composition) was reflected in the modified model
  - A value close to the actual measured value was reproduced by analyzing the scattering of muons when they pass through the detector.



Measurement system model



Model of the internal structures of the muon trajectory detector

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (3/14)

(2) Detector response analysis cases (Policy for setting the cases)

- Re-examination of conditions of the target object
  - The main influencing factors were selected from the results of evaluation conducted in FY2021
    - Type of fuel debris, porosity, volume, neutron absorption material (Gd)
- Policy for setting up the analysis cases
  - Analysis cases were set up by establishing the overall combination of conditions for each factor
- Analysis cases
  - Total 300 cases = (fuel debris composition × 4) × (porosity × 5) × (volume × 5) × (absorption material × 3)

No	Items to be analyzed	Evaluation Contents	Evaluation items	No. of cases
1	Type of debris	4 types of fuel debris compositions	Molten debris, MCCI debris, metallic debris, Uranium-rich debris	4
2	Porosity	Density was changed while keeping the composition and volume constant (Porosity is 0% in the case of normal density)	90, 80, 70, 60, 50[vol%]	5
3	Volume percent	Volume was changed while keeping the composition and weight constant (The maximum capacity of the container implies 100% volume percent)	60, 70, 80, 90, 100[vol%]	5
4	Absorption material contained	0 to 5% of Gd_2O_5 was added to the fuel debris set up in items 1 to 3	0, 2.5, 5.0 [vol%]	3

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (4/14)

(2) Detector response analysis cases (Molten debris)

Type of debris	No.	UO_2 [vol%]	ZrO_2 [vol%]	SUS [vol%]	Conc [vol%]	Porosity [%]	Volume percent [%]	Gd_2O_3 [vol%]	Debris weight [kg]	Weight of U [kg]
Molten debris	1-1~1-3	5.0	5.0	0.0	0.0	90	60	0.0, 2.5, 5.0	5.23	2.93
	1-4~1-6	5.0	5.0	0.0	0.0	90	70	0.0, 2.5, 5.0	5.23	2.93
	1-7~1-9	5.0	5.0	0.0	0.0	90	80	0.0, 2.5, 5.0	5.23	2.93
	1-10~1-12	5.0	5.0	0.0	0.0	90	90	0.0, 2.5, 5.0	5.23	2.93
	1-13~1-15	5.0	5.0	0.0	0.0	90	100	0.0, 2.5, 5.0	5.23	2.93
	1-16~1-18	10.0	10.0	0.0	0.0	80	60	0.0, 2.5, 5.0	10.46	5.86
	1-19~1-21	10.0	10.0	0.0	0.0	80	70	0.0, 2.5, 5.0	10.46	5.86
	1-22~1-24	10.0	10.0	0.0	0.0	80	80	0.0, 2.5, 5.0	10.46	5.86
	1-25~1-27	10.0	10.0	0.0	0.0	80	90	0.0, 2.5, 5.0	10.46	5.86
	1-28~1-30	10.0	10.0	0.0	0.0	80	100	0.0, 2.5, 5.0	10.46	5.86
	1-31~1-33	15.0	15.0	0.0	0.0	70	60	0.0, 2.5, 5.0	15.68	8.79
	1-34~1-36	15.0	15.0	0.0	0.0	70	70	0.0, 2.5, 5.0	15.68	8.79
	1-37~1-39	15.0	15.0	0.0	0.0	70	80	0.0, 2.5, 5.0	15.68	8.79
	1-40~1-42	15.0	15.0	0.0	0.0	70	90	0.0, 2.5, 5.0	15.68	8.79
	1-43~1-45	15.0	15.0	0.0	0.0	70	100	0.0, 2.5, 5.0	15.68	8.79
	1-46~1-48	20.0	20.0	0.0	0.0	60	60	0.0, 2.5, 5.0	20.91	11.72
	1-49~1-51	20.0	20.0	0.0	0.0	60	70	0.0, 2.5, 5.0	20.91	11.72
	1-52~1-54	20.0	20.0	0.0	0.0	60	80	0.0, 2.5, 5.0	20.91	11.72
	1-55~1-57	20.0	20.0	0.0	0.0	60	90	0.0, 2.5, 5.0	20.91	11.72
	1-58~1-60	20.0	20.0	0.0	0.0	60	100	0.0, 2.5, 5.0	20.91	11.72
	1-61~1-63	25.0	25.0	0.0	0.0	50	60	0.0, 2.5, 5.0	26.14	14.64
	1-64~1-66	25.0	25.0	0.0	0.0	50	70	0.0, 2.5, 5.0	26.14	14.64
	1-67~1-69	25.0	25.0	0.0	0.0	50	80	0.0, 2.5, 5.0	26.14	14.64
	1-70~1-72	25.0	25.0	0.0	0.0	50	90	0.0, 2.5, 5.0	26.14	14.64
	1-73~1-75	25.0	25.0	0.0	0.0	50	100	0.0, 2.5, 5.0	26.14	14.64

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (5/14)

(2) Detector response analysis cases (MCCI debris)

Type of debris	No.	UO_2 [vol%]	ZrO_2 [vol%]	SUS [vol%]	Conc [vol%]	Porosity [%]	Volume percent [%]	Gd_2O_3 [vol%]	Debris weight [kg]	Weight of U [kg]
MCCI debris	2-1~2-3	0.35	0.35	2.40	6.90	90	60	0.0, 2.5, 5.0	2.54	0.21
	2-4~2-6	0.35	0.35	2.40	6.90	90	70	0.0, 2.5, 5.0	2.54	0.21
	2-7~2-9	0.35	0.35	2.40	6.90	90	80	0.0, 2.5, 5.0	2.54	0.21
	2-10~2-12	0.35	0.35	2.40	6.90	90	90	0.0, 2.5, 5.0	2.54	0.21
	2-13~2-15	0.35	0.35	2.40	6.90	90	100	0.0, 2.5, 5.0	2.54	0.21
	2-16~2-18	0.70	0.70	4.80	13.80	80	60	0.0, 2.5, 5.0	5.09	0.41
	2-19~2-21	0.70	0.70	4.80	13.80	80	70	0.0, 2.5, 5.0	5.09	0.41
	2-22~2-24	0.70	0.70	4.80	13.80	80	80	0.0, 2.5, 5.0	5.09	0.41
	2-25~2-27	0.70	0.70	4.80	13.80	80	90	0.0, 2.5, 5.0	5.09	0.41
	2-28~2-30	0.70	0.70	4.80	13.80	80	100	0.0, 2.5, 5.0	5.09	0.41
	2-31~2-33	1.05	1.05	7.20	20.70	70	60	0.0, 2.5, 5.0	7.63	0.62
	2-34~2-36	1.05	1.05	7.20	20.70	70	70	0.0, 2.5, 5.0	7.63	0.62
	2-37~2-39	1.05	1.05	7.20	20.70	70	80	0.0, 2.5, 5.0	7.63	0.62
	2-40~2-42	1.05	1.05	7.20	20.70	70	90	0.0, 2.5, 5.0	7.63	0.62
	2-43~2-45	1.05	1.05	7.20	20.70	70	100	0.0, 2.5, 5.0	7.63	0.62
	2-46~2-48	1.40	1.40	9.60	27.60	60	60	0.0, 2.5, 5.0	10.18	0.82
	2-49~2-51	1.40	1.40	9.60	27.60	60	70	0.0, 2.5, 5.0	10.18	0.82
	2-52~2-54	1.40	1.40	9.60	27.60	60	80	0.0, 2.5, 5.0	10.18	0.82
	2-55~2-57	1.40	1.40	9.60	27.60	60	90	0.0, 2.5, 5.0	10.18	0.82
	2-58~2-60	1.40	1.40	9.60	27.60	60	100	0.0, 2.5, 5.0	10.18	0.82
	2-61~2-63	1.75	1.75	12.00	34.50	50	60	0.0, 2.5, 5.0	12.72	1.03
	2-64~2-66	1.75	1.75	12.00	34.50	50	70	0.0, 2.5, 5.0	12.72	1.03
	2-67~2-69	1.75	1.75	12.00	34.50	50	80	0.0, 2.5, 5.0	12.72	1.03
	2-70~2-72	1.75	1.75	12.00	34.50	50	90	0.0, 2.5, 5.0	12.72	1.03
	2-73~2-75	1.75	1.75	12.00	34.50	50	100	0.0, 2.5, 5.0	12.72	1.03

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (6/14)

(2) Detector response analysis cases (Metal debris)

Type of debris	No.	UO_2 [vol%]	ZrO_2 [vol%]	SUS [vol%]	Conc [vol%]	Porosity [%]	Volume percent [%]	Gd_2O_3 [vol%]	Debris weight [kg]	Weight of U [kg]
Metallic debris	3-1~3-3	0.025	0.025	9.950	0.000	90	60	0.0, 2.5, 5.0	5.15	0.01
	3-4~3-6	0.025	0.025	9.950	0.000	90	70	0.0, 2.5, 5.0	5.15	0.01
	3-7~3-9	0.025	0.025	9.950	0.000	90	80	0.0, 2.5, 5.0	5.15	0.01
	3-10~3-12	0.025	0.025	9.950	0.000	90	90	0.0, 2.5, 5.0	5.15	0.01
	3-13~3-15	0.025	0.025	9.950	0.000	90	100	0.0, 2.5, 5.0	5.15	0.01
	3-16~3-18	0.050	0.050	19.900	0.000	80	60	0.0, 2.5, 5.0	10.31	0.03
	3-19~3-21	0.050	0.050	19.900	0.000	80	70	0.0, 2.5, 5.0	10.31	0.03
	3-22~3-24	0.050	0.050	19.900	0.000	80	80	0.0, 2.5, 5.0	10.31	0.03
	3-25~3-27	0.050	0.050	19.900	0.000	80	90	0.0, 2.5, 5.0	10.31	0.03
	3-28~3-30	0.050	0.050	19.900	0.000	80	100	0.0, 2.5, 5.0	10.31	0.03
	3-31~3-33	0.075	0.075	29.850	0.000	70	60	0.0, 2.5, 5.0	15.46	0.04
	3-34~3-36	0.075	0.075	29.850	0.000	70	70	0.0, 2.5, 5.0	15.46	0.04
	3-37~3-39	0.075	0.075	29.850	0.000	70	80	0.0, 2.5, 5.0	15.46	0.04
	3-40~3-42	0.075	0.075	29.850	0.000	70	90	0.0, 2.5, 5.0	15.46	0.04
	3-43~3-45	0.075	0.075	29.850	0.000	70	100	0.0, 2.5, 5.0	15.46	0.04
	3-46~3-48	0.100	0.100	39.800	0.000	60	60	0.0, 2.5, 5.0	20.62	0.06
	3-49~3-51	0.100	0.100	39.800	0.000	60	70	0.0, 2.5, 5.0	20.62	0.06
	3-52~3-54	0.100	0.100	39.800	0.000	60	80	0.0, 2.5, 5.0	20.62	0.06
	3-55~3-57	0.100	0.100	39.800	0.000	60	90	0.0, 2.5, 5.0	20.62	0.06
	3-58~3-60	0.100	0.100	39.800	0.000	60	100	0.0, 2.5, 5.0	20.62	0.06
	3-61~3-63	0.125	0.125	49.750	0.000	50	60	0.0, 2.5, 5.0	25.77	0.07
	3-64~3-66	0.125	0.125	49.750	0.000	50	70	0.0, 2.5, 5.0	25.77	0.07
	3-67~3-69	0.125	0.125	49.750	0.000	50	80	0.0, 2.5, 5.0	25.77	0.07
	3-70~3-72	0.125	0.125	49.750	0.000	50	90	0.0, 2.5, 5.0	25.77	0.07
	3-73~3-75	0.125	0.125	49.750	0.000	50	100	0.0, 2.5, 5.0	25.77	0.07

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (7/14)

(2) Detector response analysis cases (Uranium-rich debris)

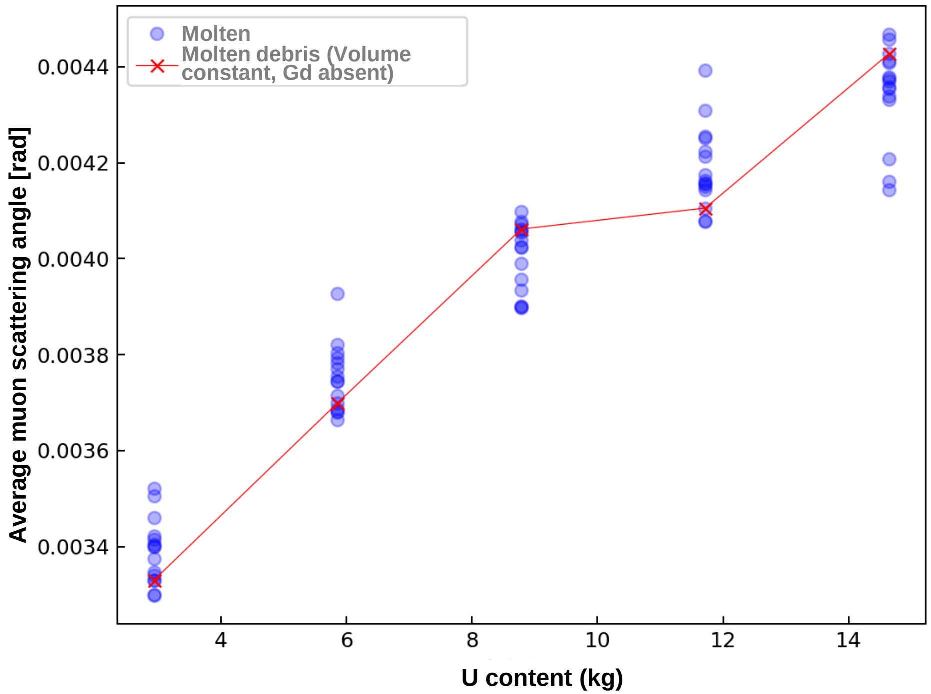
Type of debris	No.	UO_2 [vol%]	ZrO_2 [vol%]	SUS [vol%]	Conc [vol%]	Porosity [%]	Volume percent [%]	Gd_2O_3 [vol%]	Debris weight [kg]	Weight of U [kg]
Uranium-rich debris	4-1~4-3	10.0	0.0	0.0	0.0	90	60	0.0, 2.5, 5.0	6.84	5.86
	4-4~4-6	10.0	0.0	0.0	0.0	90	70	0.0, 2.5, 5.0	6.84	5.86
	4-7~4-9	10.0	0.0	0.0	0.0	90	80	0.0, 2.5, 5.0	6.84	5.86
	4-10~4-12	10.0	0.0	0.0	0.0	90	90	0.0, 2.5, 5.0	6.84	5.86
	4-13~4-15	10.0	0.0	0.0	0.0	90	100	0.0, 2.5, 5.0	6.84	5.86
	4-16~4-18	20.0	0.0	0.0	0.0	80	60	0.0, 2.5, 5.0	13.68	11.72
	4-19~4-21	20.0	0.0	0.0	0.0	80	70	0.0, 2.5, 5.0	13.68	11.72
	4-22~4-24	20.0	0.0	0.0	0.0	80	80	0.0, 2.5, 5.0	13.68	11.72
	4-25~4-27	20.0	0.0	0.0	0.0	80	90	0.0, 2.5, 5.0	13.68	11.72
	4-28~4-30	20.0	0.0	0.0	0.0	80	100	0.0, 2.5, 5.0	13.68	11.72
	4-31~4-33	30.0	0.0	0.0	0.0	70	60	0.0, 2.5, 5.0	20.52	17.57
	4-34~4-36	30.0	0.0	0.0	0.0	70	70	0.0, 2.5, 5.0	20.52	17.57
	4-37~4-39	30.0	0.0	0.0	0.0	70	80	0.0, 2.5, 5.0	20.52	17.57
	4-40~4-42	30.0	0.0	0.0	0.0	70	90	0.0, 2.5, 5.0	20.52	17.57
	4-43~4-45	30.0	0.0	0.0	0.0	70	100	0.0, 2.5, 5.0	20.52	17.57
	4-46~4-48	40.0	0.0	0.0	0.0	60	60	0.0, 2.5, 5.0	27.37	23.43
	4-49~4-51	40.0	0.0	0.0	0.0	60	70	0.0, 2.5, 5.0	27.37	23.43
	4-52~4-54	40.0	0.0	0.0	0.0	60	80	0.0, 2.5, 5.0	27.37	23.43
	4-55~4-57	40.0	0.0	0.0	0.0	60	90	0.0, 2.5, 5.0	27.37	23.43
	4-58~4-60	40.0	0.0	0.0	0.0	60	100	0.0, 2.5, 5.0	27.37	23.43
	4-61~4-63	50.0	0.0	0.0	0.0	50	60	0.0, 2.5, 5.0	34.21	29.29
	4-64~4-66	50.0	0.0	0.0	0.0	50	70	0.0, 2.5, 5.0	34.21	29.29
	4-67~4-69	50.0	0.0	0.0	0.0	50	80	0.0, 2.5, 5.0	34.21	29.29
	4-70~4-72	50.0	0.0	0.0	0.0	50	90	0.0, 2.5, 5.0	34.21	29.29
	4-73~4-75	50.0	0.0	0.0	0.0	50	100	0.0, 2.5, 5.0	34.21	29.29

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (8/14)

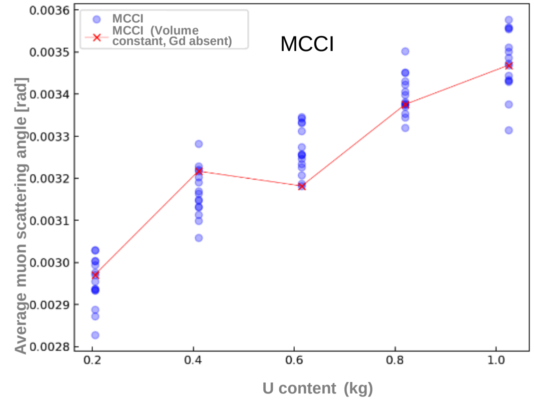
(3) Detector response analysis results

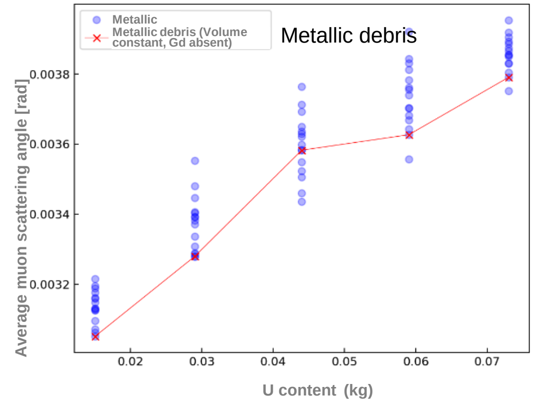
- Evaluation of the impact of the amount of U
  - Measured value had a tendency to increase corresponding to the weight of U under each debris condition.

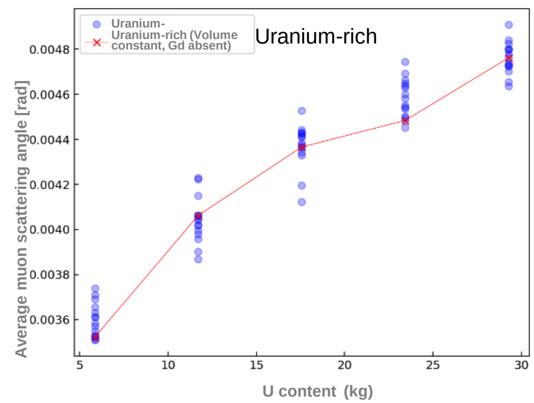


Average muon scattering angle with respect to the U content (Molten debris)

- The measured value had a very clear correlation with U content
- There were variations in the measured value due to other influencing factors even if the amount of U remained the same.



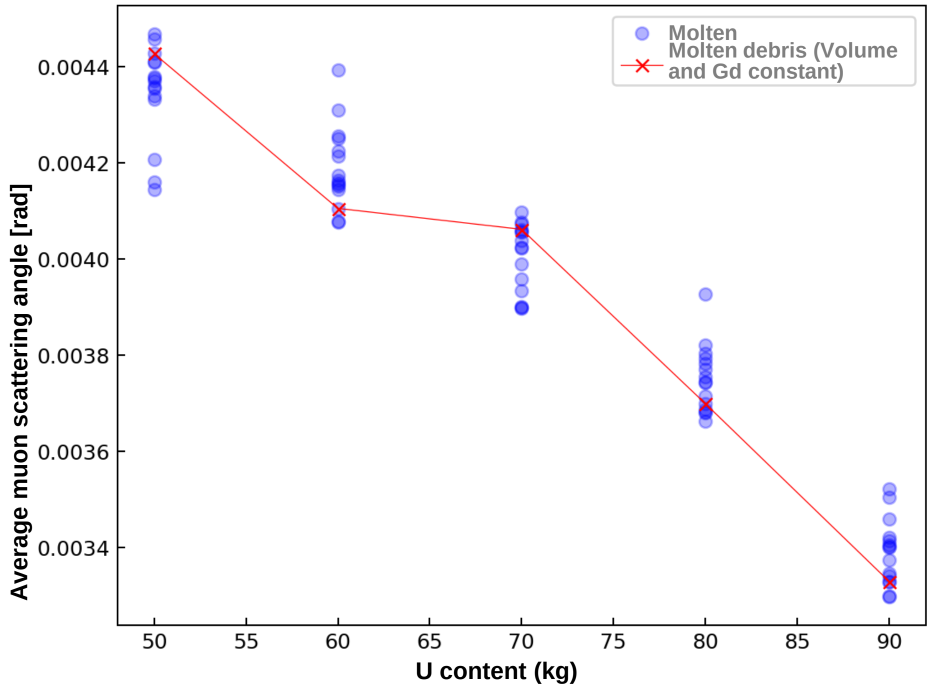




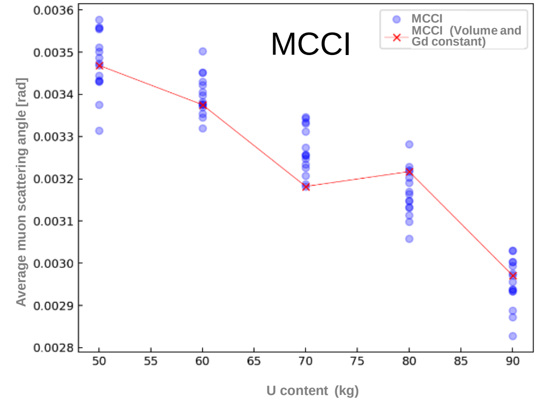
③ Muon scattering method (9/14)

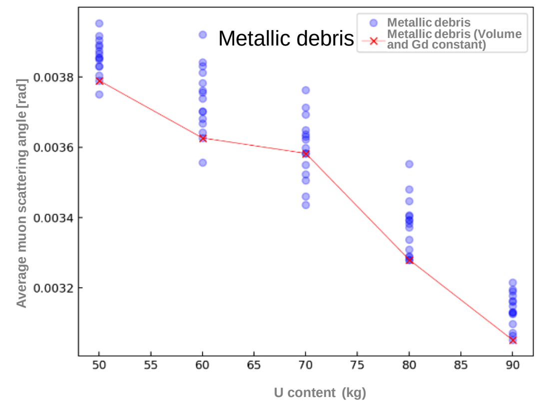
(3) Detector response analysis results

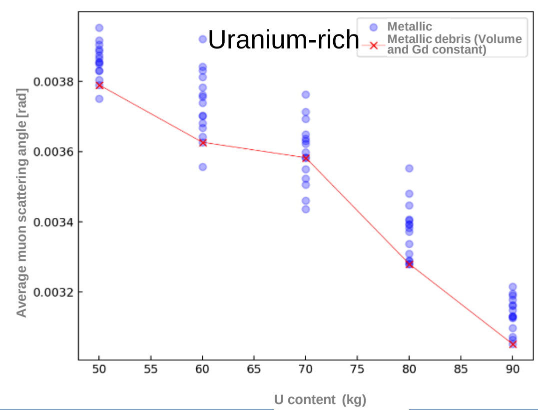
- Evaluation of the impact of porosity
  - The scattering angle decreased due to increase in porosity even with the same volume.
  - The impact of variation in weight was larger than that of variation in volume.



Impact of change in porosity (Molten debris conditions)







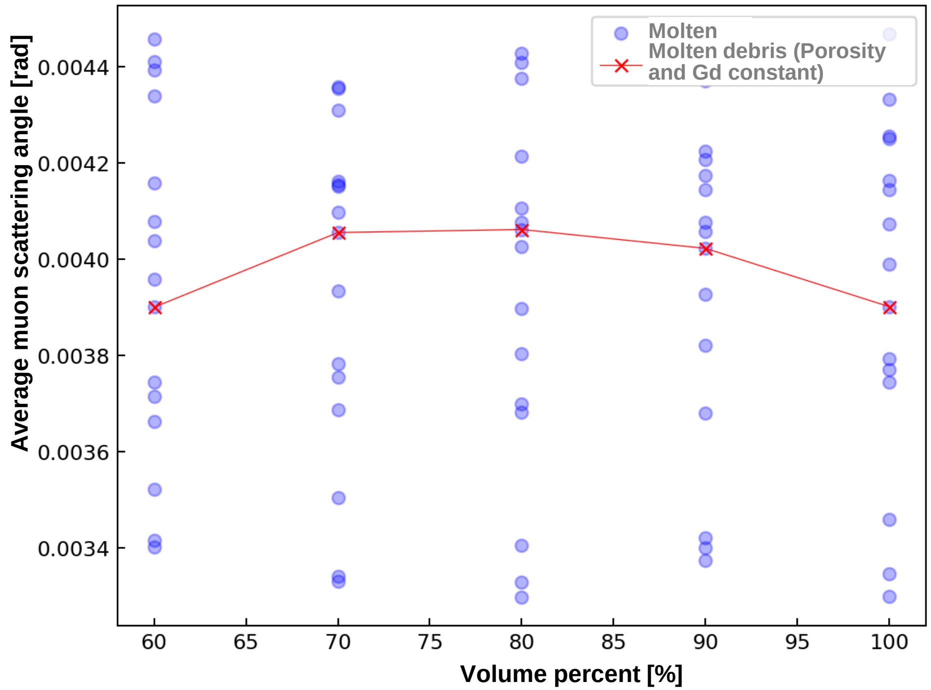
- Since the weight decreased due to increase in porosity even with the same volume, the scattering angle decreased.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

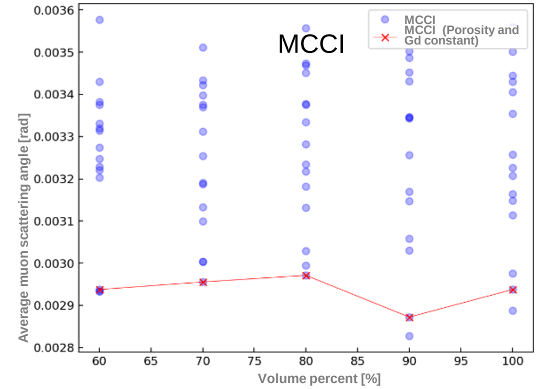
③ Muon scattering method (10/14)

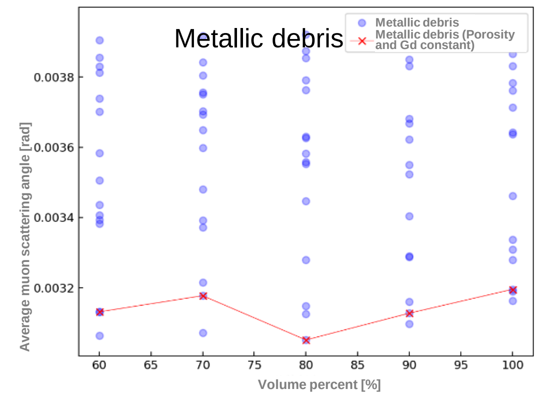
(3) Detector response analysis results

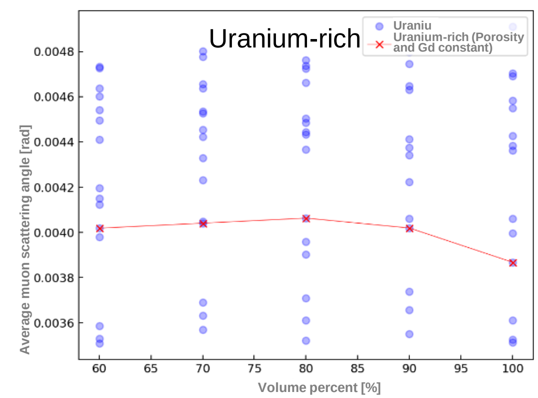
- Evaluation of the impact of volume percent
  - The extent of impact of changes in volume with the same weight was small.



Impact of change in volume (Molten debris)





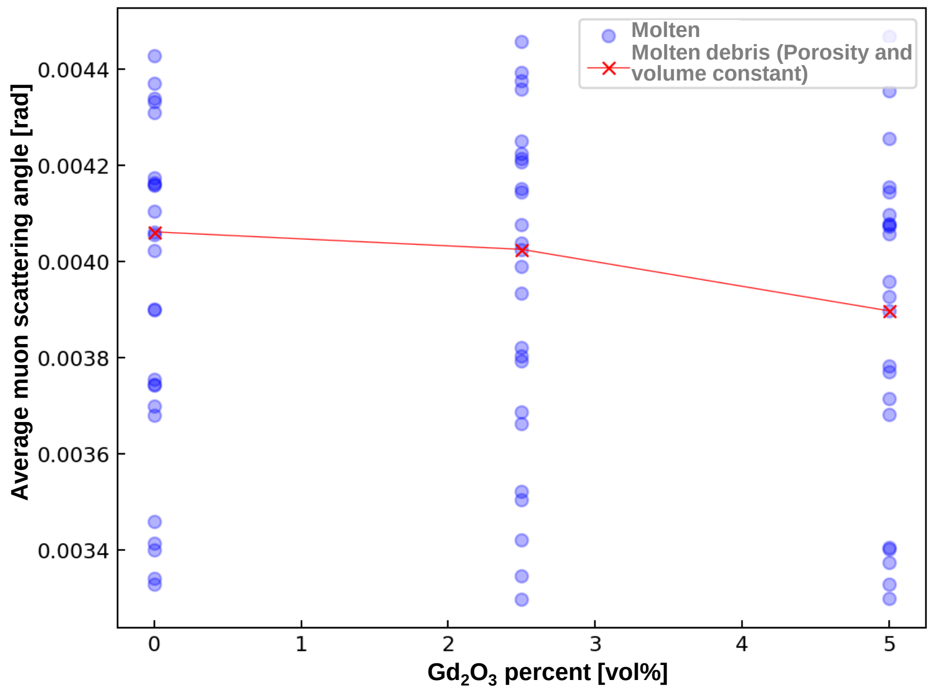


- The impact of changes in the volume with the same weight was small as compared to that of other factors, and thus no clear correlation was seen with the measured value.

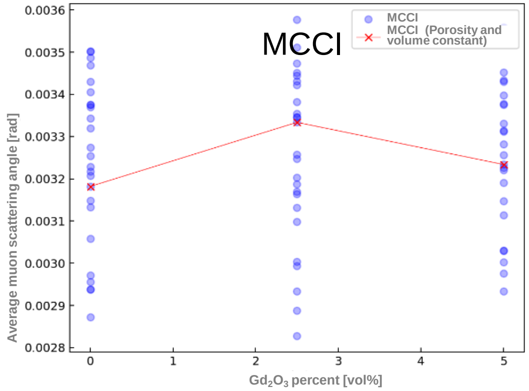
③ Muon scattering method (11/14)

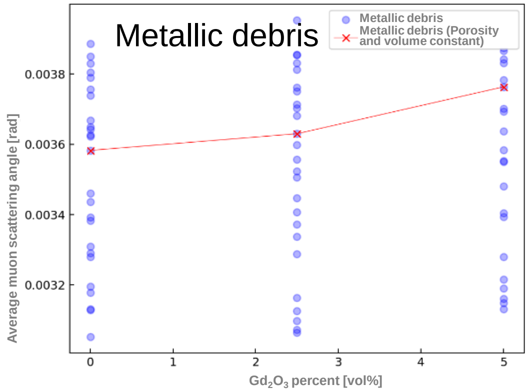
(3) Detector response analysis results

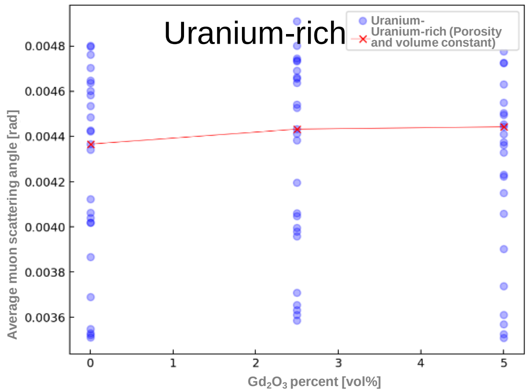
- Evaluation of the impact of neutron absorption material percentage
  - Significant trend was not observed with content of up to 5%.



Impact of neutron absorption material content (Molten debris)







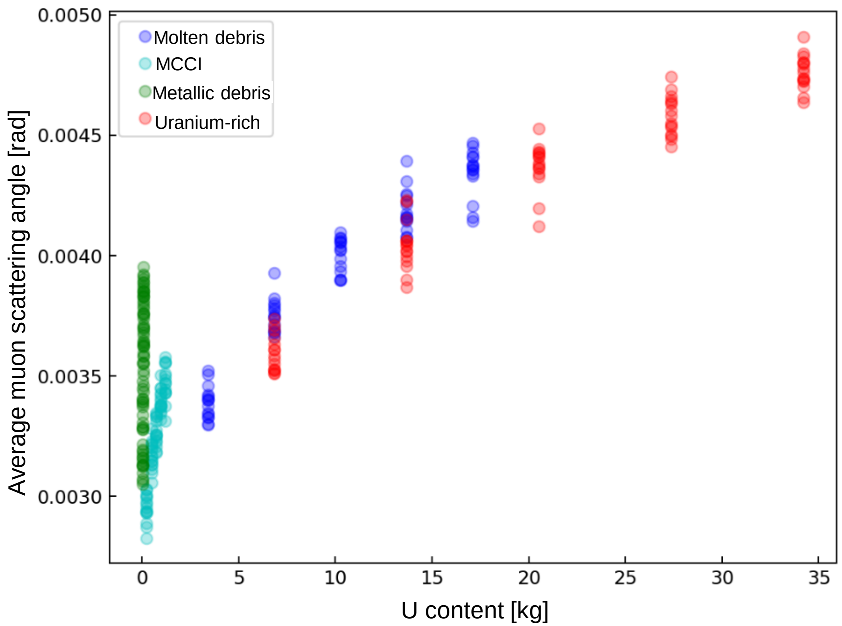
- Neutron absorption material (Gd_2O_3) was a factor that increased muon scattering, but if fuel contained only about a few % of neutron absorption material, the impact of variations caused by other factors was large and thus there appeared to be no clear correlation.

③ Muon scattering method (12/14)

(3) Detector response analysis results

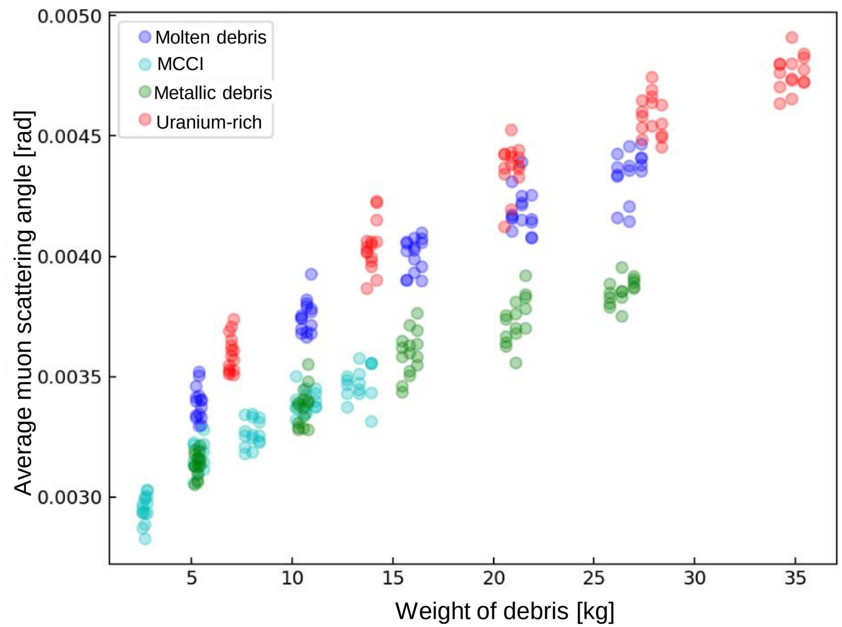
- Evaluation results
  - U content and measured value were correlated roughly with each other, but their tendency to be correlated varied depending on the type of debris.
  - Scattering per unit weight showed a tendency to reduce in the case of fuel debris with low U content.

→ Information on the type of debris is likely to be obtained by combining basic information such as weight of debris, etc.



Average muon scattering angle with respect to the U content

- A correlation was seen between U content and measured value.
- Characteristics varied by type of debris.



Average muon scattering angle with respect to the weight of debris

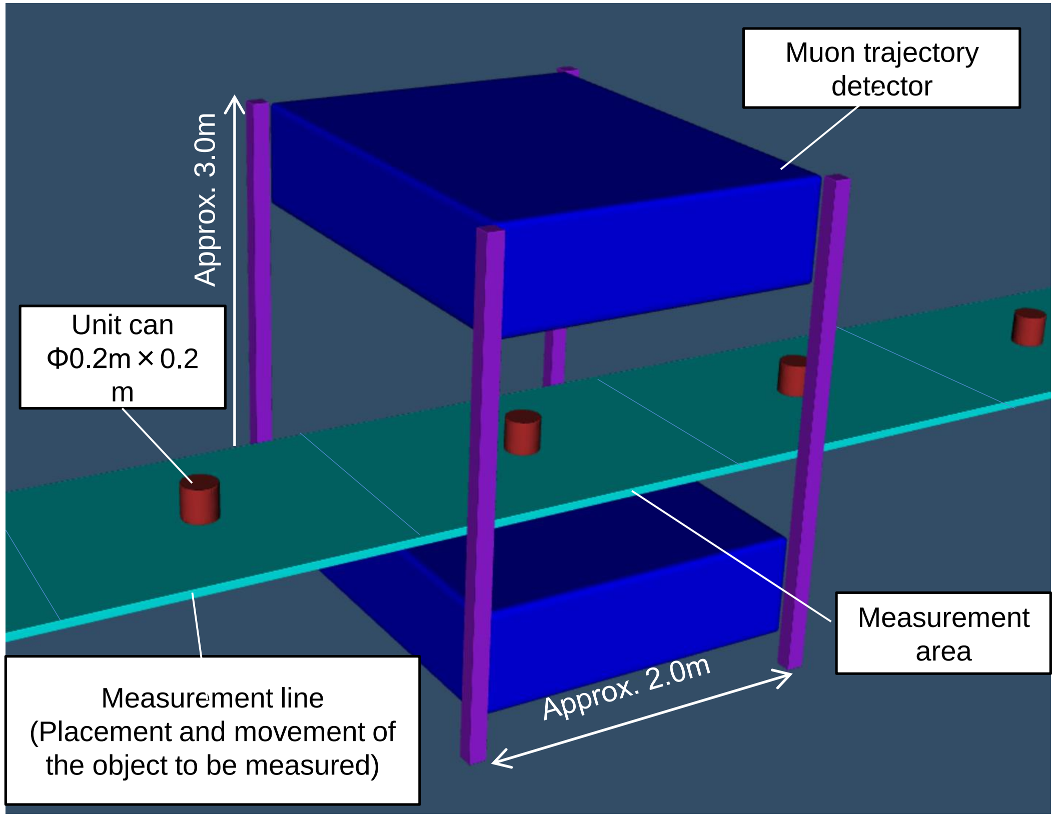
- The scattering angle per unit weight varied depending on the type of debris.
- It may be possible to anticipate the type of debris based on debris weight information.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (13/14)

(4) Development of the concept of the measuring equipment

- Expected operational environment
  - Additional building or storage pre-treatment facility
- Measurement time
  - About 1 to 2 hours/ container
- Equipment dimensions
  - Width approx. 2m × height approx. 3m
- Operating method
  - The samples (Unit can, inner waste container) are placed on the measurement line.
  - The samples that have been placed are moved to the measuring area sequentially, and are measured at the predetermined time.
  - After measurement, the next sample is measured sequentially.



The concept of the equipment for performing measurement using the muon method

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

③ Muon scattering method (14/14)

Summary and future issues

[Implementation details]

1) A simulation model concerning measurement accuracy was created in which the structure of the detector was reproduced.

2) The impact of the main factors (type of debris, porosity, volume, absorption material) identified in the past was evaluated.

- 300 cases in all with combinations of the various influencing factors were evaluated.

3) The concept of the measuring equipment used for sorting fuel debris was studied.

[Results/Contribution to development]

1) Results of simulation evaluation of the measured values by means of detector response analysis

- A mutual correlation between the muon scattering value and the weight of U present in fuel debris was verified.
- Variation in the measured value depending on the different types of fuel debris (4 types): ±20%
- Variation in the measured value depending on the variation in porosity (50 to 90%), volume (60 to 100%), absorption material (0 to 5%): ±10%

2) Results of the study on the concept of the measuring equipment

- Equipment dimensions: About W2m×D2m×H3m
- Measurement time: 1 to 2 hours

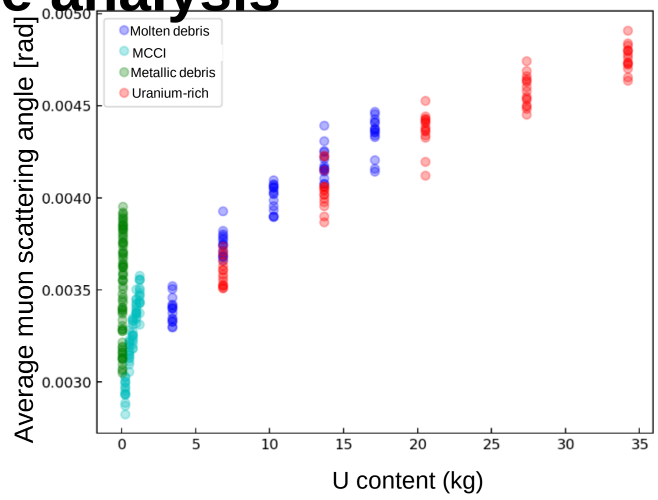
[Issues and response measures]

1) Issue: Difference in the scattering tendency depending on the type of fuel debris

Response measure: The evaluation method should be changed over to the one in which previously known information based on the major components, retrieval location, etc. of fuel debris is used.

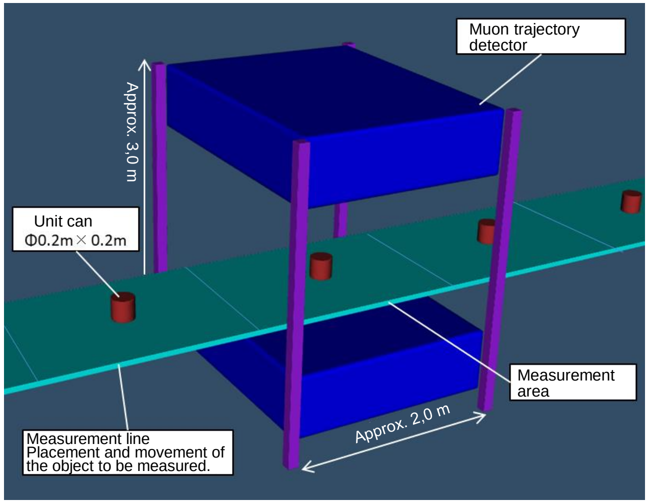
2) Issue: Optimization of the concept of the measuring equipment

Response measure: The measurement environment should be detailed and equipment specifications corresponding to the environment should be studied.



Correlation between U content and measured value (muon scattering)

- Muon scattering angle increases in response to U content
- Tendency varies depending on the fuel debris properties



Concept of the equipment for performing measurement using the muon scattering method

- The U unit can and inner container are measured using the muon detector.
- Samples can be measured without using any radiation source.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(④ X-ray CT method)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
④	X-ray CT method	X-ray detector	Accelerator based X-ray source	From the lateral side	Density	Fissile nuclide mass	Hitachi-GE	117-127 215-220

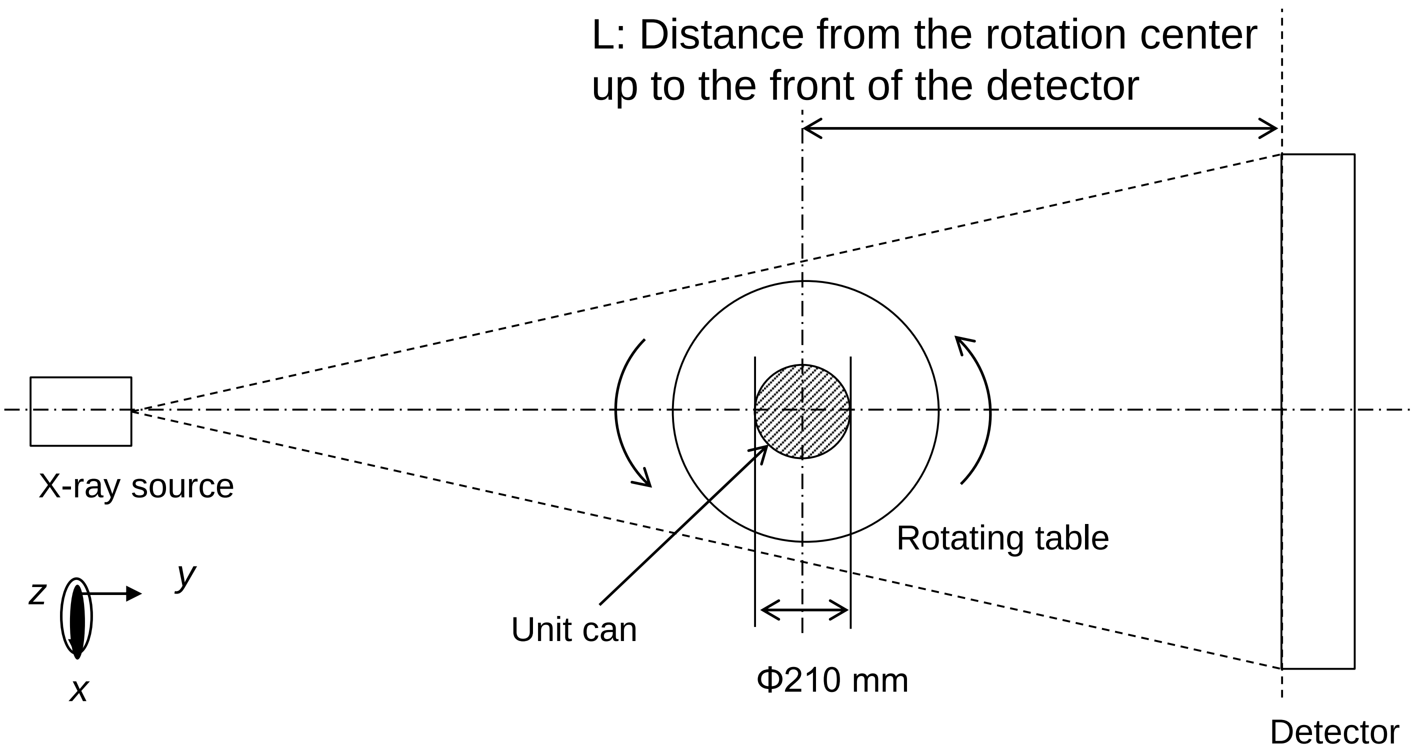
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (1/10)

<Analysis system>

Radioparency was calculated with a system equivalent to the actual system, using a CT simulator[1] in which detector parameters, etc. are incorporated.

Evaluation system used for high energy X-ray CT



*Scanning is assumed to be 1mm in the Z direction.

[1] So Kitazawa, et al., Simulations of MeV energy computed tomography, NDT & E International, Volume .38 Issue 4 (2005)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

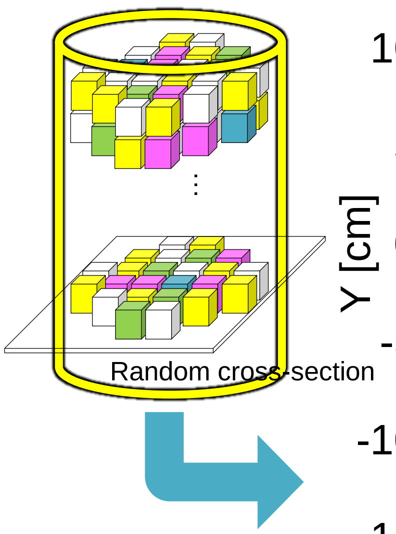
④ X-ray CT method (2/10)

<Analysis method>

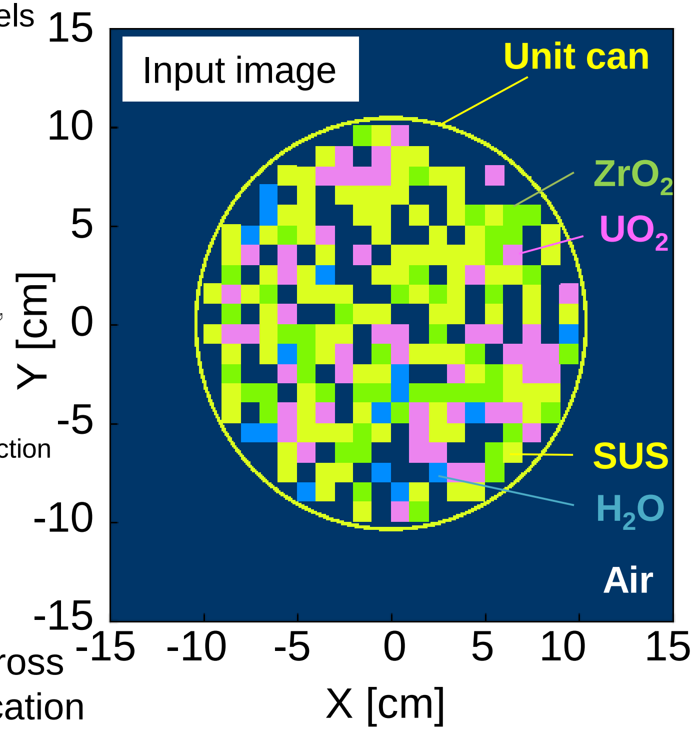
Radioparency was calculated using the heterogeneous composition distribution on arbitrary cross sections inside the container as input, and the CT image was reconstructed.

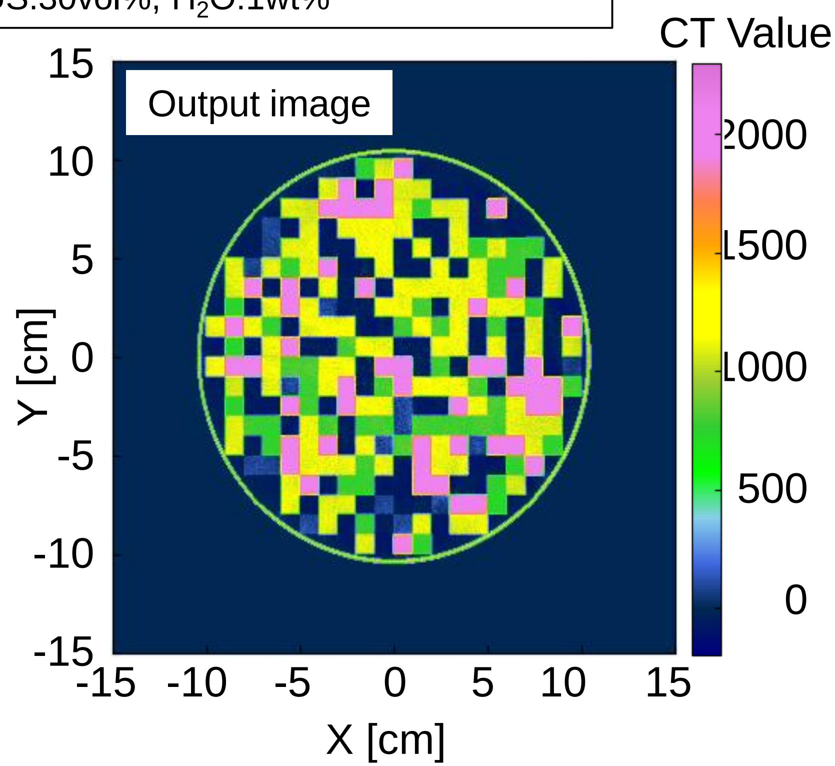
Example: FY2022 case 5-18: Metallic debris (high filling factor)
UO_2:15vol%, ZrO_2:15vol%, SUS:30vol%, H_2O:1wt%

Heterogeneous model
The inside of the container depicted in terms of voxels ($1cm^3$)



Calculated assuming a cross section of an arbitrary location





* CT value was computed considering average CT value of container (unit can) as 1000.
* CT value outside the container (unit can) was set to 0

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (3/10)

<Analysis cases>

All 14 cases related to the 3 evaluation items were analyzed.

X-ray CT analysis cases table

#	Evaluation items	Fuel debris Type	Case No.	UO_2 (UO2-01)	ZrO_2 (ZrO2-01)	SUS (SUS-01)	Concrete	Filling factor	H_2O	Gd_2O_3	B_4C	Container	Amount of U	X-ray Energy
1	**Measurement performance**	Molten debris	5-1	6.3vol%	6.3vol%	—	—	12.6vol%	1wt%	—	—	Unit can	3.7kg	6MeV
			5-2											9MeV
		MCCI debris	5-3	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	—	—	Unit can		6MeV
			5-4											9MeV
		Metallic debris	5-5	0.56vol%	0.56vol%	28.9vol%	—	30vol%	1wt%	—	—	Inner waste container		6MeV
			5-6											9MeV
2	**Material bulk density** Changing of UO_2 density	MCCI debris (Including water and absorption material)	5-7	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can		6MeV
			5-8											9MeV
3	**Quantity of nuclear fuel that is mixed** Mixing of UO_2 and other material	MCCI debris (Including water and absorption material)	5-9	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can		6MeV
			5-10											9MeV
			5-11	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can		6MeV
			5-12											9MeV
			5-13	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can		6MeV
			5-14											9MeV

Blue boxes: Analysis parameters for each evaluation item.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (4/10)

<Evaluation item 1: Measurement performance (1/2)>

The accuracy of estimating the quantity of nuclear material was evaluated with respect to cases pertaining to 3 types of fuel debris.

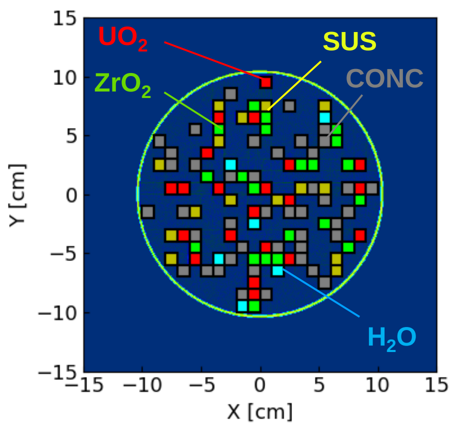
Analysis cases pertaining to the evaluation target

Evaluation items	Fuel debris Type	Case No.	UO_2 (UO2-01)	ZrO_2 (ZrO2-01)	SUS (SUS-01)	Concrete	Filling factor	H_2O	Gd_2O_3	B_4C	Container	Amount of U	Maximum X-ray energy
Measurement performance	Molten debris	5-1	6.3vol%	6.3vol%	–	–	12.6vol%	1wt%	–	–	Unit can	3.7kg	6MeV
		5-2											9MeV
	MCCI debris	5-3	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	–	–	Unit can	3.7kg	6MeV
		5-4											9MeV
	Metallic debris	5-5	0.56vol%	0.56vol%	28.9vol%	–	30vol%	1wt%	–	–	Inner waste container	3.7kg	6MeV
		5-6											9MeV

Calculation results of No. 5-3 and 5-4

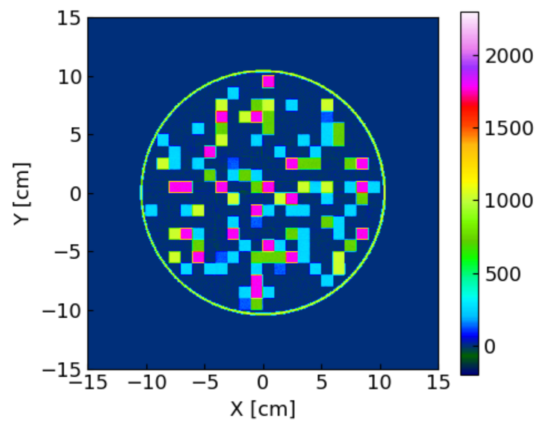
* CT value: CT value of the unit can was standardized as 1000.

Input image



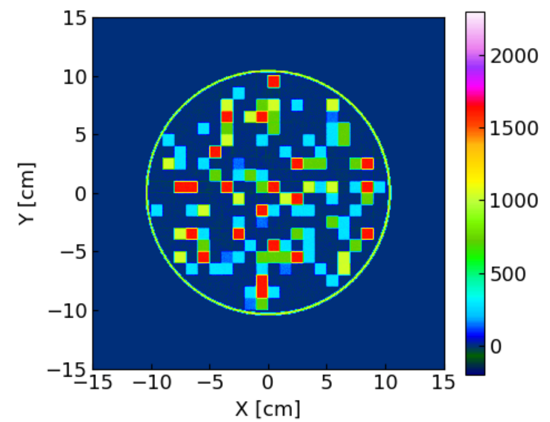
CT image (MCCI, 9MeV)

CT value*



CT image (MCCI, 6MeV)

CT Value



➢ Nuclear fuel (UO_2) and other material (SUS, CONC) can be differentiated in the image.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (5/10)

<Evaluation item 1: Measurement performance (2/2)>

The accuracy of estimating the quantity of nuclear material was evaluated with respect to cases pertaining to 3 types of fuel debris.

Procedure for evaluating measurement performance

The threshold of nuclear material was set based on the CT value of the unit can, which is a known property.

↓

Voxels for which the CT value is equal to or above the threshold of nuclear material **were identified as nuclear material voxels.**

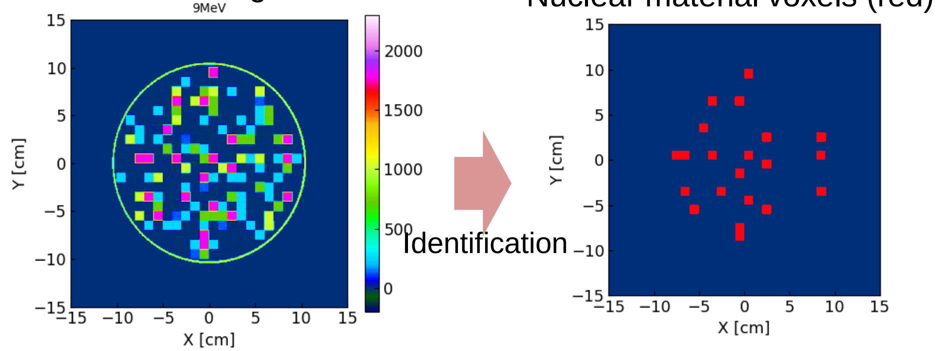
↓

Quantity of nuclear material was estimated by assigning density or uranium concentration to the nuclear material voxels.

Example：No.5-3 (MCCI，9MeV)

CT image

Nuclear material voxels (red)



Results of evaluating measurement performance

Case No.	Type of fuel debris (Container)	Maximum X-ray energy	Quantity of nuclear material (10 composition patterns were evaluated for each case) 5-1 to 5-4: 195 images were captured assuming that the composition remains constant as against the height of the unit can. 5-5 to 5-6: 298 images were captured assuming that the composition remains constant as against the height of the unit can.		
			a: Input amount of U (kg)	b: Estimated amount of U* (kg)	Estimated accuracy (b/a)
5-1	Molten debris (Unit can)	9MeV	3.638	3.619	0.995
5-2		6MeV		3.484	0.958
5-3	MCCI debris (Unit can)	9MeV		3.642	1.001
5-4		6MeV		3.494	0.960
5-5	Metallic debris (Inner waste container)	9MeV	3.684	3.548	0.963
5-6		6MeV		3.466	0.941

*Amount of U: Sum total of the mass of Uranium isotopes. Calculated assuming density 10.525g/cm³ and U-235 concentration 5% for the UO_2 volume.

- The quantity of nuclear material can be estimated for fuel debris in which nuclear material does not get mixed with other material with a maximum error of about 6%.

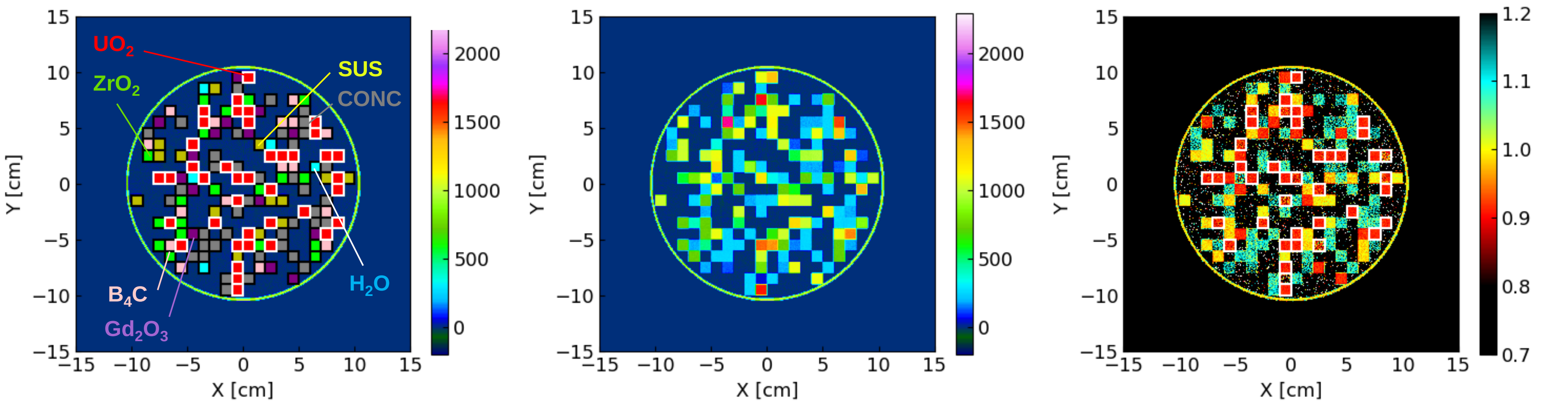
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (6/10)

<Evaluation items 2: Material bulk density (1/2)>

CT image obtained by introducing air holes of a size smaller than the spatial resolution into the nuclear material, with UO_2 bulk density varying between 1 to 99% was evaluated.

Evaluation items	Fuel debris type	Case No.	UO_2 (UO2-01)	ZrO_2 (ZrO2-01)	SUS (SUS-01)	Concrete	Filling factor	H_2O	Gd_2O_3	B_4C	Container	Amount of U	X-ray Energy
Material bulk density	MCCI debris (Including absorption material)	5-7	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol %	Unit can	3.7kg	6MeV
		5-8											9MeV



➢ It is difficult to differentiate between UO_2 with changed densities and other material based on the CT values obtained from the CT images (9MeV), however, based on the CT values obtained from the MECT images, differentiation from materials other than Gd is possible.

* CT value: CT value of the unit can was standardized as 1000, ** MECT: Multiple Energy X-ray CT

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

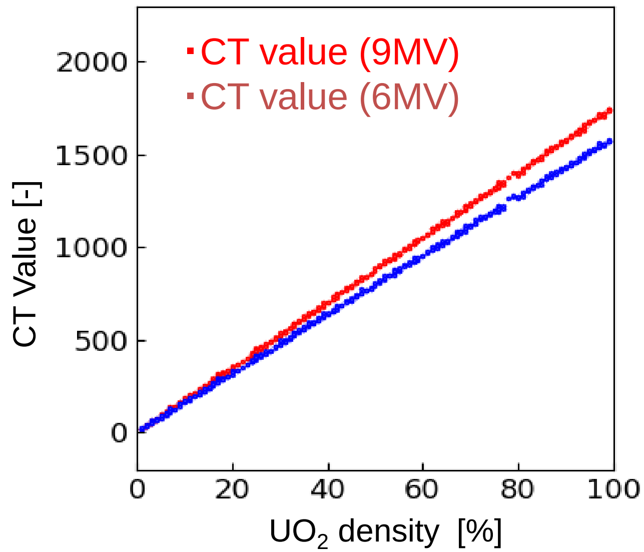
④ X-ray CT method (7/10)

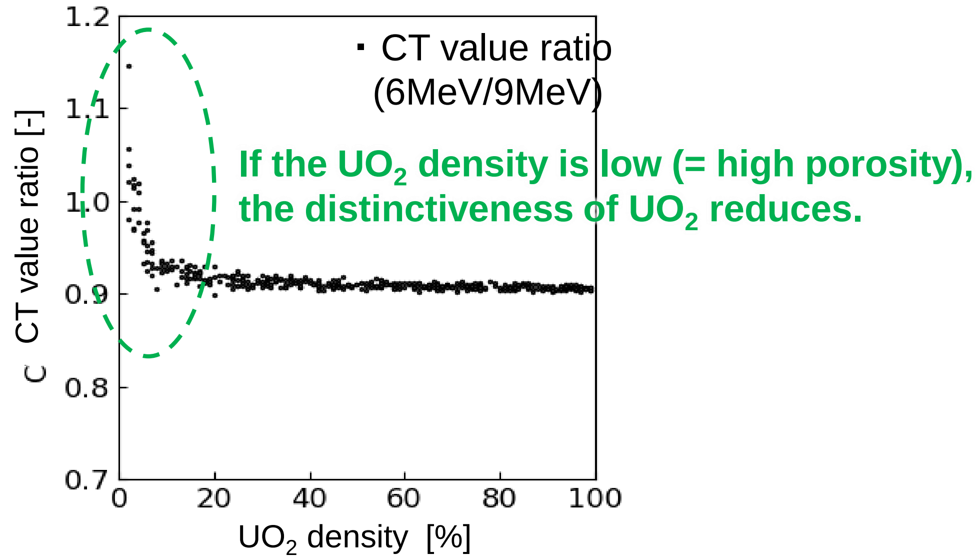
<Evaluation items 2：Material bulk density (2/2)>

CT image obtained by introducing air holes of a size smaller than the spatial resolution into the nuclear material, with UO_2 bulk density varying between 1 to 99% was evaluated.

Evaluation items	Fuel debris type	Case No.	UO_2 (UO2-01)	ZrO_2 (ZrO2-01)	SUS (SUS-01)	Concrete	Filling factor	H_2O	Gd_2O_3	B_4C	Container	Amount of U	X-ray energy
Material bulk density	MCCI debris (Including absorption material)	5-7	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol %	Unit can	3.7kg	6MeV
		5-8											9MeV

Graph related to the CT value ratio and the CT values of UO_2 corresponding to the change in density of UO_2





➢ In the case of MECT images, if the material bulk density of UO_2 is approx. 20% or lower, the distinctiveness of material reduces.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

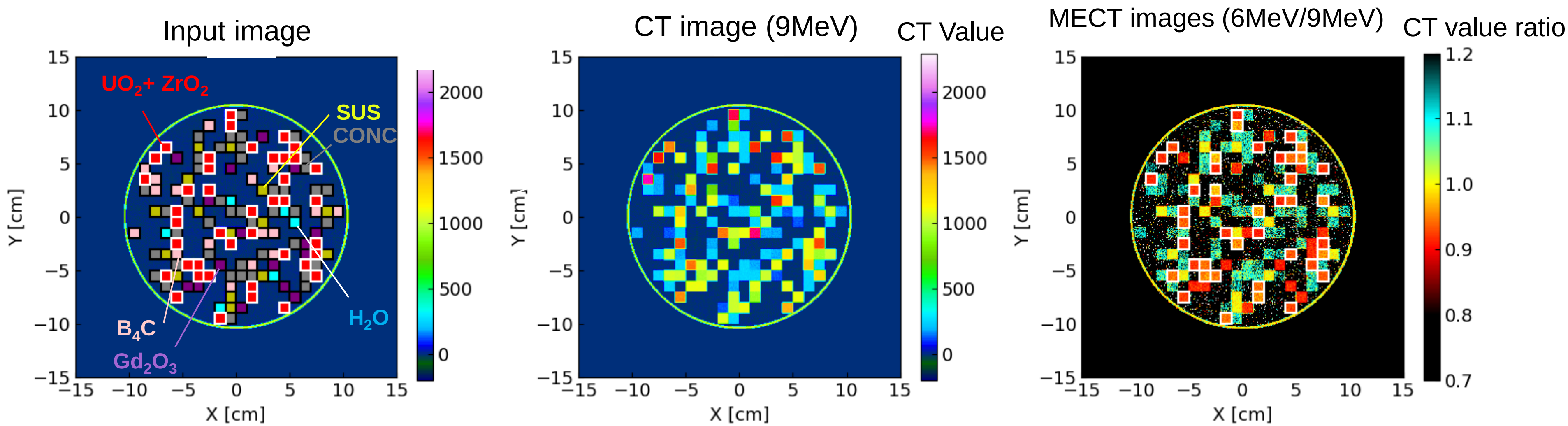
④ X-ray CT method (8/10)

<Evaluation items 3: Quantity of nuclear material that is mixed (1/ 2)>

The CT images when 1 to 99% of nuclear material (UO_2) is mixed with other material (ZrO_2, iron, concrete) were evaluated.

Evaluation items	Fuel debris Type	Case No.	UO_2 (UO2-01)	ZrO_2 (ZrO2-01)	SUS (SUS-01)	Concrete	Filling factor	H_2O	Gd_2O_3	B_4C	Container	Amount of U	Maximum X-ray energy
Quantity of nuclear material that is mixed	MCCI debris (Including absorption material)	5-9	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can	3.7kg	6MeV
		5-10											9MeV
		5-11	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can	3.7kg	6MeV
		5-12											9MeV
		5-13	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can	3.7kg	6MeV
		5-14											9MeV

No.5-9 and 5-10 (UO_2+ZrO_2)



➢ It is difficult to differentiate voxels in which all nuclear material is mixed (UO_2 +ZrO_2), based on stand-alone 9MV and MECT images.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (9/10)

<Evaluation items 3: Quantity of nuclear material that is mixed (2/ 2)>

The CT images when 1 to 99% of nuclear material (UO_2) is mixed with other material (ZrO_2, iron, concrete) were evaluated.

Evaluation items	Fuel debris type	Case No.	UO_2 (UO2-01)	ZrO_2 (ZrO2-01)	SUS (SUS-01)	Concrete	Filling factor	H_2O	Gd_2O_3	B_4C	Container	Amount of U	Maximum X-ray energy
Quantity of nuclear material that is mixed	MCCI debris (Including absorption material)	5-9	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can	3.7kg	6MeV
		5-10											9MeV
		5-11	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can	3.7kg	6MeV
		5-12											9MeV
		5-13	6.3vol%	6.3vol%	4.5vol%	12.9vol%	30vol%	1wt%	5vol%	5vol%	Unit can	3.7kg	6MeV
		5-14											9MeV

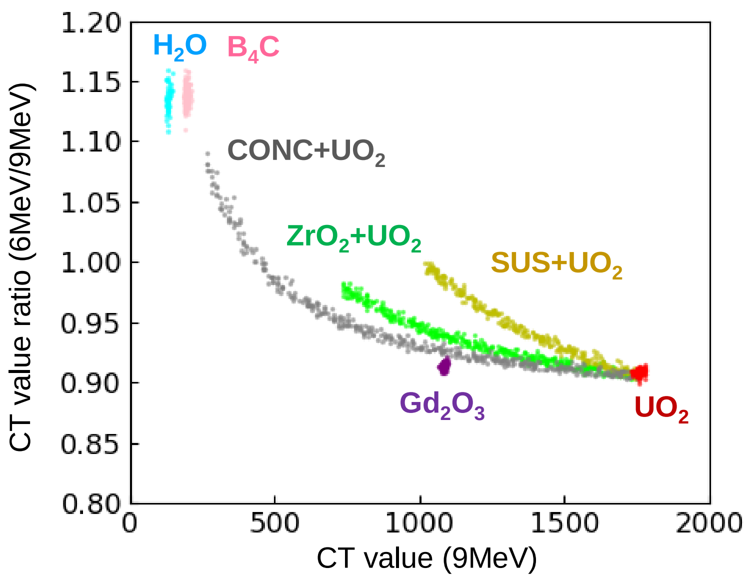


Figure on the left: Graph indicating plotting of the CT value (9MeV) and the CT value ratio (MECT)

- Based on the correlation between CT values and CT ratio, it is likely that nuclear material can be differentiated even if mixed with other material.

→ In the future, tests, etc., for verification are being planned.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

④ X-ray CT method (10/10)

<Summary and future issues>

[Implementation details]

In the X-ray CT method, radioparency was calculated using a CT simulator in which parameters equivalent to the actual equipment were incorporated, based on the specifications of existing measuring equipment, and the measurement performance, material bulk density and quantity of nuclear material that was mixed were evaluated based on the restructured CT image.

1) For measurement performance (No. 4-1 to 4-6), the accuracy of measuring the quantity of nuclear fuel material corresponding to typical fuel debris compositions such as molten debris, MCCI debris, metallic debris, etc. was evaluated.

2) For material bulk density (No. 4-7 to 4-8), the distinctiveness when the bulk density of nuclear fuel changes as a result of introduction of holes was evaluated.

3) For quantity of nuclear fuel that is mixed (No. 4-9 to 4-14), the distinctiveness when nuclear fuel is mixed with other material in varying proportions from 1 to 99% was evaluated.

[Results/Contribution to development]

1) As a result of evaluating the measurement performance, it was found that the measurement accuracy is at most 6% using conventional CT for molten debris and MCCI debris filled in unit cans and for metallic debris filled in inner waste containers when nuclear material is not mixed with other material. At this time, it was seen that the measurement accuracy tends to reduce in the case of maximum X-ray energy of 6MeV rather than 9 MeV and in the case of inner waste container rather than unit can.

2) As a result of evaluating the material bulk density, it was verified that the CT value fluctuates due to changes in bulk density, but the CT value ratio obtained by measuring MECT (Multiple Energy X-ray CT) remains constant when the nuclear fuel bulk density is approx. 20% or more, and thus it was found that there are prospects of being able to differentiate nuclear fuel.

3) As a result of evaluating the quantity of nuclear fuel mixed, it was verified that the CT value when nuclear fuel is mixed with ZrO_2, SUS, concrete and the CT value ratio are unique values depending on the material that is mixed and the quantity of nuclear fuel mixed, and thus it was found that there are prospects of being able to differentiate nuclear fuel.

4) Equipment dimensions: 4mx4m *Including footprint and maintenance area (Refer to the FY2019 Sorting PJ Report)
5) Measurement time: (*Time required for capturing images with the actual equipment)
- Unit can: 13 to 50 minutes/container (25 to 100 minutes/container in the case of MECT) *Assuming that 1 to 4 containers are measured at a time
- Inner waste container: 75 minutes/container (150 minutes/container in the case of MECT) *Assuming that 1 container is measured at a time

[Issues and response measures]

1) Issue: The results of evaluating material bulk density and quantity of nuclear fuel that is mixed are obtained through analysis, but they need to be verified through tests.
Response measure: The identifiability of material in the case of MECT should be evaluated by conducting tests.

2) Issue: In the case of unit cans, 4 containers were measured at a time and thus it was possible to evaluate in a short time, but the number of containers that can be measured at a time needs to be determined based on the measurement conditions and required accuracy.
Response measure: The correlation between measurement time and measurement accuracy need to be evaluated quantitatively.

Concrete specifications of the detector or the maximum X-ray energy will be studied through evaluations performed in 1) and 2).

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(⑤ Passive gamma rays method A)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
⑤-1	Passive gamma rays method A	Ge	None	None	Mass of fission product nuclides (Eu-154, etc.)	Fissile nuclide mass	MHI	128-140 221-233
⑤-2	Passive gamma rays method B	CZT, $LaBr_3$ etc.	None	None	Same as above	Same as above	Hitachi-GE	141-154 234-237

[Characteristics]

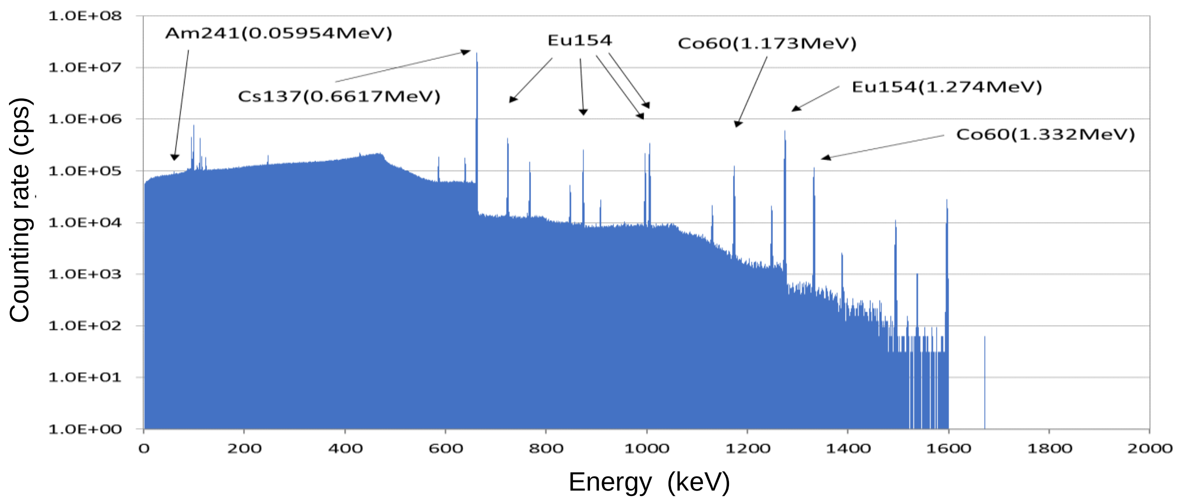
- The Ge detector was selected based on its energy resolution and track record.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

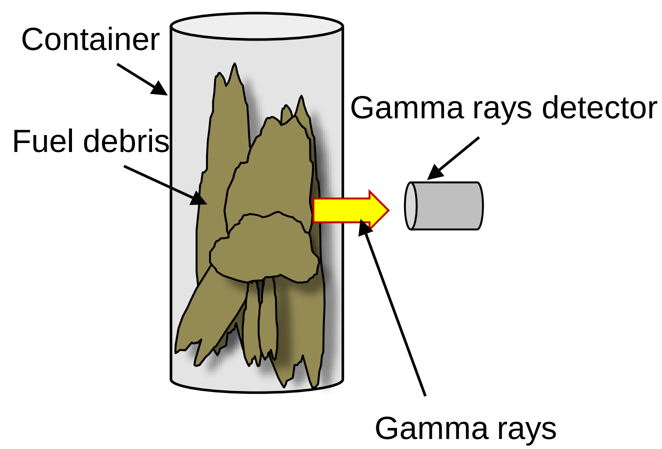
⑤-1 Items common to the passive gamma rays method

Measurement concept

- Fuel debris contains gamma rays emitting nuclides (Am-241, Cs-137, Eu-154, etc.) originating from fuel and gamma rays emitting nuclides (Co-60, etc.) originating from radioactivation of traces of impurities in metals.
- So nuclides originating from fuel need to be identified. Hence the energy spectrum of gamma rays is measured.
- Further, since the gamma flux from the nuclides originating from fuel varies depending on the burn-up, etc. or the self-shielding effect of the gamma rays differs depending on the state of enclosure, there is variation in the gamma flux reaching the measuring surface.



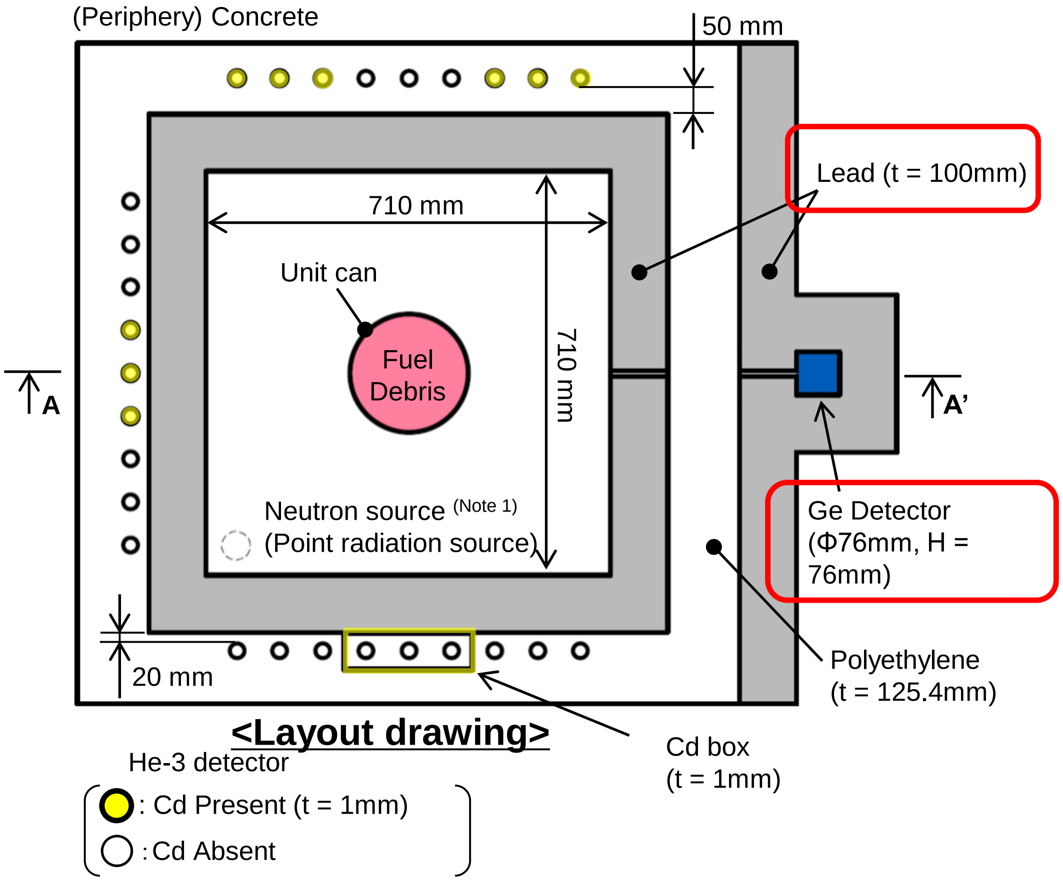
Example of analytical output (Ge detector)



4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (1/11)

<Study of the concept of the measuring equipment>･･･Concepts of the equipment that support the active n, passive n and γ measurement methods were studied **using a single unit of measuring equipment.**



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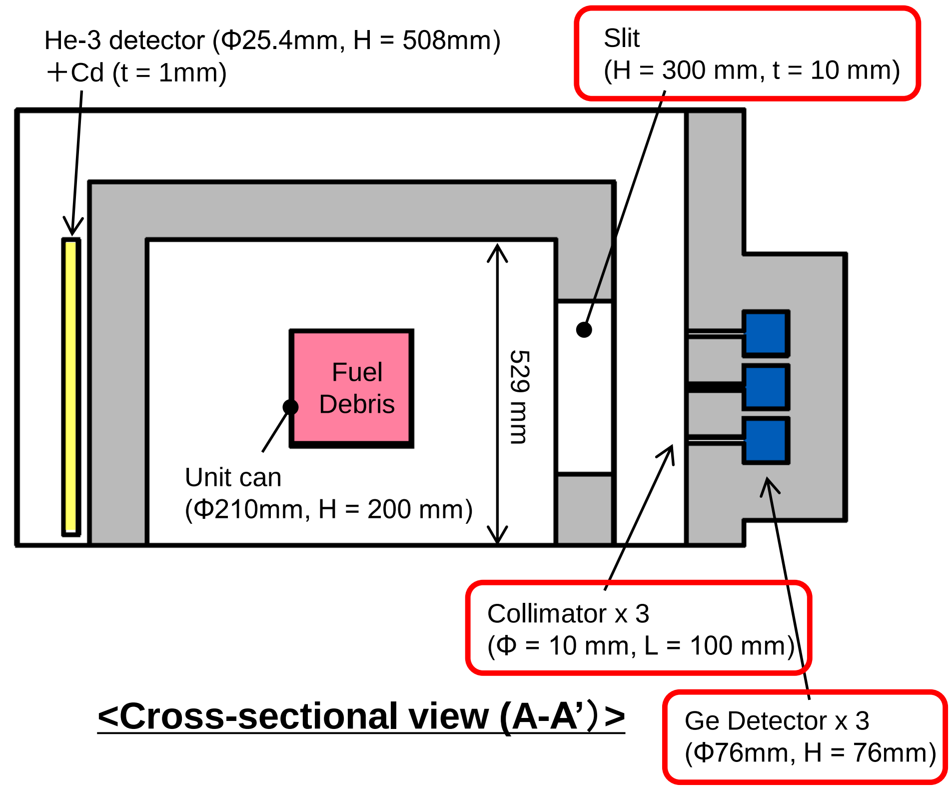


<Cross-sectional view (A-A')>

(Note 1) Neutron energy: 14.1MeV, neutron generation rate: $2x10^8$n/s,
Pulse width: 1.2μS, repetitive frequency: 100Hz, neutron generation direction: Isotropic

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (2/11)

<Study of conditions of the target object>

- Conditions of the target object: **It was assumed that "molten debris", "MCCI debris" and "Metallic debris"** (Note 1) are measured.
- The following was assumed regarding the containers to be evaluated based on the cases evaluated in FY2021.

Debris properties	Container/Shape of container	Remarks
Molten debris MCCI debris	**Unit can/**Φ210mm x H200mm	Smallest single container. Area contributing to the dose rate, represented by H200mm wherein the quantity of radiation source becomes smaller.
Metallic debris	**Waste storage container (inner container)** / □500mm×300mmH	Represented by an inner container that does not have any shielding and which is smaller than the storage container, since the thickness of the shielding of the waste storage container is yet to be determined. (From amongst the multiple options for inner (collection) containers, the typical option from the Treatment & Disposal PJ was used)

- Based on the influencing factors consolidated as results until FY2021, detector response analysis cases focusing on the parameters (**self-shielding**(Note 2) **(composition)**, **burn-up**, **presence of neutron absorption material**) identified as technical issues were set up for the study.

[Number of analyzed cases]

A: Molten debris ⇒ Total 6 cases
(Composition: 2 cases) x (Burn-up: 3 case)

B: MCCI debris ⇒ Total 6 cases
(Composition: 2 cases) x (Burn-up: 3 case)

C: Metallic debris ⇒ Total 3 cases
(Composition: 3 cases) x (Burn-up: 1 case)

Total 15 cases

⇒ Conditions of each case are listed from the next page onwards.

(Note 1) "Subsidy Project of Decommissioning and Contaminated Water Management Development of technology for fuel debris characterization and analysis FY2016 Supplementary Budget Research Report (Interim report) March FY2018

(Note 2) In the future, cases with uneven distribution also need to be studied as impact analysis of self shielding.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (3/11)

Table indicating analysis cases (Molten debris)

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
A-1	Molten Debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-2		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-3		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can
A-4		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-5		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-6		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (4/11)

Table indicating analysis cases (MCCI debris)

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
B-1	MCCI Debris	UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-2				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
B-3				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can
B-4		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	**60 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-5				H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
B-6				H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can

*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (5/11)

Table indicating analysis cases (Metallic debris)

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container*2
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
C-1	Metallic Debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 29.85 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-2		UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 44.85 vol%	**45 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-3		UO_2 : 0.48vol% ZrO_2: 0vol% SUS: 10 vol%	**10.48 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)

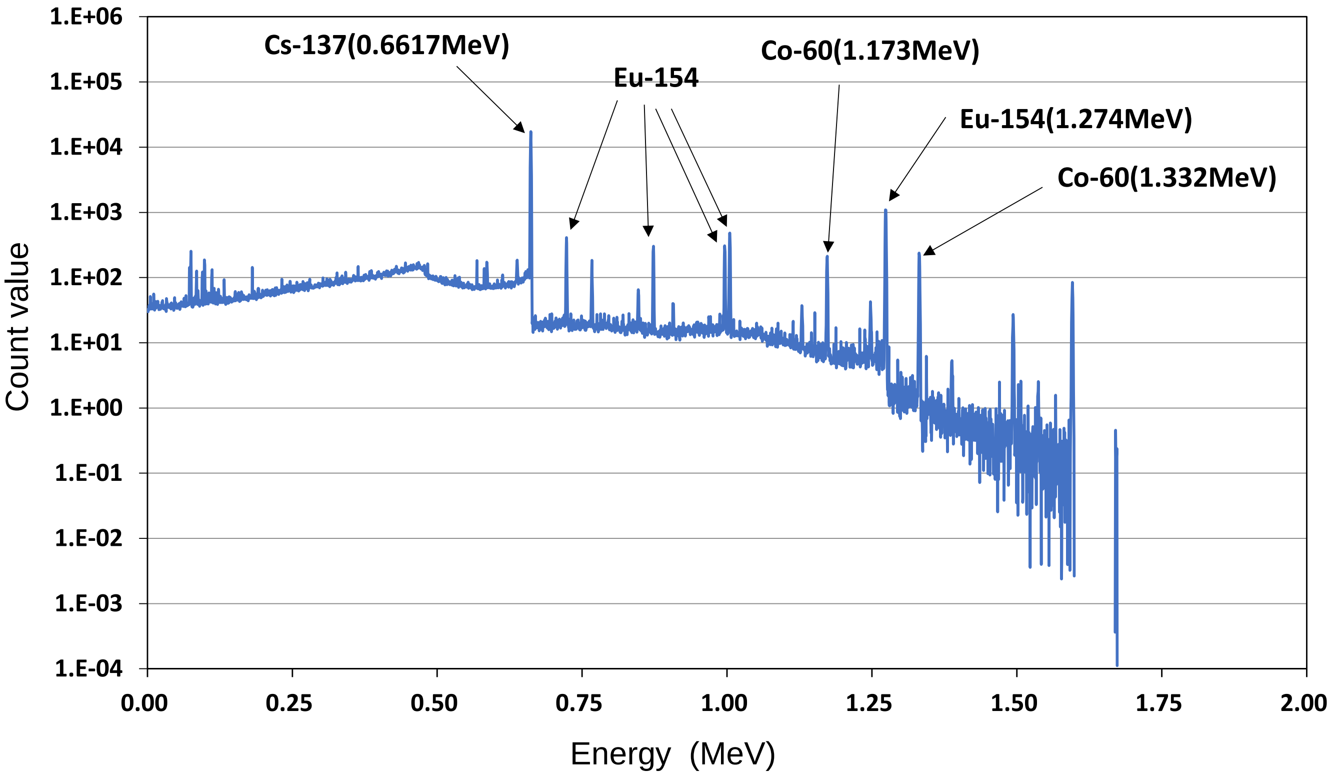
*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)
*2 Mainly made of SUS, it is assumed to be sorted as inner container during the initial stage of retrieval
*3 Overview of each case is indicated below
C-1: Base case
C-2: Case of sensitivity with respect to SUS composition
C-3: Case of sensitivity in which UO_2 has a volume percent equivalent to 3.7kg

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (6/11)

<Molten debris Detector response in the base case>

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
A-1	Molten Debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GW d/t	None	Standard	20 years	Uniform	Unit can	—

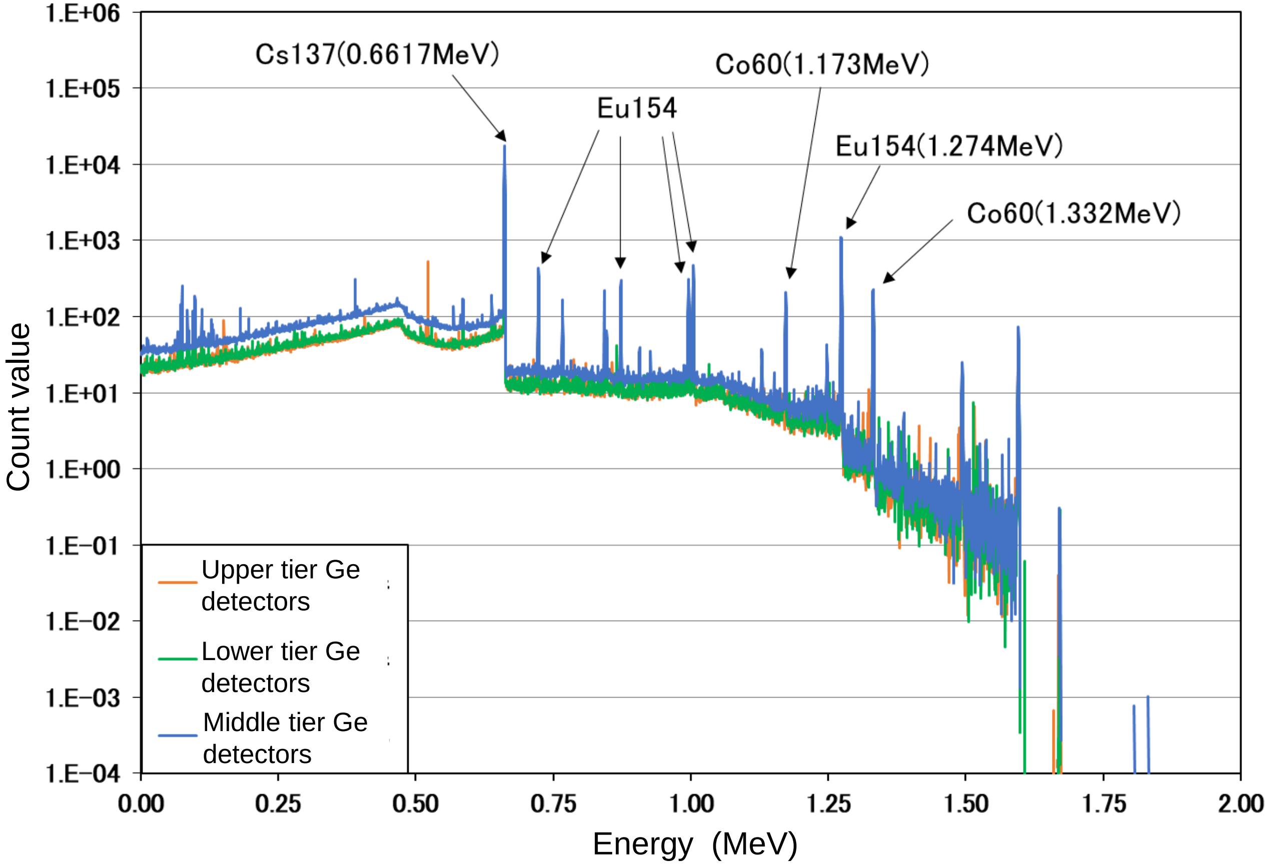


✓ The detectability of the major peaks such as Eu-154, etc. was verified through the analysis performed by creating a model of the concept of the measuring equipment.

Focusing on the 1.274MeV peak of Eu-154

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (7/11)



- Comparison of the detectability of the Ge detectors on the upper, middle and lower tiers (Molten debris base case)
  - ➢ It was verified that the Ge detectors in the middle tier had the highest count. (The upper and lower tier detectors are considered as back-up for detecting uneven distribution of the measurement targets.)

⇒ Results and considerations focusing on the Ge detectors in the middle tier that use the passive gamma rays method A are consolidated hereinafter.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

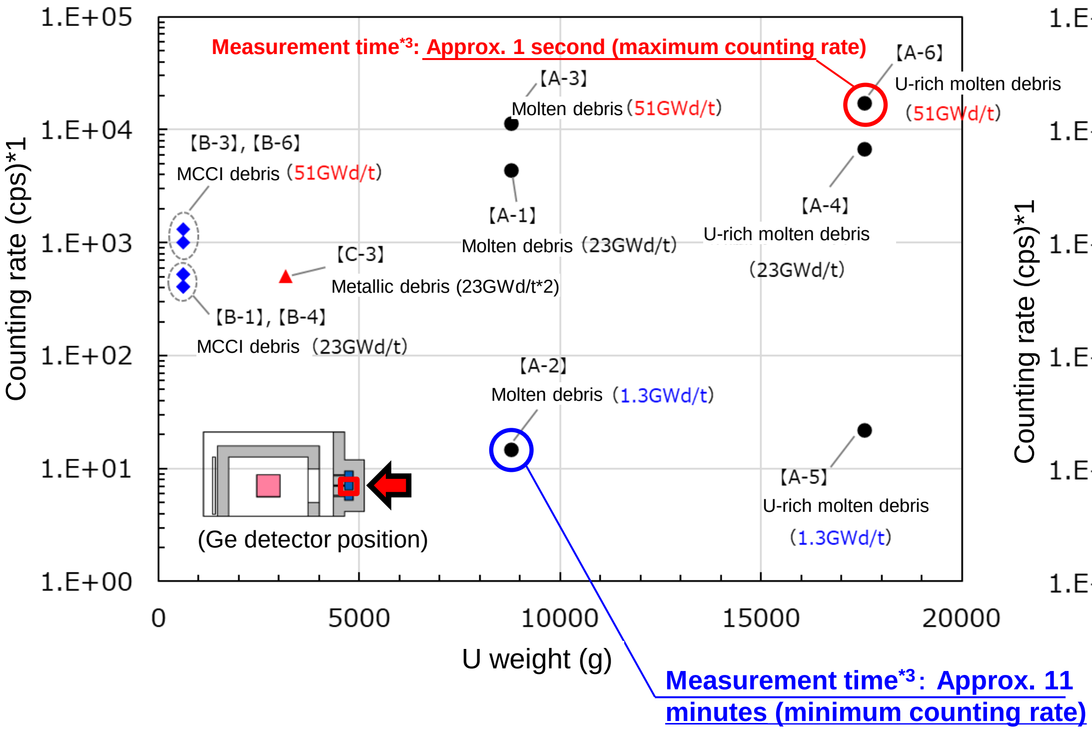
⑤-1 Passive gamma rays method A (8/11)

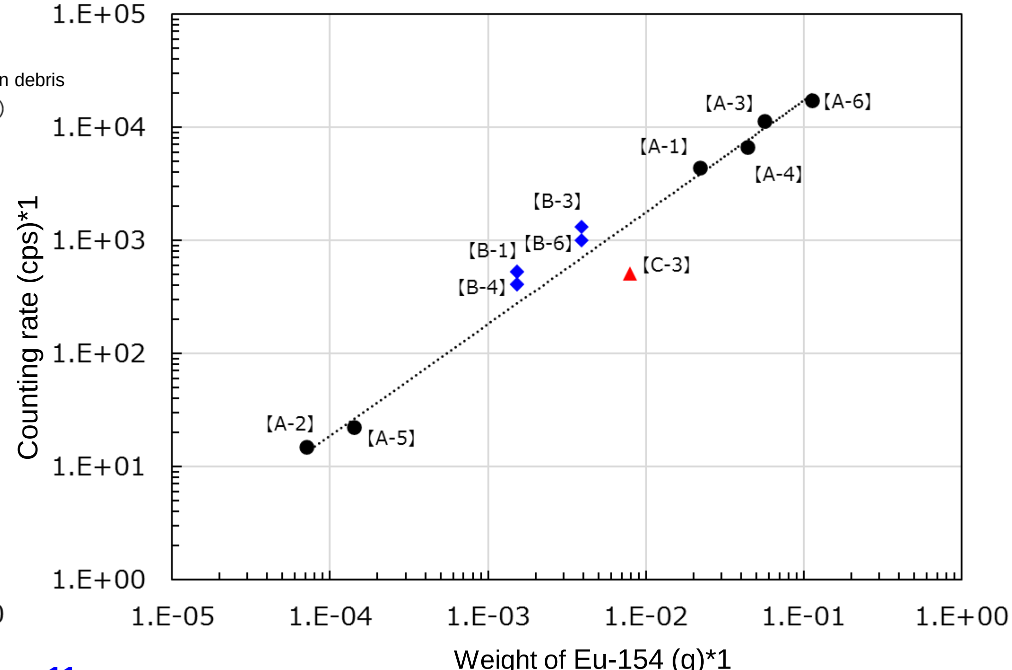
✓ Molten debris: Whether the magnitude relationship of burn-up and counting rate matches was verified.

✓ MCCI debris: It was verified that MCCI debris is not as affected by the burn-up as molten debris. However, the peak is not detected when the burn-up is low.
Since the bulk density is low, the counting rate tends to increase relatively.

✓ Metallic debris: Since the radiation source concentration is low due to the variation in the shape of the container and the filling factor, the counting rate tends to decrease relatively.
Further, the peak is not detected in cases where the amount of U is less.

✓ Common: The correlation between the weight of Eu-154 and the counting rate was verified. Also, if the carrying performance of Eu and U can be proved, it implies that there is a possibility that the burn-up impact correction method (conceptual study completed in FY2021) using the value obtained by evaluating the mass of Cm-244 by the passive neutron method and the value obtained by evaluating the mass of Eu-154 by the passive gamma rays method can be used. There is significant impact depending on the magnitude of burn-up and bulk density.



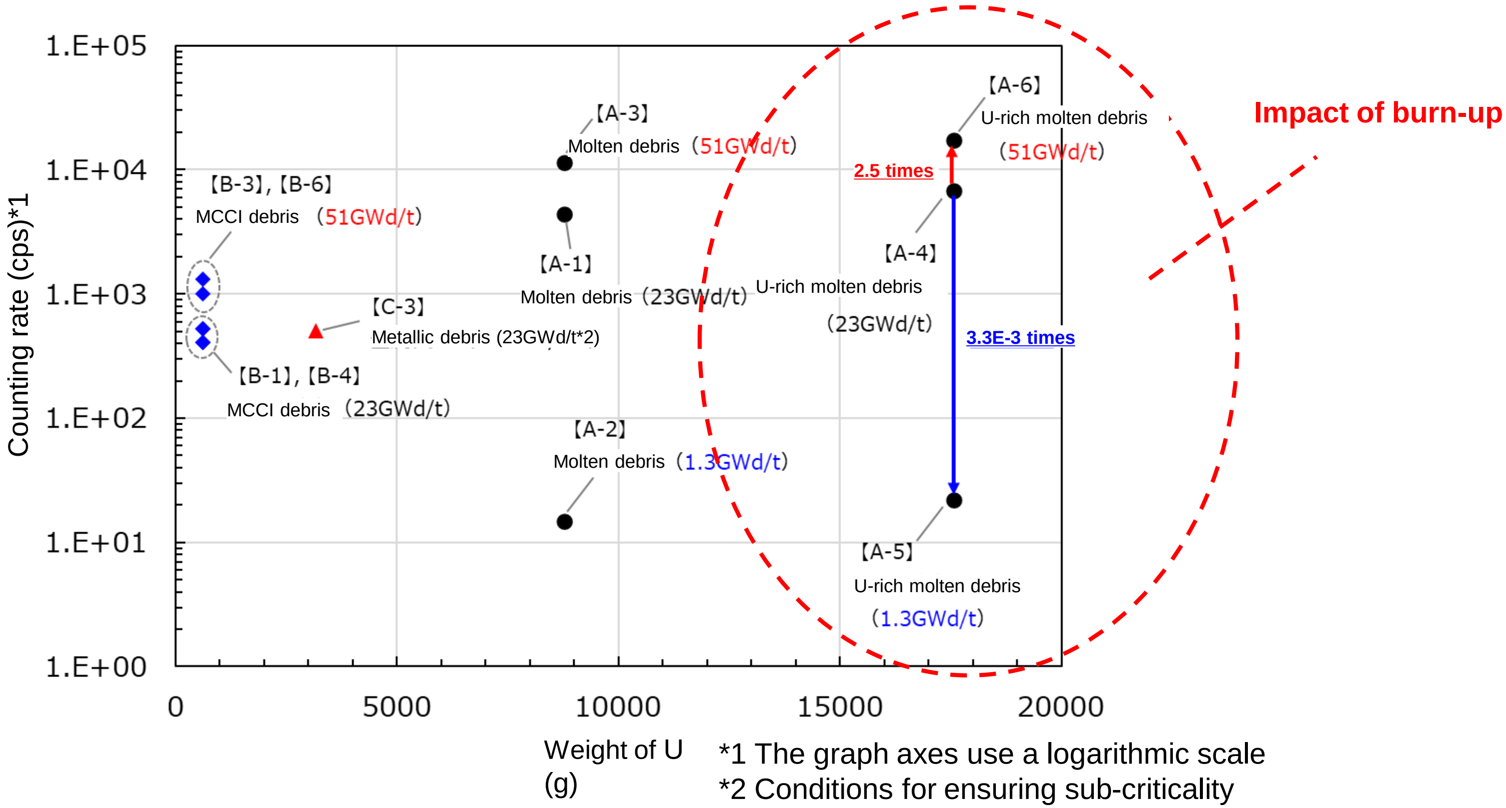


*1 The graph axes use a logarithmic scale
*2 Conditions for ensuring sub-criticality
*3 Measurement time with a 1% (10,000 count) statistical error

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (9/11)

<Analysis of the extent of impact of the influencing factors being focused on>



*1 The graph axes use a logarithmic scale
*2 Conditions for ensuring sub-criticality

⇩ Analysis of uranium rich fuel debris that has the highest impact

✓ Impact of burn-up: The count value of high burn-up (51Gwd/t) increased to approx. 2.5 times of the base case (burn-up 23GWd/t)
The count value of low burn-up (1.3GWd/t) decreased to approx. 3.3E-3 times of the base case (burn-up 23GWd/t)

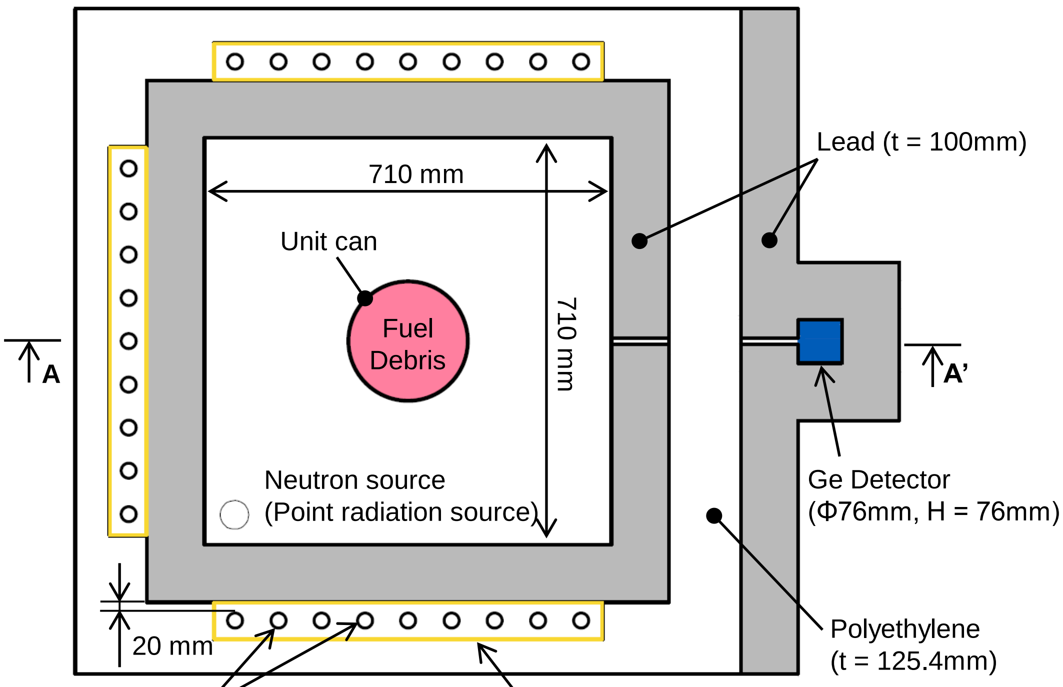
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (10/11)

<Primary proposal of the concept of the measuring equipment>

- ✓ Detectability was verified for a large number of fuel debris cases using the concept of measuring equipment used for detector response analysis.
- ✓ There were cases where the peak was not detected. Hence it is desirable to continue studying detector specifications (collimator slit, etc.).

⇒ The following measurement system was set as the primary proposal (Similar to the active neutron method A and passive neutron method A).



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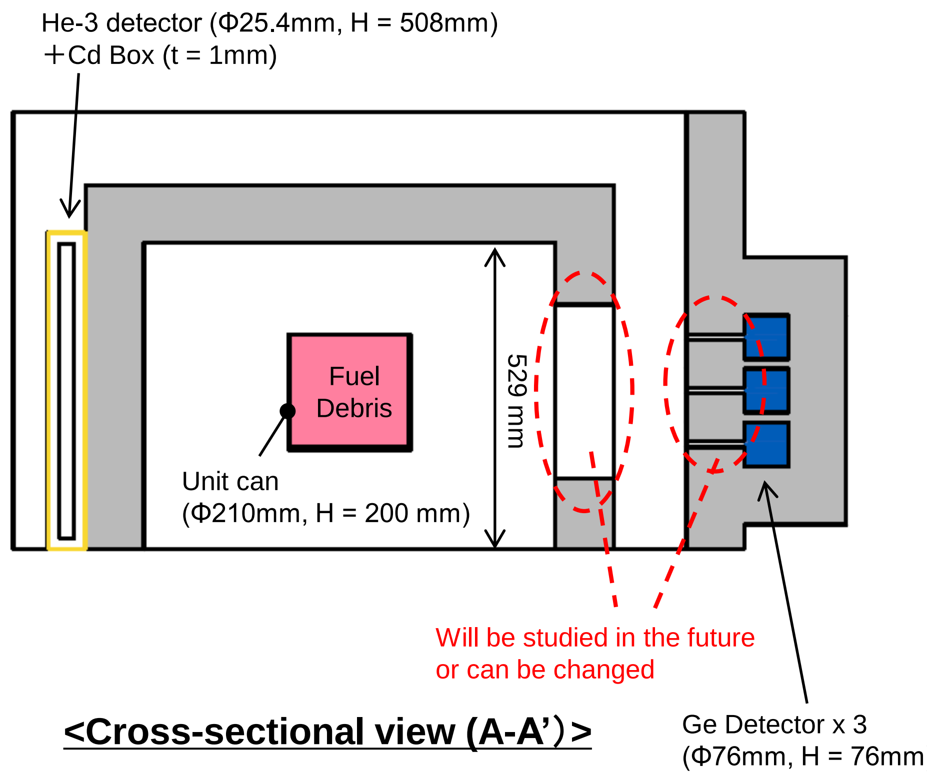


<Cross-sectional view (A-A')>

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-1 Passive gamma rays method A (11/11)

<Summary and future issues>

[Implementation details]

1) An analysis model using the passive gamma rays method was studied.
2) Detector response was analyzed **focusing on composition and burn-up**.
3) The concept of the measuring equipment used for sorting fuel debris was studied.

[Results/Contribution to development]

1) An analysis model using a combination of active neutron method, passive neutron method and passive gamma rays method was created.

2) Results of analyzing 15 cases of detector response were acquired.

・Molten debris: The magnitude relationship of burn-up and counting rate matched.

・MCCI debris: MCCI debris is not as affected by the burn-up as molten debris. However, the peak is not detected when the burn-up is low. Since the bulk density is low, the counting rate tends to increase relatively.

・Metallic debris: Since the radiation source concentration is low due to the variation in the shape of the container and the filling factor, the counting rate tends to decrease relatively. The peak is not detected in cases where the amount of U is less.

・Common: The correlation between the weight of Eu-154 and the counting rate was verified. There is significant impact depending on the magnitude of burn-up and bulk density.

3) The concept of measuring equipment using a combination of the active neutron method, passive neutron method and the passive gamma rays method was developed.

・Detector specifications: High purity Ge semiconductor detector (This time relative efficiency was considered to be 25%, but the equipment can be downsized)

・Equipment dimensions: About W5mxD4mxH3m (Compatible with unit cans and inner waste containers)

・Measurement time: Approx. 1 second (Molten debris, amount of U 17.6kg, high burn-up (51GWd/t), neutron absorption material absent)
Approx. 11 minutes (Molten debris, amount of U 8.8kg, low burn-up (1.3GWd/t), neutron absorption material absent)

[Issues and response measures]

1) Issue: Reduction of errors due to burn-up

Response measure: The correction method based on the ratio of Cm-244 and Eu-154 needs to be studied in details and the logic for explaining the carrying performance of Cm-244 and Eu-154 with U needs to be established.

2) Issue: Reduction of errors due to container specifications and bulk density

Response measure: The conversion coefficient for each container specification should be established, and the correction method based on multiple peak percentages having different energies should be studied in detail.

3) Issue: Lack of data contributing to the optimization of the equipment structure

Response measures: Parameter study on equipment structure should be enhanced by means of analysis, elemental technology verification test results should be reflected.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(⑤-2 Passive gamma rays method B)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
⑤-1	Passive gamma rays method A	Ge	None	None	Mass of fission product nuclides (Eu-154, etc.)	Fissile nuclide mass	MHI	128-140 221-233
⑤-2	Passive gamma rays method B	CZT, $LaBr_3$ etc.	None	None	Same as above	Same as above	Hitachi-GE	141-154 234-237

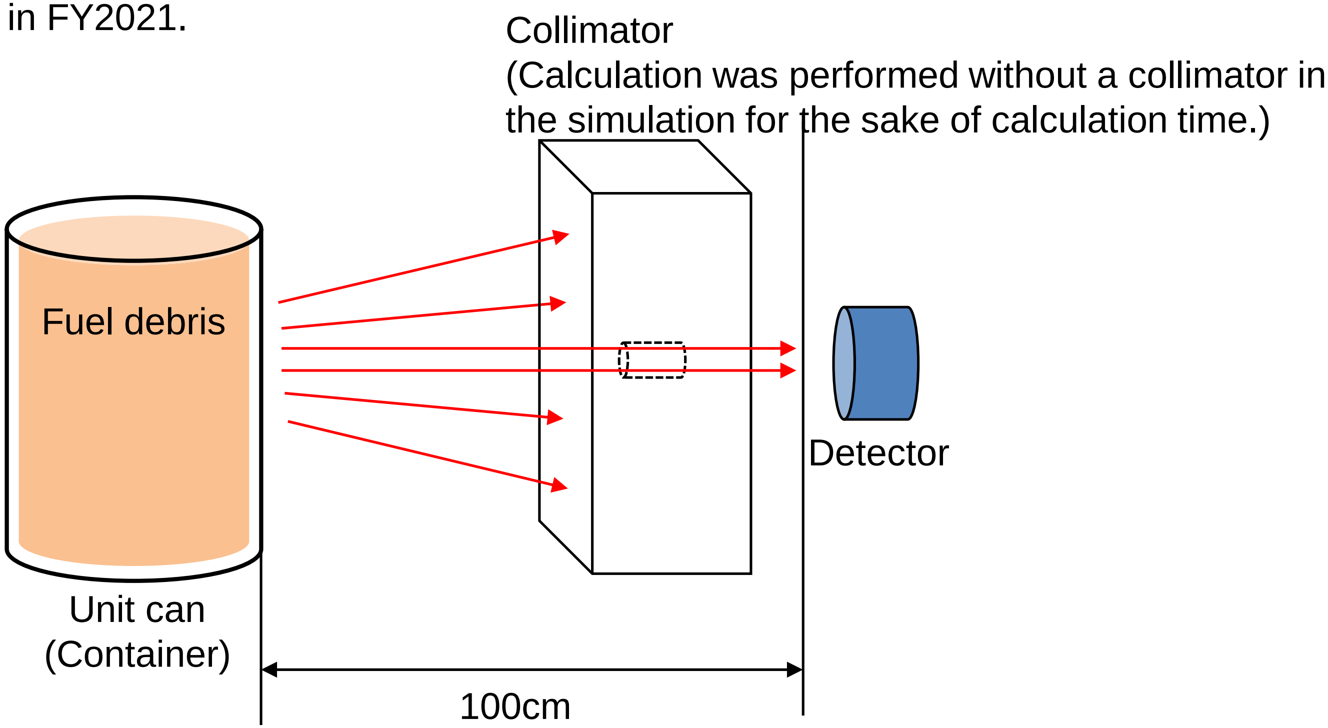
[Characteristics]

- Detectors that do not require a cooling system and can measure at a high counting rate (CZT, $LaBr_3$, etc.) were considered.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (1/13)

■Analysis system: Evaluation was performed with a system similar to the system used for detector response analysis in FY2021.



■Prospective detector

Detector	Material and shape	(Reference) Energy resolution	Remarks
CZT*1 (All cases)	Cylindrical (Diameter 7.62cm and thickness 1cm)	0.8%FWHM	H3D (University of Michigan)
$LaBr_3$*2 (Only base case)	Cylindrical (Diameter and thickness 7.62cm)	3.5%FWHM	ORTEC

*1 CZT: Cadmium zinc telluride semiconductor detector *2 $LaBr_3$: Lanthanum bromide scintillation detector

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (2/13)

➢ Detector response analysis cases

■Analysis conditions: Cases with 3.kg of U, cases with U-235 density 1.5wt%

◆Analysis cases with 3.kg of U

Analysis cases			UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Burn-up (GWd/t)	FP emission rate	Cooling period (Years)	Amount of U (kg)	Detector
Molten debris	1-1	Base (Unit can)	6.3	6.3	0	0	12.6	23.0	Standard	20	3.7	CZT $LaBr_3$
	1-2	Molten debris (Small quantity of U)	6.3	19	0	0	25.3	23.0	Standard	20	3.7	CZT
	1-3	Burn-up (low)	6.2	6.2	0	0	12.4	1.3	Standard	20	3.7	CZT
	1-4	Burn-up (high)	6.5	6.5	0	0	13.0	51.0	Standard	20	3.7	CZT
Metallic debris	1-5	Base (Inner waste container)	0.56	0.56	28.9	0	30	23.0	Standard	20	3.7	CZT $LaBr_3$
MCCI debris	1-6	Base (Unit can)	6.3	6.3	4.5	12.9	30	23.0	Standard	20	3.7	CZT $LaBr_3$
	1-7	Filling factor (high)	6.3	6.3	9.6	27.7	50	23.0	Standard	20	3.7	CZT

Analysis cases with U-235 density 1.5wt%

Analysis cases			UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Burn-up (GWd/t)	FP emission rate	Cooling period (Years)	Amount of U (kg) [U-235wt%]	Detector
Molten debris	1-8	Burn-up (low)	6.2	14.0	0	0	20.2	1.3	Standard	20	3.7 [1.5]	CZT
	1-9	Molten debris (Uranium-rich)	6.3	1.4	0	0	7.75	23.0	Standard	20	3.7 [1.5]	CZT

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (3/13)

➢ Detector response analysis cases

◆ **Additional analysis cases for evaluating the margin of error in amount of U**

Analysis cases				UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Burn-up (GWd/t)	FP emission rate	Cooling period (Years)	Amount of U (kg)	Detector
Molten debris	1-10	Medium burn-up	Filling factor (low)	3	3	0	0	6	23.0	Standard	20	1.76	CZT
	1-11		Filling factor (medium)	10	10	0	0	20	23.0	Standard	20	5.86	CZT
	1-12		Filling factor (high)	15	15	0	0	30	23.0	Standard	20	8.79	CZT
	1-13	Low burn-up	Filling factor (low)	3	3	0	0	6	1.3	Standard	20	1.80	CZT
	1-14		Filling factor (medium)	10	10	0	0	20	1.3	Standard	20	5.99	CZT
	1-15		Filling factor (high)	15	15	0	0	30	1.3	Standard	20	8.98	CZT
	1-16	High burn-up	Filling factor (low)	3	3	0	0	6	51.0	Standard	20	1.72	CZT
	1-17		Filling factor (medium)	10	10	0	0	20	51.0	Standard	20	5.72	CZT
	1-18		Filling factor (high)	15	15	0	0	30	51.0	Standard	20	8.58	CZT

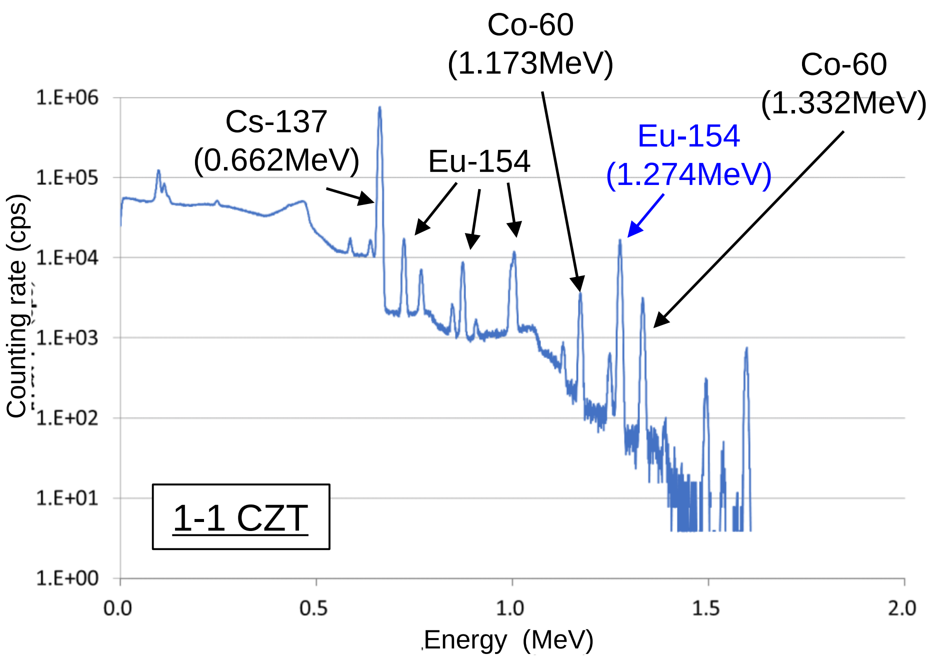
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

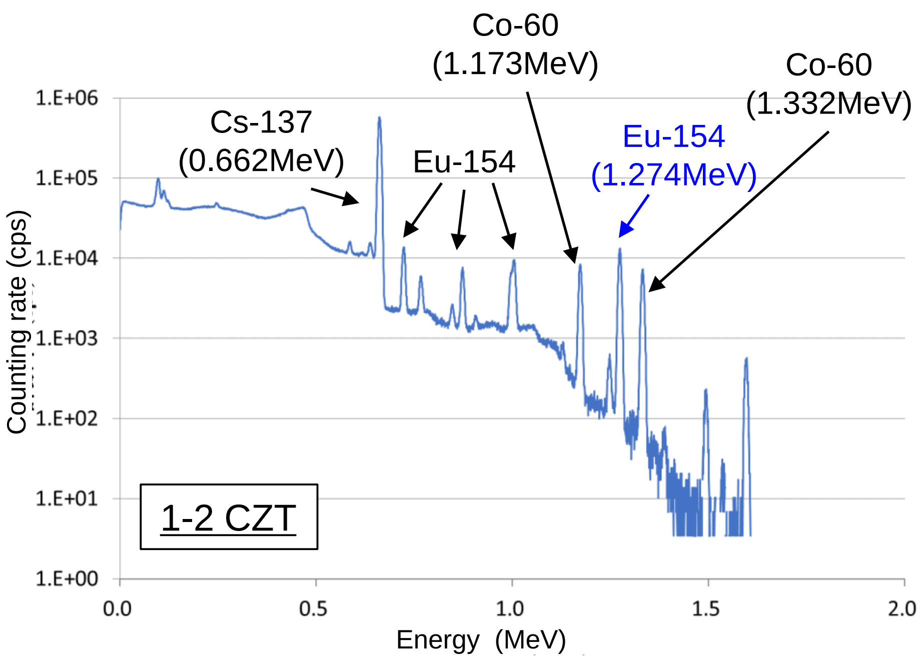
⑤-2 Passive gamma rays method B (4/13)

- All CZT analysis cases were analyzed and the 1.274MeV peak of Eu-154 was verified.
- Data was organized based on this peak counting rate.

✓ Example of detector response analysis result

Analysis cases			UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete (vol%)	Filling factor (vol%)	Burn-up (GWd/t)	FP emission rate	Cooling period (Years)	Amount of U (kg)	Detector
Molten debris	1-1	Base (Unit can)	6.3	6.3	0	0	12.6	23.0	Standard	20	3.7	CZT
	1-2	Molten debris (Small quantity of U)	6.3	19	0	0	25.3	23.0	Standard	20	3.7	CZT

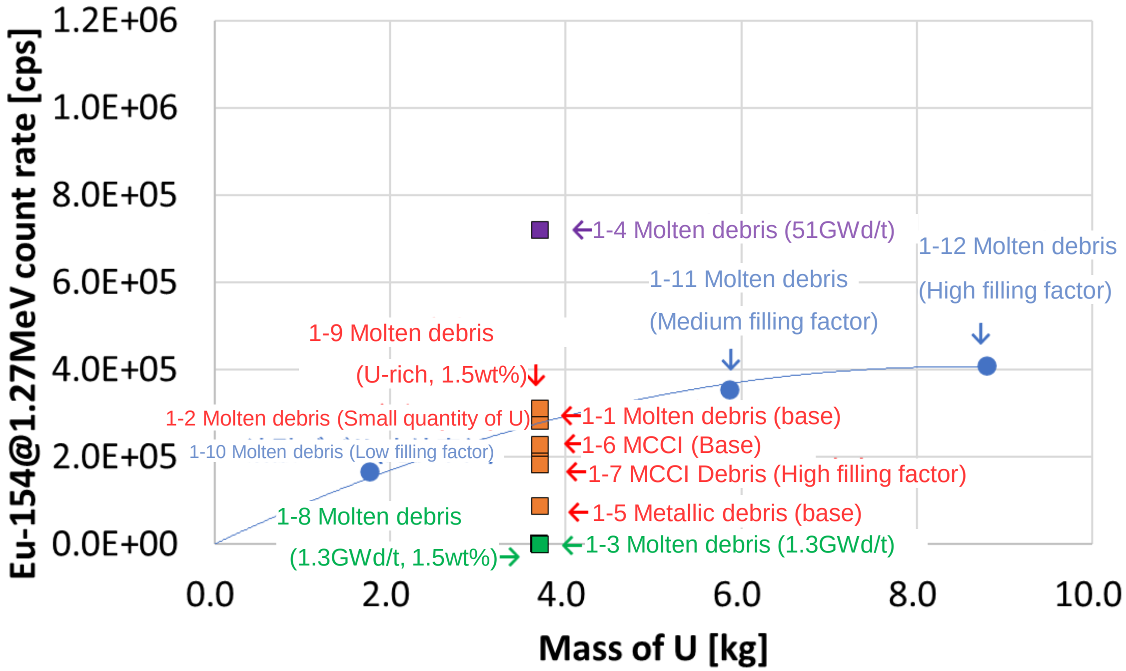




4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (5/13)

- ✓ The gamma rays peak counting rate for Eu-154 (1.274MeV) obtained as a result of CZT detector response analysis was plotted on a graph.
- ✓ In the cases analyzed this time, the counting rates varied from several times to several orders of magnitude even if the amount of U was the same (3.7kg).
- ✓ Hence there were errors in the amount of U evaluated based on the counting rates.
- ✓ An approximate curve (Blue 1-10 to 1-12) was created based on the detector response analysis performed by changing the filling factor (6, 20, 30vol%) of the molten debris (23GWd/t) and by changing the amount of U, and a comparative evaluation was performed.

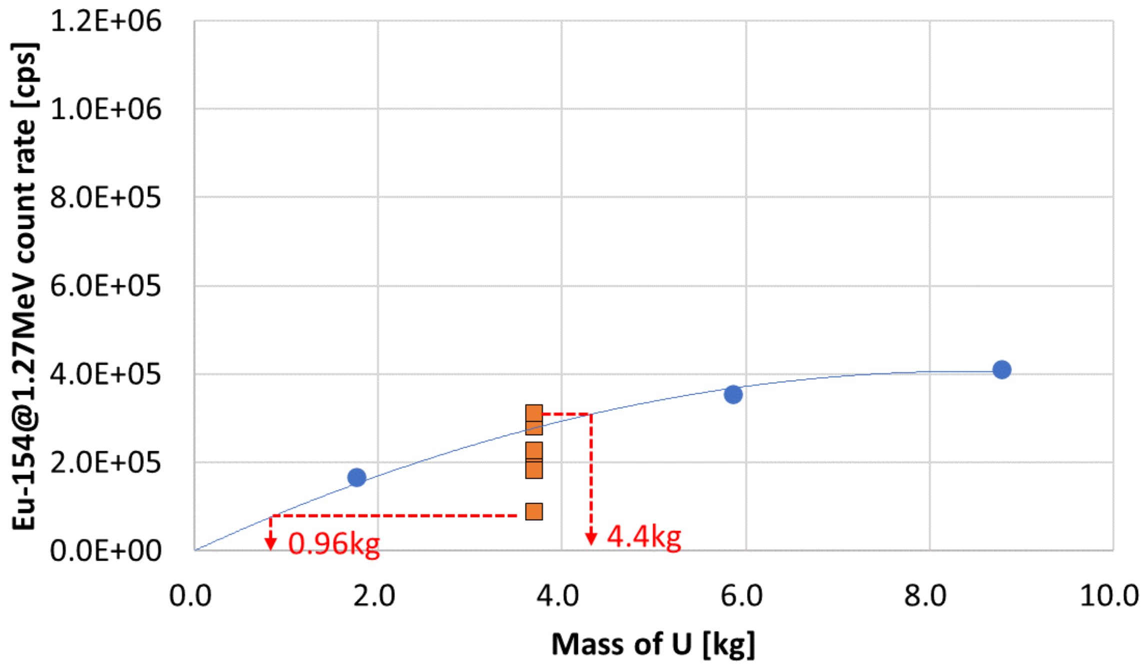


Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the amount of U (All CZT analysis cases)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (6/13)

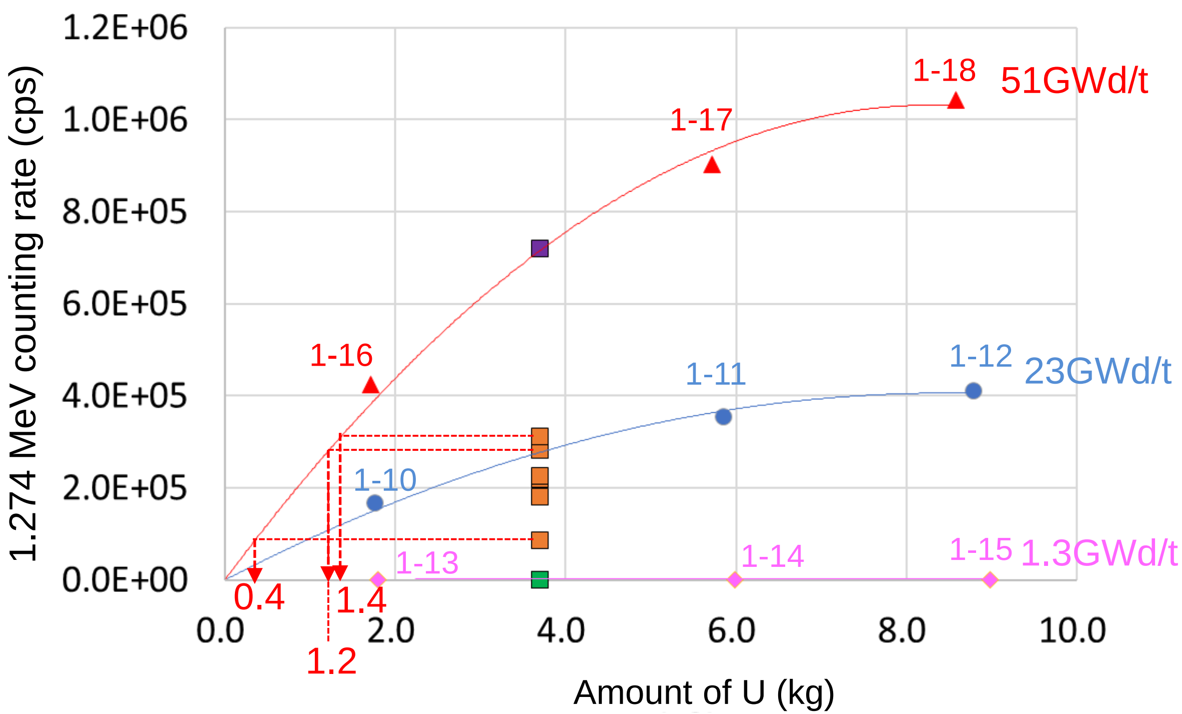
- ✓ The cases which resulted in a standard burn-up of 23Gwd/t were identified from amongst the CZT analysis cases.
- ✓ Even when the burn-up and amount of U were kept the same, there were errors in the evaluated amount of U due to the composition or the bulk density.
- ✓ As a result of performing evaluation based on the counting rate, it was found that there was margin of error of 0.96 to 4.4kg.



Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the amount of U (Analysis cases with a burn-up of 23GWd/t)

⑤-2 Passive gamma rays method B (7/13)

- ✓ When cases with a burn-up of 23Gwd/t were analyzed under conditions for burn-up 51Gwd/t, the amount of U was underestimated to be 0.4 to 1.4 kg. Taking this into consideration while conducting evaluations is a challenge.
- ✓ Similarly, when analysis was performed under conditions for 1.3Gwd/t, the amount of U was unable to be evaluated.

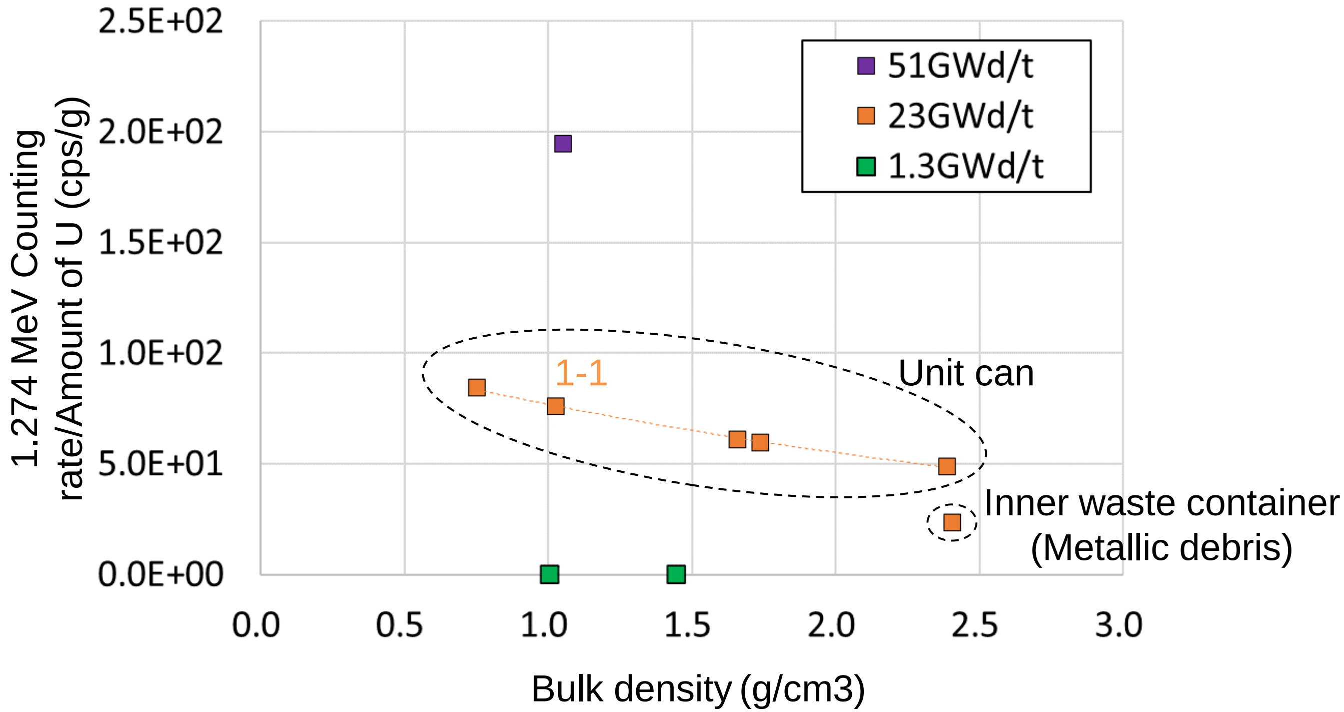


Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the amount of U (All CZT analysis cases)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (8/13)

- ✓ It is believed that if the results are organized by bulk density, the variation in composition, etc. can be corrected as long as the burn-up remains constant, and the margin of error in the amount of U can possibly be reduced.
- ✓ Further, in order to reduce the margin of error, the burn-up needs to be corrected by some way such as by using other measurement data, etc.



Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the bulk density (All CZT analysis cases)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (9/13)

➢ Study using collimator and estimation of measurement time (1)

Analysis cases			Amount of U (kg)	U-235 concentration (wt%)	Total counting rate ① (cps)	Eu-154 1.274MeV Counting rate ② (cps)	②/① (%)
Molten debris	1-1	Base (Unit can)	3.7	1.1	6.61×10^{7}	2.81×10^{5}	0.426
	1-2	Molten debris (Small quantity of U)	3.7	0.6	5.87×10^{7}	2.20×10^{5}	0.375
	1-3	Burn-up (low)	3.7	2.1	3.68×10^{6}	9.22×10^{2}	0.025
	1-4	Burn-up (high)	3.7	0.3	1.47×10^{8}	7.21×10^{5}	0.489
Metallic debris	1-5	Base (Inner waste container)	3.7	0.04	6.16×10^{8}	8.73×10^{4}	0.014
MCCI debris	1-6	Base (Unit can)	3.7	0.7	7.31×10^{7}	2.26×10^{5}	0.310
	1-7	Filling factor (high)	3.7	0.5	7.98×10^{7}	1.81×10^{5}	0.227
Molten debris	1-8	Burn-up (low)	3.7	1.5	3.92×10^{6}	8.05×10^{2}	0.021
	1-9	Molten debris (Uranium-rich)	3.7	1.5	6.95×10^{7}	3.12×10^{5}	0.449

⇒ Collimator thickness and size were studied for the 1-5 (Metallic debris) case in which the total counting rate was maximum.

- Collimator material: Lead
- Collimator thickness: Makes the rays incident on the detector considering the gamma rays attenuation coefficient for each energy spectrum container
  The thickness was set so that the total counting rate is reduced to approx. 1% (4.5kcps) of the maximum CZT counting rate (450kcps) ⇒ 15cm
- Size of collimator aperture: The counting rate of the rays passing through the collimator aperture was 99% of the maximum CZT counting rate ⇒ Φ0.2cm
- The measurement time for each case was estimated on the above assumption.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (10/13)

➢ Study using collimator and estimation of measurement time (3)

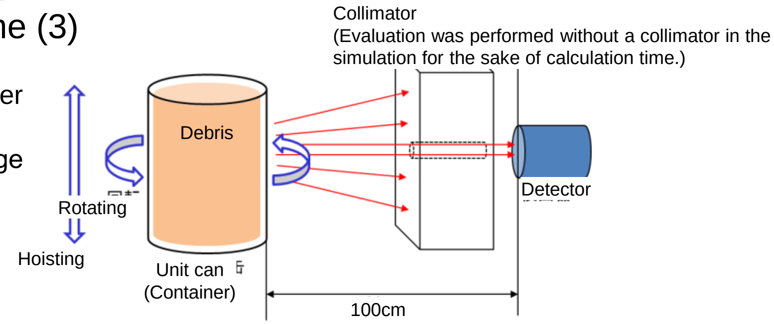
■ Assumptions while estimating the measurement time

・It was assumed that the required measurement is performed while the container makes 1 rotation.

・It was assumed that approx. Φ2.5cm of the container surface is within the range of view of the collimator.

・The number of measurements in the vertical direction of the unit can was assumed to be 21cm/2.5cm≒9 times

・The number of measurements in the vertical direction of the inner waste container was assumed to be 30cm/2.5cm≒12 times



Analysis cases			Amount of U (kg)	U-235 concentration (wt%)	Total counting rate ① (cps)	Eu-154 1.274MeV Counting rate ② (cps)	②/① (%)	Estimation and measurement time (seconds/container)		
								Statistical error 1% (10^{4} counts)	Statistical error 5% (400 Counts)	Statistical error 10% (100 Counts)
Molten debris	1-1	Base (Unit can)	3.7	1.1	6.61×10^{7}	2.81×10^{5}	0.426	4.68×10^{2}	1.87×10^{1}	4.68×10^{0}
Molten debris	1-2	Molten debris (Small quantity of U)	3.7	0.6	5.87×10^{7}	2.20×10^{5}	0.375	6.00×10^{2}	2.40×10^{1}	6.00×10^{0}
Molten debris	1-3	Burn-up (low)	3.7	2.1	3.68×10^{6}	9.22×10^{2}	0.025	1.43×10^{5} (Approx. 40 hours)	5.72×10^{3} (Approx. 1.6 hours)	1.43×10^{3} (Approx. 0.4 hours)
Molten debris	1-4	Burn-up (high)	3.7	0.3	1.47×10^{8}	7.21×10^{5}	0.489	1.83×10^{2}	7.32×10^{0}	1.83×10^{0}
Metallic debris	1-5	Base (Inner waste container)	3.7	0.04	6.16×10^{8}	8.73×10^{4}	0.014	2.02×10^{3}	8.06×10^{1}	2.02×10^{1}
MCCI debris	1-6	Base (Unit can)	3.7	0.7	7.31×10^{7}	2.26×10^{5}	0.310	5.83×10^{2}	2.33×10^{1}	5.83×10^{0}
MCCI debris	1-7	Filling factor (high)	3.7	0.5	7.98×10^{7}	1.81×10^{5}	0.227	7.28×10^{2}	2.91×10^{1}	7.28×10^{0}
Molten debris	1-8	Burn-up (low)	3.7	1.5	3.92×10^{6}	8.05×10^{2}	0.021	1.64×10^{5} (Approx. 46 hours)	6.56×10^{3} (Approx. 1.8 hours)	1.64×10^{3} (Approx. 0.5 hours)
Molten debris	1-9	Molten debris (Uranium-rich)	3.7	1.5	6.95×10^{7}	3.12×10^{5}	0.449	4.23×10^{2}	1.69×10^{1}	4.23×10^{0}

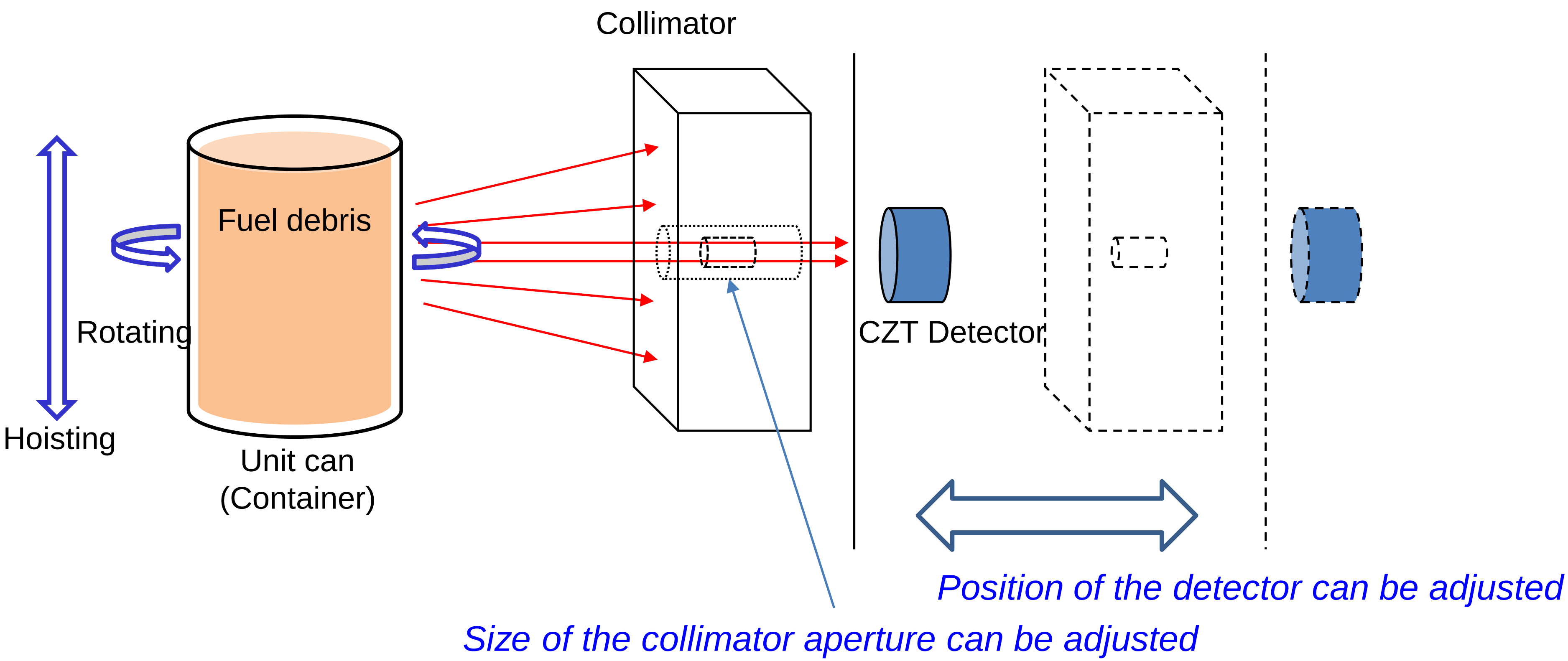
Since the measurement times differ in the order of magnitude depending on whether the counting rate is high or low, being able to adjust the size of the collimator or the distance between the container and the detector, etc. needs to be considered.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (11/13)

➢ Concept of the measuring equipment

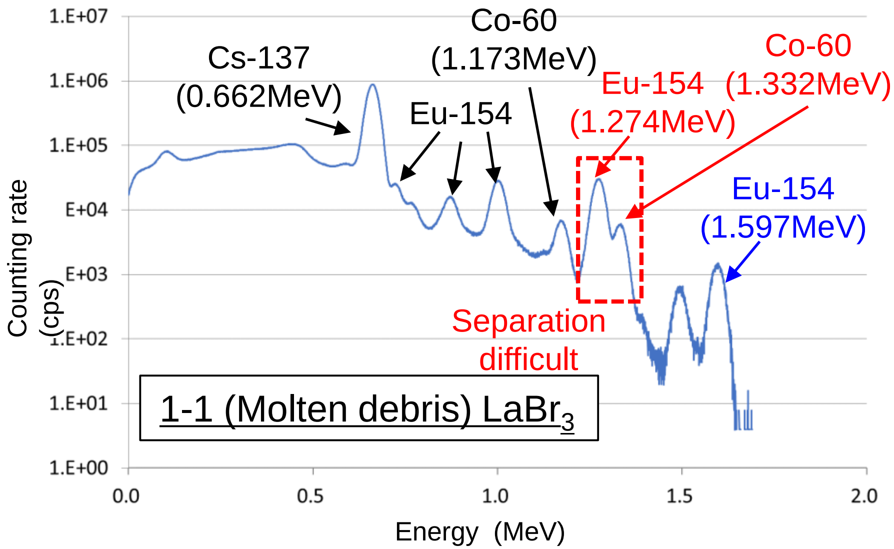
✓ The proposal of a concept of measuring equipment was studied, which is structured so that the size of the collimator or the position of the detector can be adjusted according to the target of measurement.

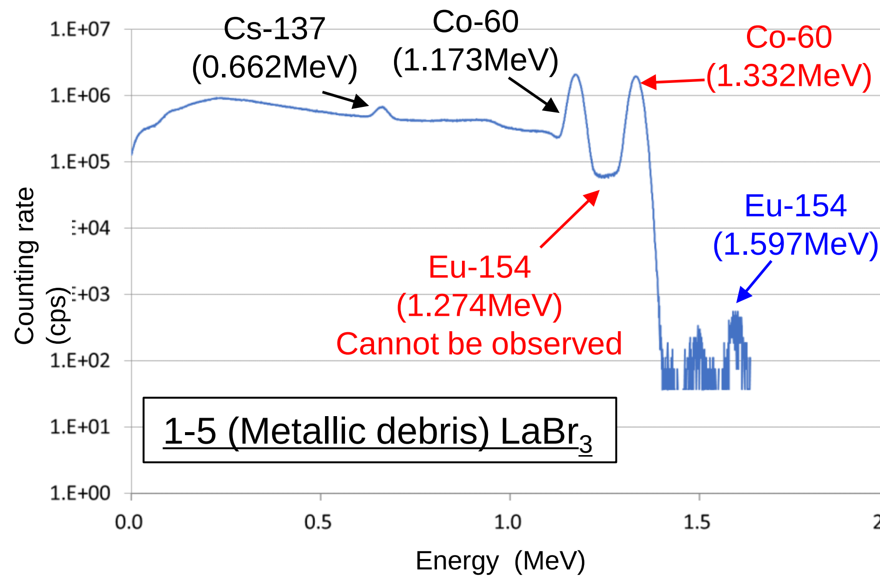


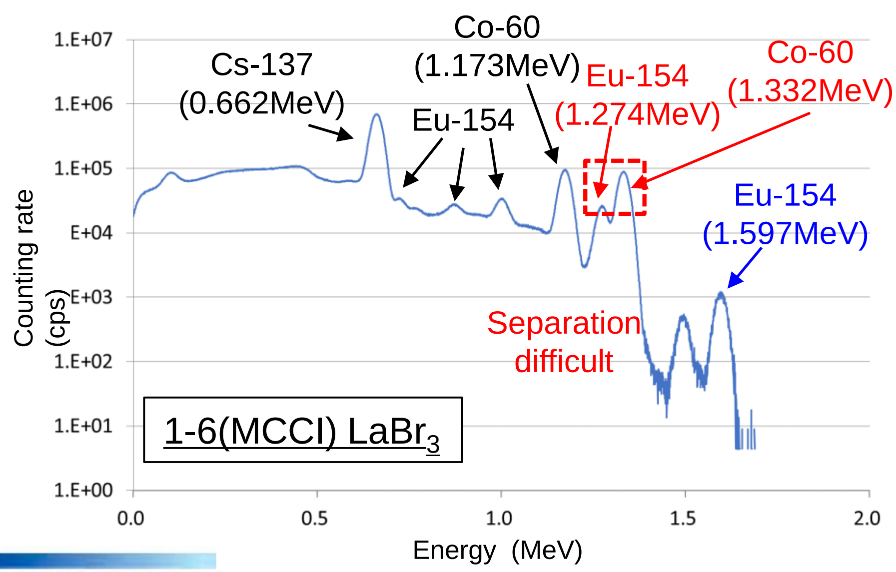
4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (12/13)

➢ LaBr$_3$ analysis results (Total 3 cases)







・In the case of molten debris and MCCI debris, it was difficult to separate the 1.274MeV peak of Eu-154 and the 1.332MeV peak of Co-60 being focused on.

・In the case of metallic debris 1.274MeV peak was unable to be observed.

・As stated above, there were cases when it was difficult to perform evaluation at the 1.274MeV peak using the LaBr$_3$ detector.

・Meanwhile, since the 1.597MeV peak of Eu-154 can be observed, it is believed that evaluation can be performed based on this peak. However, since the counting rate is smaller by two orders of magnitude as compared to the 1.274MeV peak, the measurement time is expected to be longer.

・Hence the CZT detector is superior.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

⑤-2 Passive gamma rays method B (13/13)

<Summary and future issues>

[Implementation details]

1) Study of the error in evaluating the amount of U by detector response analysis (CZT detector, $LaBr_3$ detector) in which the amount of U is set to 3.7kg which is the standard for sorting
2) Study using collimator and estimation of measurement time
3) Development of the concept of the measuring equipment based on the above results

[Results/Contribution to development]

1) ✓Detector response analysis using the CZT detector

・As a result of the evaluation performed based on the detector response analysis results, it was found that even if the amount of U was kept the same (3.7kg) there were errors in the evaluated amount of U due to the burn-up, composition or bulk density. When the burn-up was 21GWd/t, in cases where the amount of U was set at 3.7kg, the evaluated value was in the range of approx. 1.0 to 4.4kg. If the burn-up is kept the same, the impact of the composition or bulk density can be corrected and hence the error in evaluation of the amount of U is likely to reduce.

・Meanwhile, when the burn-up varied in the range of 1.3GWd/t to 51Gwd/t, there was a difference of around 3 orders of magnitude in the maximum and minimum counting rate, which cannot be corrected by the above-mentioned method.

✓Detector response analysis using $LaBr_3$ detector

・There were cases when it was difficult to separate the 1.274MeV peak of Eu-154 and the 1.332MeV peak of Co-60, or when it was difficult to observe the 1.274MeV peak. Hence it is difficult to perform evaluation based on the 1.274MeV peak using the $LaBr_3$ detector.

・Meanwhile, since the 1.597MeV peak of Eu-154 can be observed, evaluation can be performed based on this peak. However, since the counting rate is smaller by two orders of magnitude as compared to the 1.274MeV peak, the measurement time is expected to be longer.

2) The measurement time that is supposed to have a 1% statistical error largely varies in the range of approx. 3 minutes to 40 hours/container due to the difference in counting rate.
3) A proposed concept of measuring equipment that is structured so that the size of the collimator or the distance between the container and detector can be adjusted depending on the counting rate was developed.

[Issues and response measures]

1) Issue: Since there is a difference of around 3 orders of magnitude in the maximum and minimum counting rate in accordance with the variation in burn-up, a correction method other than the method of correcting the composition or the bulk density needs to be considered.

Response measure: Correction methods such as using other measurement data, etc. should be studied.

2) Issue: The measurement time largely varies in the range of several minutes to several tens of hours/container.

Response measure: Crystallization of an equipment stucture that makes it possible to adjust the size of the collimator or the distance between the container and detector should be studied.

3) Issue: The logic for explaining the carrying performance of E-154 with nuclear fuel material needs to be established.

Response measure: Accumulating evidence in cooperation with other projects, and establishing explanatory logic should be considered.

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

(Summary of the development of the concept of the measuring equipment using detector response analysis)

4.1.2 Development of the concept of the measuring equipment by means of detector response analysis

Summary of the development of the concept of the measuring equipment using detector response analysis

[Results / Contribution to development] (For details, refer to the reports on each measurement technology)

・Detector response analysis models were created assuming the concept of measuring equipment for 5 types of measurement technologies (① Active neutron method, ② Passive neutron method, ③ Muon scattering method, ④ X-ray CT method and ⑤ Passive gamma rays method).

・The conditions of the target object (container, stored material) were set for detector response analysis while taking into consideration influencing factors* that must be focused on in the case of each measurement technology.

* The results of the verification of factors having an impact on the measurement accuracy, performed during the FY2020 and FY2021 Subsidy Projects were reflected.

・Detector response analysis was performed using the above-mentioned analysis model and under the above-mentioned target object conditions.

・Based on the detector response analysis results, **the factors leading to variation in the measured values were analyzed, and response measures were studied.**

・Based on the detector response analysis results, **the primary proposal of the concept of the measuring equipment was established.**

・The data obtained from the detector response analysis was used as data for studying the method of evaluating quantity of nuclear fuel material, etc. as well.

[Issues and response measures] (For details, refer to the reports on each measurement technology)

1) Issue: Correction methods need to be established for each measurement technology in accordance with the influencing factors.
Response measure: **The correction methods proposed for each measurement technology should be studied in detail.**

2) Issue: Amongst the issues concerning the correction method, **developing the logic for explaining the carrying performance of Cm-244 and Eu-154 with U is difficult to accomplish independently in the Sorting PJ**.
Response measure: **Studies should be carried out in collaboration with related projects (Characterization PJ).** Also, it should be checked whether or not there are nuclides other than Cm-244 and Eu-154 that can be used to cross check.

3) Issue: There is lack of data contributing to the optimization of equipment structure.
Response measures: **Additional parameter studies should be conducted on equipment structure by undertaking analysis. Also, results of the elemental technology verification tests should be reflected.**

4.2 Techniques for evaluating the quantity of nuclear fuel material and study of sorting scenarios

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

4.2.2 Study of sorting scenarios

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

[Objective]

・The primary proposal pertaining to the methods for evaluating the quantity of nuclear fuel material, etc. based on the quantity measured using the active neutron method, passive neutron method, muon scattering method, X-ray CT method and passive gamma rays method (including combinations as required) should be studied, and the evaluation efficiency of the said proposed evaluation methods should be evaluated.

(Target TRL at completion: Level 3)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(Items that are common to the measurement technologies)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

Items common to the measurement technologies (1/1)

➢ Following are the study cases of the measuring equipment

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191
②-1	Passive neutron method A	He-3	None	None	Mass of spontaneous fission nuclides (Cm-244, etc.)	Same as above	MHI	81-93 192-203
②-2	Passive neutron method B	B-10	None	None	Same as above	Same as above	Hitachi-GE	94-101 204-207
③	Muon scattering method	Muon trajectory detector	None	None	Atomic weight	Same as above	Toshiba ESS	102-116 208-214
④	X-ray CT method	X-ray detector	Accelerator based X-ray source	From the lateral side	Density	Same as above	Hitachi-GE	117-127 215-220
⑤-1	Passive gamma rays method A	Ge	None	None	Mass of fission product nuclides (Eu-154, etc.)	Same as above	MHI	128-140 221-233
⑤-2	Passive gamma rays method B	CZT, $LaBr_3$, etc.	None	None	Same as above	Same as above	Hitachi-GE	141-154 234-237

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(①-1 Active neutron method A)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191

[Characteristics]

- The He-3 detector was selected based on its track record.
- D-T neutron source was selected as the irradiation source based on its neutron generation efficiency and past track record.
- Irradiation from the lateral side of the target object was selected as the neutron irradiation direction based on past track record.

①-1 Active neutron method A (1/18)

Overview of the evaluation method:

The quantity of nuclear material was estimated and evaluated based on the results of measuring the neutrons generated by the nuclear fission reaction of U-235 induced by the irradiated neutrons.

Evaluation No	Explanation
Active neutron method A -1	The weight of U-235 was evaluated based on the correlation function between the integrated counting rate of neutrons generated by nuclear fission induced by the irradiated neutrons and the set weight of U-235, and the amount of U was evaluated assuming average burn-up*.
Active neutron method A-2	The weight of U-235 was evaluated based on the correlation function between the neutron die-away time and the integrated counting rate for every unit weight of U-235 (common for unit can and inner waste container), and the amount of U was evaluated assuming average burn-up*.
Active neutron method A-2’	The weight of U-235 was evaluated based on the correlation function between the neutron die-away time and the integrated counting rate for every unit weight of U-235 (only applicable to unit can), and the amount of U was evaluated assuming average burn-up*.

*Average burn-up…23.0GWd/t

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (2/18)

Molten debris cases that were evaluated

Case No.	Debris properties	Composition inside the container: Within the filling factor: Composition	Total (Filling factor)	Outside the filling factor	Burn-up	Neutron absorption material	FP emission rate[*1]	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
A-1	Molten debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-2		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-3		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-4		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-5		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-6		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-7		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-8		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-9		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-10		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-11		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
A-12		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	**Gd_2O_3 3 vol%**	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (3/18)

MCCI debris cases that were evaluated

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
B-1	MCCI debris	UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-2				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-3				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-4		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	60 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-5				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-6				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	None	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-7		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	Gd_2O_3 3 vol%	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-8				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	Gd_2O_3 3 vol%	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-9				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	Gd_2O_3 3 vol%	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-10		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	60 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	Gd_2O_3 3 vol%	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-11				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	Gd_2O_3 3 vol%	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)
B-12				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	Gd_2O_3 3 vol%	Standard	20 years	Uniform	Unit can	D-T reaction (14.1MeV)

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (4/18)

Metallic debris cases that were evaluated

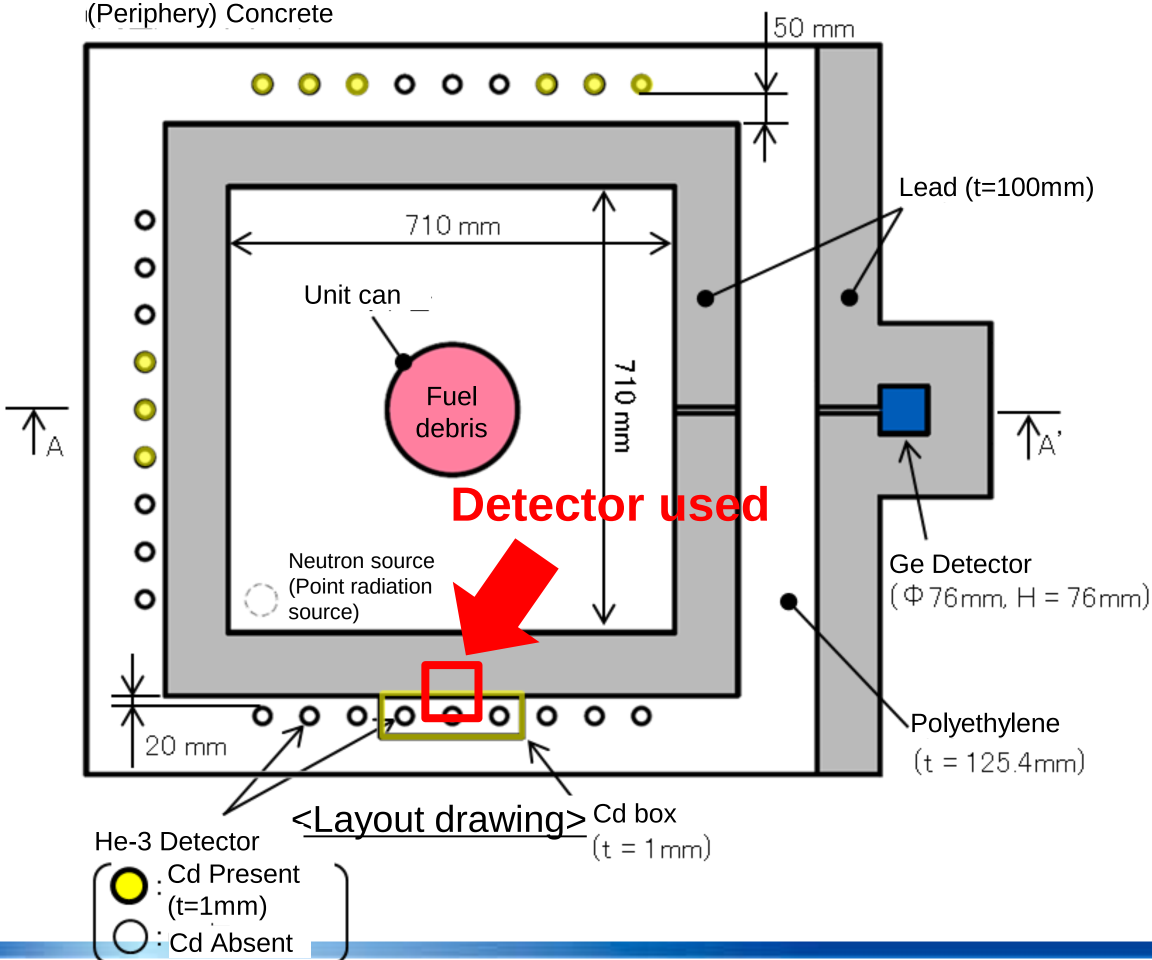
Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container*2	Source of irradiated neutrons
	Debris properties	Within the filling factor		Outside the filling factor							
		Composition	Total (Filling factor)								
C-1	Metallic debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 29.85 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)	D-T reaction (14.1MeV)
C-2		UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 44.85 vol%	**45 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)	D-T reaction (14.1MeV)
C-3		UO_2 : 0.48vol% ZrO_2: 0vol% SUS: 10 vol%	**10.48 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)	D-T reaction (14.1MeV)

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)
*2 Mainly made of SUS, it is assumed to be sorted as inner container during the initial stage of retrieval
*3 Overview of each case is indicated below.
C-1: Base case
C-2: Case of sensitivity with respect to SUS composition
C-3: Case of sensitivity in which UO_2 has a volume percent equivalent to 3.7kg

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (5/18)

Detector used:
An He-3 detector in a Cd box that can selectively measure prompt neutrons from U-235 and which does not easily get affected by thermal neutrons was used.



<Layout drawing>

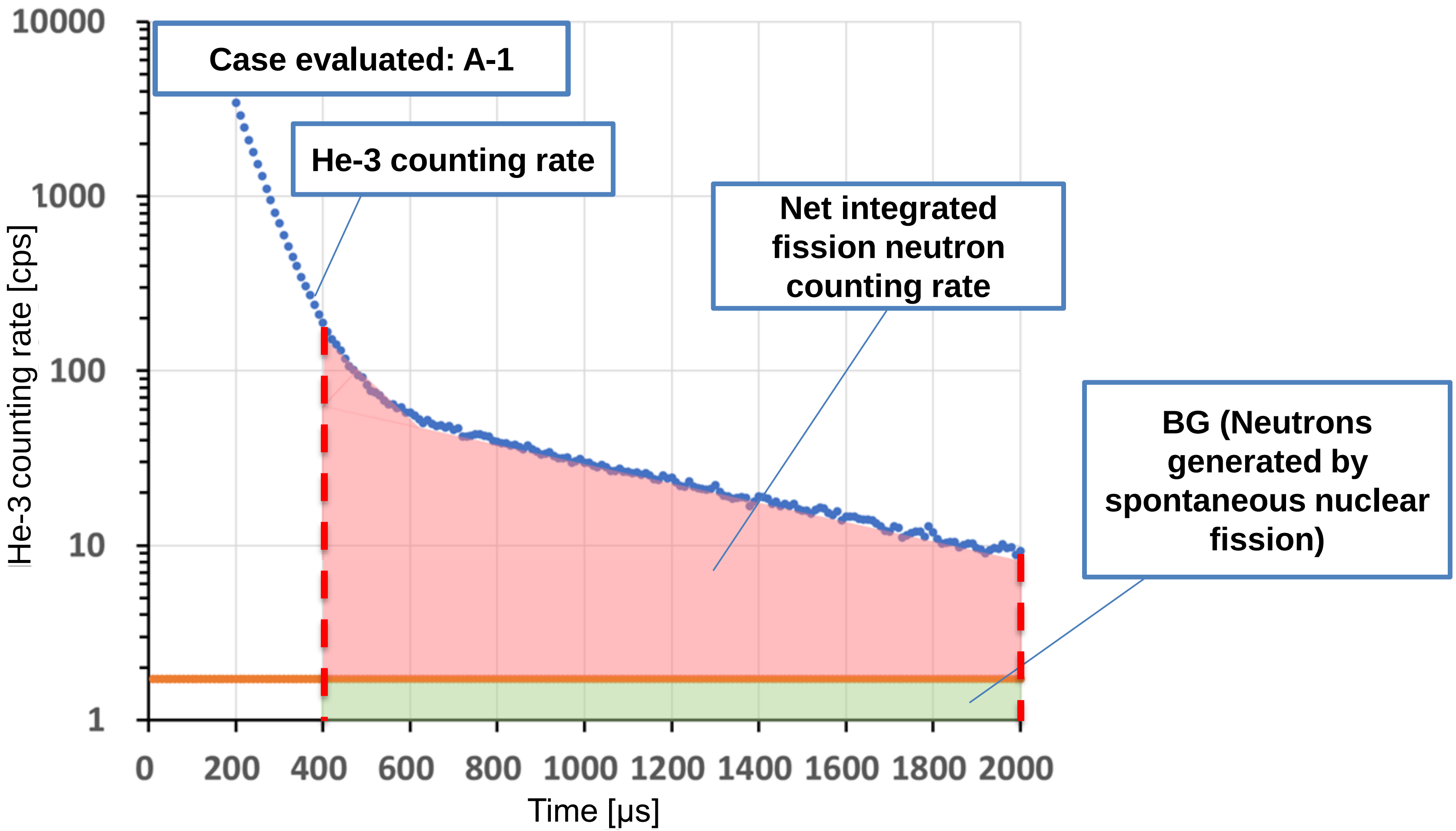
[Analysis conditions]
- Neutrons are irradiated from the neutron source 100 times (100Hz) in a second.
- Data pertaining to 100 times of neutron irradiation is accumulated.
- Time resolution is 10μs

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (6/18)

Active neutron method A-1: Overview

The weight of U-235 was evaluated based on the correlation function between the integrated counting rate of neutrons generated by nuclear fission induced by the irradiated neutrons and the set weight of U-235, and the amount of U was evaluated assuming average burn-up.

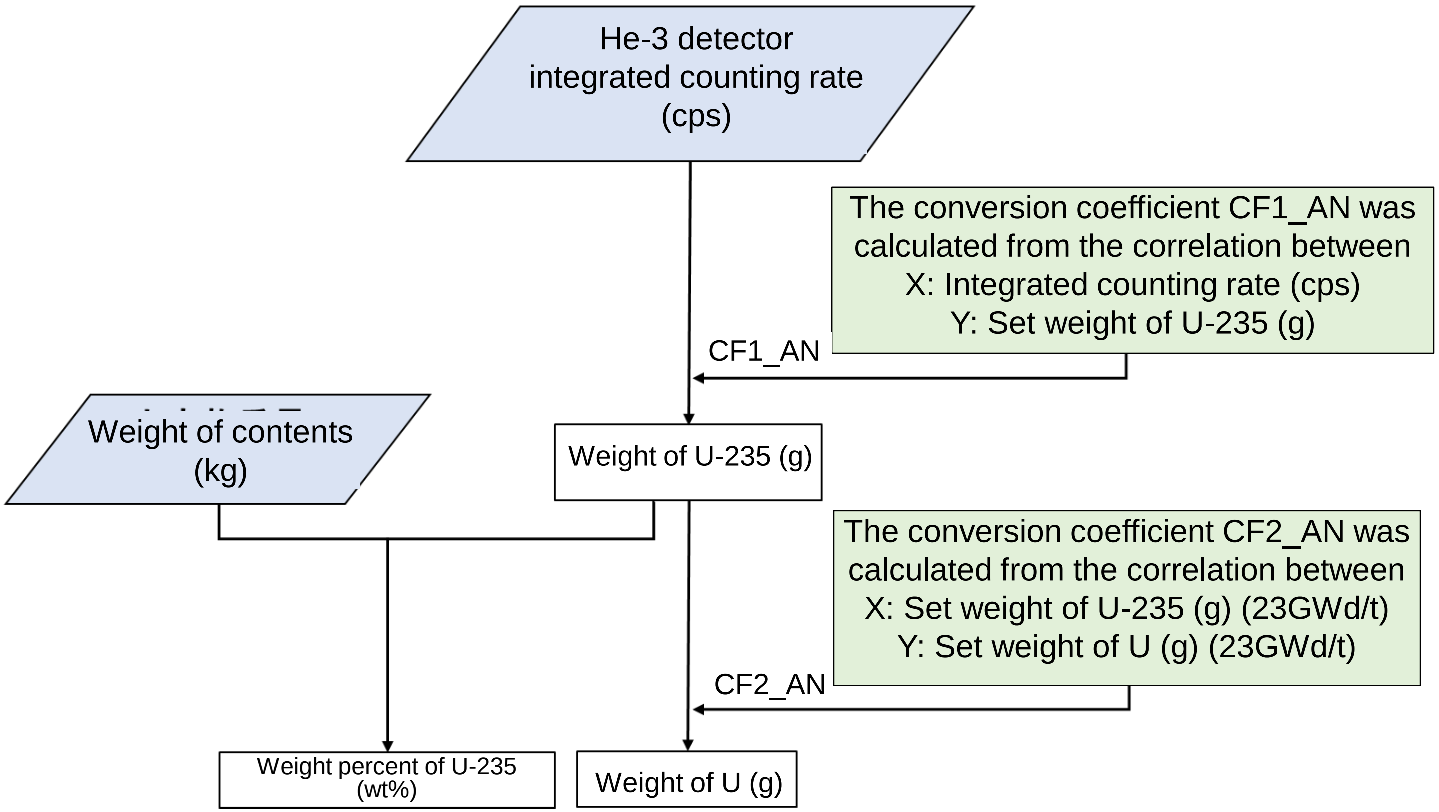


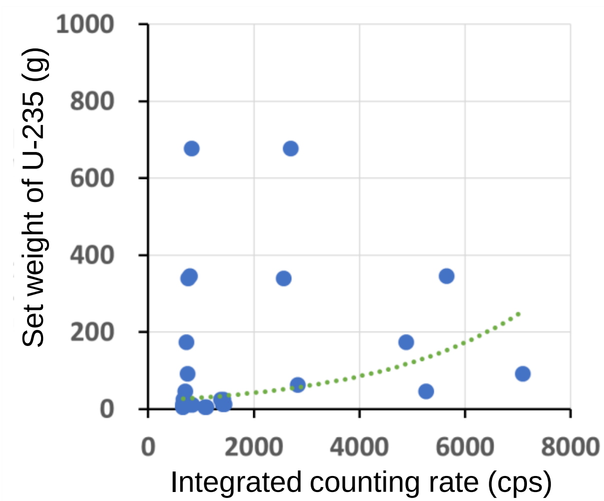
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

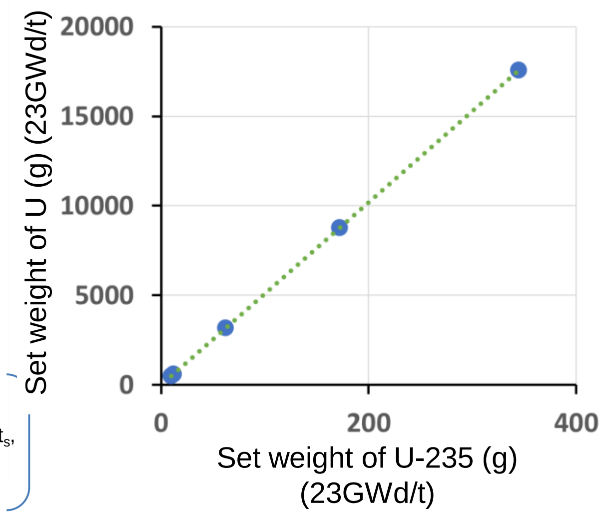
①-1 Active neutron method A (7/18)

Active neutron method A-1: Estimation and evaluation flow

The flow for estimating and evaluating the quantity of nuclear material using only the active neutron method A-1 was created.







The lower detection counting rate limit obtained from the following equation was substituted into the flow with the same lower detection limit.

$$n_n > \frac{K}{2}\left(\left(\frac{K}{t_s}\right) + 4n_b\left(\frac{1}{t_s}+\frac{1}{t_b}\right)\right)$$

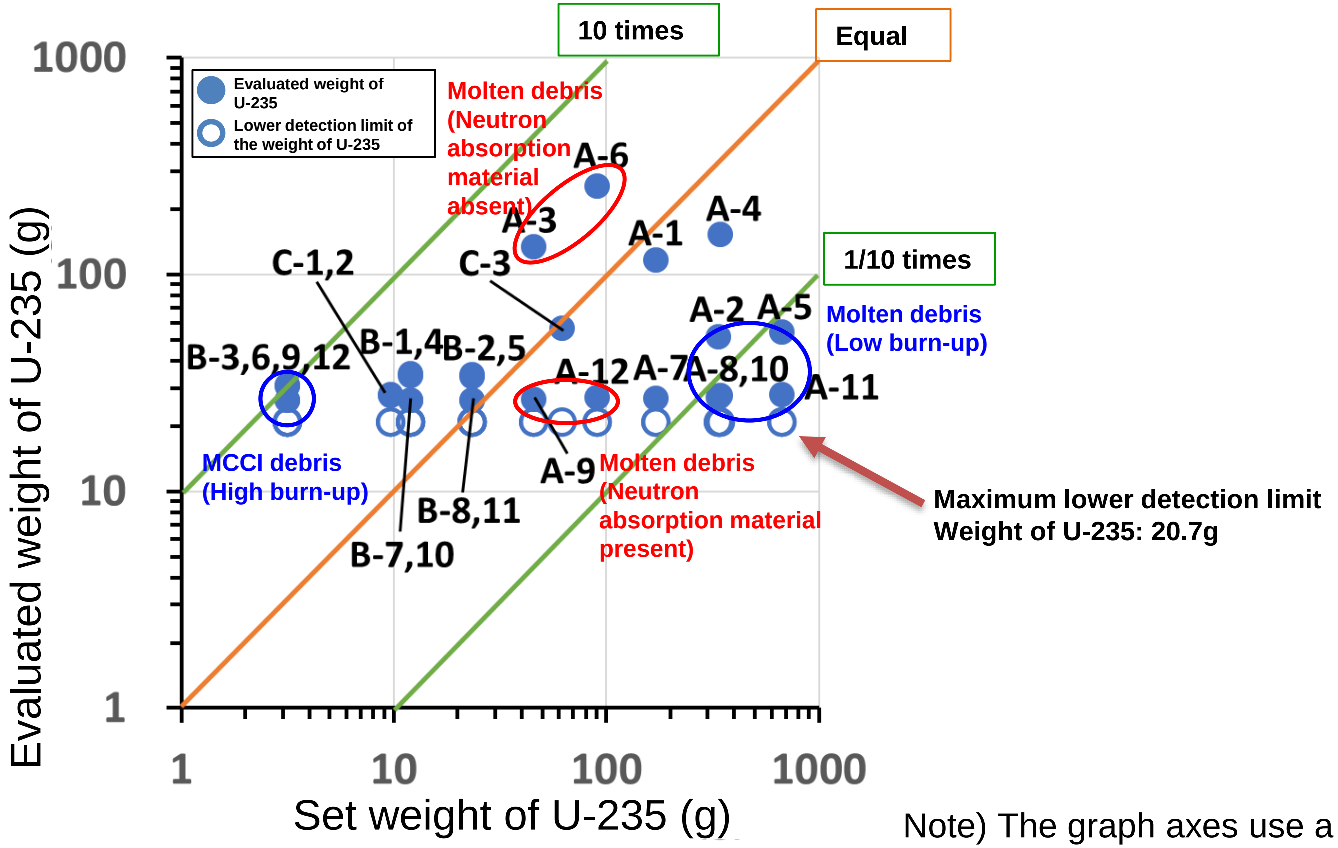
Standard deviation multiple: K=3, Count measured for the target object: N_s,
Measurement time for the target object: t_s=200(s), Measured counting rate for the target object: $n_s=N_s/t_s$,
BG measured count: N_b, BG measurement time: t_b=200(s) , BG measured counting rate: $n_b= N_b/t_b$
Net counting rate of the target object: $n_n=n_s-n_b$

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (8/18)

Active neutron method A-1: Evaluation results_U-235 weight (g)

- The evaluated weight of U-235 was at most about 10 times and at least 1/10 times or less when compared to the set weight of U-235.
- There were many cases when the counting rate was about the same even if the set weight of U-235 varied, and often the evaluated value also turned out to be about the same.
- Since the conversion coefficient was calculated based on all cases with low to high burn-up, there were major discrepancies in the high burn-up MCCI debris cases and low burn-up molten debris cases.
- The evaluated value in cases wherein neutron absorption material was present was comparatively smaller than the evaluated value in cases wherein the neutron absorption material was absent. The impact of neutron absorption material needs to be corrected.



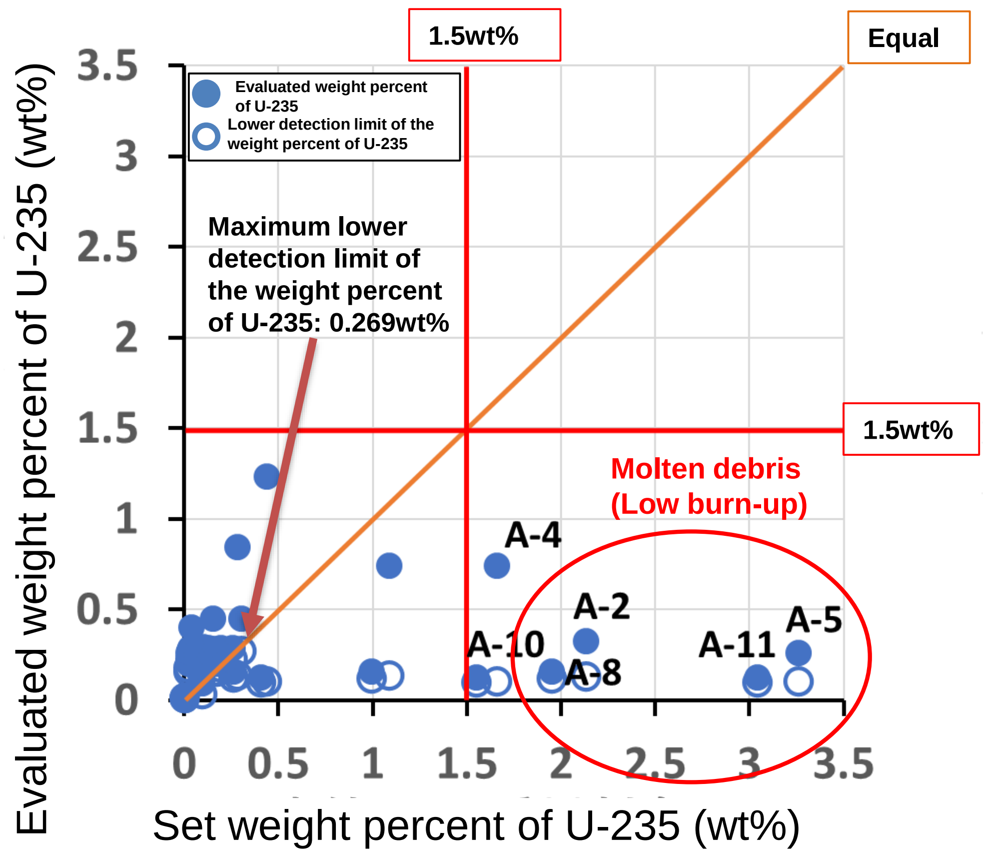
Note) The graph axes use a logarithmic scale

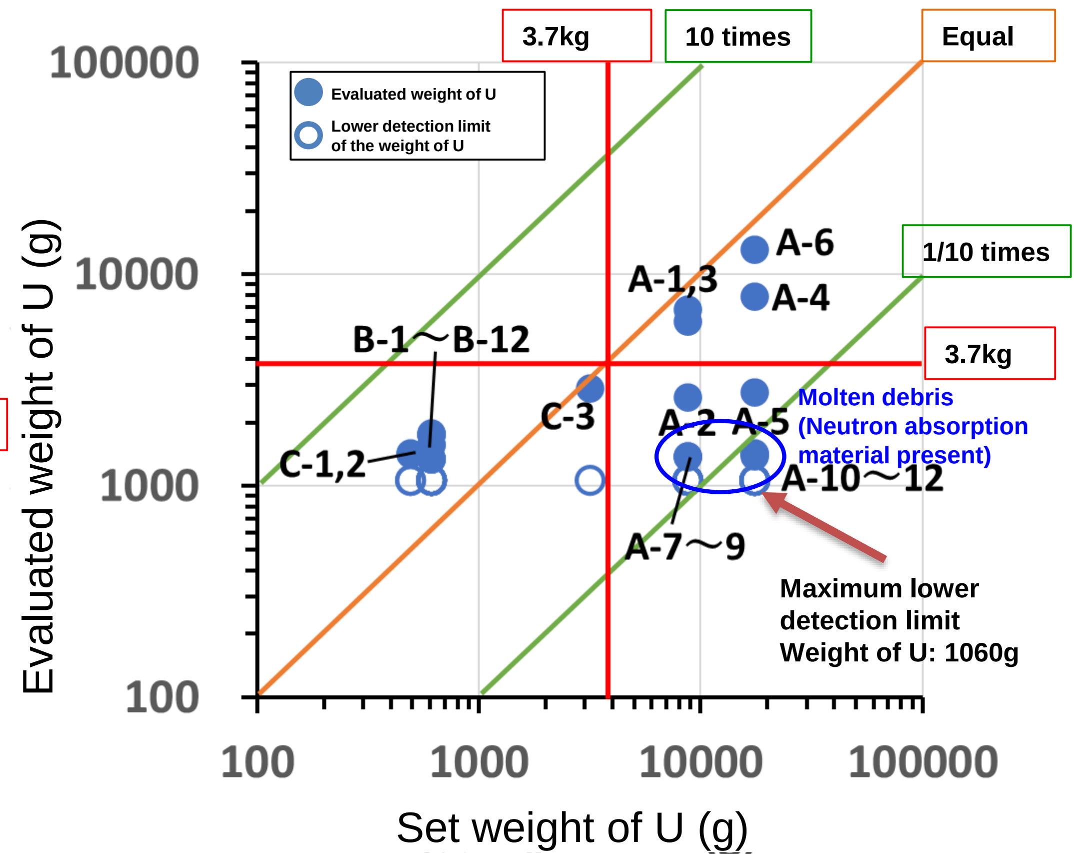
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (9/18)

Active neutron method A-1: Evaluation results_U-235 weight percent (wt%) and amount of U (g)

- There was underestimation in the case of low burn-up molten debris. The weight percent of U-235 was high in the case of low burn-up molten debris, but it is presumed that this was because of the impact of neutron absorption material (Gd) present in the fuel rods at the time of initial filling.
- There was underestimation in the case of molten debris (neutron absorption material present). Hence the impact of neutron absorption material needs to be corrected.
- Average burn-up was assumed for evaluating the amount of U from the weight of U-235. Thus correcting the impact of burn-up is a challenge.





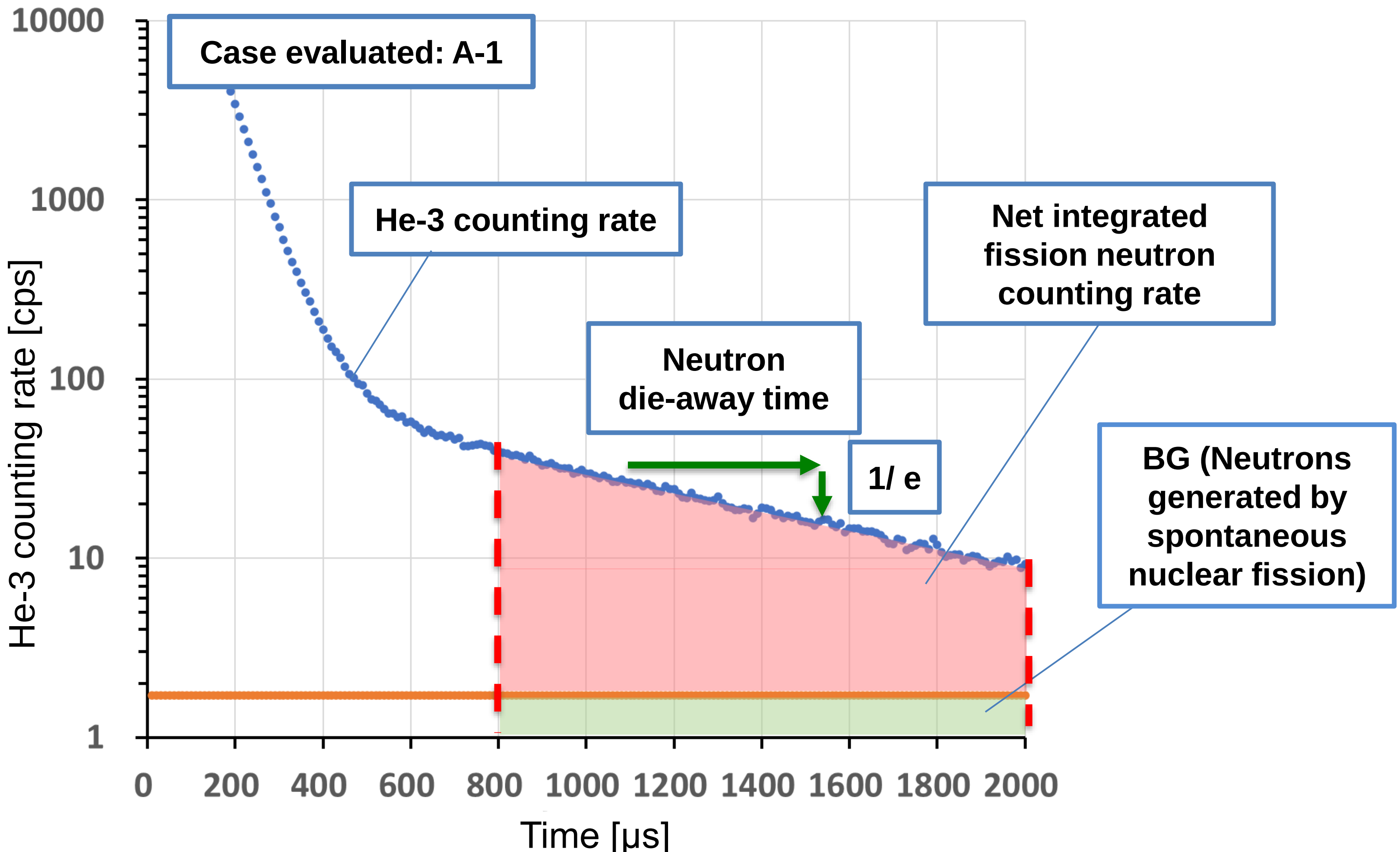
Note) The graph axes use a logarithmic scale

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (10/18)

Active neutron method A-2: Overview

The quantity of nuclear material was estimated and evaluated based on the correlation function between the neutron die-away time and the integrated counting rate for every unit weight of U-235.



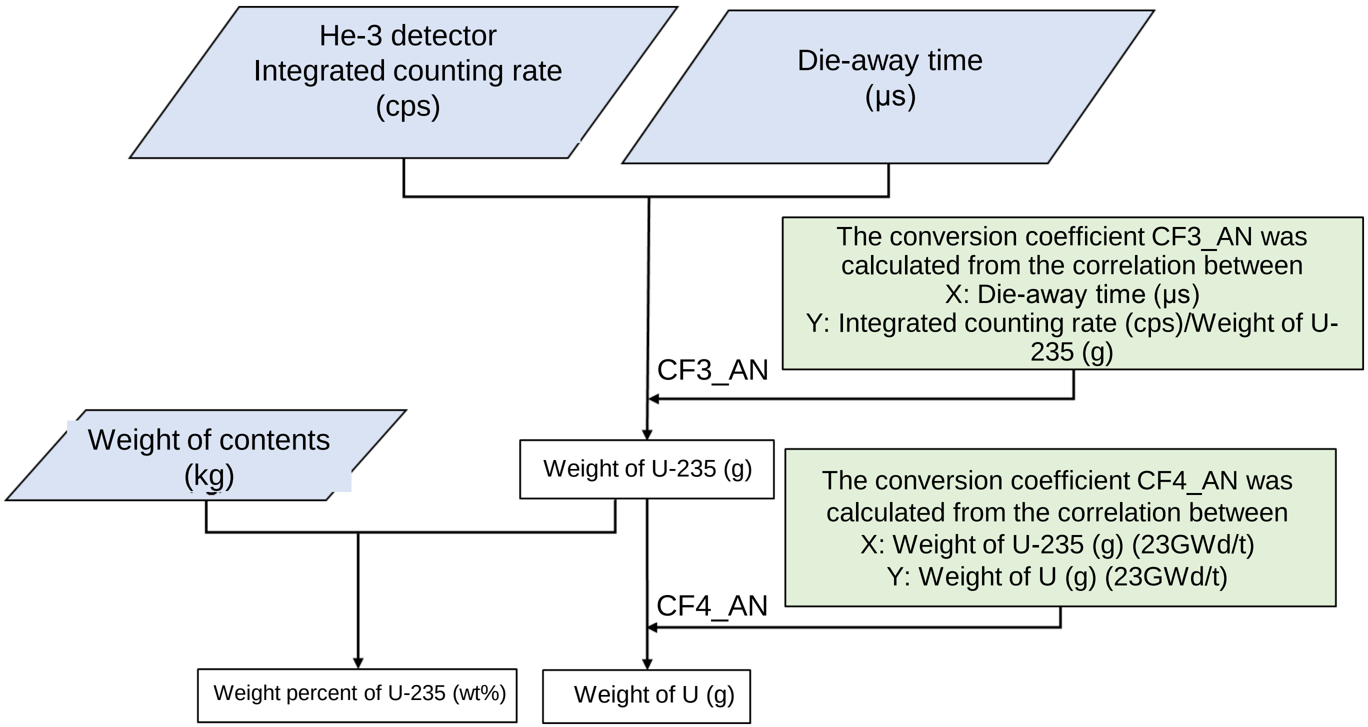
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

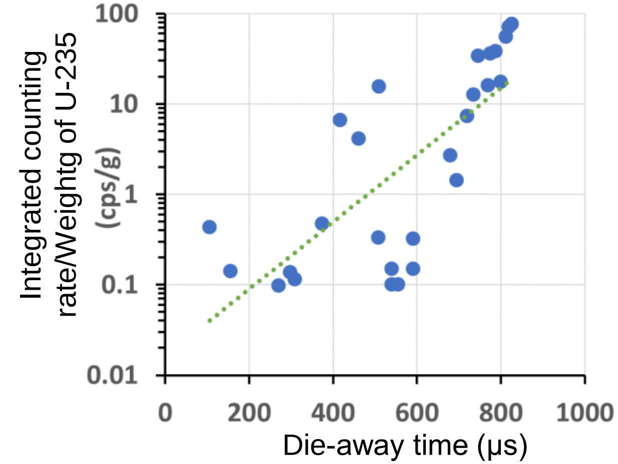
①-1 Active neutron method A (11/18)

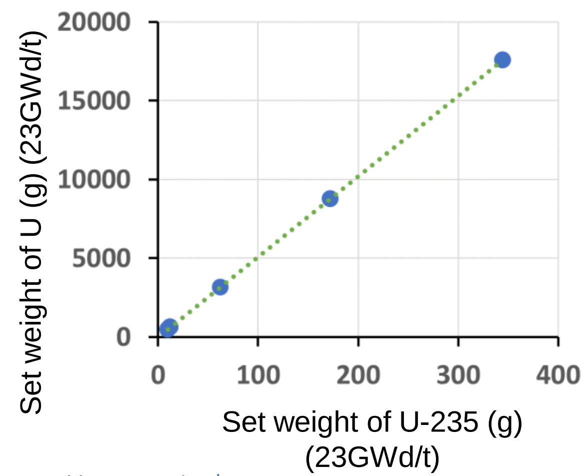
Active neutron method A-2: Estimation and evaluation flow

The flow for estimating and evaluating the quantity of nuclear material using only the active neutron method A-2 was created.

Target: Molten/MCCI/Metallic debris (All of cases A, B and C)







The lower detection counting rate limit obtained from the following equation was substituted into the flow with the same lower detection limit.

$$n_n > \frac{K}{2}\left(\left(\frac{K}{t_s}\right) + 4n_b\left(\frac{1}{t_s} + \frac{1}{t_b}\right)\right)$$

Standard deviation multiple: K=3, Count measured for the target object: N_s,
Measurement time for the target object: t_s=200(s), Measured counting rate for the target object: $n_s=N_s/t_s$,
BG measured count: N_b, BG measurement time: t_b=200(s) , BG measured counting rate: $n_b= N_b/t_b$
Net counting rate of the target object: $n_n=n_s-n_b$

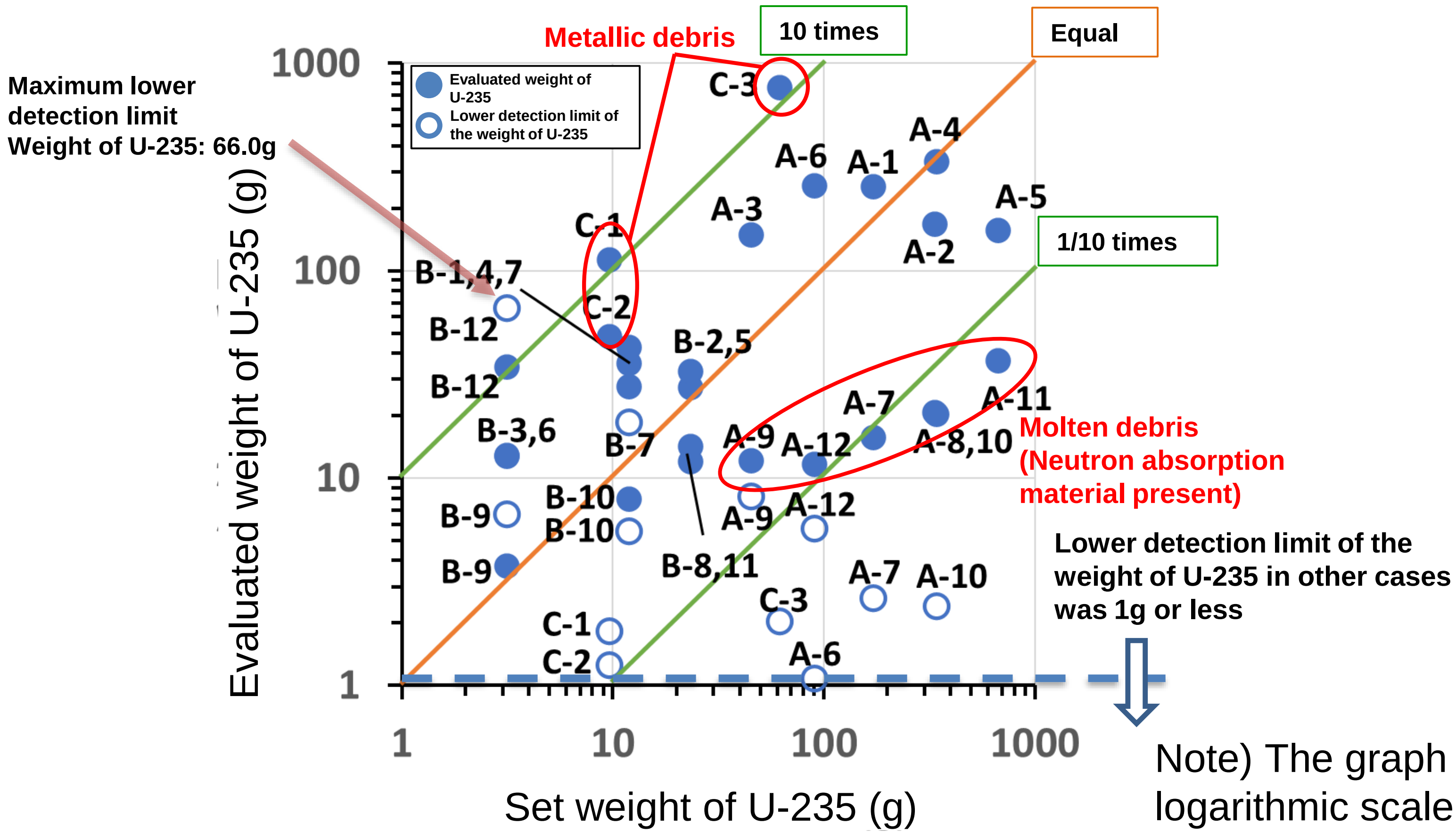
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (12/18)

Active neutron method A-2: Evaluation results_U-235 weight (g)

・The evaluated weight of U-235 was at most 10 times or more and at least 1/10 times or less when compared to the set weight of U-235.

・Since the conversion coefficient was calculated by drawing an approximate curve based on all the analysis cases pertaining to unit cans and waste storage containers, cases that were at a distance from that approximate curve had large discrepancies. During the evaluation this time, there was underestimation in the case of molten debris (neutron absorption material present) and overestimation in the case of metallic debris which had different containers.



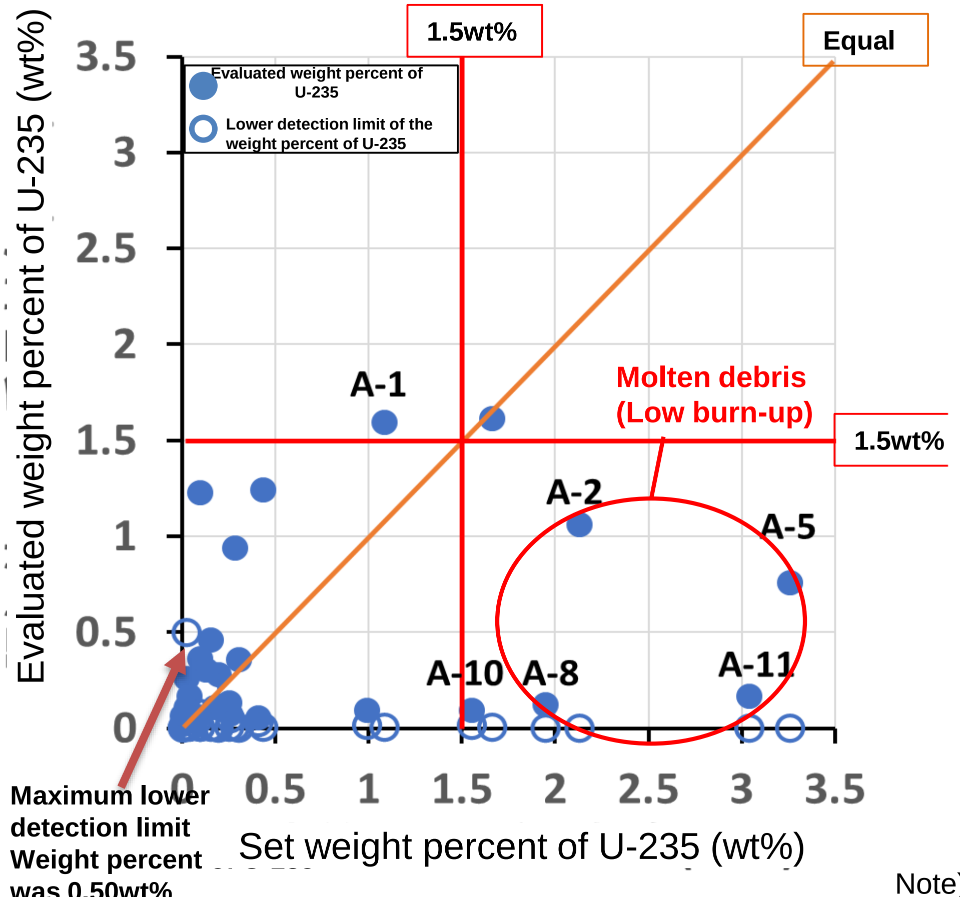
Note) The graph axes use a logarithmic scale

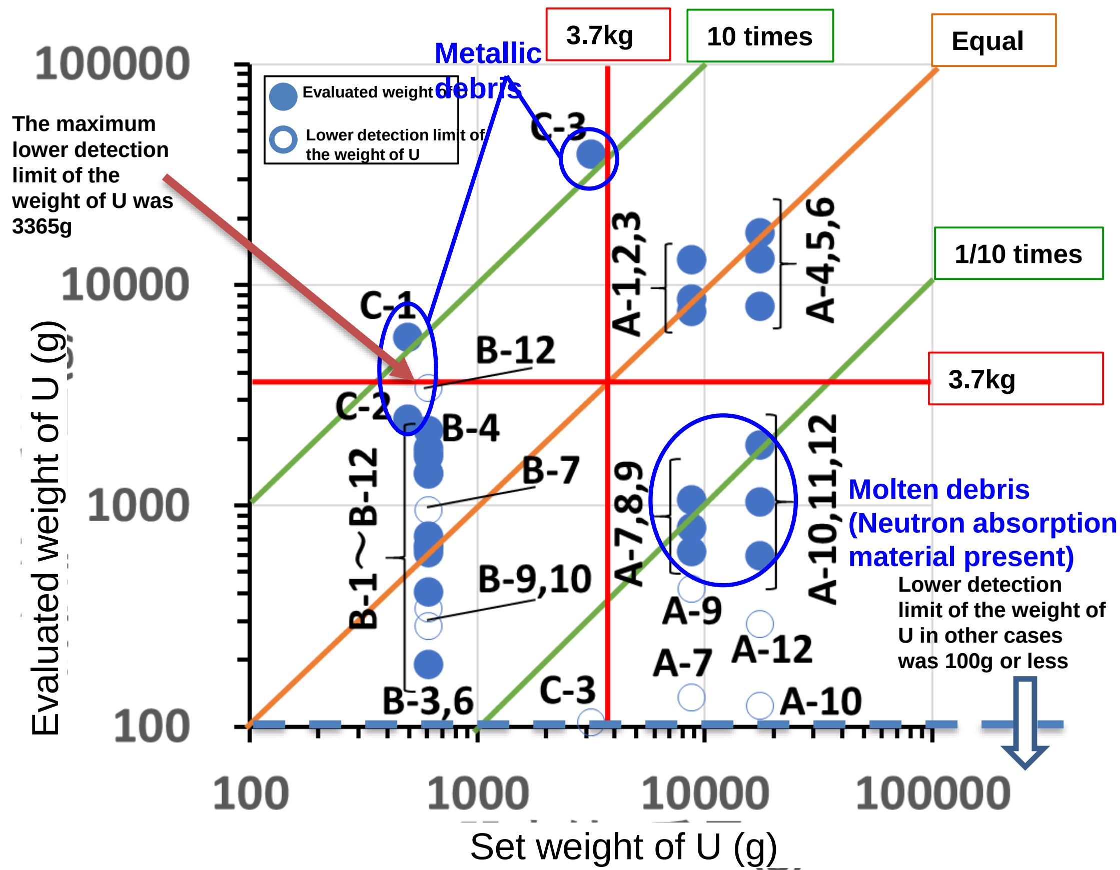
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (13/18)

Active neutron method A-2: Evaluation results_U-235 weight percent (wt%) and amount of U (g)

- There was underestimation in the case of low burn-up molten debris. The weight percent of U-235 was high in the case of low burn-up molten debris, but it is presumed that this was because of the impact of neutron absorption material (Gd) present in the fuel rods at the time of initial filling.
- Since the conversion is done from weight of U-235 to weight of U assuming average burn-up, the weight of U was underestimated in the case of molten debris (neutron absorption material present) and overestimated in the case of metallic debris which had different containers.





Note) The graph axes use a logarithmic scale

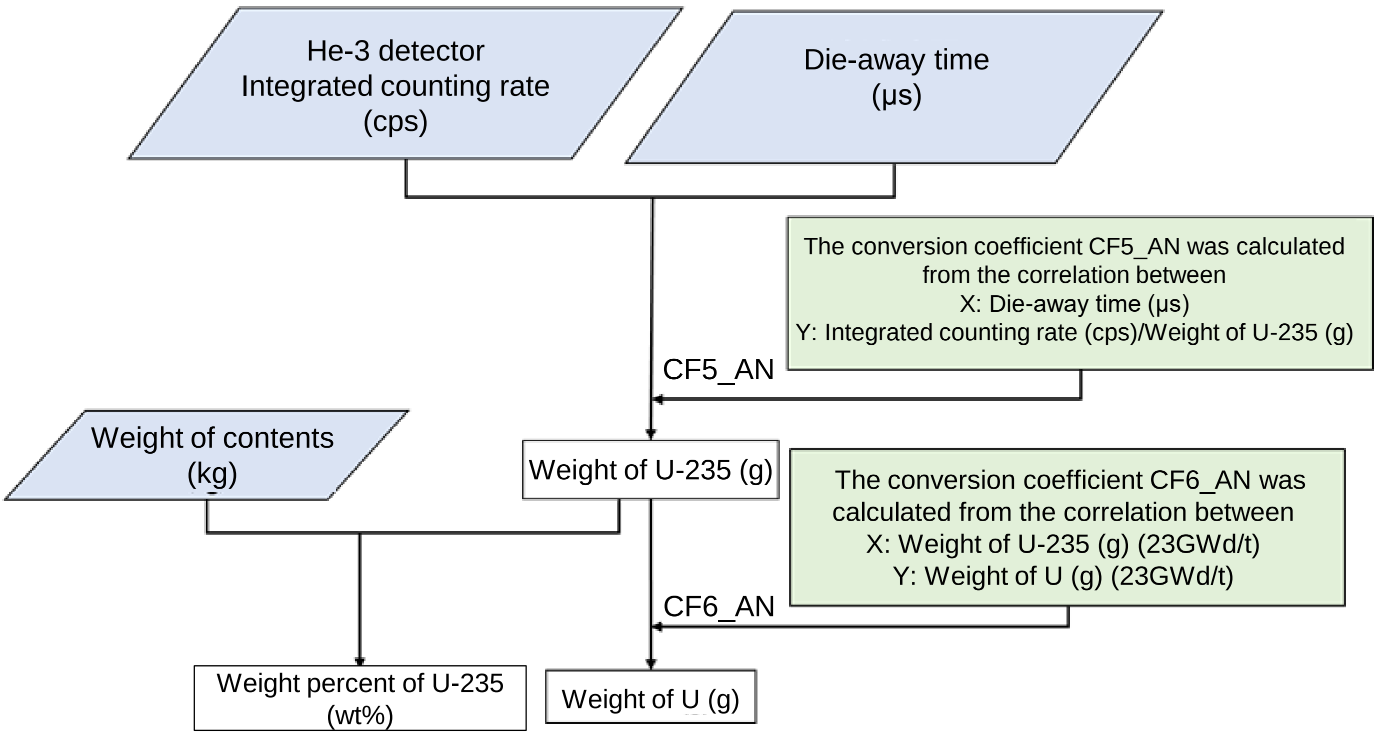
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

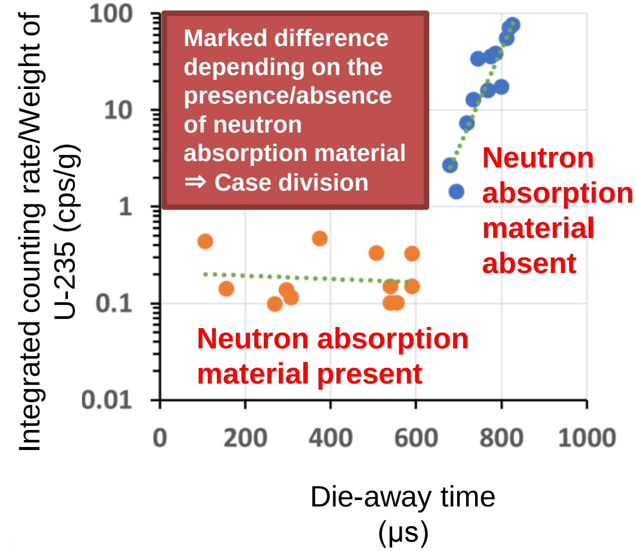
①-1 Active neutron method A (14/18)

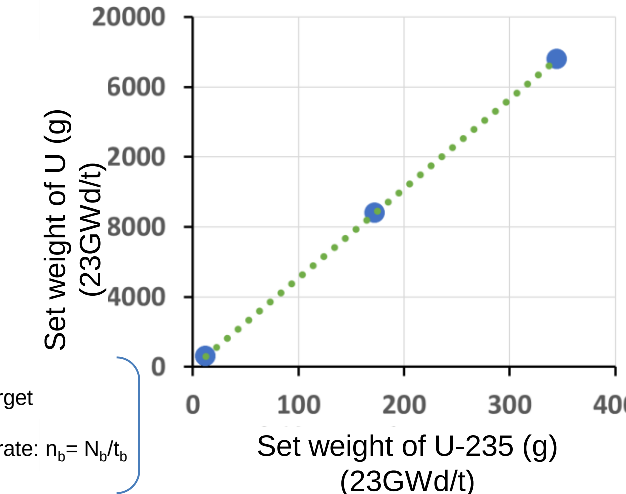
Active neutron method A-2’: Estimation and evaluation flow

The flow for estimating and evaluating the quantity of nuclear material using only the active neutron method A-2’ was created.

Target: Molten/MCCI debris in the unit can（Only cases A and B)







The lower detection counting rate limit obtained from the following equation was substituted into the flow with the same lower detection limit.

$$n_n > \frac{K}{2}\left(\left(\frac{K}{t_s}\right) + 4n_b\left(\frac{1}{t_s}+\frac{1}{t_b}\right)\right)$$

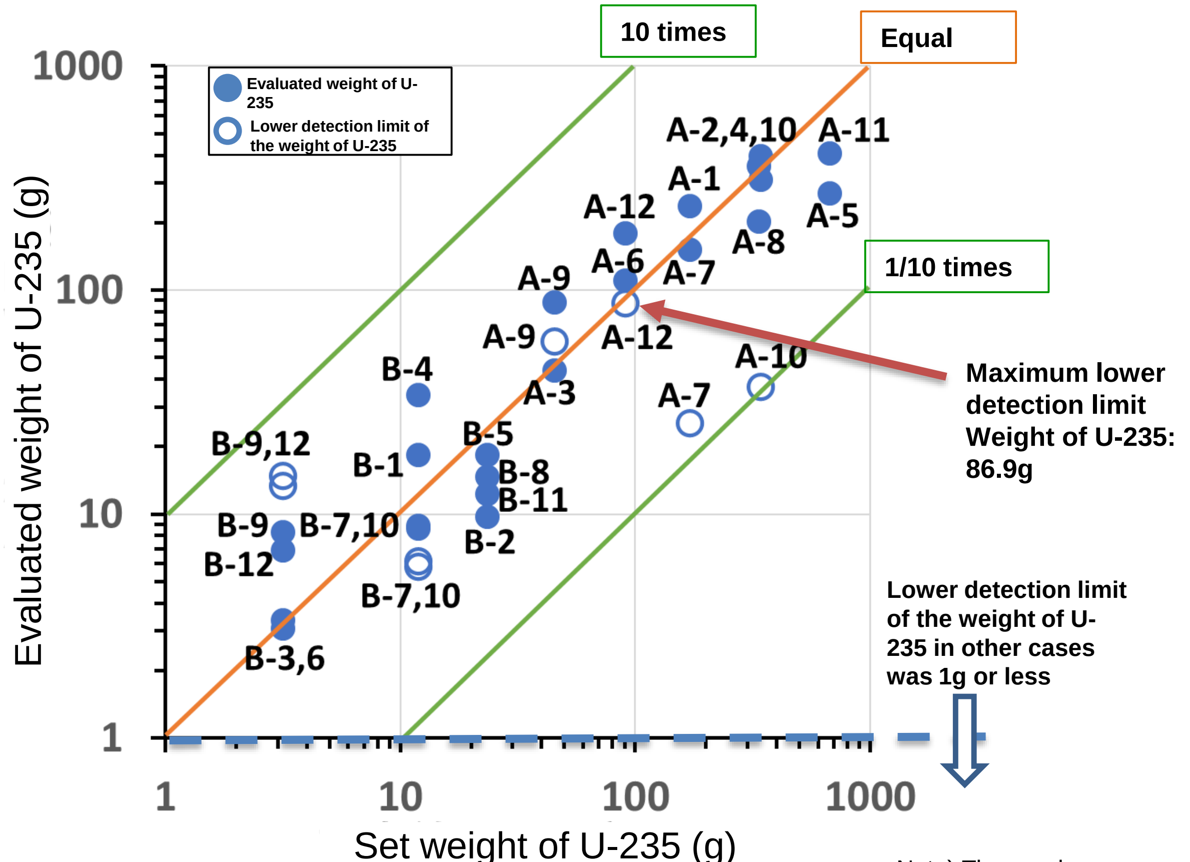
Standard deviation multiple: K=3, Count measured for the target object: N_s,
Measurement time for the target object: t_s=200(s), Measured counting rate for the target $n_s=N_s/t_s$,
BG measured count: N_b, BG measurement time: t_b=200(s) , BG measured counting rate: $n_b= N_b/t_b$
Net counting rate of the target object: $n_n=n_s-n_b$

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (15/18)

Active neutron method A-2': Evaluation results_U-235 weight (g)

・Since the conversion coefficient is calculated by narrowing down the analysis cases to unit can cases and breaking them up based on the die-away time, the evaluated value of U-235 was at most about **2 times the set value** of U-235, and thus the results suggested **that measurement accuracy can be expected to improve**.



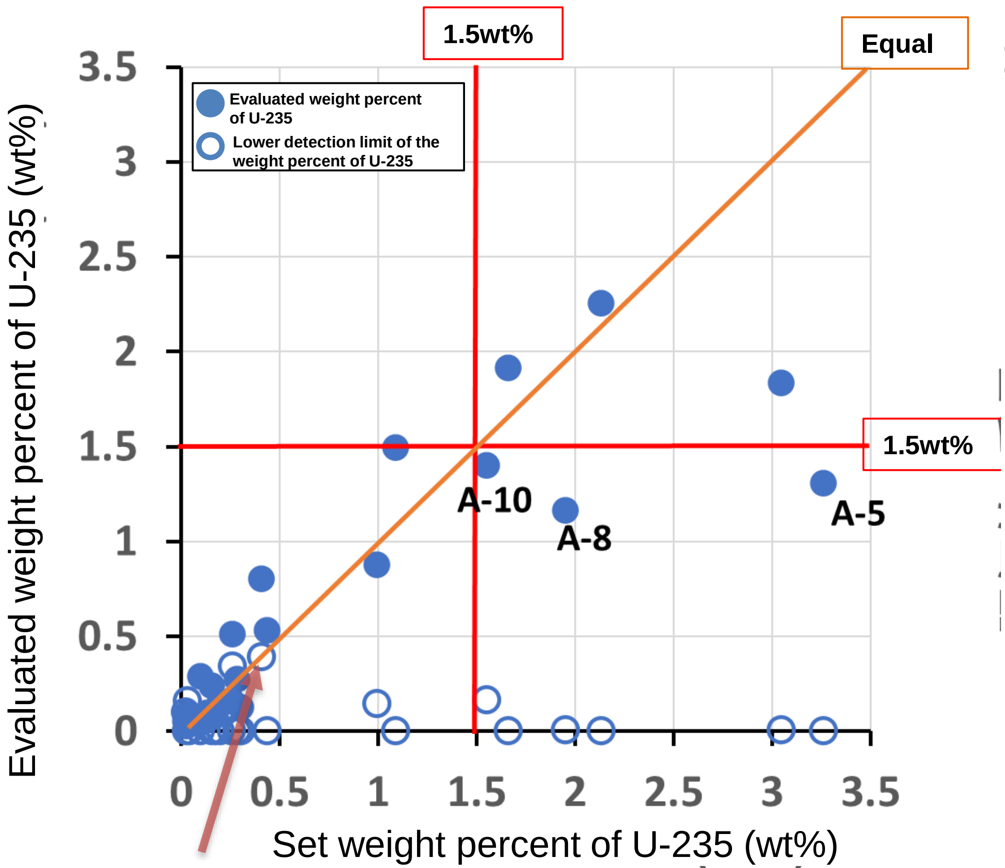
Note) The graph axes use a logarithmic scale

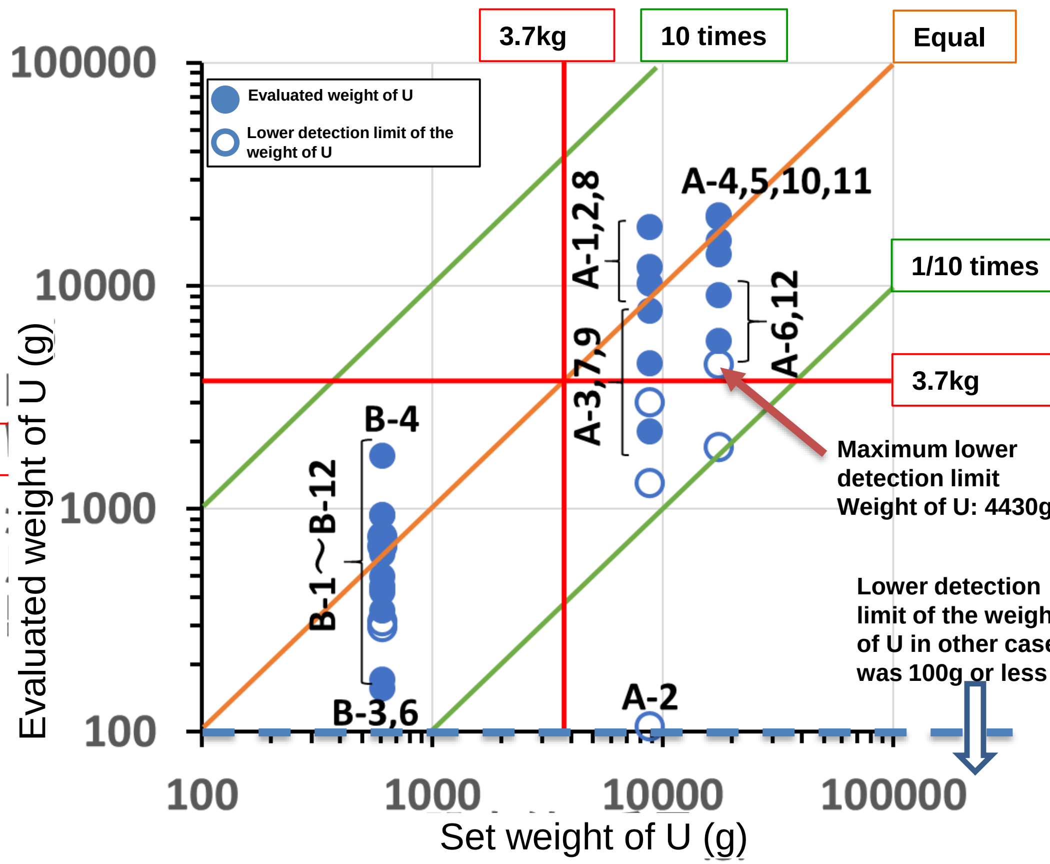
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (16/18)

Active neutron method A-2': Evaluation results_U-235 weight percent (wt%) and amount of U (g)

- The evaluated weight of U was at most about 4 times of the set weight of U.
- Average burn-up was assumed for evaluating the amount of U from the weight of U-235. **Thus correcting the impact of variations in burn-up is a challenge.**





Note) The graph axes use a logarithmic scale

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (17/18)

Results of comparing A-1, A-2 and A-2’

・Improvement in the measurement accuracy is expected using the methods A-2 and A-2’ which focus on the neutron die-away time rather than by using the A-1 method which uses only the temporal integration data.

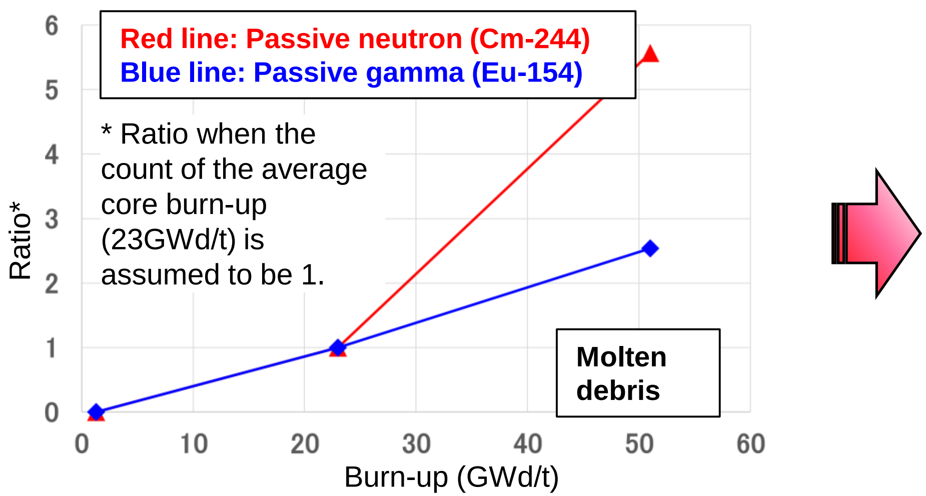
・ In the analysis cases A and B, the container in the model is a unit can whereas in the analysis cases C, the container in the model is a waste storage container (inner container). The measurement accuracy improved in the case of A-2’ that targets only unit cans rather than in the case of A-2 that targets all cases.

⇒ The conversion coefficient needs to be separated for each container shape.

Proposed measures for improving performance

・ Correction of impact of burn-up depending on the difference in correlation function between burn-up and the counting rate of Cm-244 and Eu-154

(Passive neutrons method + passive gamma rays method)



Suggests that there is a possibility of being able to correct the impact of burn-up based on the ratio of the counting rates of Cm-244 and Eu-154.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-1 Active neutron method A (18/18)

<Summary and future issues>

[Implementation details]

1) The evaluation flow for the active neutron method was studied.

2) The evaluation accuracy of the quantity of nuclear fuel material, etc. was studied.

3) The lower detection limit of the quantity of nuclear fuel material, etc. was studied.

[Results/Contribution to development]

1) The evaluation flow for the active neutron method was established.

2) The evaluation accuracy of the quantity of nuclear fuel material, etc. was estimated using the detector response analysis data.

(Comparatively good results when the evaluation is performed separately for each container specification and when the neutron die-away time is used (active neutron method A-2'))

・Weight of U-235 : At most about 2 times

・Weight percent of U-235 : At most about 2 times

・Weight of U : At most abut 4 times

3) The lower detection limit was estimated using the detector response analysis data.

・Weight percent of U-235: was at most 0.39wt% and the sorting criteria was lower than 1.5wt%

・ Weight of U was at most 4.43kg, and the sorting criteria was larger than 3.7kg, but was smaller than the set weight of U which was 17.6kg.

[Issues and response measures]

1) Issue: Reduction of errors due to burn-up

Response measure: Study of optimization of the correction method based on neutron die-away time, detailed study of correction method based on the Cm-244 and Eu-154 ratio.

2) Issue: Reduction of errors due to neutron absorption material

Response measure: Study of application of PGA method, etc.

3) Issue: Verification of the impact of diversity of other fuel debris

Response measure: Additional parameter studies on the conditions of the stored contents including heterogenous systems

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(①-2 Active neutron method B)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191

[Characteristics]

- The B-10 detector was selected since it can be used in locations with high gamma rays.
- D-T neutron source or accelerator based neutron source was selected as the irradiation source based on its neutron generation efficiency.
- Irradiation from the top of the target object was selected as the neutron irradiation direction due to higher extent of symmetry.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

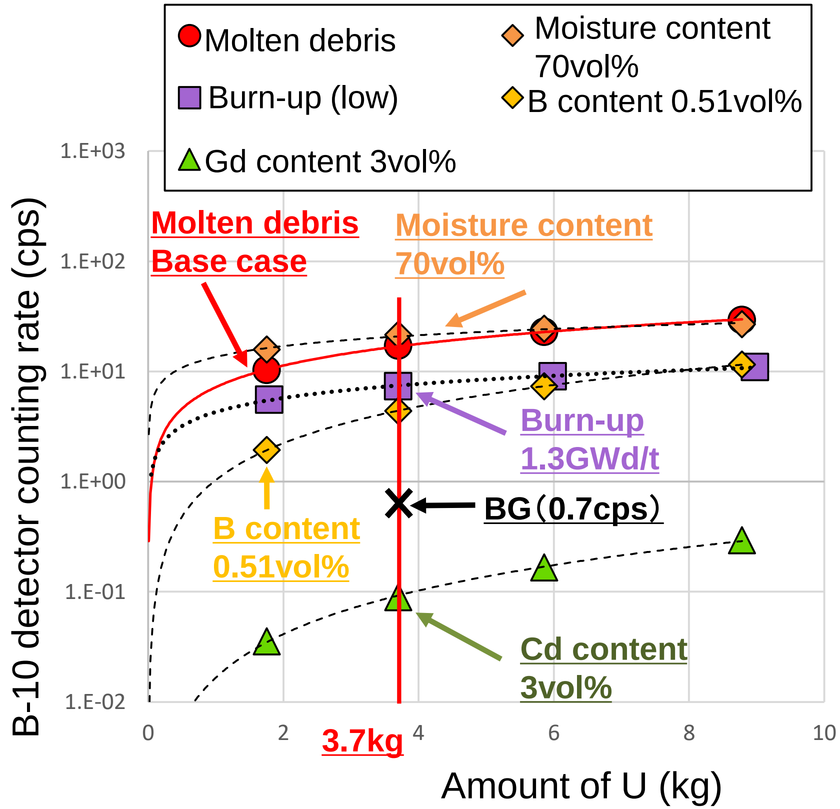
①-2 Active neutron method B (1/3)

<Issues in nuclear fuel material evaluation>

1) The neutron absorption material has a major impact and hence neutron absorption material correction is essential.

2) The impact of burn-up and moisture content is about several percents. Correction is essential for improving accuray (quantitative evaluation).

3）Since the counting rate decreases due to neutron absorption material, BG correction is necessary.



4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-2 Active neutron method B (2/3)

Neutron counting rate measurement

↓

BG correction

↓

Correction of impact of neutron absorption material

↓

Other corrections [Burn-up, moisture content]

↓

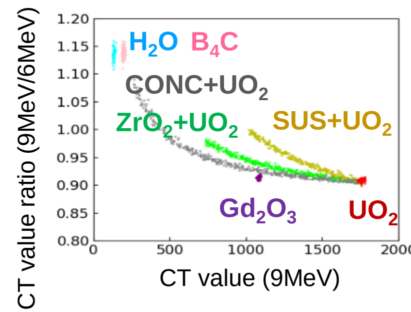
Evaluation of the weight of U

PN | PG | CT

Abbreviations used in measurement technologies
- AN: Active neutron method
- PN: Passive neutron method
- CT: X-ray CT method
- PG: Passive gamma rays method

[CT]

The evaluation methods are being studied by classifying as follows.
1) Neutron absorption material contained in fuel
2) Non-soluble neutron absorption material
3) Soluble neutron absorption material

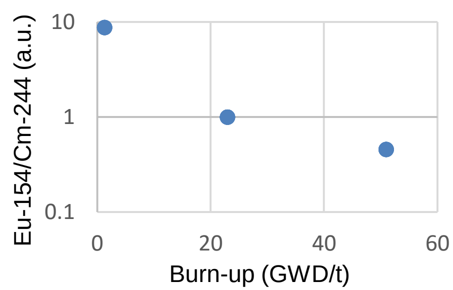


[PGA method] (AN+PG)

The method of quantifying the content of B and Gd by measuring gamma rays released from B and Gd as a result of (n,γ) reaction. (Detailed study required)

Estimation of burn-up by the PG/PN methods

- Burn-up was estimated using the relation between the Eu-154/Cm-244 weight ratio and burn-up
- Attenuation of gamma rays in the PG method is an issue



Estimation of moisture content by the AN/PN methods

- Weight of U (moisture content) was estimated using the conflicting characteristics
  "AN: Counting rate increases due to increase in moisture content"
  "PN: Counting rate decreases due to increase in moisture content"

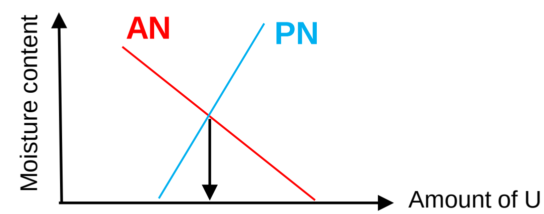


Image illustrating the dependency of the amount of U at the time of a specific counting rate on moisture content in the AN and PN methods

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

No.183

①-2 Active neutron method B (3/3)

Abbreviations used in measurement technologies
・AN: Active neutron method
・PN: Passive neutron method
・CT: X-ray CT method
・PG: Passive gamma rays method

<Summary and future issues>

[Implementation details]

1) The evaluation methods were studied based on the results of detector response analysis conducted when using the active neutron method

[Results/Contribution to development]

1) The results of studying evaluation methods are mentioned below.

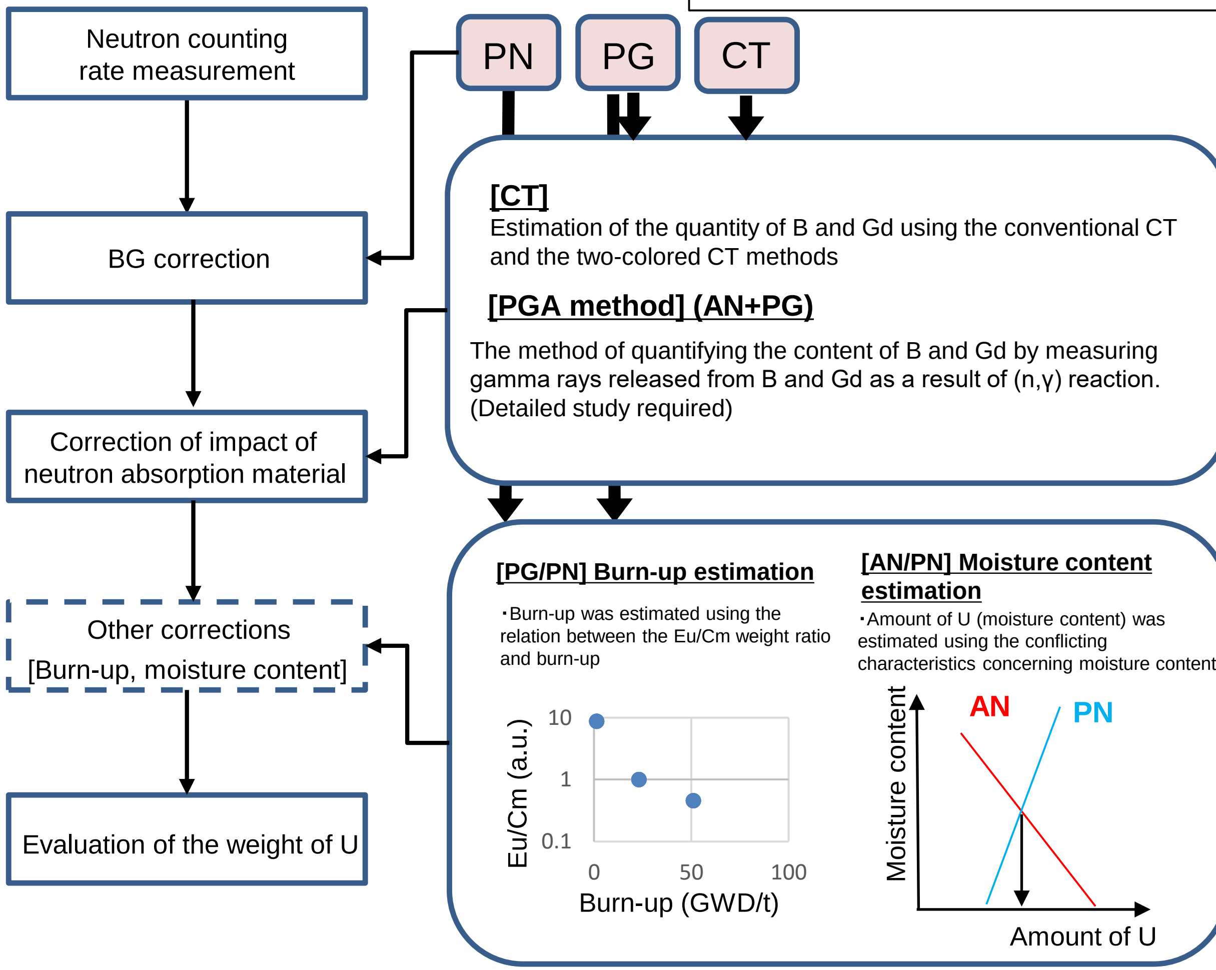
- A method of evaluating nuclear fuel material, which comprehensively incorporates the PN, PG methods as also the CT, PGA methods, etc. was proposed.
- The CT or PGA method can be used for neutron absorption material correction, the ratio of the amount of Eu (PG) and amount of Cm(PN) and the burn-up characteristics can be used for burn-up correction, and conflicting characteristics concerning moisture content in the AN and PN methods can be used for moisture content correction.

[Issues and response measures]

1) Issue: Verification of the effectiveness of the methods for neutron absorption material correction, burn-up correction and moisture content correction

Response measure:

The CT, PGA method, etc. should be evaluated for neutron absorption material correction, PG/PN methods, etc. should be evaluated for burn-up correction, and AN/PN methods should be evaluated for moisture content correction, and all these evaluations should be carried out using simulations.



4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(①-3 Active neutron method C)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
①-1	Active neutron method A	He-3	D-T	From the lateral side	Fissile nuclide mass	Fissile nuclide mass	MHI	43-55 161-179
①-2	Active neutron method B	B-10	D-T/ Accelerator based neutron source	From the top	Same as above	Same as above	Hitachi-GE	56-69 180-183
①-3	Active neutron method C (FNDI method + PGA method)	B-10 straw/He-3 (Determined based on the test)	D-T/D-D (Determined based on the test)	From the lateral side	Same as above	Same as above	JAEA	70-80 184-191

[Characteristics]

- In order to eliminate the variations in detector response brought about by the influencing factors, the Fast Neutron Direct Interrogation Method (FNDI method) was introduced which has been approved by IAEA for uranium waste (JAEA/Ningyo-toge).
- In order to correct the impact of neutron absorption material the Prompt Gamma Analysis Method (PGA method) was introduced.
- The B-10 straw detector was introduced for ensuring compatibility in high gamma irradiation locations.
- In order to enhance sensitivity of the detector when the quantity of Uranium is small, etc., the high speed neutron detector bank was introduced.

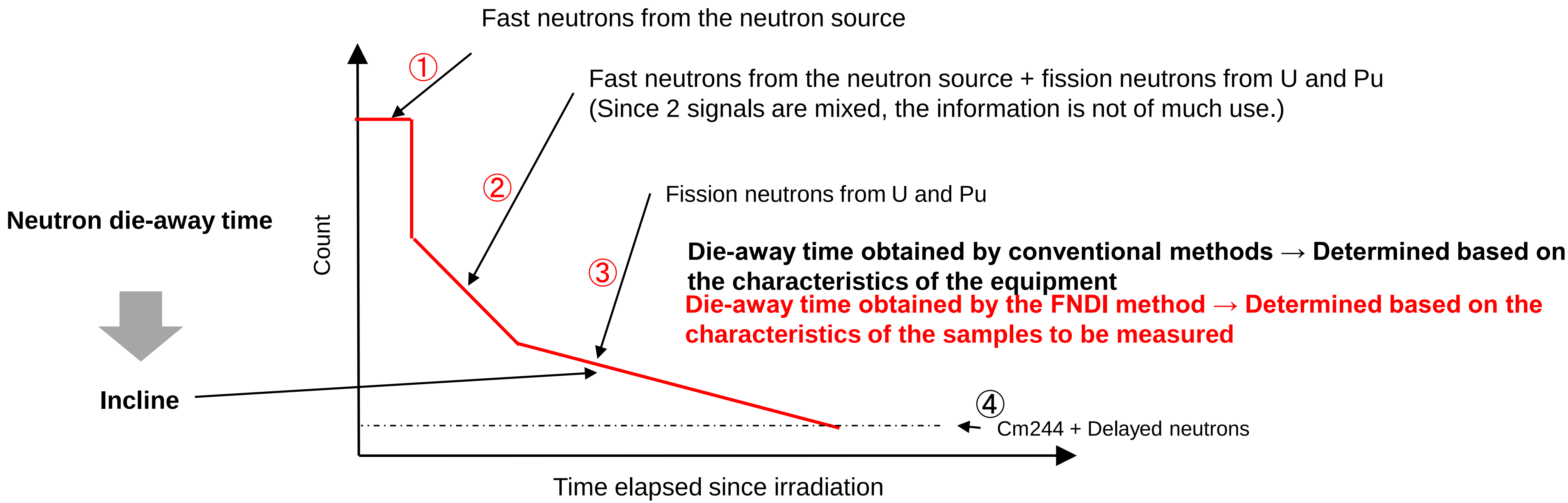
The method in which the FNDI method and the PGA method are used in combination is an improvement for resolving the issues in the conventional active neutron method, considering the diversity of fuel debris and other radioactive waste. (Refer to Attachment-1)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-3 Active neutron method C (1/7)

Purpose: To improve the efficiency of analysis using the neutron die-away time obtained by means of the Fast Neutron Direct Interrogation Method (FNDI method)

Spectrum obtained by the active neutron method



Strong point of the FNDI method: The neutron die-away time in ③ has information on the samples to be measured → Can be used for correction

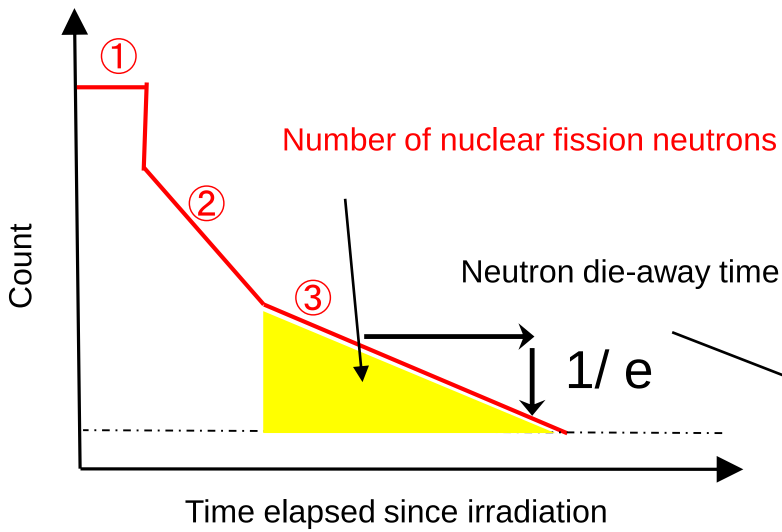
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-3 Active neutron method C (2/7)

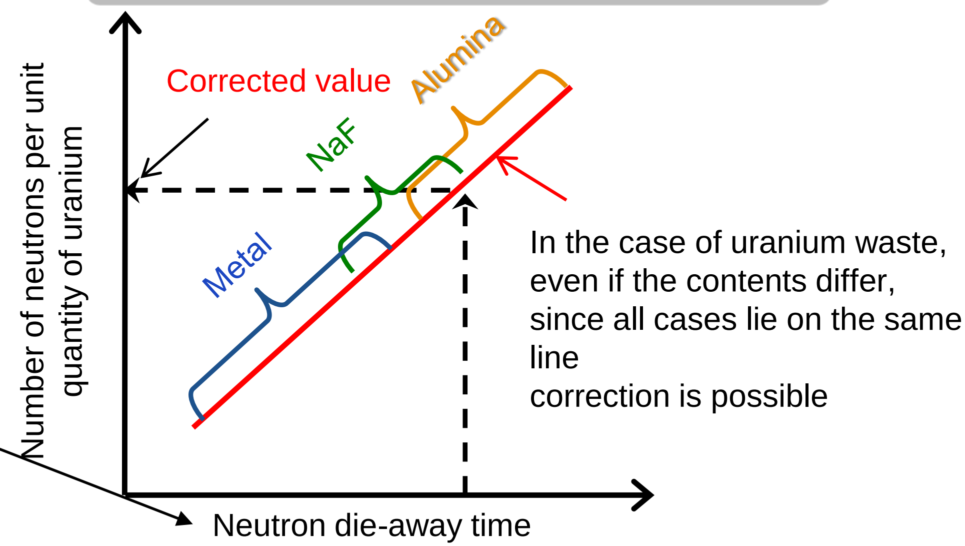
In the case of uranium waste, it is known that the quantity of uranium can be correctly obtained with the help of the corrected value obtained from the neutron die-away time.

Number of nuclear fission neutrons ÷ Corrected value ∝ Correct uranium quantity

Spectrum obtained by the FNDI method



Correlation between the neutron die-away time and the number of neutrons



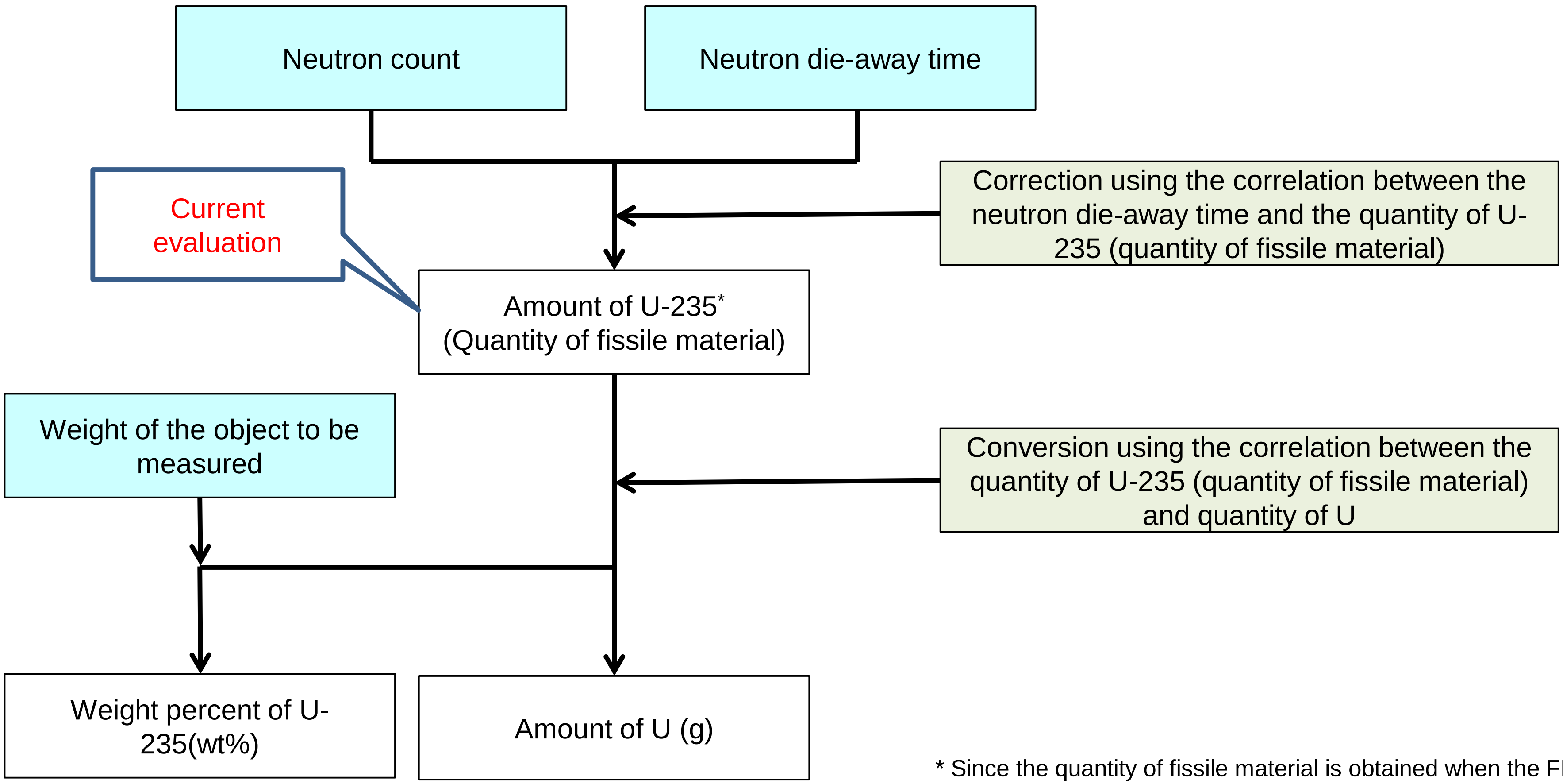
Whether or not correction is possible even when the method is used for fuel debris needs to be studied.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-3 Active neutron method C (3/7)

Estimation and Evaluation Flow

✓ The flow for estimating and evaluating the quantity of nuclear material using only the FNDI method of the active neutron method C was created.



* Since the quantity of fissile material is obtained when the FNDI method is used, it is converted to quantity of U-235

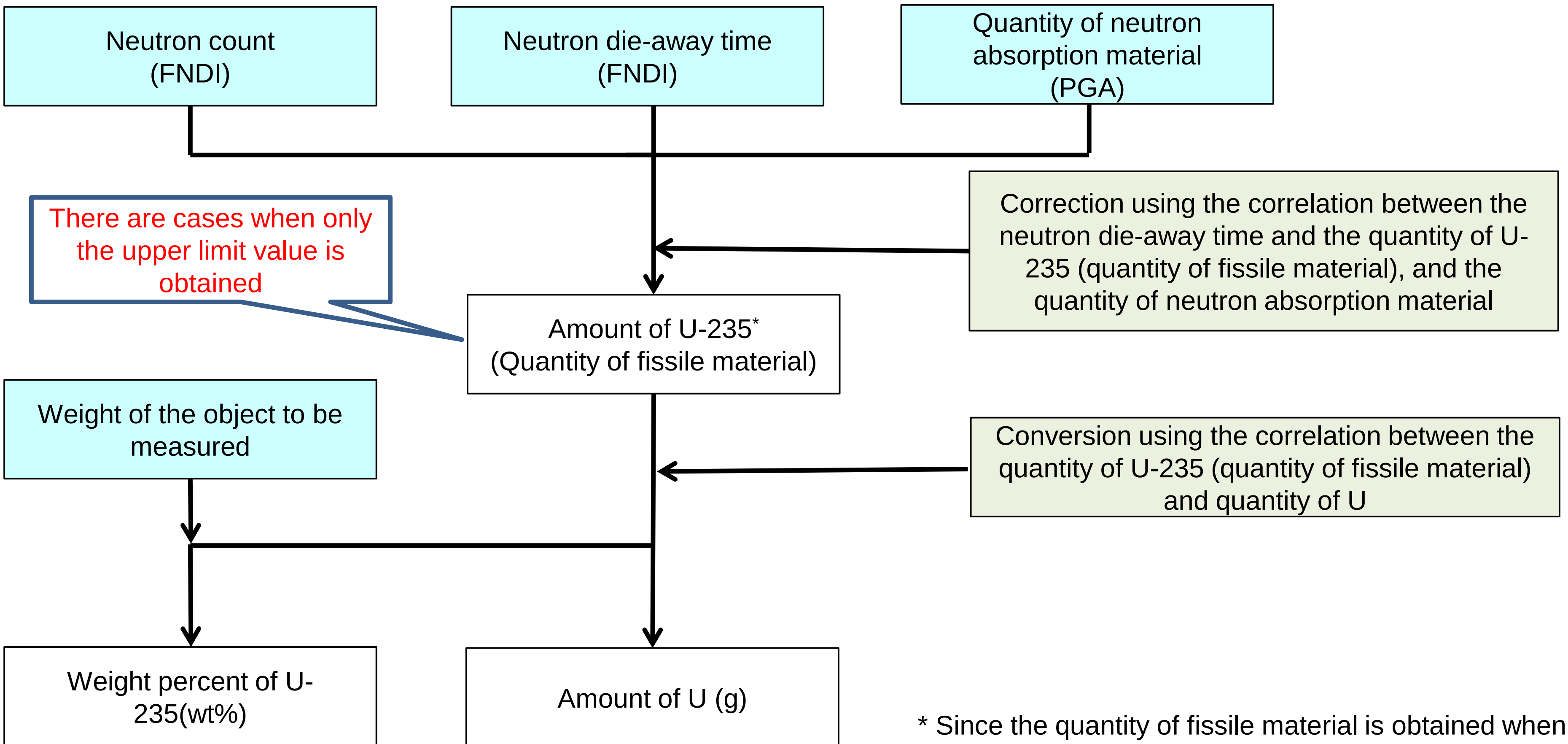
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-3 Active neutron method C (4/7)

Estimation and Evaluation Flow

Only the FNDI method was used in the evaluation this time.

✓ The flow for estimating and evaluating the quantity of nuclear material using the FNDI method of the active neutron method C + PGA method was created.



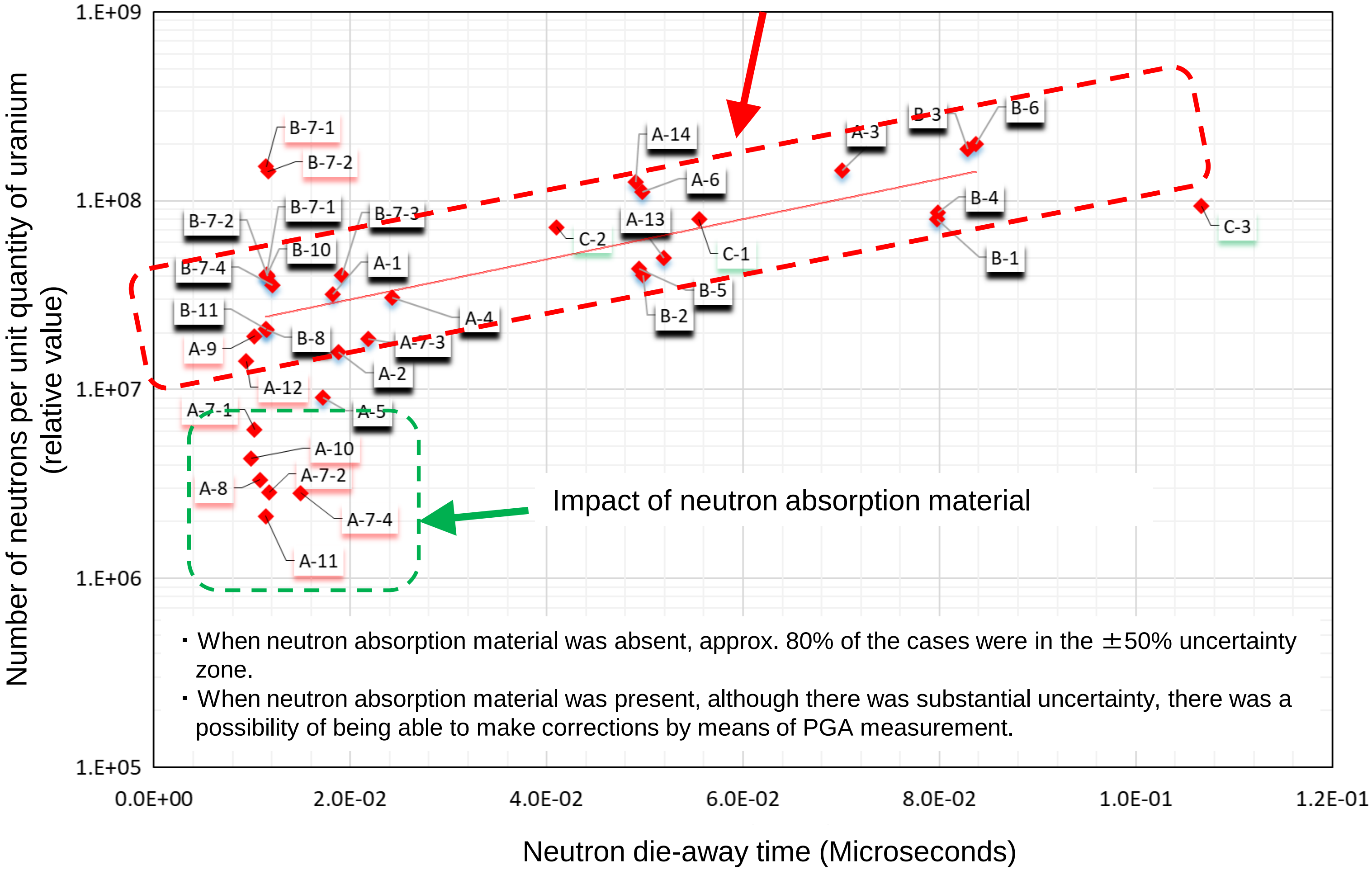
* Since the quantity of fissile material is obtained when the FNDI method is used, it is converted to quantity of U-235

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-3 Active neutron method C (5/7)

Study results

The results lie almost in a straight line and hence suggest that correction is possible.



- When neutron absorption material was absent, approx. 80% of the cases were in the ±50% uncertainty zone.
- When neutron absorption material was present, although there was substantial uncertainty, there was a possibility of being able to make corrections by means of PGA measurement.

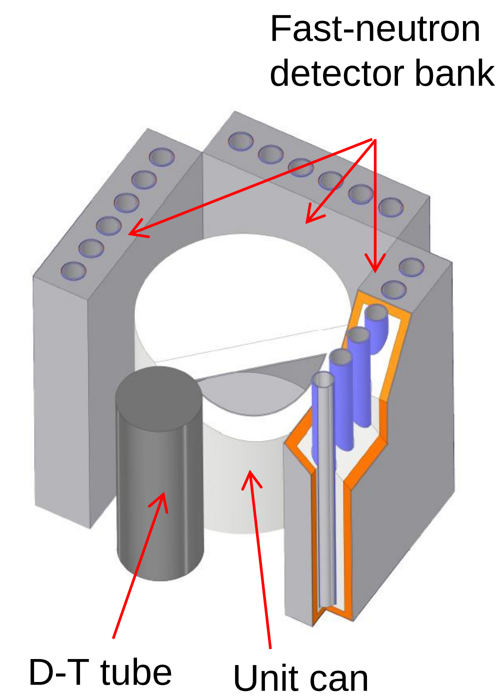


Illustration　Equipment example

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

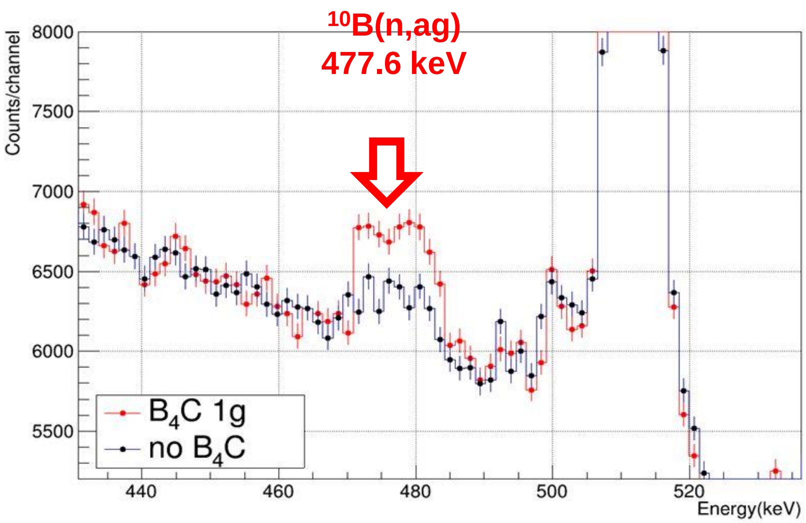
①-3 Active neutron method C (6/7)

FNDI method enables accurate measurements regardless of the contents of the samples to be measured, but can easily get influenced by the neutron absorption material (B, Gd). (Measurement cannot be performed if these neutron absorption materials are present in extreme abundance)

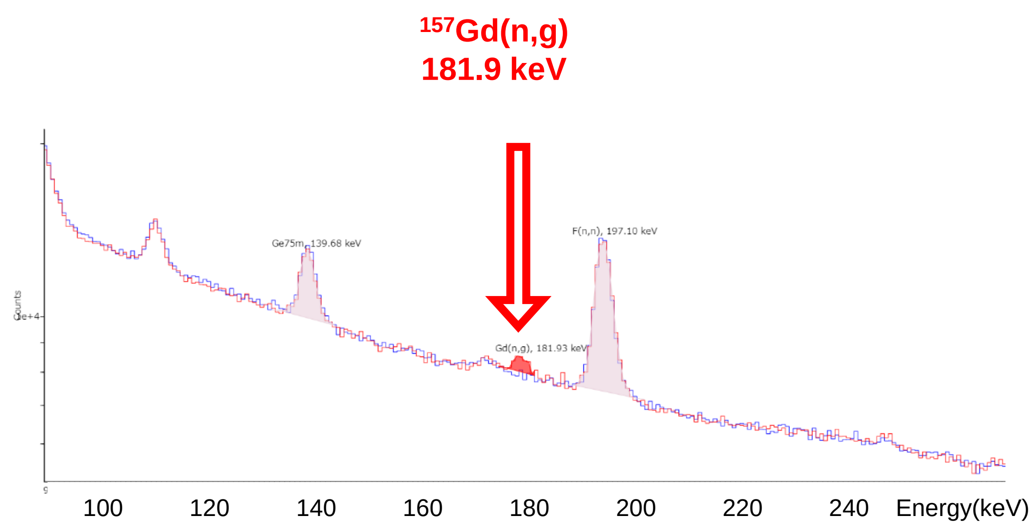
By introducing the PGA method, the impact on the FNDI method can be estimated by measuring the neutron absorption material and thus the accuracy of the FNDI method can be expected to be improved (improvement of sorting accuracy).

An example of measurement results obtained by means of the PGA method

・1g of B_4C was detected



・100g of Gd was detected



It was verified that neutron absorption material can be detected by the NDA equipment with which the FNDI method and PGA method can be implemented.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

①-3 Active neutron method C (7/7)

<Summary and future issues>

[Implementation details]

1) The correlation between the neutron die-away time and the number of nuclear fission neutrons per unit quantity of uranium when the FNDI method was used was obtained.

2) The quantity of U-235 was obtained through correction using the neutron die-away time for the 35 cases obtained as a result of simulated calculation.

3) The gamma rays from the neutron absorption material (B, Gd) generated due to the nuclear reaction resulting from neutron irradiation were measured.

[Results/Contribution to development]

1) Almost all cases obtained as a result of simulated calculation lie on a straight line on the graph with respect to the correlation between the neutron die-away time and the number of nuclear fission neutrons per unit quantity of uranium, which suggests that correction using the neutron die-away time is possible. Meanwhile, some of the samples that contained neutron absorption material did not lie on the straight line due to the impact of the neutron absorption material, and hence the correction may not function effectively.

2)

- As a result of evaluating the quantity of U-235, when the neutron absorption material was absent, the impact of the type of fuel debris or the burn-up was not prominent, and approx. 80% of the cases were in the ±50% uncertainty zone.
- When neutron absorption material was present, there were cases wherein quantity was determined even if there was about ±50% uncertainty, and the uncertainty tended to be larger as compared to when the neutron absorption material was absent. (There is a possibility of being able to carry out corrections using the quantity of neutron absorption material obtained by the PGA method.)

3) Detection of 1g of B_4C and 100g of Gd was successful in the PGA method test using neutron absorption material.

[Issues and response measures]

1) Issue: It was suggested that in many of the cases wherein neutron absorption material was absent an evaluation value with a small uncertainty would be obtained, but it was found that uncertainty tended to be larger in the cases wherein neutron absorption material was present as compared to the cases in which it was absent.

Response measure: Along with verifying the impact reduction effect of diversity through experiments by conducting elemental technology verification tests simulating diversity of samples (neutron absorption material in particular) using facilities where nuclear fuel material can be used and test equipment that can implement the active neutron method, attempts should be made to enhance the functionality of the impact reduction method.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(②-1 Passive neutron method A)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
②-1	Passive neutron method A	He-3	None	None	Mass of spontaneous fission nuclides (Cm-244, etc.)	Fissile nuclide mass	MHI	81-93 192-203
②-2	Passive neutron method B	B-10	None	None	Same as above	Same as above	Hitachi-GE	94-101 204-207

[Characteristics]

- The He-3 detector was selected based on its track record.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (1/11)

Overview of the evaluation method:
The quantity of nuclear material was estimated and evaluated based on the results of measuring neutrons that are constantly released by fuel debris containing spontaneous fission nuclides.

Measurement method	Explanation
Passive neutron method A	The weight of Cm-244 was evaluated based on the correlation function between the counting rate of neutrons released by spontaneous fission nuclides (Cm-244) and the set weight of Cm-244, and the weight of U-235 and the weight of U was evaluated assuming average burn-up*.

*Average burn-up…23.0GWd/t

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (2/11)

Molten debris cases that were evaluated

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate[*1]	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
A-1	Molten debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-2		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-3		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can
A-4		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-5		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-6		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can

*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (3/11)

MCCI debris cases that were evaluated

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
B-1	MCCI Debris	UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-2				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	None	Standard	20 years	Uniform	Unit can
B-3				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	None	Standard	20 years	Uniform	Unit can
B-4		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	60 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-5				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	None	Standard	20 years	Uniform	Unit can
B-6				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	None	Standard	20 years	Uniform	Unit can

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (4/11)

Metallic debris cases that were evaluated

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate[*1]	Cooling period	Uneven distribution	Container[*2]
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
C-1	Metallic debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 29.85 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-2		UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 44.85 vol%	**45 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-3		UO_2 : 0.48vol% ZrO_2: 0vol% SUS: 10 vol%	**10.48 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)

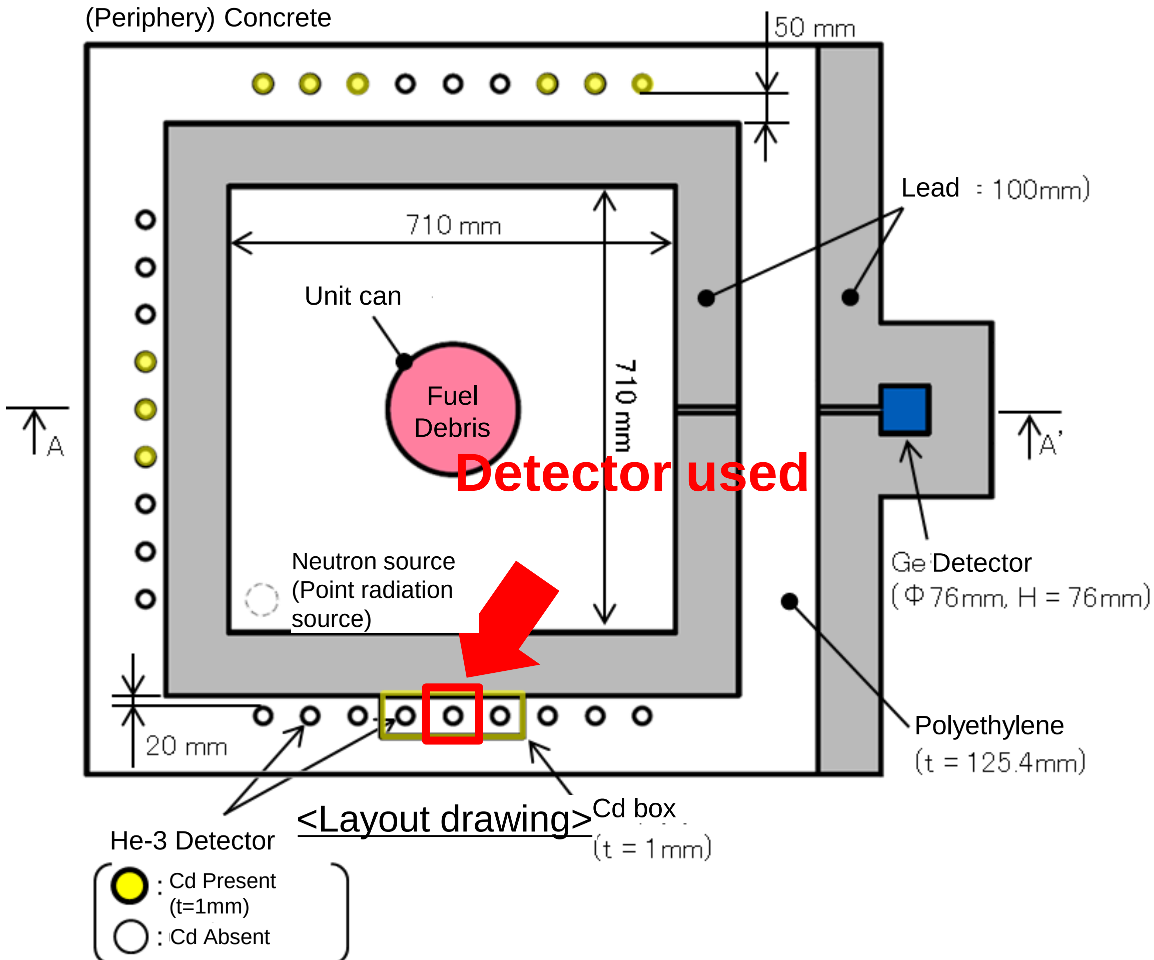
*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)
*2 Mainly made of SUS, it is assumed to be sorted as inner container during the initial stage of retrieval
*3 Overview of each case is indicated below.
- C-1: Base case
- C-2: Case of sensitivity with respect to SUS composition
- C-3: Case of sensitivity in which UO_2 has a volume percent equivalent to 3.7kg

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (5/11)

Detector used:

He-3 detector in a Cd box, which is used for the active neutron method A as well, was used.



<Layout drawing>

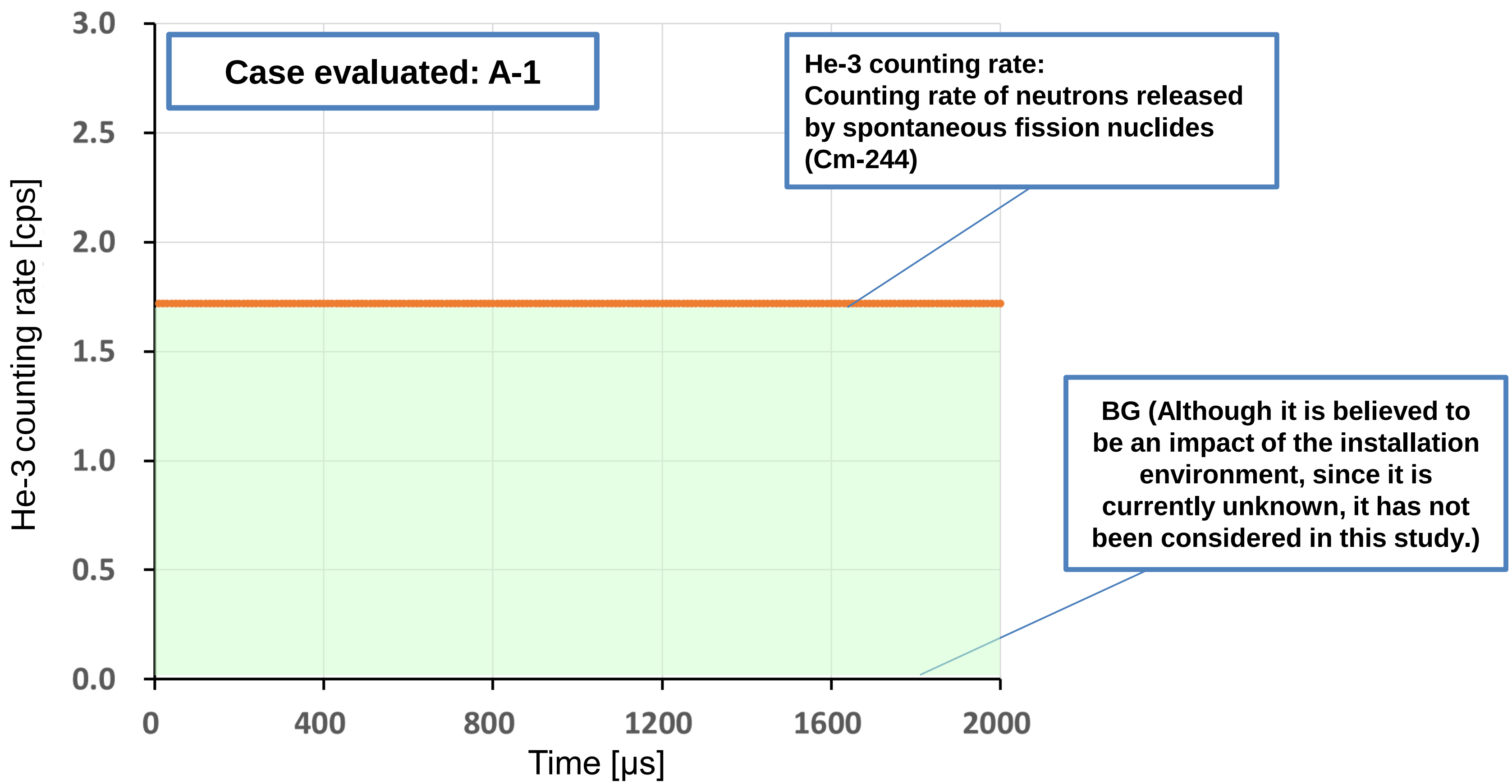
[Analysis conditions]

・Time resolution is 10μs

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (6/11)

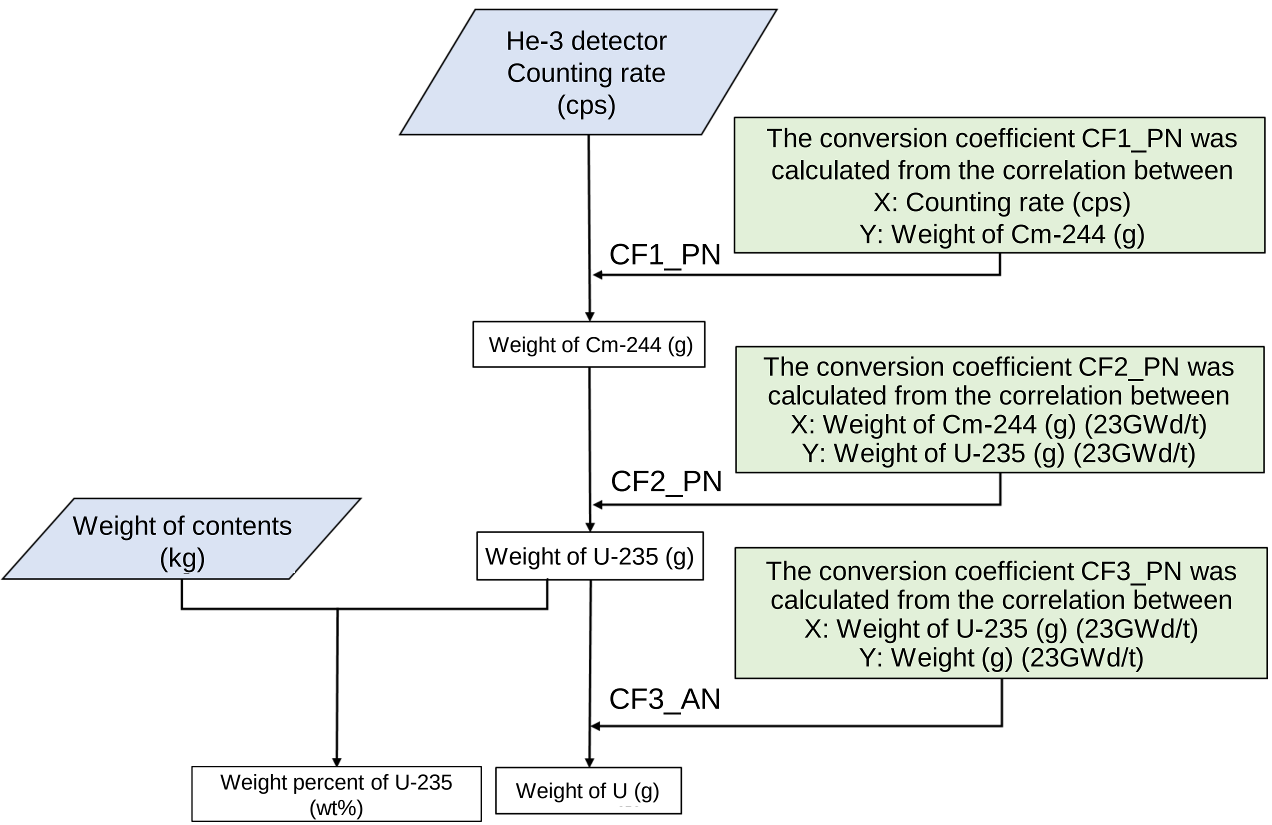
Overview:
The quantity of nuclear material was evaluated based on the correlation function between the counting rate of neutrons released by spontaneous fission nuclides (Cm-244) and the set weight of U-235.

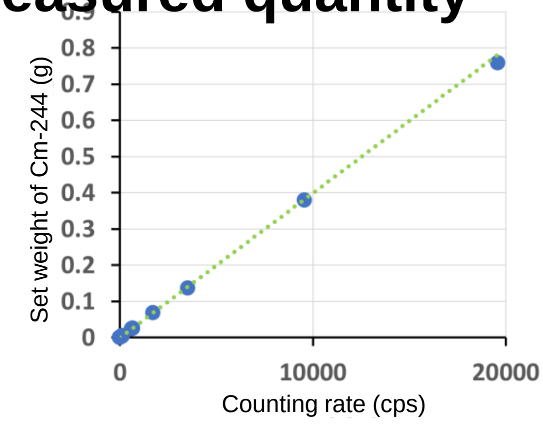


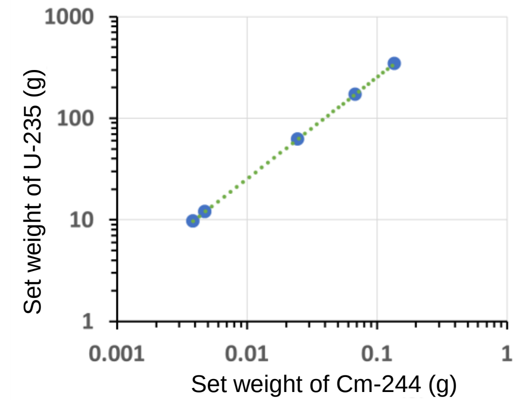
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

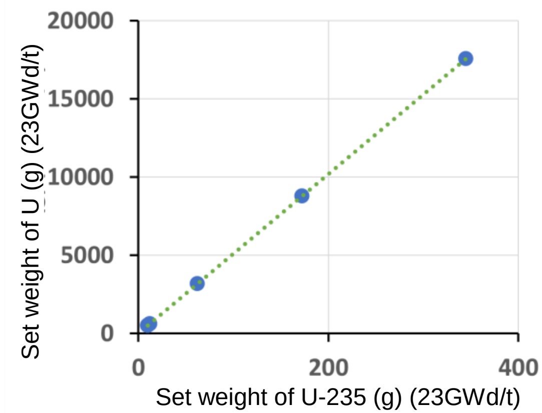
②-1 Passive neutron method A (7/11)

Estimation and Evaluation Flow：
The flow for estimating and evaluating the quantity of nuclear material using only the passive neutron method A was created.









BG was not considered in this study. The detection limit was not evaluated.

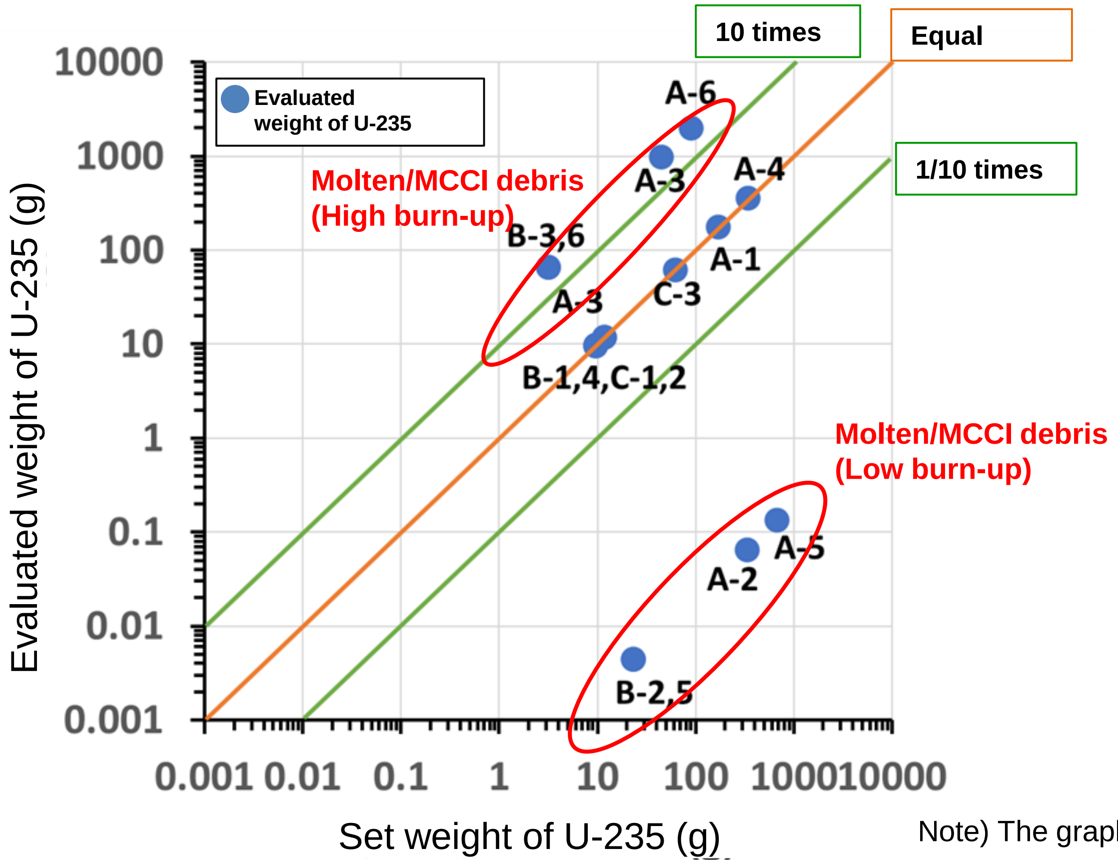
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (8/11)

Evaluation results_Weight of U-235 (g)

・ In the cases set up for evaluation this time, the evaluated value of U-235 deviated significantly from the set value of U-235 in the case of high burn-up as well as low burn-up.

・Since average burn-up was used for evaluating the weight of U-235 from the weight of Cm-244, there was overestimation in the case of high burn-up and underestimation in the case of low burn-up.



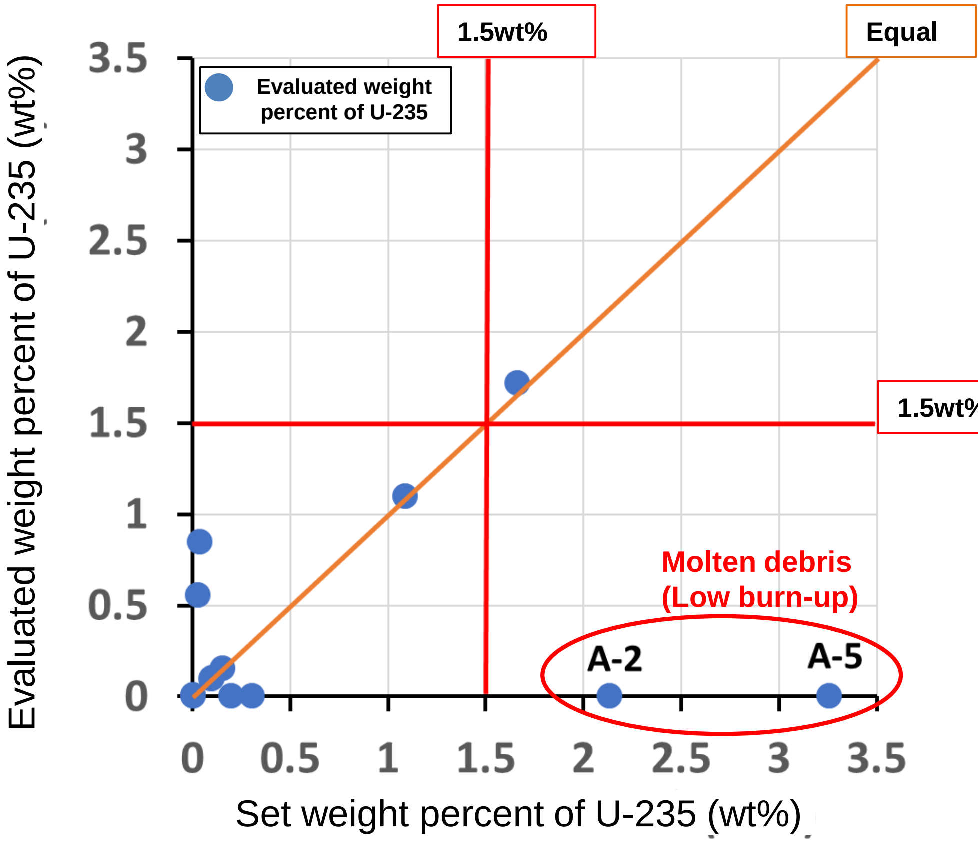
Note) The graph axes use a logarithmic scale

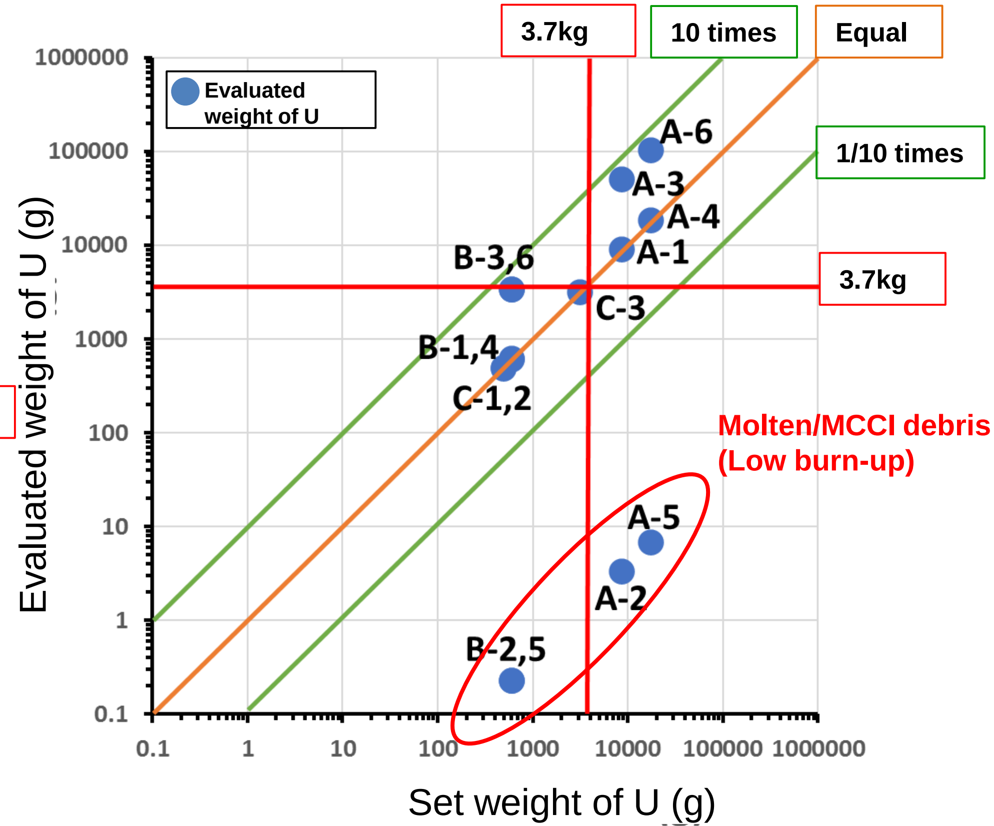
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (9/11)

Evaluation results_U-235 weight percent (wt%) and amount of U (g)

・Since average burn-up was used for evaluating the weight of U from the weight U -235, there was underestimation in the case of low burn-up.



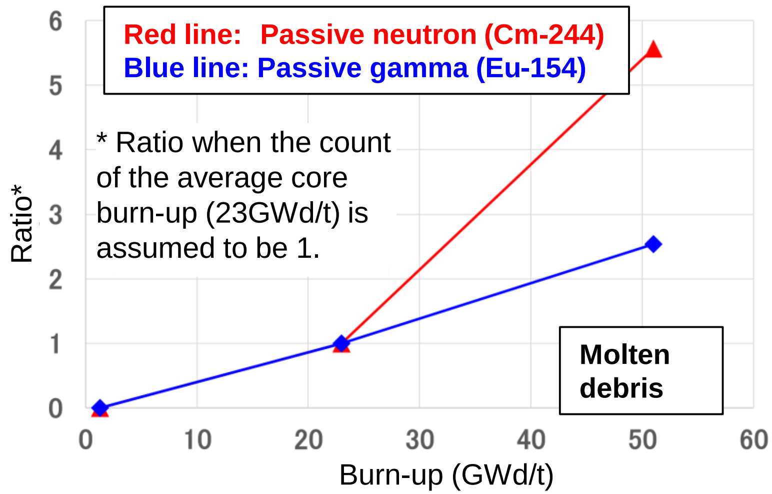


Note) The graph axes use a logarithmic scale

②-1 Passive neutron method A (10/11)

Proposed measures for improving performance

・Correction of impact of burn-up depending on the difference in correlation function between burn-up and the counting rate of Cm-244 and Eu-154(Same as No. 178)
(Passive neutrons method + passive gamma rays method)



Suggests that there is a possibility of being able to correct the impact of burn-up based on the ratio of the counting rates of Cm-244 and Eu-154.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-1 Passive neutron method A (11/11)

<Summary and future issues>

[Implementation details]

1) The evaluation flow for the passive neutron method was studied.
2) The evaluation accuracy of the quantity of nuclear fuel material, etc. was studied.

[Results/Contribution to development]

1) The evaluation flow for the passive neutron method was established.

2) The evaluation accuracy of the quantity of nuclear fuel material, etc. was estimated using the detector response analysis data.

- Weight of U-235: At most several 100 to several 1000 times (Molten debris/MCCI debris, low burn-up (1.3GWd/t))
- Weight percent of U-235: At most several 100 to several 1000 times (Molten debris/MCCI debris, low burn-up (1.3GWd/t))
- Weight of U: At most several 100 to several 1000 times (Molten debris/MCCI debris, low burn-up (1.3GWd/t))

[Issues and response measures]

1) Issue: Reduction of errors due to burn-up

Response measure: The correction method based on the ratio of Cm-244 and Eu-154 should be studied in detail.

The logic for explaining the carrying performance of Cm-244 & Eu-154 with U needs to be established.

3) Issue: Verification of the impact of diversity of other fuel debris

Response measure: Additional parameter studies on the conditions of the stored contents including heterogenous systems

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(②-2 Passive neutron method B)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
②-1	Passive neutron method A	He-3	None	None	Mass of spontaneous fission nuclides (Cm-244, etc.)	Fissile nuclide mass	MHI	81-93 192-203
②-2	Passive neutron method B	B-10	None	None	Same as above	Same as above	Hitachi-GE	94-101 204-207

[Characteristics]

- The B-10 detector was selected since it can be used in locations with high gamma rays.

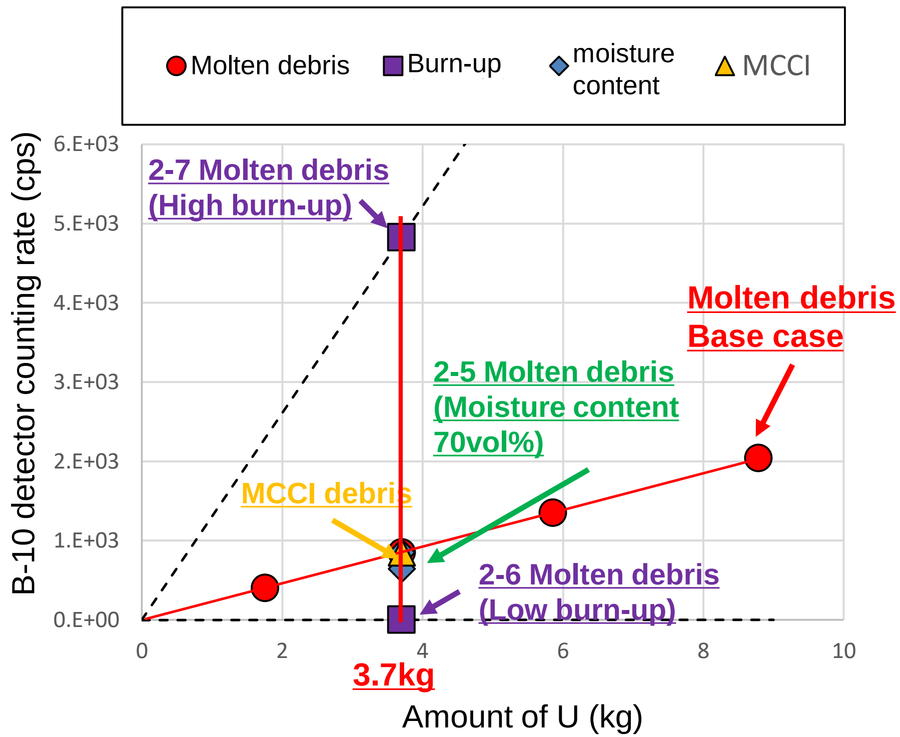
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-2 Passive neutron method B (1/3)

<Issues in nuclear fuel material evaluation>

1) As burn-up impact is large, it is essential to correct burn-up.

2) The impact of moisture content is about several percent. Correction is essential for improving accuracy (quantitative evaluation).



4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-2 Passive neutron method B (2/3)

Abbreviations used in measurement technologies
- AN: Active neutron method
- PN: Passive neutron method
- CT: X-ray CT method
- PG: Passive gamma rays method

Neutron counting rate measurement → Correction of burn-up impact → Other [Moisture content] corrections → Evaluation of the weight of U

AN / PG / CT

Estimation of burn-up by the PG/PN methods

- Burn-up was estimated using the correlation between the quantity of Eu-154/Cm-244 and burn-up.
- Attenuation of gamma rays in the PG method is an issue (Figure 2)
  ⇒ Gamma rays attenuation rate was adjusted by measuring bulk density, etc. by means of CT (Detailed study required)

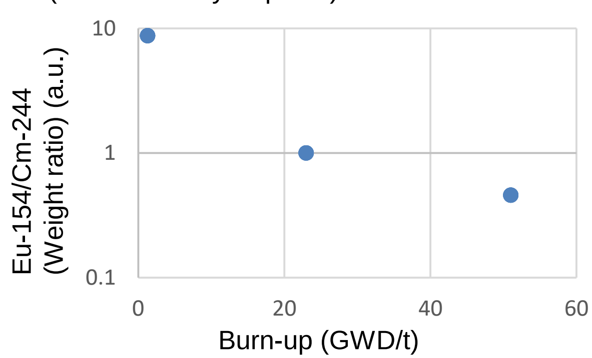


Figure 1 Burn-up dependency of Eu/Cm (weight ratio)

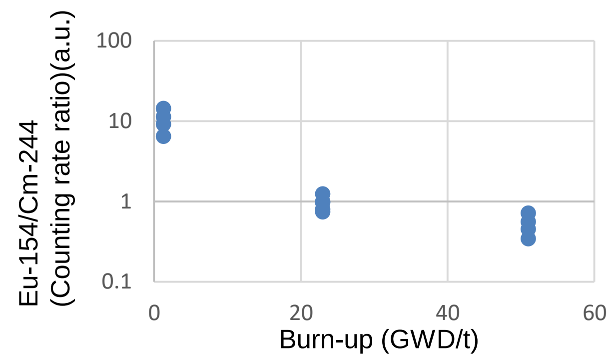


Figure 2 Burn-up dependency of Eu/Cm (Counting rate ratio)

Estimation of moisture content by the AN/PN methods

- Weight of U (moisture content) was estimated using the conflicting characteristics "AN: Counting rate increases due to increase in moisture content" "PN: Counting rate decreases due to increase in moisture content"

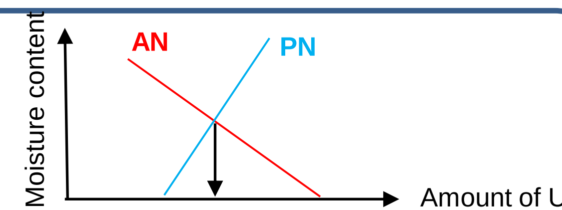


Image illustrating the dependency of the amount of U at the time of a specific counting rate on moisture content in the AN and PN methods

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

②-2 Passive neutron method B (3/3)

<Summary and future issues>

[Implementation details]

1) The evaluation methods were studied based on the results of detector response analysis conducted when using the passive neutron method

[Results/Contribution to development]

1) The results of studying evaluation methods are mentioned below

・A method of evaluating nuclear fuel material, which comprehensively incorporates the AN, PN methods as also the CT method, etc. was proposed.

・ The ratio of the amount of Eu (PG) and amount of Cm (PN) and the burn-up characteristics along with the CT correction can be used for burn-up correction, and the conflicting characteristics concerning moisture content in the AN and PN methods can be used for moisture content correction.

[Issues and response measures]

1) Issue: Verification of the effectiveness of the methods for burn-up correction and moisture content correction

Response measure: The PG/PN methods, etc. should be evaluated for burn-up correction, and AN/PN methods, etc. should be evaluated for moisture content correction, and all these evaluations should be carried out using simulations.

Abbreviations used in measurement technologies
・AN: Active neutron method
・PN: Passive neutron method
・CT: X-ray CT method
・PG: Passive gamma rays method

Neutron counting rate measurement
→ Correction of burn-up impact
→ Other [Moisture content] corrections
→ Evaluation of the weight of U

AN | PG | CT

[PG/PN] Burn-up estimation

・Burn-up was estimated using the correlation between the Eu/Cm burn-up (Figure 1).
・ Attenuation of gamma rays in the PG method is an issue (Figure 2)
⇒ Correction was carried out by means of CT (Detailed study required)

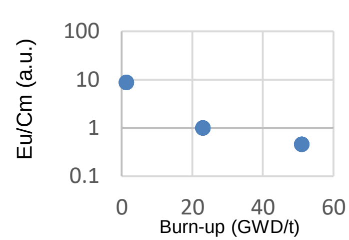


Figure 1 Burn-up dependency of Eu/Cm

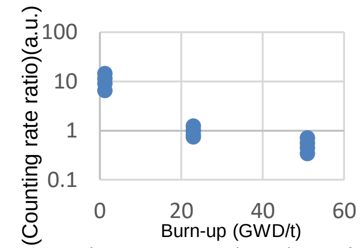
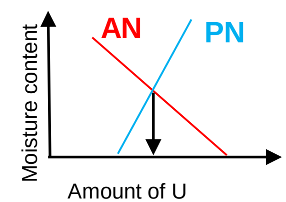


Figure 2 Burn-up dependency of counting rate ratio

[AN/PN] Moisture content estimation

・ Weight of U (moisture content) was estimated using the conflicting characteristics concerning moisture content.



4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

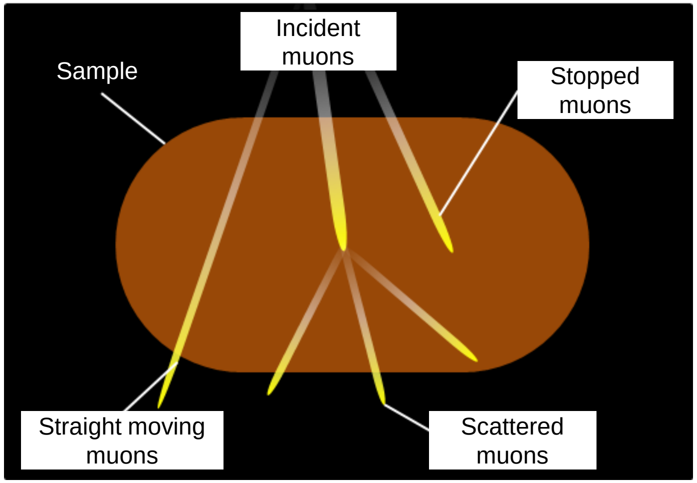
(③ Muon scattering method)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
③	Muon scattering method	Muon trajectory detector	None	None	Atomic weight	Fissile nuclide mass	Toshiba ESS	102-116 208-214

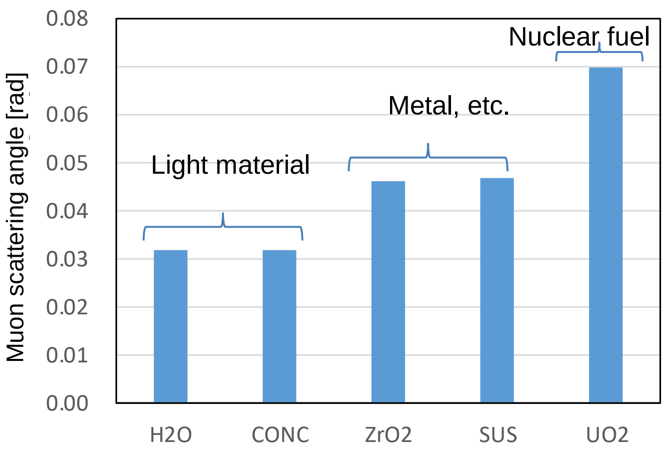
③ Muon scattering method (1/6)

(1) Establishment of the evaluation method

- The method of evaluating the weight of nuclear fuel in the fuel debris from the value obtained by measuring muons that vary by material was studied.
  - Behavior of muons in the material
    - Muon straight movement rate: The percentage of muons that pass through material
    - Muon scattering rate: The percentage of muons that scatter within material
    - Muon stopping rate: The percentage of muons that stop in the material
    - Muon scattering spectrum: The frequency distribution of the scattering angle of muons scattered within material



Main muon events



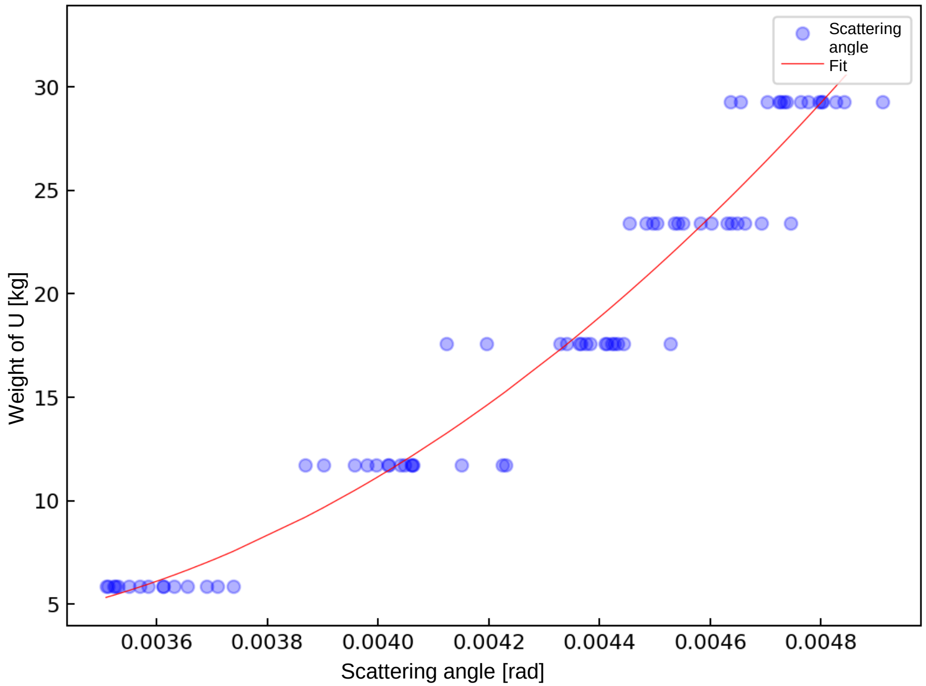
Comparison of average muon scattering in each material

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

③ Muon scattering method (2/6)

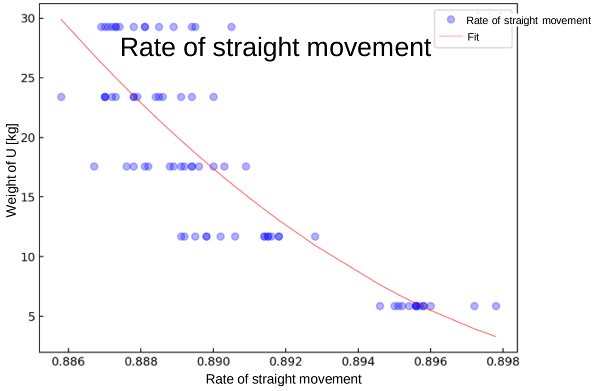
(1) Establishment of the evaluation method

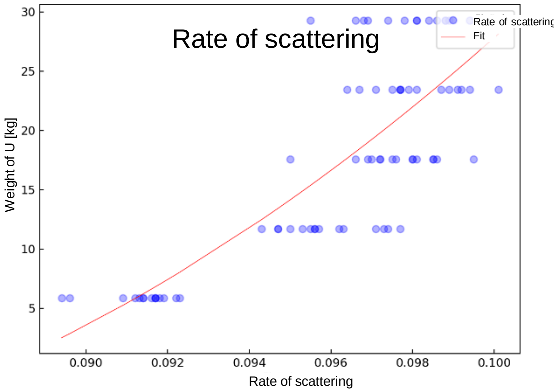
- Functions were established between the measured value and the quantity of nuclear material based on the criteria of uranium rich conditions.
- Methods to estimate the weight of U from each function were studied.

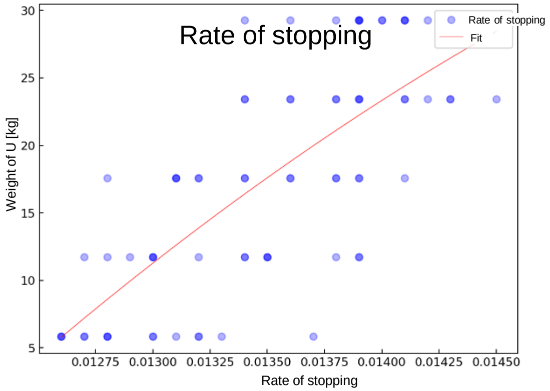


Weight of U corresponding to the muon scattering angle under uranium rich conditions

- A clear correlation between the muon scattering angle and the weight of U can be approximated with a quadratic equation.
- The rate of straight movement, rate of scattering and rate of stopping are loosely correlated.







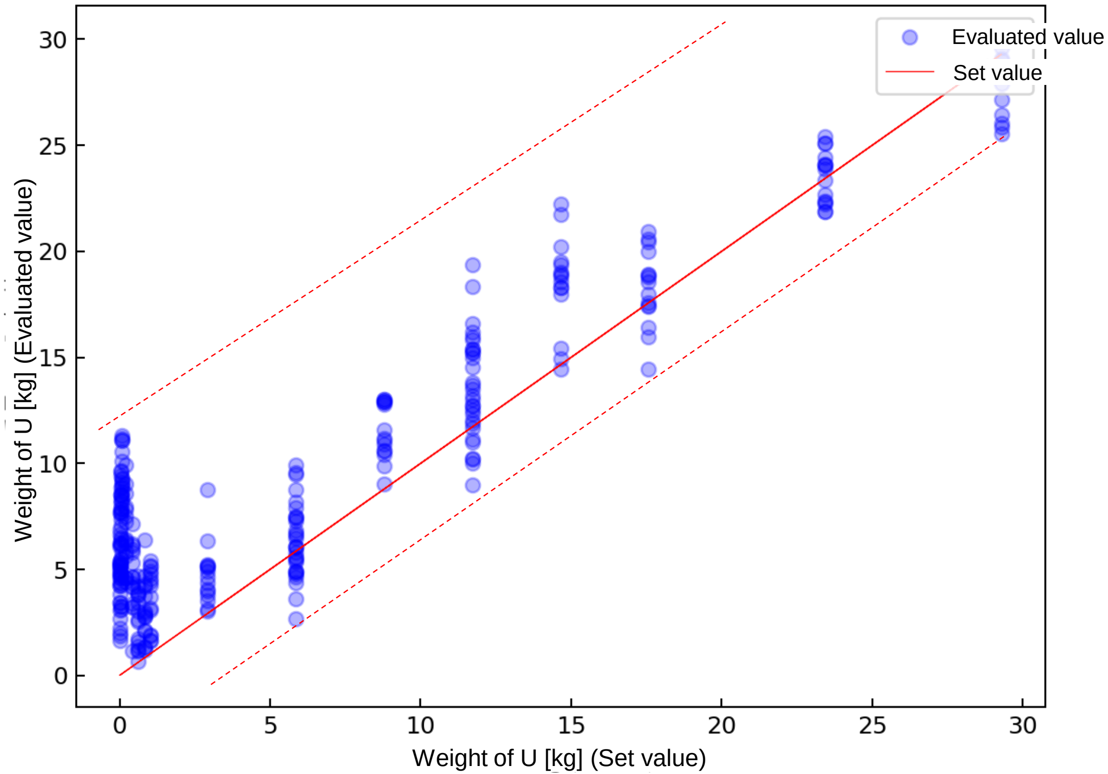
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

③ Muon scattering method (3/6)

(2) Evaluation results

- The weight of U in fuel debris was estimated using the evaluation functions created for uranium rich conditions.
  - Since the functions assume uranium rich conditions (UO_2:100%), the estimates are comparatively on the safer side.

  → There is a possibility of being able to estimate the lower limit of the weight of U that is likely to be contained in fuel debris, from the measurement results.



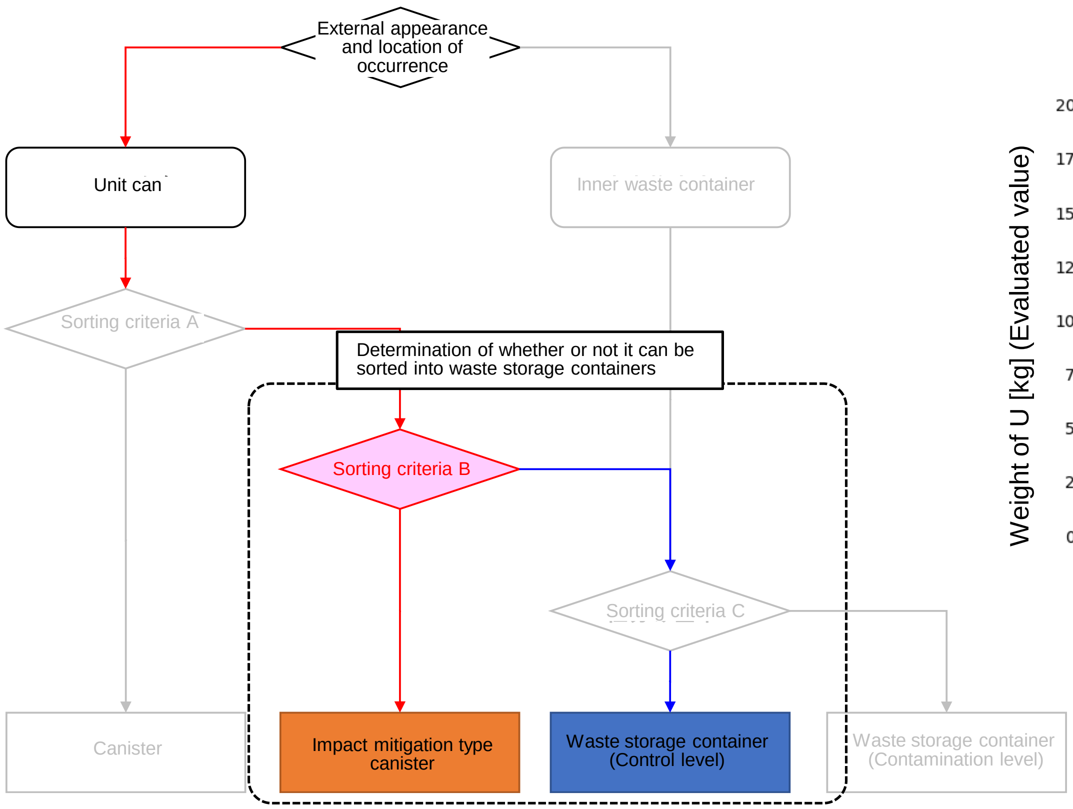
Results of estimating the weight of U using evaluation functions

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

③ Muon scattering method (4/6)

(3) The conditions for applying this method to fuel debris sorting were studied.

- Whether or not fuel debris can be sorted into waste storage containers was determined.
  - Target value: U content less than 3.7kg
  - → U content was evaluated based on the correspondence between weight of U and the measured value



Sorting flow

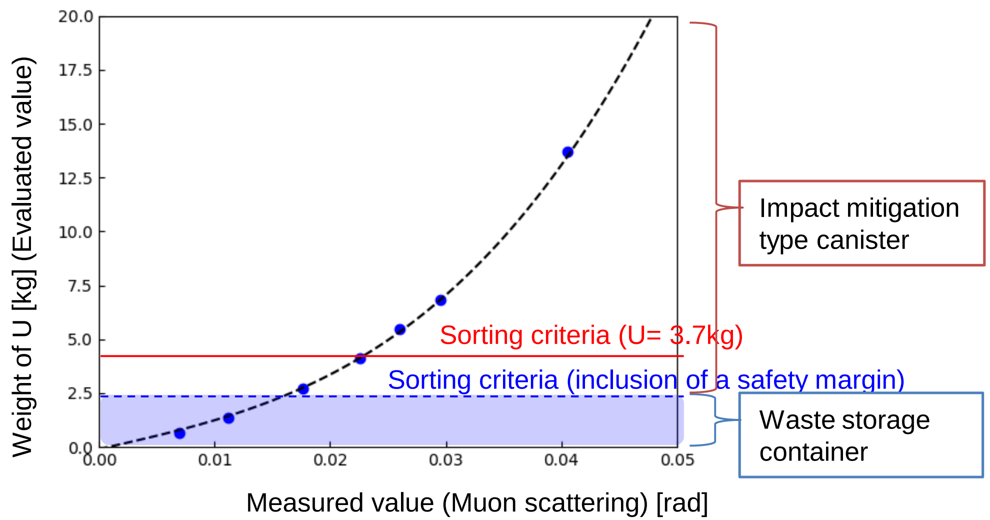


Image illustrating sorting based on evaluated weight of U

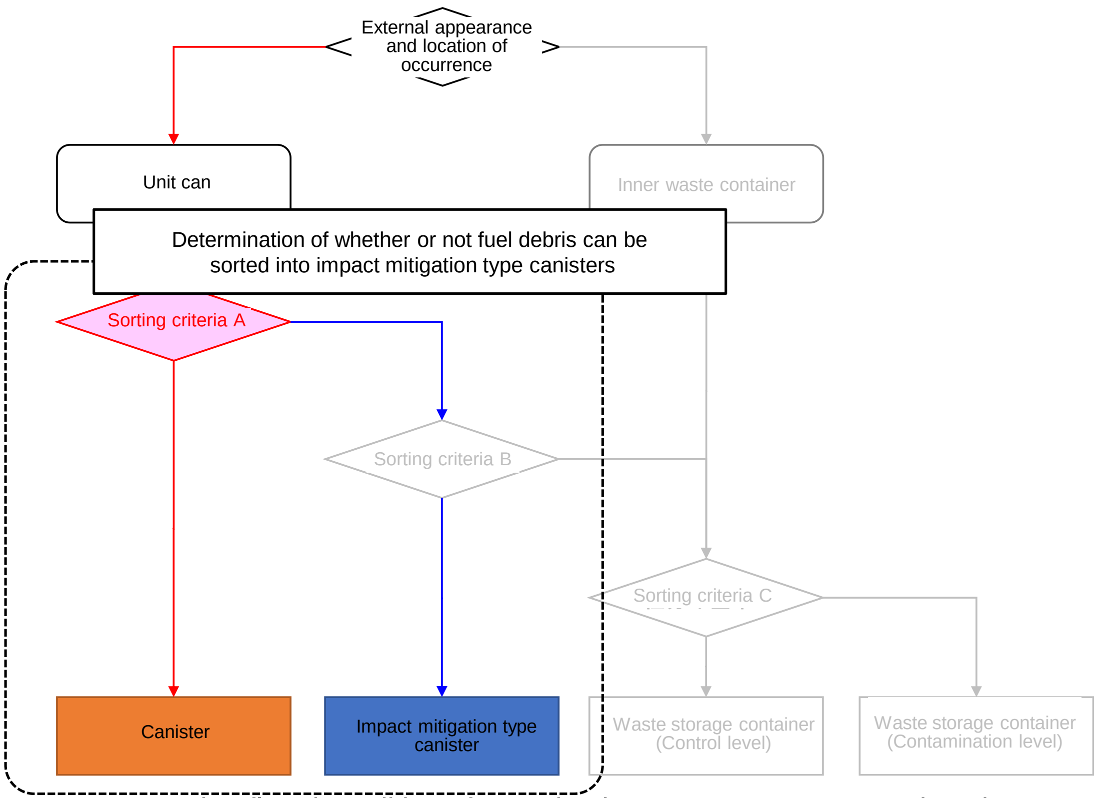
- It was determined that the fuel debris can be stored in waste storage containers if it falls below the sorting criteria considering errors.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

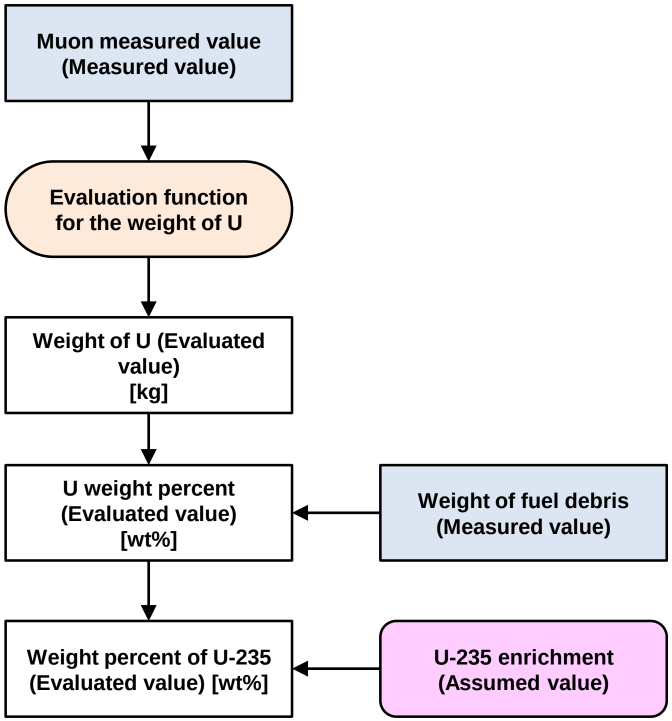
③ Muon scattering method (5/6)

(3) The conditions for applying this method to fuel debris sorting were studied.

- It was determined whether or not fuel debris can be sorted into impact mitigation type canisters
  - Target value: Containing less than 1.5wt% of U-235 (impact mitigation type canister)
  - → The U content percentage was determined based on the weight of fuel debris and weight of U.
  - → Comparison with the sorting criteria was possible by estimating the U-235 content percentage



Sorting flow (Conditions for sorting into waste storage containers)



Evaluation flow for the weight percent of U-235

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

③ Muon scattering method (6/6)

<Summary and future issues>

[Implementation details]

1) The evaluation function for estimating the weight of U in fuel debris based on the muon measured value under uranium rich conditions was created.

2) The weight of U was estimated by applying the evaluation function to molten debris, MCCI debris and metallic debris.

3) Conditions for applying the evaluation function to sorting of fuel debris were studied.

[Results/Contribution to development]

1) The accuracy of estimating the weight of U using evaluation functions was evaluated.
   - Weight of U was estimated with a variation of approx. 10kg.
   - A margin of safety was set and the possibility of application to sorting fuel debris was verified.

2) The method of determining sorting by combining other measured values was studied.
   - The percentage of U-235 was evaluated from the measured weight of fuel debris and the estimated weight of U.

[Issues and response measures]

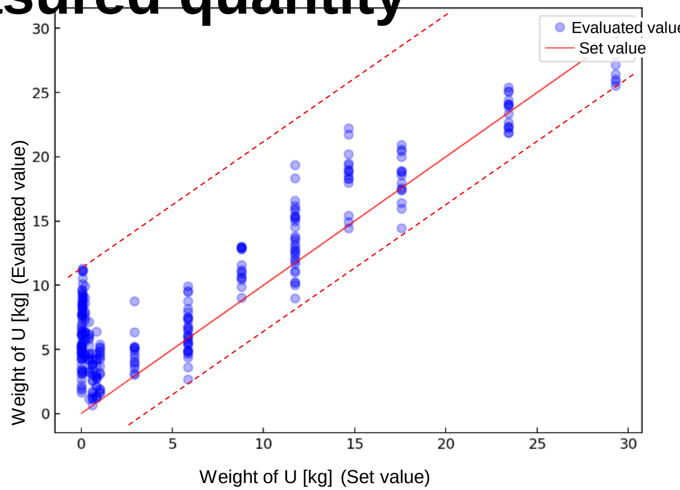
1) Issue: Evaluation function error reduction

Response measure: The evaluation function should be made more specific by increasing the analysis cases

Response measure: The accuracy should be increased by combining with basic information such as fuel debris weight, etc.

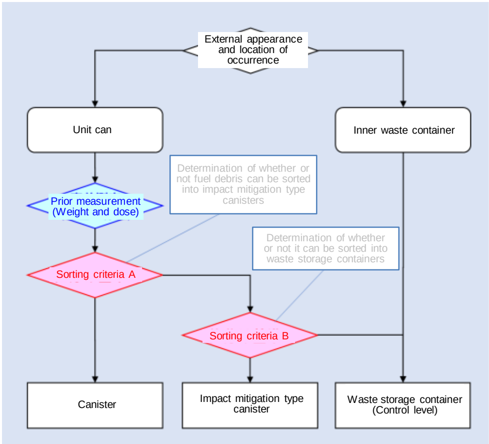
2) Issue: Study of applicability of the method of evaluation using actual measurement

Response measure: Tests on estimating the weight of material using samples with known compositions should be conducted.

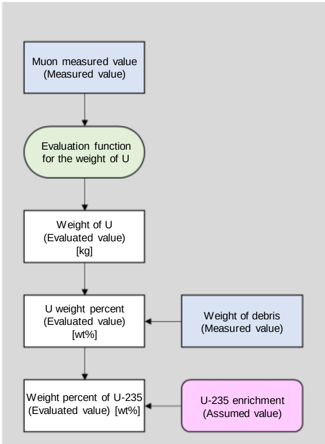


Set weight and evaluated weight of U

- Function for evaluating the weight of U from the measured value was created.
- Rough estimation of the weight of U by applying the evaluation functions



Application of sorting scenarios



Evaluation of U-235 content percentage

- Application to determination of storage into canister or waste storage container
- Evaluation of U content and U-235 content percentage

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(④ X-ray CT method)

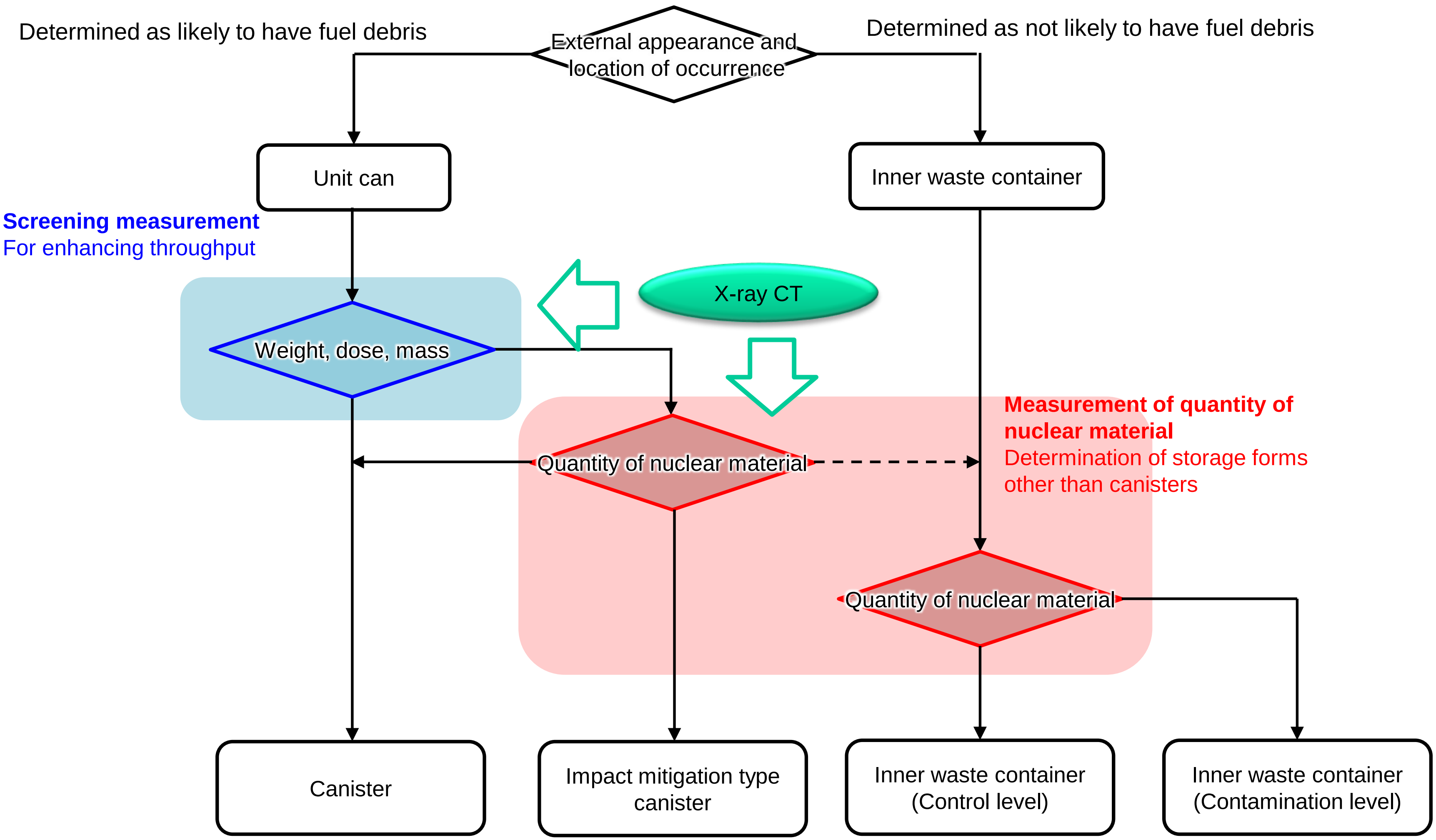
No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
④	X-ray CT method	X-ray detector	Accelerator based X-ray source	From the lateral side	Density	Fissile nuclide mass	Hitachi-GE	117-127 215-220

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

④ X-ray CT method (1/5)

<Positioning in the evaluation flow>

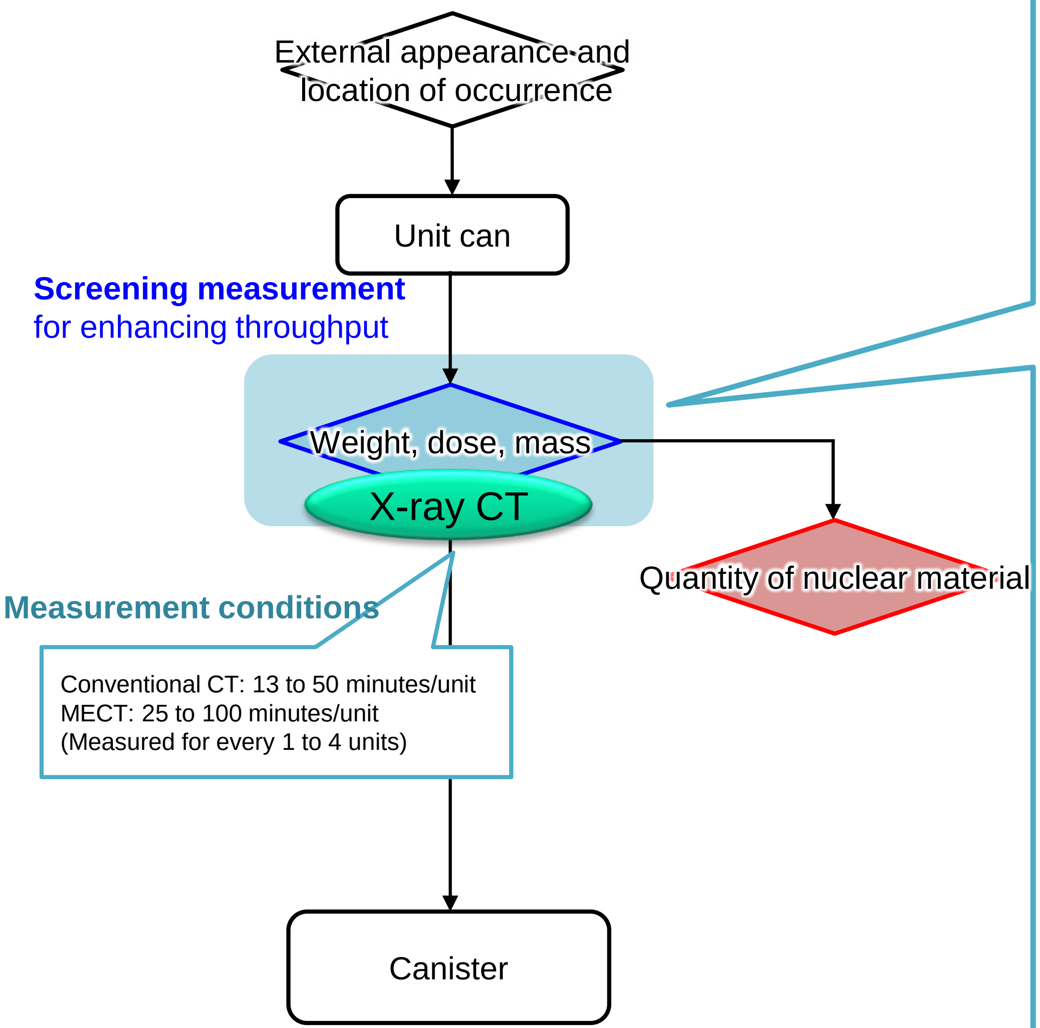
Application to screening measurement and measurement of quantity of nuclear material is anticipated.



4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

④ X-ray CT method (2/5)

<Example of screening measurement>

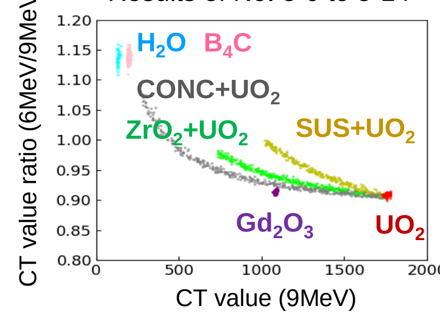


Conservative rough estimation of the quantity of nuclear material with only the X ray CT method

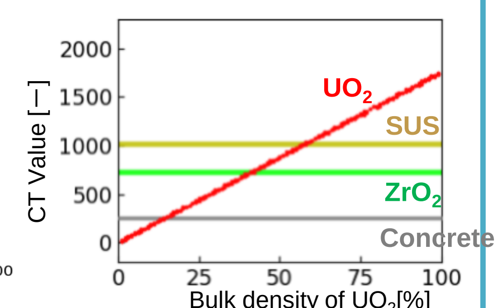
Measurement method

Determination of shape	Structure, or shape of sand, particles, lumps, etc.
Identification of material	Identification of material by conventional CT and MECT Criteria used in accordance with the shape
Calculation of the volume of nuclear material	Calculated based on the product of the number of voxels that are identified as nuclear material and the volume of the voxels
Rough estimation of the quantity of nuclear material	Quantity of uranium is calculated by conservatively setting the density and enrichment
Addition of unidentified material to the quantity of nuclear material	Material that is difficult to identify is calculated as nuclear material with changed bulk density

Results of No. 5-9 to 5-14



Results of No. 5-7

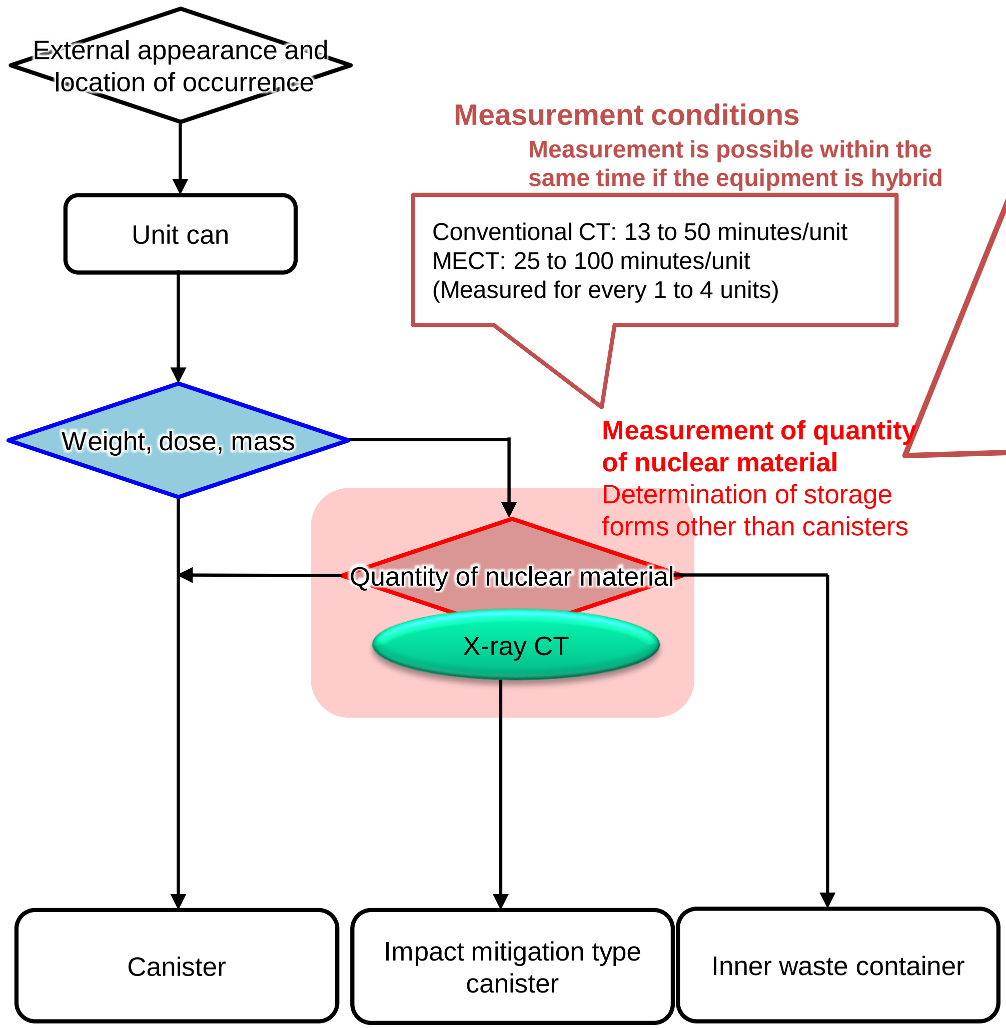


4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

④ X-ray CT method (3/5)

The quantity of nuclear material was evaluated by combining the X-ray CT method and other measurement methods.

<Example of the measurement of quantity of nuclear material>



Measurement method

Fast measurement of quantity of nuclear material using the X-ray CT method + active neutron method

■ Study of combination of measurement technologies

Table for reviewing the complementary relationship between measurement technologies

Measurement technology (limitation)	Information on how the measurement technology complements
X-ray CT (Size of nuclear fuel)	・Evaluates nuclear fuel regardless of the neutron absorption material **・Evaluates the quantity of neutron absorption material and is used for correction**
Active neutron (Neutron absorption material)	・Can evaluate nuclear fuel regardless of the size of nuclear fuel

■ Study of the method of evaluating the quantity of neutron absorption material

1) Neutron absorption material contained in fuel

Rough estimation by assigning the maximum Gd content contained in actual fuel debris to material that is identified as nuclear fuel by the X-ray CT method.

2) Non-soluble neutron absorption material[1,2]

Candidate material	State of material	Density [g/cm^3]	Size
Glass material containing B and Gd	Solid	3.3 to 4.4	About 1cm
Gd_2O_3 particles		4.3	About 0.5cm
Water glass / Gd_2O_3 granulated powder	Solidified substance	2.1	

Illustration of granulated powder of water glass/Gd_2O_3

3) Soluble neutron absorption material (Example: Boric acid solution)

Rough estimation by assigning the B content of boric acid solution to material that is identified as water by the X-ray CT method

[1] Project coordination meeting between IRID Sorting PJ and related projects (November 10, 2022) Document "Provision of information related to non-soluble neutron absorption material" provided by Toshiba ESS
[2] Subsidy Project of Decommissioning and Contaminated Water Management in the FY2015 Supplementary Budget - Development of Criticality Control Technology for Fuel Debris Research Report (FY2017 Final Report), March 2018, IRID

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

④ X-ray CT method (4/5)

<Details of the study on combination of methods for measuring quantity of nuclear material>

Example of combination of the X-ray CT method and other measurement technologies for measuring quantity of nuclear material

	Quantity measured	Factors leading to underestimation and overestimation of the quantity of nuclear fuel material (Measurements of quantity of nuclear material have been compiled from the studies carried out under the FY2021 Subsidy Projects)	Correction method using the X-ray CT method
Screening measurement	Weight	･Substances other than nuclear material are present	･Identification of nuclear material and other material
Screening measurement	Temperature	･Uneven distribution of nuclear material that serves as a source of heat	･Correction based on information on the distribution of material
Screening measurement	Dose	･FP emission rate is low ･Contains lot of metal ･Uneven distribution of material	— ･Correction based on the quantity of metal contained ･Correction based on information on the distribution of material
Measurement of quantity of nuclear material	Passive gamma rays (Eu-154)	･If there is major self shielding ･If burn-up is low ･If there is uneven distribution	･ Correction of the self-shielding coefficient — ･ Correction based on information on the distribution of material
Measurement of quantity of nuclear material	Passive neutrons (Cm-244)	･If burn-up is low ･If moisture content is high	— ･Correction by detecting moisture
Measurement of quantity of nuclear material	Active neutron (U-235, Pu-239)	･If lot of neutron absorption material is present ･If there is uneven distribution	･ Correction of neutron absorption material ･ Correction based on information on the distribution of material

➢ In the future, detailed studies are planned by conducting tests, analysis, etc.

IRID

④ X-ray CT method (5/5)

<Summary and future issues>

[Implementation details]

1) The accuracy of measuring the quantity of nuclear material by only the X-ray technology was evaluated.

2) The correction data used in the evaluation method wherein multiple measurement technologies are combined was studied.

3) The evaluation method involving neutron absorption material which includes a combination with active neutron method was studied.

[Results/Contribution to development]

1) Based on the detector response analysis, it was found that the measurement accuracy with the conventional CT methods was at most 6% for molten debris and MCCI debris filled in unit cans and for metallic debris filled in inner waste containers when nuclear material is not mixed with other material.

2) Among the items in which measurement technology had a high impact, the prospective correction data on items other than burn-up or FP emission rate (quantity of neutron absorption material contained, moisture, uneven distribution, quantity of metal or concrete, self shielding effect) was consolidated.

3) As a result of studies it was found that there are prospects of the following methods being applicable as the evaluation method for each type of neutron absorption material:
The method of detecting nuclear fuel by the X-ray CT method and calculating based on the Gd content for the absorption material contained in fuel;
The method of detecting water by the X-ray CT method and calculating by assigning B content for the soluble neutron absorption material;
The method of direct detection of absorption material with particle size 0.5 to 1.0mm by the X-ray CT method for non-soluble neutron absorption material

<Itemized as below>

・Measurement accuracy: At most 6% (When nuclear fuel is not mixed with other material)
・Influencing factor: Size of nuclear material, bulk density, mixing with other material
・Prospective correction data for other measurement technologies: Quantity of neutron absorption material contained, moisture, uneven distribution, quantity of metal or concrete, self-shielding effect

[Issues and response measures]

1) Issue: The identifiability of nuclear fuel with a changed bulk density or which is mixed with other material by means of only the X-ray CT technology was verified by detector response analysis, but a specific evaluation method has not yet been established.

1) Response measure: An algorithm for evaluating the quantity of nuclear fuel by MECT method should be developed, and the accuracy of measuring the quantity of nuclear fuel in material having diverse properties should be evaluated.

2) Issue: Specific methods for providing correction data for other measurement technologies have not yet been studied.
(Example: It is unclear what information is supposed to be provided for what material if there is uneven distribution.)

Response measure: Specific methods for providing correction data for other measurement technologies and its accuracy should be studied.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(⑤ Passive gamma rays method A)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
⑤-1	Passive gamma rays method A	Ge	None	None	Mass of fission product nuclides (Eu-154, etc.)	Fissile nuclide mass	MHI	128-140 221-233
⑤-2	Passive gamma rays method B	CZT, $LaBr_3$, etc.	None	None	Same as above	Same as above	Hitachi-GE	141-154 234-237

[Characteristics]

- The Ge detector was selected based on its energy resolution and track record.

⑤-1 Passive gamma rays method A (1/12)

Overview of the evaluation method:
The quantity of nuclear material was estimated and evaluated based on the results of measuring gamma rays that are constantly released by fuel debris.

Measurement method	Explanation
Passive gamma rays method A	The weight of Eu-154 was evaluated based on the correlation function between the counting rate of gamma rays released by fission products (Eu-154), and the weight of U-235 and the weight of U was evaluated assuming average burn-up*.

*Average burn-up…23.0GWd/t

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (2/12)

Molten debris cases that were evaluated

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
A-1	Molten debris	UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-2		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-3		UO_2 : 15 vol% ZrO_2 : 15 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can
A-4		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
A-5		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	None	Standard	20 years	Uniform	Unit can
A-6		**UO_2 : 30 vol% ZrO_2 : 0 vol%**	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	**51GWd/t**	None	Standard	20 years	Uniform	Unit can

*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (3/12)

MCCI debris cases that were evaluated

Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
B-1	MCCI debris	UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 20.7vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-2				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	None	Standard	20 years	Uniform	Unit can
B-3				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	None	Standard	20 years	Uniform	Unit can
B-4		UO_2 : 1.05vol% ZrO_2: 1.05vol% SUS: 7.2 vol% Conc: 50.7vol%	60 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Unit can
B-5				H_2O (moisture content): 1wt% Empty: Remainder	1.3GWd/t	None	Standard	20 years	Uniform	Unit can
B-6				H_2O (moisture content): 1wt% Empty: Remainder	51GWd/t	None	Standard	20 years	Uniform	Unit can

*1 "Standard"… Emission rate based on the FP emission test (Phebus-FPT4)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (4/12)

Metallic debris cases that were evaluated

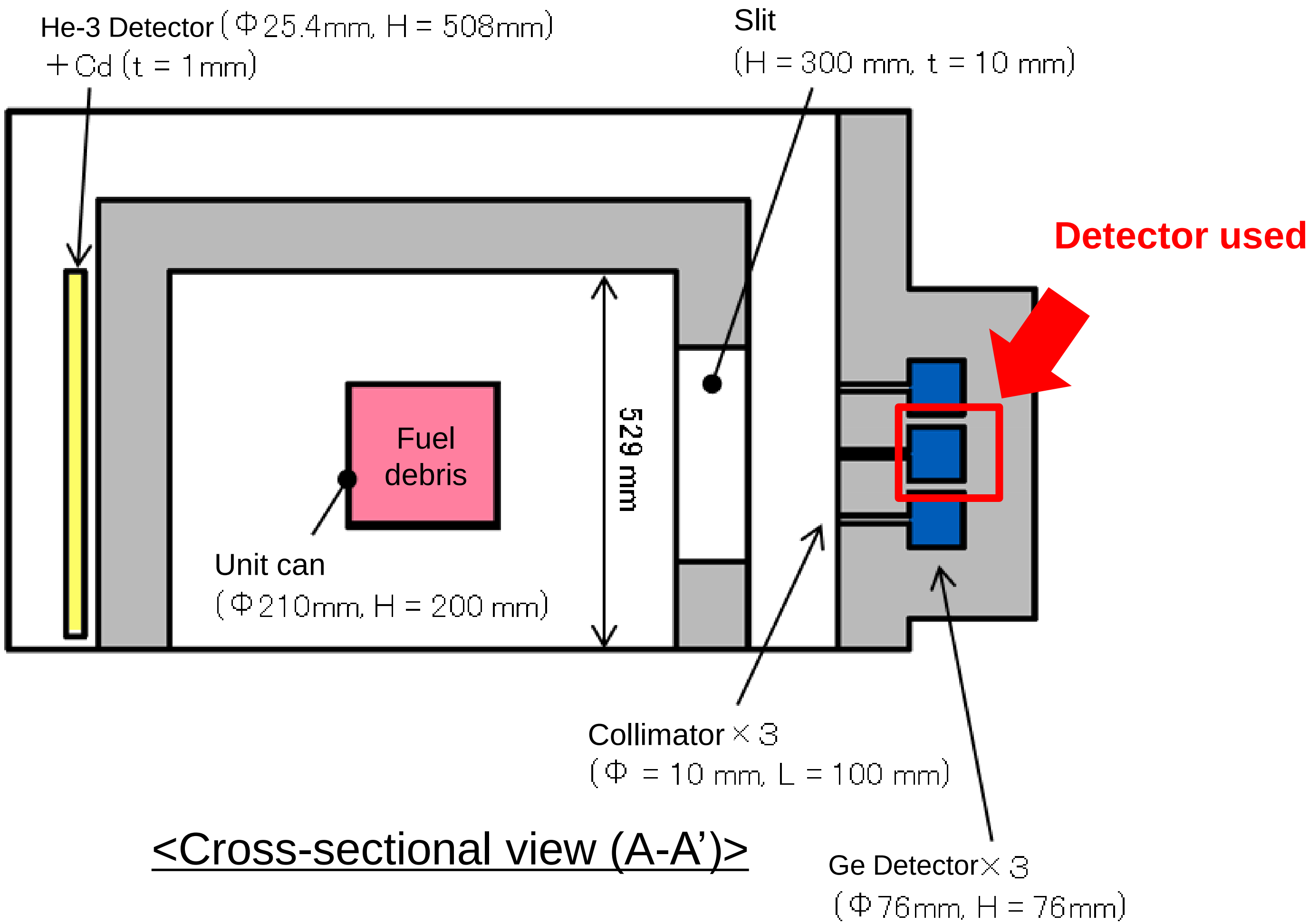
Case No.	Composition inside the container				Burn-up	Neutron absorption material	FP emission rate*1	Cooling period	Uneven distribution	Container*2
	Debris properties	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
C-1	Metallic debris	UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 29.85 vol%	30 vol%	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-2		UO_2 : 0.075vol% ZrO_2: 0.075vol% SUS: 44.85 vol%	**45 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)
C-3		UO_2 : 0.48vol% ZrO_2: 0vol% SUS: 10 vol%	**10.48 vol%**	H_2O (moisture content): 1wt% Empty: Remainder	23.0GWd/t	None	Standard	20 years	Uniform	Waste storage container (inner container)

*1 “Standard”… Emission rate based on the FP emission test (Phebus-FPT4)
*2 Mainly made of SUS, it is assumed to be sorted as inner container during the initial stage of retrieval
*3 Overview of each case is indicated below.
C-1: Base case
C-2: Case of sensitivity with respect to SUS composition
C-3: Case of sensitivity in which UO_2 has a volume percent equivalent to 3.7kg

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (5/12)

Detector used:
Since this is a homogeneous model that does not consider uneven distribution in the target object, Ge detectors which are located in the center and have the largest counting rate were used.

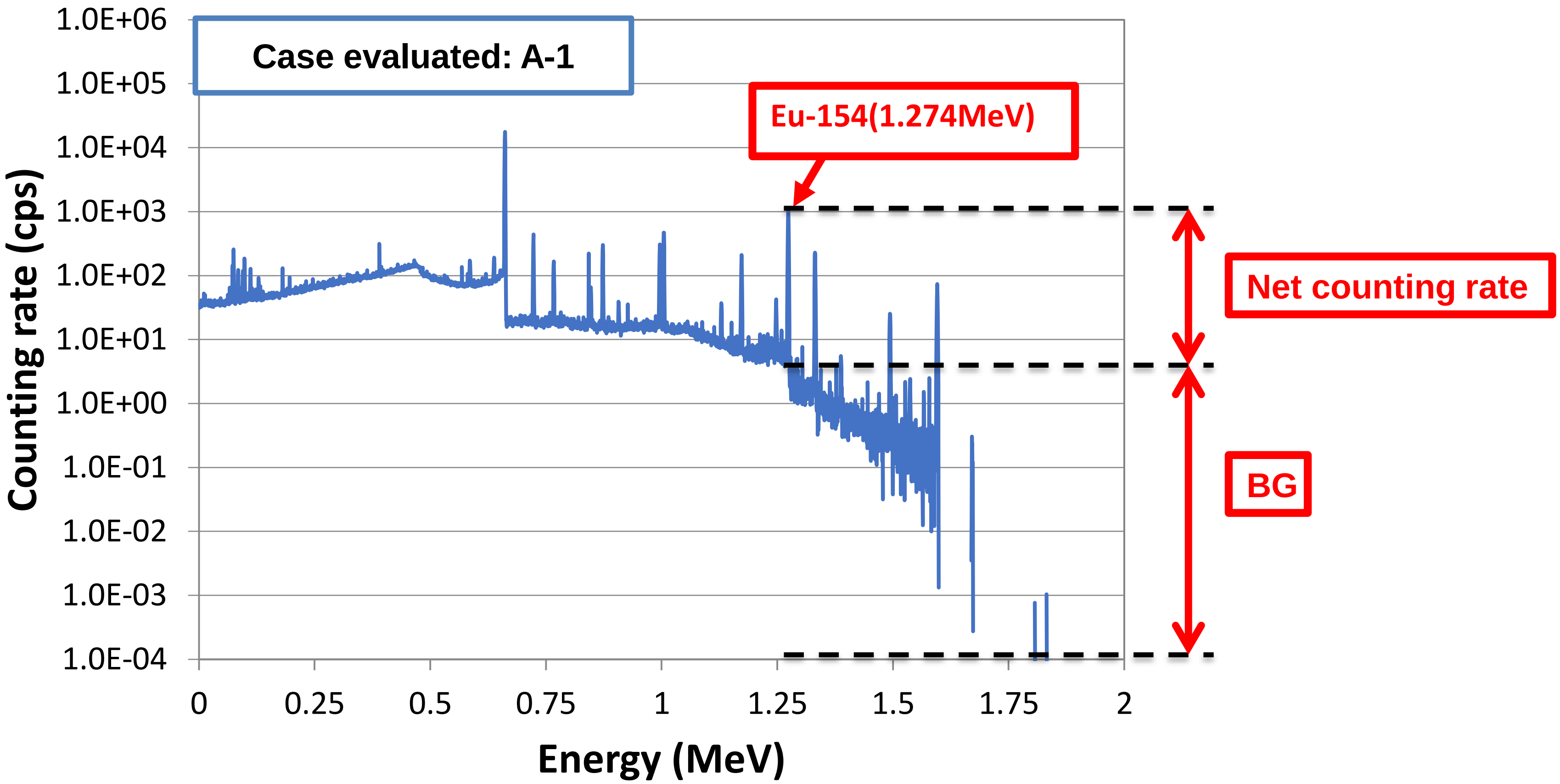


<Cross-sectional view (A-A')>

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (6/12)

Overview:
The quantity of nuclear material was estimated based on the correlation between the counting rate of 1.274MeV of Eu-154 and the amount of U, using the fact that the energy of gamma rays is characteristic to every reaction (decay) of material.



4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (7/12)

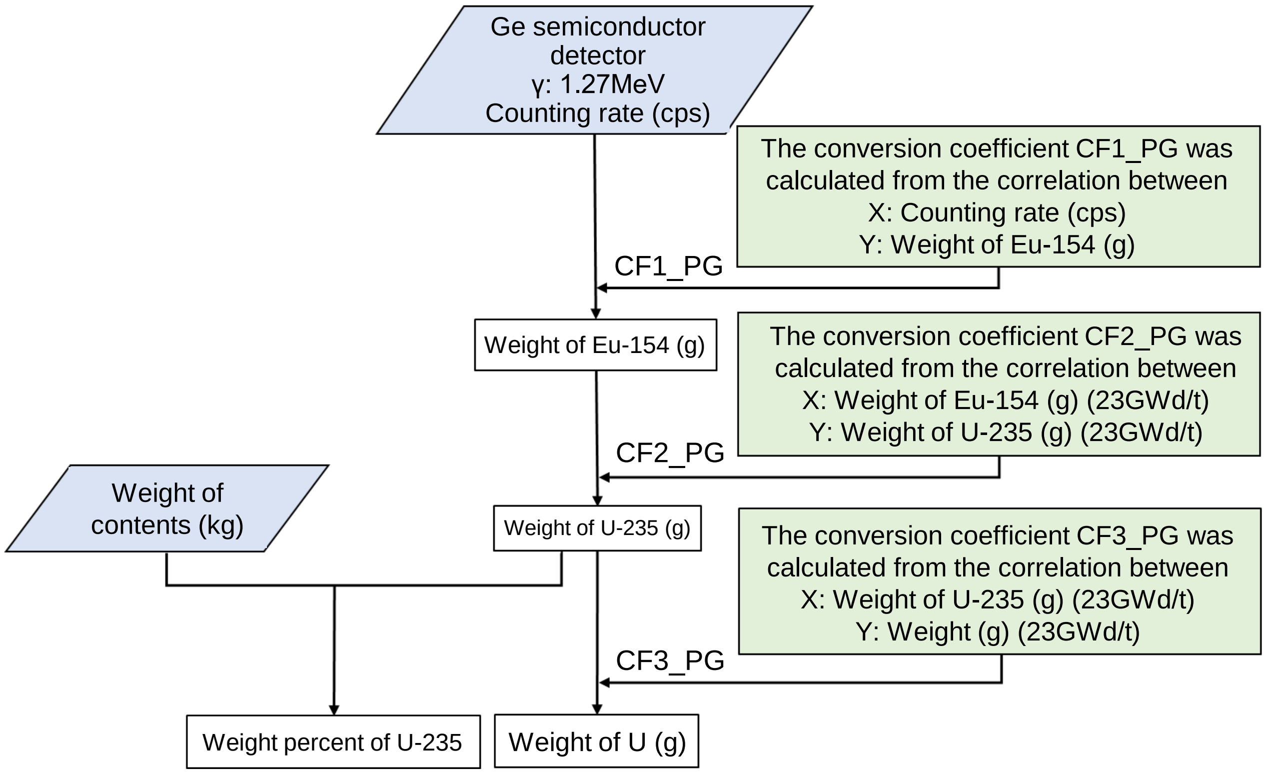
Evaluated data:
A comparative study of the main gamma rays emitting nuclides was conducted and the data on the 1.274MeV of Eu-154 was used.

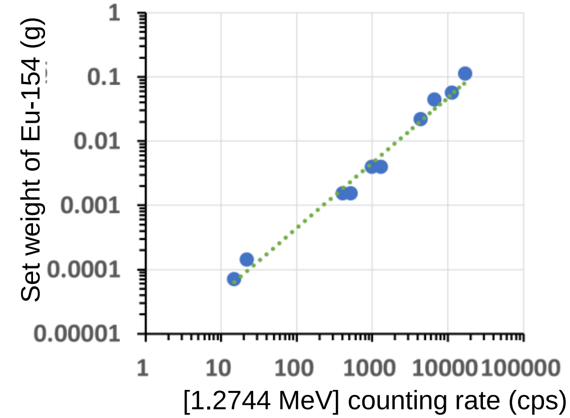
Evaluated data:	Explanation	Comprehensive evaluation
Am-241 Counting rate	･Gamma rays appearing in the 0.05954 MeV band were counted. Since there is interference from scattered rays emitted by other neutrons, it is presumed that detection would be difficult.	x
Cs-137 Counting rate	･Gamma rays (0.6617 MeV) emitted by Ba-137m which is strictly speaking a daughter nuclide were measured. ･Since Cs-137 is volatile, it is difficult to explain the composition ratio of the amount of U and the quantity of Cs-137 after the accident. Hence there is a possibility of not being able to use this while handling actual fuel debris.	△
Eu-154 (1.27MeV) Counting rate	･Fission products formed depending on the burn-up of nuclear fuel (U fuel). These nuclides are likely to be detected in fuel debris with medium to high burn-up, and are presumed to be useful in sorting.	○
Co-60 Counting rate	･Gamma rays emitting nuclides that result from activation of small quantities of impurities present in metal rather than from nuclear fuel. In order to evaluate the amount of U, the composition ratio of the amount of U and the amount of Co-60 needs to be derived.	△

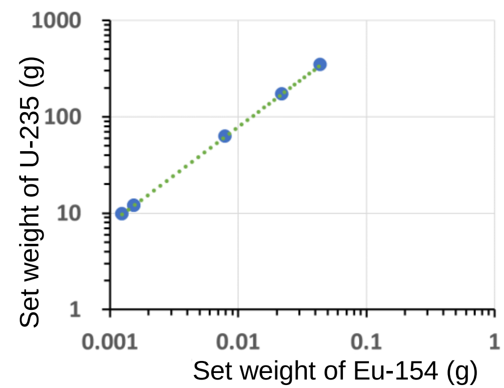
⑤-1 Passive gamma rays method A (8/12)

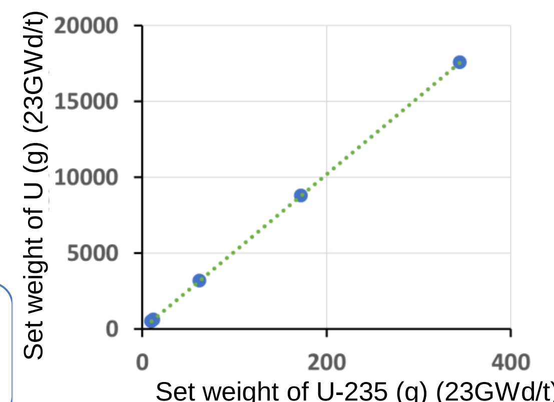
Estimation and Evaluation Flow：

The flow for estimating and evaluating the quantity of nuclear material using only the passive gamma rays method A was created.









The lower detection counting rate limit obtained from the following equation was substituted into the flow with the same lower detection limit.

$$n_n > \frac{K}{2}\left(\left(\frac{K}{t_s}\right) + 4n_b\left(\frac{1}{t_s} + \frac{1}{t_b}\right)\right)$$

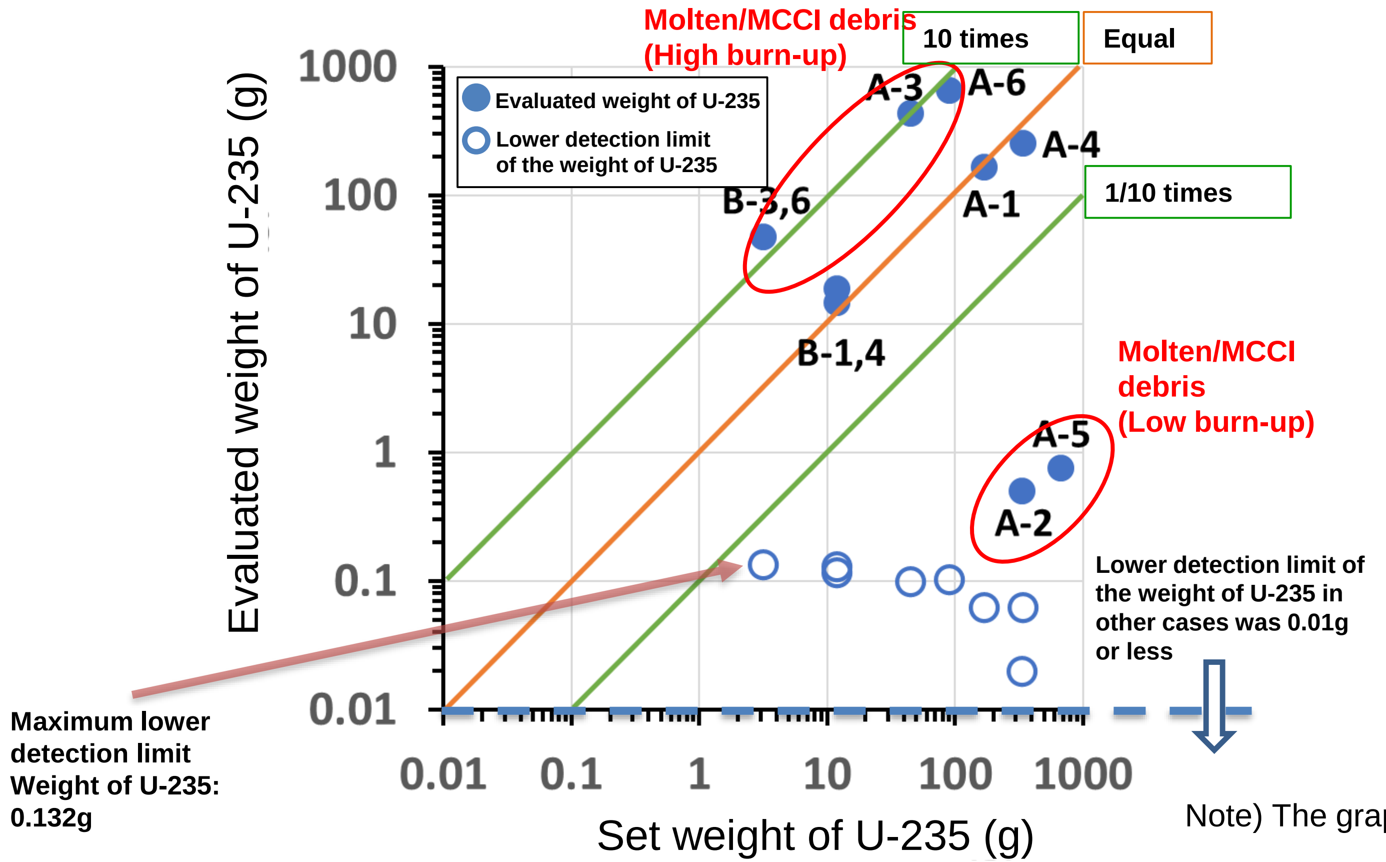
Standard deviation multiple: K=3, Count measured for the target object: N_s,
Measurement time for the target object: t_s=200(s), Measured counting rate for the target object: $n_s=N_s/t_s$,
BG measured count: N_b, BG measurement time: t_b=200(s) , BG measured counting rate: $n_b= N_b/t_b$
Net counting rate of the target object: $n_n=n_s-n_b$

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (9/12)

Evaluation results_Weight of U-235 (g)

- In the low burn-up cases B-2, 5, C-1, 2, 3 evaluation was not possible as the Eu-154(1.2744MeV) peak was not detected.
- Since average burn-up was used for evaluating the weight of U-235 from the weight of Eu-154, there was overestimation in the case of high burn-up and underestimation in the case of low burn-up.



Note) The graph axes use a logarithmic scale

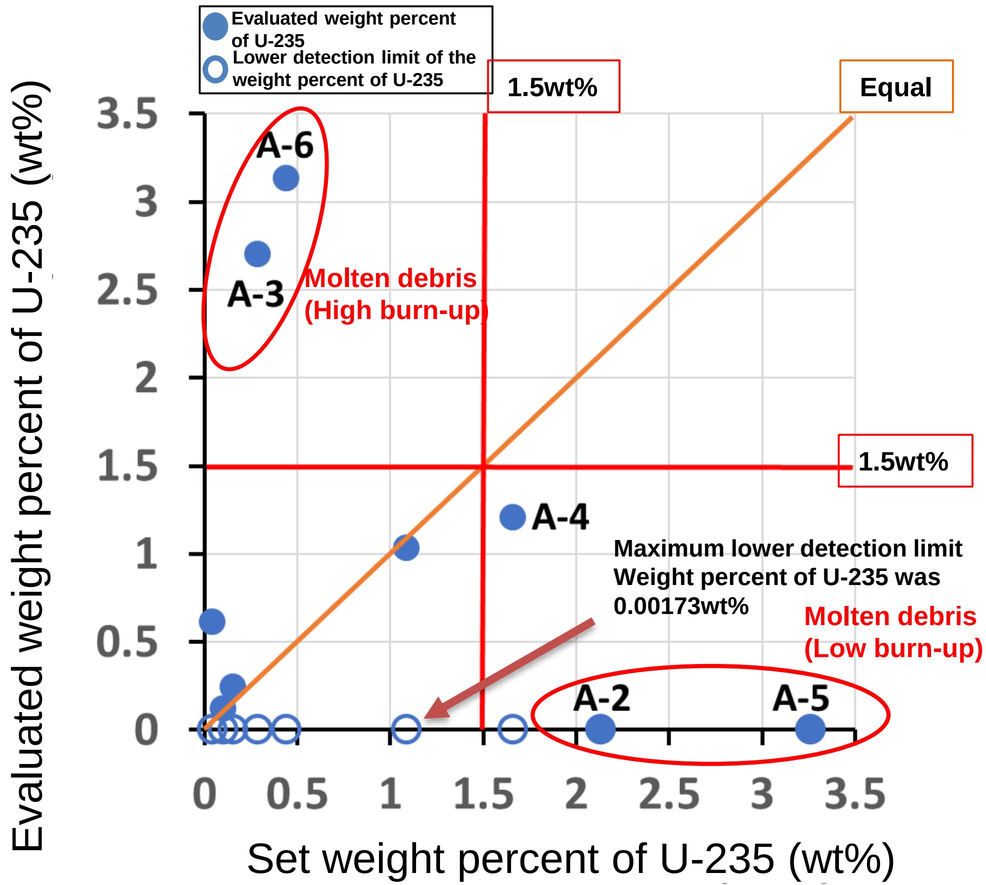
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

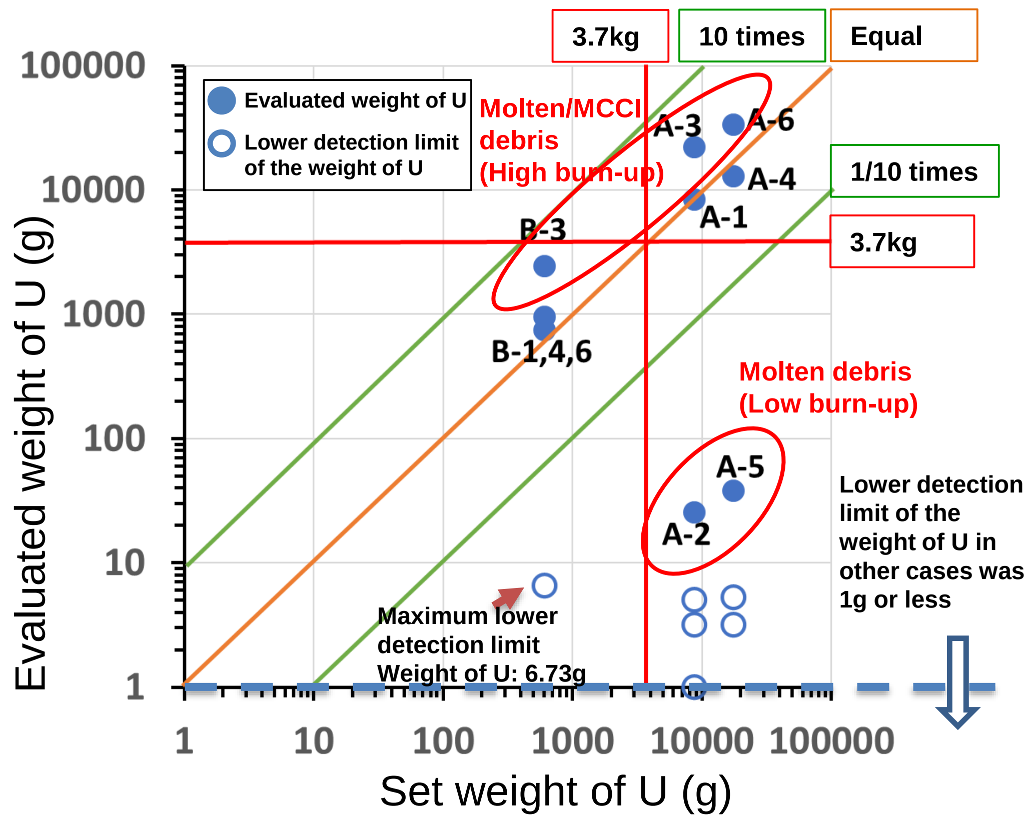
⑤-1 Passive gamma rays method A (10/12)

Evaluation results_U-235 weight percent (wt%) and amount of U (g)

・Since the positive correlation between the set weight of U and the evaluated weight of U is small, correction of impact of burn-up is a challenge.

・ Since average burn-up was used for evaluating the weight of U from the weight U-235, there was overestimation in the case of high burn-up and underestimation in the case of low burn-up.





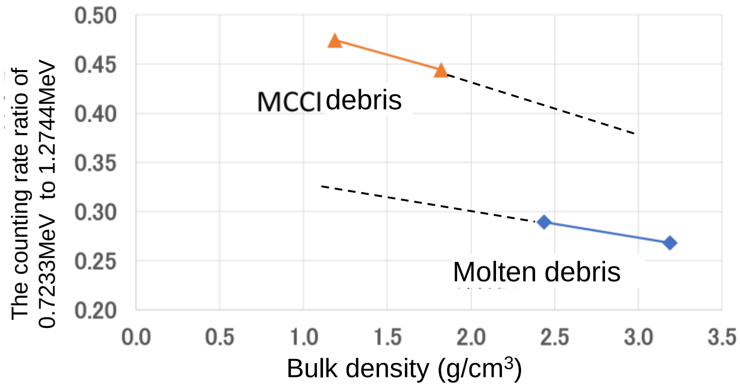
Note) The graph axes use a logarithmic scale

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (11/12)

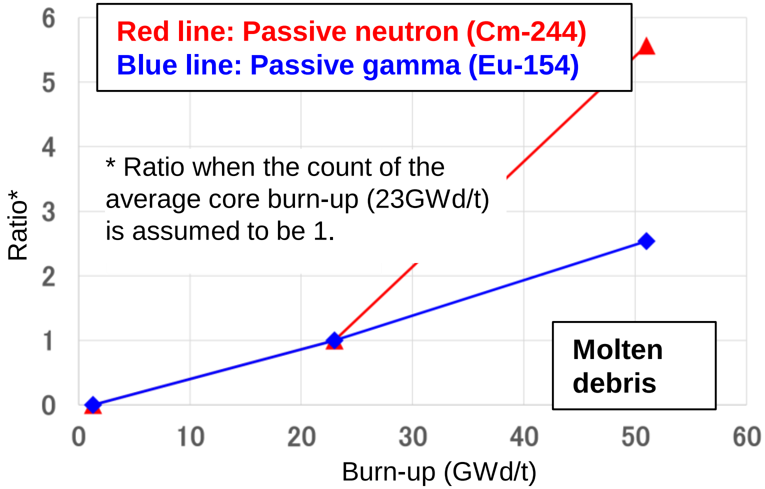
Proposed measures for improving performance

・Correction of impact of self-shielding based on multiple Eu-154 peak ratios



The peak ratios tend to vary depending on the fuel debris composition suggesting that it can be used for correcting the impact of self-shielding.

・Correction of impact of burn-up depending on the difference in correlation function between burn-up and the counting rate of Cm-244 and Eu-154(Same as No. 178) (Passive gamma rays method + Passive neutrons method)



Suggests that there is a possibility of being able to correct the impact of burn-up based on the ratio of the counting rates of Cm-244 and Eu-154.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-1 Passive gamma rays method A (12/12)

<Summary and future issues>

[Implementation details]

1) The evaluation flow for the passive gamma rays method was studied.
2) The evaluation accuracy of the quantity of nuclear fuel material, etc. was studied.
3) The lower detection limit of the quantity of nuclear fuel material, etc. was studied.

[Results/Contribution to development]

1) The evaluation flow for the passive gamma rays method was established.

2) The evaluation accuracy of the quantity of nuclear fuel material, etc. was estimated using the detector response analysis data.

- Weight of U-235: At most several 100 times (Molten debris,, low burn-up (1.3GWd/t))
- Weight percent of U-235：At most several 100 times (Molten debris, low burn-up (1.3GWd/t))
- Weight of U: At most several 100 times (Molten debris, low burn-up (1.3GWd/t))

3) The lower detection limit was estimated using the detector response analysis data.

- Weight percent of U-235：Was at most 0.00173wt% and the sorting criteria was lower than 1.5wt%.
- Weight of U: Was at most 6.73g, and the sorting criteria was lower than 3.7kg.

[Issues and response measures]

1) Issue: Reduction of errors due to burn-up

Response measure: The correction method based on the ratio of Cm-244 and Eu-154 should be studied in detail.

The logic for explaining the carrying performance of Cm-244 & Eu-154 with U needs to be established.

2) Issue: Reduction of errors due to container specifications and bulk density

Response measure: The conversion coefficient for each container specification should be established, and the correction method based on multiple peak percentages having different energies should be studied in detail.

The method of combining with the X-ray CT method should be studied.

3) Issue: Verification of the impact of diversity of other fuel debris

Response measure: Additional parameter studies on the conditions of the stored contents including heterogenous systems

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(⑤-2 Passive gamma rays method B)

No.	Measurement technology	Detector	Radiation source	Irradiation direction	Quantity measured	Quantity evaluated	Division of work	Sheet No.
⑤-1	Passive gamma rays method A	Ge	None	None	Mass of fission product nuclides (Eu-154, etc.)	Fissile nuclide mass	MHI	128-140 221-233
⑤-2	Passive gamma rays method B	CZT, $LaBr_3$, etc.	None	None	Same as above	Same as above	Hitachi-GE	141-154 234-237

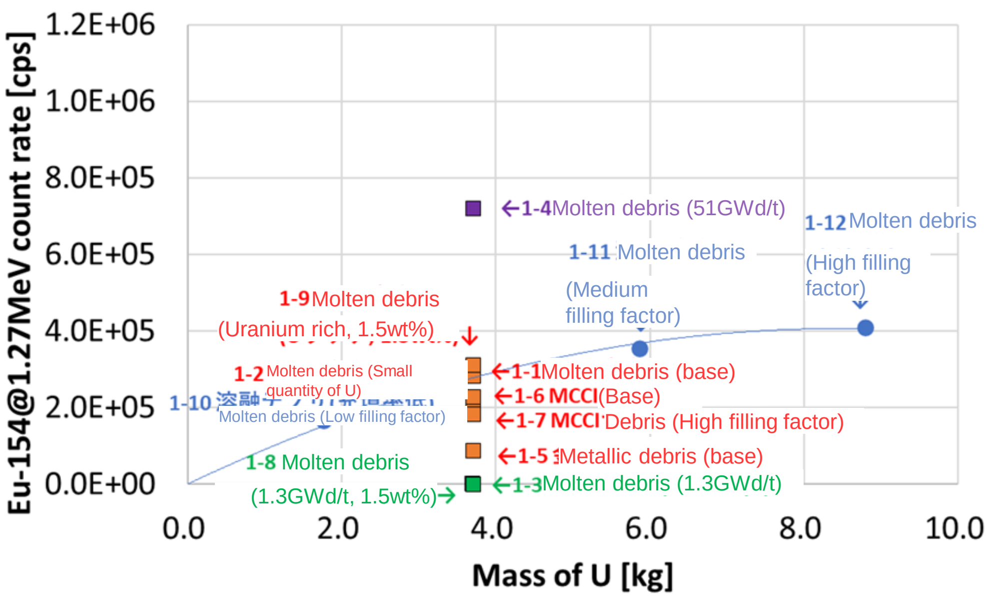
[Characteristics]

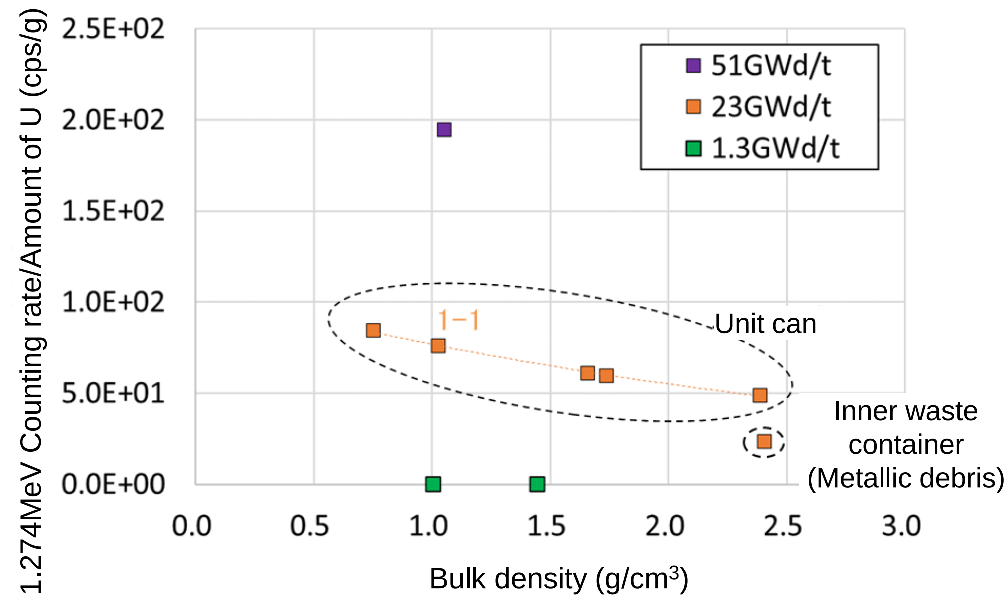
- Detectors that do not require a cooling system and can measure at a high counting rate (CZT, $LaBr_3$, etc.) were considered.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-2 Passive gamma rays method B (1/3)

- ➢ The proposed method for estimating and evaluating the quantity of nuclear material using the passive gamma rays method B was studied.
  - ✓ Since the 1.274MeV peak counting rates of Eu-154 vary due to the impact of composition, bulk density or burn-up even if the amount of U is constant (3.7kg), there were errors in the evaluated amount of U and thus evaluation with this method alone was difficult.
  - ✓ Other measurement information, etc. needs to be combined for evaluation.





Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the amount of U (All CZT analysis cases)

Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the bulk density (All CZT analysis cases)

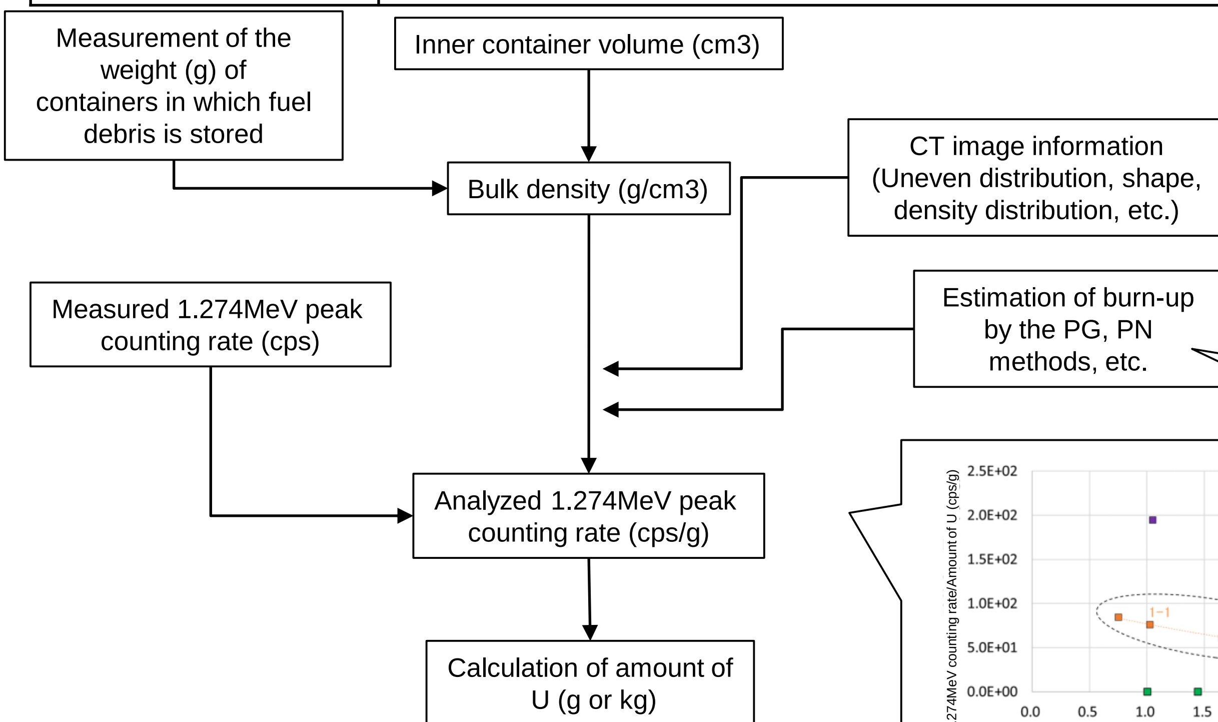
4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

⑤-2 Passive gamma rays method B (2/3)

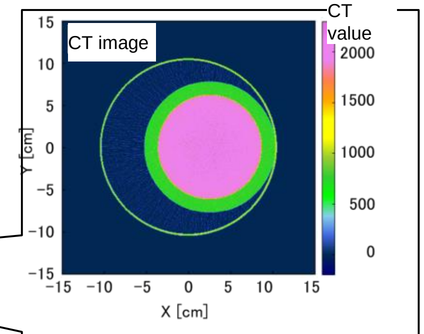
- The proposed method for estimating and evaluating the quantity of nuclear material using the passive gamma rays method B was studied.

Evaluation was difficult using only the passive gamma rays measurement information → Hence the proposed method of correction/performance improvement by combining it with other measurement information was studied.

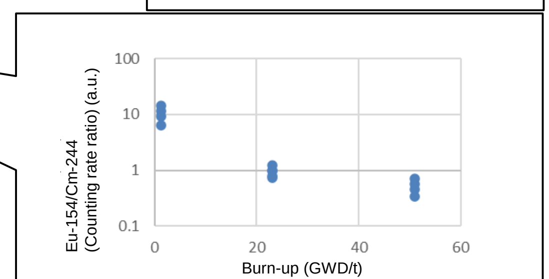
Influencing factor	Proposed method of correction/performance improvement
Composition, bulk density	Correction of impact by using weight measurement information
Uneven distribution inside the container	Correction of impact was difficult using the measurements from the passive gamma rays method alone →Impact should be corrected based on the CT image information.
Burn-up	Correction of impact was difficult using the measurements from the passive gamma rays method alone → Burn-up should be estimated by the PG, PN methods, etc.



Proposed evaluation flow using the passive gamma rays method

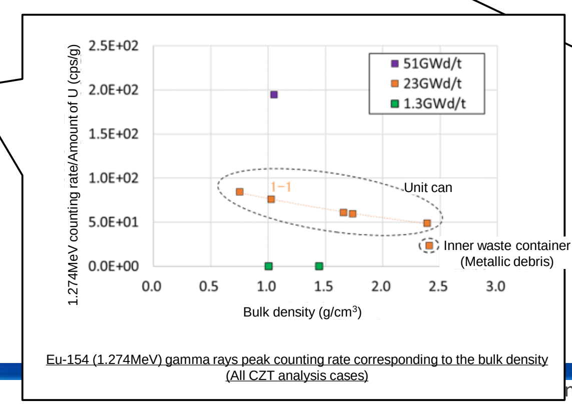


CT image



Burn-up dependency of Eu/Cm (Counting rate ratio)

* Gamma rays attenuation correction is an issue.



Eu-154 (1.274MeV) gamma rays peak counting rate corresponding to the bulk density (All CZT analysis cases)

⑤-2 Passive gamma rays method B (3/3)

<Summary and future issues>

[Implementation details]

1) Proposed methods for correcting the impact of composition or bulk density by combining other measurement information were studied.

2) Proposed methods for correcting the impact of uneven distribution inside the container by combining other measurement information were studied.

3) Proposed methods for correcting the impact of burn-up by combining other measurement information were studied.

[Results/Contribution to development]

1) The method of correcting the impact of composition or bulk density using weight measurement information was proposed.

2) The method of correcting the impact of uneven distribution inside the container using CT image information was proposed.

3) The method for estimating the burn-up using the correlation between the weight ratio of Cm and Eu and the burn-up and using the measurements obtained by the passive gamma rays method and the passive neutron method for correcting the impact of burn-up was proposed.

[Issues and response measures]

1) Issue: The method of reducing errors in the method of using the weight measurement information or the CT image data information, or the method of estimating the burn-up needs to be crystallized.

Response measure: Crystallization of the methods should be considered, and the applicability should be evaluated by means of analysis, tests, etc.

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

(Summary of the studies on the methods for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity)

4.2.1 Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

Summary of the studies on the methods for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity

[Results / Contribution to development] (For details, refer to the reports on each measurement technology)

- The primary proposal for the method of evaluating the quantity of nuclear material, etc. using 5 types of measurement technologies (① Active neutron method, ② Passive neutron method, ③ Muon scattering method, ④ X-ray CT method and ⑤ Passive gamma rays method) was established.
- **The accuracy, etc. of evaluating the quantity of nuclear fuel material, etc. was estimated** using the detector response analysis data.
- **The factors that reduce the evaluation accuracy were analyzed** based on the evaluation results **and response measures were studied.**

[Issues and response measures] (For details, refer to the reports on each measurement technology)

1) Issue: Correction methods need to be established for each measurement technology in accordance with the influencing factors.
Response measure: **The correction methods proposed for each measurement technology should be studied in detail.**

2) Issue: Amongst the issues concerning the correction method, **developing the logic for explaining the carrying performance of Cm-244 and Eu-154 with U is difficult to accomplish independently in the Sorting PJ**.
Response measure: **Studies should be carried out in collaboration with related projects (Characterization PJ）.**

3) Issue: The impact of diversity of other fuel debris needs to be verified.
Response measure: **Additional parameter studies on the conditions of the stored contents including heterogenous systems should be conducted.**

4) Issue: Performance needs to be evaluated by crystallizing the combination of measurement technologies.
Response measure: **Analysis or verification tests should be conducted by lining up the conditions of the target object,** and **the scope of application of the 5 types of measurement technologies or the information that these technologies can provide should be compared**. **Methods for evaluating the quantity of nuclear fuel material by combining these technologies should be studied, and the estimation and evaluation performance should be evaluated**.

4.2.2 Study of sorting scenarios

[Objective]

- **The scenarios of sorting using the active neutron method, passive neutron method, muon scattering method, X-ray CT method and passive gamma rays method (including their combinations as required) should be proposed.**

- **Since the studies of sorting scenarios that are required for sorting are not development items, TRL will not be set for the studies.**

4.2.2 Studies of sorting scenarios (1/8)

List of prospective scenarios

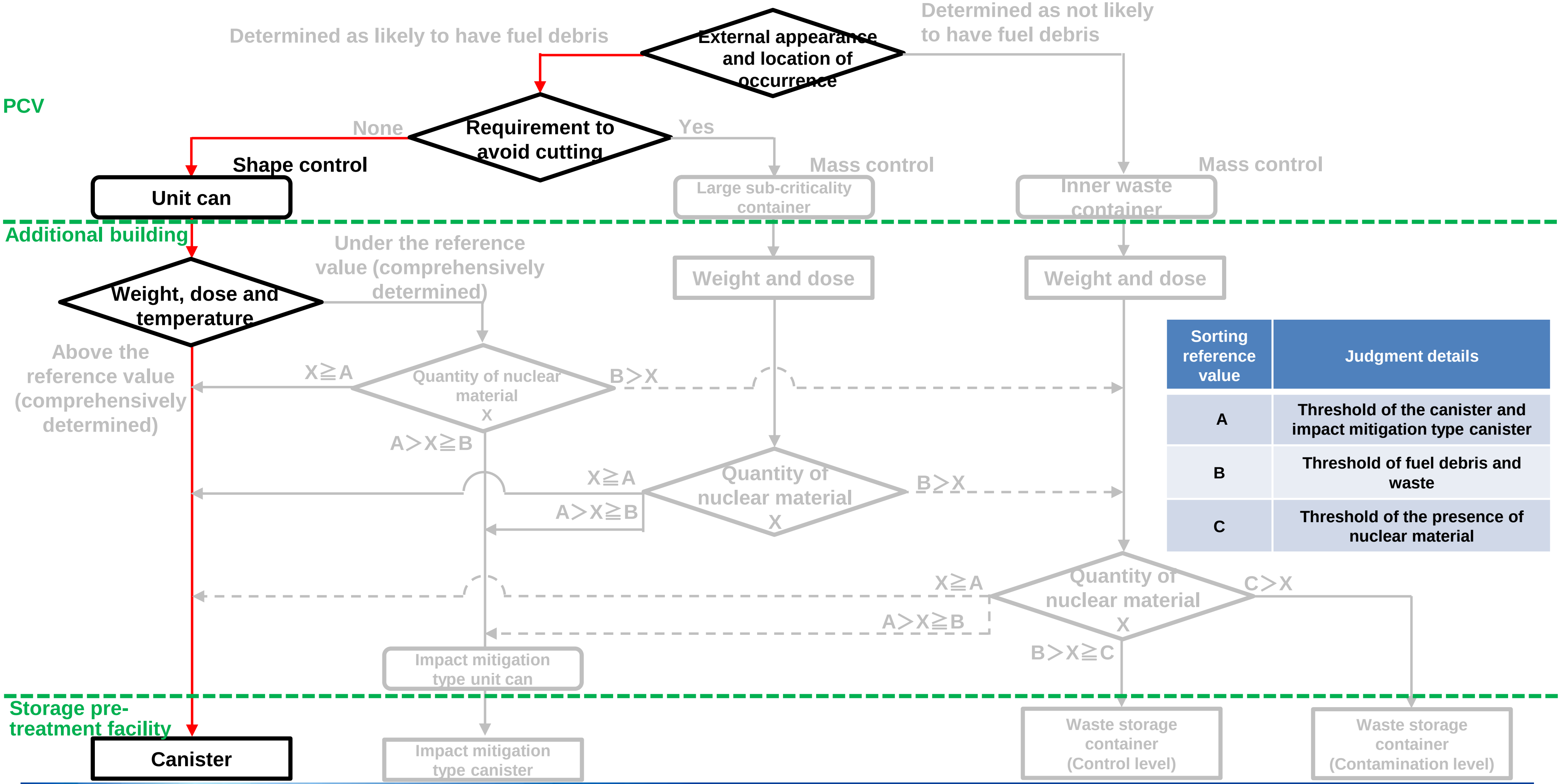
・In the initial stages of retrieval, unit cans will be used as containers for retrieval. It is assumed that as retrieval progresses, the retrieval requirements will increase and large sub-criticality containers or inner waste containers will be required.
・Unit cans are comparatively smaller amongst the containers handled, and hence it is assumed that the extent of difficulty in measurement is comparatively less.
・The sorting is assumed to be carried out in the additional building or in the storage pre-treatment facility.

No.	Scenario	Overview	Merits	Demerits
①	When sorting is **not implemented**	The fuel debris is not sorted at all, all fuel debris is retrieved in unit cans and stored in canisters.	Sorting is not required, and the route from retrieval to storage is simple.	All fuel debris needs to be cut into small pieces of 20cm or less inside the PCV itself. A huge number of canisters are required for storage.
②-1	When the Technology **Readiness Level is low at the initial stage of retrieval,** and fuel debris is sorted **in the additional building**	Quantity of nuclear material in the unit can is measured in the additional building and the material that is under the reference value is stored in waste storage containers.	The number of canisters can be expected to be reduced.	Feasibility of the arrangement in the additional building is an issue.
②-2	When the Technology **Readiness Level is low at the initial stage of retrieval,** and fuel debris is sorted **in the storage pre-treatment facility**	Quantity of nuclear material in the unit can is measured in the storage pre-treatment facility and the material that is under the reference value is stored in waste storage containers.	The number of canisters can be expected to be reduced.	Gives rise to work of removal from the transport casks that are used for transfer between buildings in the storage pre-treatment facility, and then the work of refilling.
③-1	When the Technology **Readiness Level is high in the later stage of retrieval,** and fuel debris is sorted **in the additional building**	The fuel debris is sorted in the PCV and retrieved into unit cans, large sub-criticality containers and inner waste containers depending on the external appearance, location of occurrence and whether or not there is a requirement to avoid cutting, and depending on the quantity of nuclear material measured in the additional building, these are sorted in the storage pre-treatment facility and stored in canisters, impact mitigation type canister, waste storage container (control level), waste storage container (contamination level).	A substantial reduction in the number of canisters can be expected.	The route from retrieval to storage is complex. Feasibility of the arrangement in the additional building is an issue.
③-2	When the Technology **Readiness Level is high** in **the later stage of retrieval**, and fuel debris is sorted **in the storage pre-treatment facility**	The fuel debris is sorted in the PCV and retrieved into unit cans, large sub-criticality containers and inner waste containers depending on the external appearance, location of occurrence and whether or not there is a requirement to avoid cutting, and depending on the quantity of nuclear material measured in the storage pre-treatment facility, these are sorted and stored in canisters, impact mitigation type canister, waste storage container (control level), waste storage container (contamination level).	A substantial reduction in the number of canisters can be expected.	The route from retrieval to storage is complex. Gives rise to work of removal from the transport casks that are used for transfer between buildings in the storage pre-treatment facility, and then the work of refilling.

4.2.2 Studies of sorting scenarios (2/8)

Prospective scenario ①: When sorting is not implemented

- Overview: The fuel debris is not sorted at all, **all fuel debris is retrieved in unit cans and stored in canisters.**
- Merit: Sorting is not required, and the **route** from retrieval to storage **is simple.**
- Demerit: **All fuel debris** needs to be **cut into small pieces of 20cm or less** inside the PCV itself. **A huge number of canisters** are required for storage.

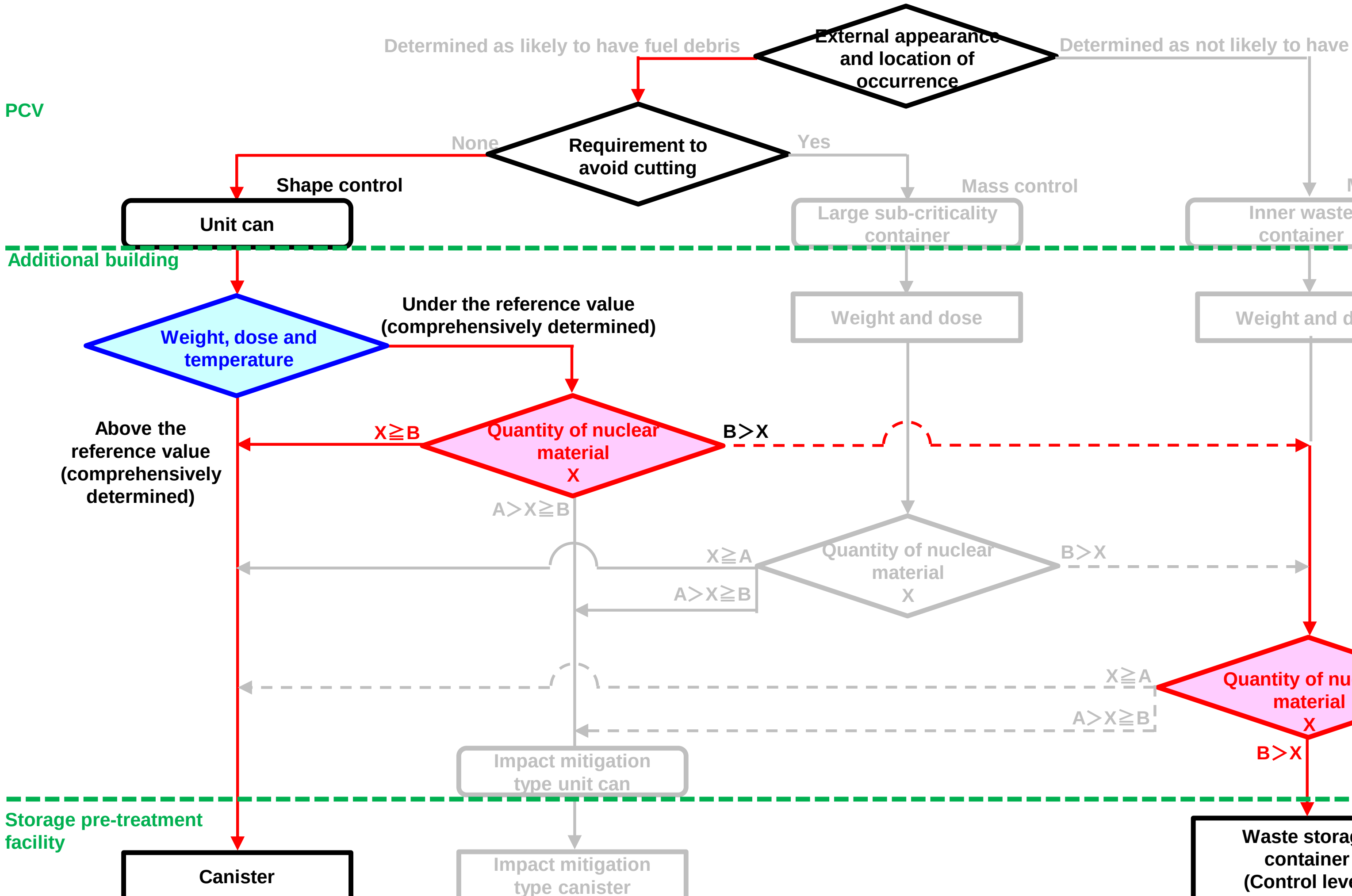


Sorting reference value	Judgment details
A	Threshold of the canister and impact mitigation type canister
B	Threshold of fuel debris and waste
C	Threshold of the presence of nuclear material

4.2.2 Studies of sorting scenarios (3/8)

Prospective scenario ②-1：When the Technology Readiness Level is low at the initial stage of retrieval, and fuel debris is sorted in the additional building.

- Overview： **Quantity of nuclear material in the unit can is measured** in the additional building and **the material that is under the reference value is stored in waste storage containers**.
- Merit： **The number of canisters** can be expected **to be reduced.**
- Demerit： **Feasibility of the arrangement** in the additional building is an issue.

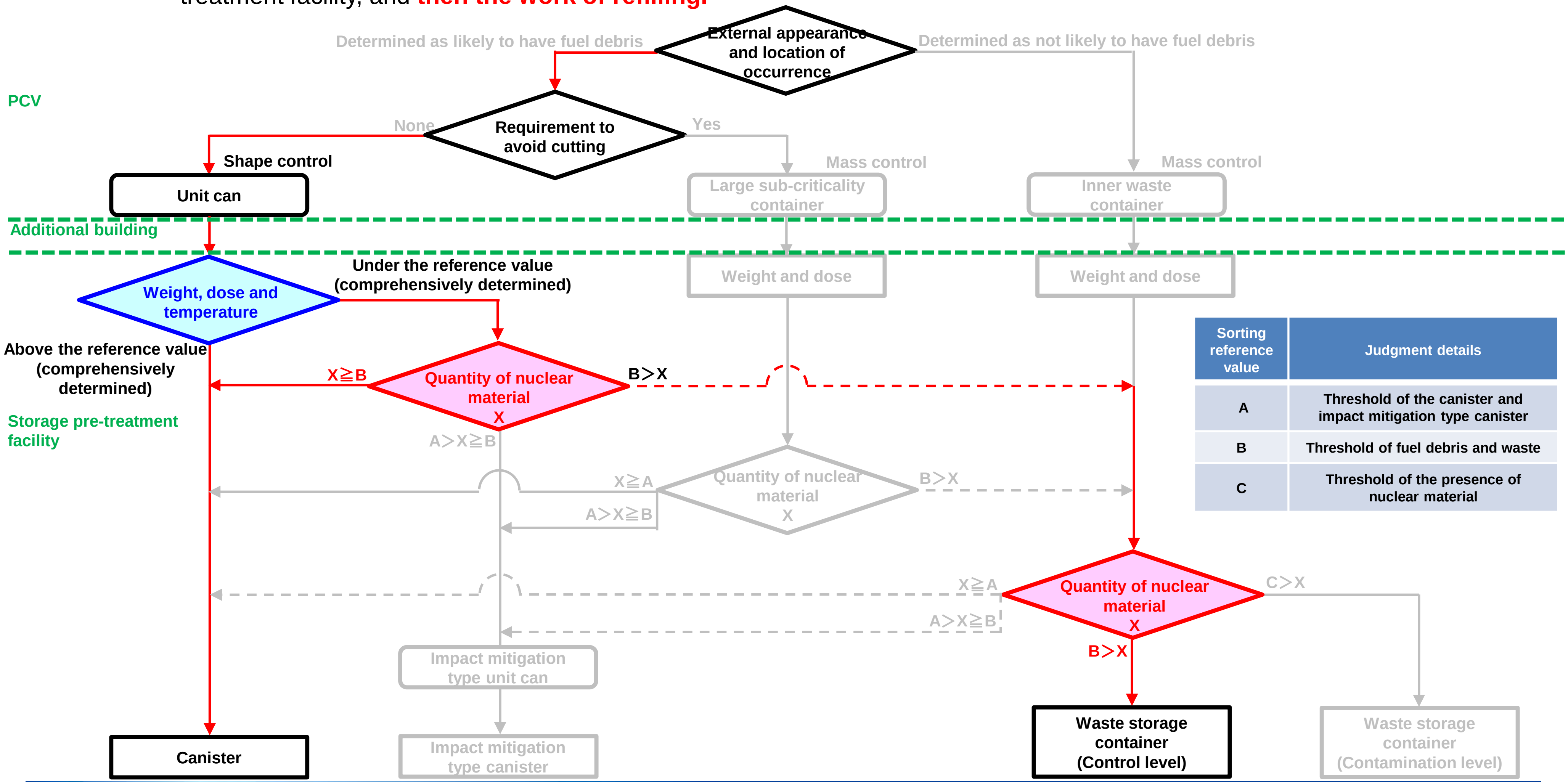


Sorting reference value	Judgment details
A	Threshold of the canister and impact mitigation type canister
B	Threshold of fuel debris and waste
C	Threshold of the presence of nuclear material

4.2.2 Studies of sorting scenarios (4/8)

Prospective scenario ②-2: When the Technology Readiness Level is low at the initial stage of retrieval, and fuel debris is sorted in the storage pre-treatment facility

- Overview: **Quantity of nuclear material in the unit can is measured** in the storage pre-treatment facility and **the material that is under the reference value is stored in waste storage containers**.
- Merit: **The number of canisters** can be expected **to be reduced.**
- Demerit: Gives rise to **work of removal from the transport casks that are used for transfer between buildings** in the storage pre-treatment facility, and **then the work of refilling.**

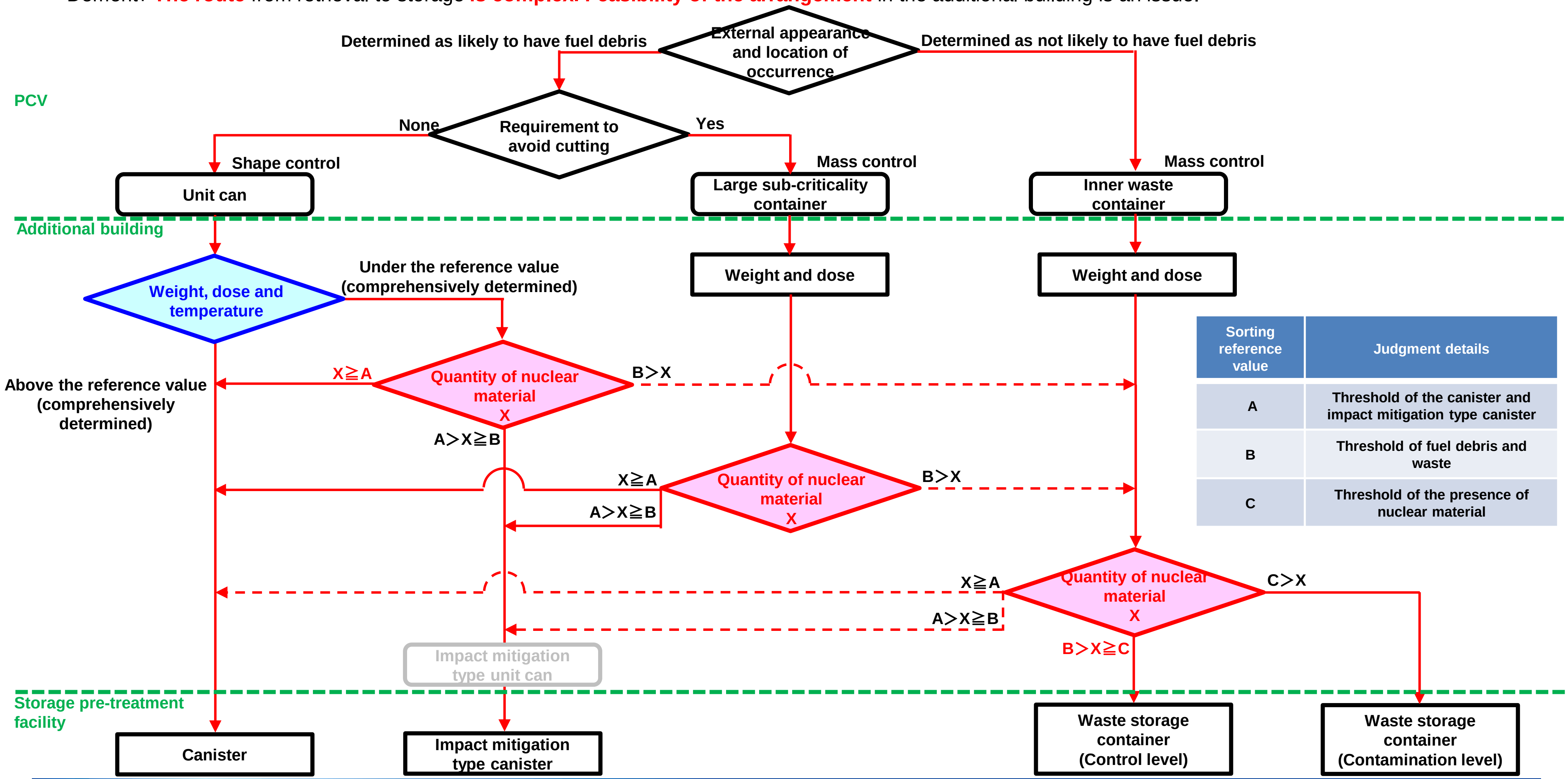


Sorting reference value	Judgment details
A	Threshold of the canister and impact mitigation type canister
B	Threshold of fuel debris and waste
C	Threshold of the presence of nuclear material

4.2.2 Studies of sorting scenarios (5/8)

Prospective scenario ③-1: When the Technology Readiness Level is high in the later stage of retrieval, and fuel debris is sorted in the additional building

- Overview: The fuel debris **is sorted** in the PCV **and retrieved into unit cans, large sub-criticality containers and inner waste containers** depending on the external appearance, location of occurrence and whether or not there is a requirement to avoid cutting, and **depending on the quantity of nuclear material** measured in the additional building, **these are sorted** in the storage pre-treatment facility **and stored in canisters, impact mitigation type canister, waste storage container (control level), waste storage container (contamination level)**.
- Merit: **A substantial reduction in the number of canisters** can be expected.
- Demerit: **The route** from retrieval to storage **is complex. Feasibility of the arrangement** in the additional building is an issue.

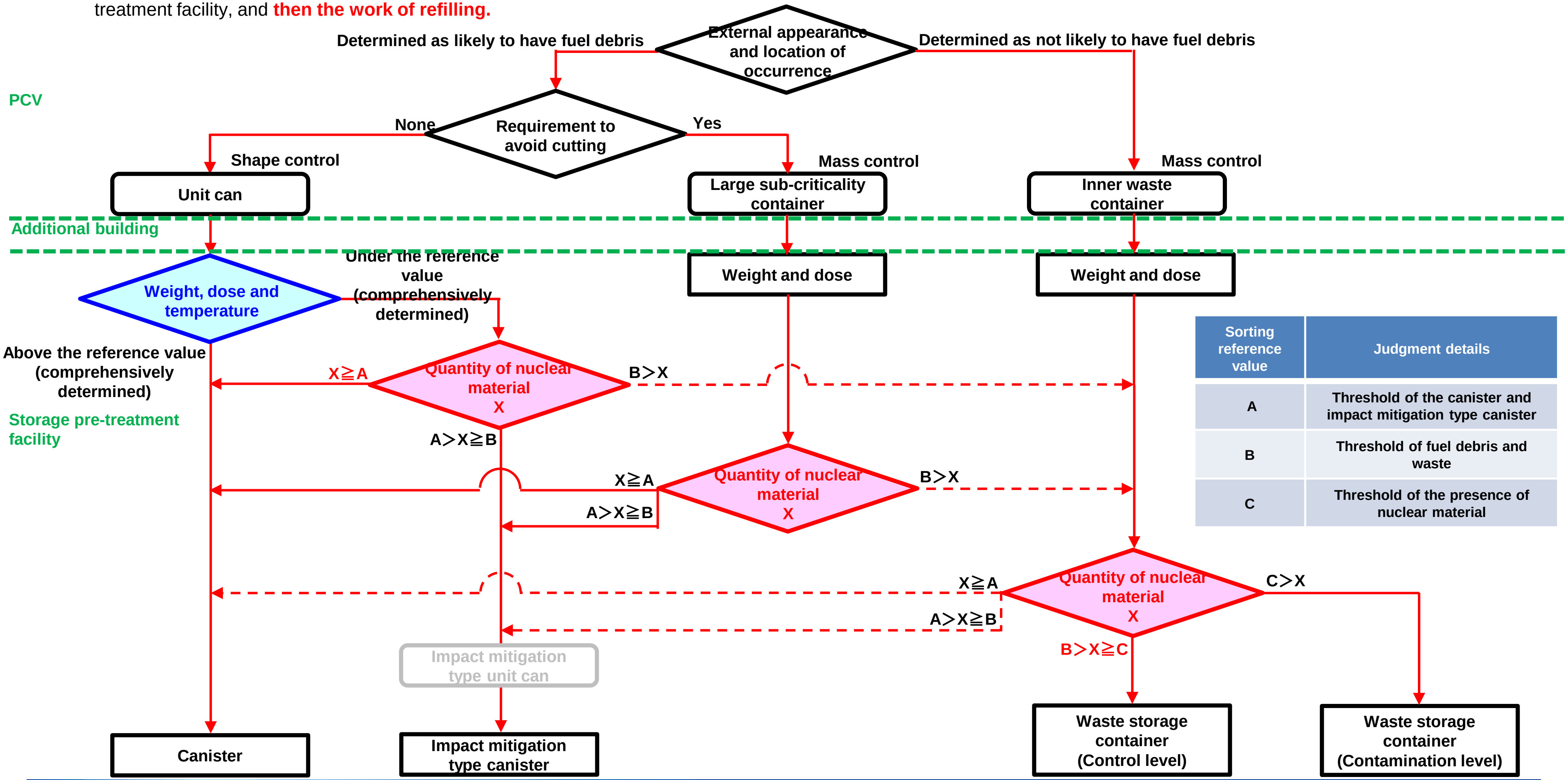


Sorting reference value	Judgment details
A	Threshold of the canister and impact mitigation type canister
B	Threshold of fuel debris and waste
C	Threshold of the presence of nuclear material

4.2.2 Studies of sorting scenarios (6/8)

Prospective scenario ③-2: When the Technology Readiness Level is high in the later stages of retrieval, and fuel debris is sorted in the storage pre-treatment facility

- Overview: **The fuel debris is sorted** in the PCV **and retrieved into unit cans, large sub-criticality containers and inner waste containers** depending on the external appearance, location of occurrence and whether or not there is a requirement to avoid cutting, **and depending on the quantity of nuclear material** measured in the storage pre-treatment facility, **these are sorted and stored in canisters, impact mitigation type canister, waste storage container (control level), waste storage container (contamination level).**
- Merit: **A substantial reduction in the number of canisters** can be expected.
- Demerit: **The route** from retrieval to storage **is complex.** Gives rise to **work of removal from the transport casks that are used for transfer between buildings** in the storage pre-treatment facility, and **then the work of refilling.**



Sorting reference value	Judgment details
A	Threshold of the canister and impact mitigation type canister
B	Threshold of fuel debris and waste
C	Threshold of the presence of nuclear material

4.2.2 Studies of sorting scenarios (7/8)

Items to be coordinated with related PJs

- In preparation for drawing up the sorting scenarios, items to be coordinated with related PJs (Retrieval PJ, Canister PJ, Waste PJ) were identified.
- **The items with a higher priority were** selected **for clarifying the requirements (conditions of the objects to be measured, target performance value) that are pre-conditions for development**.
- As a result of sharing of the latest knowledge during the joint meetings with related PJs, it was found that **both these tasks were yet to be finalized** and were thus an issue.
  In the future as well, progress in studies will be shared and knowledge will be reflected.

Process	Items to be coordinated	Issues
Retrieval	Method and criteria for differentiating fuel debris and waste **Retrieval container specifications and use** Moisture content after retrieval	The pre-conditions of the containers and the canisters that will be received by the sorting equipment need to be shared. Container specifications are to be determined except for the unit can.
Transfer between buildings	Transport cask specifications	The specifications depend on the required accuracy while differentiating fuel debris and waste at the time of retrieval and the required accuracy while sorting at the time of storage, but whether or not measurement needs to be performed using the transport cask (measurement performed without removing the unit cans) needs to be verified. Further, transport cask specifications are to be determined.
Refilling of containers	Purpose of refilling containers Details of container refilling Details of data transfer, requirement of re-measurement	The container specifications and conditions of the stored contents that are preconditions for sorting change depending on the anteroposterior relationship between refilling of containers and sorting and the contents that are refilled. Also, the details of transfer of measurement data obtained before refilling and whether or not measurement should be performed once again after refilling needs to be studied.
Draining /Drying	**Details of treatment of fuel debris and waste** Purpose of draining/drying Moisture content after draining/drying	The details of treatments such as draining/drying of fuel debris/waste, moisture content after treatment, anterioposterior relationship between draining/drying and sorting are likely to have an impact on the measurement accuracy of the sorting equipment.
Sorting	Anterioposterior relationship with other processes Container specifications at the time of measurement Moisture content at the time of measurement **Sorting reference value**	The measurement accuracy of the sorting equipment and the sorting scenarios change depending on the anterioposterior relationship with other processes or the measurement conditions.
Storage	**Storage container specifications and arrangement**	The sorting reference value changes depending on the storage container specifications and arrangement.

4.2.2 Studies of sorting scenarios (8/8)

Summary of the studies of sorting scenarios

[Results / Contribution to development]

・**Prospective scenarios were tentatively presented from the perspective of the time and location of application** by assuming the following 5 cases of sorting scenarios, crystallizing their respective sorting flows and comparing them.

① When sorting is not implemented
② When the Technology Readiness Level is low at the initial stage of retrieval, and fuel debris is sorted in the additional building.
③ When the Technology Readiness Level is low at the initial stage of retrieval, and fuel debris is sorted in the storage pre-treatment facility
④ When the Technology Readiness Level is high in the later stage of retrieval, and fuel debris is sorted in the additional building.
⑤ When the Technology Readiness Level is high in the later stage of retrieval, and fuel debris is sorted in the storage pre-treatment facility

・Although the technology (including combinations) for measuring the quantity of nuclear fuel material is to be determined, **it was established that the throughput of measuring the quantity of nuclear fuel material is reduced when combined with screening measurement** based on weight, temperature, dose, etc.

・In preparation for drawing up the sorting scenarios, **items to be coordinated with related PJs (Retrieval PJ, Canister PJ, Waste PJ) were identified. "Retrieval container specifications and use", "Details of treatment of fuel debris/waste for reducing the moisture content", Sorting reference value" and "Storage container specifications and arrangement"** were selected as items **with high priority** in particular.

・As a result of holding joint meetings with related PJs and sharing the latest knowledge, it was found that **both tasks were yet to be finalized** and were thus an issue.

[Issues and response measures]

1) Issue: Information required for drawing up sorting scenarios is yet to be determined.
Response measure: **A mechanism for horizontal dissemination with related PJs should be developed** so that information can be reflected without fail once it has been determined. (Example: Regularly holding joint meetings, etc.)

2) Issue: In order to determine the sorting scenario to be used, the effect of streamlining the work from retrieval by sorting to storage needs to be evaluated.
Response measure: Although the conditions of the objects to be measured need to be assumed, **the effect of streamlining such as reducing the number of canisters or the area of the storage building for each of the sorting scenarios should be evaluated**.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

[Objective]

・In the future, in order to verify the feasibility of sorting using the following measurement technologies, testing methods should be planned for issues that need to be verified by conducting experiments, based on the results of simulation tests or simple tests.

(Target TRL at completion: Level 2)

① Active neutron method…In the future, the results of verification will be applicable to the active neutron methods A, B as well as C in common.

② Passive neutron method…In the future, the results of verification will be applicable to the passive neutron methods A and B in common.

③ Muon scattering method

④ X-ray CT method

⑤ Passive gamma rays method…In the future, the results of verification will be applicable to the passive gamma rays methods A and B in common.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

(① Active neutron method)

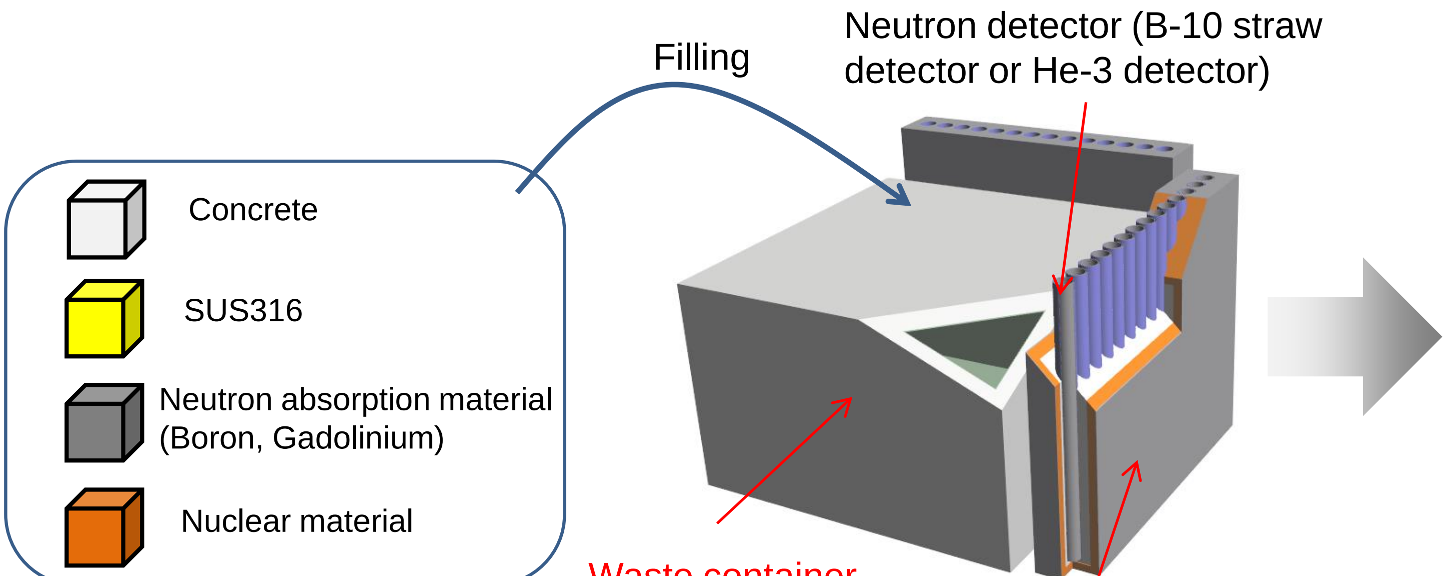
4.3 Study of elemental technology verification test methods using existing equipment, etc.

① Active neutron method (1/10)

(a) Tests related to the evaluation of the impact of neutron absorption material, etc.

[Test contents]

The active neutron method is influenced by the neutron absorption materials (Boron or Gadolinium) contained in the object to be measured. The method of evaluating the impact of neutron absorption material by creating representative simulated samples containing such neutron absorption materials and conducting tests using the JAEA active neutron method equipment JAWAS-T was studied.



Molded into blocks so that various compositions can be simulated
(Nuclear material is stored in block shaped cases)

Waste container (simulated) (500x500x300mm)
Unit can (simulated) manufactured as well. (Φ210mm, H200mm)

Neutron detector bank (Example)

JAWAS-T@NUCEF

4.3 Study of elemental technology verification test methods using existing equipment, etc.

① Active neutron method (2/10)

(a) Tests related to the evaluation of the impact of neutron absorption material, etc.

Tests related to evaluating the impact of neutron absorption material, etc. were conducted using JAWAS-T located in JAEA NUCEF.

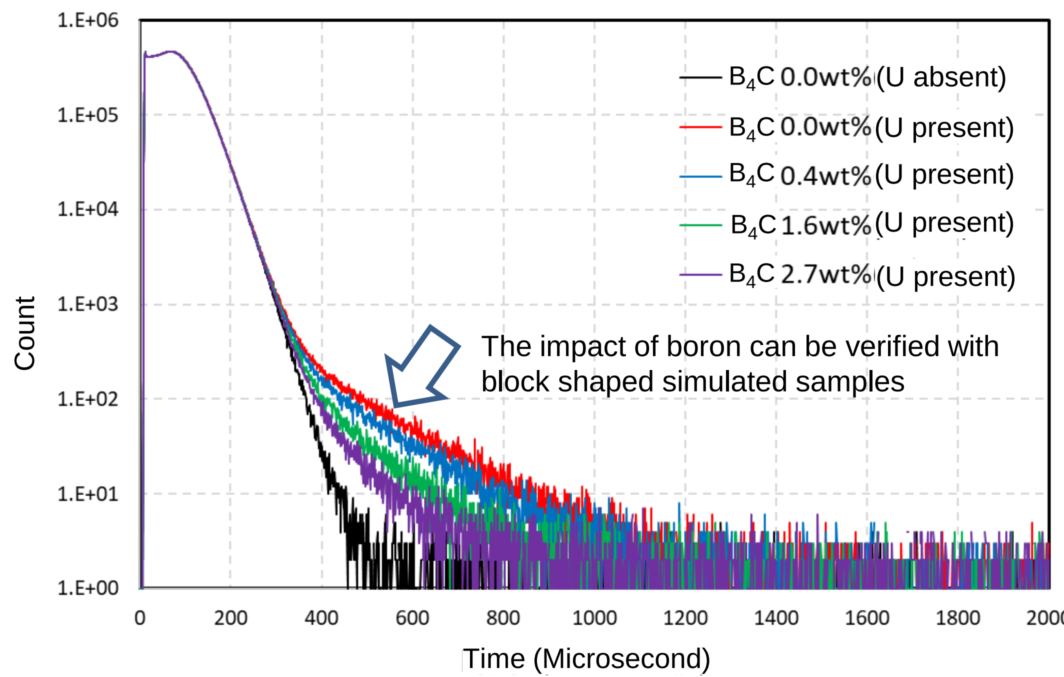
Manufactured blocks (Left: Concrete, Right: SUS)

Concrete blocks

Unit can (Φ210mm, h200mm)

B_4C rubber (Nuclear material under this)

JAWAS-T@NUCEF



An example of measurement results obtained by means of the FNDI method (Measurement time: 15 minutes)

- Block shaped simulated samples were manufactured for replicating a variety of fuel debris.
- It was found that the impact of neutron absorption material can be evaluated by conducting tests using block shaped simulated samples.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

① Active neutron method (3/10)

(b) Performance test of the neutron detector for the DDA method

[Background]

- In the case of the DDA method (Differential Die-away Analysis method) or the FNDI method, the nuclear fuel mass is obtained by irradiating the samples to be measured with neutrons and then detecting the fission neutrons released as a result of the fission reaction. Hence, the performance of the neutron detector has a major impact on the accuracy of the analysis.
- There were concerns of a short supply of the He-3 detector in the long term, and these detectors are sensitive to gamma rays as well to some extent.
- B-10 (lined) detector is less sensitive to gamma rays as compared to the He-3 detector and is less likely to get influenced by the gamma rays released by fuel debris. However, there is the issue of it having reduced neutron detection sensitivity.
- In the recent years, B-10 straw detector that has a significantly higher neutron detection sensitivity as compared to the conventional B-10 lined detector has been developed, however, it almost has no track record of being used in the case of DDA method or FNDI method.

[Test contents]

- The basic applicability to the DDA and FNDI methods was verified by integrating the B-10 straw detector into the JAWAS-T equipment and obtaining the time distribution spectrum.
- The sensitivity of the B-10 straw detector to neutrons and gamma rays was compared to the conventional He-3 detector and B-10 lined detector.
- The likelihood of ascertaining the conditions inside the container by means of neutron imaging was verified.

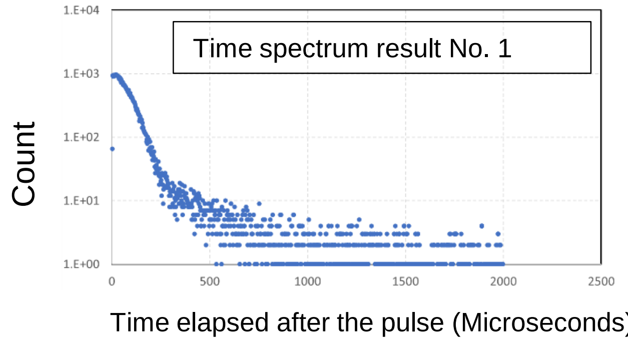
4.3 Study of elemental technology verification test methods using existing equipment, etc.

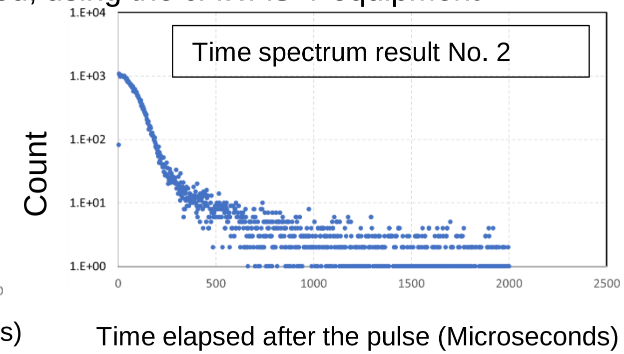
① Active neutron method (4/10)

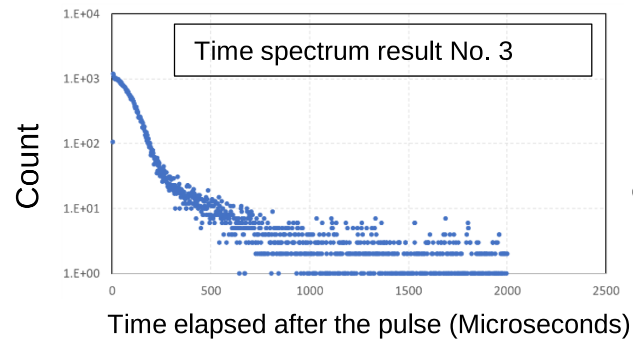
(b) Performance test of the neutron detector for the DDA method - Temporal characteristic test using JAWAS-T -

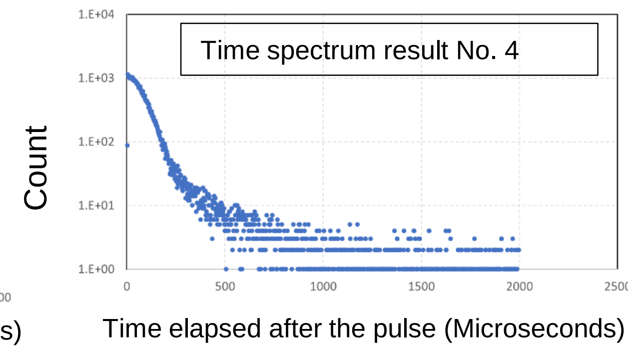
Example of the results of measurements performed when D-T neutrons (100 Hz) were irradiated, using the JAWAS-T equipment

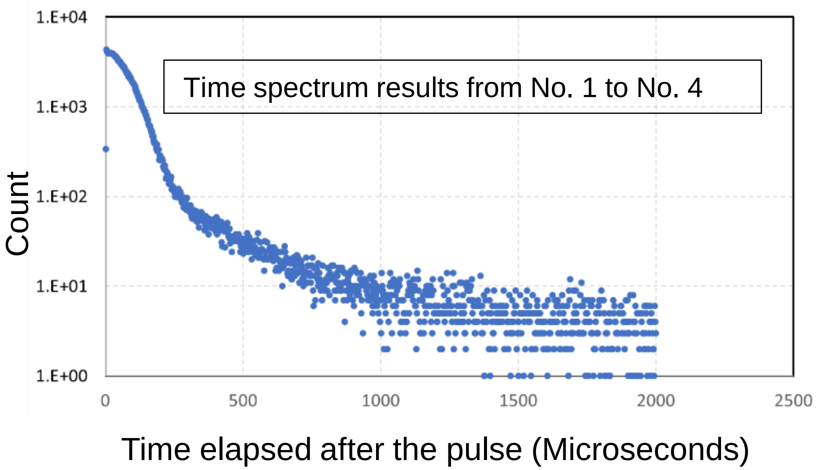
B-10 straw detector (Total 4 units: No.1, No.2, No.3, No.4 from the left
1 unit consists of 7 numbers of B-10 straw detectors lined up in a row)











- ➢ The spectrum results from the 4 detectors were almost uniform without the impact of any mutual interference, etc. Thus it was found to be a favorable measurement system.
- ➢ The time shift in the neutron count after the pulse was measured. Hence it was found that this detector can be used for the DDA method as well as the FNDI method (has sufficient temporal characteristics).

4.3 Study of elemental technology verification test methods using existing equipment, etc.

① Active neutron method (5/10)

(b) Performance test of the neutron detector for the DDA method - Sensitivity to neutrons and gamma rays -

Tests were conducted for comparing the basic performance of B-10 lined detector which is a conventional neutron detector with that of the B-10 straw detector.

Detector	Neutron sensitivity*	Gamma rays sensitivity*
B-10 lined	**1.0**	**1.0**
B-10 straw	**1.8**	**0.8**

* Ratio when the B-10 lined detector was considered to be 1.0 (Neutron： ^{252}Cf, Gamma rays: ^{60}Co, ^{137}Cs)

- The neutron sensitivity was higher than the B-10 lined detector, and almost the same as the value (2 times) expected from a vapor deposited area.
- The gamma rays sensitivity was almost the same as the B-10 lined detector.

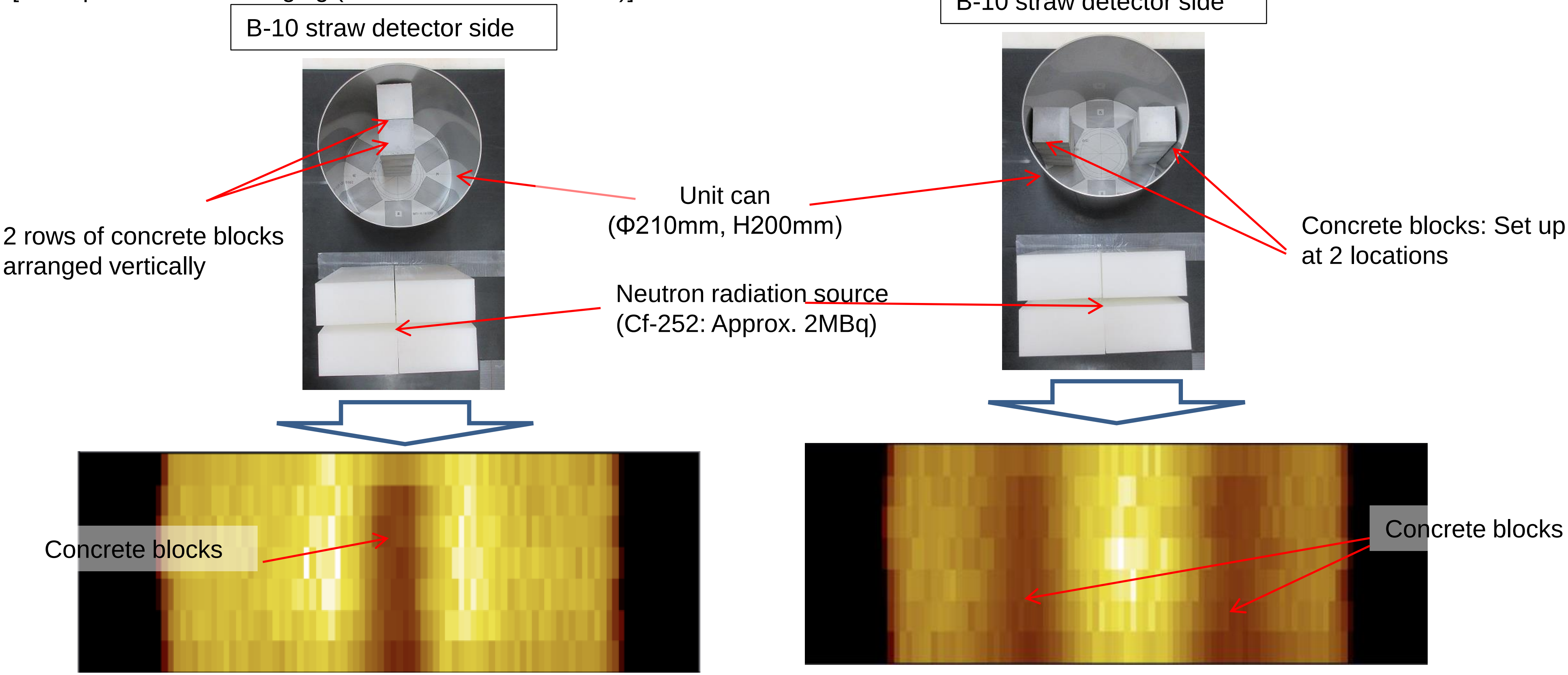
4.3 Study of elemental technology verification test methods using existing equipment, etc.

① Active neutron method (6/10)

(b) Performance test of the neutron detector for the DDA method - Neutron imaging -

The neutron detection position can be measured by measuring the wave height at both ends of the detector.

[Example of neutron imaging (Measured for 10 minutes)]



- The basic shape of the object to be measured was ascertained.
- There is a possibility of being able to reduce the measurement errors caused by uneven distribution, etc. in the object to be measured.

① Active neutron method (7/10)

(b) Performance test of the neutron detector for the DDA method - Summary -

The basic performance and basic data on the neutron detector that is required for studying the conceptual design, etc. pertaining to the active neutron method in the future was obtained.

- **As a result of the temporal characteristics test of the B-10 straw detector conducted using the JAWAS-T equipment, the neutron temporal distribution spectrum was obtained and it was found that this detector can be used for measurement by the DDA method or the FNDI method.**
- **The neutron sensitivity of the B-10 straw detector was about 2 times of the conventional B-10 lined detector, and was about the same as the sensitivity expected from the vapor deposited area of B-10.**
- **The gamma rays sensitivity of the B-10 straw detector was about the same as the B-10 lined detector.**
- **There is a possibility that B-10 straw detector imaging can reduce the degradation of measurement accuracy caused by uneven distribution in the object to be measured.**

4.3 Study of elemental technology verification test methods using existing equipment, etc.

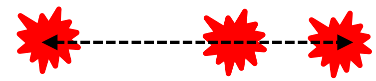
① Active neutron method (8/10)

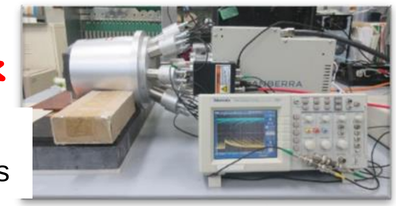
(c) High counting rate gamma rays measurement test

[Test contents]

If the quantity of neutron absorption material can be found out by the PGA (Prompt Gamma Analysis) method which is expected to be able to measure boron, gadolinium, etc., quantification or improving the accuracy of the sorting criteria, etc. can be expected by correcting the data obtained by DDA measurement.

As part of the performance evaluation of PGA, the impact that the counting rate has on the energy resolution of gamma rays was studied.

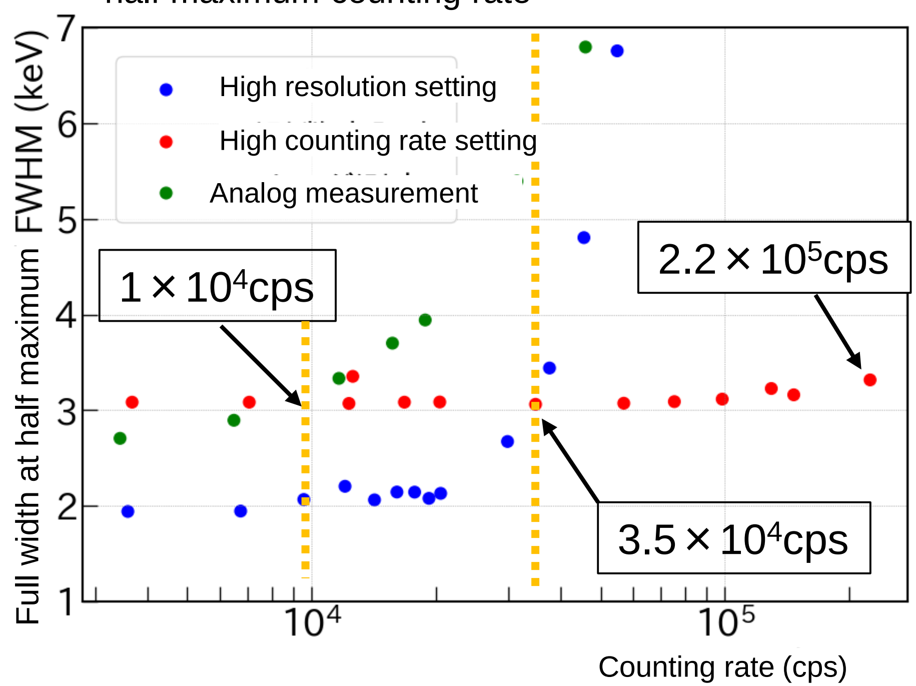




Change in position and number of radiation sources

- ✓ Cs-137 radiation source was measured using the Ge detector.
- ✓ Spectra under various counting rates were obtained.
- ✓ Measurement was performed using 2 types of equipment (2 types of waveform shapings were set in the digital equipment)
  - ・Analog
  - ・Digital (Waveforms were set for high resolution measurement)
  - ・Digital (Waveforms were set for high counting rate measurement)

Dependency of the gamma rays peak on full width at half maximum counting rate



● Analog measurement results

- ✓ Resolution gradually degraded along with the counting rate
- ✓ About the same with the digital equipment (high counting rate setting) at $1x10^4$cps

● Digital (high resolution setting) measurement results

- ✓ There were no major fluctuations in resolution until $2x10^4$cps
- ✓ The resolution suddenly degraded at $2x10^4$cps or more
- ✓ About the same as the digital equipment (high counting rate setting) at $3.5x10^4$cps
- ✓ It degraded further at $3.5x10^4$cps or more

● Digital (high counting rate setting) measurement results

- ✓ There were no major fluctuations in resolution until $2.2x10^5$cps
- ✓ Measurement is difficult at $2.2x10^5$cps or more

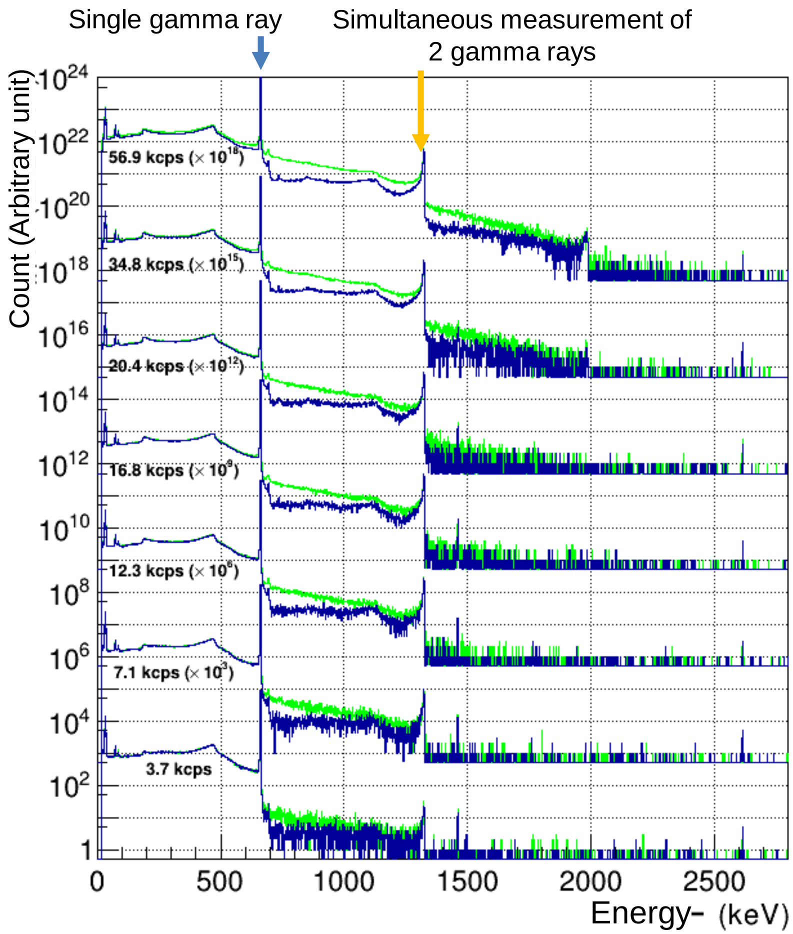
4.3 Study of elemental technology verification test methods using existing equipment, etc.

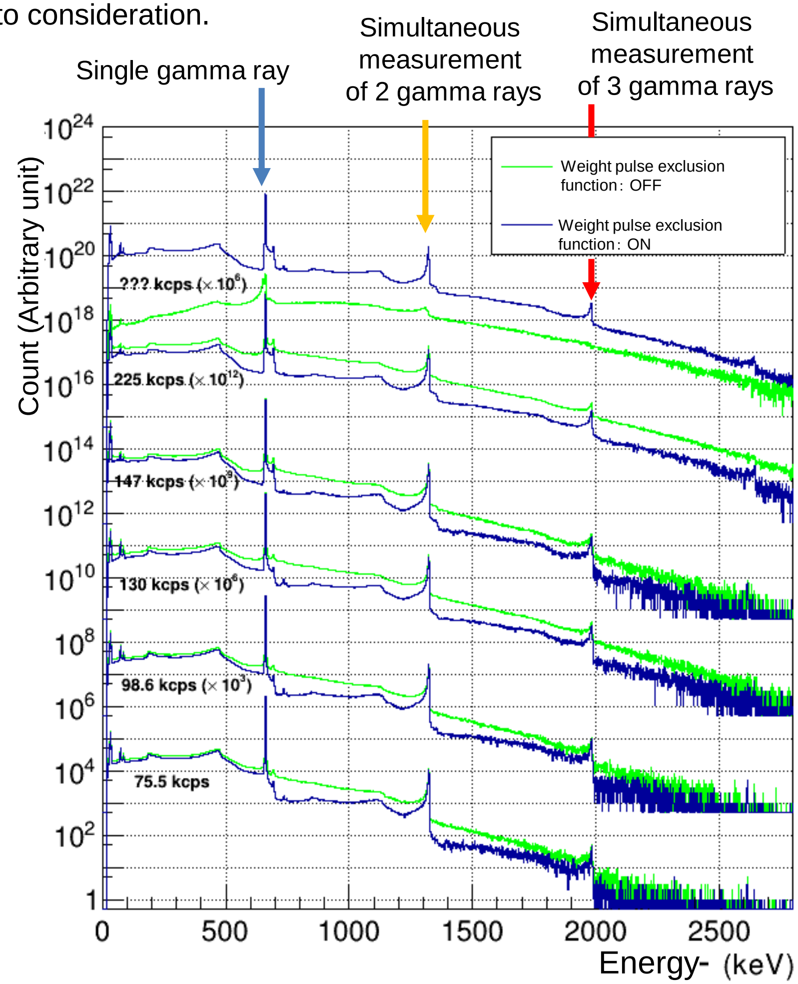
① Active neutron method (9/10)

(c) High counting rate gamma rays measurement test

Counting rate dependency of Cs137 gamma rays spectrum (High counting rate setting)

- ✓ The events (pile-up) when a multitude of gamma rays are simultaneously detected increase when the counting rate is high.
- ✓ Due to pile-up, it becomes difficult to detect feeble gamma rays.
- ✓ Mixing of highly radioactive nuclides (diversity of fuel debris) needs to be taken into consideration.





4.3 Study of elemental technology verification test methods using existing equipment, etc.

① Active neutron method (10/10)

Some additions
(Items to be implemented in FY2023 mentioned inside the pink frame)

Summary

(a) It was found that the impact of neutron absorption material can be evaluated by using block shaped simulated samples during the tests related to evaluating the impact of neutron absorption material, etc.

(b) Based on the performance test of the neutron detector for the DDA method, it was found that B-10 straw detector which has a smaller gamma rays impact as compared to the He-3 detector can be used for DDA measurement. Also, the basic performance and basic data on the neutron detector that is required for studying the conceptual design, etc. of the equipment or for the elemental technology verification test of the active neutron method in the future, was obtained.

(c) During the high counting rate gamma rays measurement test, knowledge was obtained related to the impact of counting rate on the gamma rays energy resolution obtained through the Ge detector, and which contributes to the PGA performance evaluation.

[Issues]

Along with verifying the impact reduction effect of diversity (neutron absorption material in particular) through experiments by conducting elemental technology verification tests using block shaped simulated samples that can replicate the diversity of debris, attempts need to be made to enhance the functionality of the impact reduction method.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

(② Passive neutron method)

4.3 Study of elemental technology verification test methods using existing equipment, etc.

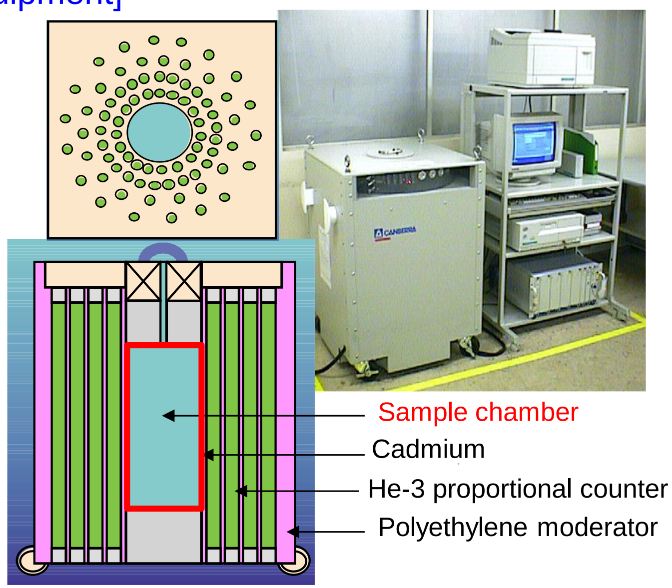
② Passive neutron method (1/10)

(a) Tests and studies assuming the use of passive neutron method equipment

[Aim of the elemental technology verification test]

- To verify the impact that the major influencing factors (quantity of neutron absorption material, amount of moisture) have on measurement accuracy through actual measurement.
- To study the techniques for reducing the impact on measurement accuracy through actual measurement and simulation.
- To verify the accuracy estimated through simulation, and in addition, to study accuracy improvement measures as required.

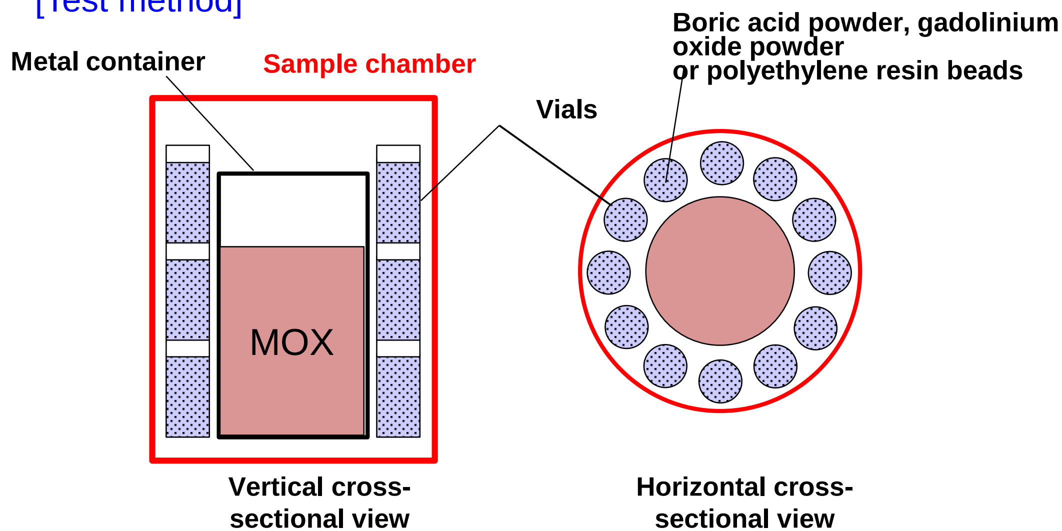
[Test equipment]



Test equipment: PSMC
(Plutonium Scrap Multiplicity Counter)

*** Refer to Attachment-1 for details about the PSMC equipment.**

[Test method]



Testing system

- **MOX samples enclosed in a metal container were set up in the sample chamber of the PSMC equipment, and multiple vials containing neutron absorption material or neutron moderator were placed around it.**
- **Diversity was simulated by changing the MOX composition, material inside the vials and the number of vials.**

4.3 Study of elemental technology verification test methods using existing equipment, etc.

② Passive neutron method (2/10)

Specifications of the simulated fuel debris samples

- **Specifications of the simulated fuel debris samples that take into consideration the neutron absorption material (B, Gd) and neutron moderator (water) identified as the influencing factors while measuring fuel debris were studied during the simulation implemented under the Government-led R&D Program on Decommissioning and Contaminated Water Management (FY2020 and FY2021) (Since it was difficult to use water from the perspective of criticality safety, polyethylene was used instead).**

Basic model (MOX fuel)

Model category	Nuclear fuel material ID
Only MOX	MOX-1
	MOX-2
	MOX-3

Basic model + B

Quantity equivalent to 1.3 to 9.8vol% B_4C

Model category	Nuclear fuel material ID	B-10(g)	B-10/Fissile Weight ratio
MOX+B1	MOX-1	9	0.01
	MOX-2		0.01
	MOX-3		0.01
MOX+B2	MOX-1	18	0.03
	MOX-2		0.02
	MOX-3		0.01
MOX+B3	MOX-1	36	0.05
	MOX-2		0.03
	MOX-3		0.03

Basic model + Gd

Quantity equivalent to 13.0 to 54.5vol% Gd_2O_3

Model category	Nuclear fuel material ID	Gd(g)	Gd/Fissile Weight ratio
MOX+Gd1	MOX-1	95	0.13
	MOX-2		0.09
	MOX-3		0.07
MOX+Gd2	MOX-1	190	0.27
	MOX-2		0.18
	MOX-3		0.13
MOX+Gd3	MOX-1	381	0.54
	MOX-2		0.36
	MOX-3		0.27

Basic model + Polyethylene

Quantity equivalent to 8.4 to 42.5vol% H_2O

Model category	Nuclear fuel material ID	Poly(g)
MOX+poly1	MOX-1	132
	MOX-2	
	MOX-3	
MOX+Poly2	MOX-1	263
	MOX-2	
	MOX-3	
MOX+poly3	MOX-1	527
	MOX-2	
	MOX-3	

Simulation tests on 30 cases resulting from a combination of fuel weight, neutron absorption material and neutron moderator were studied.

* The specifications of the simulated fuel debris samples are likely to change depending on issues, etc. that arise in actual measurement.
The B-10/Fissile weight ratio obtained from the average composition of the fuel and control rods from 1F1 at the point in time when 10 years have passed since the accident, was 0.08.
The Gd/Fissile weight ratio obtained from the average composition of the fuel and the quantity of Gd contained in the fuel with lowest burn-up 5.23GWd/t from 1F1 at the point in time when 10 years have passed since the accident, was 0.04.

② Passive neutron method (3/10)

Specifications of the simulated fuel debris samples

MOX fuel samples

Information on nuclear fuel material

Nuclear fuel material ID	MOX (g)	Pu (g)	U (g)	Pu240eff. (g)	Fissile (g)	Fissile/Pu240eff.
MOX-1	2748	1094	1242	452	709	1.6
MOX-2	4122	1641	1863	678	1063	1.6
MOX-3	5497	2188	2484	903	1418	1.6

Isotopic composition ratio of nuclear fuel material

Nuclear fuel material ID	Pu-238 (%)	Pu-239 (%)	Pu-240 (%)	Pu-241 (%)	Pu-242 (%)	Am-241 (%)	U-233 (%)	U-234 (%)	U-235 (%)	U-236 (%)	U-238 (%)
MOX-1 to 3	1.261	62.135	28.479	2.396	5.729	7.996	0.000	0.004	0.220	0.001	99.775

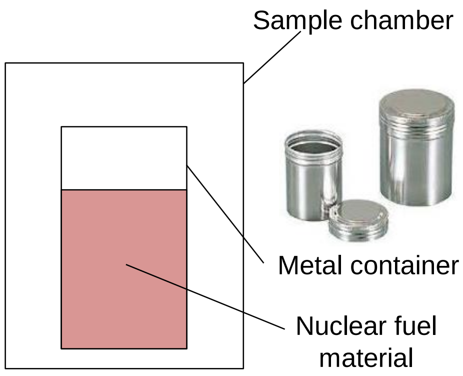
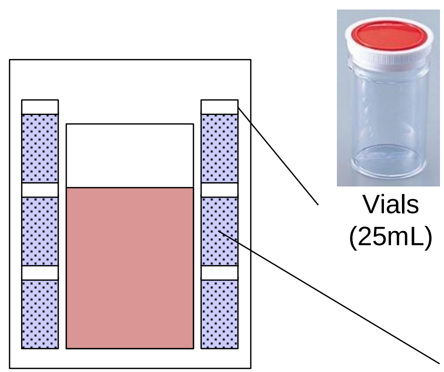
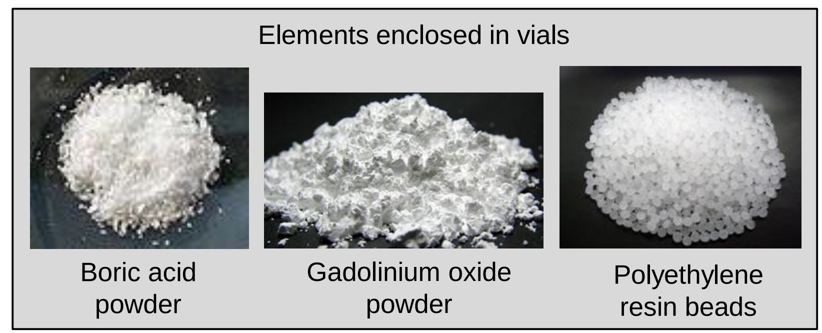
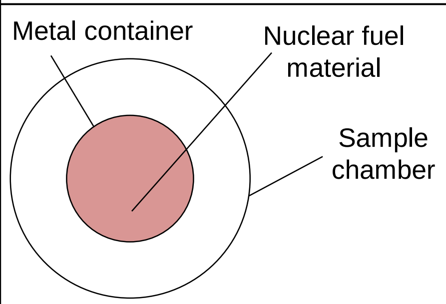
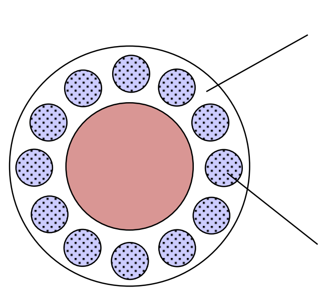
* The weight of nuclear fuel material mentioned has been rounded off.
The weight and composition of the nuclear fuel materials selected for preparing the simulated fuel debris samples is likely to change in association with the operation of the facility.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

② Passive neutron method (4/10)

Case models assumed in the tests

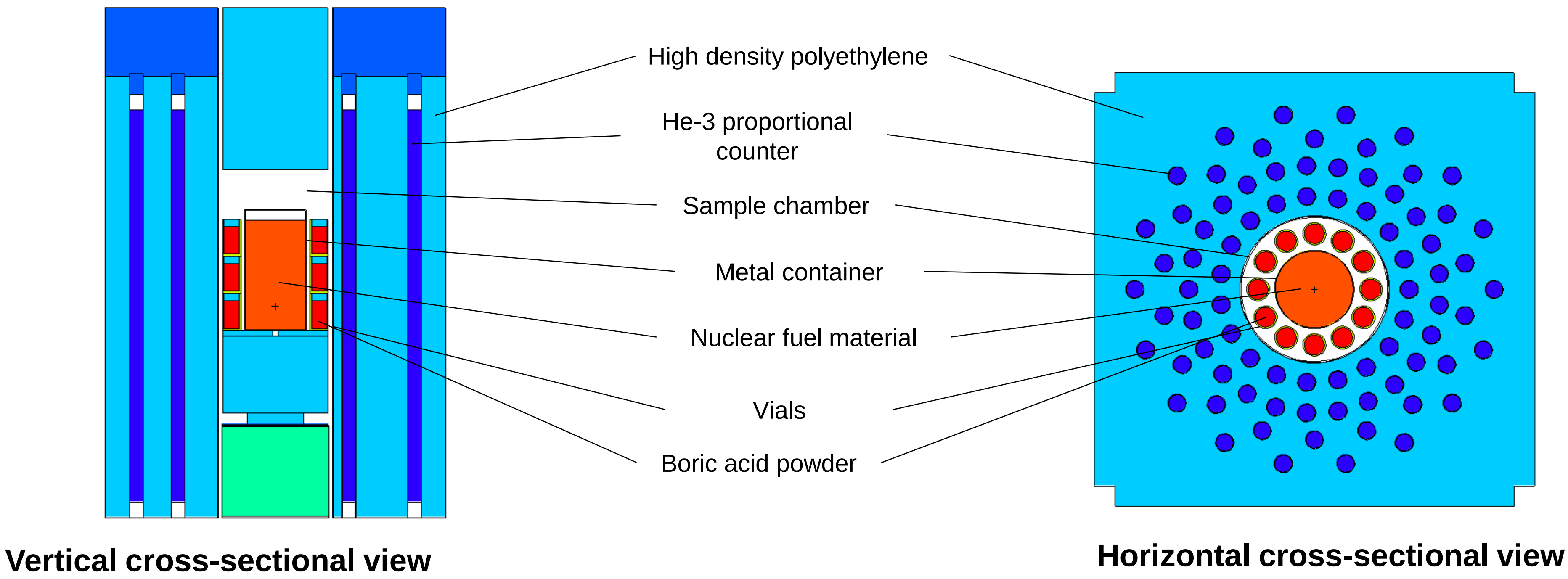
- **The case models assumed in the tests and the measurement systems for each case model were studied (Since preparing simulated fuel debris samples mixed with nuclear fuel material as well as elements (B, Gd, Polyethylene) is not permitted, fuel debris was simulated by placing the elements in the vicinity of the nuclear fuel material).**

Model category	Only MOX	MOX+B1 to MOX+B3	MOX+Gd1 to MOX+Gd3	MOX+Poly1 to MOX+Poly3
Main elements used for preparing the samples	MOX powder	MOX powder Boric acid powder	MOX powder Gadolinium oxide powder	MOX powder Polyethylene resin beads (instead of water)
Measurement system (Vertical cross-sectional view)				
Measurement system (Horizontal cross-sectional view)				

② Passive neutron method (5/10)

Simulation method

- Computational code: MCNPX2.7.0
- Nuclear data library: JENDL-4.0 (Ace format)



Simulation model for measuring simulated fuel debris samples while taking into consideration the neutron absorption material (B) in the PSMC equipment

② Passive neutron method (6/10)

Principle employed in the method for reducing the impact of diversity

① Neutron coincidence counting method

The neutron coincidence counting method is a method of quantifying nuclides resulting from spontaneous nuclear fission in which the impact of counting neutrons that are a result of the (α,n) reaction, etc. and which do not occur coincidently is eliminated by selectively counting the neutrons that are simultaneously released in a large number due to nuclear fission.

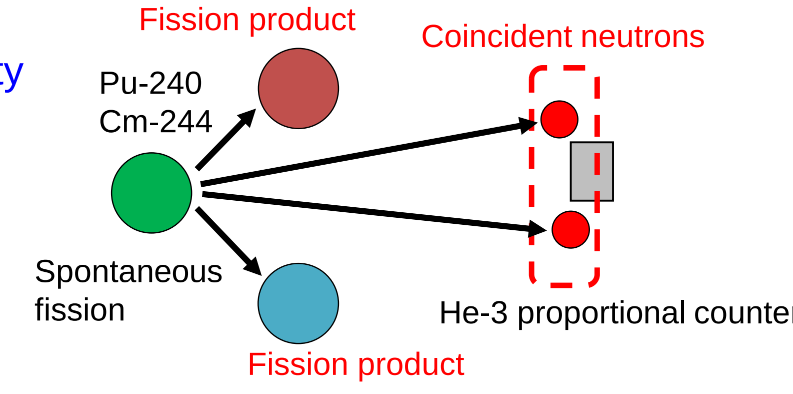


Figure The concept of coincidental occurrence of neutrons that are released by spontaneous fission

② Differential Die-away Self-Interrogation (DDSI) method

The DDSI method is a method of evaluating the extent of reduction in the number of neutrons due to the neutron absorption material or the increase in the number of neutrons due to induced fission, which are measured with a delay due to moderation as compared to the spontaneous fission neutrons, by focusing on the difference in the distribution of the time in which spontaneous fission neutrons and induced fission neutrons are detected.

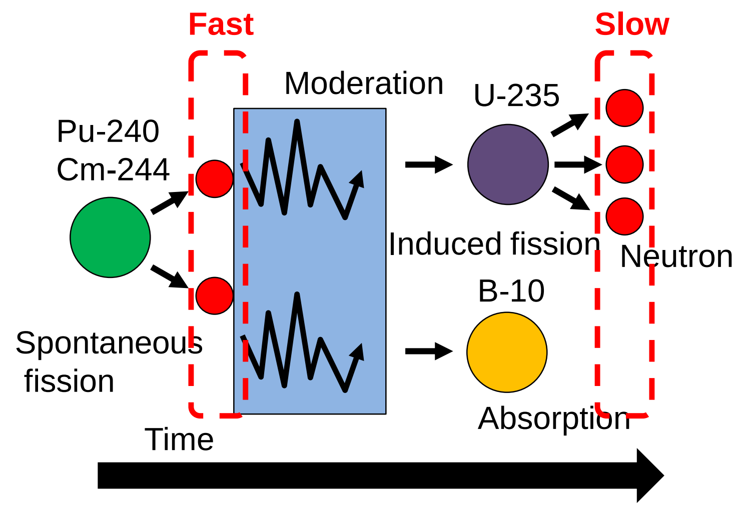


Figure Difference in the time required for detecting the spontaneous fission neutrons and the induced fission neutrons

By using these methods, the measurement errors caused by the diversity of the contents of the container are expected to be reduced. This was verified by simulating the testing and studying system.

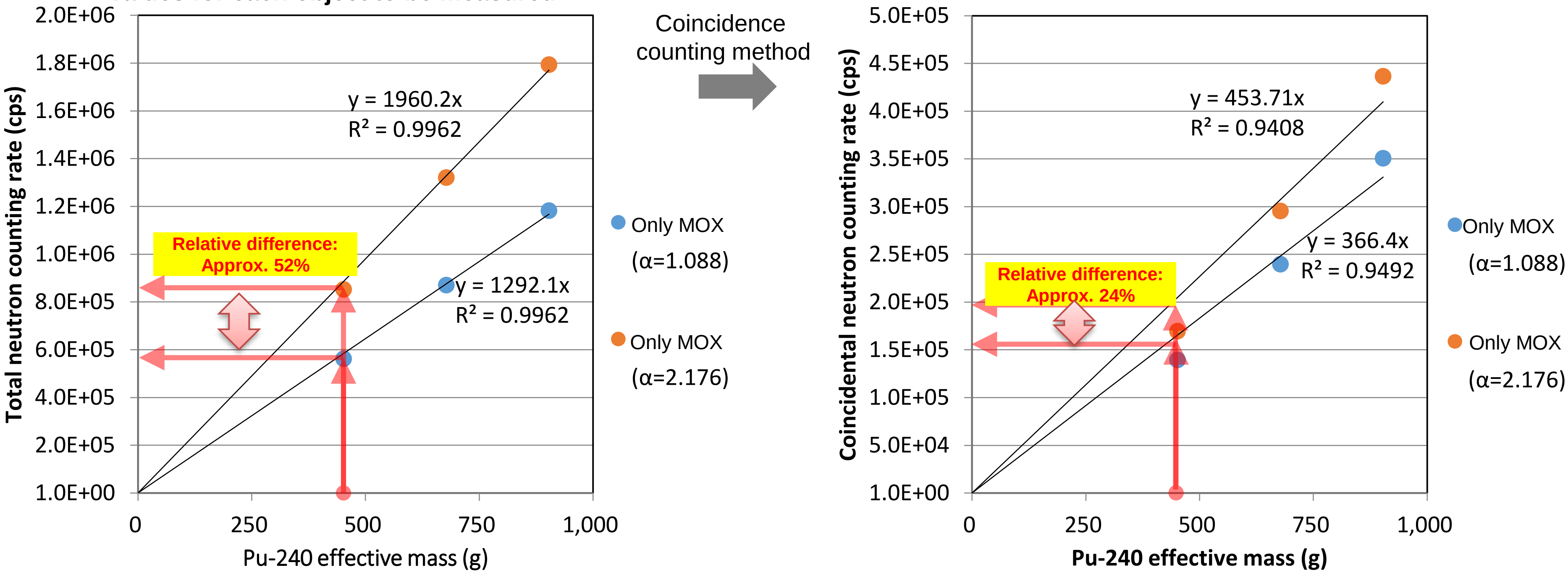
4.3 Study of elemental technology verification test methods using existing equipment, etc.

② Passive neutron method (7/10)

Results of the tests and studies on the method for reducing the impact of diversity

[Test on the neutron coincidence counting method]

- **Simulation was performed in which PSMC measurement of MOX samples having different (α, n) reaction neutrons to spontaneous fission neutrons ratios (α values) was assumed, and the impact of the α values on the measured values (Total neutron counting rate and coincidental neutron counting rate) was evaluated.**
- **It was verified that the neutron coincidence counting method was effective for fuel debris that is expected to have different α values for each object to be measured.**



Correlation between the total neutron counting rate and the Pu-240 effective mass

Correlation between the coincidental neutron counting rate and the Pu-240 effective mass

Note: When the α values of the actual fuel debris are so small that they can be ignored, the relative difference between the total neutron counting rate and the coincidental neutron counting rate is large and the value is not expected to change.

Since in the case of actual fuel debris mainly the Cm-244 effective mass is measured, an evaluation method in which the Cm-244 effective mass is converted to U/Pu amount becomes necessary.

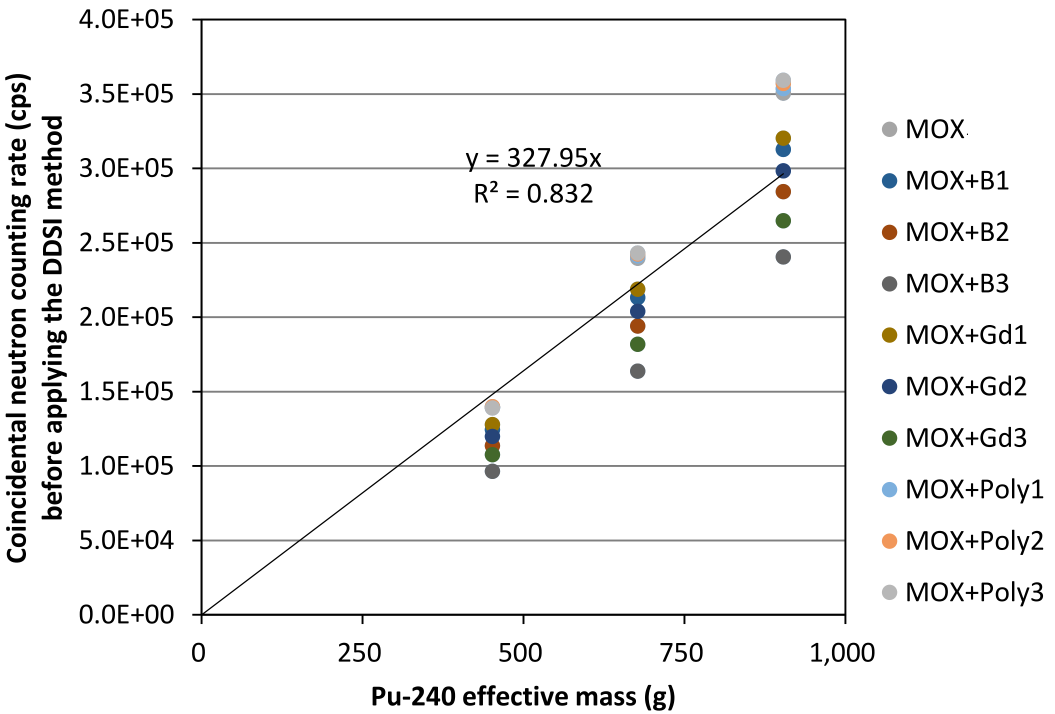
4.3 Study of elemental technology verification test methods using existing equipment, etc.

② Passive neutron method (8/10)

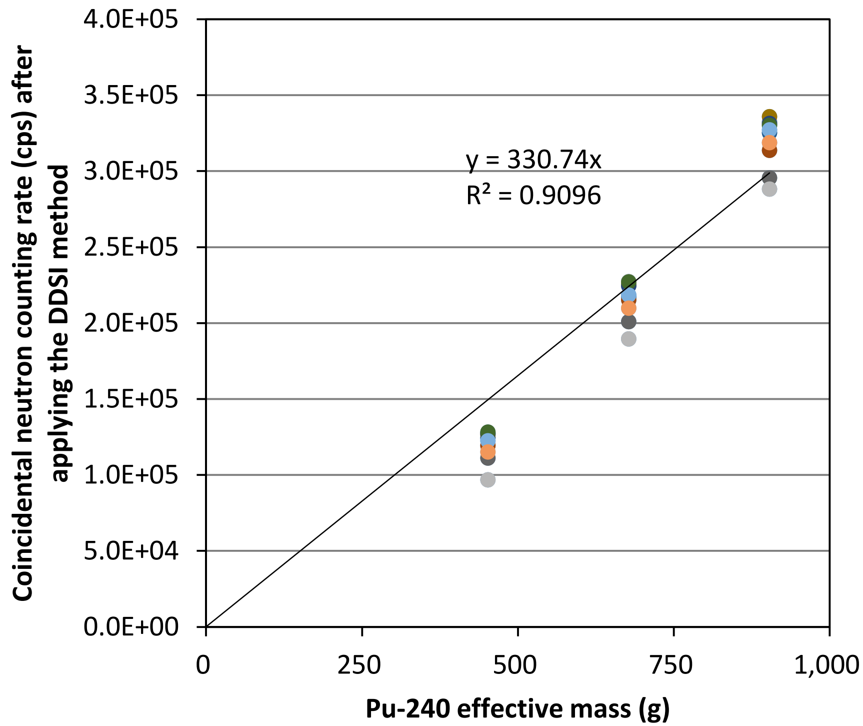
Results of the tests and studies on the method for reducing the impact of diversity

[DDSI method applicability evaluation test]

- **A simulation was performed in which it was assumed that simulated fuel debris samples are measured by the DDSI method using PSMC.**
- **It was verified that the relative accuracy with Pu-240 effective mass improved when coincidental neutron counting rate corrected using the DDSI method was used, than when the coincidental neutron counting rate that was not corrected was used. Thus prospects of the DDSI method applicability evaluation test being feasible were seen.**



Correlation between the coincidental neutron counting rate (before applying DDSI method) and the Pu-240 effective mass



Correlation between the coincidental neutron counting rate (after applying DDSI method) and the Pu-240 effective mass

Note: Since in the case of actual fuel debris mainly the Cm-244 effective mass is measured, an evaluation method in which the Cm-244 effective mass is converted to U/Pu amount becomes necessary.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

② Passive neutron method (9/10)

(b) Study of TMI-2 fuel debris neutron measurement method

Average burn-up: Approx. 3GWd/t. Evaluation of the extremely minute radiation source from the TMI-2 fuel debris 40 years or more after the accident.

TMI-2 fuel debris computational model (Tentative)

Shape: Spherical (radius 1cm)   MCNP6.2 calculation
Burn-up: 3.25 (GWd/t)
Composition: $(U_{0.5}, Zr_{0.5})O_2$, bulk density 6.18 (g/cm^3)
Date of evaluation: December 2024

External appearance and characteristics of the bubble detector

Neutron irradiation

Use application: Neutron detection in confined spaces in a high gamma rays environment inside the PCV or prior sorting based on tentative field measurement of retrieval samples (Development of criteria based on the location of retrieval)

- Integrated neutron dosimeter (For fast neutrons)
- Small, light (19mmΦ×145mm, 58g), moderator not required
- Power cable not required
- Gamma rays resistance: Verified up to approx. 10(kGy) in the Co60 irradiation test
- Lower detection limit neutron flux in air: Verified up to 10 (n/cm^2/s)
- Measurement track record with MOX (1kg)

[Study results]

Evaluation of gamma dose rate

Distance (cm) from the surface	0	1	5	10
Dose rate (mSv/h)	253.6	42.9	4.5	1.3

Neutron fluence rate evaluation

Energy range	Fluence rate (n/cm^2/s)
Less than 5 (eV)	0.00E+00
5 (eV) or more, less than 100 (keV)	1.02E-05
100 (keV) or more	5.49E-01

Requirements of the neutron detector

Under the above-mentioned gamma rays environment, neutron flux with about 0.55 (n/cm^2/s) can be detected.

- Sufficient gamma radiation resistance
- Difficult to detect neutrons with 0.55 (n/cm^2/s)

4.3 Study of elemental technology verification test methods using existing equipment, etc.

② Passive neutron method (10/10)

Summary

- A testing system was developed that assumes that the existing passive neutron method equipment (PSMC) and MOX samples are used and that simulates diversity of fuel debris by arranging neutron absorption material or neutron moderator around the MOX samples.
- A simulation model of the testing system was developed for studying the method for verifying applicability of the passive neutron method.
- The neutron coincidence counting method was proposed as a measure to reduce the impact of α value fluctuations, and the effectiveness of the applicability test of that method was verified by simulation.
- The DDSI method was proposed as a measure to reduce the impact of neutron absorption and neutron multiplication inside the container, and the effectiveness of the applicability test of that method was verified by simulation.
- The requirements for detecting passive neutrons in TMI-2 fuel debris (approx. 3GWd/t, 44 years old) were verified.

[Issues]

- Since in the case of actual fuel debris mainly the Cm-244 effective mass is measured, an evaluation method in which the Cm-244 effective mass is converted to U/Pu amount becomes necessary. Thus uncertainties stemming from the evaluation method are incidental.
- Verification of the effectiveness of the passive neutron method for fuel debris that is more than 40 years old and has a low burn-up of several GWd/t

4.3 Study of elemental technology verification test methods using existing equipment, etc.

(③ Muon scattering method)

③ Muon scattering method (1/6)

(1) Development policy

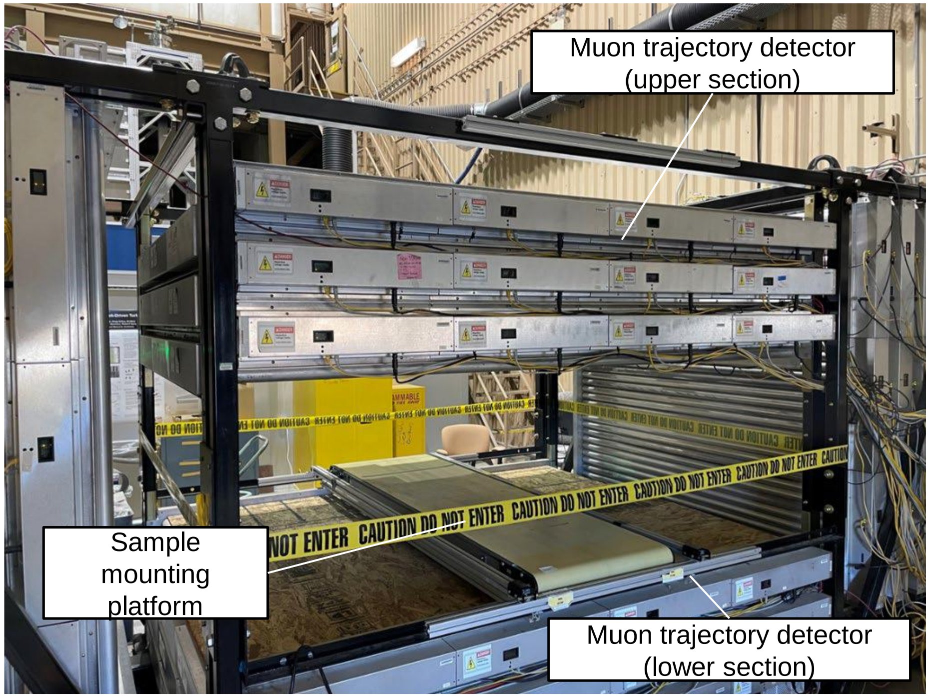
- Development goals
  - Development of equipment that can be used for measuring fuel debris (Muon trajectory detector)
  - Demonstration of the technology by measuring fuel debris using the developed equipment
- Current issues
  - Acquisition of basic muon characteristics for setting the simulation conditions
  - Creation of the specifications of the equipment for measuring fuel debris
- FY2022 test plan
  - Muon measurement tests using existing equipment
    - Acquisition of basic muon characteristics
    - Acquisition of muon scattering data with respect to multiple materials
  - Test manufacturing of sensors
    - Test manufacturing of some of the sensors that constitute the muon trajectory detector
- Future plans
  - Development of test equipment for 1F (Development of measurement system by assembling sensors)
  - Measurement of fuel (hot tests) assuming the fuel debris measurement conditions

4.3 Study of elemental technology verification test methods using existing equipment, etc.

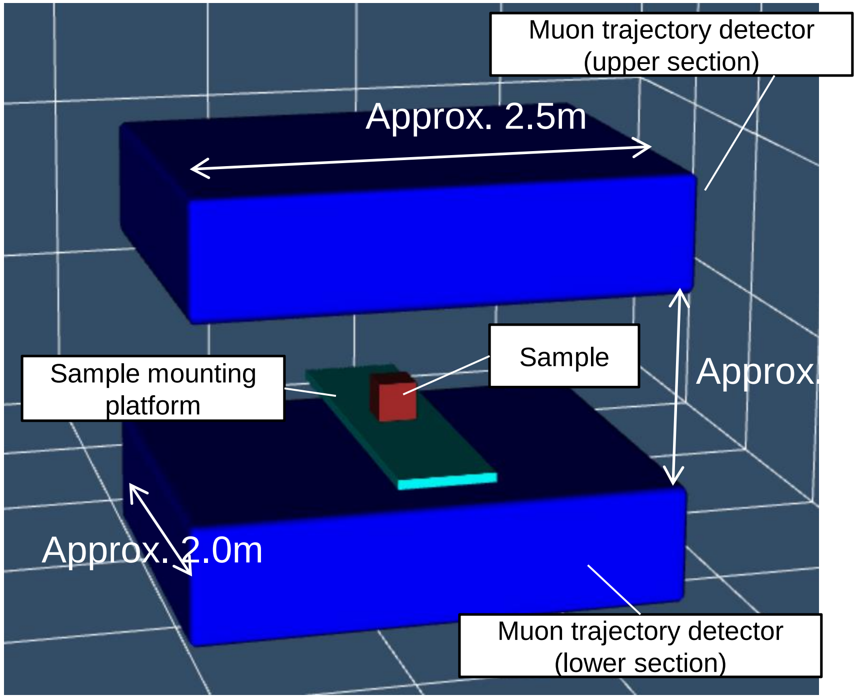
③ Muon scattering method (2/6)

(2) Elemental technology verification test

- Measurement tests were conducted using the muon trajectory detector at the Los Alamos National Laboratory.
  - Acquisition of the basic characteristics during muon measurement
  - Acquisition of muon scattering data for various materials by measuring multiple material samples



Muon trajectory detector (Los Alamos National Laboratory)



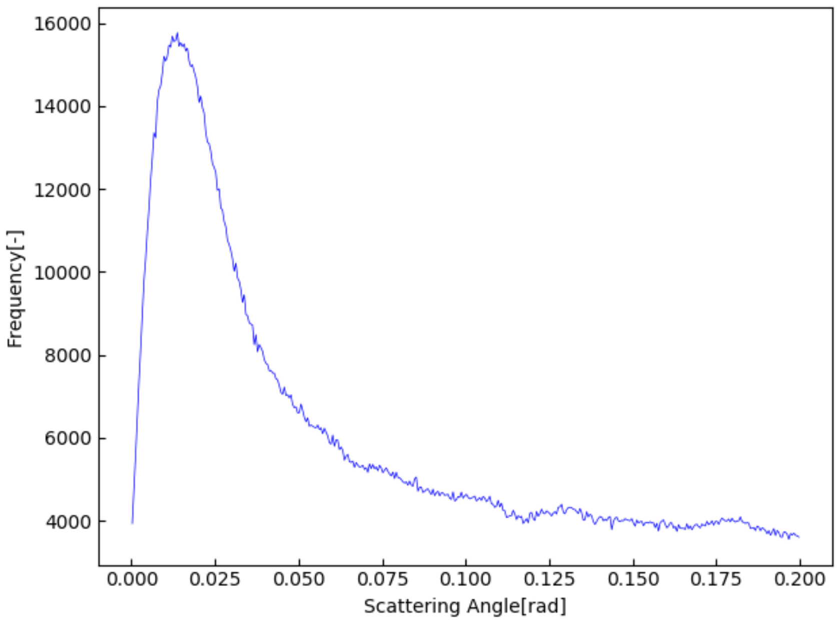
Measurement system

4.3 Study of elemental technology verification test methods using existing equipment, etc.

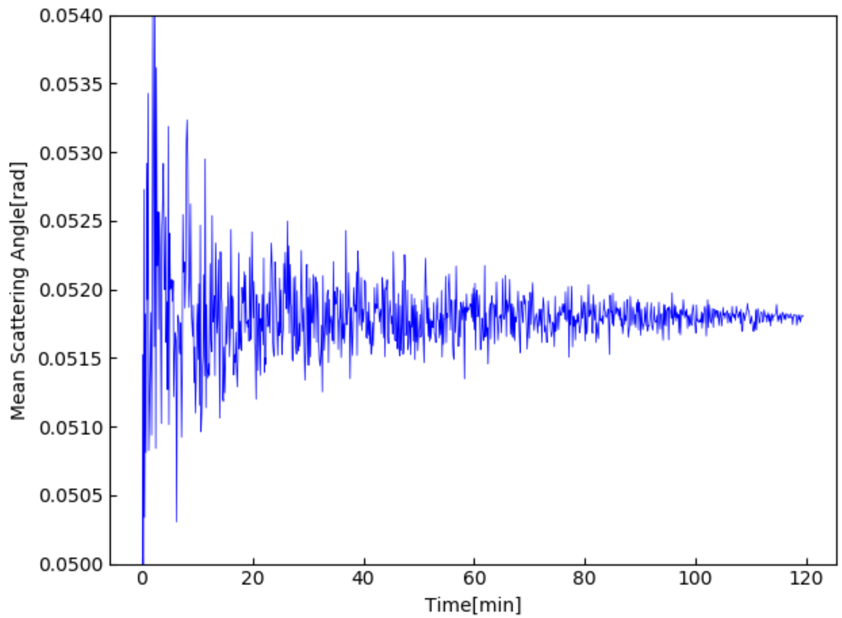
③ Muon scattering method (3/6)

(2) Elemental technology verification test

- Muon scattering angle spectrum
  - Acquisition of muon scattering angle spectrum (analysis criteria) while the sample is not mounted
- Shift in mean scattering angle with respect to the measurement time
  - Evaluation of the variations in muon scattering angle with respect to the measurement time



Muon scattering angle spectrum (without sample)



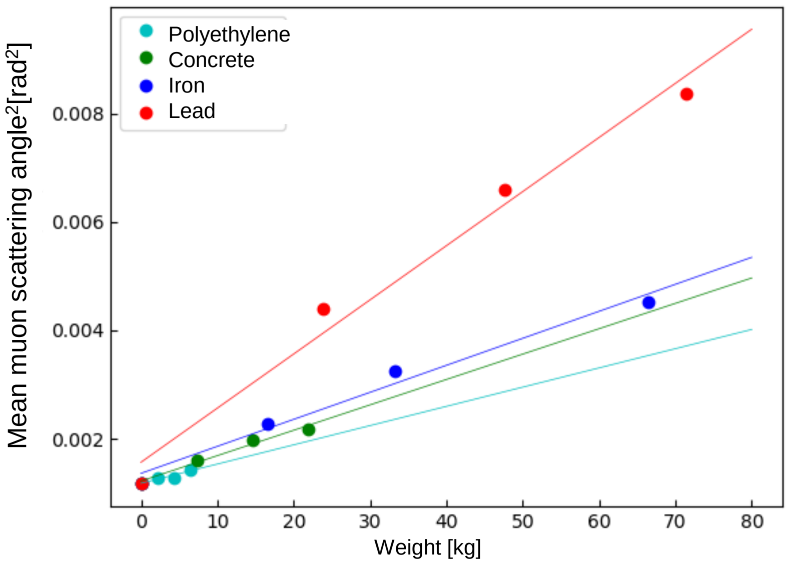
Variations in the mean muon scattering angle with respect to the measurement time

- Reflection into the simulation evaluation as scattering angle criteria
- Measurement time was set to 2 hours for reducing statistical errors

③ Muon scattering method (4/6)

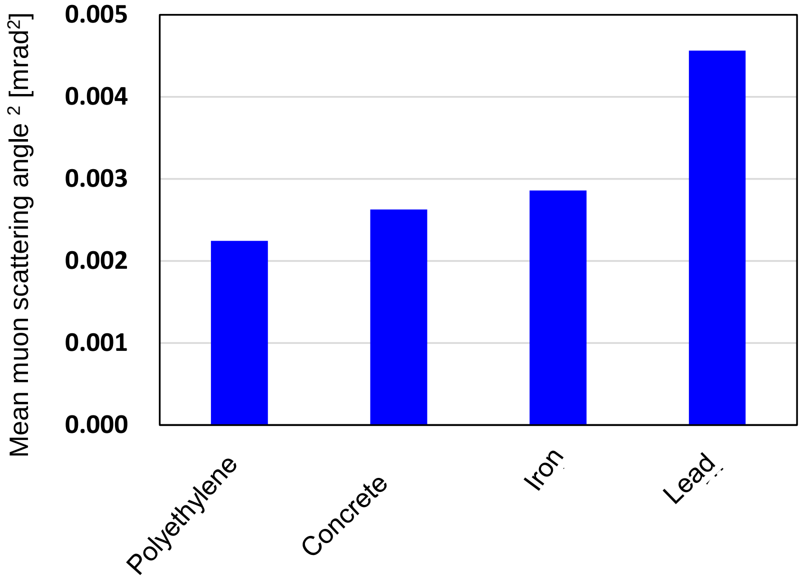
(2) Elemental technology verification test

- Muon scattering measurement for the material samples
  - Target sample: Polyethylene, concrete, iron and lead
- Measurement results
  - Acquisition of the actual measured muon scattering angles for the types and weight of the sample materials
  - Reflection of the simulation conditions reflecting actual measured values into the calibration



Mean muon scattering angle for each sample

- Evaluation of the characteristics of the muon scattering angle using the difference in weight



Mean muon scattering angle for the conversion value of 30kg of each sample

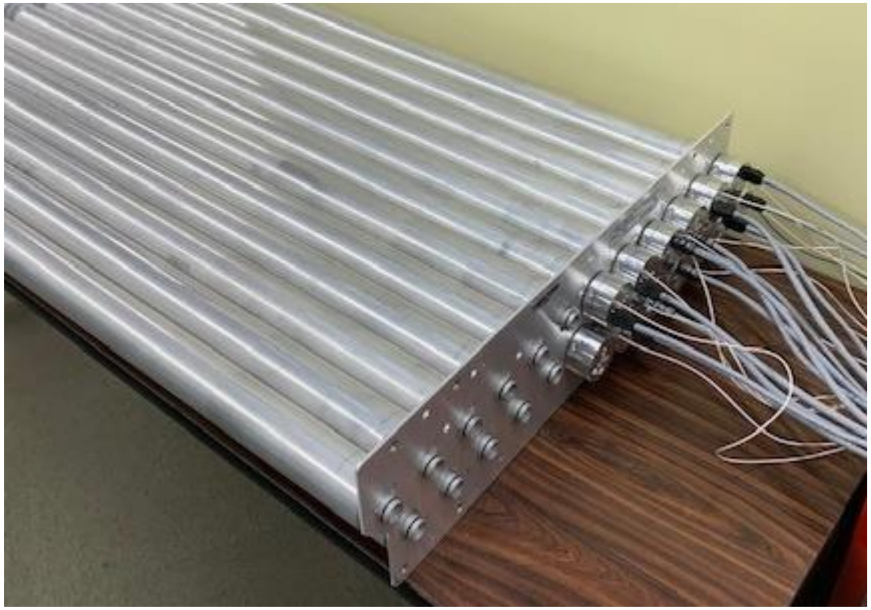
- It was verified that the moun scattering angle differs for each material

4.3 Study of elemental technology verification test methods using existing equipment, etc.

③ Muon scattering method (5/6)

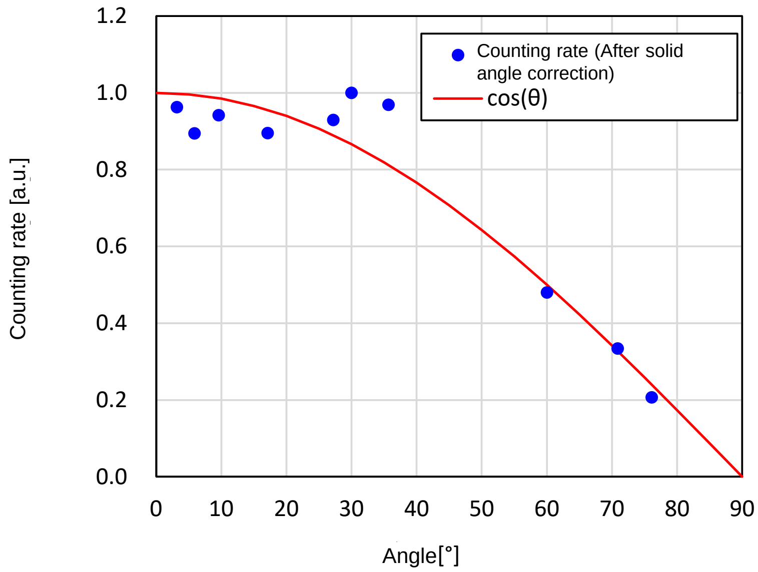
(2) Elemental technology verification test

- Test manufacturing of sensors
  - Sensors (Drift tube detector) that constitute the muon trajectory detector were test manufactured and their operation was verified.
- Muon incidence angle distribution
  - The dependency of the muon counting rate on the incidence angle was measured.



Drift tube detector

- Used as elemental technology in the development of equipment for measuring fuel debris



Muon incidence angle distribution evaluation results

- Will be reflected as conditions set up in simulations in the future.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

③ Muon scattering method (6/6)

Summary and future issues

[Implementation details]

1) Basic muon characteristics were acquired using existing equipment, etc.
2) Muon scattering was measured for multiple types of material samples.
3) Sensors were test manufactured for developing the muon trajectory detector.
4) Test plans were studied.

[Results/Contribution to development]

1) Data on basic muon characteristics was acquired.
   - Statistical errors based on the muon scattering angle spectrum, muon incidence angle distribution and the measurement time
2) Muon scattering data with respect to multiple materials was acquired.
   - It was verified that the muon scattering angle differs depending on the type of material.
3) The verification of operation of the sensors that were test manufactured for the 1F measurement equipment was completed.
4) Test plans were created.
   - Muon scattering angle measurement tests on samples including fuel debris
   - Creation of nuclear fuel weight evaluation function based on actual measured data

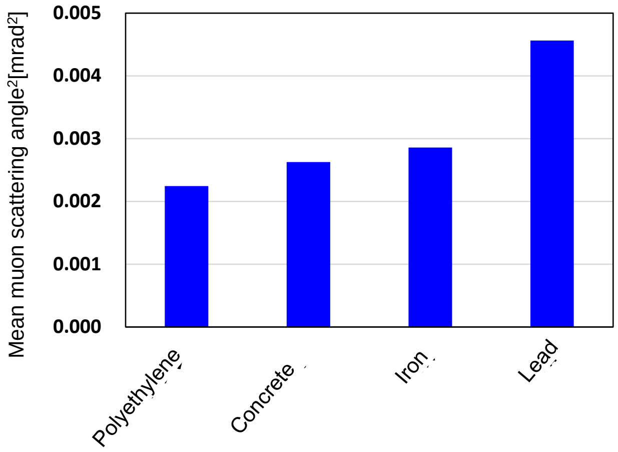
[Issues]

1) Issue: Estimation of the weight of nuclear fuel which is mixed with several other materials

2) Issue: Development of sensors and measurement systems that can be operated in the 1F measurement environment

Muon trajectory detector (Los Alamos National Laboratory)

- The scattering from samples and muon specific scattering was acquired using the existing measurement equipment.



Measurement values of samples with the same weight

- Muon scattering was measured for multiple samples
- Scattering differs depending on the material

4.3 Study of elemental technology verification test methods using existing equipment, etc.

(④ X-ray CT method)

4.3 Study of elemental technology verification test methods using existing equipment, etc.

④ X-ray CT method (1/4)

Test overview

The test plan was created this year, and tests and additional analyses are planned to be implemented in the future.

■ Purpose of the tests:

Tests are planned to be implemented with the following purpose in preparation for detailed studies related to the methods of evaluating sorting scenarios, quantity of nuclear fuel material, etc.

- Verifying the trends in the results of analyses conducted so far this year by performing tests
- Test manufacturing and measuring simulated fuel debris, disseminating the knowledge related to fuel debris properties, and studying the measured data that can be provided for correcting other measurement technologies

■Test items:

1: Test for evaluating the impact of bulk density of material

2: Test for capturing images of the simulated non-radioactive MCCI test pieces

4.3 Study of elemental technology verification test methods using existing equipment, etc.

④ X-ray CT method (2/4)

Test item 1: Test for evaluating the impact of bulk density of material

<Test details> Applicability of MECT* with respect to the composition of fuel debris with changed bulk density brought about by introducing pores will be verified.

* MECT：Multiple-Energy X-ray CT

Issues

- When pores that are smaller than spatial resolution are introduced into fuel debris, the bulk density of materials that are contained in fuel debris changes. Hence there is a possibility of conventional CT not being able to differentiate materials such as fuel debris, etc. (Issue identified during the FY2020-2021 subsidy projects)

Purpose of the test

- To evaluate the ability to differentiate material assuming that the bulk density of material has changed, by measuring the quantity of material corresponding to the atomic number by means of the method of irradiating multiple energy X-rays (MECT).

Test items

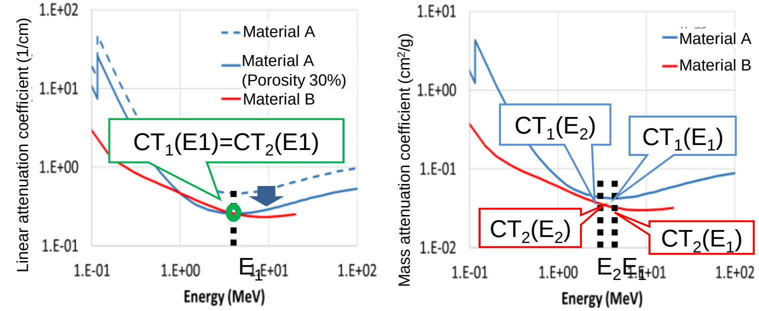
- Evaluation of the ability to differentiate materials by MECT related to material bulk density

  Test pieces will be prepared by changing the bulk density of materials by filling the container that is equivalent to the unit can with non-radioactive material of varied particle sizes, and quantities of material obtained by capturing images with the conventional CT and the MECT will be compared.

■ Difference in the way materials are differentiated by the conventional CT method and by MECT

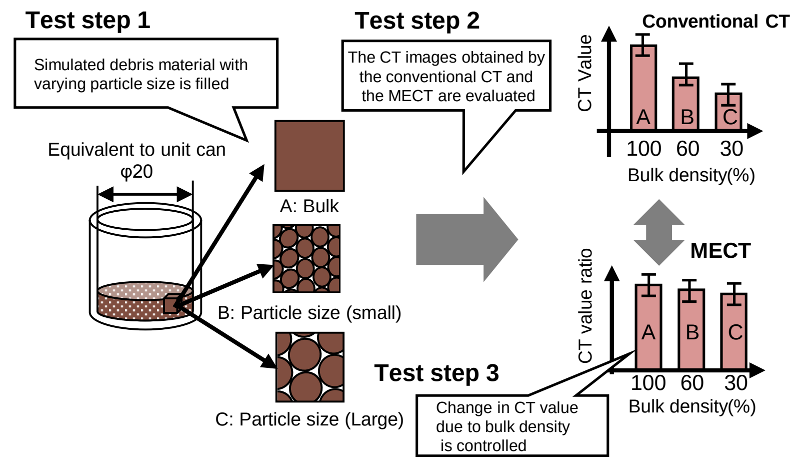
Quantity measured by the conventional CT (*Linear attenuation coefficient μ_l*)
Even if the material varies, **sometimes the same CT value is indicated due to change in density, and hence it is difficult to differentiate.**

Quantity measured by MECT (Ratio of mass attenuation coefficient μ_m)
The impact of density is eliminated by taking the ratio of CT images obtained using 2 or more types of energy X-rays.



$CT_i(E_2)/CT_i(E_1) = \mu_{m1}(E_2)/\mu_{m2}(E_1)$, (i=1,2)

■ Image illustrating the study of testing method



4.3 Study of elemental technology verification test methods using existing equipment, etc.

④ X-ray CT method (3/4)

Test Item 2: Test for capturing images of the simulated non-radioactive MCCI test pieces

<Test details> Images of the simulated non-radioactive MCCI test pieces will be captured and data on debris properties will be acquired and analyzed.

Issues

- There is little information related to composition or uneven distribution of fuel debris which have a comparatively large impact on the measurement technologies, and hence it is difficult to consider combining multiple measurement technologies.

Purpose of the test

- To acquire information related to composition or uneven distribution pertaining to the simulated non-radioactive MCCI test pieces.

Test item

① Evaluation of the properties of all the simulated debris
Uneven distribution of the shape, bulk density and composition of all the test pieces will be evaluated and categorized by levels with varying properties.

② Evaluation of the properties of the processed simulated debris
Uneven distribution of the shape, density and composition of the test pieces filled in a container that is equivalent to a unit can and which are processed from the upper, middle and lower levels will be evaluated.

* Comparative evaluation based on measurements performed separately will be conducted in the future.

Image illustrating test item ①

Upgrading of Fundamental Technology for Retrieval of Fuel Debris and Internal Structures_FY2018 Research Results Report

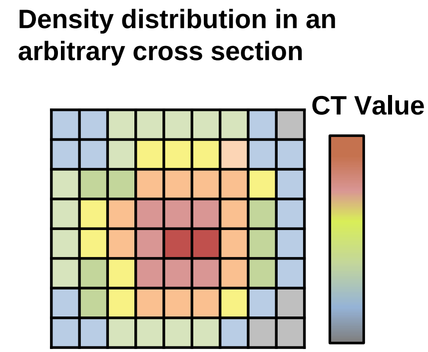
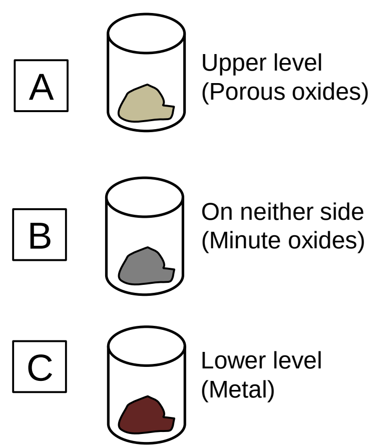
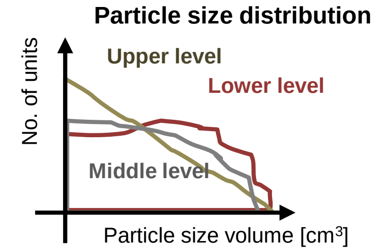
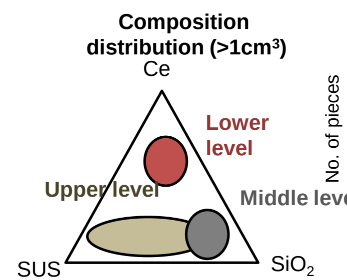
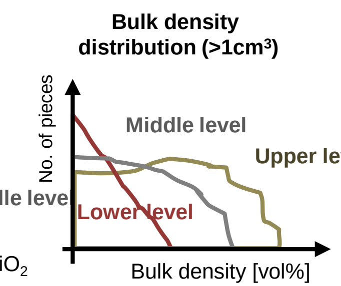


Image illustrating test item ②









4.3 Study of elemental technology verification test methods using existing equipment, etc.

④ X-ray CT method (4/4)

<Summary and future issues>

[Implementation details]

･Upon obtaining the results of studying the detector response analysis and the methods for evaluating the quantity of nuclear fuel material, 2 test methods were considered.

[Results/Contribution to development]

･ Test 1: Test for evaluating the impact of bulk density of material
Test pieces were prepared by changing the bulk density of materials by filling the container that is equivalent to the unit can with non-radioactive material of varied particle sizes, and quantities of material obtained by capturing images with the conventional CT and the MECT were compared.

･ Test 2: Test for capturing images of the simulated non-radioactive MCCI test pieces
- Evaluation of properties of all the simulated debris
Uneven distribution of the shape, bulk density and composition of all the test pieces were evaluated and categorized by levels with varying properties.
- Evaluation of properties of all the simulated debris filled in the container
Uneven distribution of the shape, density and composition of the test pieces filled in a container that is equivalent to a unit can and which are processed from the upper, middle and lower levels were evaluated.

[Issues]

･ Test piece manufacturing and testing (Future implementation is considered)
- Test 1: Selection of particle size and material
- Test 2: Study of evaluation method by separately testing the composition

4.3 Study of elemental technology verification test methods using existing equipment, etc.

(⑤ Passive gamma rays method)

4.3 Study of elemental technology verification test methods using existing equipment, etc.

⑤ Passive gamma rays method (1/5)

Study of TMI-2 fuel debris passive gamma rays spectrum measurement

[Study procedure]

TMI-2 debris literature research
(Range of fuel compostions, etc. at the time of accident)

↓

Investigation of the TMI-2 fuel debris stored by JAEA

(Size, weight, bulk density, retrieval location, etc.)

↓

TMI-2 fuel debris radiation source estimation
(Neutron beams and gamma rays)

↓

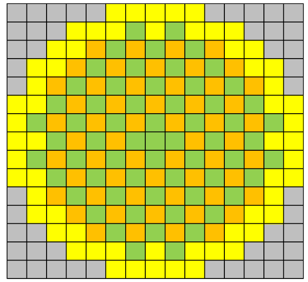
Selection of the prospective samples and testing methods
(Neutron measurement, Gamma rays measurement)

↓

Detailed study of testing methods
(Neutron measurement, Gamma rays measurement)

⟷

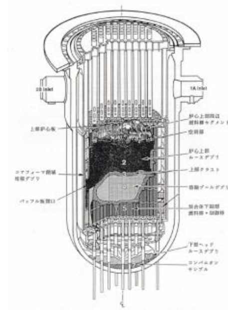
Coordination with the hot laboratory (RFEF)
(Scope of permission and authorization/safety management regulations, limitations of the facility and the equipment that can be introduced, machine time, expenses, etc.)



15x15 type PWR assemblies (17 GT)

- 1.98 w/o (56 assemblies)
- 2.64 w/o (61 assemblies)
- 2.96 w/o (60 assemblies)

Average core burn-up: 3.250 GWd/t
Minimum burn-up node: 0.910 GWd/t
Maximum burn-up node: 6.213 GWd/t



TMI-2 core specifications investigation

ORIGEN2 calculation → Creation of radiation source for gamma rays coming from fuel
Past analyses → Addition of radiation source to the activated radiation source (Co-60)
95% Cs release rate is assumed

→

Investigation of the fuel debris stored by JAEA

Evaluation of radiation source on the day of measurement
(Decay calculation + radiation source calculation)

40 years or more after the accident

→

Estimation of the range of radiation source of the debris samples

[Measured value expected from the elemental technology verification test]

- Acquisition of gamma rays spectrum data from the High Resolution Germanium Detectors (HPGe) with collimate shielding
- Acquisition of spectrum data from the small and light gamma rays detector ($CeBr_3$, etc.)

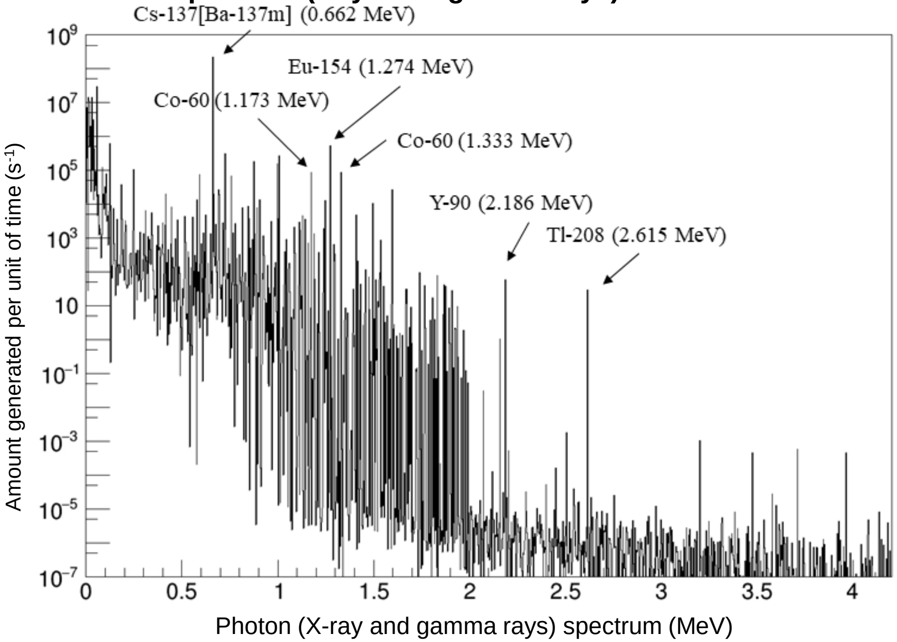
4.3 Study of elemental technology verification test methods using existing equipment, etc.

⑤ Passive gamma rays method (2/5)

Study of TMI-2 fuel debris passive gamma rays spectrum measurement [Radiation source and dose rate evaluation results]

Computational model (Tentative)
Burn-up 3.25 GWd/t (TMI-2 Fuel debris mean)
Shape: Spherical (radius 1cm)
Main composition: $(U_{0.5},Zr_{0.5})O_2$(Bulk density 6.18 g/cm^3)
Date: December 2024 (after 46 year)

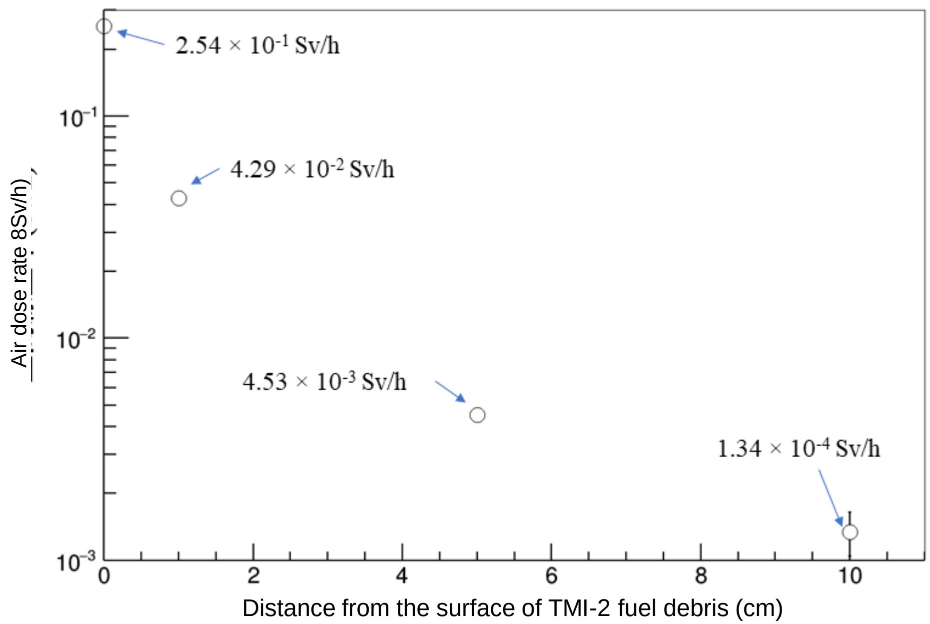
Rate of emission of photons (x-rys and gamma rays) from the TMI-2 fuel debris



Verification of the possibility of being able to observe the following gamma rays peaks

- 662keV of Cs-137 (Ba-137m) and Eu-154 (1.274MeV)
- 2.615MeV of T;-208 which is a progeny nuclide of Pu-236, etc.
- 2.186MeV of Y-90 (half life 64.1h)

Air dose rate in the vicinity of the TMI-2 fuel debris



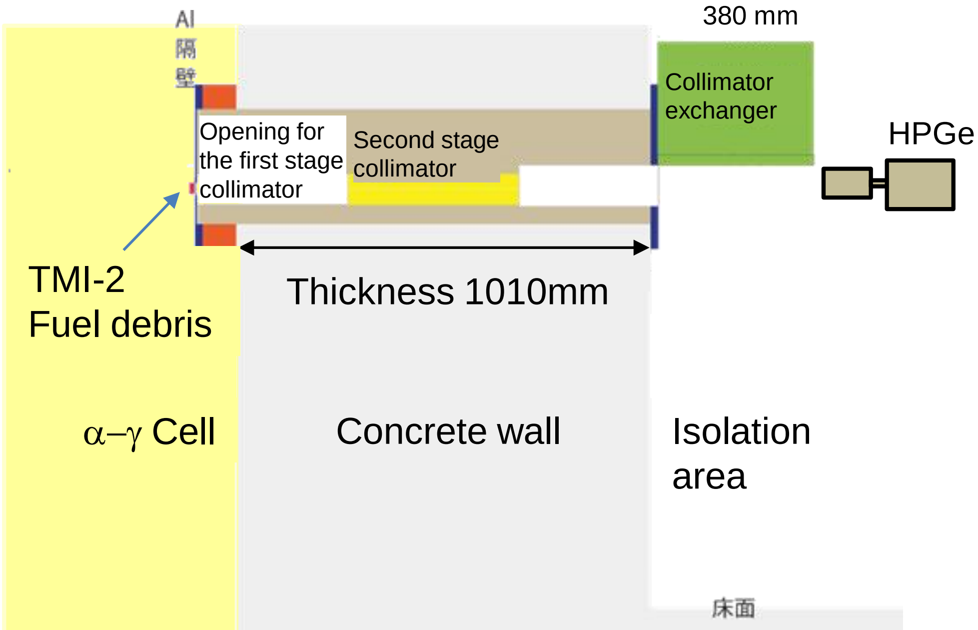
- Surface dose rate estimated to be approx. 250mSv/h or less
- Estimation of the dose rate within the range up to 10 cm from the surface: approx. 0.13 to 250mS/v

4.3 Study of elemental technology verification test methods using existing equipment, etc.

⑤ Passive gamma rays method (3/5)

Study of TMI-2 fuel debris passive gamma rays spectrum measurement

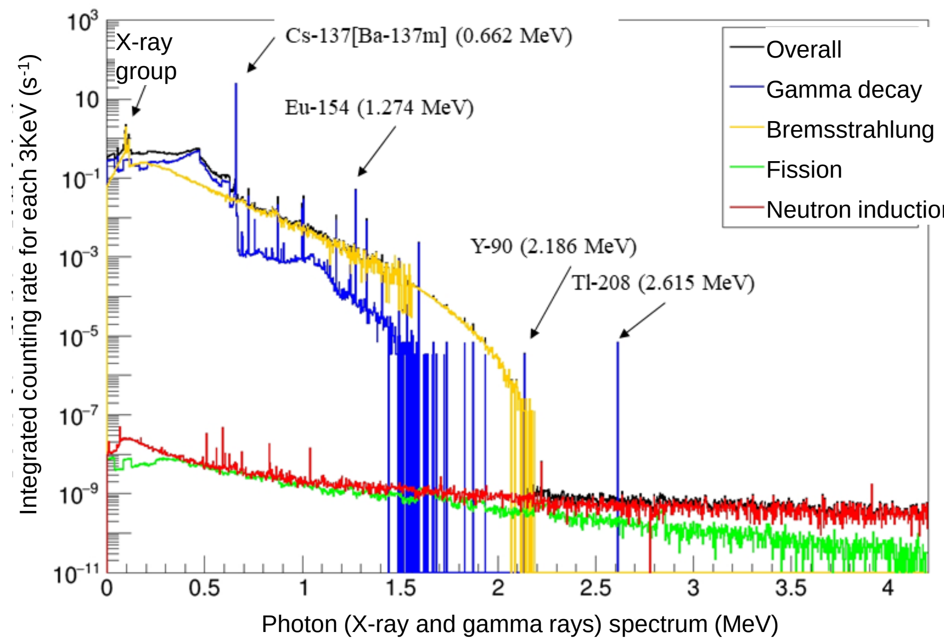
[Simulation model]



HPGe detector (Efficiency 30%)

[Simulation results]

HPGe detector response



[Expected counting rate]

- ❑ 1 count or more in 1 second for 0.662MeV of Cs-137(Ba-137m)
- ❑ Several counts in 1 minute for 1.274MeV of Eu-154 and the X-ray group
- ❑ Several counts in 1 hour for 2.615MeV of Tl-208 (progeny nuclide of U-232 and Pu-236)

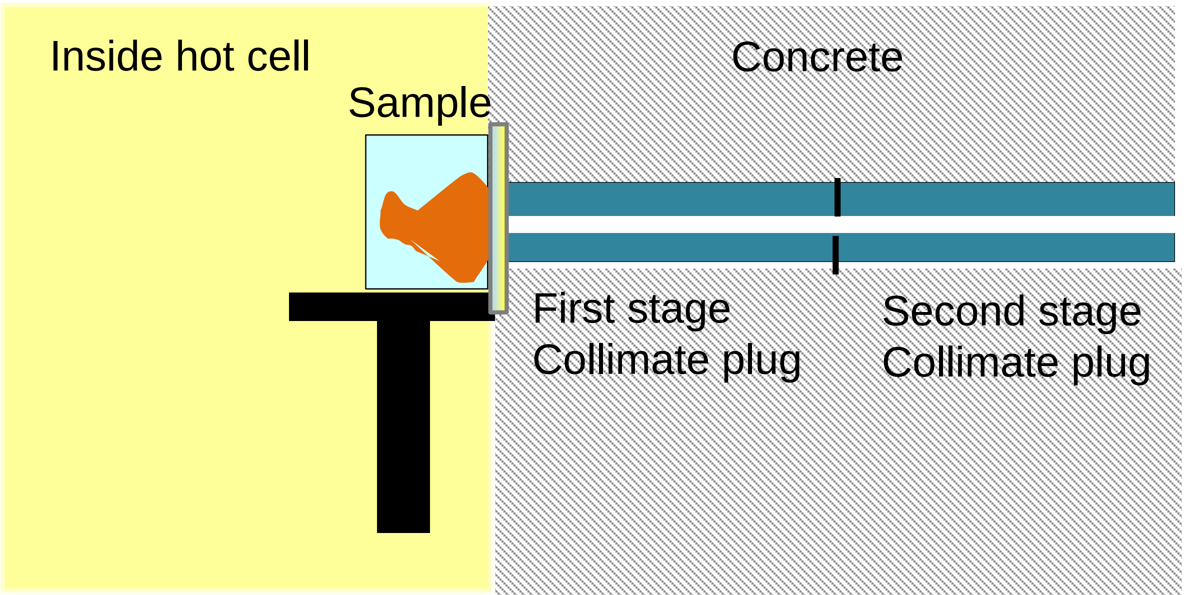
4.3 Study of elemental technology verification test methods using existing equipment, etc.

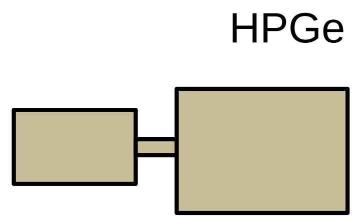
⑤ Passive gamma rays method (4/5)

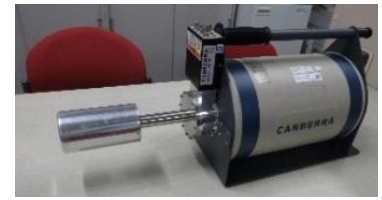
Study of TMI-2 fuel debris passive gamma rays spectrum measurement

[Elemental technology testing method based on the study results]

Collimate shielded HPGe measurement







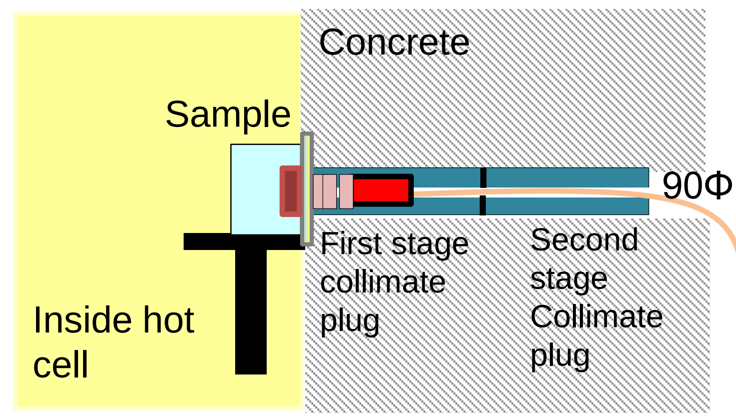
Sample: ① TMI-2 fuel debris (approx. 3GWd/t)
② Cut pieces of spent fuel from light water reactor (approx. 50 to 60GWd/t)

→ With respect to 1F fuel debris having a wide burn-up range

- ❑ Acquisition of data contributing to the study of the method of collimate shielding
- ❑ Identification of issues in actual measurement which cannot be anticipated through simulation

  Ascertaining of (BG impact, pile-up, sum peak, dead time impact, etc.)
- ❑ Study of the possibility of measuring radiation such as Tl-208 or X-rays, etc. which does not require verification of carrying performance with U

Measurement by small gamma rays detector



- ❑ Sample surface dose rate evaluated to be approx. 250mSv/h
- ❑ The small detector being assumed has a gamma rays resistance of several Sv/h or more and hence is applicable.

⑤ Passive gamma rays method (5/5)

[Summary]

- The test of measuring TMI-2 fuel debris from 46 years or more in the past when the accident occurred and which has a burn-up of approx. 3GWd/t, using HPGe was studied through simulation.

- The following 2 points can be put forth anticipating that measurement can be performed.
  - ・1 count or more in 1 second for 0.662MeV of Cs-137(Ba-137m)
  - ・Several counts in 1 minute for 1.274MeV of Eu-154 and the X-ray group

- The applicability of the small gamma rays detector was studied and it was found that the detector can be used from the perspective of radiation resistance.

- Prospects of being able to detect 1.27MeV gamma rays released by Eu-154 were obtained.

- The following was believed to be important for the 2.614MeV gamma rays released by Tl-208.
  - ・Shielding from environmental background
  - ・Using a detector that is suitable for measuring high energy gamma rays

[Issues]

- Identifying issues in actual measurement by comparing the results of simulation carried out under ideal conditions and the values obtained by actually measuring the samples in the hot cell, and in addition, studying measures to improve the accuracy of simulation based on these comparisons.

4.3 Study of elemental technology verification test methods using existing equipment, etc.

(Summary related to the study of elemental technology verification test methods using existing equipment, etc.)

4.3 Study of elemental technology verification test methods using existing equipment, etc.

Some additions
(Items to be implemented in FY2023 are in the pink frame)

Summary related to the study of elemental technology verification test methods using existing equipment, etc.

[Results / Contribution to development] (For details, refer to the reports on each measurement technology)

Active neutron method

・It was found that the impact of neutron absorption material can be evaluated by using block shaped simulated samples. Knowledge was obtained related to the impact that counting rate has on the energy resolution while using a Ge detector with the PGA method. The basic data related to selecting the neutron detector required for studying the concept of the equipment in the future was obtained.

Passive neutron method

・The simulated fuel debris testing method that can verify the accuracy of passive neutron method simulation was created. It was verified that the impact of fluctuations in (α,n) reactions anticipated in the case of diverse fuel debris on the measured values can be reduced, by simulating the neutron coincidence counting method. The effectiveness of the applicability test of the DDSI method was verified by simulation.

Muon scattering method

・Data on basic characteristics such as statistical errors based on the muon scattering angle spectrum, muon incidence angle distribution and the measurement time was obtained. Muon scattering data for samples with different weights and material types was obtained. The verification of operation of the sensors that were test manufactured for the 1F measurement equipment was completed.

X-ray CT method

・Tests for evaluating the impact of bulk density of materials and tests for capturing images of the simulated non-radioactive MCCI test pieces were planned in preparation for detailed studies related to the methods of evaluating sorting scenarios, quantity of nuclear fuel material, etc.

Passive gamma rays method

・The methods for conducting tests using actual fuel debris for verifying the passive gamma rays simulation accuracy and for identifying issues in actual measurement were created. The gamma rays peak with which measurement can be expected to be performed under severe conditions with low burn-up and long-term aging was identified. The method of testing the applicability of small gamma rays detectors using the distal end of the collimator was created.

[Issues] (For details, refer to the reports on each measurement technology)

・**In the future, the elemental technology verification test set up as mentioned above will be conducted.**

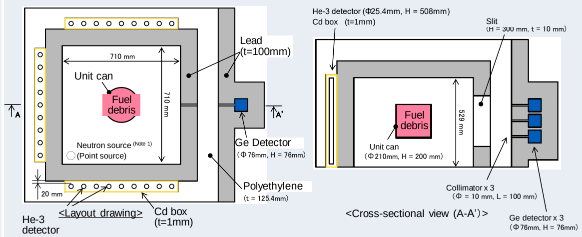
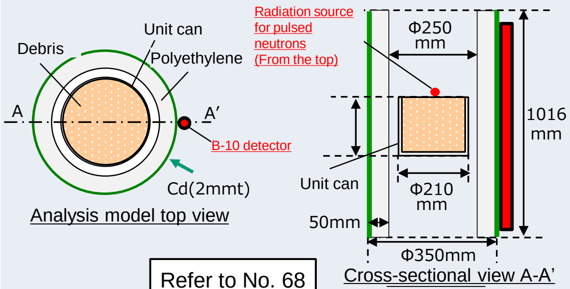
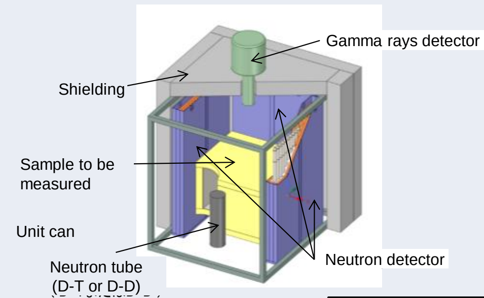
・The results of the elemental technology verification test will be reflected in simulation accuracy verification, verification of the measures for improving accuracy of the method of evaluating nuclear fuel material, etc., detailed study of sorting scenarios, etc.

・For fuel debris that is difficult to simulate (example: mixtures including combustion fuels) due to limitations in terms of permission and authorization and safety management of the existing facilities and equipment, data on prediction accuracy of the quantity of nuclear fuel material will be supplemented by simulations for which accuracy will be verified through verification tests conducted in the future.

5. Summary

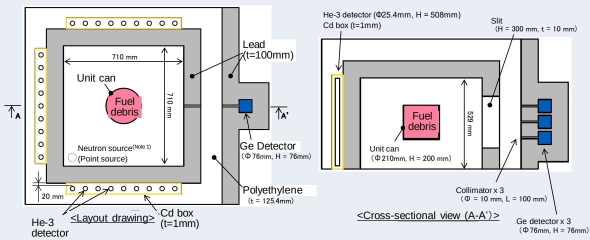
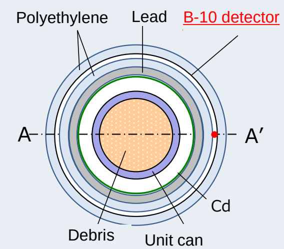
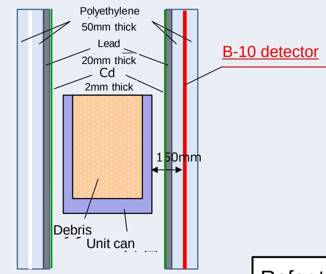
5. Summary

Consolidation of results for each measurement technology (① Active neutron method)

Measurement technology	① Active neutron method		
	A	B	C
Conceptual diagram of the equipment	 ・The concept of equipment using a combination of the active neutron method, passive neutron method and the passive gamma rays method Refer to No. 54	 Refer to No. 68	 Refer to No. 80
Detector	・He-3	・B-10	・B-10 straw／He-3
Radiation source	・D-T	・D-T／Accelerator based neutron source	・D-T／D-D
Irradiation direction	・From the lateral side	・From the top	・From the lateral side
Dimensions	・W 5m × D 4m × H 3m (Compatible with unit can and inner waste container)	・To be determined	・・W 1.5m × D 1.5m × H 2m
Measurement time	・Approx. 3 seconds (Molten debris, amount of U 17.6kg, high burn-up (51GWd/t), neutron absorption material absent) ・Approx. 120 minutes (MCCI debris, amount of U 0.6kg, high burn-up (51GWd/t), neutron absorption material present)	・Approx. 10 minutes (Amount of U 3.7kg) ・With an increase in the quantity contained in the neutron absorption material (several vol%) the counting rate becomes equal to or lower than BG (Cannot be measured)	・About 10-20 minutes
Evaluation accuracy	・Weight of U-235 : At most about 2 times ・Weight percent of U-235 : At most about 2 times ・Weight of U : At most abut 4 times	・Counting rate: several percents (Weight of U 3.7kg)	・Quantity of U-235: ±50% (80% of when the neutron absorption material is absent)
Issues and response measures	・Reduction in errors due to burn-up ⇒ Correction using the neutron die-away time (Only A, B), combination of the passive neutron method and passive gamma rays method (Correction using the ratio of Cm-244 and Eu-154) ・Reduction in errors due to neutron absorption material ⇒ Correction by using the PGA method, combination with the X-ray CT method ・Reduction in errors due to the moisture content ⇒ Combination of active neutron method and passive neutron method ・Optimization of the efficiency and homogeneity of induced fission ⇒ Specifications of the neutron source (D-T, D-D, accelerator based neutron source), study of moderator placement, elemental technology verification test ・Improvement in neutron measurement sensitivity ⇒ Specifications of detector (He-3, B-10, B-10 straw), detector placement, study of moderator placement, elemental technology verification test ・Verification of the impact of diversity in debris ⇒ Additional parameter studies on the conditions of the stored contents including heterogeneous systems		

・Knowledge on issues and response measures obtained by using the active neutron method A, B and C will be shared and utilized for the development of the equipment for the active neutron method.
・The content mentioned in the table is based on the results of this project, and is planned to be changed during research and development in the future. Note that this does not guarantee future equipment specifications and performance.

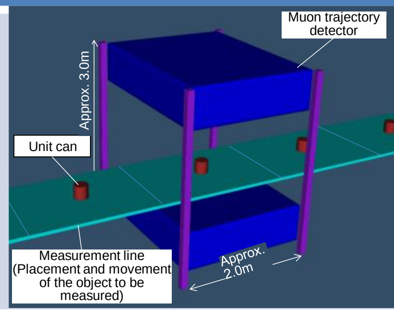
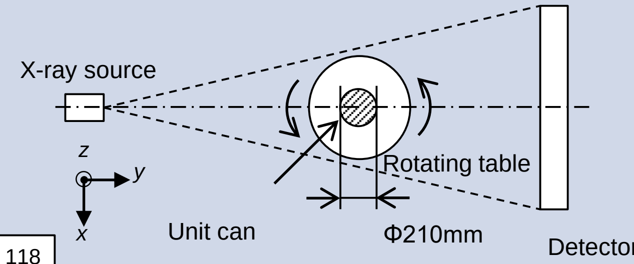
Consolidation of results for each measurement technology (② Passive neutron method)

Measurement technology	② Passive neutron method	
	A	B
Conceptual diagram of the equipment	 ・The concept of equipment using a combination of the active neutron method, passive neutron method and the passive gamma rays method	 Analysis model top view  Cross-sectional view A-A' Refer to No. 100
Detector	・He-3 Refer to No.92	・B-10
Radiation source	・None	・None
Irradiation direction	・None	・None
Dimensions	・W 5m x D 4m x H 3m	・To be determined
Measurement time	・Approx. 1 second (Molten debris, amount of U 17.6kg, high burn-up (51GWd/t), neutron absorption material absent) ・Approx. 65 hours (MCCI debris, amount of U 0.6kg, low burn-up (1.3GWd/t), neutron absorption material absent)	・ Approx. 10 seconds (Molten debris, amount of U 3.7kg) ・ Approx. 9 hours (Low burn-up (1.3GWd/t)
Evaluation accuracy	・ Quantity of U-235: At most several 100 to several 1000 times (Molten debris/MCCI debris, low burn-up (1.3GWd/t)) ・ Weight percent of U-235: At most several 100 to several 1000 times (Molten debris/MCCI debris, low burn-up (1.3GWd/t)) ・ Weight of U: At most several 100 to several 1000 times (Molten debris/MCCI debris, low burn-up (1.3GWd/t))	・Counting rate: 3.6E-4 to 5.7E+0 times (Burn-up 1.3 to 51GWd/t as against 23GWd/t) ・Counting rate: 1 to 0.76 times (Moisture content 0.1 to 41wt% as against 1wt%)
Issues and response measures	・Reduction in errors due to burn-up ⇒ Combination of passive neutron method and passive gamma rays method (Correction using the ratio of Cm-244 and Eu-154) The logic for explaining the carrying performance of Cm-244 & Eu-154 with U needs to be established. ・Reduction in errors due to the moisture content ⇒ Combination of active neutron method and passive neutron method ・Improvement in neutron measurement sensitivity ⇒ Specifications of detector (He-3, B-10, B-10 straw), detector placement, study of moderator placement, elemental technology verification test ・Verification of the impact of diversity in fuel debris ⇒ Additional parameter studies on the conditions of the stored contents including heterogeneous systems	

・Knowledge on issues and response measures obtained by using the passive neutron methods A and B will be shared and utilized for the development of the equipment for the passive neutron method.

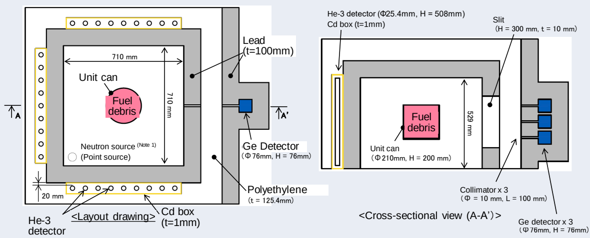
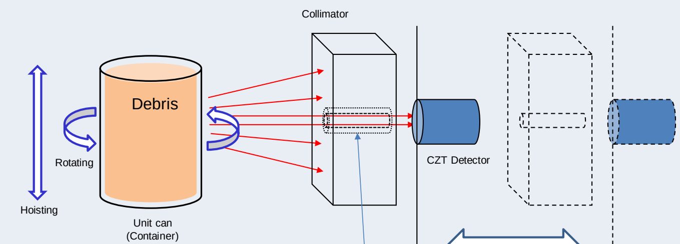
・The content mentioned in the table is based on the results of this project, and is planned to be changed during research and development in the future. Note that this does not guarantee future equipment specifications and performance.

Consolidation of results for each measurement technology (③ Muon scattering method/④ X-ray CT method)

Measurement technology	③ Muon scattering method	④ X-ray CT method
Conceptual diagram of the equipment	 Refer to No. 115	Refer to No. 118 
Detector	･Muon trajectory detector	･X-ray detector
Radiation source	･None	･Accelerator based X-ray source
Irradiation direction	･None	･ From the lateral side
Dimensions	･Entire length 2m	･ 4m×4m Including footprint and maintenance area
Measurement time	･1 to 2 hours	･ Unit can: 13 to 50 minutes/1 to 4 containers (25 to 100 minutes/container in the case of MECT) ･ Inner waste container： 75 minutes/container (150 minutes/container in the case of MECT)
Evaluation accuracy	･Amount of U: Evaluation on comparatively safer side	･Quantity of UO_2: At most 6% (When nuclear fuel is not mixed with other material)
Issues and proposal to combine measurement technologies	･Study of the method for reducing the errors in evaluation functions ⇒ Study of combination with other methods	･ Reduction in errors due to neutron absorption material in the active neutron method ･ Reduction in errors due to moisture content in the passive neutron method ･ Reduction in errors due to self-shielding and uneven distribution in the passive gamma rays method
Other issues and response measures	･Detector response analysis ⇒ Dealing with the difference in scattering trend due to the type of debris, verification of detailed detector performance, and reflection into the simulation ･Development of the concept of the measurement equipment ⇒ Verification of the measurement environment and operating conditions, study of measurement equipment specifications in accordance with the measurement environment ･Study of the method for reducing errors in evaluation functions ⇒ Study of the method of switching the evaluation function depending on the type of debris ･Estimation of the weight of material using actual measurements ⇒ Material weight estimation test using samples with known compositions	･ The methods for evaluating changes in bulk density or the ability to differentiate nuclear material that is mixed with other material have not yet been developed ⇒ Development of an algorithm for evaluating the quantity of nuclear fuel material by MECT, elemental technology verification test ･ The specific method for providing correction data for other measurement technologies has not yet been studied. ⇒ Study of specific methods for providing correction data and the accuracy of that data ･ The detailed conditions for simultaneously measuring multiple unit cans in order to reduce the measurement time have not yet been studied. ⇒ Quantitative evaluation of the correlation between measurement time and measurement accuracy ･ Study of specifications of the detectors and maximum X-ray energy by means of the above.

・The content mentioned in the table is based on the results of this project, and is planned to be changed during research and development in the future. Note that this does not guarantee future equipment specifications and performance.

Consolidation of results for each measurement technology (⑤ Passive gamma rays method)

Measurement technology	⑤ Passive gamma rays method	
	A	B
Conceptual diagram of the equipment	 ・The concept of equipment using a combination of the active neutron method, passive neutron method and the passive gamma rays method Refer to No. 139	 Refer to No. 152
Detector	・Ge	・CZT, $LaBr_3$, etc.
Radiation source	・None	・None
Irradiation direction	・None	・None
Dimensions	・W 5m × D 4m × H 3m	・To be determined
Measurement time	・Approx. 1 second (Molten debris, amount of U 17.6kg, high burn-up (51GWd/t), neutron absorption material absent) ・ Approx. 11 minutes (Molten debris, amount of U 8.8kg, low burn-up (1.3GWd/t), neutron absorption material absent)	・ Approx. 3 minutes to 40 hours/container (・CZT detector (1.274MeV peak), statistical error 1%) ・ In the case of LaBr3 detector, there are cases when it is difficult to separate the 1.274MeV peak from the 1.332MeV peak of Co-60, and there are cases when the 1.274MeV peak cannot be observed ⇒ 1.597MeV peak can be observed, but the counting rate is smaller by two orders of magnitude as compared to the 1.274MeV peak, and hence the measurement time is expected to be longer.
Evaluation accuracy	・Weight of U-235: At most several 100 times (Molten debris, low burn-up (1.3GWd/t)) ・Weight percent of U-235: At most several 100 times (Molten debris, low burn-up (1.3GWd/t)) ・Weight of U: At most several 100 times (Molten debris, low burn-up (1.3GWd/t))	・Amount of U: Approx. 1.0 to 4.4kg (Amount of U 3.7kg, burn-up 23GWd/t, CZT detector (1.274MeV peak) (When the burn-up varies, there is a difference of about 3 orders of magnitude in the maximum and minimum counting rate)
Issues and response measures	・Reduction in errors due to burn-up ⇒ Combination of passive neutron method and passive gamma rays method (Correction using the ratio of Cm-244 and Eu-154) The logic for explaining the carrying performance of Cm-244 & Eu-154 with U needs to be established. ・ Reduction in errors due to container specifications, bulk density ⇒ Establishment of the conversion coefficient of each container specification, detailed study of the correction method based on the multiple peak ratios having different energies, combination with weight measurement, combination with the X-ray CT method. ・ The measurement time largely differs from about several minutes to several hours/container ⇒ Study on crystallization of equipment configuration which makes it possible to change the collimator size or the distance between the container and detector ・ Verification of the impact of diversity in fuel debris ⇒ Additional parameter studies on the conditions of the stored contents including heterogeneous systems	

・Knowledge on issues and response measures obtained by using the passive gamma rays method A and B will be shared and utilized for the development of the equipment for the passive gamma rays method.
・The content mentioned in the table is based on the results of this project, and is planned to be changed during research and development in the future. Note that this does not guarantee future equipment specifications and performance.

5. Summary

[Results / Contribution to development]

・The following results were obtained with respect to the 5 types of prospective measurements (*1), and development of non-destructive measurement technologies for sorting made progress.

*1 ① Active neutron method, ② Passive neutron method, ③ Muon scattering method, ④ X-ray CT method, ⑤ Passive gamma rays method

Study of the target performance values required for sorting (Target TRL: Not set)

・Sorting criteria and measurement time were set as the equipment performance that influences feasibility of sorting and their target values were established as the target performance values of the non-destructive measurement equipment.

Development of the concept of the measurement equipment by means of detector response analysis (Target TRL: Level 3 ⇒ Achieved TRL: Level 3)

・The concept of the measuring equipment that uses detector response analysis was established for the non-destructive measurement equipment.

Study of the techniques for evaluating the quantity of nuclear fuel material, etc. based on the measured quantity (Target TRL: Level 3 ⇒ Achieved TRL: Level 3)

・The primary proposal pertaining to the technique for estimating and evaluating the quantity of nuclear fuel material, etc. based on the quantity measured (including combinations as required) was studied, and evaluation performance was evaluated.

Study of the sorting scenarios (Target TRL: Not set)

・Multiple sorting scenarios with different non-destructive measurement equipment application time, Technology Readiness Level and application location were proposed.

Study of the elemental technology verification test methods using existing equipment, etc. (Target TRL: Level 2 ⇒ Achieved TRL: Level 2)

・In the future, testing methods should be planned for issues that need to be verified by conducting experiments, based on the results of simulation tests or simple tests.

[Issues and response measures]

1) Issue: The results of each implementation item need to be reflected and updated mutually.

Response measure: In the future, the results of each implementation item will be repeatedly reflected mutually.

Appendix-1 Supplementary Explanation of Technical Terms

Active neutron method

In this project, the method of non-destructive measurement for ascertaining the quantity of material inside the object to be measured by irradiating neutrons from outside the object to be measured and without breaking the object to be measured is collectively referred to as "Active neutron method".

Due to the differences in the method of measurement or the principle of measurement (what is measured and how is the target quantity evaluated), the "Active neutron method" consists of the following methods.

- Differential Die-away Analysis Method (DDA method)

  The method of detecting or quantifying the nuclear fissile material (Example: ^{235}U+^{239}Pu+^{241}PU) by irradiating neutrons and analyzing the time response of the nuclear fission neutrons being measured.
  The Fast Neutron Direct Interrogation Method (FNDI method) is a type of DDA method.

- Prompt Gamma Analysis Method (PGA method)

  The method of detecting or quantifying isotopes contained in the material to be measured by irradiating neutrons, and measuring the energy spectrum of prompt gamma rays released as a result of nuclear reactions such as (n,γ) reactions.

- Neutron Resonance Transmission Analysis (NRTA method)*

  The method of detecting or quantifying nuclides from the resonance energy characteristic to nuclides contained in the object to be measured, by irradiating neutrons, and converting the time spectrum of the neutrons that have penetrated the object to be measured into energy spectrum.

*** NRTA method is outside the scope of studies conducted in this project.**

Active neutron method (FNDI method + PGA method)

The Fast Neutron Direct Interrogation Method (FNDI method)

In the case of the conventional active neutron method, the fast neutrons are decelerated throughout the equipment and the measurement sample is irradiated with thermal neutrons. Hence this method is susceptible to the impact of diversity of samples.
Meanwhile, the FNDI method is an improved method in which the measurement samples are irradiated with thermal neutrons, and the quantity of nuclear material is obtained by selectively measuring neutrons released by the nuclear fission reaction in the samples. Hence it is highly applicable to waste that is diverse such as fuel debris.

Figure Simulated diverse uranium waste used in the test using the FNDI method

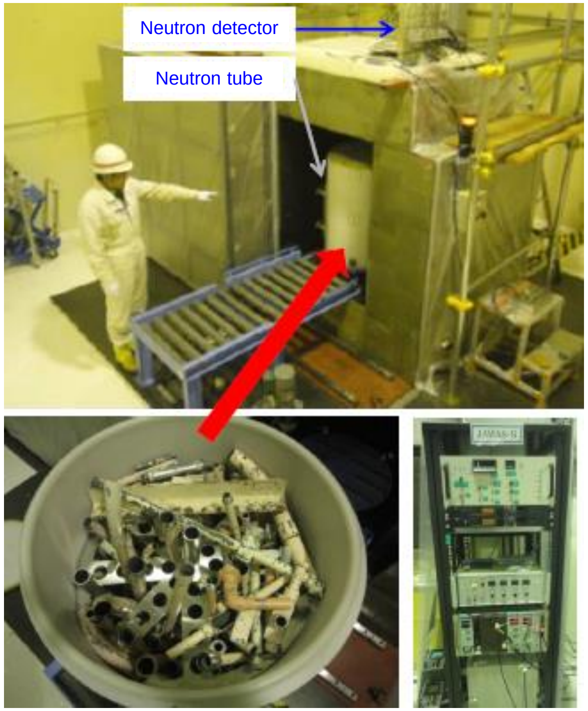


Figure JAWAS-N equipment

The FNDI method is a proprietary technology of Japan and was used for the first time in the JAEA Waste Assay System, a non-destructive measurement equipment for measuring 200L drums at the Ningyo Toge Environmental Engineering Center (JAWAS-N).

This equipment has been put to practical use as a material accountancy system that can measure several grams of natural uranium, takes about 10 minutes per drum and typically has a measurement uncertainty of 20% or less. It has been approved by the IAEA and has a proven track record of having measured 1802 drums.

JAWAS-T (Non-destructive measurement experimental equipment based on the FNDI method)

JAWAS-T is the non-destructive measurement experimental equipment based on the active neutron method installed in Research Building B (BECKY) at Nuclear Fuel Cycle Safety Engineering Research Facility (NUCEF) of the Japan Atomic Energy Agency (JAEA). Since this equipment is used for developing non-destructive measurement technologies for quantifying nuclear fuel material with high accuracy, which contribute to safeguards, this equipment is more flexible and suitable for conducting a variety of experiments as compared to non-destructive measurement equipment with specialized functions available in the market. Specifically, it is possible to quantify uranium and plutonium in the container by the Fast Neutron Direct Interrogation Method (FNDI method), which is an improvement on the Differential Die-away Analysis Method (DDA method), by using the powerful D-T neutron tubes and the highly sensitive He-3 neutron detectors.

JAWAS-N which has been put to practical use at JAEA’s Ningyo Toge Environmental Engineering Center was developed due to the tests conducted using the equipment developed earlier.

Figure JAWAS-T equipment

[Reference] Masao Komeda, Yosuke Toh, New data processing method for nuclear material measurement using pulsed neutrons, Applied Radiation and Isotopes, 188, 110391 (2022).

Active neutron method (FNDI method + PGA method)

Combination of the FNDI method and the Prompt Gamma Analysis Method (PGA method)

PGA method is a technique for identifying and measuring the quantity of material contained in the samples by measuring gamma rays characteristic to the material, which are generated as a result of the nuclear reaction brought about by irradiating the samples to be measured with neutrons.

FNDI method enables accurate measurements regardless of the contents of the samples to be measured, but can easily get influenced by the neutron absorption material (B, Gd). (Measurement cannot be performed if these neutron absorption materials are present in extreme abundance)

Hence, by introducing the PGA method, the neutron absorption material is measured, thus enhancing the accuracy of the FNDI method (Enhancement of sorting accuracy).

Also, depending on the conditions, moisture, iron, chromium present in the samples can be expected to be measured by the PGA method.

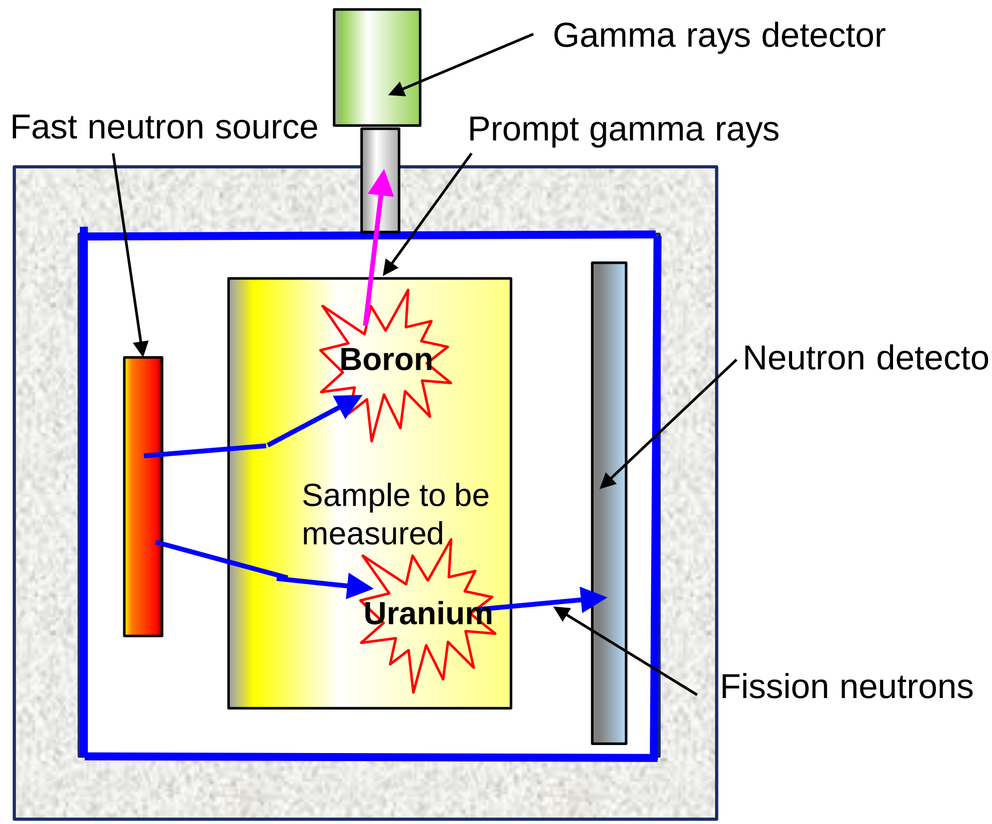


Figure Illustration of the concept of the FNDI method + PGA method

The passive neutron method equipment assumed in the elemental technology verification test

Plutonium Scrap Multiplicity Counter (PSMC)

PSMC is a non-destructive measurement equipment for measuring the quantity of Pu in the nuclear fuel material containing impurities. The equipment is structured so that there is a sample chamber at the center, and neutron moderators (polyethylene) or neutron detectors (He-3 proportional counter), etc. are placed around it.

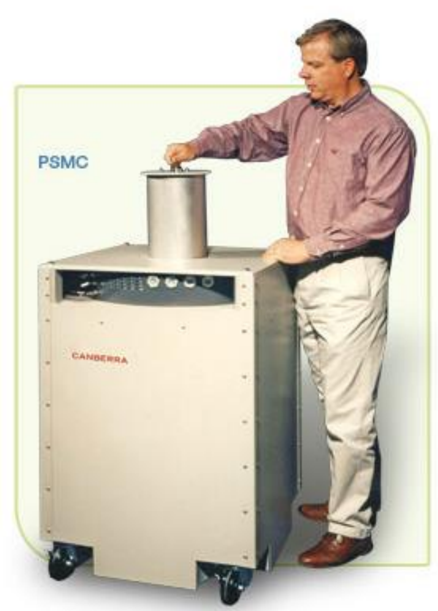
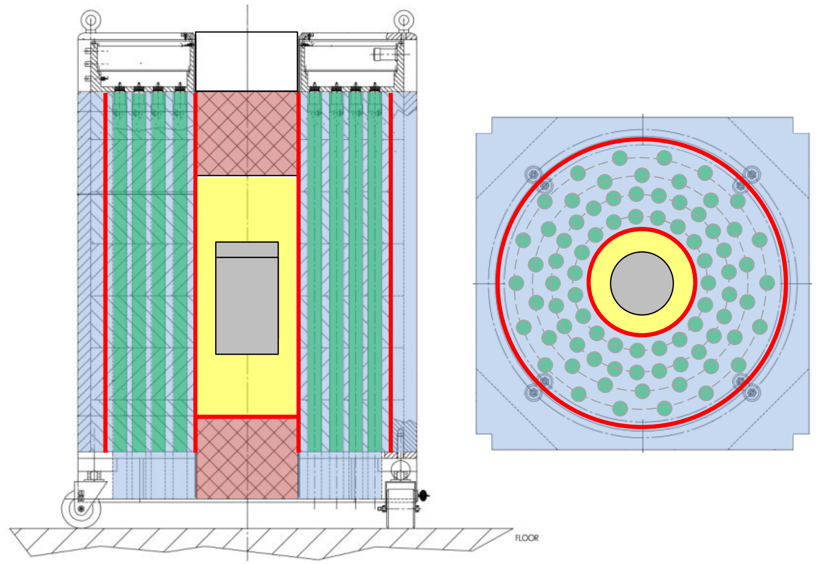


Figure External appearance of PSMC*1



Sample chamber	He-3 proportional counter
Nuclear fuel material	Graphite
High density polyethylene	Cadmium

Figure Cross-section of PSMC

The equipment can detect approx. 55% of the neutrons released from the samples to be measured.

It is used for material accountancy and safeguards in plutonium handling facilities around the world.

*1 Mirion Technologies (Canberra) KK Product Line-up Plutonium Scrap Multiplicity Counter (PSMC)
https://www.canberra.com/jp/products/wm_psmc.html

The passive neutron method equipment assumed in the elemental technology verification test

Neutron coincidence counting method

The neutron coincidence counting method is a method of quantifying nuclides resulting from spontaneous nuclear fission in which the impact of counting neutrons that are a result of the (α,n) reaction, etc. and which do not occur coincidentally is eliminated by selectively counting the neutrons that are simultaneously released in a large number due to nuclear fission of plutonium nuclides.

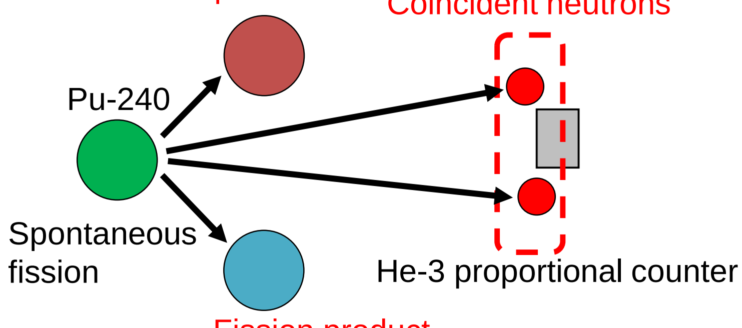


Figure The concept of coincidental occurrence of neutrons that are released by spontaneous fission

Differential Die-away Self-Interrogation Method (DDSI method)

The DDSI method is a method of evaluating the extent of reduction in the number of neutrons due to the neutron absorption material or the increase in the number of neutrons due to induced fission, which are measured with a delay due to moderation as compared to the spontaneous fission neutrons, by focusing on the difference in the distribution of the time in which spontaneous fission neutrons and induced fission neutrons are detected.

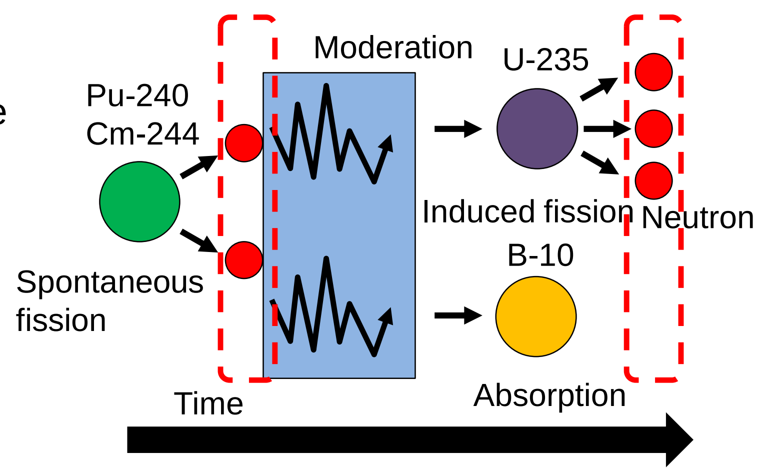


Figure Difference in the time required for detecting the spontaneous fission neutrons and the induced fission neutrons

By using these methods the measurement errors caused by the diversity of the contents of the container can be reduced.

Comparison of neutron detectors

[He-3 detector]

Since this detector has a high neutron detection sensitivity, it has an extensive track record of being used in the active neutron method equipment or the passive neutron method equipment for safeguards. However, in fields with high gamma radiation, there is shielding due to lead, etc., and hence gamma radiation noise needs to be reduced.

[B-10 detector]

This detector has an extensive track record as a neutron detector, but falls short of neutron detection sensitivity when compared with He-3 detector. In radiation fields where the neutrons and gamma rays are mixed, the sensitivity to gamma rays is relatively less than the He-3 detector, and hence it can become advantageous from the perspective of the ratio of the neutrons to be measured to the gamma rays that become noise (S/N).

[B-10 straw detector]

This is a B-10 detector that was newly developed in recent years aiming for high efficiency. In this detector, multiple slender B-10 detectors are bound together with the expectation of achieving a balance between high sensitivity towards neutrons and a high S/N ratio.

Additional explanation of the B-10 straw detector

The B-10 straw detector has been developed and manufactured by Proportional Technologies, Inc. (PTI) in the US as an alternative to the He-3 detector due to concerns about short supply of He-3 detectors.

- Since in this detector as well, neutrons are detected as a result of the $^{10}B(n,\alpha)^{7}Li$ reaction similar the conventional B-10 lined detector, the detection efficiency largely depends on the B-10 vapor deposition area.
- There are slender tubes called straw inside the detector, and vapors of B-10 are deposited on the inner side of those straws thereby increasing the B-10 vapor deposition area in an attempt to improve detection efficiency.
- Besides standard cylindrical straws, there are star shaped straws with improved detection efficiency due to a larger vapor deposition area as well.

Appendix-1 Supplementary Explanation of Technical Terms (9/9)

Comparison of gamma ray detectors

[HPGe]

- Extremely high energy resolution.
- Requires cooling by means of liquid nitrogen, etc.
- Cannot withstand high counting rate.

[CZT]

- High energy resolution (Falls short of HPGe).
- Can be used at room temperature.
- Can measure at a higher counting rate than HPGe.

[$LaBr_3$]

- High energy resolution.
- Can measure at a high counting rate.
- Large background since it contains radioactive material.

[$CeBr_3$]

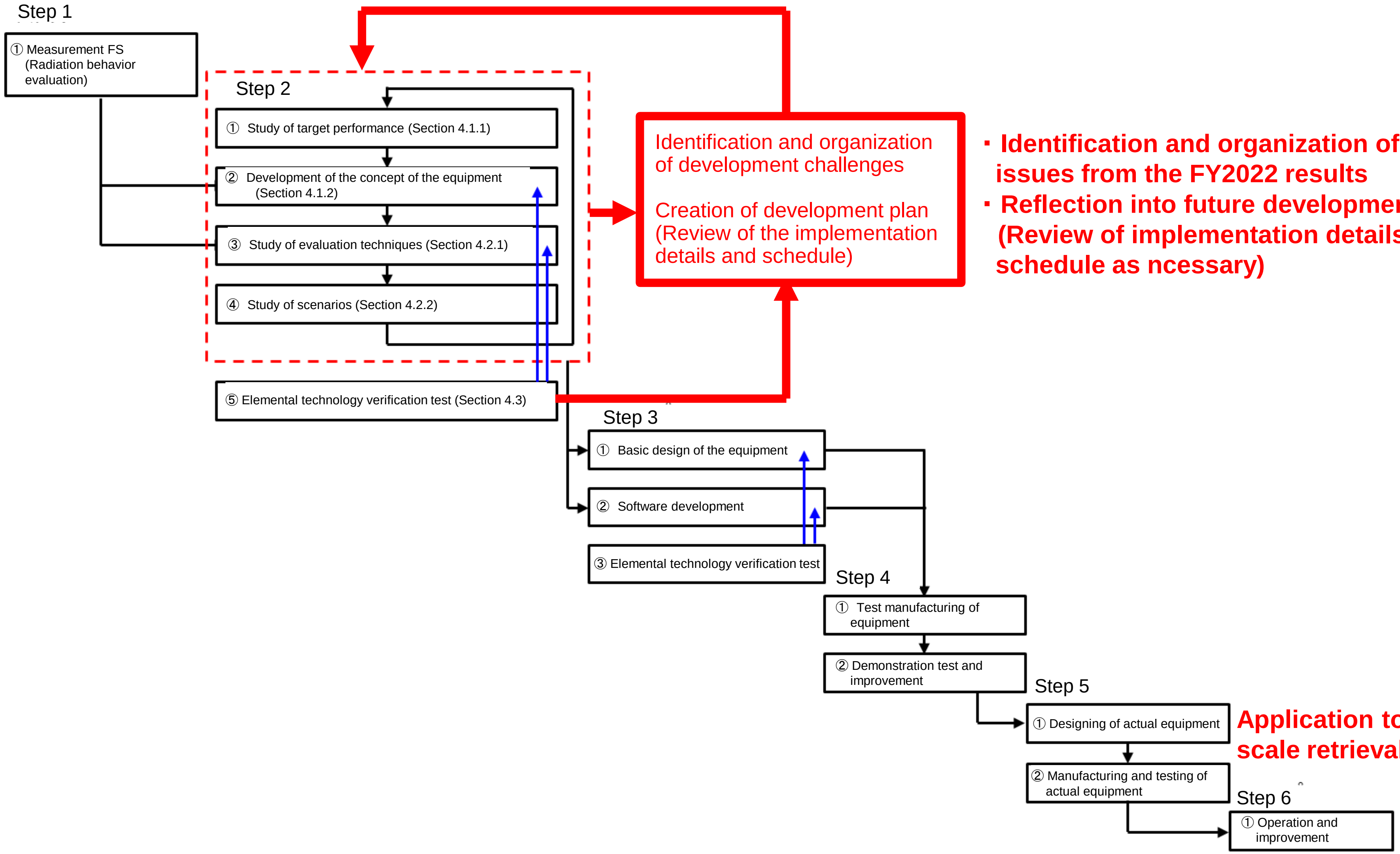
- High energy resolution (Falls short of $LaBr_3$).
- Can measure at a high counting rate.
- Does not contain radioactive material.

[BGO]

- Extremely high detection efficiency. (Used mainly as a prospective HPGe detector)
- Can measure at a high counting rate.
- Bad energy resolution.

Appendix-2 Future Challenges (Reported in FY2021)

Development steps



- **Identification and organization of new issues from the FY2022 results**
- **Reflection into future development plans (Review of implementation details and schedule as ncessary)**

Application to large scale retrieval

Importance of the issues

Classification	Viewpoint for considering the issue important	Example of identified issue
A	Issue concerning the principle - Unprecedented	Development of an algorithm for estimating the quantity of nuclear material based on the measured values
B	Issues that will require time to be resolved	Issues that cannot be resolved unless implemented before the test
C	Issues beyond the scope of development of the sorting and distinction technology	The properties of debris are unknown, and there are major uncertainties in the preconditions for development. Issues that could arise based on new findings when these unknowns are ascertained.

Appendix-2 Future challenges

FY2022 Identification results (① Active neutron method, ② Passive neutron method, ⑤ Passive gamma rays method (1/2))

The issues considered to be important from among the technological issues identified with respect to each individual measurement method have been consolidated. Status of progress made in FY2022 has been added.

No.	Item	Details	Response policy	Corresponding development Step	Status of progress made in FY2022
1	Method of converting the measured value to evaluation value	Whether or not Cm244 and U accompany each other is unknown	The analyst will be requested to verify the accompaniment by means of a sampling analysis of fuel debris.	2-① C	Issues have been shared with related PJs.
2	Algorithm (Estimation of the quantity of nuclear material)	If fuel with different burn-ups is mixed, the method of converting the effective mass of Cm244 into amount of U/Pu is yet to be determined.	The correlation between the number of spontaneous fission neutrons produced and the quantity of U/Pu will be studied using a mixed simulation of fuel debris composition from the 3D nuclide inventory data.	2-③ A, B	The primary proposal for the method of estimating and evaluating the quantity of nuclear material has been established.
3	Verification of simulation accuracy	Issues concerning simulation and the prediction accuracy have not been ascertained.	Prediction accuracy will be verified and calibrated by testing simulated debris.	2-⑤ B	Elemental technology verification test has been planned.
4	Calibration test	It is difficult to conduct a calibration test in which the actual system, contents and radiation source intensity are simulated.	A mock calibration test will be conducted and the validity of the calibration curve obtained from the simulation will be evaluated.	2-⑤ B	Elemental technology verification test has been planned.
5	Method of converting the measured value to evaluation value	Whether or not Eu154 and U accompany each other is unknown.	The analyst will be requested to verify the accompaniment by means of a sampling analysis of fuel debris.	2-① C	Issues have been shared with related PJs.
6	Correction of the self-shielding effect	The self-shielding effect of gamma rays depends on fuel debris (density, amount of U, uneven distribution, etc.) and is diverse.	The method of correcting self-shielding by means of simulation using the full energy peak of the energy of multiple γ rays emitted from Eu154, etc., will be studied.	2-③ A, B	The primary proposal for the method of estimating and evaluating the quantity of nuclear material has been established.
7	Error reduction (Neutron absorption material)	In the DDA (FNDI) method, if more than a certain level of neutron absorption material is present, the fission components cannot be observed.	Verification of the scope of application by means of simulated tests using Gd and B, or the introduction of prompt gamma rays method, etc. will be studied.	2-① 2-⑤ A, B	It was verified that neutron absorption material can be detected by the PGA method.

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

Appendix-2 Future challenges

FY2022 Identification results (① Active neutron method, ② Passive neutron method, ⑤ Passive gamma rays method (2/2))

The issues considered to be important from among the technological issues identified with respect to each individual measurement method have been consolidated. Progress made in FY2022 has been added.

No.	Item	Details	Response policy	Corresponding development Step (Note)	Progress made in FY2022
8	Measurement cell	Splitting or merging of cells during neutron measurement and passive γ rays measurement	A comparative evaluation of the streamlining of layout due to merging / reduction in processing time due to splitting will be conducted.	2-②	Primary proposal of the concept of the measuring equipment has been established.
9	Optimization of the layout of detectors	Streamlined layout of the neutron generator, detector, shield, moderator, etc.	The device will be configured for the process in which the side to be measured will be moved and measurement will be carried out sequentially.	2-② (2-⑤)	Primary proposal of the concept of the measuring equipment has been established.
10	Radiation resistance	Irradiation degradation of the detector, electronic equipment, cables, etc.	･Radiation resistant components and equipment will be used. ･Shield will be installed	2-② (2-①, 2-⑤)	—
11	Performance assessment analysis	Performance assessment under the most stringent conditions of effective signals / disturbing signals	The scope of measurement and the performance (accuracy, measurement time, etc.) will be evaluated by means of performance evaluation analysis.	2-② (2-①, 2-⑤)	Primary proposal of the concept of the measuring equipment has been established.
12	Algorithm	Difficulty in developing a generic and versatile algorithm	Algorithms exclusive to the category of the target of measurement will be used.	2-③ A, B	The primary proposal for the method of estimating and evaluating the quantity of nuclear material has been established.
13	Study of measurement technique other than the DDA method	Possibility of enhancing the measurement accuracy by a measurement technique other than the DDA method studied this year	Introduction of the PGA method will be considered.	2-③ A, B	It was verified that neutron absorption material can be detected by the PGA method.
14	γ rays generated due to the nuclear reaction of neutrons	Need for a design that considers the γ rays generated due to the nuclear reaction of neutrons	Understanding the phenomenon by comparing the simulation and the test.	2-②, 2-③, 2-⑤ B	Elemental technology verification test has been planned.
15	Accumulation of contamination	Reduction in detection sensitivity due to accumulation of leaked fuel debris	･Measurement using sealed containers ･A design that enables decontamination inside the equipment	3-① onwards	—
16	Ease of maintenance	Enhancement of the maintainability of the numerous detectors	A structure that enables direct maintenance from outside the cell	3-① onwards	—

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

Appendix-2 Future challenges

FY2021 identification (③ Muon scattering method)

The issues considered to be important from among the technological issues identified with respect to each individual measurement method have been consolidated. Progress made in FY2022 has been added.

No.	Item	Details	Response policy	Corresponding development Step Note)	Progress made in FY2022
1	Estimation of the amount of U	Development of the technique of evaluating the amount of U from the muon scattering distribution	・Statistics, functions, etc. that have a strong correlation with amount of U will be selected from the muon scattering distribution. ・Methods for enhancing the accuracy of estimating the amount of U by combining with other measured values will be studied.	2-③ 2-⑤ 3-① A	The primary proposal for the method of estimating and evaluating the quantity of nuclear material has been established.
2	Background radiation originating from fuel debris	The radiation generated by fuel debris (mainly gamma rays) is incident upon the sensor in the detector which results in dead time with respect to muons.	・Background reduction effect will be evaluated by evaluating the gamma rays flux and neutron flux resulting from the measurement conditions.	2-① 2-② 2-⑤ B	—
3	Placement of detector	The distance between the sample and the detector needs to be increased in order to reduce the background radiation originating from fuel debris, but the larger the distance between detectors the lower is the muon counting rate.	・The correlation of the detector placement with the counting rate of background radiation and the muon counting rate will be evaluated. ・A measurement system that can sufficiently reduce the background radiation will be studied.	2-② 2-④ 3-①	Primary proposal of the concept of the measuring equipment has been established.
4	Shielding	The sample needs to be covered with a shield in order to reduce the background radiation originating from fuel debris, but the larger the shield lower is the muon scattering angle measurement accuracy.	・The correlation of the amount of shielding with the counting rate of background radiation and the muon scattering angle measurement accuracy will be evaluated. ・The shielding thickness that can sufficiently reduce the background radiation will be studied.	2-② 2-④ 3-①	—
5	Detector specifications	The detector is made up of numerous sensors, each individual sensor has dead time for a certain time after the incidence of gamma rays. The gamma rays counting rate can be reduced by downsizing each individual sensor, the cost increases.	・Sensor size and performance corresponding to the background conditions will be studied.	2-② 2-⑤ 3-① 3-②	Primary proposal of the concept of the measuring equipment has been established. Elemental technology verification test has been planned.
6	Fluctuation in the measured value depending on the shape of fuel debris	The measured value fluctuates depending on the shape of fuel debris even though its composition and weight are the same.	・The method of correcting the measured value by estimating the shape of fuel debris based on the spatial distribution of muon scattering angle, will be studied.	2-③ 3-② A	Evaluation of the impact of porosity during simulation

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

Appendix-2 Future challenges

FY2021 Identification (④ X-ray CT method (1/2))

The issues considered to be important from among the technological issues identified with respect to each individual measurement method have been consolidated. Progress made in FY2022 has been added.

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No.	Item	Details	Response policy	Corresponding development Step	Progress made in FY2022
1	Measurement principle	・Since only information on density can be obtained from past radioparency measurements, a measurement method that enables evaluation of the quantity of nuclear fuel material by making a distinction between nuclear fuel and structures (iron, concrete), etc. needs to be studied.	・As a distinction can be made between nuclear fuel and structures (iron, concrete), etc. by means of radioparency measurement using different X-ray energies, the same measurement method will be studied.	2−① 2- ② 2−③ 2−⑤ B	Improvement in ability to differentiate material by MECT was verified through simulation.
2	Impact of spatial resolution, etc.	・Fuel debris that is smaller than the spatial resolution is difficult to distinguish using the CT value.	・The method of calculating the quantity of nuclear fuel that is mixed, based on the increase from the CT value when only iron or concrete are present, will be studied.	2−① 2- ② 2−③ 2−⑤ A, B	Elemental technology verification test has been planned.
3	High dose rate gamma rays noise impact	・Since the dose rate of fuel debris changes extensively, the S/N of the image could deteriorate and the measurement accuracy is likely to worsen.	・The necessity of a shield installed in front of the detector for reducing the dose rate of gamma rays will be studied.	2−① 2- ②	－
4	Estimation of the quantity of nuclear material algorithm	・An algorithm for estimating the quantity of nuclear material based on the values measured by radioparency measurement using different X-ray energies, is required. ・An estimation algorithm that combines the radioparency measurement method with other measurement methods is required.	・The relation between each material and the CT values will be evaluated beforehand, and the nuclear material will be identified based on the CT value. ・The method of providing information on distribution of iron, concrete, neutron absorbing agent, etc. that are factors inhibiting evaluation of the quantity of nuclear material using other measurement methods, using the CT measured values, and performing evaluation will be studied.	2−③ 3- ② A, B	The primary proposal for the method of estimating and evaluating the quantity of nuclear material has been established.

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

Appendix-2 Future challenges

FY2021 Identification (④ X-ray CT method (2/2))

The issues considered to be important from among the technological issues identified with respect to each individual measurement method have been consolidated. Progress made in FY2022 has been added.

No.	Item	Details	Response policy	Corresponding development Step Note)	Progress made in FY2022
5	Reduction of background radiation	･The larger the background, longer it takes for the target nuclides to be detected, and the lower detectable limit is likely to worsen.	･Since the dose rate of accelerator based X-rays is higher than the background dose rate, a combined use of the shield in existing equipment for preventing leakage of X-rays to the outside will be studied.	2−① 3−① 4−①	−
6	Accumulation of contamination	･Fuel debris that has leaked from the container when it was measured is likely to accumulate inside the equipment.	･A sealed container will be used. ･A design that enables decontamination inside the equipment will be used.	4−①	−
7	Radiation resistance (γ rays)	･The detectors, electronic equipment, cables, etc. in the vicinity of the measurement cell are expected to undergo irradiation degradation.	･Since the dose rate of accelerator based X-rays is higher than the fuel debris dose rate, design of existing equipment can be used for the shield, etc.	3−① 4−①	−
8	Radiation resistance (neutrons)	･The detector is expected to degrade faster due to the spontaneous fission neutrons.	･The need to install a shield will be studied.	3−① 4−①	−
9	Ease of maintenance	･It is assumed that the shields around the equipment need to be handled during maintenance.	･The possibility of being able to carry out direct maintenance from outside the cell will be studied. ･Measures need to be taken to ensure maintainability of the radiation source, detector, etc.	3−① 4−①	−
10	Daily inspection	･Calibration needs to be performed on a daily basis in order to monitor ageing degradation or random failures, and for accurate measurement.	･There is a proven track record of carrying out measurement for a period of 10 to 15 seconds without loading fuel debris and monitoring the status of the device, during normal operation.	4−①	−

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

Appendix-2 Future challenges

Development plan

Item	2020	2021	Short term (until FY2024)	Mid- and long-term (FY2025 onwards)
Key dates			Setting up of scenarios and updating of the mid- and long-term plan ▽ ▽	Increase in scale of retrieval ▽
Step 1 (Measurement FS)				
Step 2 (Measurement concept / scenario development) ① Study of target performance value ② Development of the concept of the device by means of analysis ③ Study of evaluation methods for nuclear fuel material, etc. ④ Re-examination of sorting scenario ⑤ Elemental technology verification test				
Step 3 (Basic design and software development) ① Basic design of the device ② Software development ③ Elemental technology verification test (ongoing)			Start of Step 3 when future prospects can be seen in Step 2	
Step 4 (Test manufacturing and comprehensive verification test) ① Test manufacturing of measuring apparatus ② Demonstration test (Hot, etc.), improvement				
Step 5 (Manufacturing of actual equipment) ① Designing of actual equipment ② Manufacturing, installation and testing of actual equipment			Coordination of retrieval conditions, etc.	Incorporation into improvement of evaluation method Actual fuel debris analysis results Starting of operation Operation (improved)
			Retrieval PJ	Analysis facility