Subsidy Project of Decommissioning and Contaminated Water Management
Started Since FY2020

Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals

(Development of Technology for Sorting and Distinction Between Fuel Debris and Radioactive Waste)

Final Report

August 2022

International Research Institute for Nuclear Decommissioning
(IRID)

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Research Background and Purpose

(Excerpts from solicitation information)

[Purpose of developing technology for sorting and distinction between fuel debris and radioactive waste]

- **During the decommissioning of the Fukushima Daiichi Nuclear Power Station, it is not logical to regard all objects retrieved from inside the Primary Containment Vessel (PCV) 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 amount of nuclear fuel material contained in the retrieved objects as a guideline.**
- **Prospective measurement technologies that can measure the amount of nuclear fuel material have been provided during the Decommissioning and Contaminated Water Management Project (“Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Reactor Internals” (FY2019-2020) Same shall apply hereinafter). However, evaluation of the measurement errors, which is necessary for establishing the method of sorting and distinction based on the amount of nuclear fuel material, has not been started.**
- **Hence, it is essential to select factors influencing measurement errors arising from the amount of material other than nuclear fuel material (water content, quantity of metallic components, quantity of control rods, quantity of concrete resulting from MCCI (Molten Core Concrete Interaction), etc.) contained in the objects retrieved from inside the PCV, the status of filling inside the canisters, etc., and analyze and evaluate the impact that they have on measurement errors, in order to select the required measurement technologies and equipment for establishing sorting technology in the future, with the measurement technologies^{*1} studied during the Decommissioning and Contaminated Water Management Project in mind.**

  ***1) Passive gamma rays measurement, passive neutron measurement, active neutron measurement, radioaparency measurement, cosmic rays scattering measurement**

- **Technology for the following items will be developed.**

  ① Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

  ② Study of future research and development plans aiming for application of sorting technology to actual equipment

Objective

[Project goal]
To create the research and development plan aiming for future application to actual equipment and identification of issues in the measurement technologies, which is required for developing technology 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.

[Development steps based on the solicitation information and positioning of this year's research]

(Step 0) Investigation of the technology concerning sorting and distinction (FY2019-2020)

(Step 1) Feasibility study of measurement (Analyzing the possibility) ⇐ This year's research (TRL2)

① Setting the purpose and target (shape, density, etc.) of measurement
② Nuclear materials → Evaluating the behavior of radiation incident upon the detector
③ Identification, etc. of technical issues contributing to the concept of measurement

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

(Step 3) Basic design and software development

(Step 4) Comprehensive verification tests using test manufacturing, simulated radiation source, etc.

(Step 5) Fabrication of actual equipment

(Step 6) Actual operation

* The results taking into consideration the positioning of this year's research in the development plan up to practical application at the start of the project have been referred to for the above-mentioned details. Investigation → Feasibility Study → Concept → Basic design →Verification test →Fabricating actual equipment →Actual operation are defined as the steps involved in general development.

Implementation Items, their Correlations, and Relations with Other Research (1/2)

[Overview of implementation]

Factors influencing measurement errors arising from the amount 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 selected, with the prospective measurement technologies[*1)] provided during the FY2019 Decommissioning and Contaminated Water Management Project in mind, and their impact on measurement errors was analyzed and evaluated by means of simulation.

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

Factors that were expected to influence measurement errors of prospective measurement technologies[*1)] provided during the Decommissioning and Contaminated Water Management Project were selected, the fluctuation range of each factor for each measurement technology was analytically simulated, and the extent to which each factor influences the measurement errors was analyzed and evaluated. Also, the necessity to continue further analysis and evaluation in the future, and issues in technological development that will become necessary in the future for reducing the measurement errors were studied.

(2) Study of future research and development plans aiming for application of sorting technology to actual equipment

Technical issues described above (1) that must be resolved in the future for the purpose of practical application of the sorting technology were identified based on the evaluation results and technical issues studied in FY2019. Further, organizing the conditions required according to the mid-and-long term research and development plan for resolving those technical issues was considered.

***1）Passive gamma rays measurement, passive neutron measurement, active neutron measurement, active/passive neutrons + passive gamma rays measurement, radioaparency measurement, cosmic rays scattering measurement**

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

The following information was exchanged with other projects.

Input and output information related to the FY2020 Subsidy Project of Decommissioning and Contaminated Water Management
- Development of technology for further increasing the retrieval scale of fuel debris and reactor internals
(Development of technology for sorting and distinction between fuel debris and radioactive waste)

ID	Requesting project	Providing project	Content (overview)	Required by (time-line)	Use application of information	Remarks
1	Debris Retrieval PJ	Characterization PJ	Fuel debris characterization	November 2020	Setting the analytical conditions for analytical evaluation of the parameters influencing measurement errors in the measurement technologies	Information exchange as needed
2	Debris Retrieval PJ	Canister PJ	Shape of canister	November 2020	Setting the analytical conditions for analytical evaluation of the parameters influencing measurement errors in the measurement technologies	Information exchange as needed
3	Debris Retrieval PJ	Treatment and Disposal PJ	Shape of the waste storage container	November 2020	Setting the analytical conditions for analytical evaluation of the parameters influencing measurement errors in the measurement technologies	Information exchange as needed
4	Debris Retrieval PJ	Canister PJ	Process for containing, transfer and storage of fuel debris, and future development plans concerning those systems	April 2021	Identification of technical issues for the purpose of practical application of the sorting and distinction technology, and pre-conditions for consolidating the goals of the main processes in developing the sorting and distinction technology	Information exchange as needed

Note) In this document, other related projects are expressed with the following abbreviations.

Debris Retrieval PJ: Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris and Reactor Internals
Characterization PJ: Development of Technology for Fuel Debris Characterization and Analysis
Canister PJ: Development of Technology for Containing, Transfer and Storage of Fuel Debris
Treatment and Disposal PJ: Research and Development for Treatment and Disposal of Solid Wastes

Implementation Schedule

1 Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

③ Analytical simulation

④ Study of the necessity of detailed analysis and consolidation of technical issues

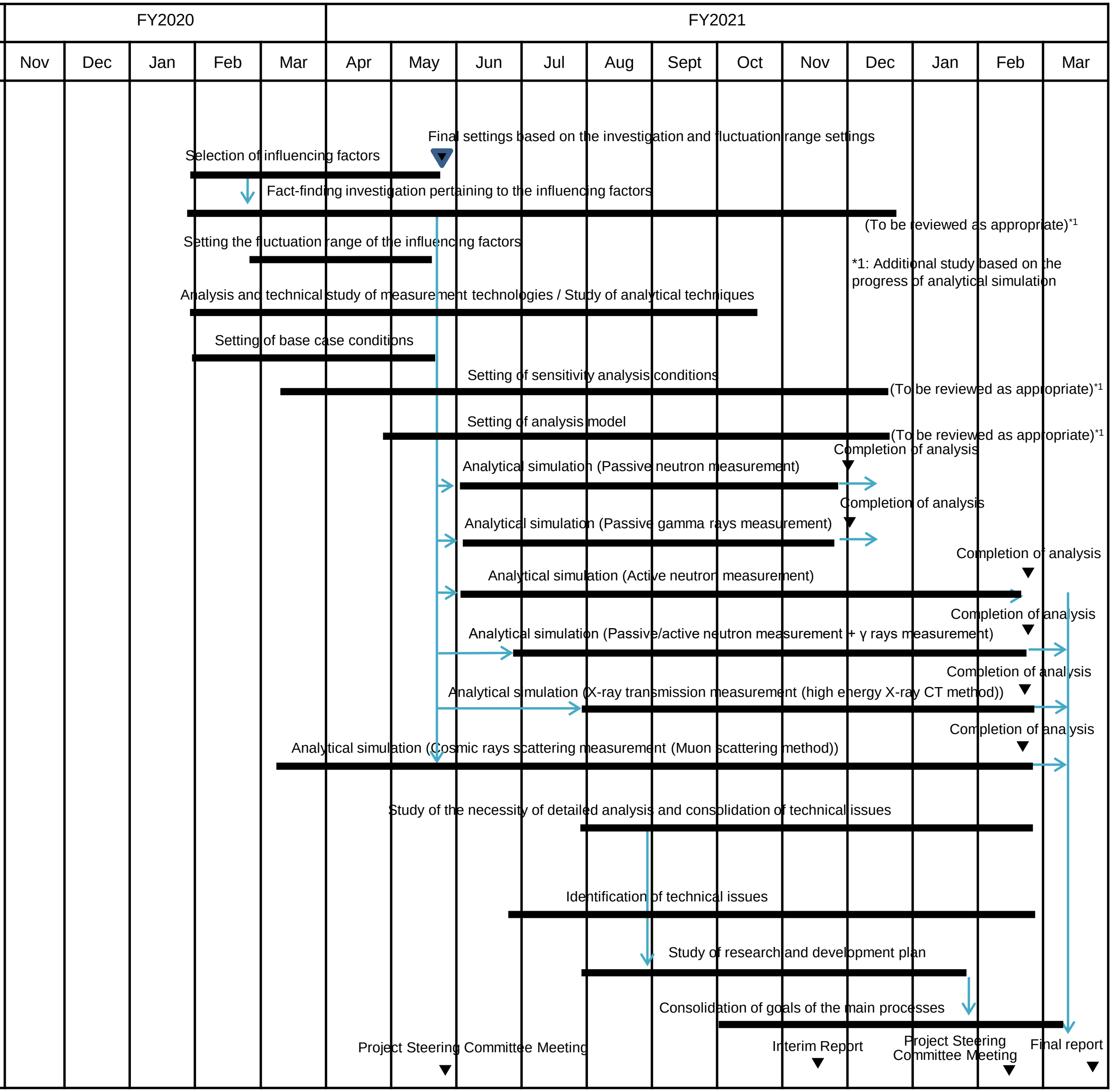
2 Study of future research and development plans aiming for application of sorting technology to actual equipment

① Identification of technical issues for the purpose of practical application of the sorting technology

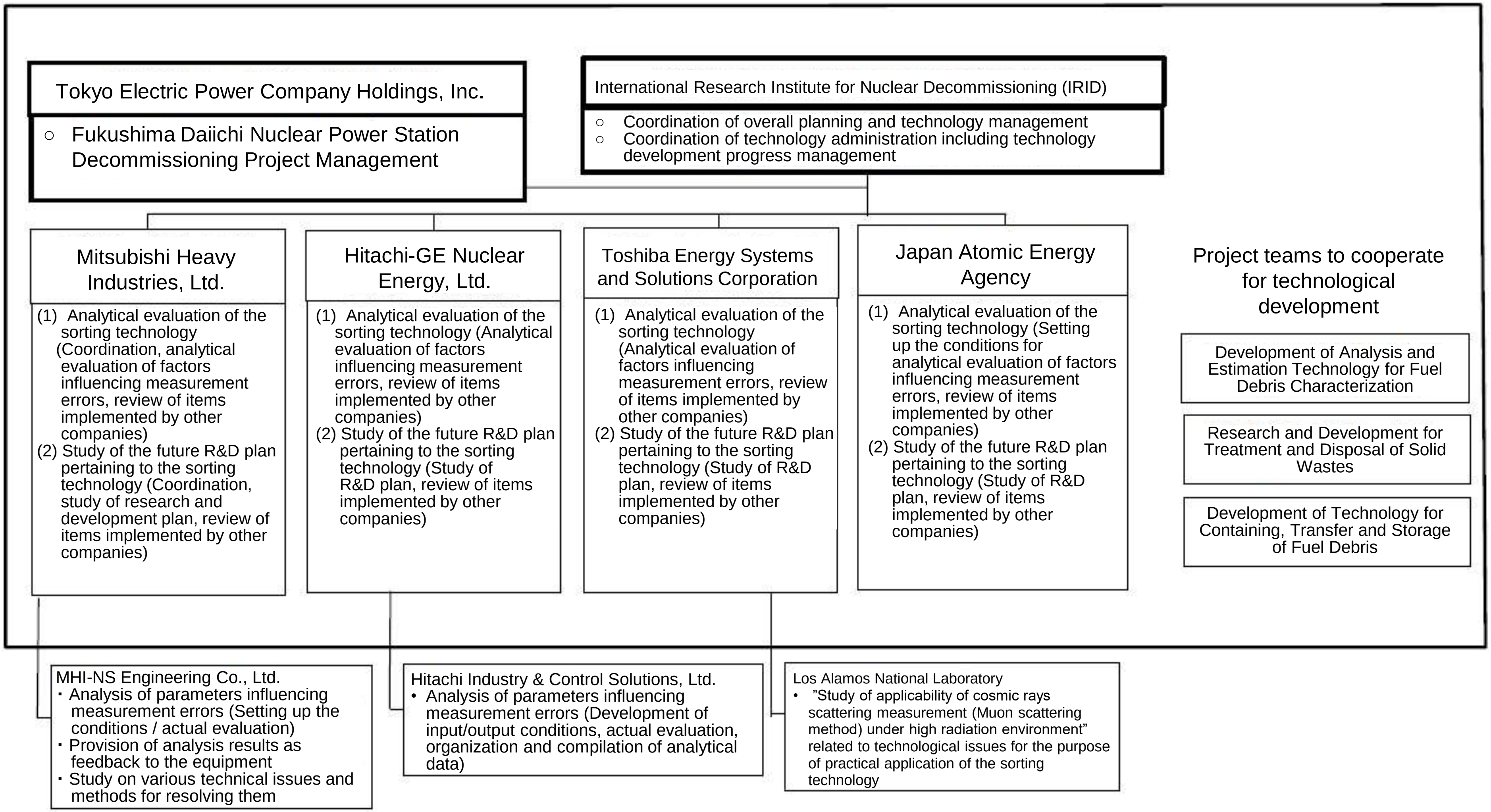
② Study of research and development plan (contents, duration, conditions)

③ Consolidation of goals of the main processes

Major milestones (Debriefing session / presentation, etc.)



Project Organization



Tokyo Electric Power Company Holdings, Inc.

○ Fukushima Daiichi Nuclear Power Station Decommissioning Project Management

International Research Institute for Nuclear Decommissioning (IRID)

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

Mitsubishi Heavy Industries, Ltd.

(1) Analytical evaluation of the sorting technology (Coordination, analytical evaluation of factors influencing measurement errors, review of items implemented by other companies)
(2) Study of the future R&D plan pertaining to the sorting technology (Coordination, study of research and development plan, review of items implemented by other companies)

Hitachi-GE Nuclear Energy, Ltd.

(1) Analytical evaluation of the sorting technology (Analytical evaluation of factors influencing measurement errors, review of items implemented by other companies)
(2) Study of the future R&D plan pertaining to the sorting technology (Study of R&D plan, review of items implemented by other companies)

Toshiba Energy Systems and Solutions Corporation

(1) Analytical evaluation of the sorting technology (Analytical evaluation of factors influencing measurement errors, review of items implemented by other companies)
(2) Study of the future R&D plan pertaining to the sorting technology (Study of R&D plan, review of items implemented by other companies)

Japan Atomic Energy Agency

(1) Analytical evaluation of the sorting technology (Setting up the conditions for analytical evaluation of factors influencing measurement errors, review of items implemented by other companies)
(2) Study of the future R&D plan pertaining to the sorting technology (Study of R&D plan, review of items implemented by other companies)

Project teams to cooperate for technological development

- Development of Analysis and Estimation Technology for Fuel Debris Characterization
- Research and Development for Treatment and Disposal of Solid Wastes
- Development of Technology for Containing, Transfer and Storage of Fuel Debris

MHI-NS Engineering Co., Ltd.

- Analysis of parameters influencing measurement errors (Setting up the conditions / actual evaluation)
- Provision of analysis results as feedback to the equipment
- Study on various technical issues and methods for resolving them

Hitachi Industry & Control Solutions, Ltd.

- Analysis of parameters influencing measurement errors (Development of input/output conditions, actual evaluation, organization and compilation of analytical data)

Los Alamos National Laboratory

- ”Study of applicability of cosmic rays scattering measurement (Muon scattering method) under high radiation environment” related to technological issues for the purpose of practical application of the sorting technology

Items reported in the final report

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
  2.2.1 Passive neutrons
  2.2.2 Passive gamma rays
  2.2.3 Active neutrons
  2.2.4 Passive/active neutrons + passive gamma rays
  2.2.5 X-ray transmission measurement
  2.2.6 Cosmic rays scattering measurement

2. Implementation Details – (1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

Identification of assumed variation parameters

The assumed validation parameters for each measurement technology were identified, including the reason for selection.

② Setting the fluctuation range of the influencing factors

Organization of variation parameters

The variation parameters that were identified above were organized. The parameters that were likely to have comparable effects as per the analytical simulation model were organized.

Organization of variation parameters required for each measurement technology

The identified parameters were examind against the measurement principle for each measurement technology to determine if they have an impact. At this time, the reason was indicated as well. Also, the studies of the analytical parameters was prioritized so that a significant conclusion can be obtained.

Organization of the resulting influencing factors

The results, including the validity of the reason, were organized.

Study of the maximum and minimum values of the parameters

The maximum and minimum values of the parameters were studied along with the reasons and basis, while stepping further up to the measurement technology.

③ Analytical simulation

Determination of analytical conditions and implementation of analytical simulation

The analytical conditions were determined and analytical simulation was implemented for each measurement technology.

2. Implementation Details - (1) ① Selection of influencing factors (1/2)

The parameters that were likely to fluctuate in the case of each measurement technology were identified, and from amongst them, influencing factors (① to ⑩) that were likely to have a significant influence on the measurement errors were identified. Also, the measurement techniques that the influencing factors influenced and their basis were consolidated.

Table Prospective measurement technologies

Symbol	Measurement technology
Pn	Passive neutron measurement technology
Pγ	Passive gamma rays measurement technology
An	Active neutron measurement technology
PAn+Pγ	Passive/active neutron measurement + γ rays measurement technology
X	X-ray transmission measurement (High energy X-ray CT method)
M	Cosmic rays scattering measurement (Muon scattering method)

Table: Results of selecting the factors influencing measurement errors (1/2)

Influencing factor		Measurement technique that the factors influence	Basis of the measurement technique
Fuel debris properties	① Fuel debris composition	All	The absorption/scattering effect of radiation differs depending on the difference in fuel debris composition (mixing ratio of fuel components and structures).
	Gd content (percentage)	Pn, An, PAn+Pγ, M	The absorption/scattering effect (energy distribution) of radiation (particularly neutrons) emitted by fuel debris differs depending on the difference in amount contained (percentage).
	B content (percentage)	Pn, An, PAn+Pγ, M	Same as above
	MOX	All	The radiation emitted by fuel debris is different than that emitted by uranium fuel. Also, fuel debris composition changes and the absorption/scattering effect of radiation differs as well.
Fuel debris based	② Burn-up	Pn, Pγ, An, PAn+Pγ, M	Since the composition of the fission products (FP) and the actinoids that form the fuel debris changes, the type of radiation, the absorption/scattering effect of radiation in the fuel debris, etc. differs.
	③ FP emission rate	Pγ, X, M	The rate of emission of FP nuclides along with fuel meltdown. The rate of emission of volatile FP nuclides at the time of fuel meltdown has an impact on the intensity of gamma rays and distribution of energy emitted by the fuel debris.
	④ Cooling period	Pn, Pγ, An, PAn+Pγ, M	Same as “② Burn-up”

2. Implementation Details - (1) ① Selection of influencing factors (2/2)

Table Prospective measurement technologies

Symbol	Measurement technology
Pn	Passive neutron measurement technology
Pγ	Passive gamma rays measurement technology
An	Active neutron measurement technology
PAn+Pγ	Passive/active neutron measurement + γ rays measurement technology
X	X-ray transmission measurement (High energy X-ray CT method)
M	Cosmic rays scattering measurement (Muon scattering method)

Table: Results of selecting the factors influencing measurement errors (2/2)

Influencing factor		Measurement technique that the factors influence	Basis of the measurement technique
Status of storage in containers	⑤ Moisture content	Pn, An, PAn+Pγ, M	The absorption/scattering effect (energy distribution) of radiation (particularly neutrons) emitted by fuel debris differs depending on the difference in moisture content.
	⑥ Filling rate	All	Absorption/scattering effect of radiation differs inside the container.
	⑦ Uneven distribution	All	Same as above
	⑧ Container	All	The intensity (beam, etc.) of radiation reaching the detector differ depending on the container.
Measuring system	⑨ Irradiating radiation source	An, PAn+Pγ, X	The mutual interactions within materials such as fuel debris, etc. differs depending on the energy of the irradiating radiation source (neutrons, X-ray).
	⑩ Detector	All	The intensity (beam, etc.) of radiation reaching the detector differs depending on the location of the detector, and thickness of shield and moderator, for each measurement technique.

2. Implementation Details - (1) ② Setting the fluctuation range of the influencing factors (1/2)

On the basis of the properties of fuel debris and the principle of each measurement technology, the fluctuation range (minimum to maximum, etc.) of the identified influencing factors（① to ⑩）were set. (Table below)

Table : Results of setting the fluctuation range of the influencing factors (1/2)

<table>
<tr><th>Item</th><th>Influencing factor</th><th>Fluctuation range of the influencing factor</th><th>Basis of the measurement technique</th></tr>
<tr><td rowspan="4">Fuel debris properties</td><td>① Fuel debris composition</td><td>The fluctuation range was set based on the mixing ratio of fuel components (UO_2) and structures (ZrO_2, SUS, concrete).
(Details were organized based on the analysis conditions.)</td><td>Since there can be infinite number of combinations of the mixture of fuel (UO_2) and structures (ZrO_2, SUS, concrete) in fuel debris, the following was assumed as the typical state of fuel debris.
・ Molten debris(Note 1)
・ Uranium-rich debris
・ Metallic debris(Note 1)
・ MCCI debris(Note 1)
<table><tr><th>Type</th><th>Definition</th></tr><tr><td>Molten debris</td><td>Fuel debris in which $(U,Zr)O_2$ is the major component</td></tr><tr><td>Uranium-rich debris</td><td>Fuel debris in which UO_2 is the major component</td></tr><tr><td>Metallic debris</td><td>Metallic layer accumulated at the bottom due to difference in density</td></tr><tr><td>MCCI debris</td><td>Layer of oxides consisting of concrete components</td></tr></table></td></tr>
<tr><td>Gd content (percentage)</td><td>Minimum Gd content contained in actual fuel debris to maximum Gd content after more gets added at the time of retrieval</td><td>(1) Combustible Gd contained in fuel, (2) Gd_2O_3 added to maintain sub-criticality were assumed. (1) is considered to be likely to mix evenly in fuel debris, and hence was assumed to be equivalent to “actual conditions”. The largest amount of (2) was assumed to be likely to be in the container.</td></tr>
<tr><td>B content (percentage)</td><td>From 0% to maximum B content after more gets added at the time of retrieval</td><td>(1) B contained in control rods, (2) B_4C added to maintain sub-criticality were assumed. However, as control rods melt before fuel rods, considering the likelihood of control rods not mixing evenly in fuel debris and fuel debris that does not contain control rods being retrieved, (1) was assumed to be 0%. The largest amount of (2) was assumed to be likely to be in the container.</td></tr>
<tr><td>MOX</td><td>MOX present or MOX absent</td><td>MOX fuel is not loaded in Units 1 and 2. MOX fuel is loaded in Unit 3.</td></tr>
<tr><td rowspan="3">Fuel debris based</td><td>② Burn-up</td><td>Approx. 1.3 to approx. 51.3GWd/t</td><td>1.3GWd/t is the lowest burn-up per node in Unit 2 excluding the region with natural uranium. It is the least in Units 1 to 3 and includes the minimum value of other units as well.
51.3GWd/t is the highest burn-up per node in Unit 2. It is the highest in Units 1 to 3 and includes the maximum value of other units as well.</td></tr>
<tr><td>③ FP emission rate</td><td>Emission of volatile FP such as Cs, etc. absent to emission present (99%)</td><td>The rate of emission of volatile FP nuclides at the time of fuel meltdown has an impact on the intensity of gamma rays and distribution of energy emitted by the fuel debris. Hence 0 emission to high emission was assumed.</td></tr>
<tr><td>④ Cooling period</td><td>20 to 40 years after the accident</td><td>From full-scale retrieval (FY2031) to Completion of decommissioning based on the Mid-and-Long-Term Roadmap.</td></tr>
</table>

(Note 1) “Subsidy Project of Decommissioning and Contaminated Water Management (Development of technology for fuel debris characterization and analysis)” in the FY2016 Supplementary Budget Research Report (Interim report) March 2018

2. Implementation Details - (1) ② Setting the fluctuation range of the influencing factors (2/2)

Table : Results of setting the fluctuation range of the influencing factors (2/2)

Item	Influencing factor		Fluctuation range of the influencing factor	Basis of the measurement technique
Status of storage in containers	⑤ Moisture content		0.1wt% to 70vol%	0.1wt% was set based on the target drying value of 0.1wt% (Note 2) from the Canister PJ, on the premise that drying is performed before measurement. 70vol% was set by rounding up the maximum moisture content of 65.1vol% (residual amount of water considering the causes of error) from the draining test data.
	⑥ Filling rate		10 to 50vol%	A fluctuation of ±20% from the filling rate of 30% (based on the information from the Subsidy Project of Development of Technology for Containing, Transfer and Storage of Fuel Debris) based on the specifications of the unit can was assumed.
	⑦ Uneven distribution		Following indicate extremely uneven distribution. ・ Radiation source unevenly located at the center of the container ・ Radiation source unevenly located near the surface of the container	If fuel debris is collected in containers, there can be infinite possibilities of uneven distribution. Hence, extremely uneven distribution was assumed and first the extent of impact was verified.
	⑧ Container		Following are containers that are being considered in the projects. ・ Unit can ・ Canister ・ Waste storage container (or inner container)	From the perspective of verifying applicability, containers from the Debris Retrieval PJ and Canister PJ that are currently being implemented, were considered. ・ Unit can ・ Canister (Note 2) ・ Waste storage container (or inner container）
Measuring system	⑨ Irradiating radiation source	Active neutron measurement	1.13MeV (average energy) 2.45MeV 14MeV	1.13MeV: Photonuclear reaction due to Bremsstrahlung X-rays 2.45MeV: D-D reaction 14MeV: D-T reaction
		X-ray transmission measurement	Maximum x-ray energy 6MeV 9MeV 15MeV	Selected based on the length up to which X-rays can penetrate through the objects filled inside the container, and the X-ray energy of the linear electron accelerator for non-destructive inspection that is available as a product in the market.
	⑩ Detector (Location of the detector, shielding thickness, etc.)		Set for each measurement technology	—

(Note 2) Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March 2021

(Note 3) Subsidy Project of Decommissioning and Contaminated Water Management in the FY2014 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March 2017

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
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  2.2.2 Passive gamma rays
  2.2.3 Active neutrons
  2.2.4 Passive/active neutrons + passive gamma rays
  2.2.5 X-ray transmission measurement
  2.2.6 Cosmic rays scattering measurement

2. Implementation Details – (1) ③ Analytical simulation (Division of implementation)

I. Development of fuel debris radiation source model: Japan Atomic Energy Agency (JAEA)

II. Analytical simulation of each measurement technique: As per the table below

No.	Measurement technology (*1)	Analysis led by	Applicable code (Cross-sectional library) (*2)
1	Passive neutron measurement technology	MHI* Hitachi-GE**	MCNP5 (JENDL4.0) PHITS 3.20 (JENDL4.0)
2	Passive gamma rays measurement technology	MHI Hitachi-GE	MCNP5 (JENDL4.0) PHITS 3.20 (JENDL4.0)
3	Active neutron measurement technology	MHI Hitachi-GE	MCNP5 (JENDL4.0) PHITS 3.20 (JENDL4.0)
4	Passive/active neutron measurement + Gamma rays measurement technology	MHI	MCNP5 (JENDL4.0)
5	X-ray transmission measurement (High energy X-ray CT method)	Hitachi-GE	PHITS 3.20 (JENDL4.0)
6	Cosmic rays scattering measurement (Muon scattering method)	Toshiba ESS Corporation***	MCNP6 (ENDF/B-VII)

*1: Measurement technology selected as a prospective technology that can be applied for sorting and distinction, during the FY2019 study.

*2: The applicable code and cross-sectional library is different for each company, but in the case of the measurement technologies for which the analysis work will be split between MHI and Hitachi-GE, trial calculations were performed while keeping the calculation system and radiation source conditions the same, the results of those calculations were compared, and it was verified that results meeting the goals of the feasibility study this time can be obtained.

The applicable code and cross-sectional library of Toshiba ESS is used extensively and has a proven track record.

*Mitsubishi Heavy Industries, Ltd.: MHI

**Hitachi GE Nuclear Energy, Ltd.: Hitachi GE

***Toshiba Energy Systems and Solution Corporation: Toshiba ESS

2. Implementation Details – (1) ③ Analytical simulation（Overall flow）

① Selection of influencing factors
② Setting the fluctuation range of the influencing factors

③ Analytical simulation

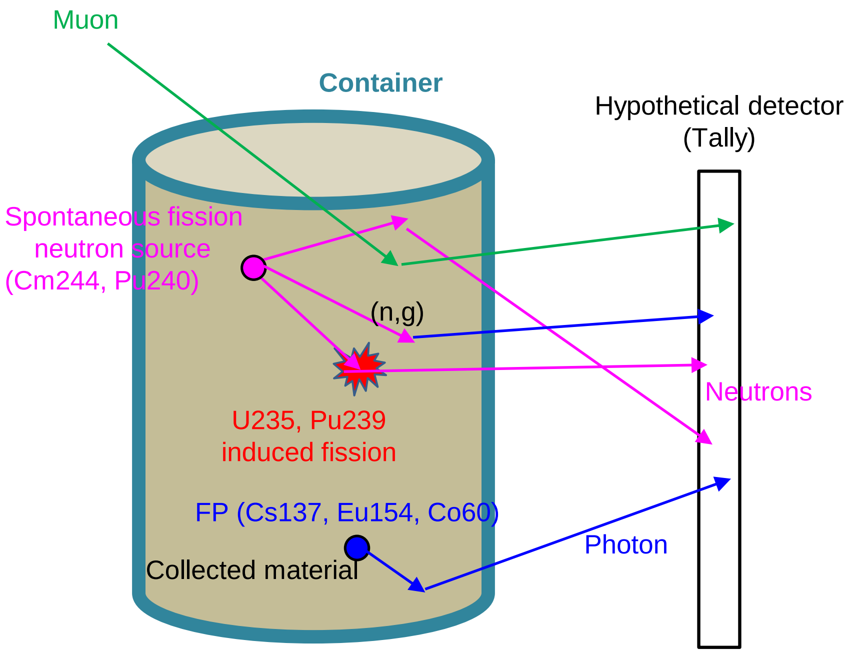
Development of the fuel debris radiation source model (data on every material)

Development of model for the fuel debris collected 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

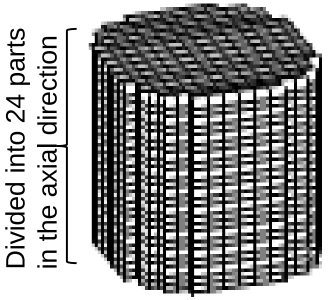
Evaluation of the beam in front of the detector for each sensitivity analysis case (Including the detector response depending on the method or case)

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



2.1Analysis conditions – Development of fuel debris radiation source model (1/2)

A model depicting the basic composition, photon source, and neutron source to be used for analyzing various types of fuel debris was developed.



3D nuclide inventory data (Note 1)
Example of Unit 2: 13,152 regions
(Burnable poison and trace impurities are considered)

Combustion composition of fuel
Activation composition of the structures

Approx. 1,600 nuclides

Volatile FP emission simulation

Noble gas, Cs, etc. 19 elements

Calculation of nuclide decay

Approx. 1,600 nuclides

Conditions for creating radiation source depending on the influencing factors (Conditions in blue are base cases)

- Region with minimum burn-up (1.3GWd/t)(Note 2)
- Entire reactor core region (23GWd/t)
- Region with maximum burn-up (51GWd/t)

- High emission rate (99%) model
- Model based on the FP emission test (Note 3)
- No emission model

- Duration of decay after accident: 40 years (Around FY2051)
- Duration of decay after accident: 30 years (Around FY2041)
- Time period of starting further scale up (20 years：around FY2031)

Element	Emission rate (%)
Noble gas	99
I	97
Cs	84
Te	80
Mo	77
Rb	53
Cd	44
Ba	35
Sb	30
Pd	27
Ag	9.2
Tc	7.1
Ru	1.8
Sr	1.4

The percentage of emission (100% - emission rate = residual ratio) until it anchors as fuel debris after the accident.

Development of radiation model per unit volume element (□:voxel) for each radioactive material (UO_2/MOX, ZrO_2, SUS)

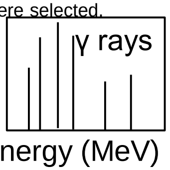
Creation of photon source

Composition for calculating particle transport

Creation of neutron source

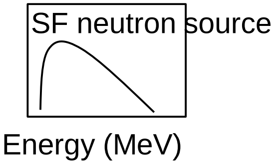
A line spectrum of approx. 33,500 units was created from the nuclear data (ENDF/B-VIII.0 decay library), and radiation source with major contribution of (ExI) and I, where I is the strength and E is the energy, and radiation source of major nuclides (Eu154, etc.) that are targeted in the passive gamma rays method were selected.

For the rest, a 47 group structure (10keV-20MeV) was used to reduce the number of groups.



Nuclides that largely contribute to the absorption reaction rate and the overall reaction rate were selected (approx. 99.8% of the whole) from nuclides that can be handled with the nuclide transport library of the MCNP, PHITS, GEANT codes.

The total number of spontaneous fission (SF) nuclides was obtained considering SF nuclides (60 nuclides) from Th232 to Fm257. The neutron energy spectrum was expressed in terms of Watts for the effective mass represented by the nuclides with maximum contribution (Cm224 or Pu240).

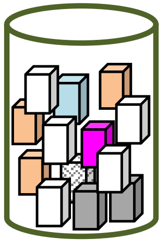


(Note 1) Atomic Energy Society of Japan (AESJ) FY2021 Spring Annual Meeting (3B01, 3B02), FY2021 Fall Meeting (1I06).
(Note 2) Represented by Unit 2 as Unit 2 encompasses the burn-up range of Units 1 and 3. The region with natural uranium is not included while indicating the minimum burn-up.
（Note 3）PHEBUS-FPT4 test：Nucl. Eng. and Technol. 38(2), pp.163-174 (2006).

2.1Analysis conditions – Development of fuel debris radiation source model (2/2)

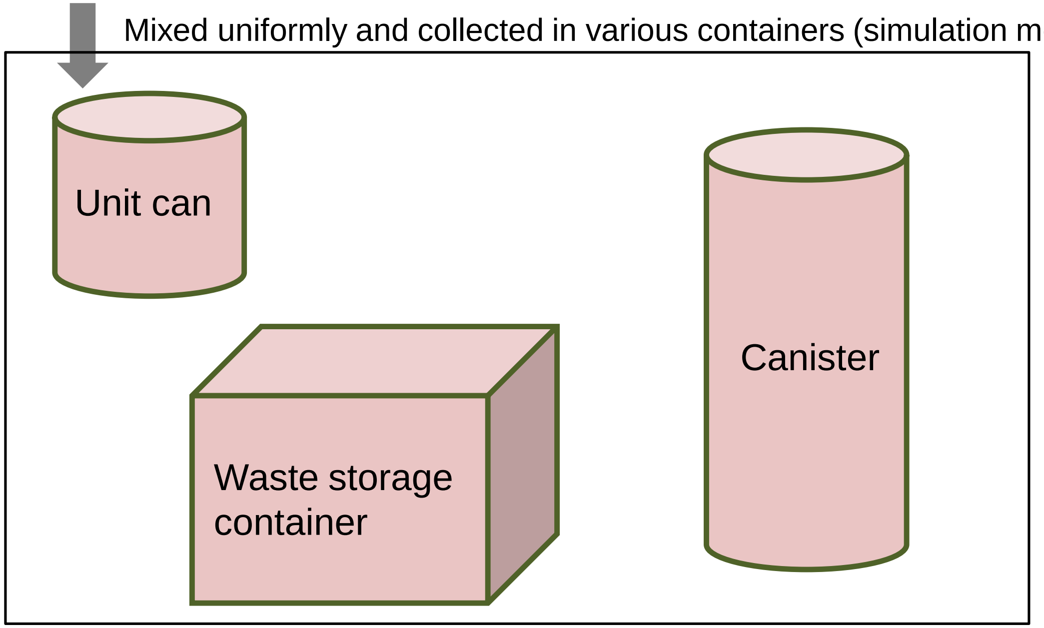
Development of voxel-based mixed fuel debris model for simulation

- Handling of a great number of sensitivity analysis cases in an integrated manner
- 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.)

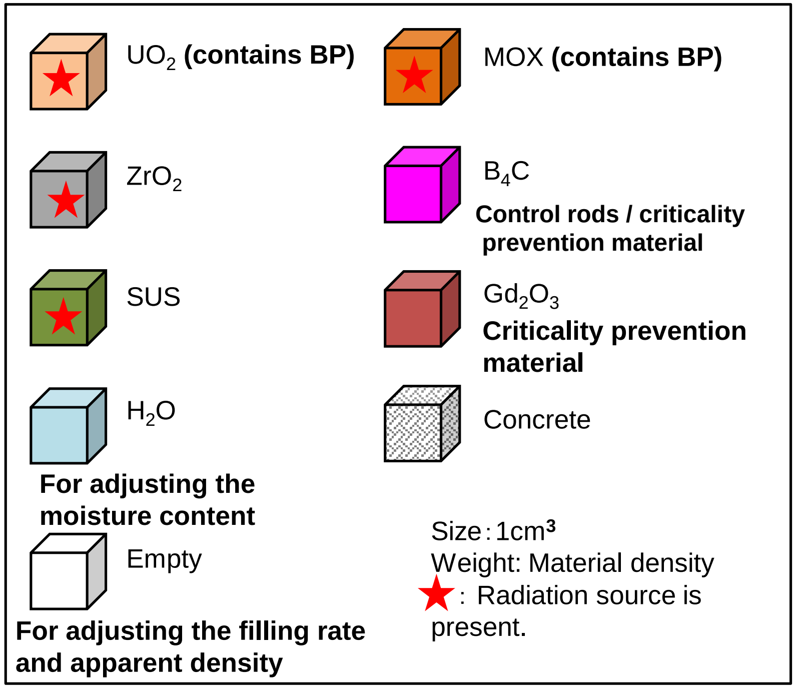


A variety of fuel debris was simulated by adjusting the number of voxels for each material collected in the hypothetical container.
(The radiation source is proportionate to the number of voxels.)

Mixed uniformly and collected in various containers (simulation model)



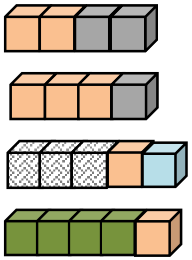
Fuel debris material (voxel)



- 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 rate and apparent density**

Size：1cm³
Weight: Material density
★： Radiation source is present.

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



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

2.1Analysis conditions - Base case analysis conditions (1/2)

◆ Setting of base case analysis conditions

(Sensitivity analysis: The sensitivity with respect to the minimum to maximum analysis results of individual influencing factors (parameters) was investigated on the basis of the analysis results (beam, etc.) based on these conditions.)

Table: Base case analysis conditions

Item	Parameters		Values	Approach towards setting the conditions
Radiation source	Burn-up		23GWd/t	Recent average burn-up of the Unit 2 reactor core planned to be investigated (Note 1)
	FP emission rate		Standard emission model	Emission rate based on the FP emission test (Phebus-FPT4)
	Cooling period		20 years	Time period of start of full-scale retrieval (FY2031)
Radiation transport computation container model	Target container		Unit can	Container: Smallest single container The mesh structure on the side and bottom was not modeled (Thickness was considered as well) Height: Area contributing to the dose rate, represented by 200mm wherein the amount of radiation source becomes smaller Other information about the container: According to the information from the Canister PJ and Debris Retrieval PJ
	Irradiated radiation energy	Active neutron measurement	14MeV	D-T reaction
		X-ray transmission measurement	9MeV	Has the ability to penetrate through the measurement target, shows intermediate values for the X-ray energy of the linear electron accelerator for non-destructive inspection that is supplied as a product.
Radiation transport computation fuel debris composition model	Fuel debris composition (Volume ratio)		UO_2: 50% ZrO_2: 50% SUS: 0% Conc: 0% Gd_2O_3: 0% B_4C: 0% MOX: 0% Empty (porosity): 0%	・ Assumed to be molten debris. (mixture of UO_2 and ZrO_2) The mixing ratio was according to the information from the Characterization PJ. ・ The combustible Gd contained in the fuel was considered in the UO_2 composition. (Gd_2O_3 (Note 2) was set to be absent.) ・ As control rods melt before fuel rods, they were assumed to not mix uniformly in the fuel debris. (B_4C (Note 3) was set to be absent.) ・ MOX fuel was not considered. ・ The porosity was considered to be 0%
	Moisture content (wt%)		1wt%	Value set based on the risk of hydrogen burning. (During the transport period (7 days), hydrogen concentration inside the canister reduces the 1.5wt% moisture content that has reached 4vol%.) According to the information from the Canister PJ
	Filling rate (vol.%)		30vol% (Empty: 70vol%)	According to the information from the Debris Retrieval PJ*
	Uneven distribution		-	The homogeneous model was used (UO_2, ZrO_2, H_2O, Empty were uniformly distributed inside the unit can.)

(Note 1) JAEA-Data-Code-2012-018, (Note 2) Criticality prevention material added for maintaining criticality was assumed.
(Note 3) Absorption material inside the 1F control rods was assumed.
*Subsidy Project of Development of Fuel Debris Retrieval

2.1 Analysis conditions - Base case analysis conditions (2/2)

Table : Pre-conditions (Container and density)

Item	Conditions	Values	Basis
Container	Depth	200mm	Area contributing to the dose rate, represented by 200mm wherein the amount of radiation source becomes smaller
	Outer diameter	210mm	Planned value (According to the information from the Debris Retrieval PJ)
	Inner diameter	206mm	
	Wall thickness	Side: 2mm Bottom: 5mm	The mesh structure on the side and bottom was not considered.
	Material	SUS316L	According to the information from the Canister PJ
	Density	7.98g/cm^3	According to JIS G 4304 (SUS316L)
Actual density	UO_2	10.525g/cm^3	Actual conditions
	ZrO_2	5.56g/cm^3	Actual conditions
	H_2O	1.0g/cm^3	From the Chronological Scientific Tables FY2018 (Set by rounding up the density of 0.99820g/cm^3 at 1atm and 20℃)
	Air	0g/cm^3	Handled as void

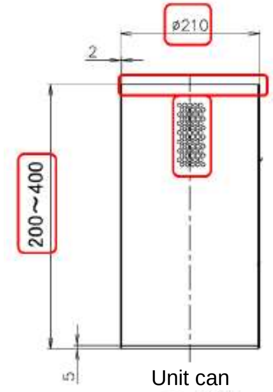
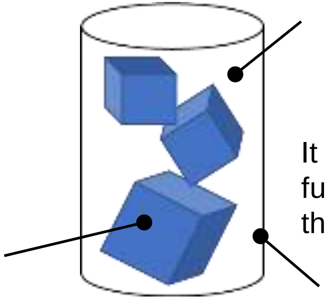
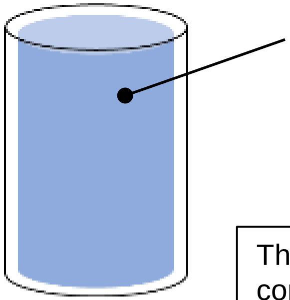


Figure Proposed structure of the unit can

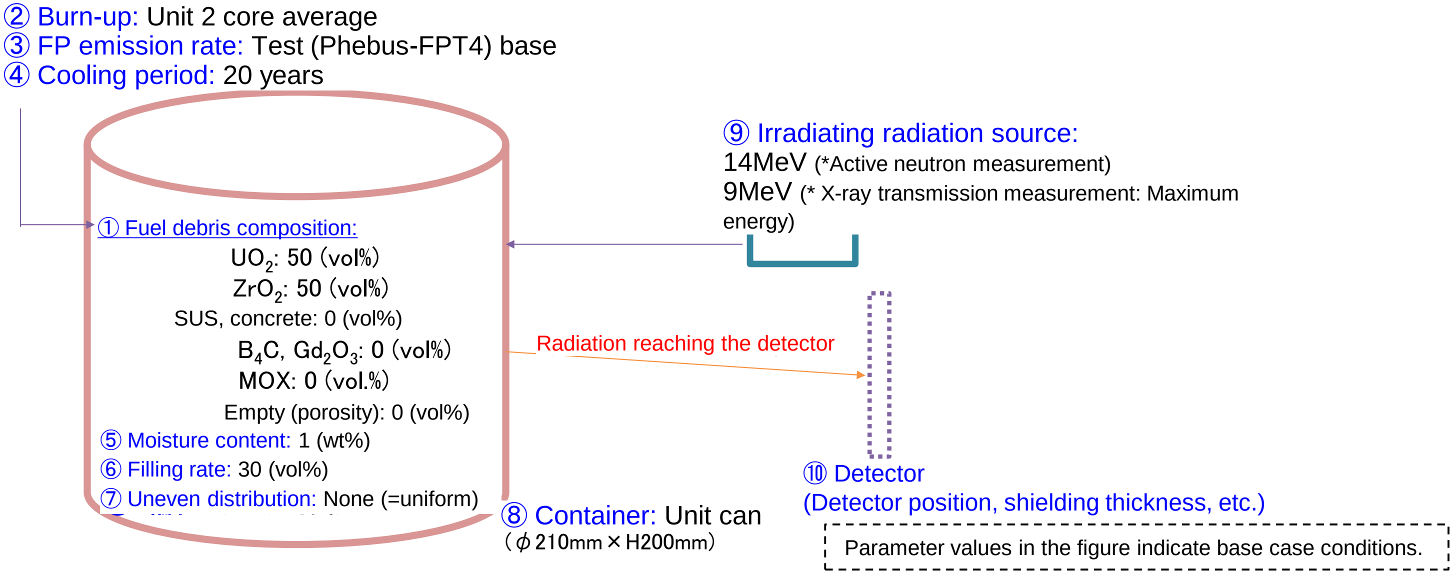
From the Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March 2021

Table : Policy for developing models

Image illustrating the assumed state of containing of fuel debris (example)	Analysis model
Air (Empty) or Water (H_2O)  It was assumed that clumped fuel debris is randomly filled in the container. Fuel debris (UO_2, ZrO_2) Container (Unit can)	 Abundance of each component material (UO_2, ZrO_2, H_2O, Empty) was mixed throughout the container. Further, the filling rate was modeled by homologizing it with the apparent density of fuel debris with respect to the total capacity of the fuel debris canister. The model of the detector system conforms to each measurement method.

2.1 Analysis conditions - Procedure of sensitivity analysis

- The variations in the beam, etc. that reaches the detection surface were verified based on the fluctuation range of the influencing factor as per the procedures given below.
  1. With the results obtained using base case conditions as a guideline, individual influencing factors were changed to verify variations.
  2. From the above-mentioned results, in order to understand physical phenomenon and enable systematic speculation regarding variations that occur when multiple influencing factors are closely connected, cases wherein multiple influencing factors were changed were analyzed as typical cases as well.



② Burn-up: Unit 2 core average
③ FP emission rate: Test (Phebus-FPT4) base
④ Cooling period: 20 years

① Fuel debris composition:
UO_2: 50 (vol%)
ZrO_2: 50 (vol%)
SUS, concrete: 0 (vol%)
B_4C, Gd_2O_3: 0 (vol%)
MOX: 0 (vol.%)
Empty (porosity): 0 (vol%)
⑤ Moisture content: 1 (wt%)
⑥ Filling rate: 30 (vol%)
⑦ Uneven distribution: None (=uniform)

⑧ Container: Unit can
(ϕ210mm×H200mm)

⑨ Irradiating radiation source:
14MeV (*Active neutron measurement)
9MeV (* X-ray transmission measurement: Maximum energy)

Radiation reaching the detector

⑩ Detector
(Detector position, shielding thickness, etc.)

Parameter values in the figure indicate base case conditions.

- Based on the above analytical evaluation, in order to reduce (predict) the variations caused by influencing factors, "④ Study of the necessity of detailed analysis and consolidation of technical issues" will be implemented, and will be linked to future research and development planning.

2.1Analysis conditions - Influencing factors to undergo sensitivity analysis for the measurement techniques

Influencing factors to undergo sensitivity analysis (parameter study) for the measurement techniques are indicated by "○" in the table. Its basis has been listed as well.

Influencing factor	Measurement technique						Basis, etc.
	Passive neutron	Passive γ	Active neutron	Combination (Note 1)	X-ray	Cosmic rays (Note2)	
① Fuel debris composition	○	○	○	○	○	○	The absorption/scattering effect of radiation differs depending on the fuel debris composition.
Gd content (percentage)	○	–	○	○	–	○	The absorption/scattering effect (energy distribution) of radiation (particularly neutrons) emitted by fuel debris differs depending on the difference in amount contained (percentage).
B content (percentage)	○	–	○	–	–	○	Same as above
MOX	○	○	○	–	○	○	The source of radiation emitted by fuel debris is different. Also, as the fuel debris composition changes, the absorption/scattering effect of radiation differs as well.
② Burn-up	○	○	○	○	–	○	Same as above
③ FP (fission product) emission rate	–	○	–	–	○	○	Same as above
④ Cooling period	○	○	○	–	–	○	Same as above
⑤ Moisture content	○	–	○	–	–	○	The absorption/scattering effect (energy distribution) of radiation (particularly neutrons) emitted by fuel debris differs depending on the difference in moisture content.
⑥ Filling rate	○	○	○	○	○	○	Absorption/scattering effect of radiation differs inside the container.
⑦ Uneven distribution	○	○	○	○	○	○	Same as above
⑧ Container	○	○	○	–	○	○	The intensity (beam, etc.) of radiation reaching the detector differs depending on the container.
⑨ Irradiating radiation source	–	–	○	–	○	–	The mutual interactions within materials such as fuel debris, etc. differ depending on the energy of the irradiating radiation source (neutrons, X-ray). (*) Only active n measurement, radiopacency measurement
⑩ Detector (Location of the detector, shielding thickness, etc.)	○(Note 3)	○(Note 3)	○(Note 3)	–	○(Note 3)	○	The intensity (beam, etc.) of radiation reaching the detector differs depending on the location of the detector, and thickness of shield (moderator), for each measurement technique.

(Note 1) Passive/active neutrons + passive gamma rays

(Note 2) Influence of all factors was investigated except ⑨ that is not related to cosmic rays scattering measurement (Muon scattering method). Only the influence of change in composition was handled in the 4 cases of MOX, burn-up, FP emission rate and cooling period.

(Note 3) representative detector position, moderator, etc. were set.

2.1Analysis conditions - Sensitivity analysis conditions (1/2)

The analysis conditions for the influencing factors (① to ⑩) to undergo sensitivity analysis (parameter study) were set.

Table: Sensitivity analysis conditions (1/2)

Item	Influencing factor	Fluctuation range of the influencing factor	Analysis conditions
Fuel debris properties	① Fuel debris composition	The fluctuation range was set based on the mixing ratio of fuel components (UO_2) and structures (ZrO_2, SUS, concrete).	Since there can be infinite number of combinations of the mixture of fuel (UO_2) and structures (ZrO_2, SUS, concrete) in fuel debris, the following was assumed as the typical state of fuel debris. ・ Molten debris^(Note 1)^ ・ Uranium-rich debris ・ Metallic debris^(Note 1)^ ・ MCCI (Molten Core Concrete Interaction) debris^(Note 1)^ Total 8 cases. (**Refer to No. 26** for details.)
	Gd content (percentage)	Minimum Gd content contained in actual fuel debris to maximum Gd content after more gets added at the time of retrieval	(1) Actual conditions ← **Base** (2) Set assuming Gd_2O_3 is added to maintain sub-criticality.
	B content (percentage)	From 0% to maximum B content after more gets added at the time of retrieval (Note that, as control rods melt before fuel rods, considering the likelihood of control rods not mixing evenly in fuel debris and fuel debris that does not contain control rods being retrieved, the minimum content was assumed to be 0%.)	(1) 0% ← **Base** (2) B_4C/UO_2 volume ratio = 0.034 (Equivalent to actual conditions: Core average of the amount of B mixed before the accident) (3) Set assuming B_4C is added to maintain criticality.
	MOX	MOX present or MOX absent	(1) MOX absent (Units 1 and 2) ← **Base** (2) MOX present (Unit 3)
Fuel debris based (Composition of fuel components (UO_2, ZrO_2) and intensity of radiation source)	② Burn-up	Approx. 1.3 to approx. 51.3GW/t	(1) Approx. 1.3GWd/t (Lowest burn-up per node) (2) Approx. 23Gwd/t (Average) ← **Base** (3) Approx. 51.3GWd/t (Highest burn-up per node)
	③ FP emission rate	Volatile FP emission absent to emission present (99%) (Refer to No. 14 for details.)	(1) Zero emission (2) Emission rate based on the FP emission test (Phebus-FPT4) ← **Base** (3) High emission (99%）
	④ Cooling period	20 to 40 years after the accident	(1) 20 years after the accident ← **Base** (2) 30 years after the accident (3) 40 years after the accident

(Note 1) "Subsidy Project of Decommissioning and Contaminated Water Management (Development of technology for fuel debris characterization and analysis)" in the FY2016 Supplementary Budget Research Report (Interim report） March 2018

2.1 Analysis conditions - Sensitivity analysis conditions (2/2)

Table: Sensitivity analysis conditions (2/2)

Item	Influencing factor		Fluctuation range of the influencing factor	Analysis conditions
Status of storage in containers	⑤ Moisture content		0.1wt% to 70vol% 0.1wt% was set based on the target drying value of 0.1wt% (Note 1) from the Canister PJ, on the premise that drying is performed before measurement. 70vol% was set by rounding up the maximum moisture content of 65.1vol% (residual amount of water considering the causes of error)(Note 2) from the draining test data.	(1) 0.1wt% (2) 1wt% ← **Base** (3) Set upon seeing the results of (1), (2), and (4) and considering the necessity. (4) 70vol%
	⑥ Filling rate		10 to 50vol% A fluctuation of ±20% from the filling rate of 30% (based on the information from the subsidy project of Development of Fuel Debris Retrieval) based on the specifications of the unit can was assumed.	(1) 10vol% (2) 30vol% ← **Base** (3) 50vol%
	⑦ Uneven distribution		Following indicate extremely uneven distribution. ・ Radiation source unevenly located at the center of the container ・ Radiation source unevenly located near the surface of the container	Same as on the left (Refer to **No. 27** for details)
	⑧ Container		Following are containers that are being considered in the projects. ・ Unit can ・ Canister ・ Waste storage container (or inner container)	(1) Unit can ← **Base** (2) Canister (3) Waste storage container (**Refer to No. 28** for details.)
Measuring system	⑨ Irradiating radiation source	Active neutron measurement	1.13MeV (average energy) 2.45MeV 14MeV	(1) 1.13MeV: Photonuclear reaction due to Bremsstrahlung X-rays (2) 2.45MeV (D-D reaction) (3) 14MeV (D-T reaction) ← **Base**
		X-ray transmission measurement	Maximum x-ray energy 6MeV 9MeV 15MeV	(1) 6MeV (2) 9MeV ← **Base** (3) 15MeV
	⑩ Detector (Location of the detector, shielding thickness, etc.)		Set for each measurement technology	Same as on the left (For details, refer to the models of the measurement techniques in Section 2.2.)

(Note 1): Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March 2021

(Note 2): Subsidy Project of Decommissioning and Contaminated Water Management in the FY2014 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March 2017

2.1 Analysis conditions - Sensitivity analysis conditions - Fuel debris composition (Details)

- Fuel debris composition based on the FY2018 report of the Characterization PJ (Molten debris < Base >, metallic debris, MCCI (Molten Core Concrete Interaction) debris) ＋ Uranium-rich debris was assumed.
- The sensitivity of nuclear fuel components, SUS and concrete to fluctuations in fuel debris components was investigated.

(Since components other than UO_2 become shielding material, cases in which the detection efficiency gets worsened and cases in which measurement is affected were investigated.)

Chart enumerating the fuel debris composition (voxel) and volume ratio (vol%)

Fuel debris	Composition inside the container (Note 1)								Reason (basis)
	Fuel debris components				Other				
	UO_2	ZrO_2	SUS	Concrete	Gd_2O_3	B_4C	H_2O	Empty	
Molten debris	15% (50%)	15% (50%)	0%	0%	Base: 0% Fluctuations considered based on sensitivity analysis	Base: 0% Fluctuations considered based on sensitivity analysis	Base: 1wt% Fluctuations considered based on sensitivity analysis	Base: Volume excluding fuel debris + H_2O Fluctuations considered based on sensitivity analysis	Based on FY2018 report of the Characterization PJ*
	7.5% (25%)	22.5% (75%)	0%	0%					Sensitivity investigation based on fluctuations in nuclear fuel components
Uranium-rich debris	30% (100%)	0% (0%)	0%	0%					Sensitivity investigation based on fluctuations in nuclear fuel components
Metallic debris	0.075% (0.25%)	0.075% (0.25%)	29.85% (99.5%)	0%					Based on FY2018 report of the Characterization PJ
MCCI	1.05% (3.5%)	1.05% (3.5%)	7.2% (24%)	20.7% (69%)					Based on FY2018 report of the Characterization PJ
Sensitivity investigation based on other material components that form fuel debris	15% (25%)	15% (25%)	30% (50%)	0%					Sensitivity investigation based on fluctuations in SUS
	15% (25%)	15% (25%)	0%	30% (50%)					Sensitivity investigation based on fluctuations in concrete components
	15% (33.3%)	15% (33.3%)	0%	15% (33.3%)					Sensitivity investigation based on fluctuations in concrete components **(Only neutron measurement)**

(Note 1) Percentage inside the container. (Percentage when fuel debris components are considered as 100% is mentioned inside parentheses.)

*Subsidy Project of Development of Fuel Debris Characterization

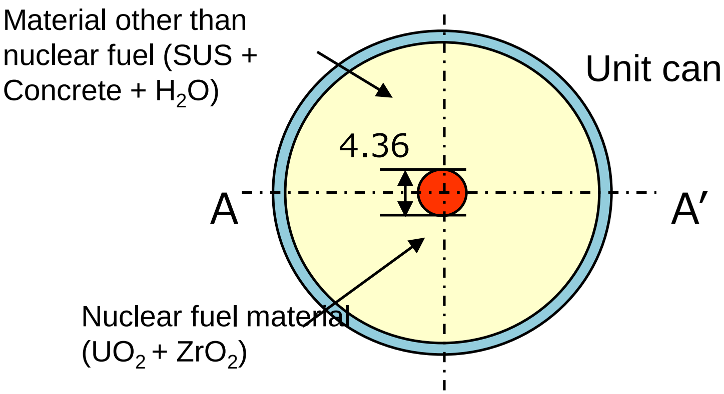
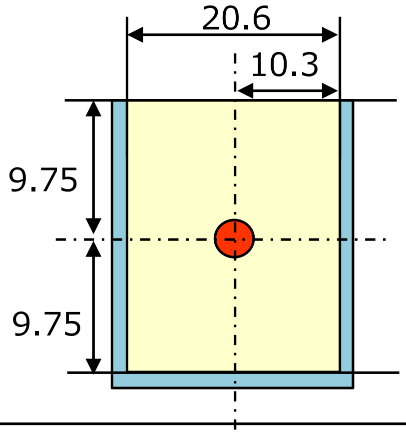
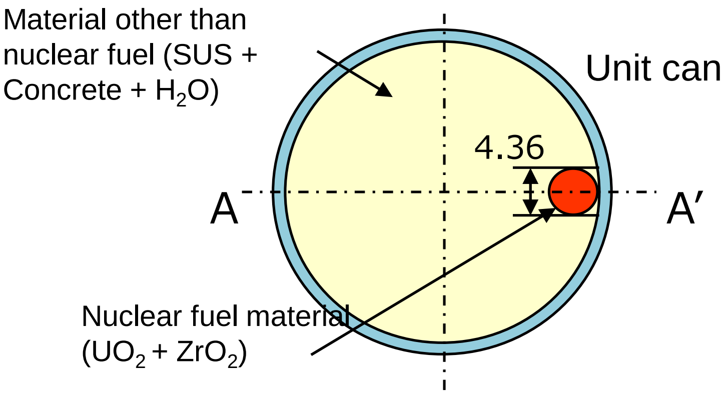
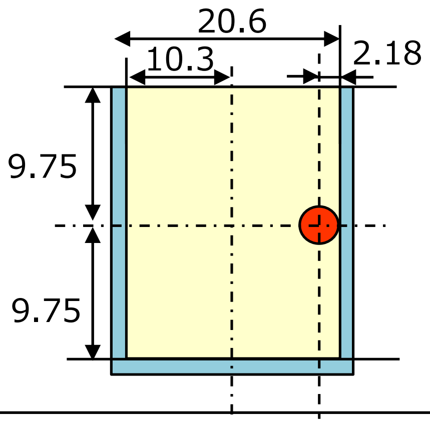
2.1 Analysis conditions - Sensitivity analysis conditions - Uneven distribution model

■ System for analyzing cases of uneven distribution

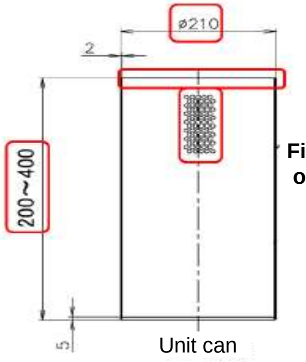
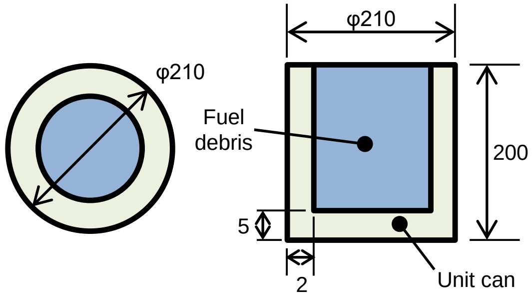
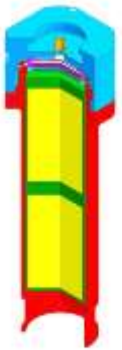
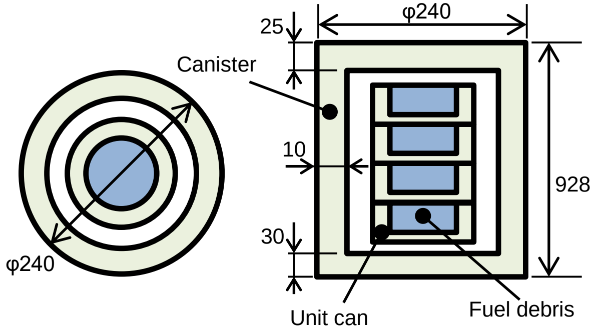
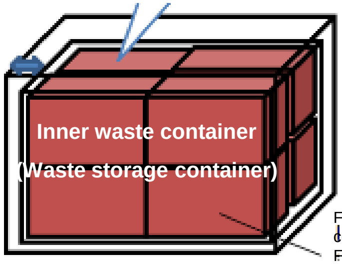
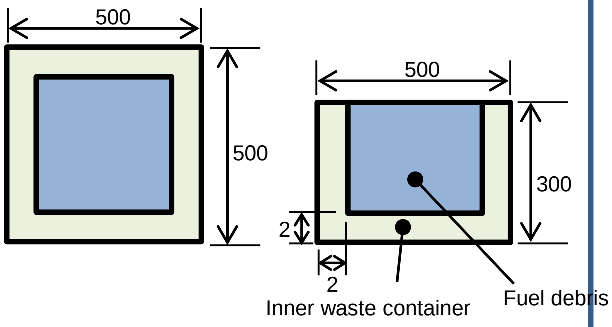
Nuclear fuel material (UO_2 and ZrO_2) and other material was separated and distributed unevenly in the container.

Example: Cases of uneven distribution of MCCI (Molten Core Concrete Interaction) analyzed with the Passive γ, neutron, Active neutron methods: At the center in the horizontal direction (#1-24) and on the exterior surface in the horizontal direction (#1-25)

Unit [cm]

	Top view	Transverse cross-sectional view (A-A')
MCCI at the center in the horizontal direction		
MCCI on the exterior surface in the horizontal direction		

2.1 Analysis conditions - Sensitivity analysis conditions – Shape of the container

Type of container	Shape of container	Evaluation model (Unit: mm)
1. Unit can **φ 210mm × 200mmH** **Plate thickness 2mm** **[Reference: Subsidy project of Development of Fuel Debris Retrieval]**	 **Figure: Proposed structure of the unit can** From the Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March FY2021	 Horizontal cross-section Vertical cross-section
2. Canister **φ 240mm × 928mmH** **Plate thickness 10mm** **[Reference: Subsidy project of Development of Technology for Containing, Transfer and Storage of Fuel Debris]**	 Figure Proposed structure of canister (simple installation structure / inner diameter 220mm / without air supply mechanism) From the "Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget (Development of Technology for Containing, Transfer and Storage of Fuel Debris)" FY2020 Final Report dated June FY2021	 Horizontal cross-section Vertical cross-section
3. Inner waste container **500mm□ × 300mmH** **Plate thickness 2mm** **[Reference: Subsidy Project of Research and Development of Treatment and Disposal of Solid Waste]**	 Figure: Proposed structure of the waste storage container From the Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget (R&D for Treatment and Disposal of Solid Wastes)" FY2019 Accomplishment Report dated December FY2020	 Horizontal cross-section Vertical cross-section

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

③ Analytical simulation

2.1 Analysis conditions

2. 2 Analysis results

2.2.1 Passive neutrons

2.2.2 Passive gamma rays

2.2.3 Active neutrons

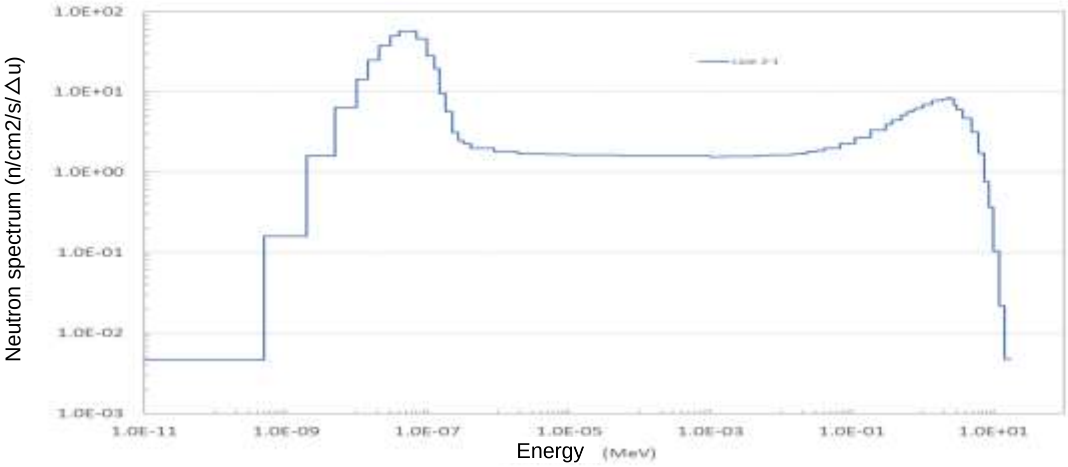
2.2.4 Passive/active neutrons + passive gamma rays

2.2.5 X-ray transmission measurement

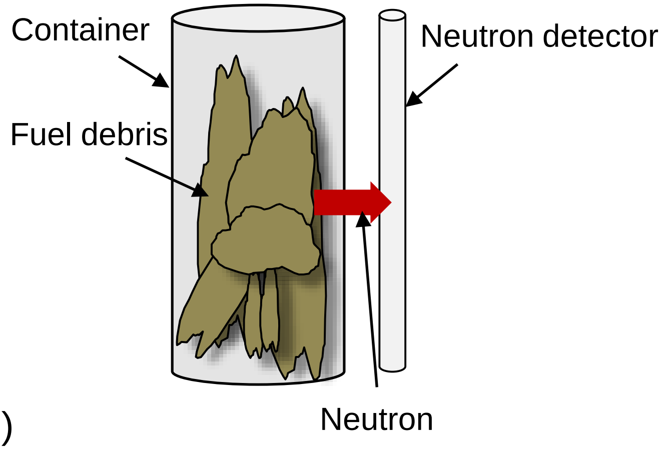
	① Fuel debris composition	Gd content	B content	MOX	② Burn-up	③ FP emission rate	④ Cooling period	⑤ Moisture content	⑥ Filling rate	⑦ Uneven distribution	⑧ Container	⑨ Irradiating radiation source	⑩ Detector
2.2.1 Passive n	No. 37 No. 40 No. 42 No. 45	No. 52 to 54	No. 52 to 54	No. 42	No. 38 No. 43	–	No. 41 No. 46	No. 39 No. 44	No. 37 No. 40 No. 42 No. 45	No. 58 to 62	No. 50	–	No. 47 No. 48 No. 56 No. 72 to 75

2.2.1 Passive neutrons - Measurement concept

- Fuel debris contains nuclides (Cm-244, etc.) that originate from fuel and emit neutrons as a result of spontaneous fission.
- In particular, since Cm-224 predominantly becomes a neutron generating nuclide as combustion progresses, it is assumed that this nuclide will be measured.
- However, the neutron beam becomes relatively small when the neutrons get absorbed due to the moisture contained in fuel debris or due to the neutron absorption material (Gd,B_4C) for maintaining sub-criticality, or when fuel has a low burn-up.
- Thus, the width of the neutron beam that reaches the measuring surface varies depending on the properties of fuel debris.
- Hence, **by determining the width to be measured based on the analytical evaluation, issues such as the measurement range of the detector required for the measurement system, adjustment of the measurement distance or the neutron moderator system, etc. were identified.**



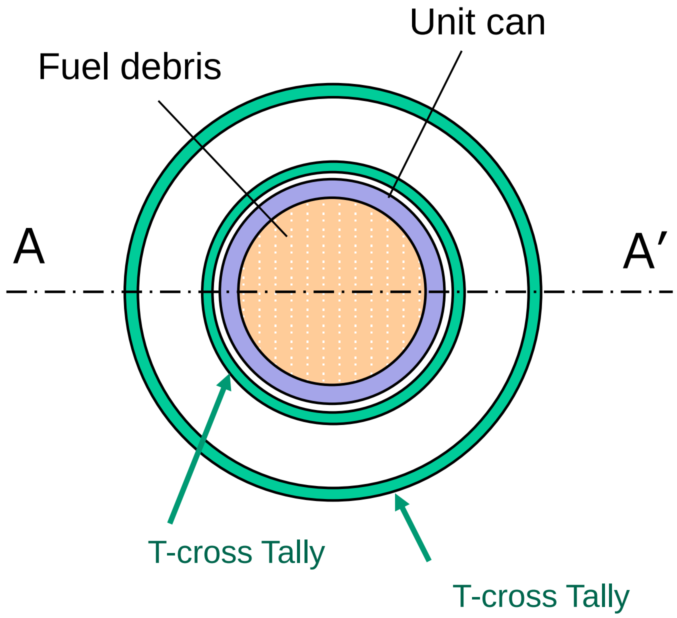
Example of analysis output (Moderator: Polyethylene)



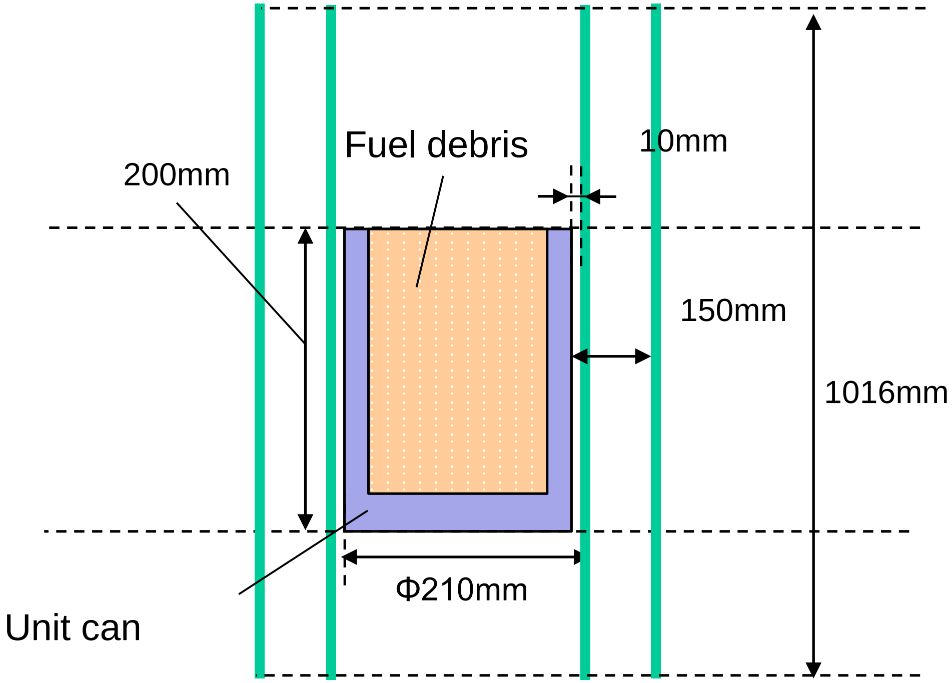
2.2.1 Passive neutrons - Analysis model

In order to make it possible to study the changes in the radiation flux depending on the distance from the container, multiple layers of space were provided for cylindrical detectors at a fixed distance from the container (unit can, etc.).

→ The detectors were selected and placed based on the changes in the radiation flux.
The changes were used for studying shielding, etc.



Analysis model top view



A-A’ cross sectional view

2.2.1 Passive neutrons– Analysis model

Flow of study from beam to the detector installation location, detector response, etc.（PHITS analysis case)

The installation method, etc. of the prospective detector was studied for the base case as per the flow mentioned below.

The prospective detector was selected based on the **detection sensitivity (cps/nv) and γ tolerance dose rate (Gy/h)** → He-3, B-10, etc.

* Detection sensitivity: Sensitivity with respect to neutrons (cps/nv), γ tolerance dose rate: maximum γ dose rate (Gy/h) such that γ/n can be differentiated

Acquisition of beam data

⓪ **Calculation cases for detector simulation** were selected from the energy spectrum of the neutron flux originating from fuel debris.

① **Distance (mm) from the container to the detector or the shielding thickness (mm)** was set based on the dose rate (Gy/h) of the gamma flux originating from fuel debris and the gamma tolerance (Gy/h) of the prospective detector.

② **Moderator thickness (mm)** required for decelerating the fast neutrons was set based on the energy spectrum of the neutron flux originating from fuel debris.

③ **Cadmium thickness (mm)** required for controlling back-scattering of thermal neutrons was set based on the energy spectrum of the neutron flux when a moderator is present.

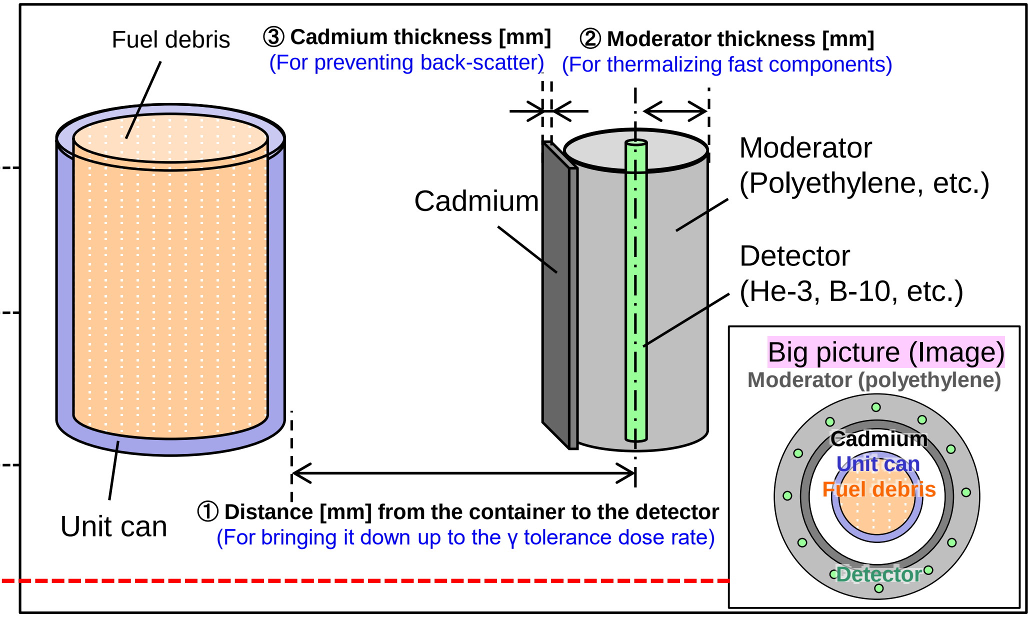
Detector simulation was performed with the above-mentioned conditions for determination (calculation cases, detector position, etc.).
(Big picture image)

Measurement time for each container was studied based on the detector simulation results

Following are 2 **beam data**. Output result of MCNP/PHITS, etc.

- ･Neutron flux originating from fuel debris (no moderator)
- ･ Gamma flux originating from fuel debris

* Neutron / gamma flux = Energy flux Φ(E)[1/cm^2/s] from every neutron / gamma ray



Applicability assessment items

1) Placement of detector … Parameters set for ① to ③ for each individual prospective detector

2) Measurement time … Calculated in terms of count rate (cps) from neutron flux (nv) and detector sensitivity (cps/nv) for each individual prospective detector after the installation of ① to ③
Preliminary calculation of measurement time was performed based on the required statistical parameters.

3) Possibility of detection … Whether or not each individual prospective detector can be used, based on the measurement time limitations

2.2.1 Passive neutrons - Table listing the analysis cases (1/3)

- Considering the analysis conditions described in No. 2-1 as the base case, the analysis conditions that changed to influencing factors (No. 2-2 to 29) were assumed as the sensitivity analysis conditions. **All 29 cases**
- Influencing factors that changed from the base case under the sensitivity analysis conditions are highlighted blue. Here, the parameters that changed in association with the above-mentioned changes are indicated by yellow hatching.

Case No.	Composition inside the container *1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Changed parameter
	Type of fuel debris	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
2-1	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (water content): 1wt% Empty : Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Base case
2-2		**UO_2 : 7.5vol%(25vol%)** **ZrO_2 : 22.5vol%(75vol%)**	30vol%	H_2O (water content): 1wt% Empty : Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (UO_2, ZrO_2)
2-3		**MOX : 30vol%**	30vol%	H_2O (water content): 1wt% Empty : Remainder	**0GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	MOX
2-4		UO_2 : 5vol%(50vol%) ZrO_2 : 5vol%(50vol%)	**10vol%**	H_2O (water content): 1wt% Empty : Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	filling factor
2-5		UO_2 : 25vol%(50vol%) ZrO_2 :25vol%(50vol%)	**50vol%**	H_2O (water content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	filling factor
2-6		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**Gd_2O_3 : 3vol%** H_2O (water content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Gd content
2-7		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**G_d2O_3 : 30vol%** H_2O (water content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Gd content
2-8		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**B_4C : 0.51vol%** H_2O (water content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	B content
2-9		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**B_4C : 10vol%** H_2O (water content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	B content
2-10		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**H_2O (water content): 0.1wt%** Empty : Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Moisture content

2.2.1 Passive neutrons - Table listing the analysis cases (2/3)

Case No.	Composition inside the container *1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Changed parameter
	Type of fuel debris	Within the filling factor		Outside the filling factor						
		Composition	Total (filling factor)							
2-11	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**H_2O (Moisture content): 70vol%** Empty : 0vol%	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Moisture content
2-12		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Burn-up
2-13		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**51GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Burn-up
2-14		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	**30 years**	Uniform	Unit can (Φ210mm x H200mm)	Cooling period
2-15		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	**40 years**	Uniform	Unit can (Φ210mm x H200mm)	Cooling period
2-16		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Center)**	Unit can (Φ210mm x H200mm)	Uneven distribution
2-17		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Exterior surface)**	Unit can (Φ210mm x H200mm)	Uneven distribution
2-18		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	**Canister (Φ220mm x H840mm, Thickness 10mm)**	Container
2-19		**UO_2 : 0.48vol%[3.7kg]** **SUS : 10vol%(95.4vol%)**	**10.48vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	**Waste storage container (Internal container □ Φ500mm x H300mm)**	Container
2-20	Uranium-rich	**UO_2 : 30vol%**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (type)

2.2.1 Passive neutrons - Table listing the analysis cases (3/3)

Case No.	Composition inside the container *1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Changed parameter
	Type of fuel debris	Within the filling factor		Outside the filling factor						
		Composition	Total (Filling factor)							
2-21	Metallic debris	**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (type)
2-22		UO_2 : 15vol%(25vol%) ZrO_2 : 15vol%(25vol%) **SUS : 30vol%(50vol%)**	**60vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (SUS)
2-23	MCCI	**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (type)
2-24		UO_2 : 15vol%(33.3vol%) ZrO_2 : 15vol%(33.3vol%) **Concrete : 15vol%(33.3vol%)**	**45vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (Concrete)
2-25		UO_2 : 15vol%(25vol%) ZrO_2 : 15vol%(25vol%) **Concrete : 30vol%(50vol%)**	**60vol%**	H_2O (Moisture content) 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (Concrete)
2-26	Metallic debris	**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Center)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution
2-27		**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Exterior surface)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution
2-28	MCCI	**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Center)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution
2-29		**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Exterior surface)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution

*1: Percentage inside the container. Percentage, when 100% is considered to be within the filling rate, is mentioned inside parentheses

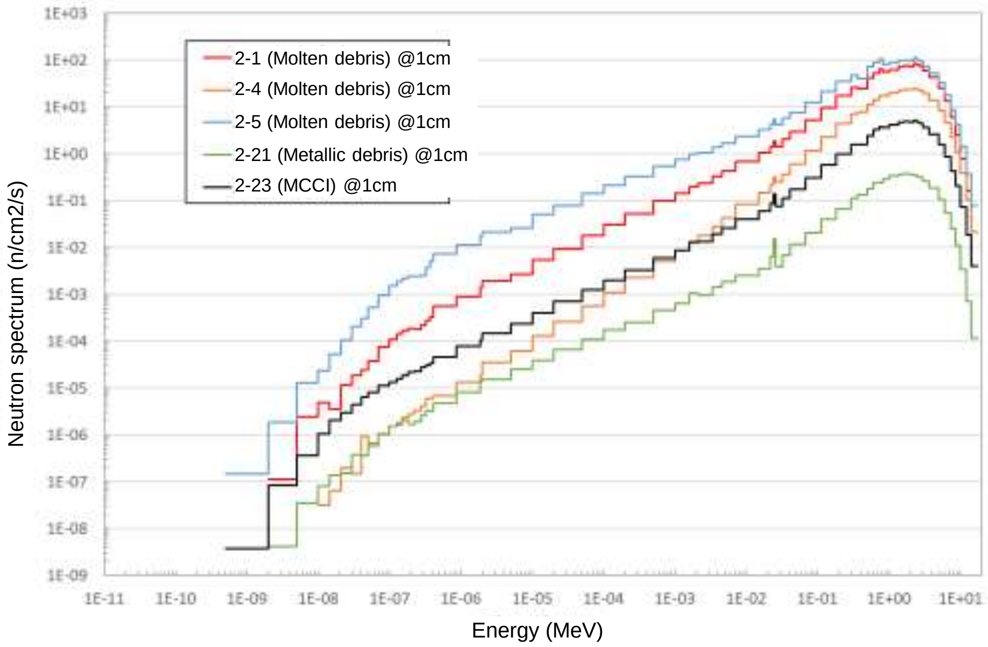
2.2.1 Passive neutrons - Analysis cases

- Sensitivity analysis related to the following analysis conditions was conducted, and the trend with respect to each influencing factor has been consolidated.

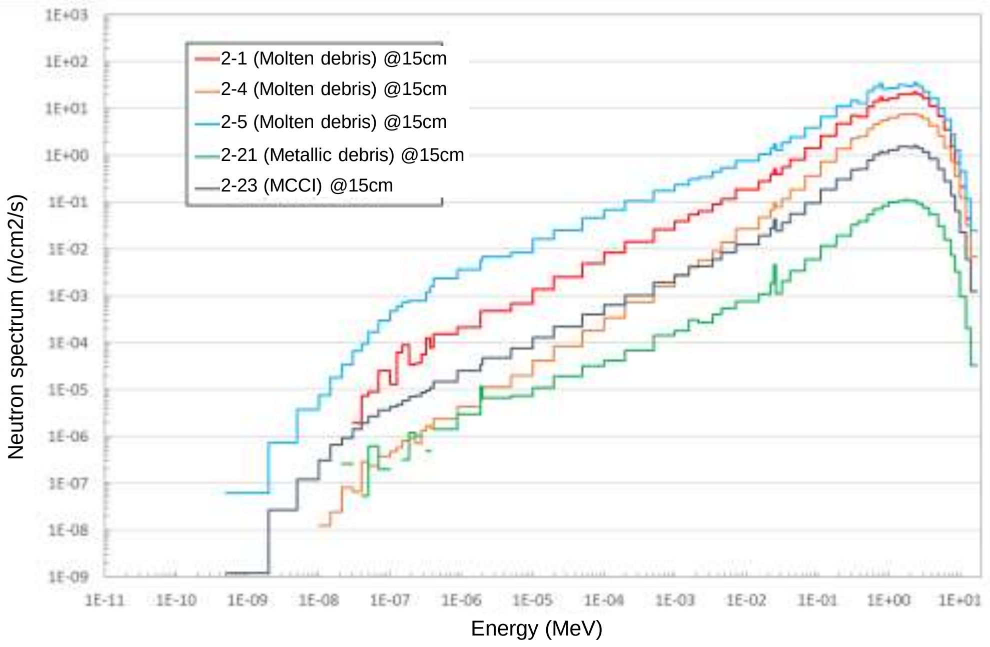
Case		UO_2	ZrO_2	SUS	Concrete	Total (Filling rate)	Moisture content	Burn-up (GWd/t)	Cooling period (Years)	Remarks U content considered as the analysis condition
2-1	Base	15vol%	15vol%	0vol%	-	30vol%	1wt%	23.0	20	8.79kg
2-3	MOX	MOX 30vol%	0vol%	0vol%	-	30vol%	1wt%	0.0	20	17.0kg
2-4	Filling rate (low)	5vol%	5vol%	0vol%	-	10vol%	1wt%	23.0	20	2.93kg
2-5	Filling rate (high)	25vol%	25vol%	0vol%	-	50vol%	1wt%	23.0	20	14.6kg
2-10	Moisture content (low)	15vol%	15vol%	0vol%	-	30vol%	0.1wt%	23.0	20	8.79kg
2-11	Moisture content (high)	15vol%	15vol%	0vol%	-	30vol%	70vol%	23.0	20	8.79kg
2-12	Burn-up (low)	15vol%	15vol%	0vol%	-	30vol%	1wt%	1.3	20	8.98kg
2-13	Burn-up (high)	15vol%	15vol%	0vol%	-	30vol%	1wt%	51.0	20	8.58kg
2-14	Cooling period	15vol%	15vol%	0vol%	-	30vol%	1wt%	23.0	30	8.79kg
2-15	Cooling period	15vol%	15vol%	0vol%	-	30vol%	1wt%	23.0	40	8.79kg
2-21	Metallic debris	0.075vol%	0.075vol%	29.85vol%	-	30vol%	1wt%	23.0	20	0.04kg
2-23	MCCI debris	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	1wt%	23.0	20	0.615kg
2-24	MCCI debris	15vol%	15vol%	0vol%	15vol%	45vol%	1wt%	23.0	20	8.79kg
2-25	MCCI debris	15vol%	15vol%	0vol%	30vol%	60vol%	1wt%	23.0	20	8.79kg

2.2 Analysis results

2.2.1 Passive neutrons - Analysis results [Fuel debris type]



Neutron spectrum at 1cm of the container surface

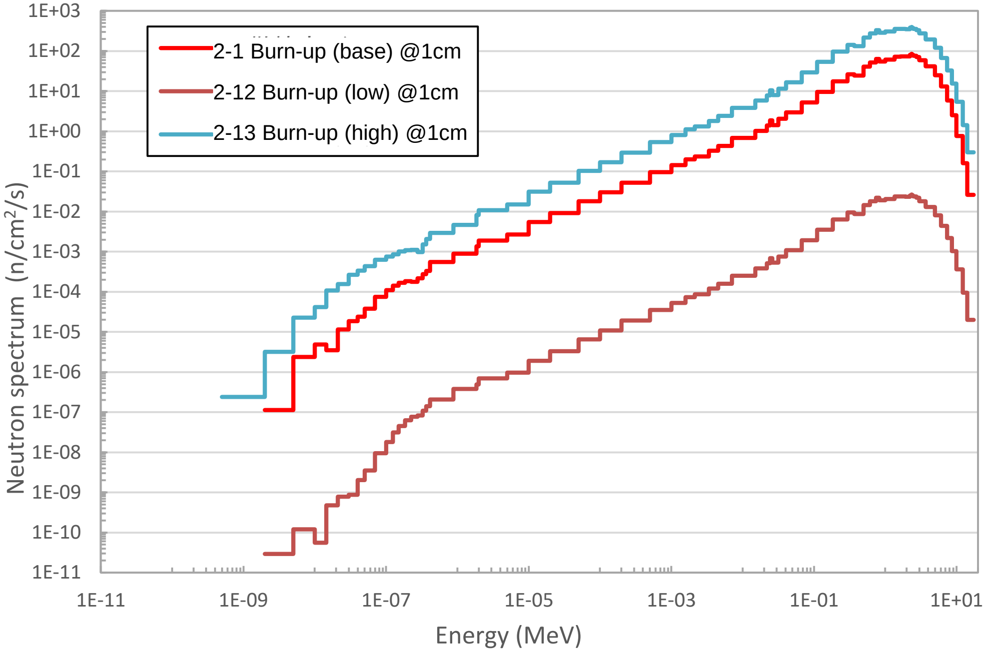


Neutron spectrum at 15cm of the container surface

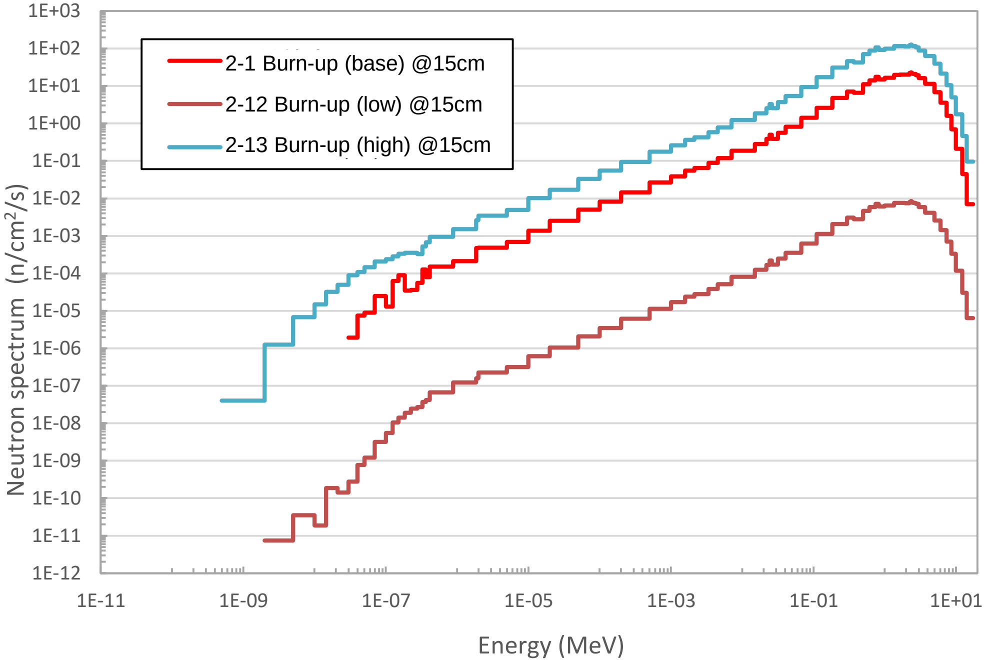
Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate
2-1	**Molten debris**	**15vol% (50vol%)**	**15vol% (50vol%)**	0vol%	0vol%	**30vol%**
2-4		**5vol% (50vol%)**	**5vol% (50vol%)**	0vol%	0vol%	**10vol%**
2-5		**25vol% (50vol%)**	**25vol% (50vol%)**	0vol%	0vol%	**50vol%**
2-21	**Metallic debris**	**0.075vol% (0.25vol%)**	**0.075vol% (0.25vol%)**	**29.85vol% (99.5vol%)**	0vol%	30vol%
2-23	**MCCI**	**1.05vol% (3.5vol%)**	**1.05vol% (3.5vol%)**	**7.2vol% (24vol%)**	**20.7vol% (69vol%)**	30vol%

→ As compared to molten debris, the shape of the neutron spectrum of MCCI and metallic debris indicated an increase in thermal neutron flux.

2.2.1 Passive neutrons - Analysis results [Burn-up]



Neutron spectrum at 1cm of the container surface

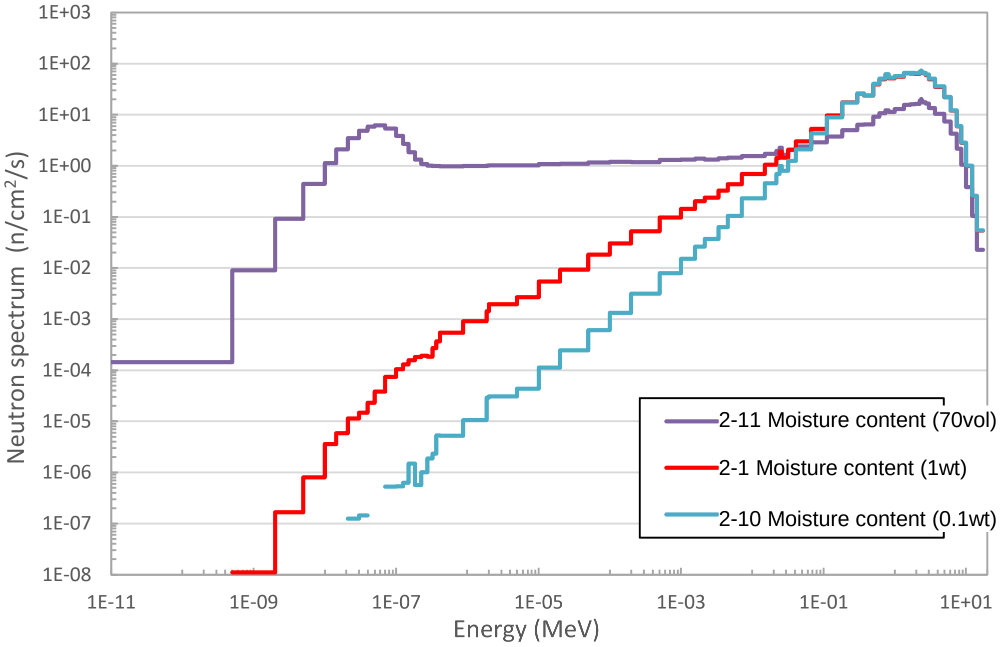


Neutron spectrum at 15cm of the container surface

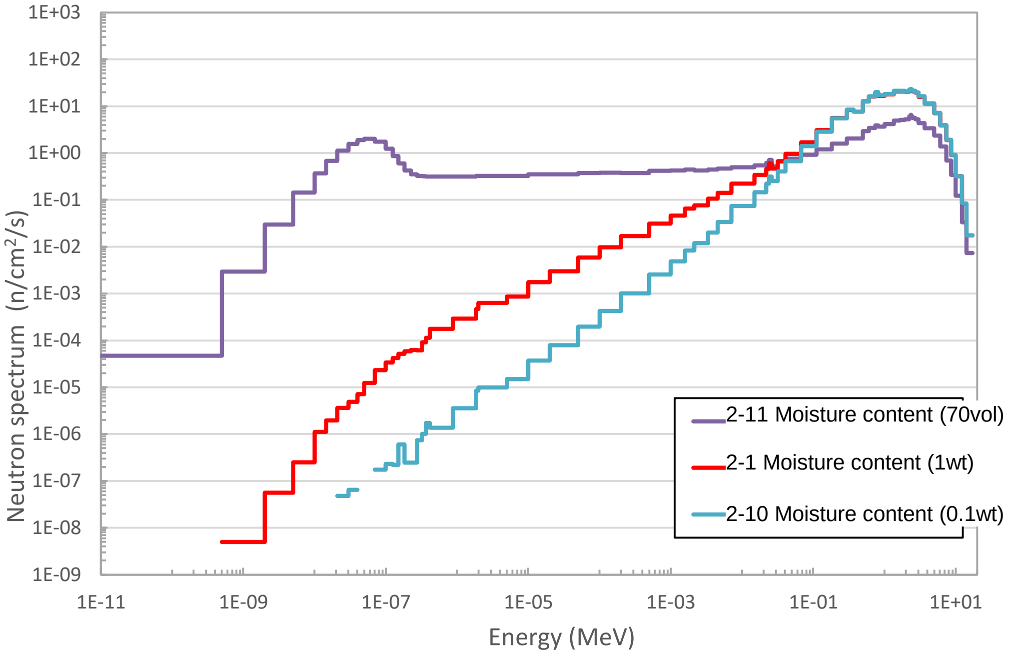
→ The intensity of neutron beams changed depending on burn-up, but the shape of the neutron spectrum did not change.

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate	Burn-up (GWd/t)
2-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	**23.0**
2-12		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	**1.3**
2-13		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	**51.0**

2.2.1 Passive neutrons - Analysis results [Moisture content]



Neutron spectrum at 1cm of the container surface

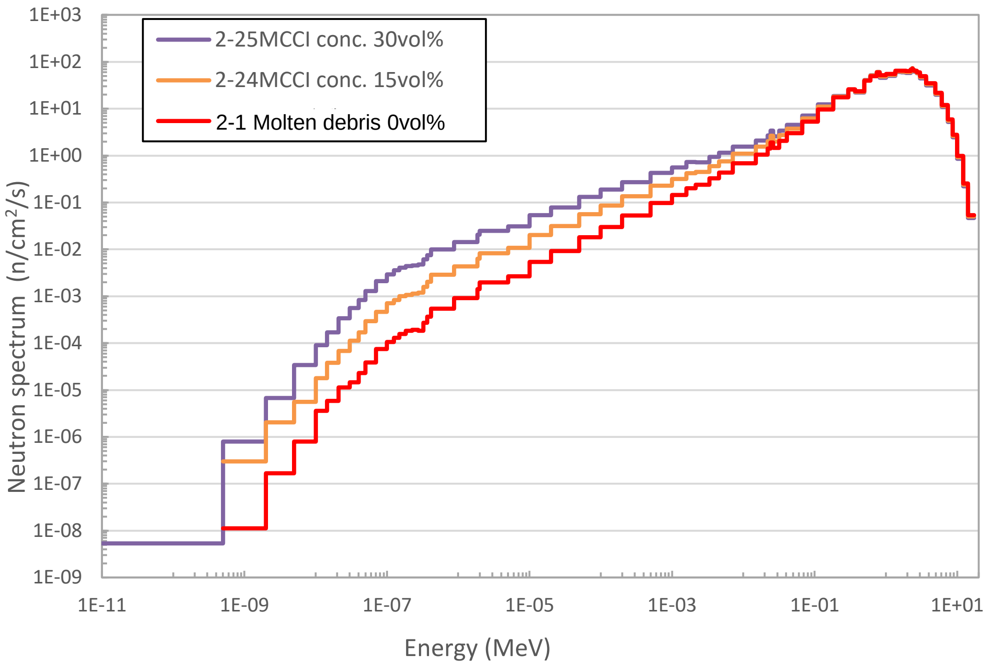


Neutron spectrum at 15cm of the container surface

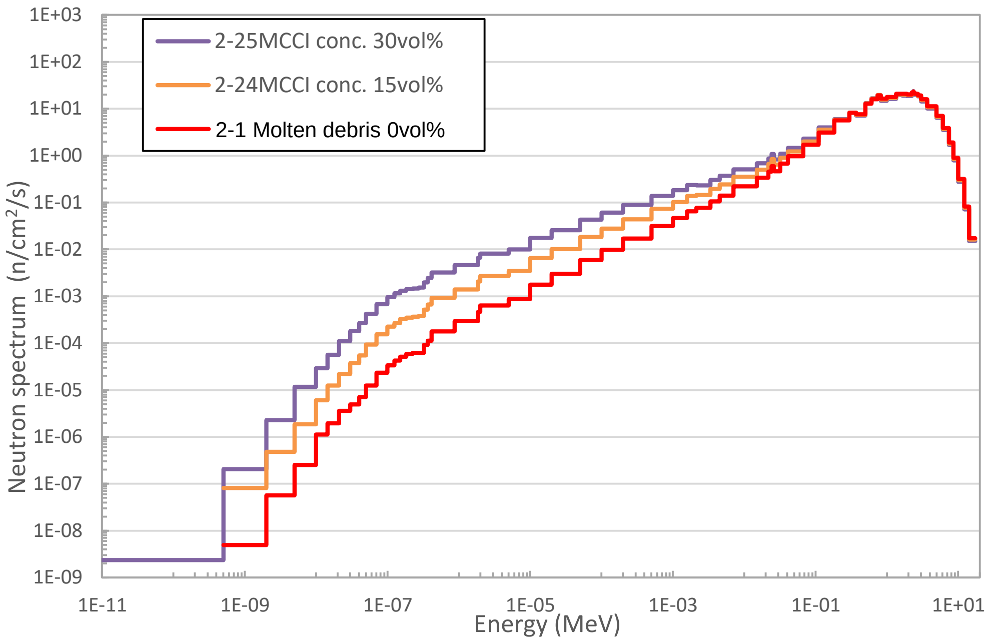
→ **As moisture content increased, fast neutron flux decreased and thermal neutron flux increased.**

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate	Moisture content
2-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	**1wt%**
2-10		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	**0.1wt%**
2-11		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	**70vol%**

2.2.1 Passive neutrons - Analysis results [MCCI]



Neutron spectrum at 1cm of the container surface



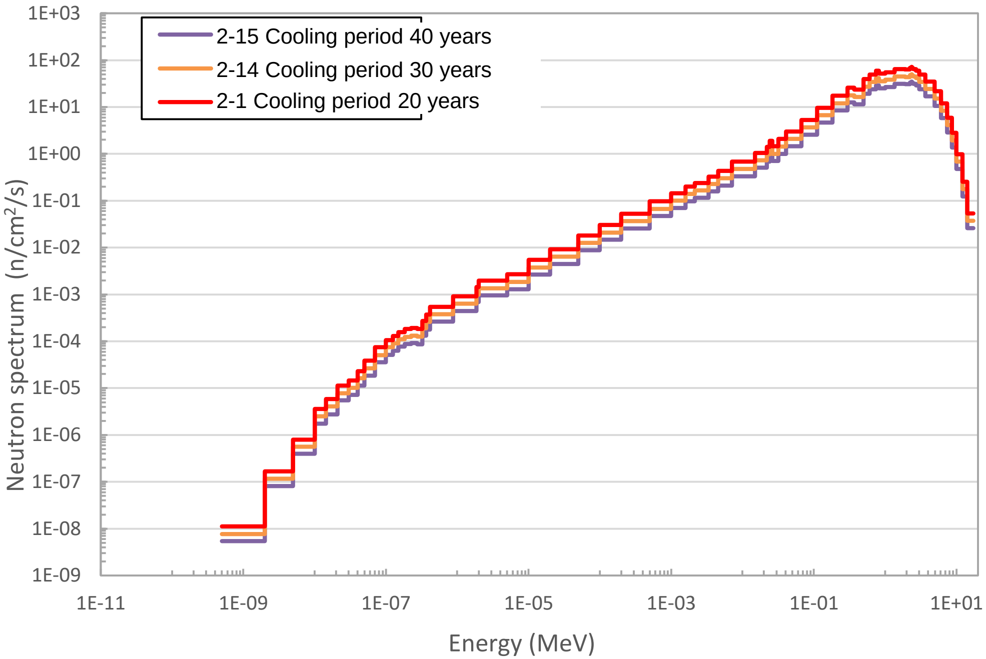
Neutron spectrum at 15cm of the container surface

→ As concrete increased, thermal neutron flux increased.

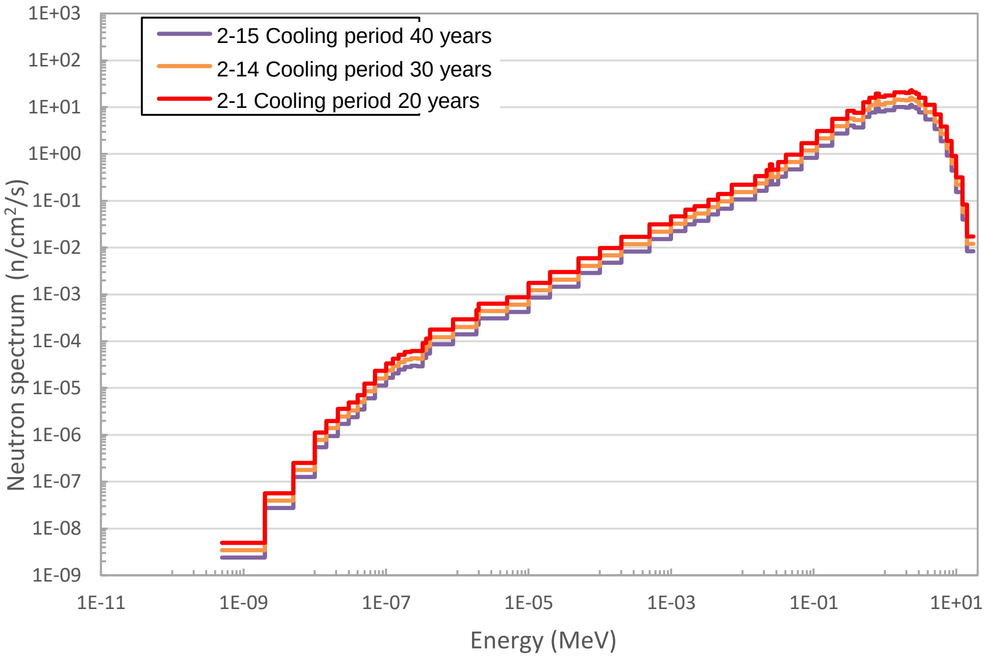
Case No.	Type of fuel debris	UO$_2$	ZrO$_2$	SUS	Concrete	Filling rate
2-1	**Molten debris**	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	**30vol%**
2-24	**MCCI**	15vol% (33vol%)	15vol% (33vol%)	0vol%	**15vol% (33vol%)**	**45vol%**
2-25	**MCCI**	15vol% (25vol%)	15vol% (25vol%)	0vol%	**30vol% (50vol%)**	**60vol%**

2.2 Analysis results

2.2.1 Passive neutrons - Analysis results [Cooling period]



Neutron spectrum at 1cm of the container surface



Neutron spectrum at 15cm of the container surface

Based on the dose rate obtained from the results of this analysis and the results of passive gamma rays analysis, the study process mentioned in No. 32 ⓪ to ③ is planned to be implemented.

→ **The intensity of neutron beams changed depending on cooling period, but the shape of the neutron spectrum did not change.**

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate	Cooling period [Years]
2-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	20
2-14		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	30
2-15		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	40

→ Fast neutrons and thermal neutrons (integrated value) flux was evaluated based on the above results.

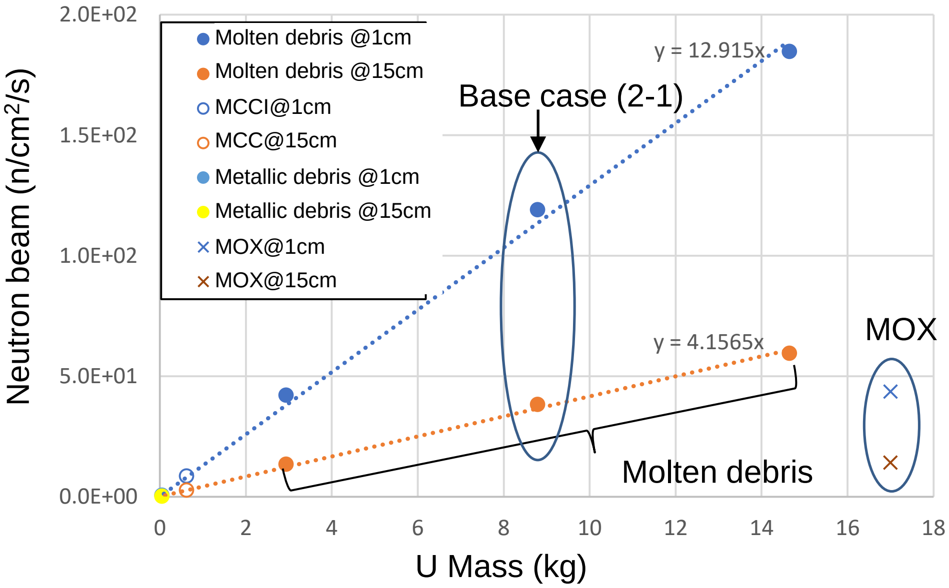
2.2.1 Passive neutrons - Analysis results [U Mass]

Fast neutrons (0.5MeV to 5MeV)

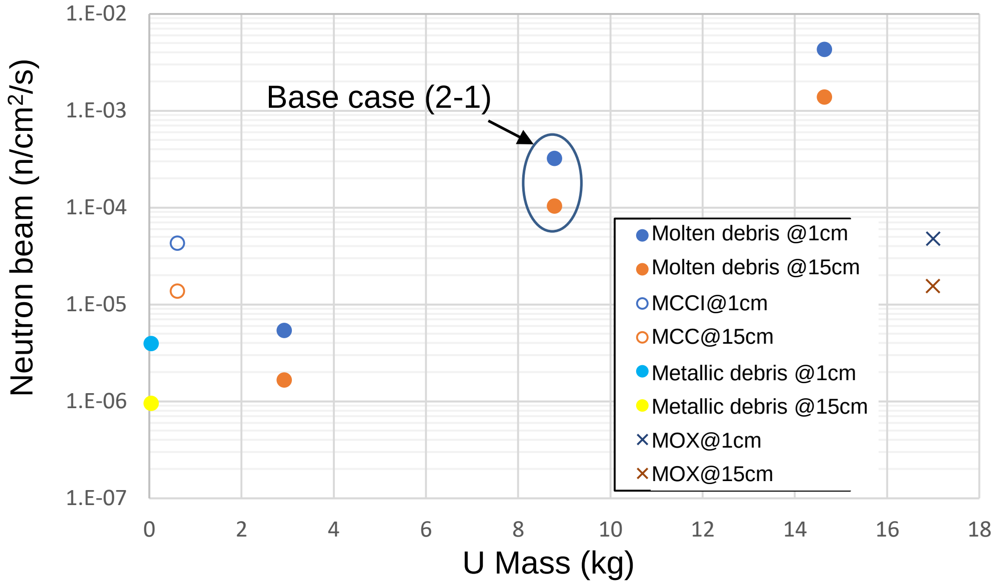
Case No.	Type of fuel debris	U Mass (kg)	1cm ($n/cm^2/s$)	15cm ($n/cm^2/s$)
2-1	Molten debris	8.786	1.19E+02	3.83E+01
2-4	Molten debris	2.929	4.21E+01	1.35E+01
2-5	Molten debris	14.643	1.85E+02	5.95E+01
2-21	Metallic debris	0.044	3.00E—02	6.37E—02
2-23	MCCI	0.615	8.57E+00	2.75E+00
2-3	MOX	17.0	4.36E+01	1.40E+01

Thermal neutrons (0.4eV or less)

Case No.	U Mass (kg)	1cm ($n/cm^2/s$)	15cm ($n/cm^2/s$)
2-1	8.786	3.20E-04	1.03E-04
2-4	2.929	5.37E-06	1.66E-06
2-5	14.643	4.28E-03	1.38E-03
2-21	0.044	3.94E-06	9.53E-07
2-23	0.615	4.28E-05	1.37E-05
2-3	17.0	4.78E-05	1.54E-05



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



Thermal neutrons (Integrated value of 0.4eV or less)

→ **Fast neutron flux was almost directly proportional to the U mass in the case of molten debris, MCCI and metallic debris. As MOX was almost unburnt, less number of neutrons were generated. Hence it is not considered to be directly proportional to U mass.**

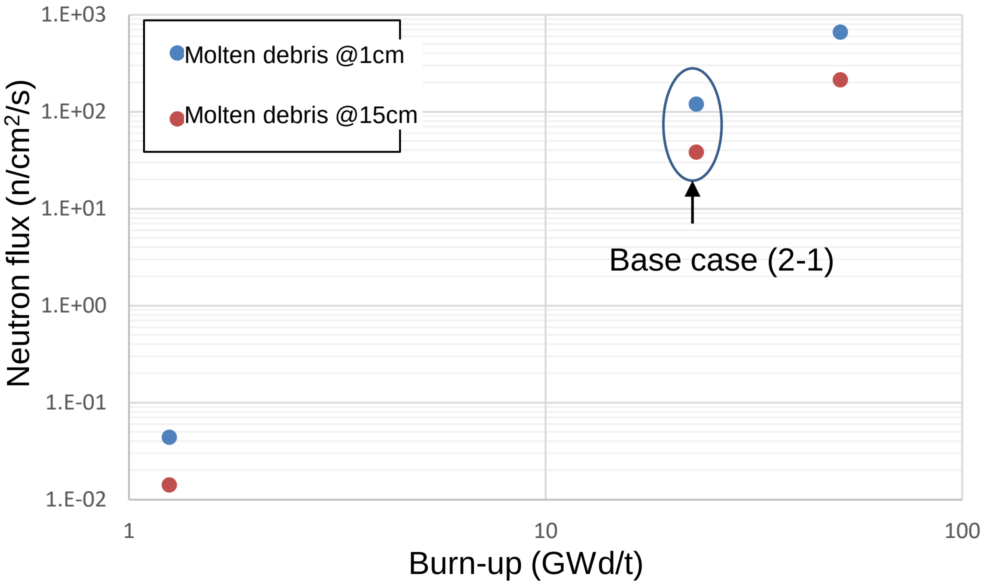
2.2.1 Passive neutrons - Analysis results [Burn-up]

Fast neutrons (0.5MeV to 5MeV)

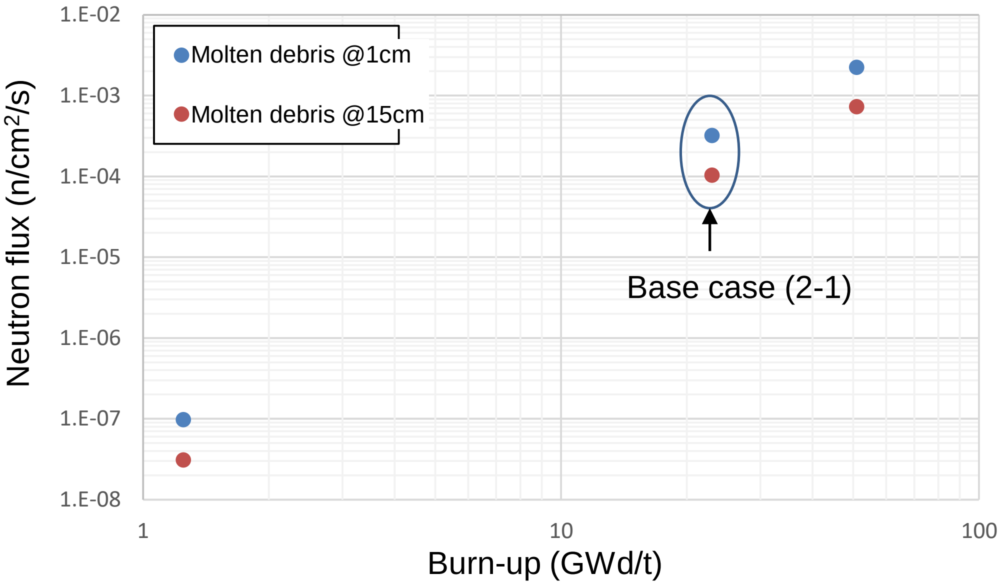
Case No.	Type of fuel debris	Burn-up (GWd/t)	1cm (n/cm²/s)	15cm (n/cm²/s)
2-12	Molten debris	1.3	4.38E-02	1.41E-02
2-1	Molten debris	23.0	1.19E+02	3.83E+01
2-13	Molten debris	51.0	6.63E+02	2.13E+02

Thermal neutrons (0.4eV or less)

Case No.	Burn-up (GWd/t)	1cm (n/cm²/s)	15cm (n/cm²/s)
2-12	1.3	9.69E-08	3.09E-08
2-1	23.0	3.20E-04	1.03E-04
2-13	51.0	2.23E-03	7.29E-04



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



Thermal neutrons (Integrated value of 0.4eV or less)

→ The neutron flux leaking from the container largely changed by orders of magnitude depending on the burn-up.

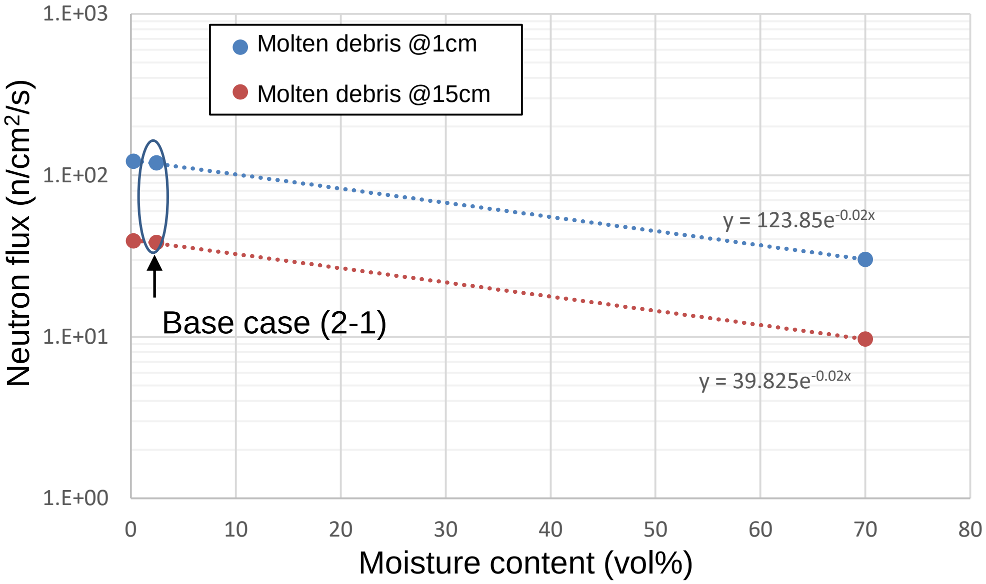
2.2.1 Passive neutrons - Analysis results [Moisture content]

Fast neutrons (0.5MeV to 5MeV)

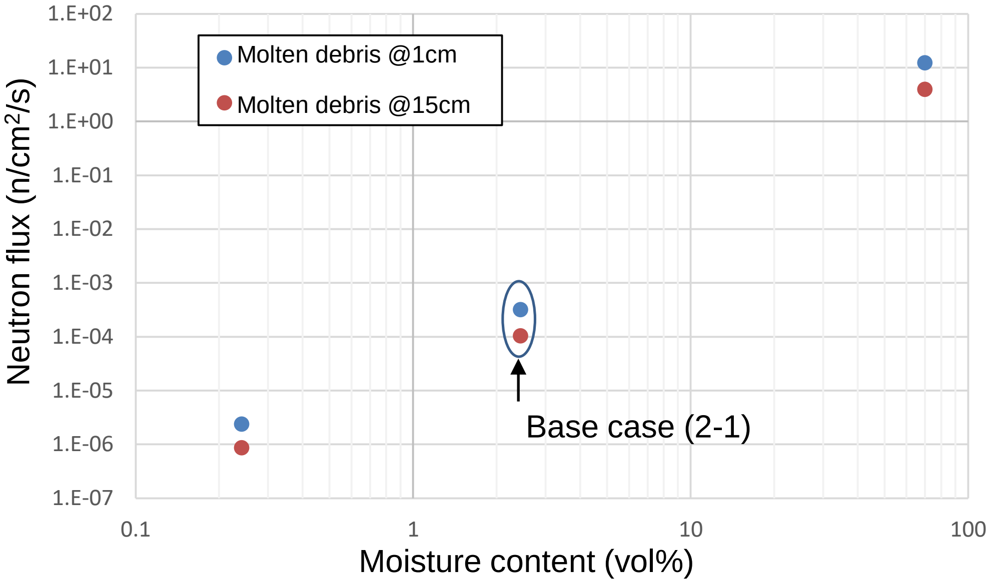
Case No.	Type of fuel debris	Moisture content (vol%)	1cm ($n/cm^2/s$)	15cm ($n/cm^2/s$)
2-10	Molten debris	0.24	1.22E+02	3.92E+01
2-1	Molten debris	2.44	1.19E+02	3.83E+01
2-11	Molten debris	70.0	3.01E+01	9.64E+00

Thermal neutrons (0.4eV or less)

Case No.	Moisture content (vol%)	1cm ($n/cm^2/s$)	15cm ($n/cm^2/s$)
2-10	0.24	2.37E-06	8.68E-07
2-1	2.44	3.20E-04	1.03E-04
2-11	70.0	1.22E+01	3.93E+00



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



Thermal neutrons (Integrated value of 0.4eV or less)

→ **Along with the increase in moisture content, the fast neutron flux decreased, and the thermal neutron flux increased largely by orders of magnitude.**

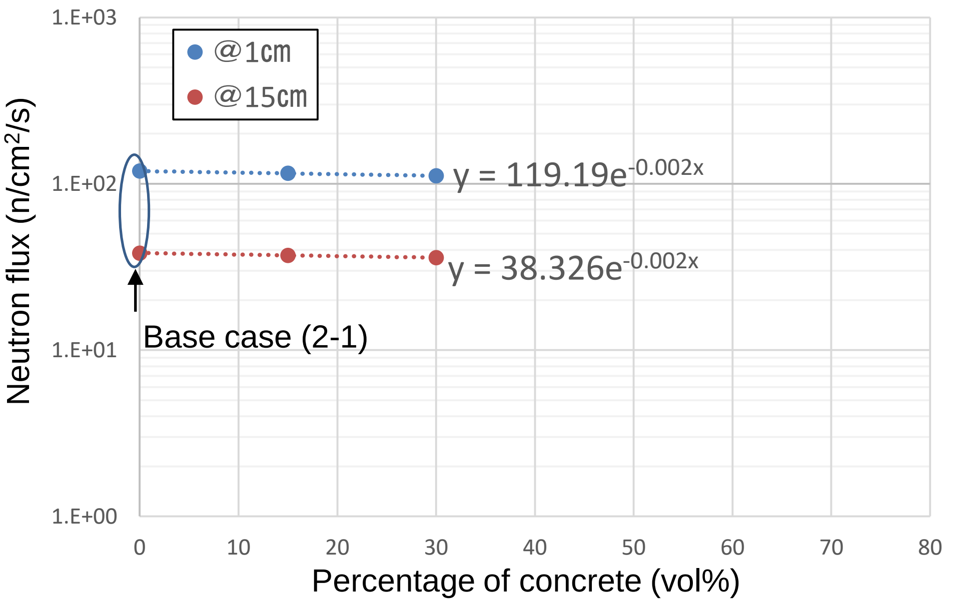
2.2.1 Passive neutrons - Analysis results [MCCI]

Fast neutrons (0.5MeV to 5MeV)

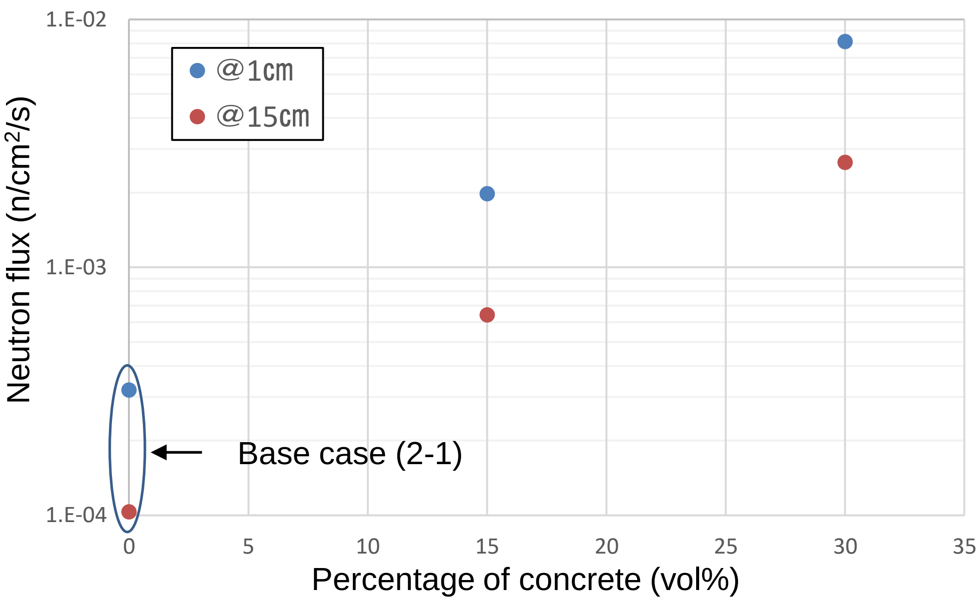
Case No.	Type of fuel debris	Percentage of concrete (vol%)	1cm ($n/cm^2/s$)	15cm ($n/cm^2/s$)
2-1	Molten debris	0	1.19E+02	3.83E+01
2-24	MCCI	15	1.15E+02	3.72E+01
2-25	MCCI	30	1.12E+02	3.59E+01

Thermal neutrons (0.4eV or less)

Case No.	Percentage of concrete (vol%)	1cm ($n/cm^2/s$)	15cm ($n/cm^2/s$)
2-1	0	3.20E-04	1.03E-04
2-24	15	1.98E-03	6.44E-04
2-25	30	8.15E-03	2.65E-03



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



Thermal neutrons (Integrated value of 0.4eV or less)

→ **Along with the increase in percentage of concrete, even though there was just a slight decrease in the fast neutron flux, the thermal neutron flux increased by orders of magnitude.**

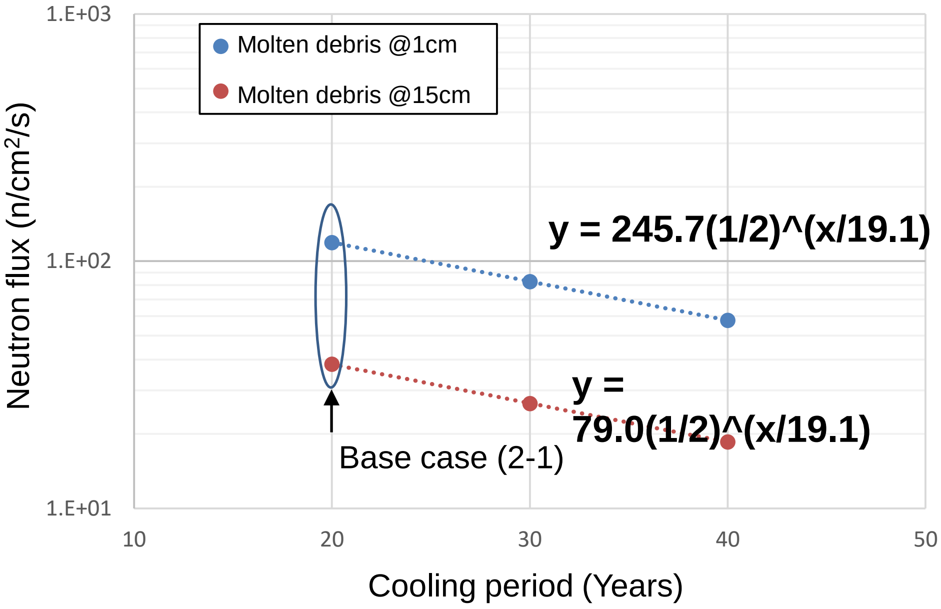
2.2.1 Passive neutrons - Analysis results [Cooling period]

Fast neutrons (0.5MeV to 5MeV)

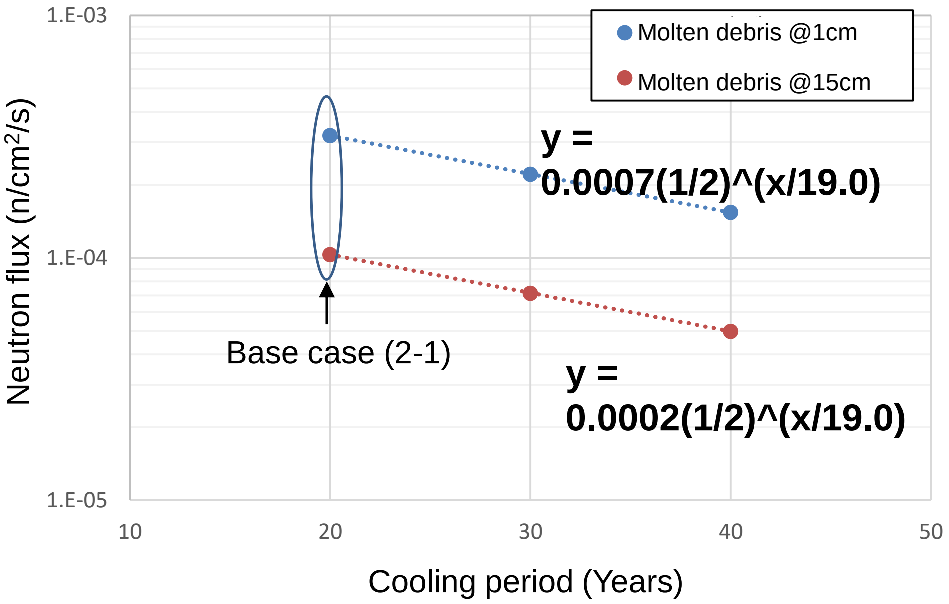
Case No.	Type of fuel debris	Cooling period (Years)	1cm (n/cm²/s)	15cm (n/cm²/s)
2-1	Molten debris	20	1.19E+02	3.83E+01
2-14	Molten debris	30	8.26E+01	2.66E+01
2-15	Molten debris	40	5.77E+01	1.86E+01

Thermal neutrons (0.4eV or less)

Case No.	Cooling period (Years)	1cm (n/cm²/s)	15cm (n/cm²/s)
2-1	20	3.20E-04	1.03E-04
2-14	30	2.21E-04	7.15E-05
2-15	40	1.54E-04	4.98E-05



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



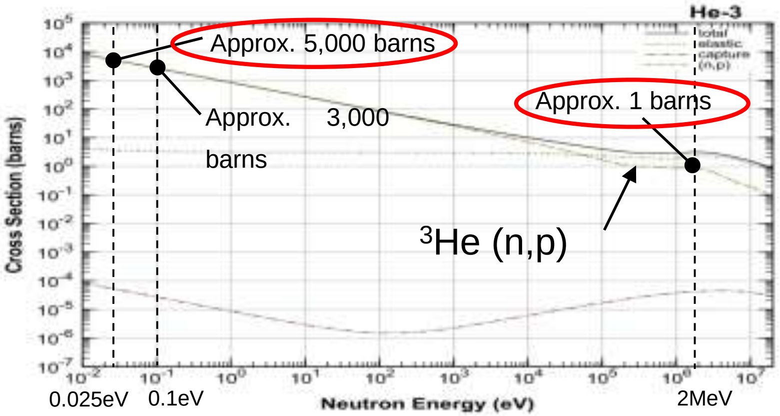
Thermal neutrons (Integrated value of 0.4eV or less)

→ **The half-life of the neutron flux was 19.1 years which is slightly longer than the α decay half-life of Cm-244 which is the main neutron radiation source.**

2.2.1 Passive neutrons - Analysis results

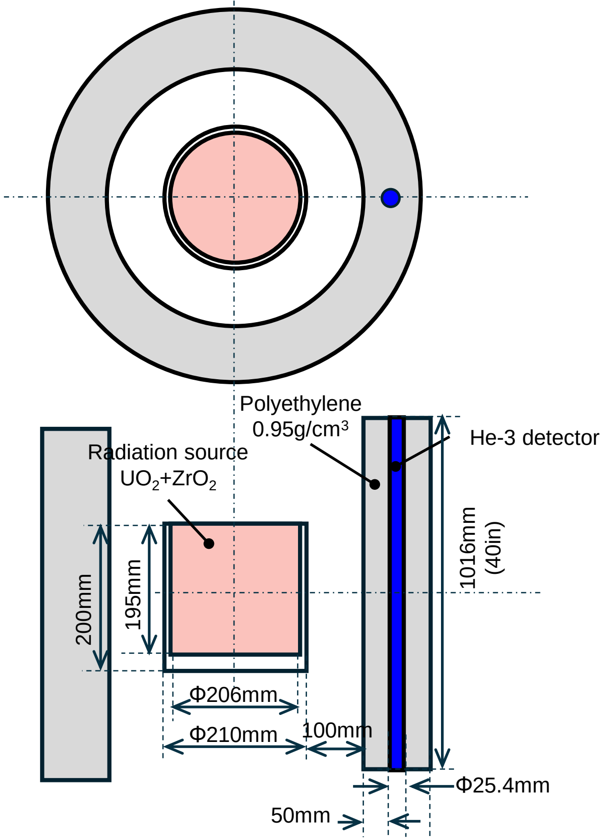
Study of a representative detector, measurement system (for identifying issues) (1/2)

- representative detector : Helium 3 proportional counter
- Size and shape of detector : 1 inch cylindrical detector, length 40 inches
- Moderator : High density polyethylene
- Distance up to the detector : 150mm
  (From the outer surface of the unit can
  to the outer surface of the detector)

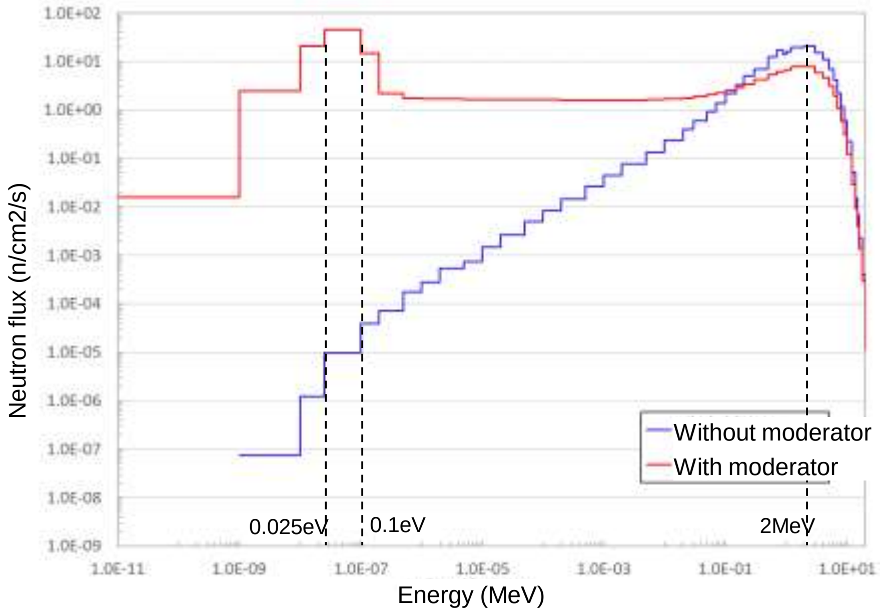


He-3 cross sectional area (From JENDL4.0)

<Analysis model>



<Detector response>



Neutron flux (Radiation source: Trial calculation case, detector distance 15cm)

→ By installing polyethylene, measurement efficiency of He-3 detector increased several 1000 times.

2.2.1 Passive neutrons - Analysis results

Study of a representative detector, measurement system (for identifying issues) (2/2)

Relation between U content and incident beams

***Burn-up constant at 23GWd/t**

<Helium 3 proportional counter Incident beam>

- As a result of the analysis in which only the amount of Uranium was changed, it was found that the amount of Uranium and all incident beams have a positive correlation.
- Even under conditions wherein polyethylene is present, Uranium content and incident beams were proportionate.

→ However, the inclination is believed to largely change with variations in other parameters such as burn-up of fuel debris, etc. (Refer to No. 43)

- The impact of the self-shielding effect caused by changes in the density (filling rate) of fuel debris did not appear significantly in any of the incident beams.

2.2.1 Passive neutrons – Other sensitivity analyses (1/8)

The sensitivity of the neutron count rate was studied with respect to the following influencing factors:

- Neutron absorption material
- Configuration of container
- Fuel debris composition (SUS)

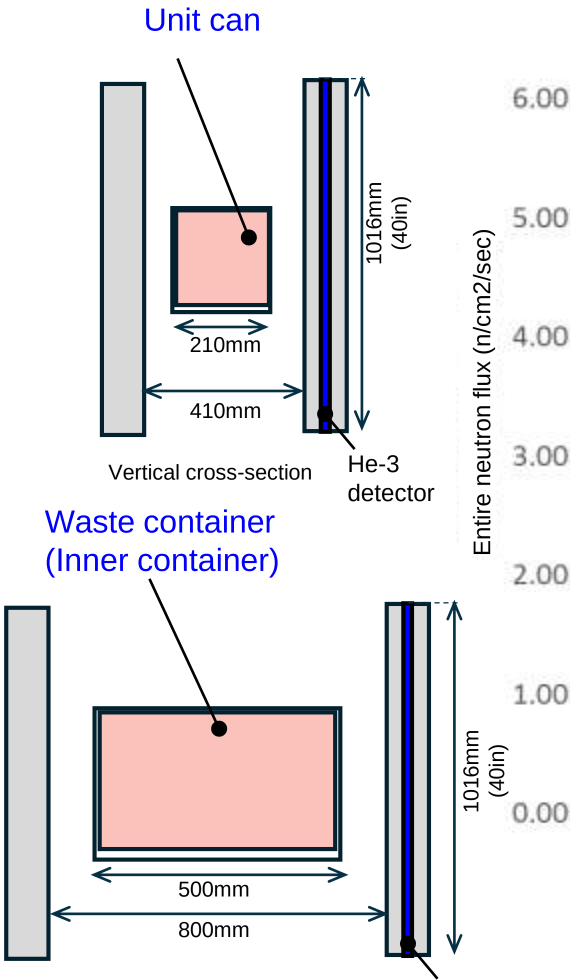
Case No.	UO_2	ZrO_2	SUS	Total (Filling rate)	Other conditions	Remarks
2-1	15vol%	15vol%	0vol%	30vol%	-	Base
2-2	7.5vol%	22.5vol%	0vol%	30vol%	-	Molten debris
2-6	0vol%	15vol%	0vol%	30vol%	Gd_2O_3: Moderate	Gd content
2-7	15vol%	15vol%	0vol%	30vol%	Gd_2O_3: High	
2-8	15vol%	15vol%	0vol%	30vol%	B_4C: Moderate	B content
2-9	15vol%	15vol%	0vol%	30vol%	B_4C: High	
2-18	15vol%	15vol%	0vol%	30vol%	Canister (Φ220mm × H840mm)	Shape of container
2-19	15vol%	15vol%	0vol%	30vol%	Waste storage container	
2-20	30vol%	0vol%	0vol%	30vol%	-	Molten debris
2-21	0.075vol%	0.075vol%	29.85vol%	30vol%	-	Metallic debris
2-22	15vol%	15vol%	30vol%	60vol%	-	Metallic debris

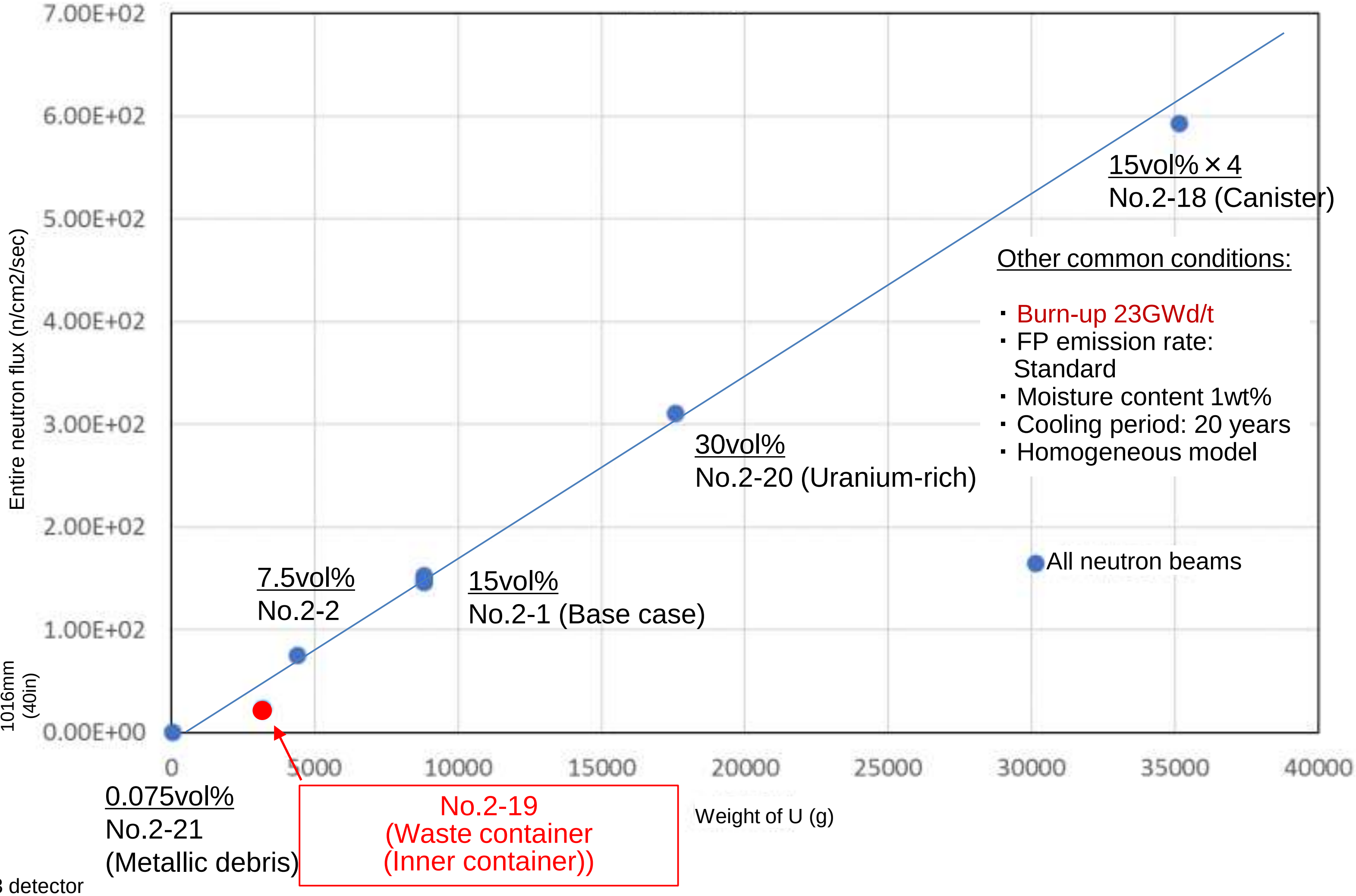
2.2.1 Passive neutrons – Other sensitivity analyses (2/8)

Waste storage container (Inner container)（No. 2 - 19）

- **Impact due to difference in shape of container**

→ If the container is bigger than the unit can, the distance up to the detector increases. Hence incident beams decrease.





Other common conditions:

- Burn-up 23GWd/t
- FP emission rate: Standard
- Moisture content 1wt%
- Cooling period: 20 years
- Homogeneous model

2.2.1 Passive neutrons – Other sensitivity analyses (3/8)

- Impact depending on the amount of neutron absorption material (Gadolinium, Boron) contained

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate	Neutron absorption material	Remarks
2-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	-	Base
2-6		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	Gd_2O_3: 3vol%	Gd content: Moderate
2-7		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	Gd_2O_3: 30vol%	Gd content: High
2-8		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	B_4C: 0.51vol%	B content: Moderate (Equivalent to actual conditions: Set based on the core average of the amount of B mixed before the accident)
2-9		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	B_4C: 10vol%	B content: High

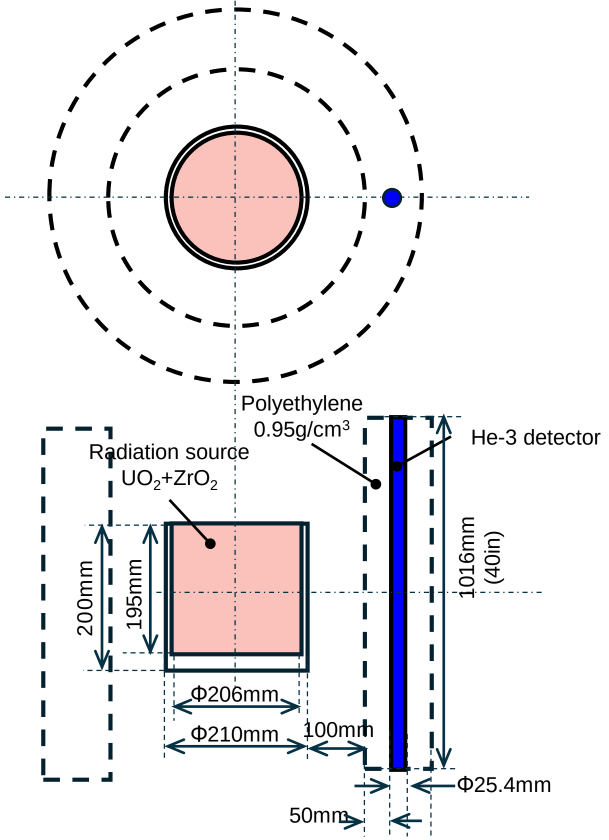
Other common conditions:

・Burn-up 23GWd/t
・FP (fission product) emission rate: Standard
・Moisture content 1wt%
・Homogeneous model
・Container: Unit can

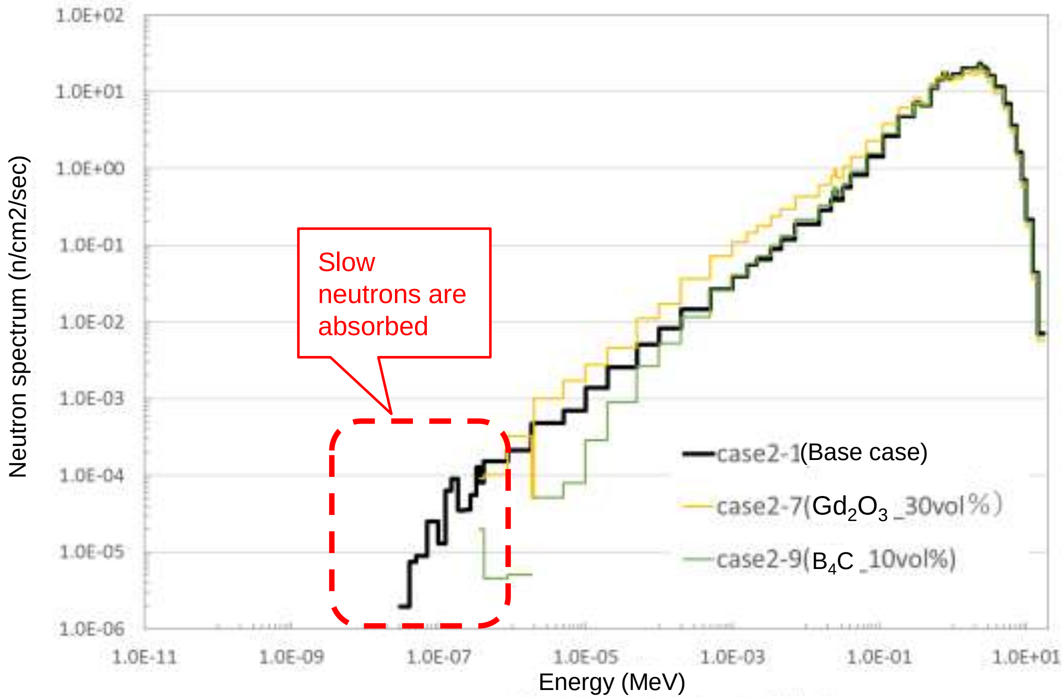
2.2.1 Passive neutrons – Other sensitivity analyses (4/8)

Relation between the amount of neutron absorption material (Gadolinium, Boron) contained and the incident beams (1/3)

<Analysis model> [Without polyethylene]



<Helium 3 proportional counter Incident beam>



Slow neutrons are absorbed

Neutron spectrum at the location of the detector

→・**In cases with neutron absorption material, as slow neutrons (<1eV) got absorbed, they did not appear in the spectrum.**

・Since the cross-sectional area of Gd is large in the MeV region as well, the neutron flux between the fast and slow neutrons is greater than the base case.

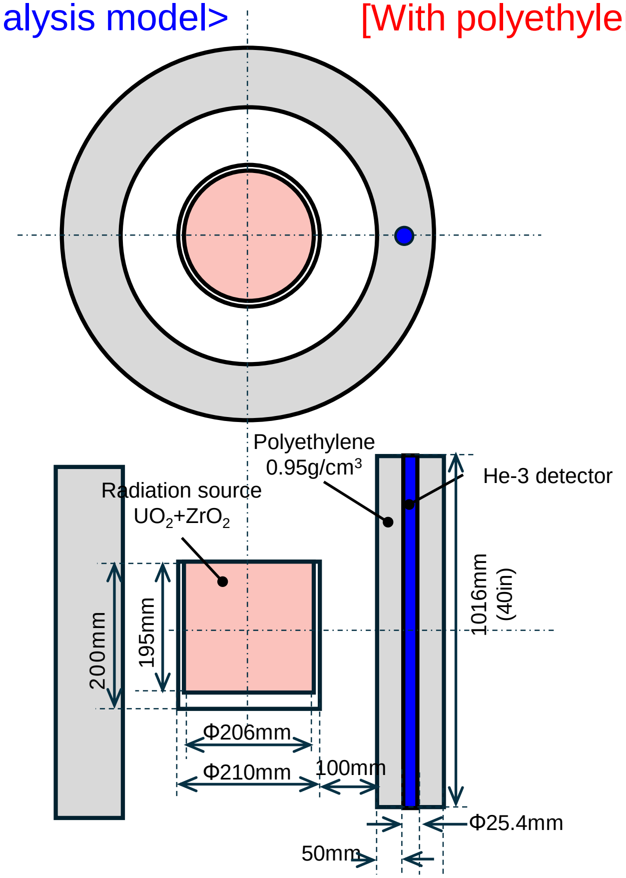
・Since the absorption cross section of B in the KeV region is large, the neutron flux is lower than even the base case.

2.2.1 Passive neutrons – Other sensitivity analyses (5/8)

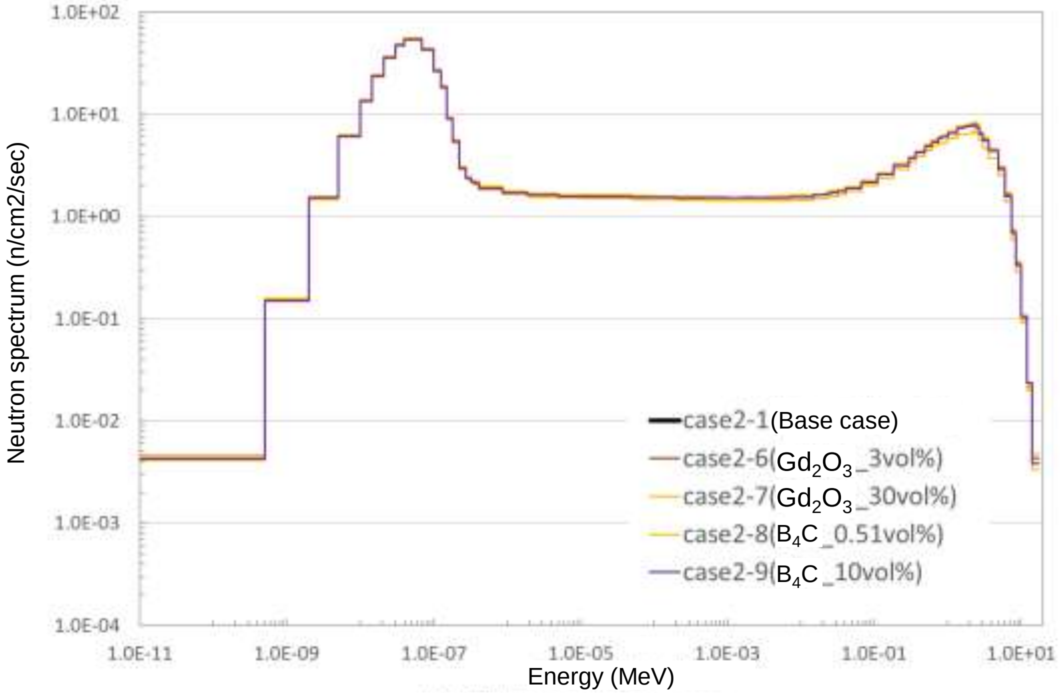
Relation between the amount of neutron absorption material (Gadolinium, Boron) contained and the incident beams (2/3)

<Analysis model>

[With polyethylene]



<Helium 3 proportional counter Incident beam>



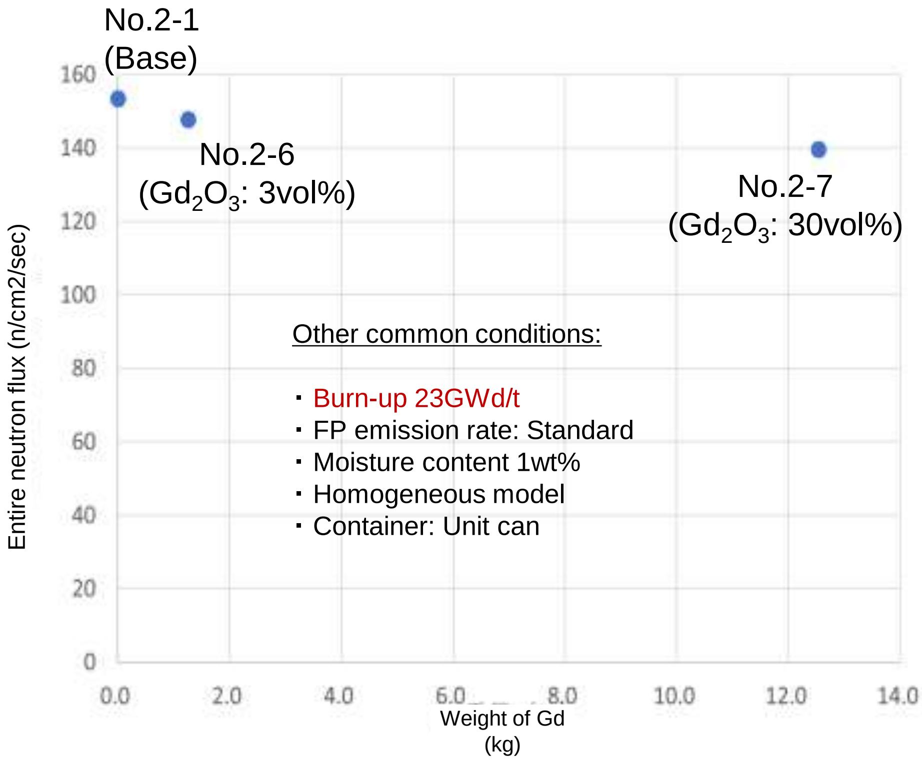
Neutron spectrum at the location of the detector

→ Impact of the neutron absorption material did not appear significantly in the spectrum.

(The slow neutrons inside the unit can are absorbed by the neutron absorption material, but slow neutrons on the unit can side of polyethylene do not reach up to the detector region due to the deceleration/absorption effect of polyethylene regardless of the presence of the absorption material, and are believed to not have any impact.)

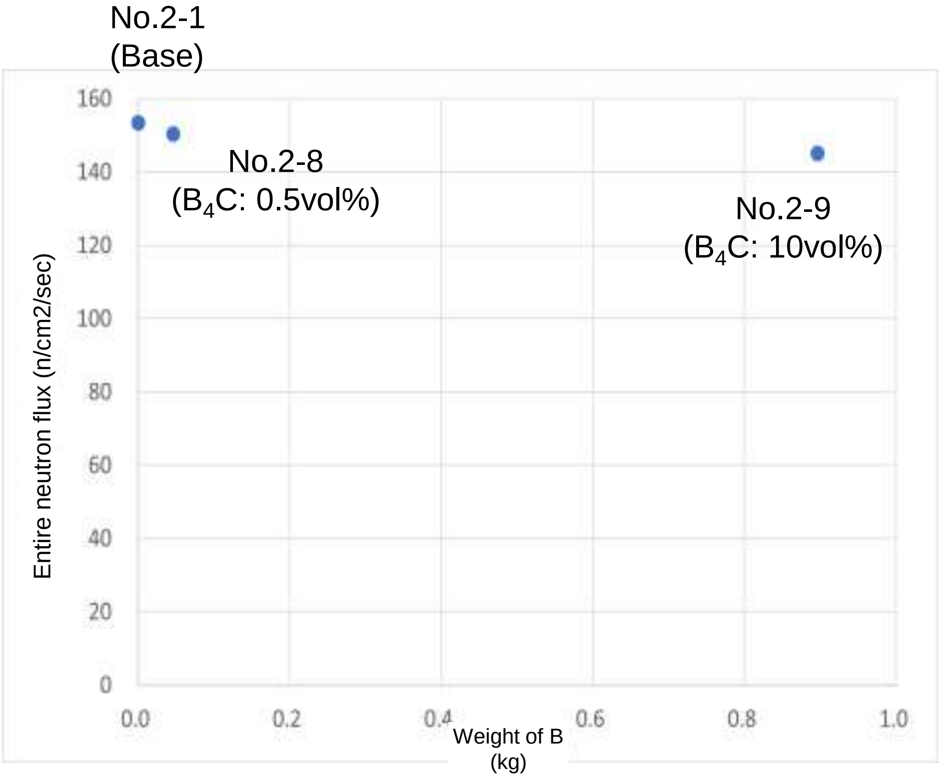
2.2.1 Passive neutrons – Other sensitivity analyses (6/8)

Relation between the amount of neutron absorption material (Gadolinium, Boron) contained and the incident beams (3/3)



Other common conditions:

- Burn-up 23GWd/t
- FP emission rate: Standard
- Moisture content 1wt%
- Homogeneous model
- Container: Unit can



→ **Even if neutron absorption material was added, there was hardly any decrease in the entire neutron flux.**

- As the spectrum in the thermal neutron energy region that is mainly detected by the He-3 detector does not change depending on the amount of Gd and B added, it is believed to have only a slight impact on the neutron count.

2.2.1 Passive neutrons – Other sensitivity analyses (7/8)

Response spectrum for a representative detector

- Correlation with Uranium content

Case		UO_2	ZrO_2	SUS	Concrete	Total (Filling rate)	U content setting
2-1	Base	15vol%	15vol%	0vol%	-	30vol%	8.79kg
2-2	Molten debris (Spot with less U)	7.5vol%	22.5vol%	0vol%	-	30vol%	2.93kg
2-18	Canister	15vol%	15vol%	0vol%	-	30vol%	35.1kg
2-20	Molten debris (Uranium-rich)	30vol%	0vol%	0vol%	-	30vol%	17.6kg
2-21	Metallic debris	0.075vol%	0.075vol%	29.85vol%	-	30vol%	0.04kg
2-22	Metallic debris (Lot of SUS)	15vol%	15vol%	30vol%	-	60vol%	8.79kg

Other common conditions:

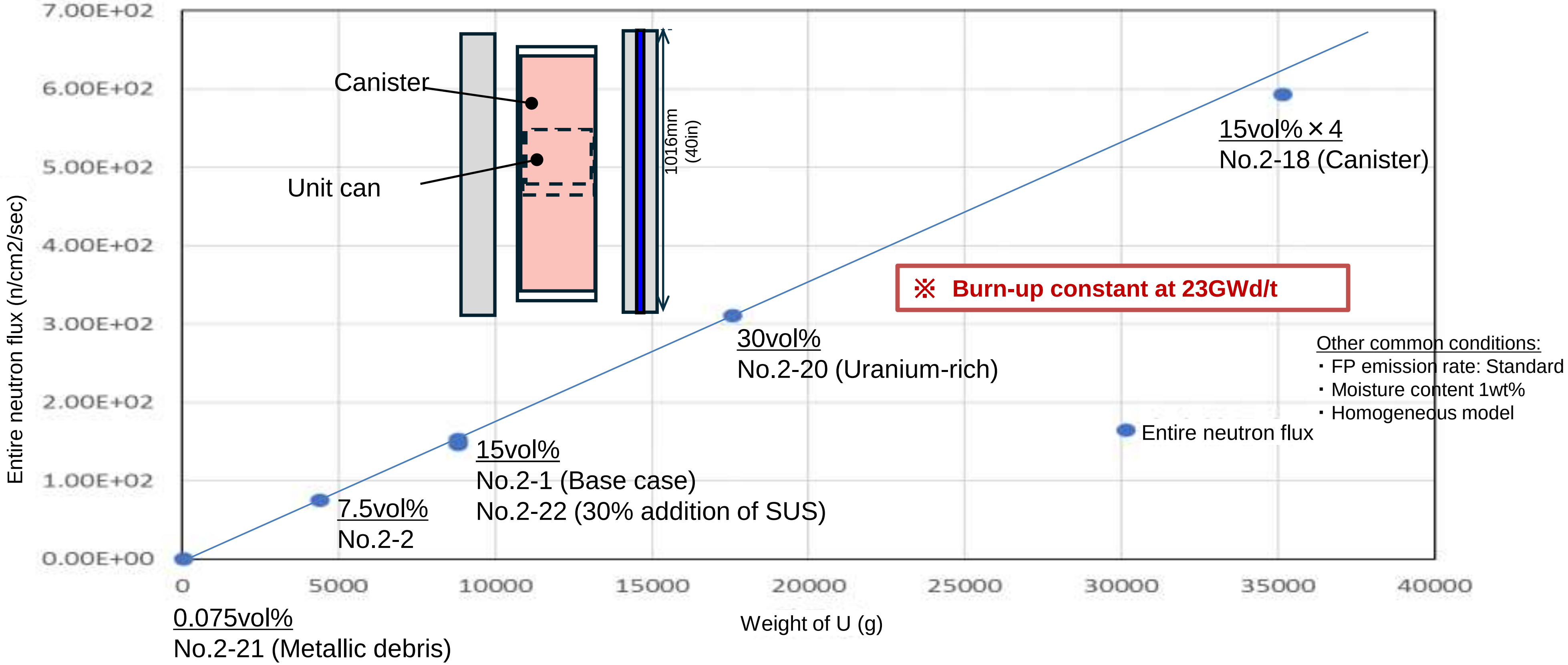
- Burn-up 23GWd/t
- FP emission rate: Standard
- Moisture content 1wt%
- Homogeneous model

2.2 Analysis results

2.2.1 Passive neutrons – Other sensitivity analyses (8/8)

Response spectrum for a representative detector

Correlation of U content and beams incident upon the Helium 3 proportional counter



※ Burn-up constant at 23GWd/t

Other common conditions:
- FP emission rate: Standard
- Moisture content 1wt%
- Homogeneous model

→・**Quantity of U and all incident beams had a positive correlation (when the burn-up was constant)**

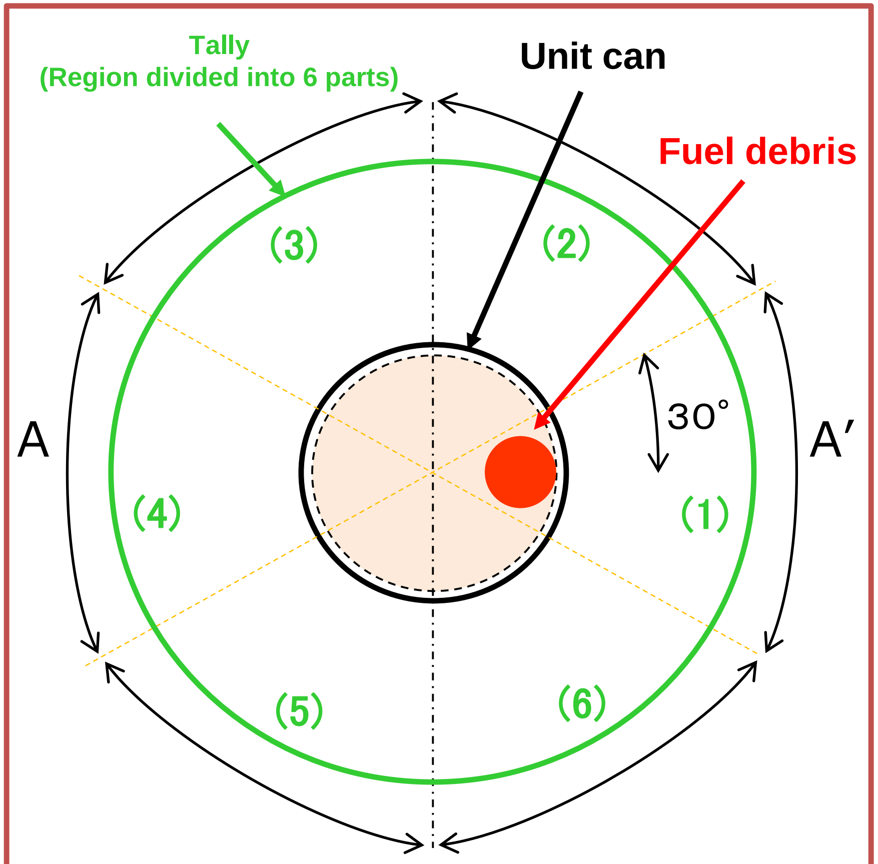
- The impact of the self-shielding effect caused by changes in the density (filling rate) of fuel debris does not appear significantly in all the incident beams.
- The impact is minor even when SUS is present (Case 2-22).
- In the case of canister (Φ220mm×H840mm), since neutrons emitted from the top and bottom ends of the container are likely to leak outside the system, the neutron flux becomes lower than the direct line of proportion of the unit can (Case 2-18).

2.2.1 Passive neutrons – Sensitivity analysis Uneven distribution (1/6)

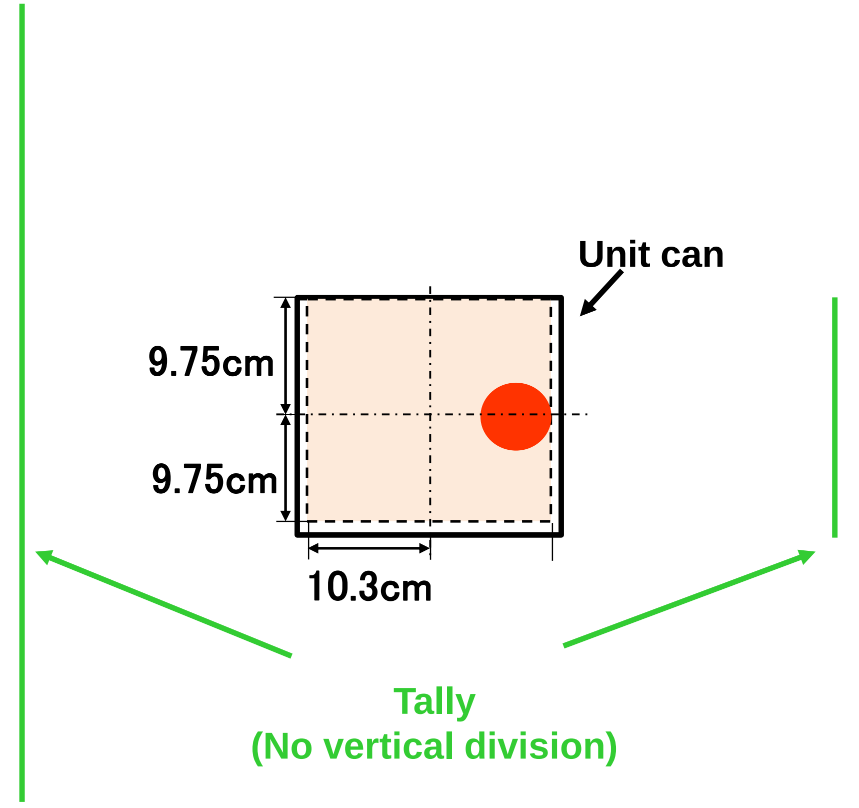
Analysis by changing the method of filling fuel debris into the container

■Tally settings of the uneven distribution cases

#The tally was divided into 6 parts for the horizontal direction (outer surface) cases only.



Top view

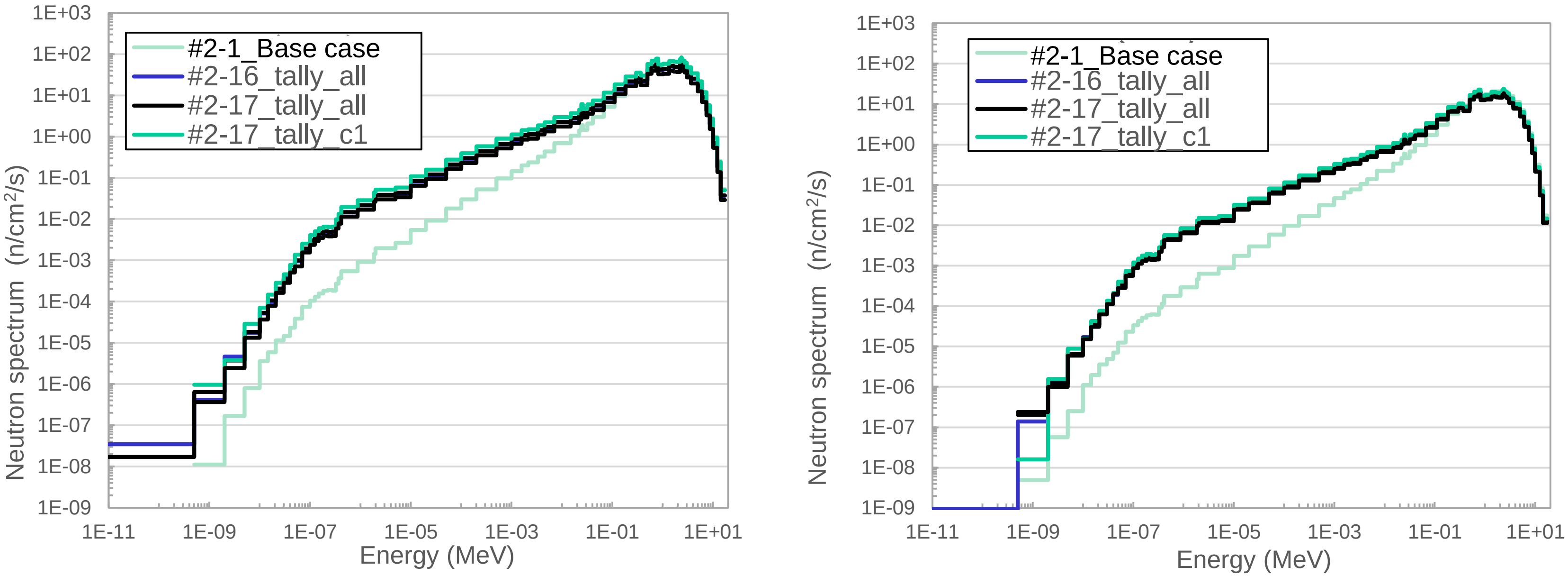


Cross sectional view A-A’

The location and dimensions for installing the tally for the unit can are the same as described in slide No. 56.

2.2.1 Passive neutrons – Sensitivity analysis Uneven distribution (2/6)

Molten debris Uneven distribution case spectrum



Neutron spectrum at 1cm of the container surface Neutron spectrum at 15cm of the container surface

→ **When fuel debris was thickened, thermal neutron flux increased. Even when fuel debris was unevenly distributed, the shape of the neutron spectrum did not change depending on the location of the sensor.**

2.2 Analysis results

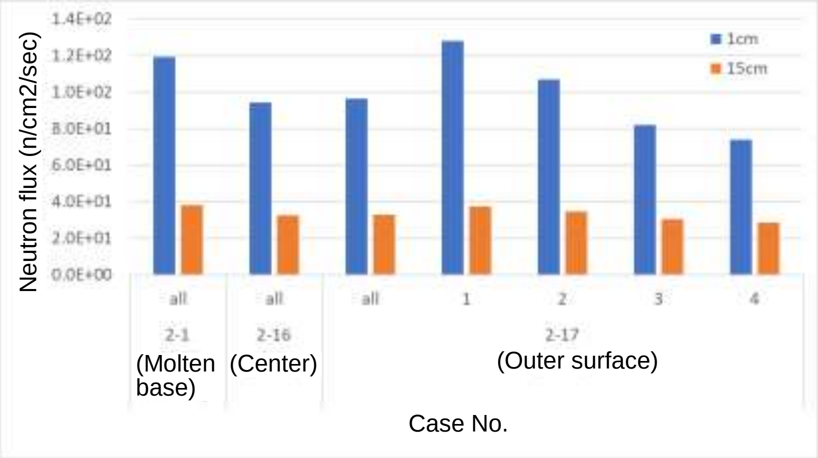
2.2.1 Passive neutrons – Sensitivity analysis Uneven distribution (3/6) Molten debris

Fast neutrons (0.5MeV to 5MeV)

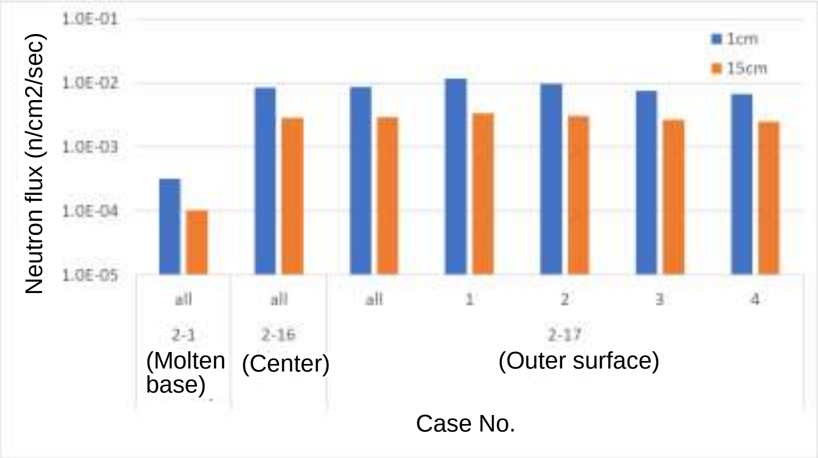
Case No.	tally	1cm (n/cm²/s)	15cm (n/cm²/s)
2-1 (Molten base)	all	1.19E+02	3.83E+01
2-16 (Center)	all	9.44E+01	3.27E+01
2-17 (Outer surface)	all	9.65E+01	3.28E+01
	1	1.28E+02	3.74E+01
	2	1.07E+02	3.47E+01
	3	8.18E+01	3.05E+01
	4	7.39E+01	2.88E+01

Thermal neutrons (0.4eV or less)

Case No.	tally	1cm (n/cm²/s)	15cm (n/cm²/s)
2-1 (Molten base)	all	3.20E-04	1.03E-04
2-16 (Center)	all	8.41E-03	2.84E-03
2-17 (Outer surface)	all	8.71E-03	2.90E-03
	1	1.15E-02	3.38E-03
	2	9.61E-03	3.08E-03
	3	7.47E-03	2.67E-03
	4	6.71E-03	2.49E-03



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



Thermal neutrons (Integrated value of 0.4eV or less)

→ ・**When fuel debris was unevenly distributed, thermal neutron flux was 1 order of magnitude higher than the base case, but the impact of uneven distribution on the measurement position was not more than 2 times.**

・**The farther away the fast neutron flux was from the surface of the container, the smaller was the fluctuation.**

2.2 Analysis results

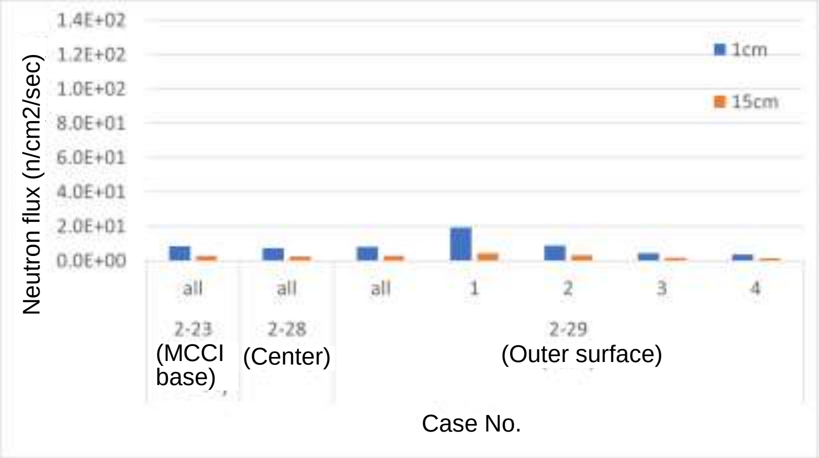
2.2.1 Passive neutrons – Sensitivity analysis Uneven distribution (4/6) MCCI

Fast neutrons (0.5MeV to 5MeV)

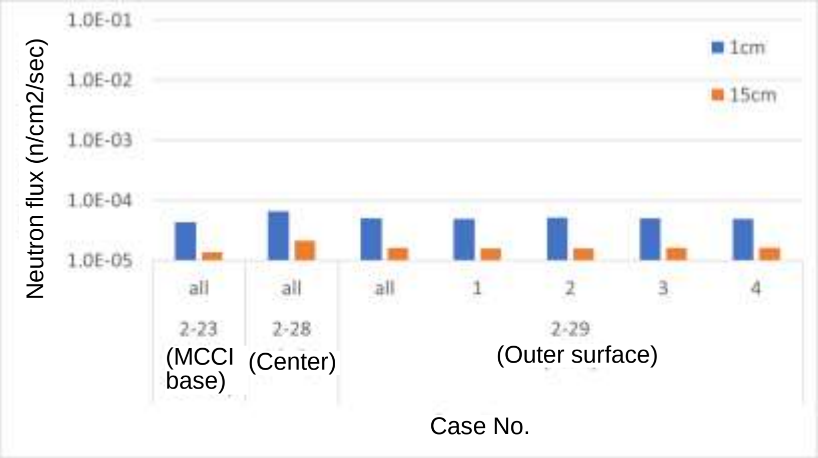
Case No.	tally	1cm (n/cm^2/s)	15cm (n/cm^2/s)
2-23 (MCCI base)	all	8.57E+00	2.75E+00
2-28 (Center)	all	7.19E+00	2.51E+00
2-29 (Outer surface)	all	8.16E+00	2.65E+00
	1	1.93E+01	4.42E+00
	2	8.68E+00	3.16E+00
	3	4.37E+00	1.83E+00
	4	3.57E+00	1.49E+00

Thermal neutrons (0.4eV or less)

Case No.	tally	1cm (n/cm^2/s)	15cm (n/cm^2/s)
2-23 (MCCI base)	all	4.28E-05	1.37E-05
2-28 (Center)	all	6.57E-05	2.12E-05
2-29 (Outer surface)	all	5.04E-05	1.62E-05
	1	4.87E-05	1.59E-05
	2	5.14E-05	1.58E-05
	3	4.96E-05	1.63E-05
	4	4.87E-05	1.63E-05



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



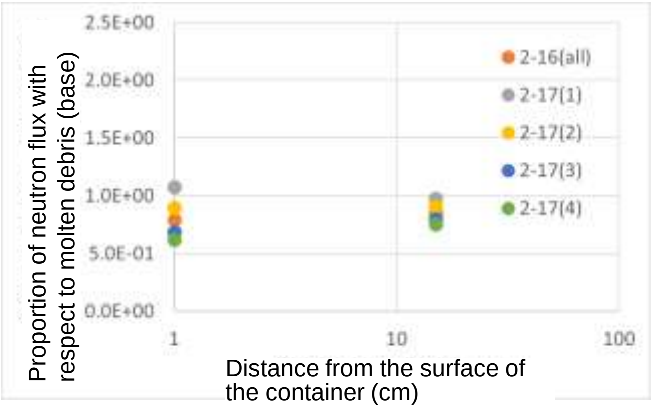
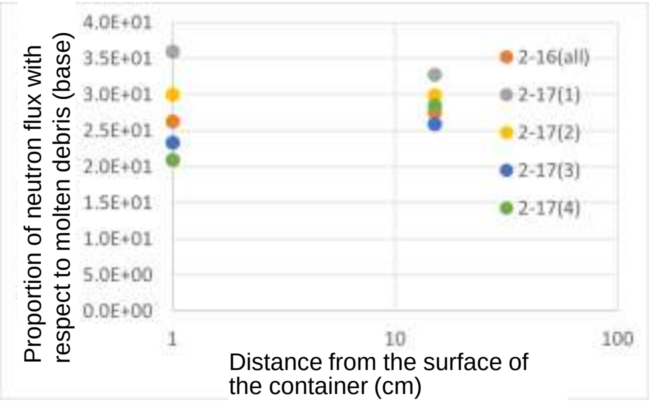
Thermal neutrons (Integrated value of 0.4eV or less)

→ **The farther away the fast neutron flux was from the surface of the container, the smaller was the fluctuation caused by uneven distribution of fuel debris.**
The fluctuation in thermal neutron flux was by and large small.

2.2 Analysis results

2.2.1 Passive neutrons – Sensitivity analysis Uneven distribution (5/6)

Comparison of the beams from molten debris and MCCI

<table>
<tr><th></th><th>Fast neutrons (Integrated value of 0.5MeV to 5MeV)</th><th>Thermal neutrons (Integrated value of 0.4eV or less)</th></tr>
<tr><td>Molten debris</td><td>
</td><td>
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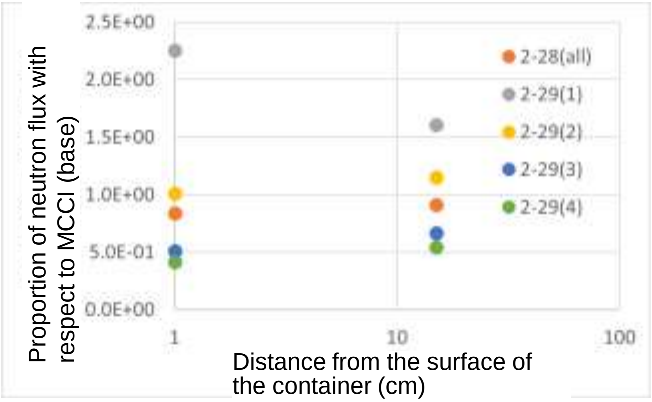
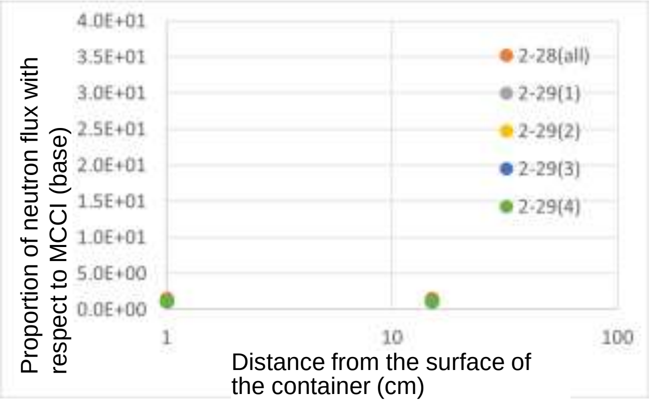
<tr><td>MCCI</td><td>
</td><td>
</td></tr>
</table>

→ **・The fluctuations due to uneven distribution were larger in fast neutron flux in the case of MCCI as against molten debris.**

・The impact of uneven distribution on thermal neutron flux was small as compared to the case of molten debris.

2.2.1 Passive neutrons – Sensitivity analysis Uneven distribution (6/6)

➢ Uneven distribution of metallic debris

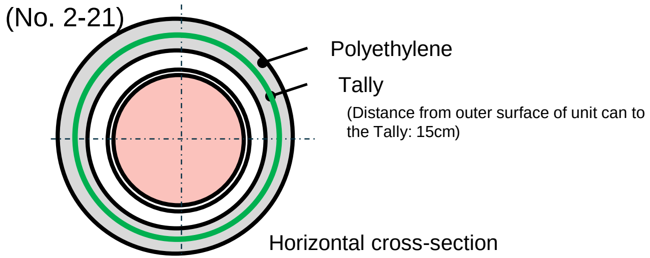
Impact was verified by means of the flux after penetrating polyethylene.

→・Since the distance up to the tally changes due to uneven distribution, there is variation in the incident beams.

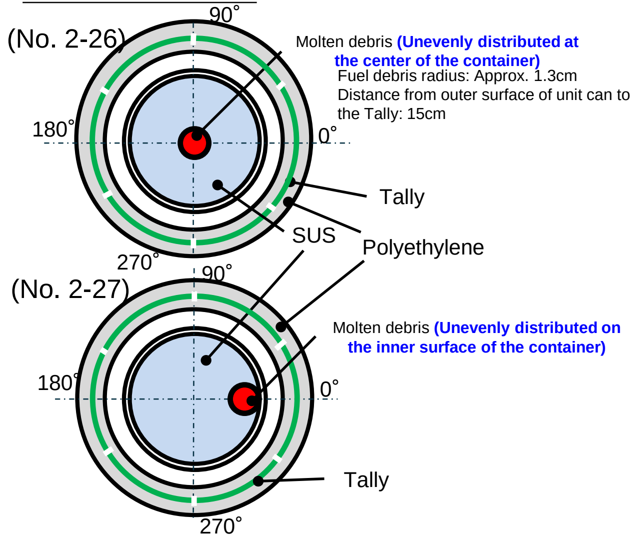
・Since self-shielding effect does not appear in passive neutron measurement, there is little variation due to uneven distribution of the fuel debris locations as compared to passive gamma measurement.

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Filling rate	Uneven distribution
2-21	Metallic debris	0.075vol%	0.075vol%	29.85vol%	30vol%	Uniform
2-26 2-27	Metallic debris	0.075vol%	0.075vol%	29.85vol%	30vol%	Uneven distribution

<Uniform>

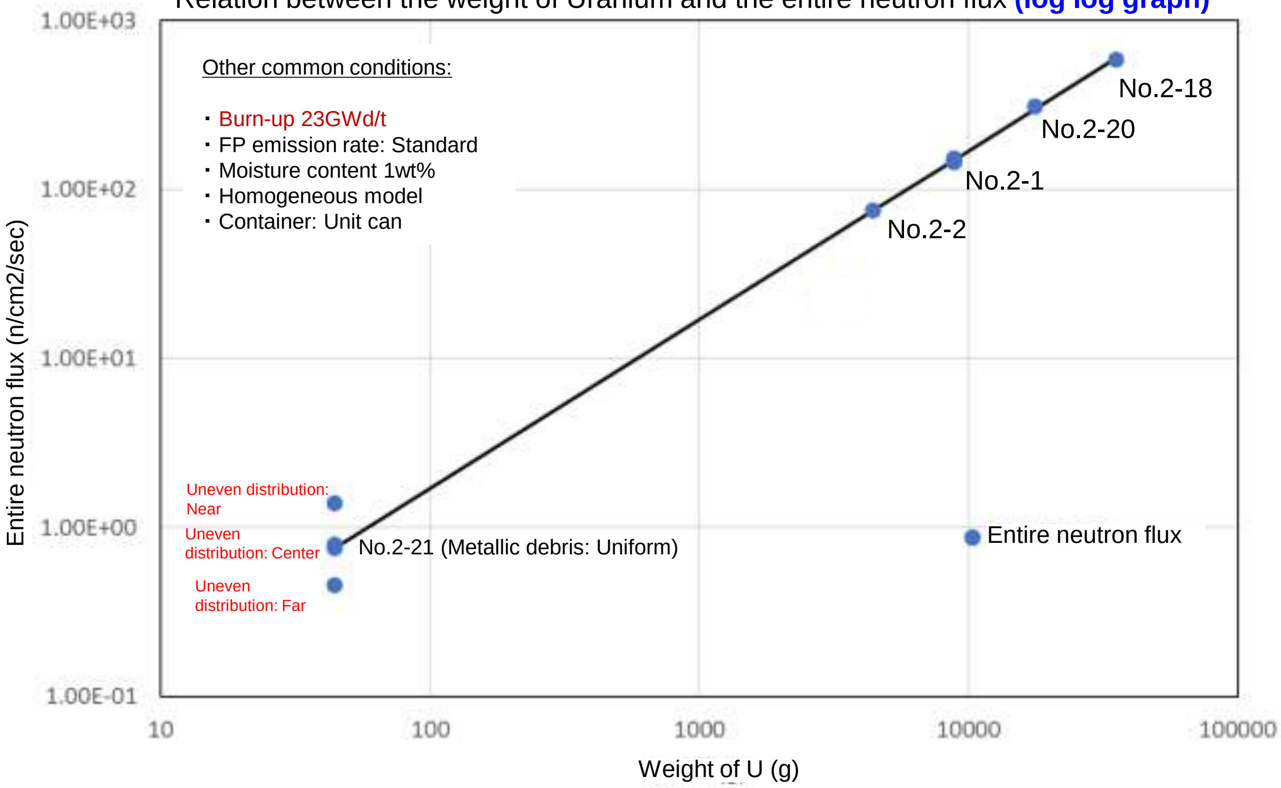


<Uneven distribution>



Horizontal cross-section

Relation between the weight of Uranium and the entire neutron flux **(log log graph)**



2.2 Analysis results

2.2.1 Passive neutrons – Additional sensitivity analyses (1/8)

■ Cases with a combination of fluctuations in 2 influencing factors

		Molten										Metallic	MCCI
		Fuel debris composition	MOX	Filling factor	Gd content	B content	Moisture content	Burn-up	Cooling period	Uneven distribution	Container		
Molten	Fuel debris composition		-	x Increase/decrease in flux depending on the filling factor	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x	-	-
	MOX			x Increase/decrease in flux depending on the filling factor	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	-	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x	△	△
	Filling factor				x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x Can be evaluated by means of the linear sum of each parameter	x	△	△
	Gd content					△	○ **1 case (High Gd - H$_2$0 50vol%)**		x	△	x	○ **1 case (High Gd)**	○ **1 case (High Gd)**
	B content						○ **1 case (High B - H_2 O 50vol%)**		x	△	x	○ **1 case (High B)**	○ **1 case (High B)**
	Moisture content									△		○ **1 case (70vol%)**	○ **1 case (70vol%)**
	Burn-up											x	x
	Cooling period											x Attenuates depending on half-life	x Attenuates depending on half-life
	Uneven distribution											△	△
	Container											x	x
Metallic													-
MCCI													

- ･In order to compare the impact of Gd and B respectively, analysis was performed by setting the same volume ratio for both.
- ･If the filling rate is 30vol% and water is 70vol%, there is no room to add Gd or B.
- ･As against this, the proposal of keeping the water at 50vol%, adding 10vol% each of Gd and B and analyzing, was studied.
- ･For further comparison, the molten debris base case was analyzed by keeping water at 50vol%.

In order to check the extent of impact of Gd, B and moisture content, cases with combinations of maximum setting values of the factors were additionally analyzed. (The base cases of the above-mentioned factors have the minimum value or a small value)

8 +1 (Water 50vol%) = 9 Case

■ Cases wherein influencing factors in which the neutron count rate is the least were combined: 1 case

Filling rate	Gd content	B content	Moisture content	Burn-up	Uneven distribution
10vol% (UO_2:ZrO_2 =5vol%:5vol%)	High (Gd_2O_3 30vol%)	High (B_4C 10vol%)	H_2O 50vol%	Low (1.3GWd/t)	At the center in the horizontal direction

Total
10 cases

- The molten debris base case was used for other factors.

･If filling rate is 30vol%, moisture content is 70vol%, Gd is 30vol%, B is 10vol%, then 100vol% is exceeded.
･Proposed parameters: The following conditions wherein water is 50vol% were studied.
If filling rate is 10vol%, moisture content is 50vol%, Gd is 30vol%, B is 10vol%, then the total is 100vol%.
In this instance, even the case mentioned above with a combination of 2 influencing factors was analyzed while keeping water at 50vol%.

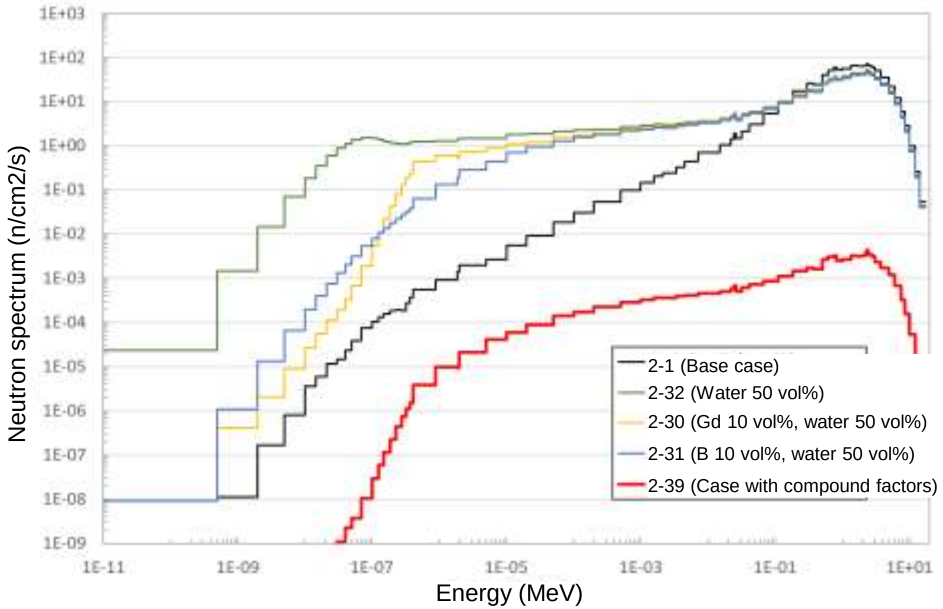
2.2 Analysis results

2.2.1 Passive neutrons – Additional sensitivity analyses (2/8)

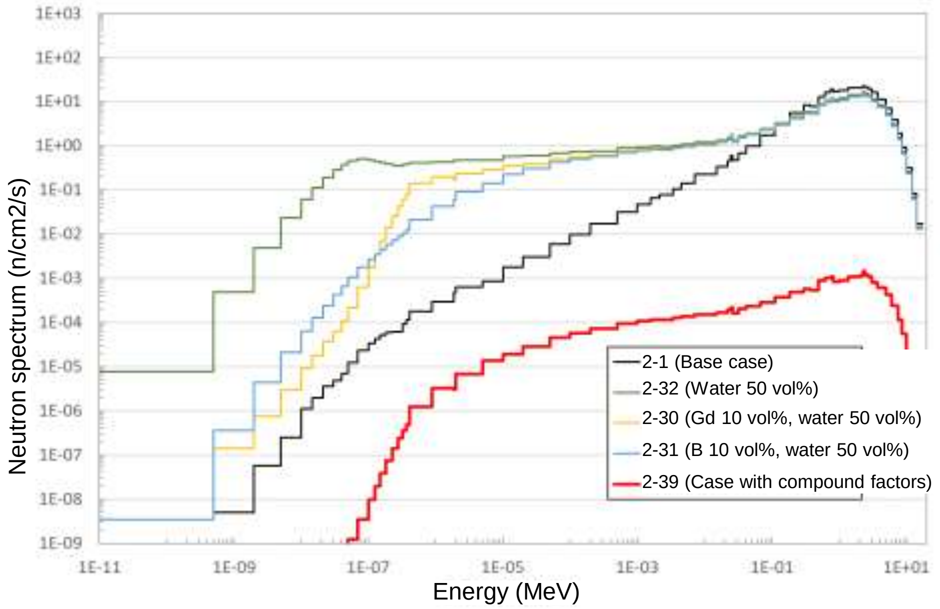
Case		UO_2	ZrO_2	SUS	Concrete	Total (Filling rate)	Moisture content	Gd_2O_3	B_4C	Burn-up (GWd/t)	Cooling Period (Years)	Uneven distribution	Remarks U content considered as the analysis condition
2-1	Base	15 vol%	15 vol%	0 vol%	-	30 vol%	1wt%			23.0	20	Uniform	8.79kg
	Step 2 analysis cases												
2-30	Molten/ High Gd/ Water 50vol%	15 vol%	15 vol%	0 vol%	-	30 vol%	50 vol%	10 vol%	0 vol%	23.0	20	Uniform	8.79kg
2-31	Molten/ High B / Water 50vol%	15 vol%	15 vol%	0 vol%	-	30 vol%	50 vol%	0 vol%	10 vol%	23.0	20	Uniform	8.79kg
2-32	Molten / Water 50vol%	15 vol%	15 vol%	0 vol%	-	30 vol%	50 vol%	0 vol%	0 vol%	23.0	20	Uniform	8.79kg
2-33	Metal / High Gd	0.075 vol%	0.075 vol%	29.85 vol%	-	30 vol%	1wt%	30 vol%	0 vol%	23.0	20	Uniform	0.0439kg
2-34	Metal / High B	0.075 vol%	0.075 vol%	29.85 vol%	-	30 vol%	1wt%	0 vol%	10 vol%	23.0	20	Uniform	0.0439kg
2-35	Metal / Water 70%	0.075 vol%	0.075 vol%	29.85 vol%	-	30 vol%	70 vol%	0 vol%	0 vol%	23.0	20	Uniform	0.0439kg
2-36	MCCI / High Gd	1.05 vol%	1.05 vol%	7.2 vol%	20.7 vol%	30 vol%	1wt%	30 vol%	0 vol%	23.0	20	Uniform	0.615kg
2-37	MCCI / High B	1.05 vol%	1.05 vol%	7.2 vol%	20.7 vol%	30 vol%	1wt%	0 vol%	10 vol%	23.0	20	Uniform	0.615kg
2-38	MCCI / High water content	1.05 vol%	1.05 vol%	7.2 vol%	20.7 vol%	30 vol%	70 vol%	0 vol%	0 vol%	23.0	20	Uniform	0.615kg
2-39	Molten compound factors	5 vol%	5 vol%	0 vol%	-	10 vol%	50 vol%	30 vol%	10 vol%	1.3	20	Horizontal direction (Center)	2.93kg

2.2.1 Passive neutrons – Additional sensitivity analyses (3/8)

Molten debris



Neutron spectrum at 1cm of the container surface



Neutron spectrum at 15cm of the container surface

→ Neutron flux decreased on the whole in the cases with compound factors.

2.2 Analysis results

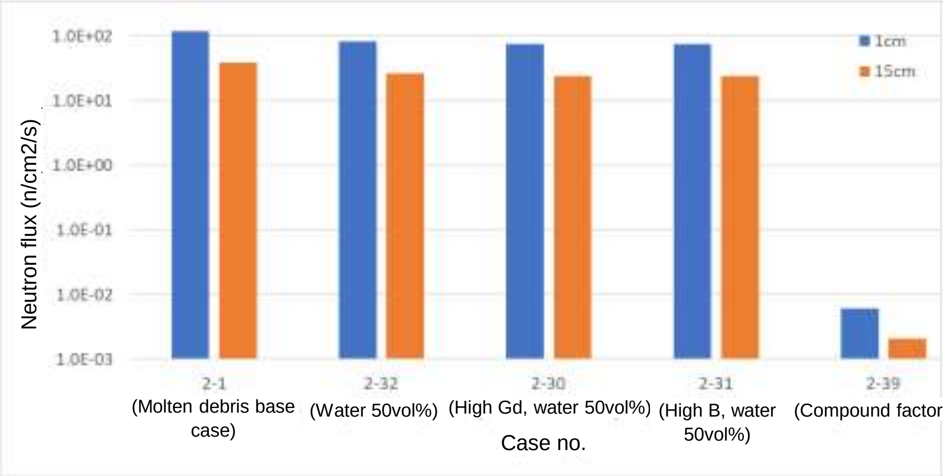
2.2.1 Passive neutrons – Additional sensitivity analyses (4/8) Molten debris

Fast neutrons (0.5MeV to 5MeV)

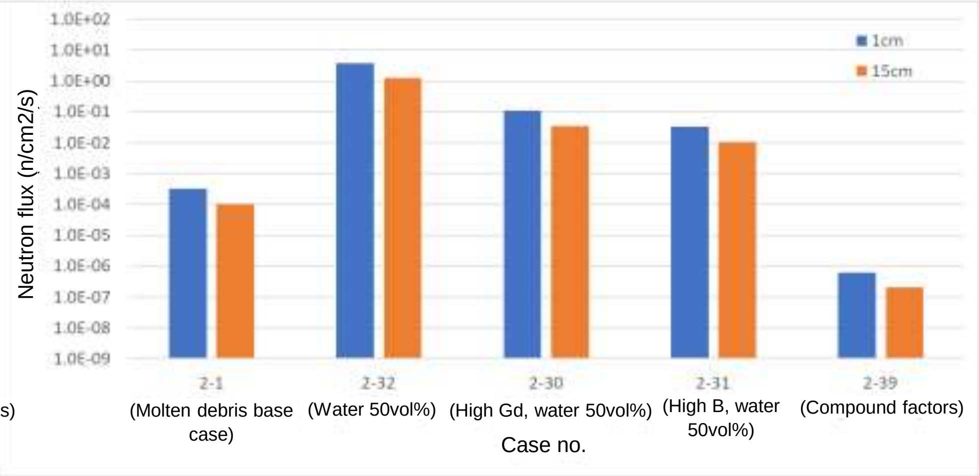
Case No.	1cm (n/cm²/s)	15cm (n/cm²/s)
2-1 (Molten debris base case)	1.19E+02	3.83E+01
2- 32 (Water 50vol%)	8.18E+01	2.63E+01
2-30 (Gd 10vol%)	7.43E+01	2.39E+01
2-31 (B 10vol%)	7.46E+01	2.40E+01
2-39 (Compound factors)	6.12E-03	2.07E-03

Thermal neutrons (0.4eV or less)

Case No.	1cm (n/cm²/s)	15cm (n/cm²/s)
2-1 (Molten debris base case)	3.20E-04	1.03E-04
2- 32 (Water 50vol%)	3.73E+00	1.21E+00
2-30 (Gd 10vol%)	1.08E-01	3.48E-02
2-31 (B 10vol%)	3.22E-02	1.04E-02
2-39 (Compound factors)	6.15E-07	2.01E-07



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



Thermal neutrons (Integrated value of 0.4eV or less)

→ **・Fast neutron flux in the case with compound factors decreased up to 5 digits of magnitude from the base case.**

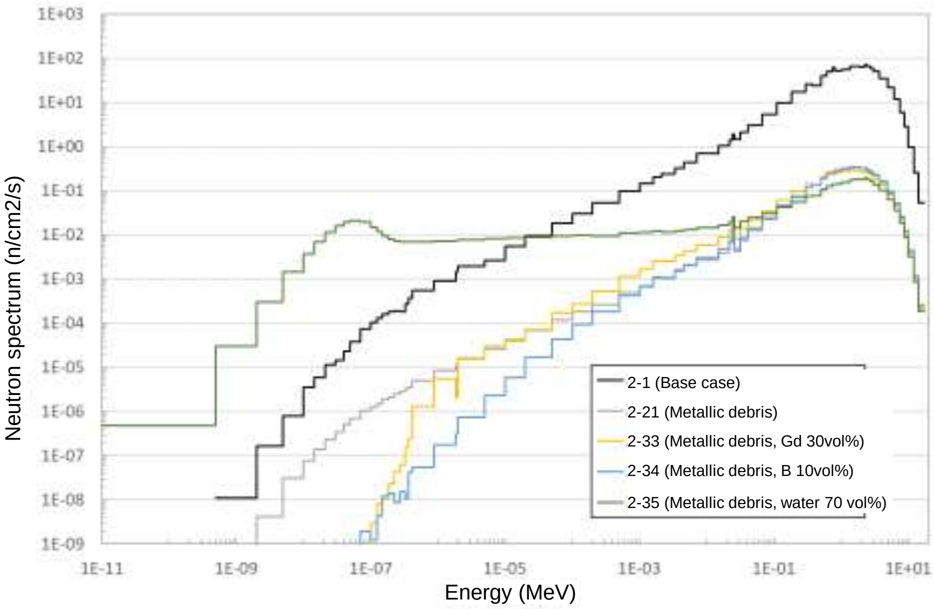
・In the high Gd/B content cases and cases in which there was no Gd/B content, when the water was 50vol%, the difference in fast neutron flux was about 9%.

・Thermal neutron beams fluctuated exponentially.

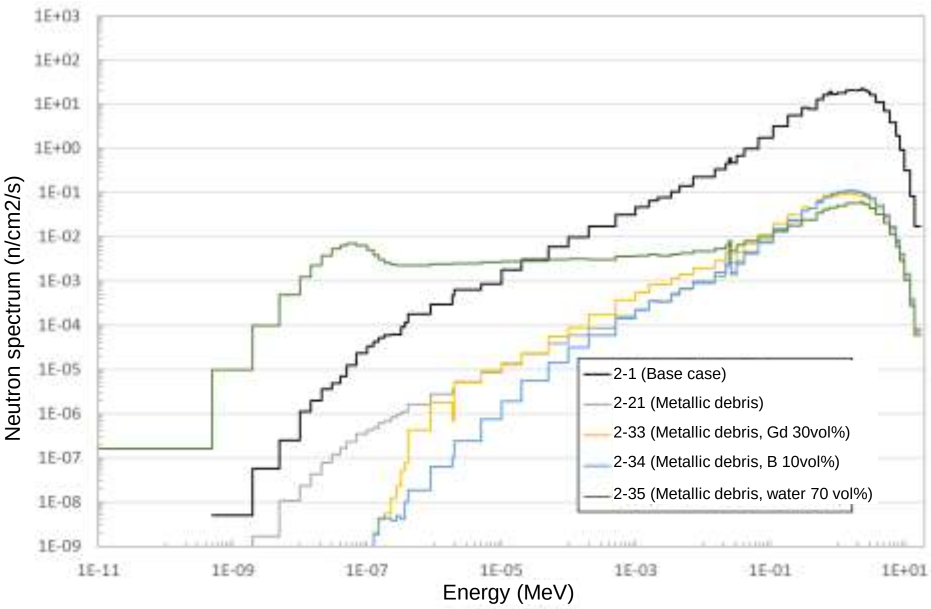
2.2 Analysis results

2.2.1 Passive neutrons – Additional sensitivity analyses (5/8)

Metallic debris



Neutron spectrum at 1cm of the container surface



Neutron spectrum at 15cm of the container surface

→ The spectrum of Gd 30vol% sharply decreased in the case of 1eV or less.

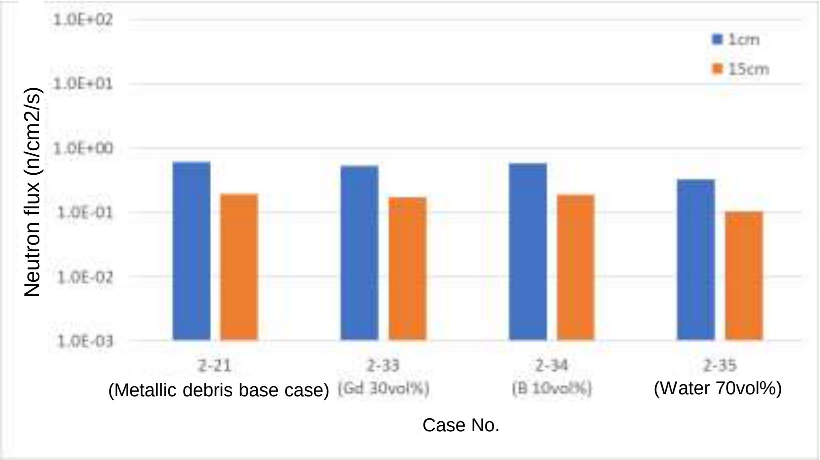
2.2.1 Passive neutrons – Additional sensitivity analyses (6/8) Metallic debris

Fast neutrons (0.5MeV to 5MeV)

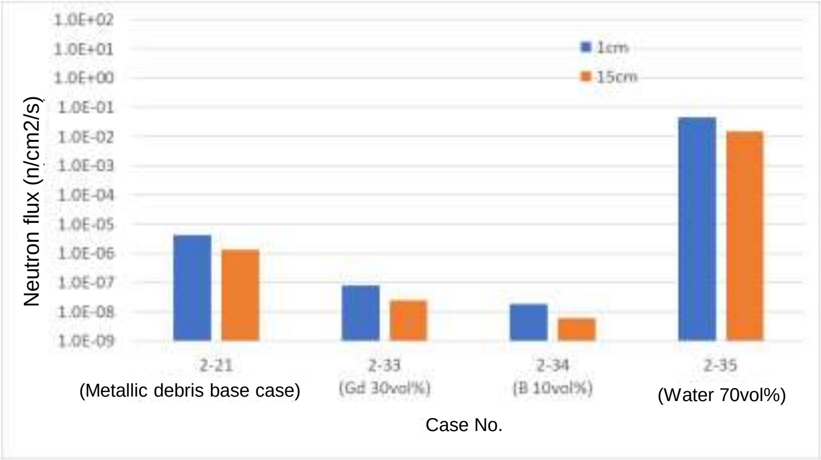
Case No.	1cm (n/cm²/s)	15cm (n/cm²/s)
2-21 (Metallic debris base case)	6.00E-01	1.93E-01
2-33 (Gd 30vol%)	5.27E-01	1.70E-01
2-34 (B 10vol%)	5.84E-01	1.88E-01
2-35 (Water 70vol%)	3.26E-01	1.05E-01

Thermal neutrons (0.4eV or less)

Case No.	1cm (n/cm²/s)	15cm (n/cm²/s)
2-21 (Metallic debris base case)	4.17E-06	1.36E-06
2-33 (Gd 30vol%)	7.69E-08	2.46E-08
2-34 (B 10vol%)	1.83E-08	6.00E-09
2-35 (Water 70vol%)	4.58E-02	1.49E-02



Fast neutrons (Integrated value of 0.5MeV to 5MeV)

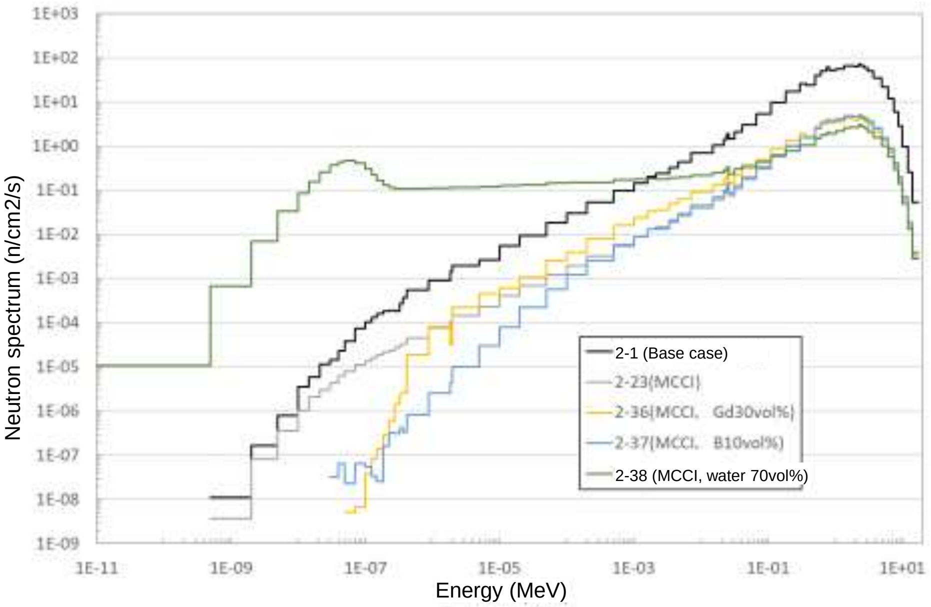


Thermal neutrons (Integrated value of 0.4eV or less)

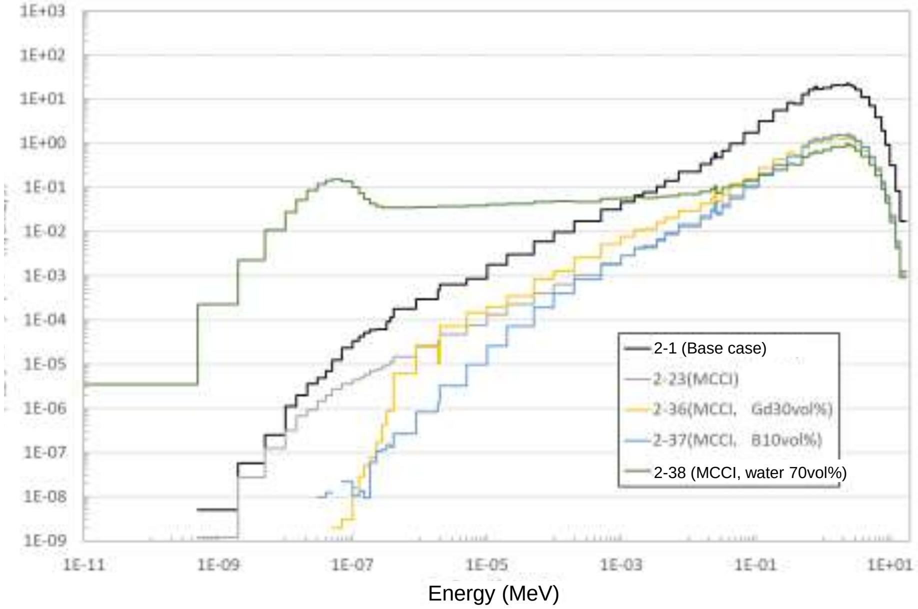
→ ・**Fast neutron flux decreased to about half of that in the case of metallic debris base case with 70vol% of water.**
・**Thermal neutron flux fluctuated exponentially.**

2.2.1 Passive neutrons – Additional sensitivity analyses (7/8)

MCCI



Neutron spectrum at 1cm of the container surface



Neutron spectrum at 15cm of the container surface

→ **The spectrum of Gd 30vol% sharply decreased in the case of 1eV or less.**

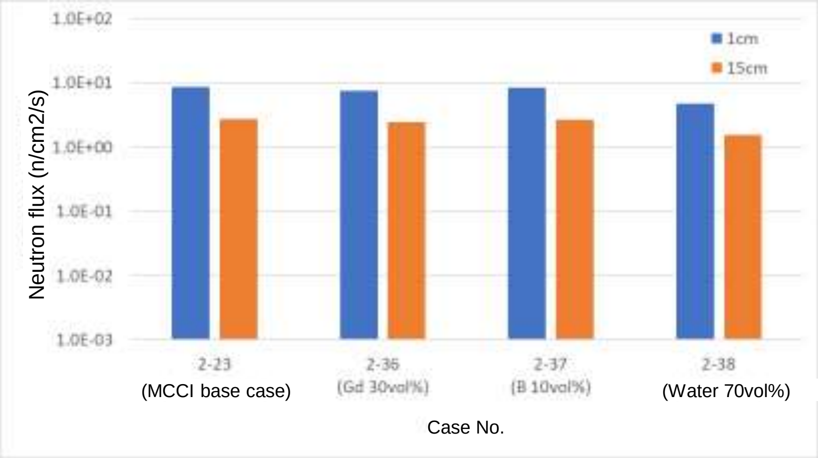
2.2.1 Passive neutrons – Additional sensitivity analysis (8/8)

Fast neutrons (0.5MeV to 5MeV)

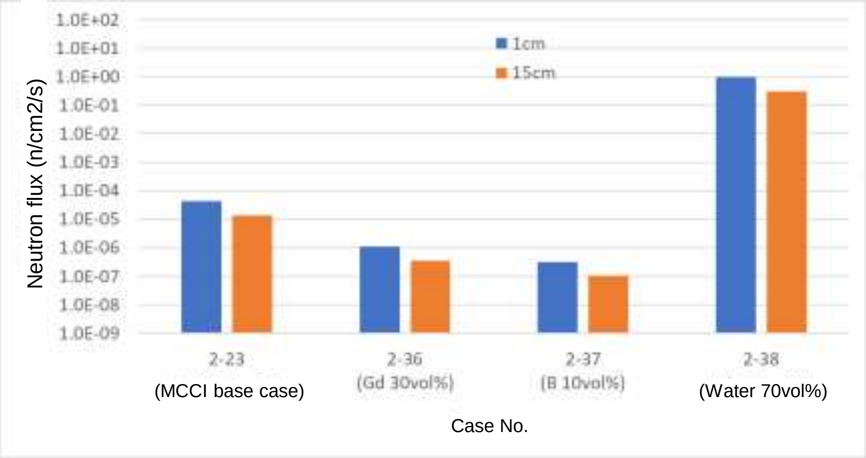
Case No.	1cm (n/cm²/s)	15cm (n/cm²/s)
2-23 (MCCI base case)	8.57E+00	2.75E+00
2-36 (Gd 30vol%)	7.56E+00	2.43E+00
2-37 (B 10vol%)	8.36E+00	2.69E+00
2-38 (Water 70vol%)	4.80E+00	1.54E+00

Thermal neutrons (0.4eV or less)

Case No.	1cm (n/cm²/s)	15cm (n/cm²/s)
2-23 (MCCI base case)	4.28E-05	1.37E-05
2-36 (Gd 30vol%)	1.09E-06	3.50E-07
2-37 (B 10vol%)	3.18E-07	1.07E-07
2-38 (Water 70vol%)	9.54E-01	3.11E-01



Fast neutrons (Integrated value of 0.5MeV to 5MeV)



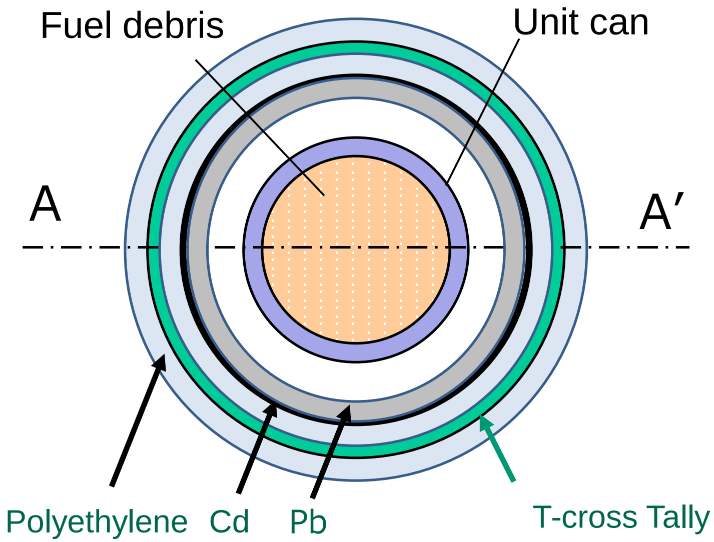
Thermal neutrons (Integrated value of 0.4eV or less)

→ **・Fast neutron flux decreased to about half of that in the case of metallic debris base case with 70vol% water.**
・Thermal neutron flux fluctuated exponentially.

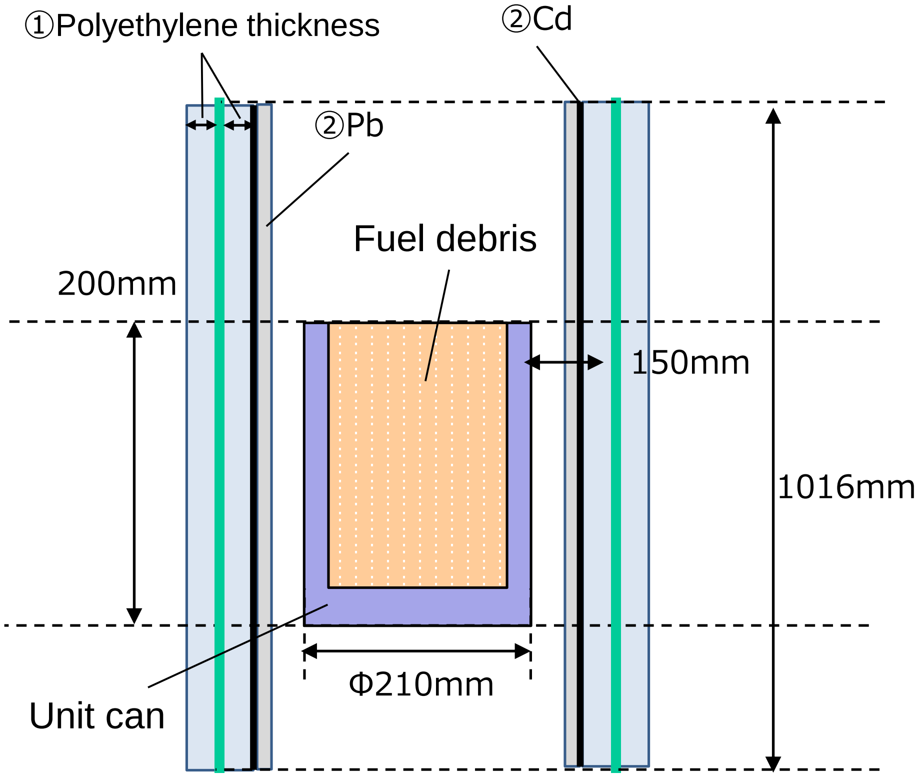
2.2.1 Passive neutrons - Detector response

Study procedure

- Simulation evaluation [Fuel debris conditions (Molten debris Base case No. 2-1)]
  - ① Optimization of polyethylene thickness
  - ② Cd impact, Pb impact
- Detector response (measurement time) evaluation



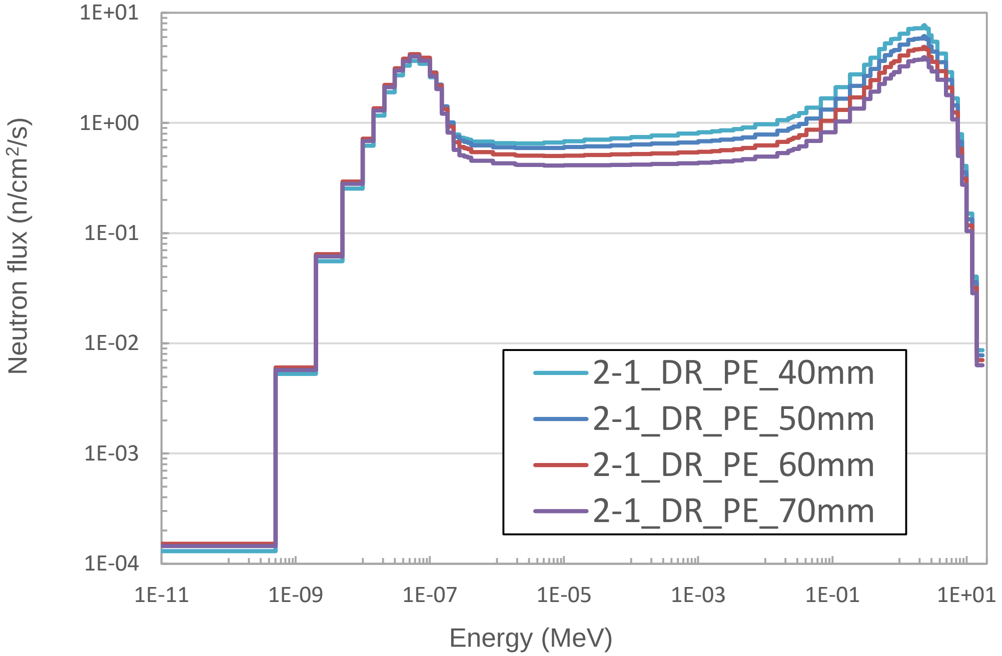
Analysis model top view



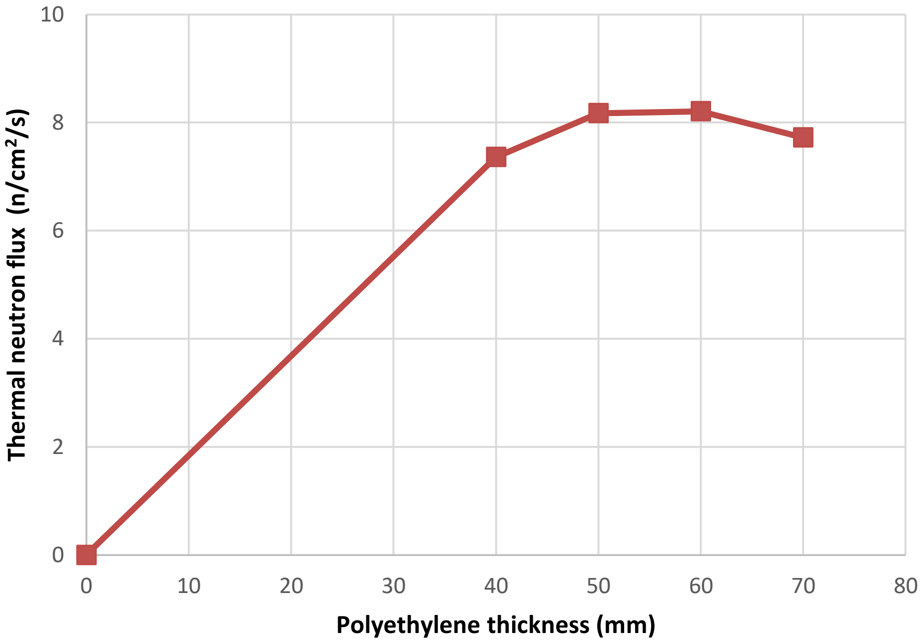
Cross sectional view A-A'

2.2 Analysis results

2.2.1 Passive neutrons - Detector response ① Polyethylene thickness



Neutron spectrum at 15cm of the container surface



Dependence of thermal neutron flux on polyethylene thickness

→ ・**Thermal neutron flux was the maximum when polyethylene thickness was 50mm to 60mm.**
[Hereinafter, 50mm thick polyethylene will be used.]

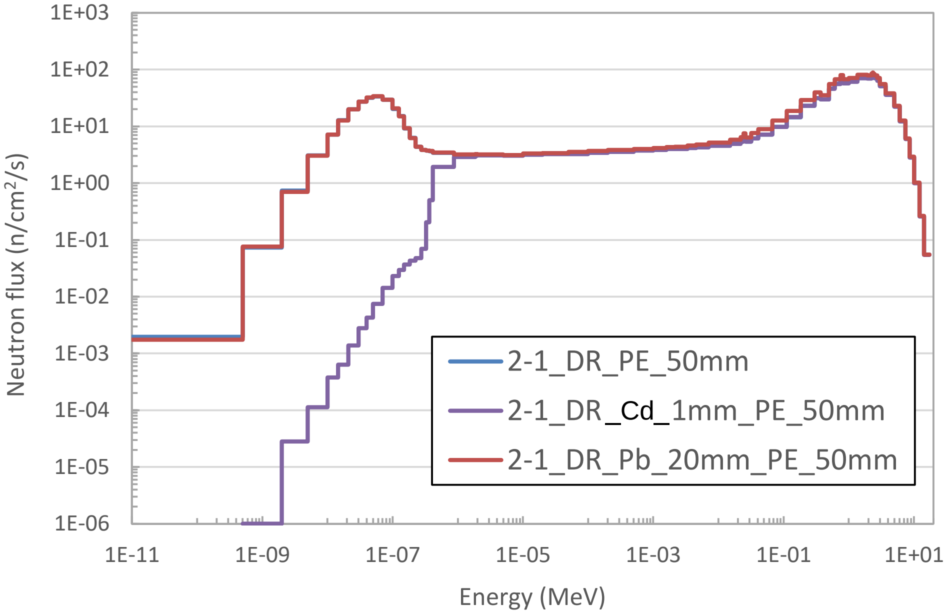
2.2 Analysis results

2.2.1 Passive neutrons – Detector response ② Cd impact, Pb impact

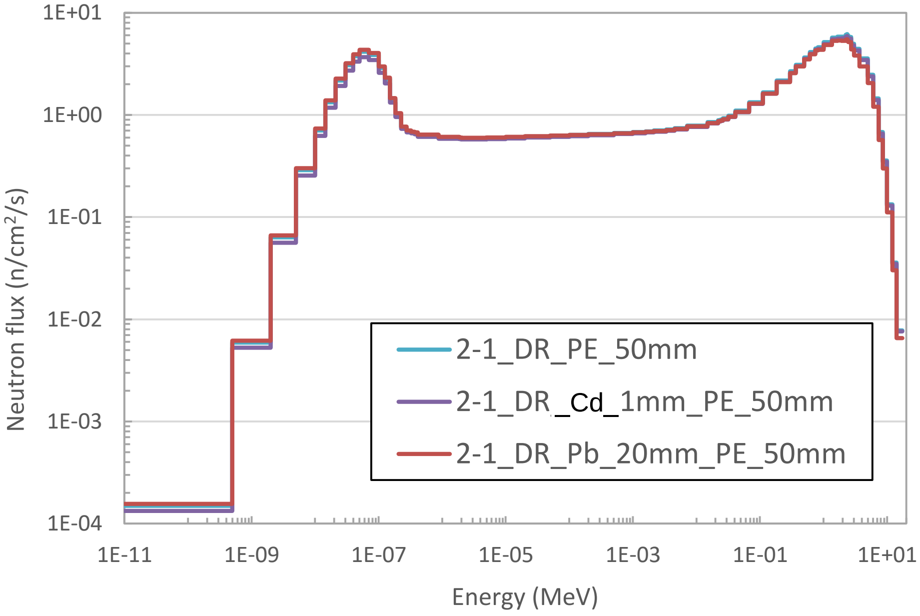
- Cd impact: Polyethylene 50mm + **Cd 1mm**
- Pb impact: Polyethylene 50mm + **Pb 20mm**

Thermal neutrons (0.4eV or less)

Case (2-1 Base case)	15cm (n/cm^2/s)
PE50mm	8.17
PE50mm+Cd1mm	7.33
PE50mm+Pb20mm	8.52



Neutron spectrum at 1cm of the container surface



Neutron spectrum at 15cm of the container surface

→ **・With Cd1mm, thermal neutron flux reduced by orders of magnitude at 1cm of the container surface ⇒ It controls the incidence of thermal neutron flux upon fuel debris.**

・There was a small variation in the shape of the neutron spectrum at the 15cm position of the container surface due to Cd1mm, Pb20mm.

[Hereinafter＋ 50mm thick polyethylene and Pb20mm+Cd1mm will be used.]

2.2.1 Passive neutrons - Detector response (Evaluation of measurement time)

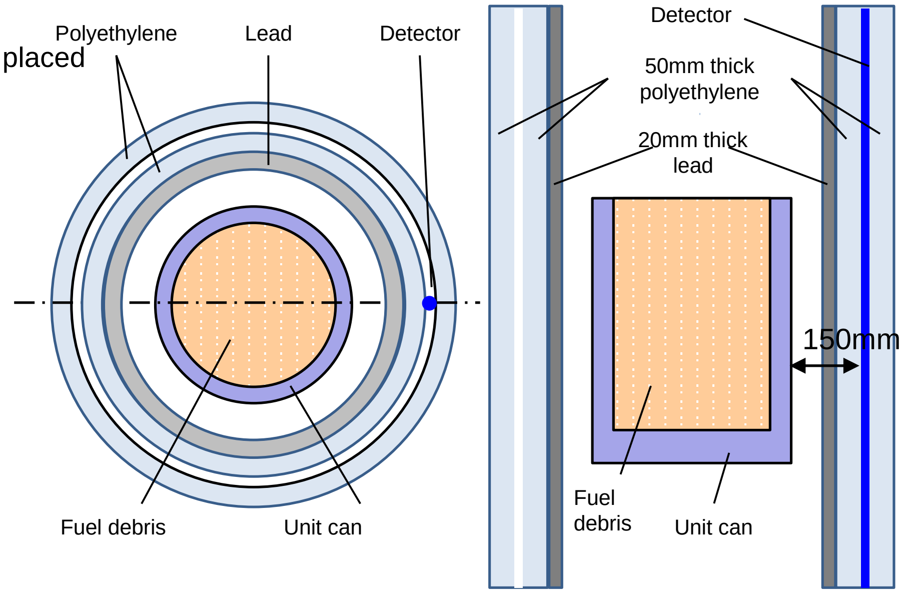
[Preconditions]

- Fuel debris to be evaluated: Molten debris Case 2-1 (Base case), Metallic debris Case 2-21 (Small amount of Uranium)

Case		UO_2 (vol%)	ZrO_2 (vol%)	SUS (vol%)	Concrete	Total (Filling rate)	Moisture content	Gd_2O_3	B_4C	Burn-up (GWd/t)	Cooling period (Year)	Uneven distribution	U content
2-1	Molten debris	15	15	0	-	30vol%	1wt%	-	-	23.0	20	Consistent	8.79kg
2-21	Metallic debris	0.075	0.075	29.85	-	30vol%	1wt%	-	-	23.0	20	Consistent	0.04kg

- Placement of detector, etc.

The detector was placed 15 cm from the container surface, 50mm polyethylene was placed on the inside and outside of the detector, 20mm lead was placed on the inner side of the inner polyethylene.



- Detector Note 1)

① He detector: Φ25.5mm, effective length 500mm,

Sensitivity 63.7 cps/(n/cm²/s)

② B-10 detector: Φ25.5mm, effective length 1,000mm,

Sensitivity 12.3 cps/(n/cm²/s)

- Detector Maximum gamma dose rate Note 2)

① He detector: approx. 0.1 Gy/h

② B-10 detector: approx. 10 Gy/h

The dose rate at a distance of 15cm from the container surface was approx. 1Gy/h (according to the 2.2.2 Passive Gamma Rays - Analysis Results (2/7 and 3/7)), and as a result of installing 20mm lead, the dose rate at the location of the detector in this system was **approx. 0.1Gy/h**.

・Issue: When 20mm lead is installed, there is no margin in the gamma dose rate of the He detector. Optimization of the detector shielding or its installation location needs to be studied in the future.

Note 1) https://etd.canon/ja/product/category/proportional/npc.html

Note 2) Neutron Detectors T.W.Crane, M. Baker (1997)

2.2.1 Passive neutrons - Detector response (Evaluation of measurement time)

1. Molten debris (Case 2-1) [Base case] (1 detector)
   1) Thermal neutron flux: From the position of the detector in the system having 50mm polyethylene + 20mm Pb (15cm from the container surface): **8.52 (n/cm^2/s)**
   2) Count rate and measurement time (Measurement time required for 1σ error 1% (10,000 counts)):
      ① He detector: 5.43E+02 cps (= 8.52 x 63.7) ⇒ **18 seconds** (= 10,000/5.43E+02)
      ② B-10 detector : 1.05E+02 cps (= 8.52 x 12.3) ⇒ **95 seconds** (= 10,000/1.05E+02)

2. Metallic debris (Case 2-21) [Small amount of Uranium]
   1) Thermal neutron flux: **3.88E-02 (= 8.52 x 0.04kg/8.79kg) (n/cm^2/s)**
      (Assumed to be proportionate to U mass based on 2.2.2 Passive Neutrons - Analysis Results [U Mass] on Slide No. 66)
   2) Count rate and measurement time (measurement time required for 1σ error 1% (10,000 counts))
      a) **When there was 1 detector**
         ① He detector: 2.47 cps (= 3.88E-02 x 63.7) ⇒ **approx. 4,000 seconds** (= 10,000/2.47)
         ② B-10 detector: 0.477 cps (= 3.88E-02 x 12.3) ⇒ **approx. 21,000 seconds** (= 10,000/0.477)
      b) **When there were 60 detectors** (Maximum number of detectors lined up at a distance of 15cm from the container surface)
         ① He detector: **approx. 70 seconds**
         ② B-10 detector: **approx. 350 seconds**

- **Issue: In the case of fuel debris that contains a small amount of Uranium (Example: metallic debris), the measurement time was long particularly in the case of B-10 detectors.**

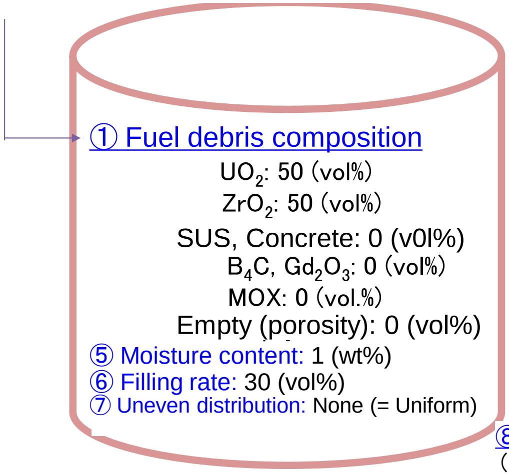
2.2.1 Passive neutrons – Summary

➢ Major findings obtained from the analysis:

Impact	Influencing factor	Findings
Major	② Burn-up ⑤ Moisture content	・The shape of the neutron spectrum that leaks from the container does not change **depending on the burn-up,** however, the flux changes largely by the order of magnitude. **[Refer to No. 43]** ・**When moisture content increases**, the fast neutron flux decreases and thermal neutron flux increases. **[Refer to No. 44]**
Minor	① Fuel debris composition: (Neutron absorption material) (③ FP emission rate*1) ④ Cooling period ⑥ Filling rate: **⑦ Uneven distribution** ⑧ Container	・The shape of the neutron spectrum and the neutron flux in the thermal energy area change due to the neutron absorption material, but these changes do not appear significantly at the location of the detector having a polyethylene moderator. ・There is a possibility of correcting the cooling period by means of the retrieval time period and half-life. ・The filling rate has a minor impact. **・The farther away the fast neutron flux is from the surface of the container, the smaller is its impact.** ・There is a possibility of being able to correct the shape of the container.

*1 ③ The FP emission rate is the emission rate of gamma rays and does not have an impact on the measurement of neutron radiation.

② Burn-up: Unit 2 core average
③ FP emission rate: Test (Pheus-FPT4) base
④ Cooling period: 20 years



① Fuel debris composition
UO_2: 50 (vol%)
ZrO_2: 50 (vol%)
SUS, Concrete: 0 (v0l%)
B_4C, Gd_2O_3: 0 (vol%)
MOX: 0 (vol.%)
Empty (porosity): 0 (vol%)
⑤ Moisture content: 1 (wt%)
⑥ Filling rate: 30 (vol%)
⑦ Uneven distribution: None (= Uniform)
⑧ Container: Unit can
(φ210mm×H200mm)

Parameter values in the figure indicate base case conditions.

➢ Study of the necessity of detailed analysis and consolidation of technical issues：

- Analysis of the extent of impact of heterogeneity on the flux on the measuring surface
- There is a possibility of correcting the rate of change in flux by **correcting the impact of the burn-up** in fuel debris.
- The flux reduces by the order of magnitude due to multiple influencing factors. And, even with the same amount of nuclear material, neutron flux differs by the order of magnitude depending on the difference in burn-up. Hence a measurement method that covers a broad range will be studied.

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

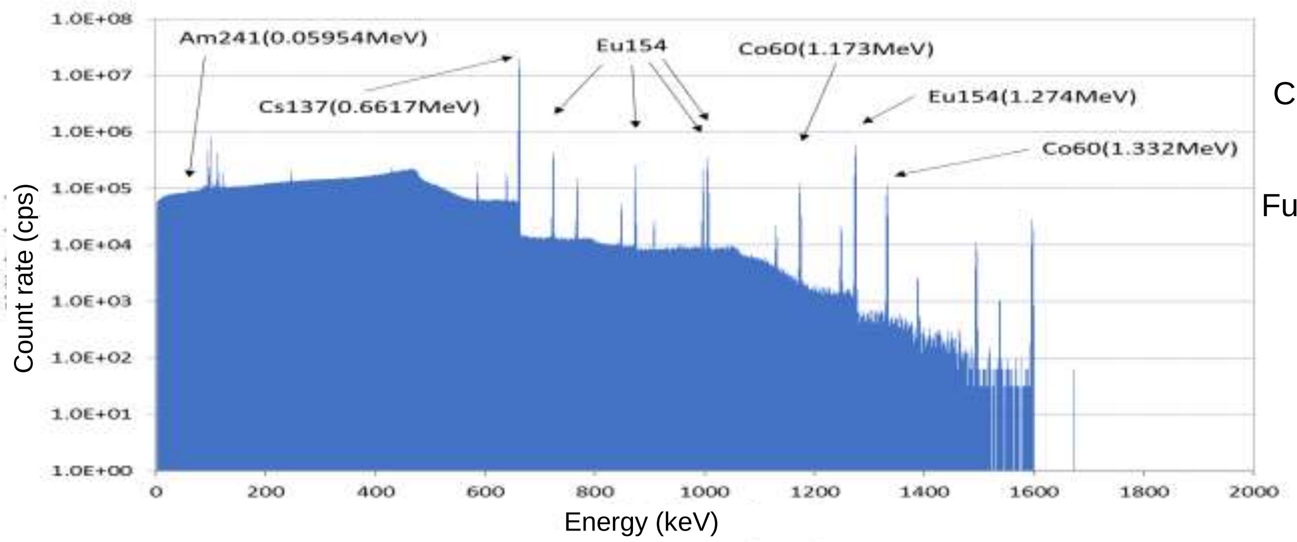
③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
  2.2.1 Passive neutrons
  2.2.2 Passive gamma
  2.2.3 Active neutrons
  2.2.4 Passive/active neutrons + passive gamma rays
  2.2.5 X-ray transmission measurement
  2.2.6 Cosmic rays scattering measurement

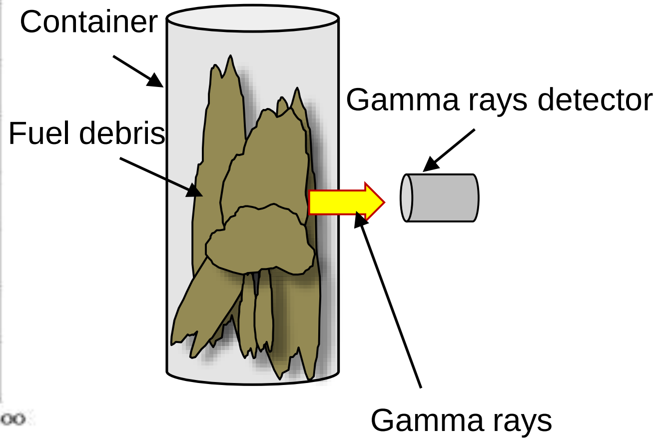
	① Fuel debris composition	Gd content	B content	MOX	② Burn-up	③ FP emission rate	④ Cooling period	⑤ Moisture content	⑥ Filling rate	⑦ Uneven distribution	⑧ Container	⑨ Irradiating radiation source	⑩ Detector
2.2.2 Passive γ	No.83 No.85 to 87 No.93	–	–	No.85 No.86 No.88 No.91	No.85 No.86 No.88	No.85 No.86 No.88	No.85 No.86 No.88 No.92	–	No.85 to 87	No.97 No.98	No.94 No.95	–	No.84 No.89 No.100 No.101

2.2.2 Passive gamma rays - Measurement concept

- Fuel debris contains gamma rays emitting nuclides (Am-241,Cs-137,Eu-154, etc.) originating from fuel and gamma rays emitting nuclides (C-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.
- Hence, **by determining the width to be measured by means of analytical evaluation, issues such as selection of the nuclides to be measured, the measurement range of the detector required for the measurement system, changeability of the measurement distance or shielding, collimator, etc. were identified.**



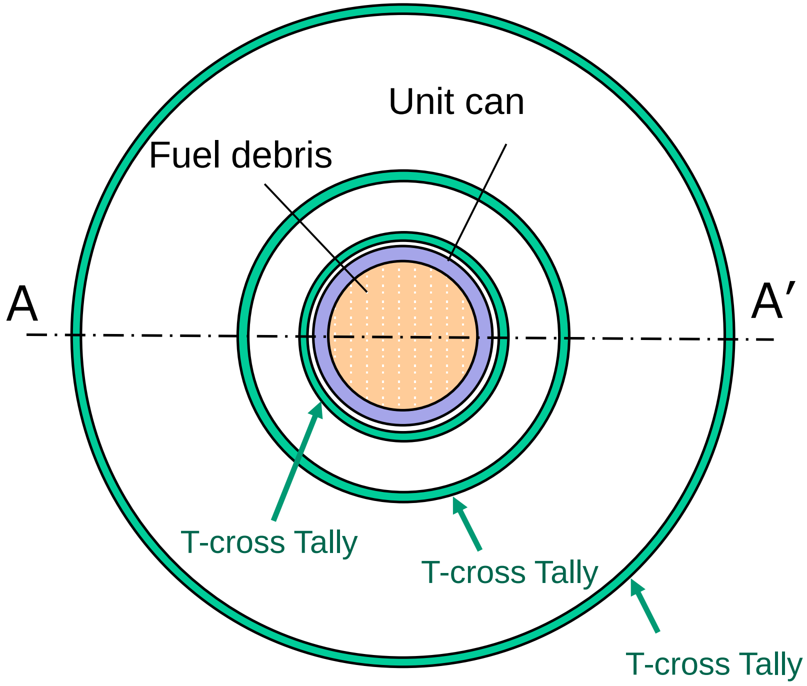
Example of analytical output (Ge detector)



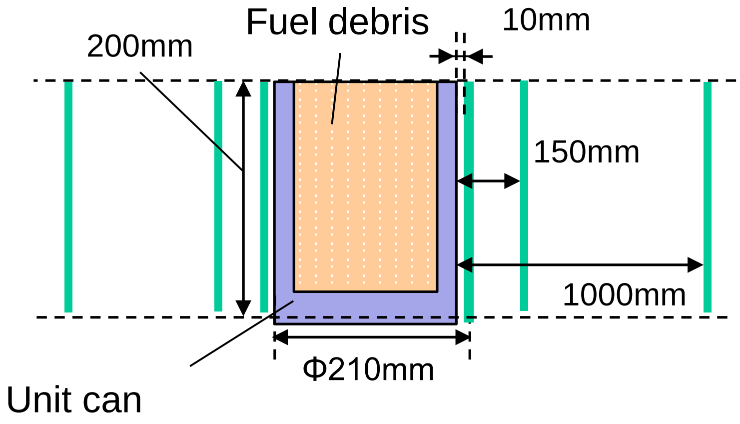
2.2.2 Passive gamma rays - Analysis model

In order to make it possible to study the changes in the radiation flux depending on the distance from the container, multiple layers of space were provided for cylindrical detectors at a fixed distance from the container (unit can, etc.).

→ The radiation dose rate calculated based on the changes in radiation flux will be used for selecting the detector, and studying the shielding, collimator, etc.



Analysis model top view



Cross-sectional view A-A'

2.2.2 Passive gamma rays - Table listing the analysis cases (1/2)

- Considering the analysis conditions described in No. 1-1 as the base case, the analysis conditions with changed influencing factors (No. 1-2 to 24) were assumed as the sensitivity analysis conditions. **All 24 cases**
- Influencing factors that changed from the base case under the sensitivity analysis conditions are highlighted blue. Here, the parameters that changed in association with the above-mentioned changes are indicated by yellow hatching.

Case No.	Composition inside the container*1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Changed parameter
	Type of fuel debris	Within the filing factor		Outside the filling factor						
		Composition	Total (Filling factor)							
1-1	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	UO_2 (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Base case
1-2		**UO_2 : 7.5vol%(25vol%) ZrO_2 : 22.5vol%(75vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (UO2, ZrO2)
1-3		**MOX : 30vol%**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**0GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	MOX
1-4		UO_2 : 5vol%(50vol%) ZrO_2 : 5vol%(50vol%)	**10vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Filling factor
1-5		UO_2 : 25vol%(50vol%) ZrO_2 :25vol%(50vol%)	**50vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Filling factor
1-6		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Burn-up
1-7		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**51GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Burn-up
1-8		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	**Zero emission**	20 years	Uniform	Unit can (Φ210mm x H200mm)	FP emission rate
1-9		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	**High emission**	20 years	Uniform	Unit can (Φ210mm x H200mm)	FP emission rate
1-10		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	**30 years**	Uniform	Unit can (Φ210mm x H200mm)	Cooling period
1-11	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	**40 years**	Uniform	Unit can (Φ210mm x H200mm)	Cooling period
1-12		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Center)**	Unit can (Φ210mm x H200mm)	Uneven distribution
1-13		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (Outer surface)**	Unit can (Φ210mm x H200mm)	Uneven distribution
1-14		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	**Canister (Φ220mm x H840mm, Thickness 10mm)**	Container
1-15		**UO_2 : 0.48vol%[3.7kg] SUS : 10vol%(95.4vol%)**	**10.48vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	**Waste storage container (Inner container □Φ500mm x H300mm)**	Container

2.2 Analysis results

2.2.2 Passive gamma rays - Table listing the analysis cases (2/2)

Case No.	Composition inside the container*1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Changed parameter
	Type of fuel debris	Within the filing factor		Outside the filling factor						
		Composition	Total (Filling factor)							
1-16	Uranium-rich	**UO_2 : 30vol%**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type)
1-17	Metallic debris	**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type)
1-18		UO_2 : 15vol%(25vol%) ZrO_2 : 15vol%(25vol%) **SUS : 30vol%(50vol%)**	**60vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (SUS)
1-19	MCCI	**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type)
1-20		UO_2 : 15vol%(25vol%) ZrO_2 : 15vol%(25vol%) **Concrete : 30vol%(50vol%)**	**60vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	Fuel debris composition (Concrete)
1-21	Metallic debris	**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (center)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution
1-22		**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (outer surface)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution
1-23	MCCI	**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (center)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution
1-24		**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (outer surface)**	Unit can (Φ210mm x H200mm)	Fuel debris composition (Type) Uneven distribution

*1 : Percentage inside the container. Percentage, when 100% is considered to be within the filling rate, is mentioned inside parentheses.

2.2 Analysis results

2.2.2 Passive gamma rays - Table listing the analysis cases

- Sensitivity analysis related to the following analysis conditions was conducted, and the trend with respect to each influencing factor has been consolidated.

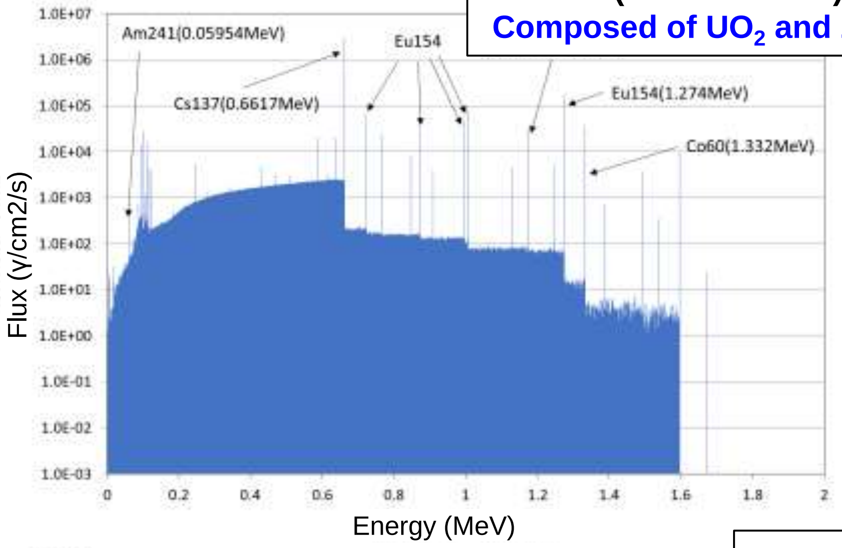
Case		UO_2	ZrO_2	SUS	Concrete	Total (Filling rate)	Burn-up (GWd/t)	FP emission rate	Cooling period (Years)	Remarks U content considered as the analysis condition
1-1	Base	15vol%	15vol%	0vol%	-	30vol%	23.0	Standard	20	8.79kg
1-2	Molten debris (Small quantity of U)	7.5vol%	22.5vol%	0vol%	-	30vol%	23.0	Standard	20	4.39kg
1-3	MOX	MOX 30vol%	0vol%	0vol%	-	30vol%	0.0	Standard	20	17.0kg
1-4	Filling rate (low)	5vol%	5vol%	0vol%	-	10vol%	23.0	Standard	20	2.93kg
1-5	Filling rate (high)	25vol%	25vol%	0vol%	-	50vol%	23.0	Standard	20	14.6kg
1-6	Burn-up (low)	15vol%	15vol%	0vol%	-	30vol%	1.3	Standard	20	8.98kg
1-7	Burn-up (high)	15vol%	15vol%	0vol%	-	30vol%	51.0	Standard	20	8.58kg
1-8	FP emission rate	15vol%	15vol%	0vol%	-	30vol%	23.0	Zero emission	20	8.77kg
1-9	FP emission rate	15vol%	15vol%	0vol%	-	30vol%	23.0	High emission	20	8.82kg
1-10	Cooling period	15vol%	15vol%	0vol%	-	30vol%	23.0	Standard	30	8.79kg
1-11	Cooling period	15vol%	15vol%	0vol%	-	30vol%	23.0	Standard	40	8.79kg
1-16	Molten debris (Uranium-rich)	30vol%	0vol%	0vol%	-	30vol%	23.0	Standard	20	17.6kg
1-17	Metallic debris	0.075vol%	0.075vol%	29.85vol%	-	30vol%	23.0	Standard	20	0.04kg
1-19	MCCI debris	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	23.0	Standard	20	0.615kg

2.2 Analysis results

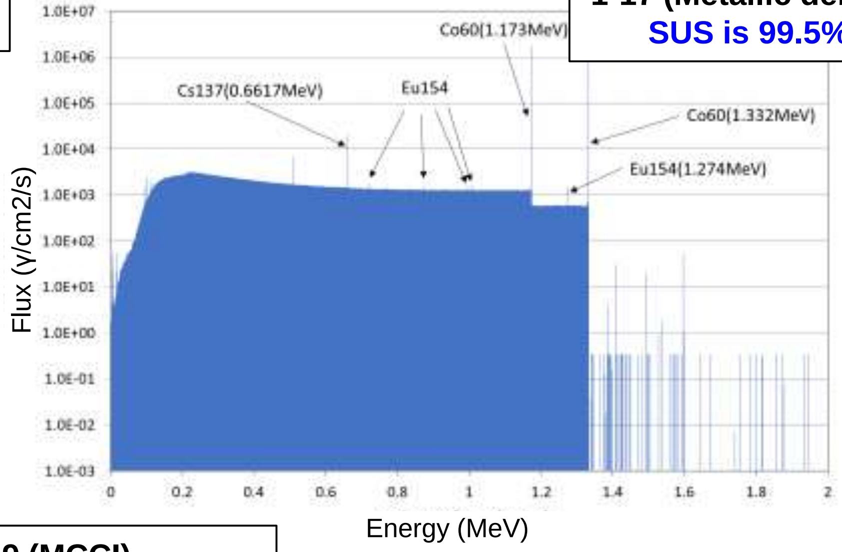
2.2.2 Passive gamma rays - Analysis results (1/7)

Flux at a position that is 100cm away from the container surface - Analysis of sensitivity to the type of fuel debris

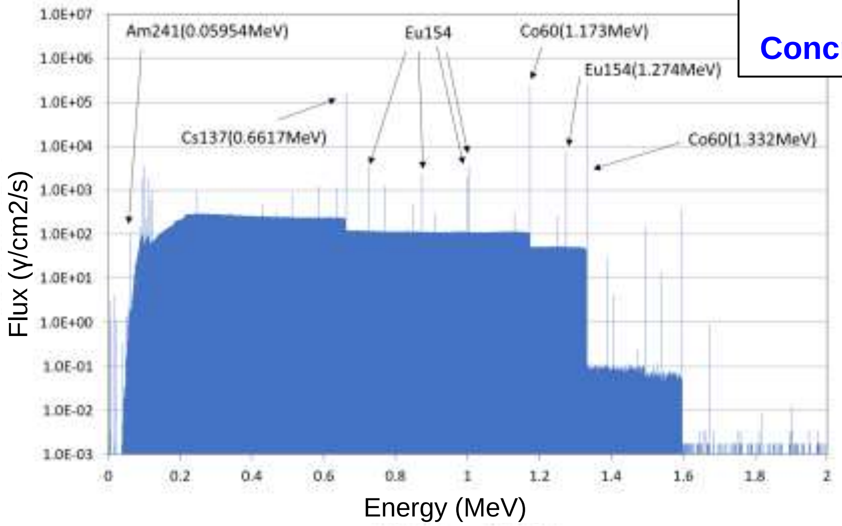
1-1 (Molten debris)
Composed of UO_2 and ZrO_2



1-17 (Metallic debris)
SUS is 99.5%



1-19 (MCCI)
Concrete 69% and SUS 24%



Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate
1-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%
1-17	Metallic debris	0.075vol% (0.25vol%)	0.075vol% (0.25vol%)	29.85vol% (99.5vol%)	0vol%	30vol%
1-19	MCCI	1.05vol% (3.5vol%)	1.05vol% (3.5vol%)	7.2vol% (24vol%)	20.7vol% (69vol%)	30vol%

Flux spectrum largely differed in the case of molten debris, metallic debris and MCCI.

→ Evaluation was carried out using the above-mentioned flux, focusing on the dose rate and the peak of Eu-154 (1.27MeV).

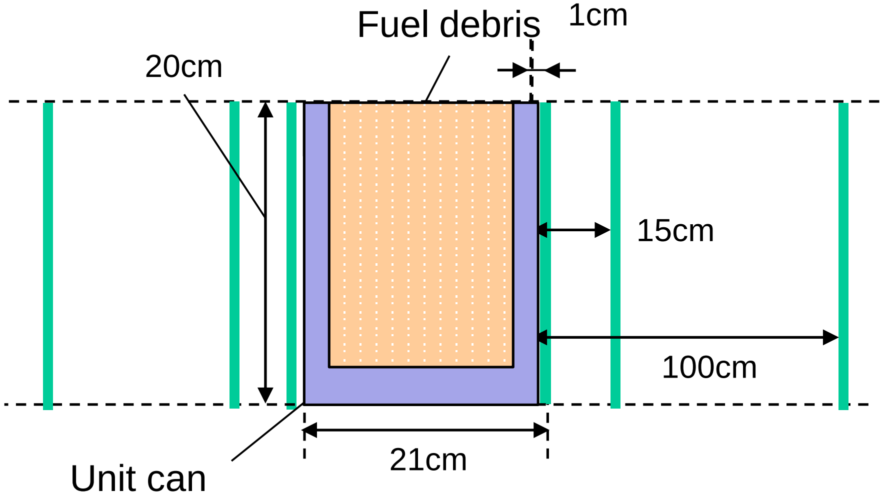
2.2.2 Passive gamma rays - Analysis results (2/7)

Changes in flux depending on distance from the center of the container

In order to study the placement of the detector based on the dose rate, the changes in the flux from the container surface were evaluated.

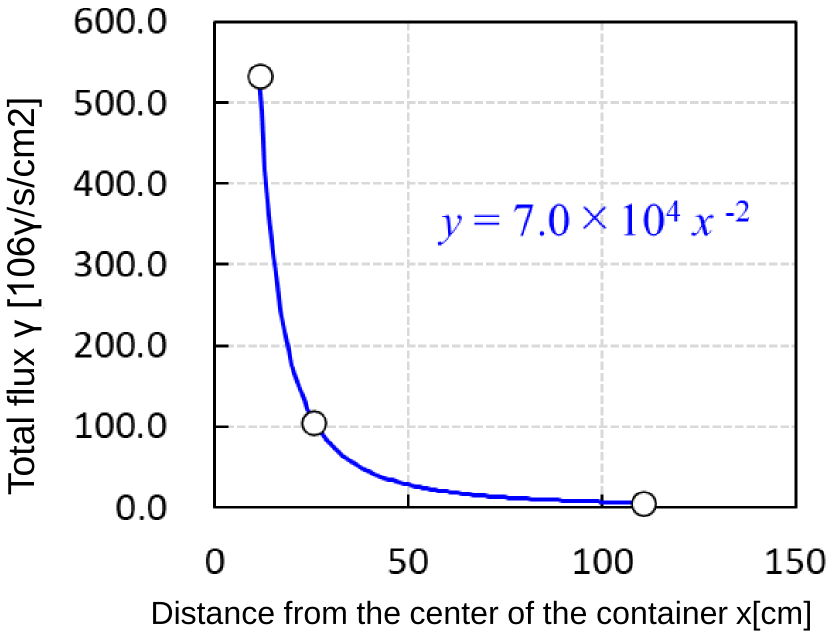
Evaluation was carried out based on the flux from a distance of 1cm, 15cm and 100cm from the container surface by fitting the detector.
→ Changes in the flux are proportional to the square of the distance from the center of the container.

Simulation system



Distance [cm] from the container surface	Distance [cm] from the center of the container	Total flux [γ/s/cm^2]
1	11.5	5.3×10^{8}
15	25.5	1.0×10^{8}
100	115.5	5.2×10^{6}

Changes in flux from the center of the container

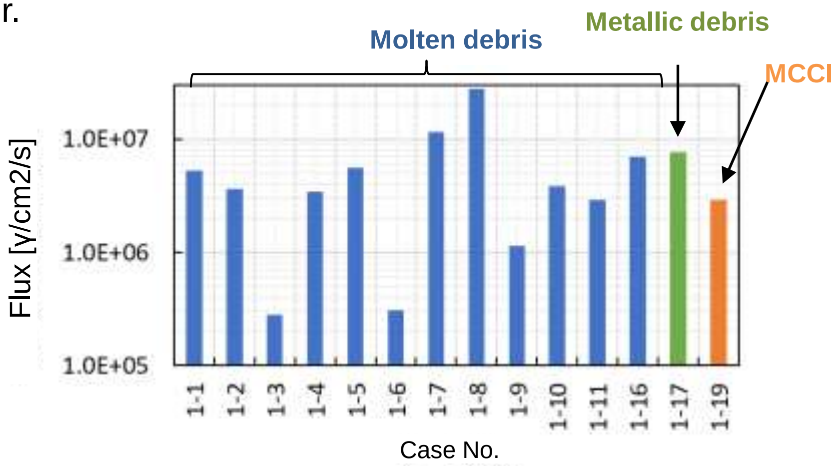


2.2.2 Passive gamma rays - Analysis results (3/7)

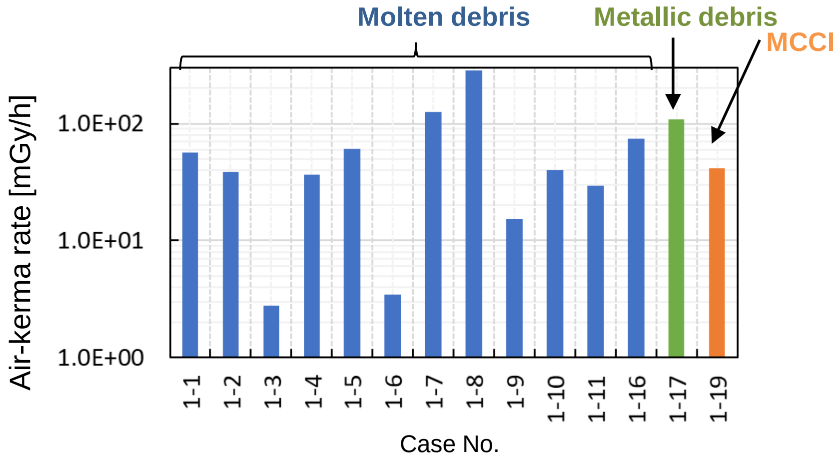
Conversion of flux to air kerma rate

Conversion of flux [γ/cm^2/s] to air kerma rate [mGy/h]

- The placement, shielding, etc. of the gamma rays detector was used for evaluating the impact of gamma rays on the neutron detector.



Flux [γ/cm^2/s] at a position that is 100cm from the container surface



Air kerma rate [mGy/h] at a position that is 100cm from the container surface

Linear interpolation of the conversion coefficient using JAEA data as reference

JAERI-Data/Code 2000-044
Shielding Calculation Constants for Use in Effective Dose Evaluation for Photons, Neutrons, and Bremsstrahlung from Beta-rays

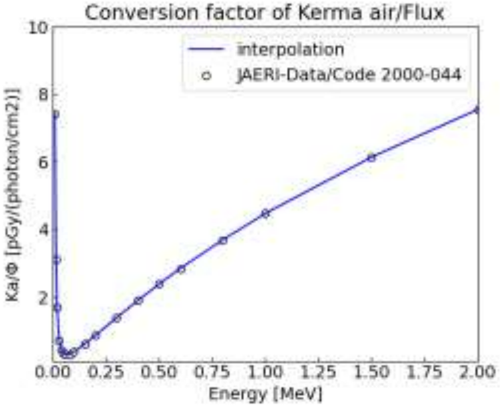
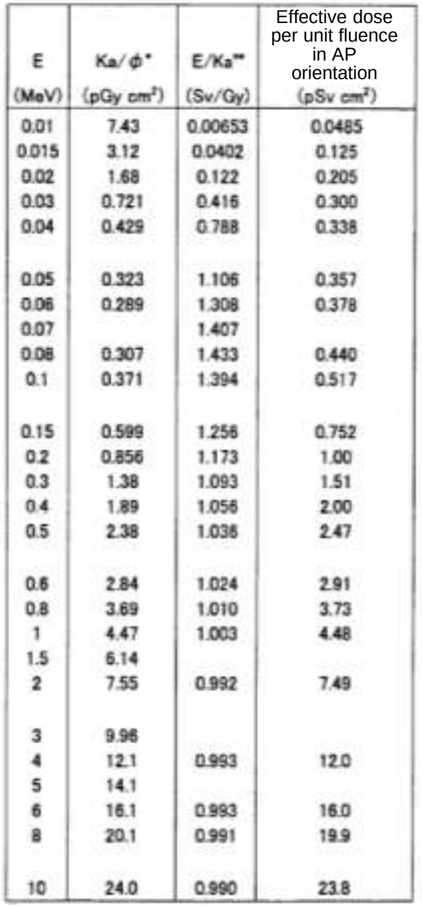


Table 3.3 Dose Conversion Coefficients for converting photons into effective dose in AP orientation



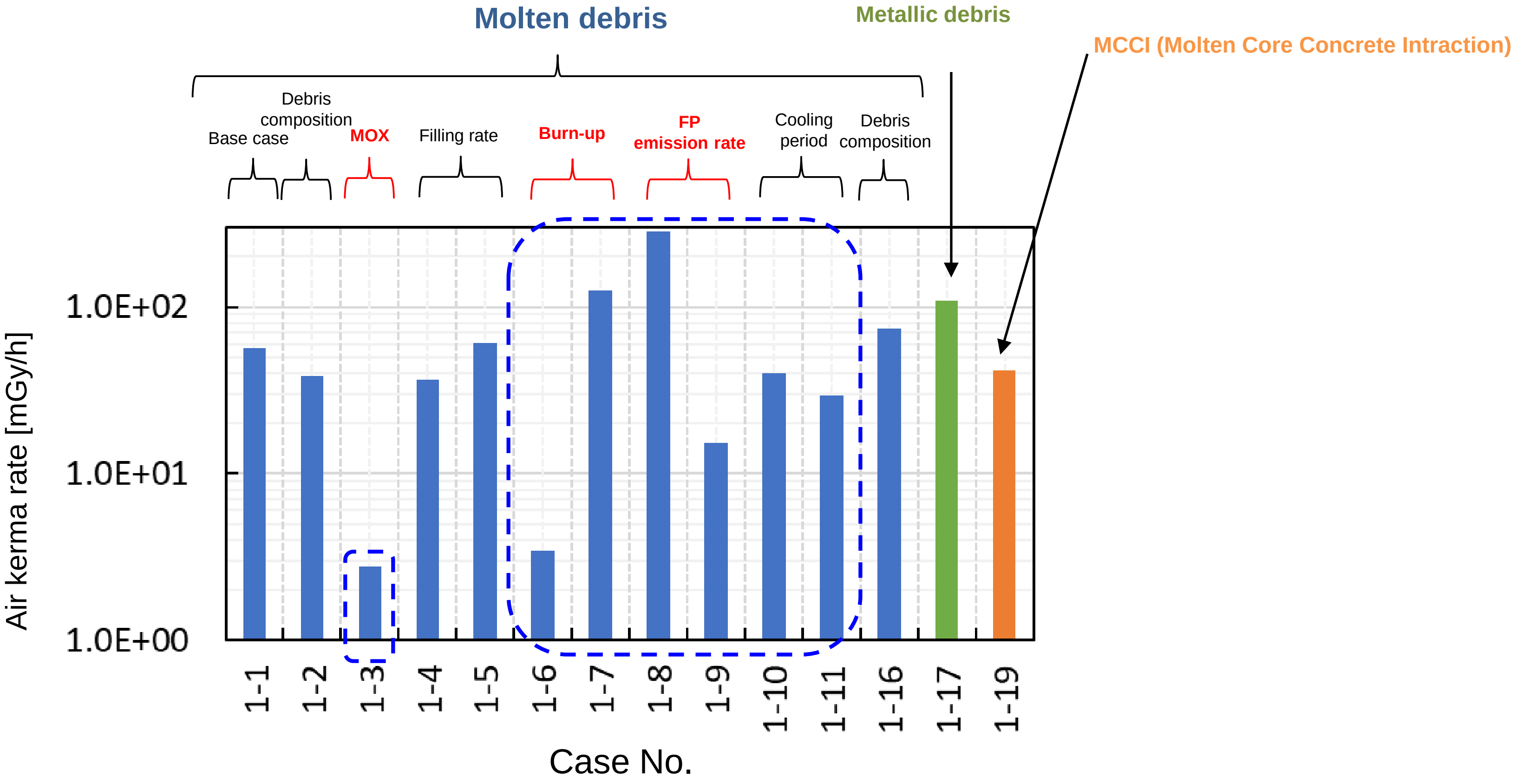
E (MeV)	Ka/φ* (pGy cm^2)	E/Ka** (Sv/Gy)	Effective dose per unit fluence in AP orientation (pSv cm^2)
0.01	7.43	0.00653	0.0485
0.015	3.12	0.0402	0.125
0.02	1.68	0.122	0.205
0.03	0.721	0.416	0.300
0.04	0.429	0.788	0.338
0.05	0.323	1.106	0.357
0.06	0.289	1.308	0.378
0.07		1.407	
0.08	0.307	1.433	0.440
0.1	0.371	1.394	0.517
0.15	0.599	1.256	0.752
0.2	0.856	1.173	1.00
0.3	1.38	1.093	1.51
0.4	1.89	1.056	2.00
0.5	2.38	1.036	2.47
0.6	2.84	1.024	2.91
0.8	3.69	1.010	3.73
1	4.47	1.003	4.48
1.5	6.14		
2	7.55	0.992	7.49
3	9.96		
4	12.1	0.993	12.0
5	14.1		
6	16.1	0.993	16.0
8	20.1	0.991	19.9
10	24.0	0.990	23.8

*) Conversion coefficient for air kerma
**) Effective dose in AP orientation per unit air kerma in free air

2.2.2 Passive gamma rays - Analysis results (4/7)

Evaluation of air kerma rate

Air kerma rate [mGy/h] at a position that is 100cm from the container surface (Repeated)



Air kerma rate fluctuations were larger when the fuel-based parameters were changed than when the fuel debris composition was changed.

→ In particular, the dose rate largely changes due to the effect of MOX, burn-up and FP emission rate.

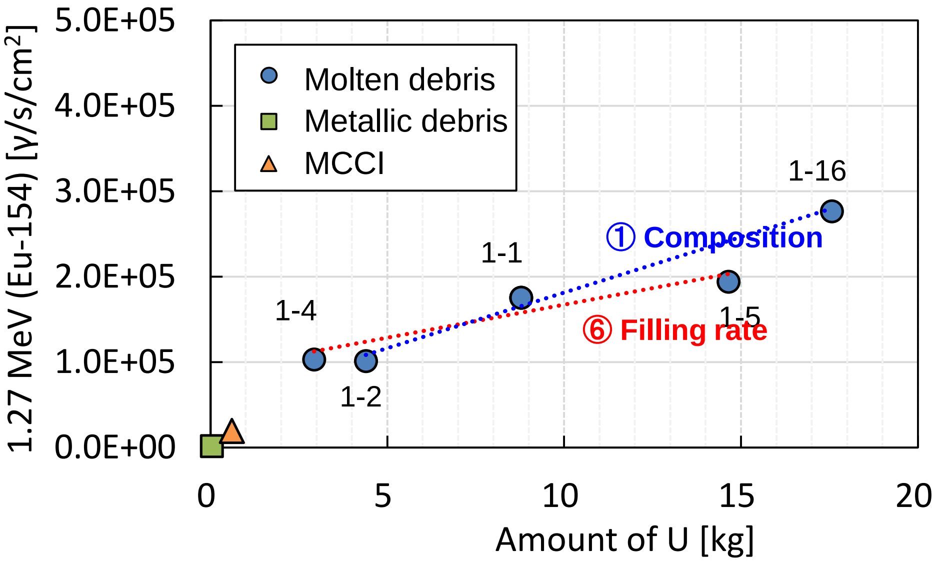
2.2.2 Passive gamma rays - Analysis results (5/7)

Eu-154 (fuel debris composition) with respect to the amount of U

Passive gamma rays analysis results (Analysis performed by changing ① **Fuel debris composition** and ⑥ **Filling rate)**

Case No.	Fuel debris Type	Filling rate (vol.%)	Entire fuel debris (kg)	Amount of U* (kg)	Total flux [γ/s/cm^2]	1.27MeV peak (Eu-154) [γ/s/cm^2]
1-1	Molten debris	30	15.8	8.79	5.23×10^6	1.77×10^5
1-2	Molten debris	30	13.4	4.39	3.63×10^6	1.01×10^5
1-4	Molten debris	10	5.28	2.93	3.40×10^6	1.03×10^5
1-5	Molten debris	50	26.4	14.6	5.63×10^6	1.94×10^5
1-16	Molten debris	30	20.5	17.6	6.93×10^6	2.77×10^5
1-17	Metallic debris	30	15.6	0.0439	7.63×10^6	1.50×10^3
1-19	MCCI	30	7.71	0.615	1.08×10^6	7.15×10^3

*Amount of U = Total mass of Uranium isotopes
MCCI: Molten Core Concrete Interaction



← Flux of 1.27 MeV (Eu-154) with respect to amount of U

If only fuel debris composition and filling rate were changed, the flux of Eu-154 peak was proportionate to the amount of U.

→ There is a possibility of being able to **perform quantitative evaluation of the amount of U based on the gamma rays from Eu-154**

2.2 Analysis results

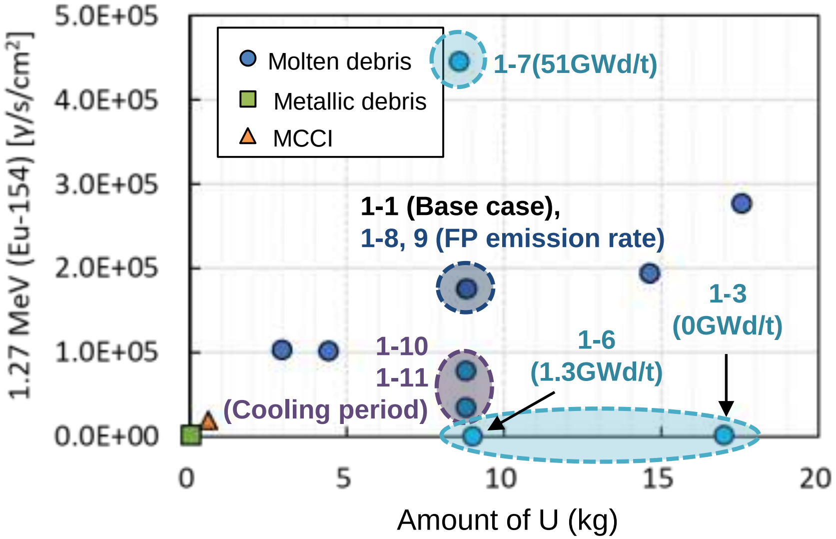
2.2.2 Passive gamma rays - Analysis results (6/7)

Eu-154 (fuel based) with respect to the amount of U

Passive gamma rays analysis results (Analysis performed by changing ② **Burn-up, ③ FP emission rate and ④ Cooling period)**

Case No.	Burn-up [GWd/t]	FP emission rate	Cooling period [Years]	Entire fuel debris (kg)	Amount of U*1 (kg)	Total flux [γ/s/cm^2]	1.27MeV peak (Eu-154) [γ/s/cm^2]
1-1	**23**	Standard	20	15.8	8.79	5.23×10^{6}	1.75×10^{5}
1-3	**0*2**	Standard	20	20.3	17.0	2.80×10^{5}	1.02×10^{3}
1-6	**1.3**	Standard	20	15.8	8.98	3.06×10^{5}	5.92×10^{2}
1-7	**51**	Standard	20	15.8	8.58	1.16×10^{6}	4.45×10^{5}
1-8	23	**Zero emission**	20	15.8	8.77	2.81×10^{7}	1.76×10^{5}
1-9	23	**High emission**	20	15.8	8.82	1.15×10^{6}	1.75×10^{5}
1-10	23	Standard	**30**	15.8	8.79	3.81×10^{6}	7.84×10^{4}
1-11	23	Standard	**40**	15.8	8.79	2.89×10^{6}	3.50×10^{4}

*1 Amount of U = Total mass of Uranium isotopes, *2 The MOX fuel in Case no. 1-3 has extremely low burn-up



← Flux of 1.27 MeV (Eu-154) with respect to amount of U

Even when fuel debris composition ratio was the same, **when burn-up changed the correlation between Eu-154 and amount of U deteriorated.**
(Eu-154 affects the quantitative evaluation of the amount of U in the order of Burn-up > Cooling period > FP emission rate.)

2.2 Analysis results

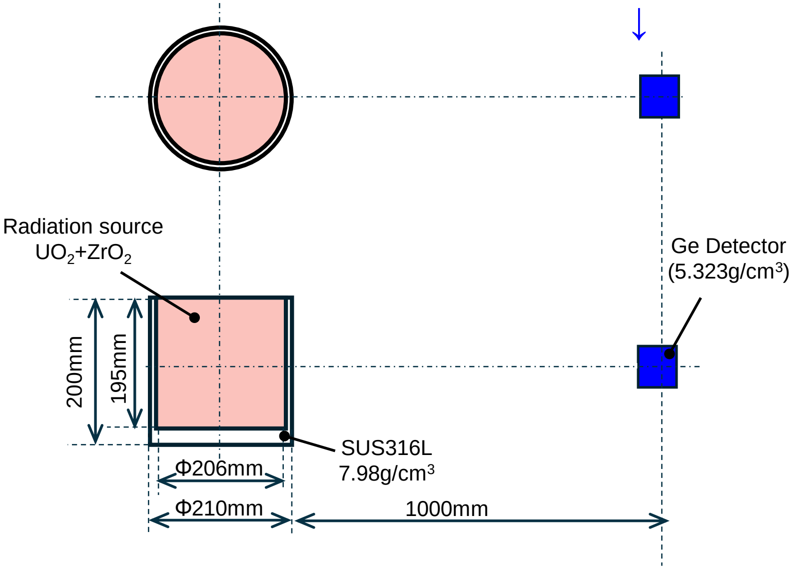
2.2.2 Passive gamma rays - Analysis results (7/7)

Response spectrum for a representative detector (Example of output for identifying issues)

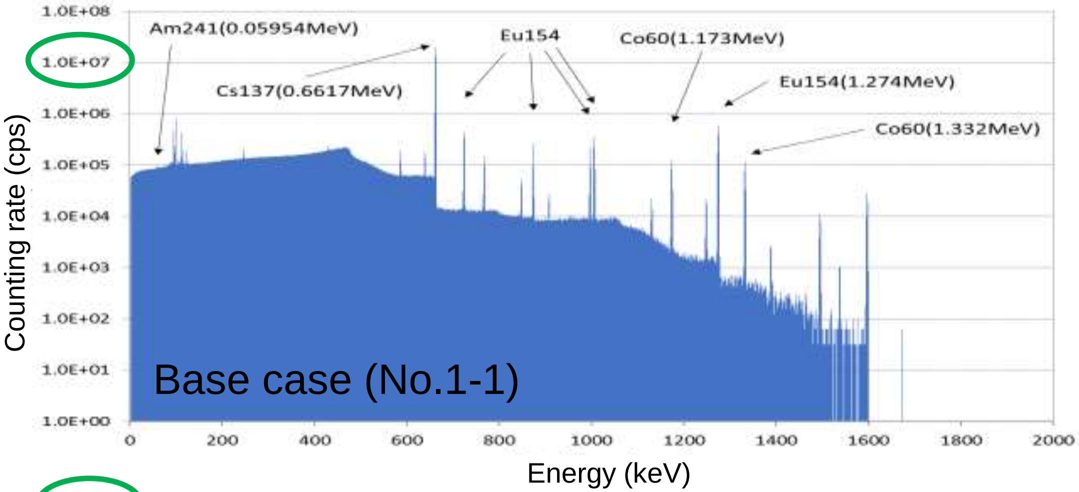
- representative detector: High purity germanium semiconductor detector
- Size and shape of detector : 3 inch cylindrical detector
- Distance up to the detector: 1000mm (From outer surface of the unit can to the center of the detector)

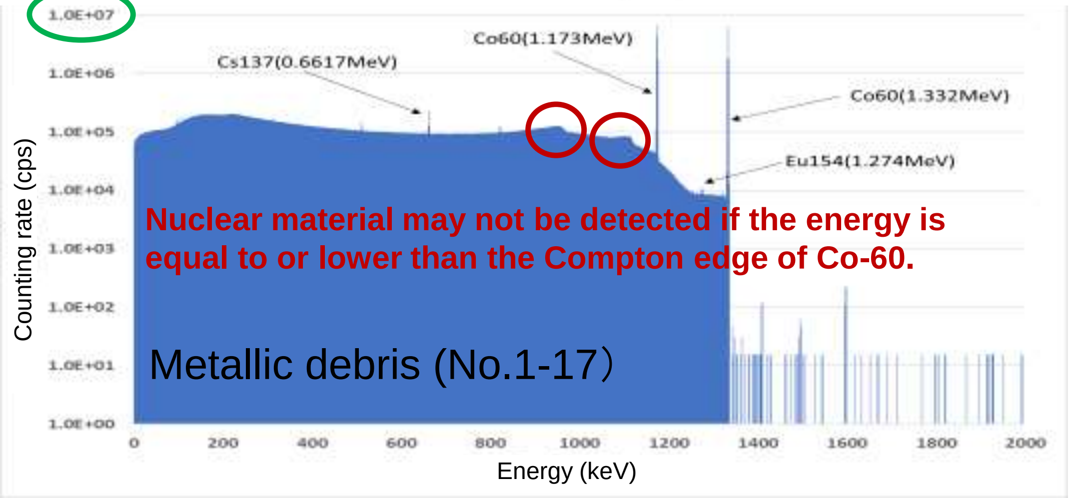
<Analysis model>

Lead collimator was required because of a high count rate



<Detector response>





Nuclear material may not be detected if the energy is equal to or lower than the Compton edge of Co-60.

Further, if Eu-154 is not co-present with U, nuclear material cannot be detected.

2.2.2 Passive gamma rays – Other sensitivity analyses (1/6)

The sensitivity to incident beams was studied with respect to the following influencing factors:

- MOX
- Cooling period
- Shape of container
- Implementation of analysis related to fluctuations in fuel debris composition (SUS)

Case No.	UO_2	ZrO_2	SUS	Total (Filling rate)	Other conditions	Remarks
1-1	15vol%	15vol%	0vol%	30vol%	-	Base
1-2	7.5vol%	22.5vol%	0vol%	30vol%	-	Molten debris
1-3	0vol%	15vol%	0vol%	30vol%	$Pu0_2$: 15vol%	MOX
1-10	15vol%	15vol%	0vol%	30vol%	Cooling period: 30 years	Cooling period
1-11	15vol%	15vol%	0vol%	30vol%	Cooling period: 40 years	
1-14	15vol%	15vol%	0vol%	30vol%	Canister (Φ220mm × H840mm)	Shape of container
1-15	15vol%	15vol%	0vol%	30vol%	Waste storage container	
1-16	30vol%	0vol%	0vol%	30vol%	-	Molten debris
1-17	0.075vol%	0.075vol%	29.85vol%	30vol%	-	Metallic debris
1-18	15vol%	15vol%	30vol%	60vol%		Metallic debris

2.2 Analysis results

2.2.2 Passive gamma rays – Other sensitivity analyses (2/6)

➢ Impact due to difference in UO_2 fuel and MOX fuel

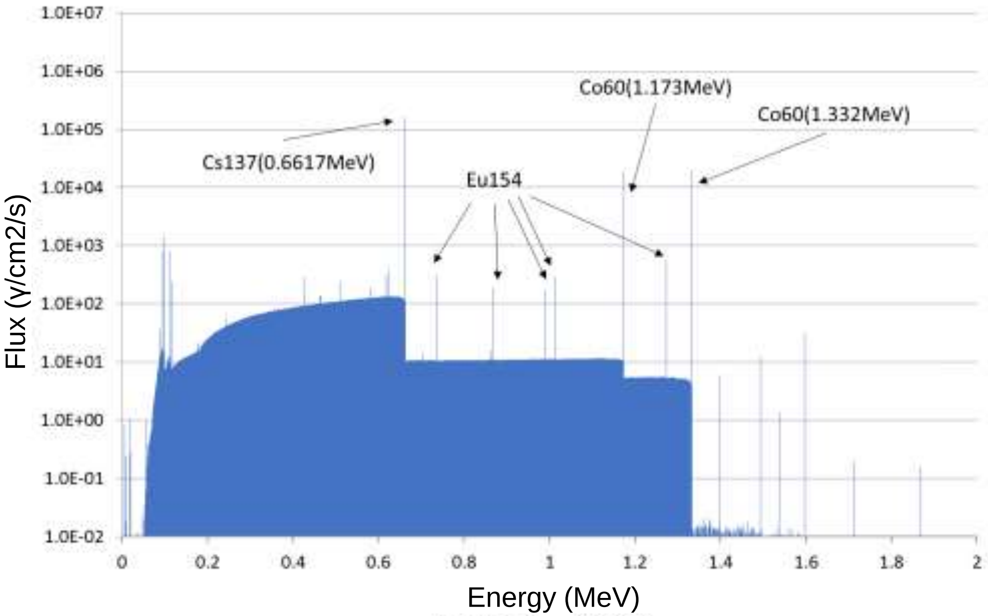
Other common conditions:

- FP emission rate: Standard
- Moisture content 1wt%
- Homogeneous model
- Container: Unit can

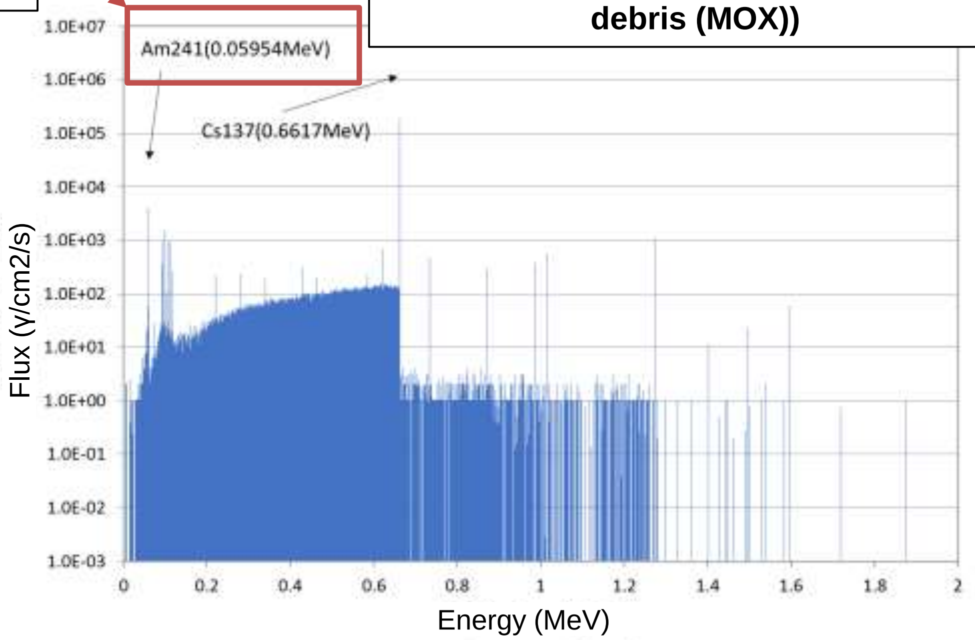
・Am-241 peak generated by Pu contained in MOX was seen.
(However, from the perspective of detector response,
it may not be detected as it is hidden in the Compton zone of Cs-137.)

Case No.	Type of fuel debris	UO_2	ZrO_2	PuO_2	Filling rate	Burn-up
1-6	Molten debris	15vol%	15vol%	0vol%	30vol%	1.3GWd/t
1-3		0vol%	0vol%	30vol%	30vol%	0GWd/t

Flux at 100cm from the container surface



1-6 (Low burn-up of molten debris (UO_2))



1-3 (Extremely low burn-up of molten debris (MOX))

2.2.2 Passive gamma rays – Other sensitivity analyses (3/6)

➢ Impact due to difference in cooling period

- Incident flux **attenuated based on the half-life** specific to the nuclide.

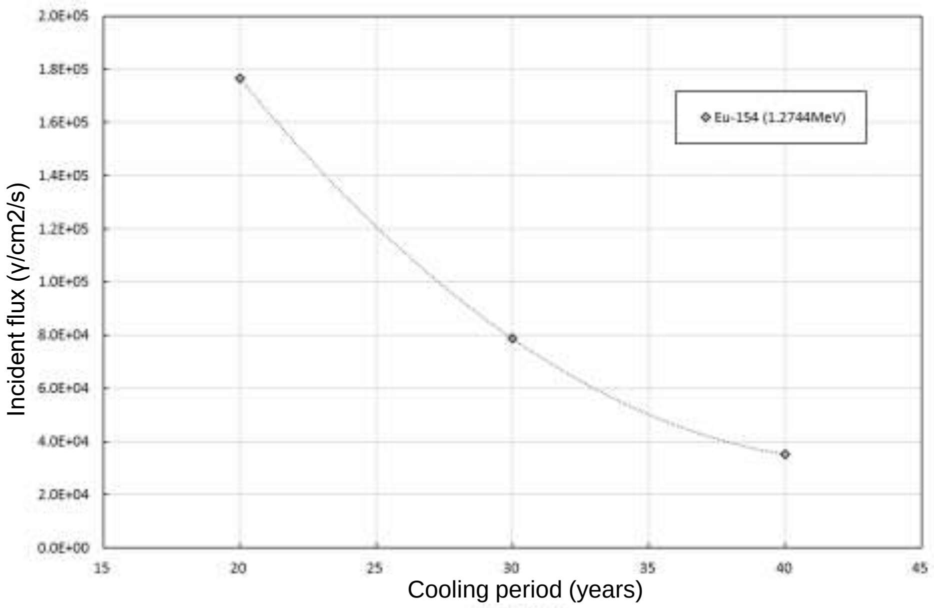
Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate	Cooling period
1-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	20 years
1-10		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	30 years
1-11		15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%	40 years

Other common conditions:

- Burn-up 23GWd/t
- FP emission rate: Standard
- Moisture content 1wt%
- Homogeneous model
- Container: Unit can

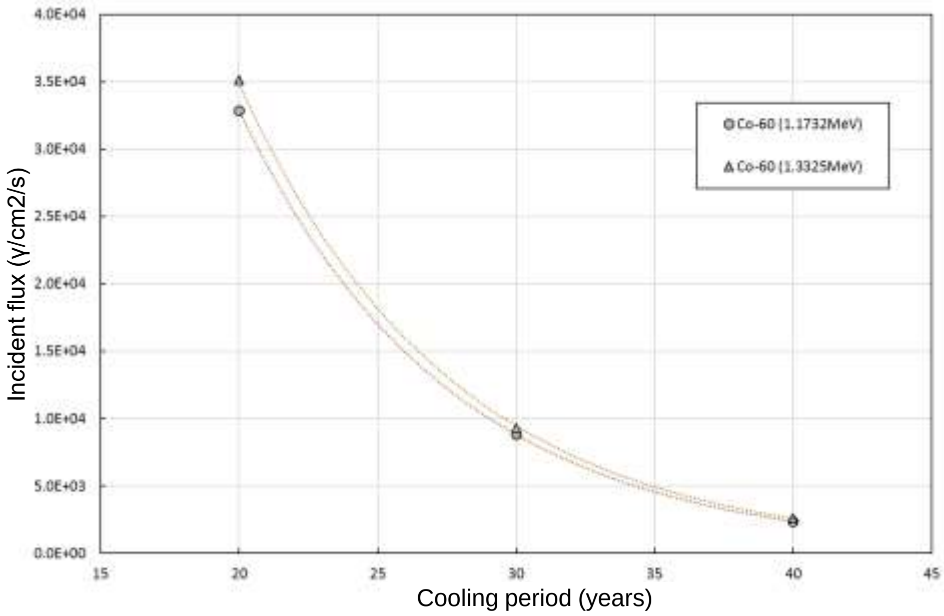
Flux at 100cm from the container surface

Eu-154



Half-life: approx. 8.6 years
⇒ Attenuates approx. 1/5 times in 20 years

Co-60



Half-life: approx. 5.3 years
⇒ Attenuates approx. 1/14 times in 20 years

2.2.2 Passive gamma rays – Other sensitivity analyses (4/6)

➢ Impact due to difference in SUS content

・As apparent density increased, incident flux decreased due to the self-shielding effect.

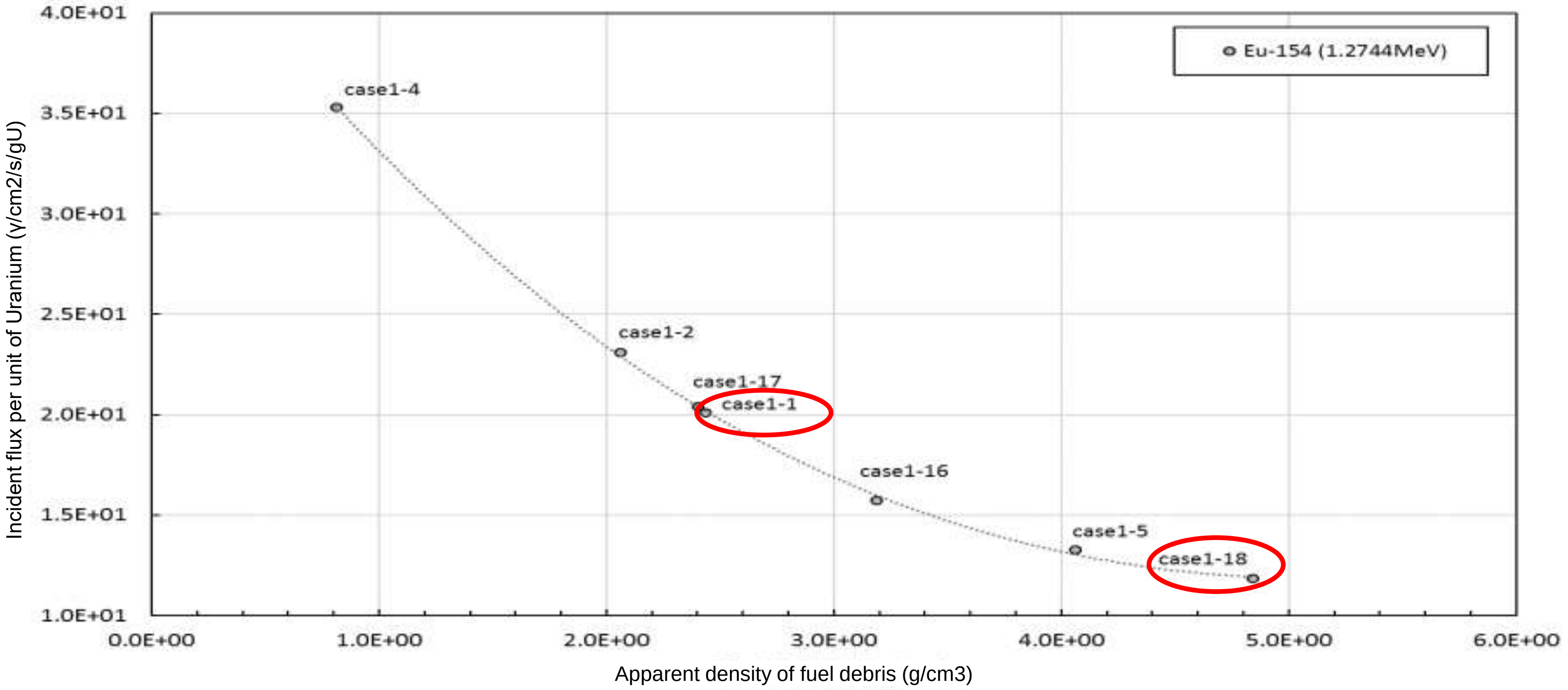
Flux at 100cm from the container surface

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate
1-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%
1-18	Metallic debris	15vol% (25vol%)	15vol% (25vol%)	30vol% (50vol%)	0vol%	60vol%

Other common conditions:

- ・Burn-up 23GWd/t
- ・FP emission rate: Standard
- ・Moisture content 1wt%
- ・Homogeneous model
- ・Container: Unit can

Fuel debris apparent density and incident flux per unit of Uranium



2.2 Analysis results

2.2.2 Passive gamma rays – Other sensitivity analyses (5/6)

Waste storage container (Inner container)（No. 1-15）

- **Impact due to difference in shape of container**

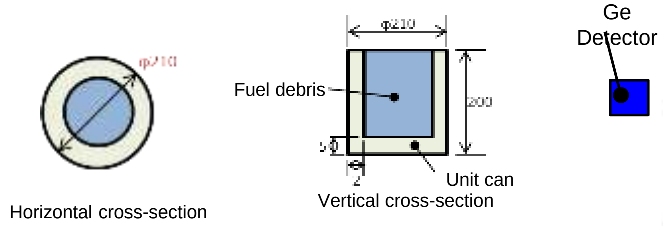
・Since the container was larger than the unit can as well, incident flux decreased due to self-shielding effect.

Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Filling rate	Container
1-4	Molten debris	5vol%	5vol%	0vol%	10vol%	Unit can
1-15	Metallic Waste	0.5vol% （3.7kg)	0vol%	10vol%	10.5vol%	Waste container (Inner container)

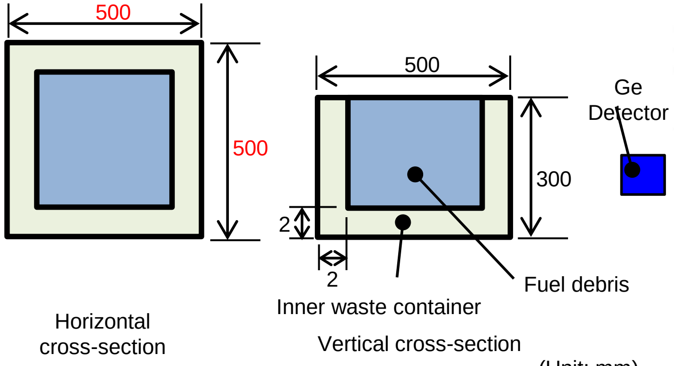
Other common conditions:

- ・Burn-up 23GWd/t
- ・FP emission rate: Standard
- ・Moisture content 1wt%
- ・Cooling period: 20 years
- ・Homogeneous model

<Unit can>

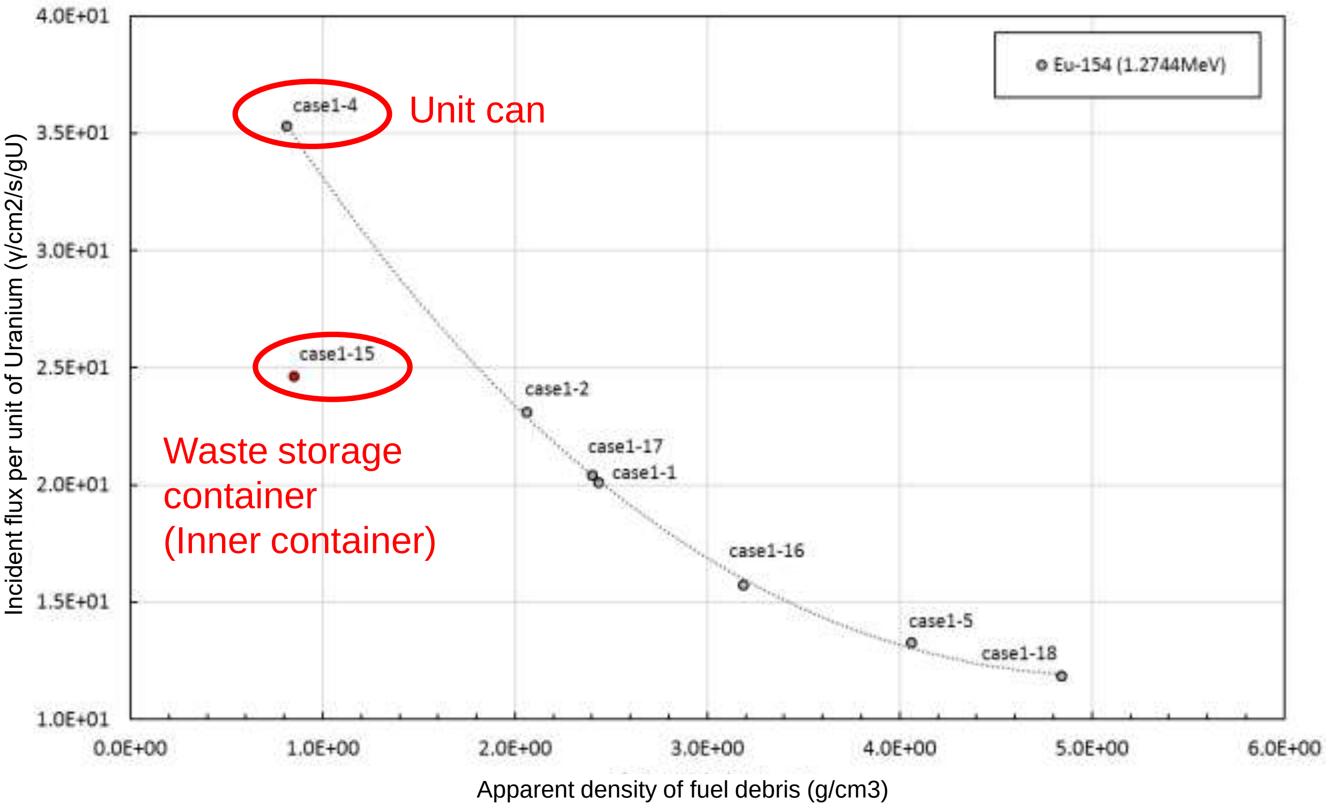


<Waste container (Inner container)>



(Unit: mm)

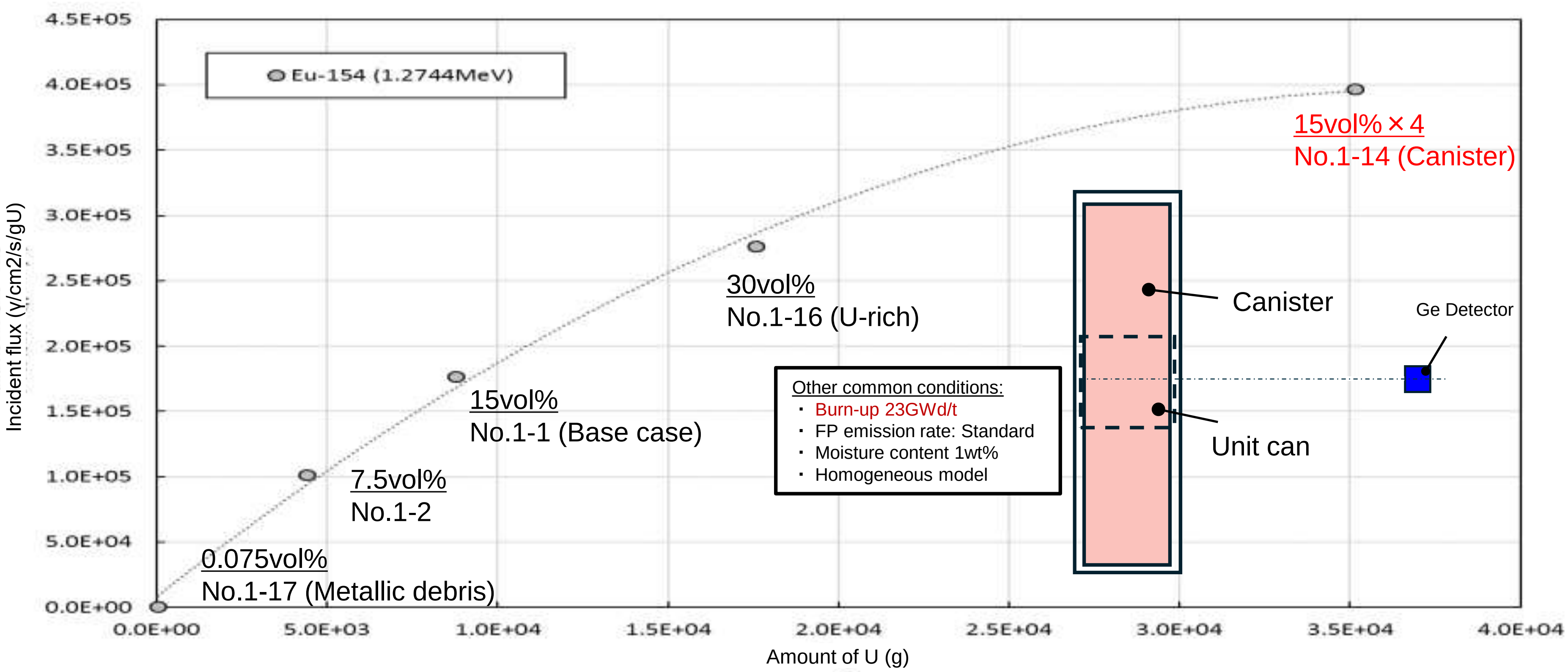
Fuel debris apparent density and incident flux per unit of Uranium



2.2.2 Passive gamma rays – Other sensitivity analyses (6/6)

➢ Impact due to difference in shape of container

Relation between U content and incident flux (at 100cm from the container surface)



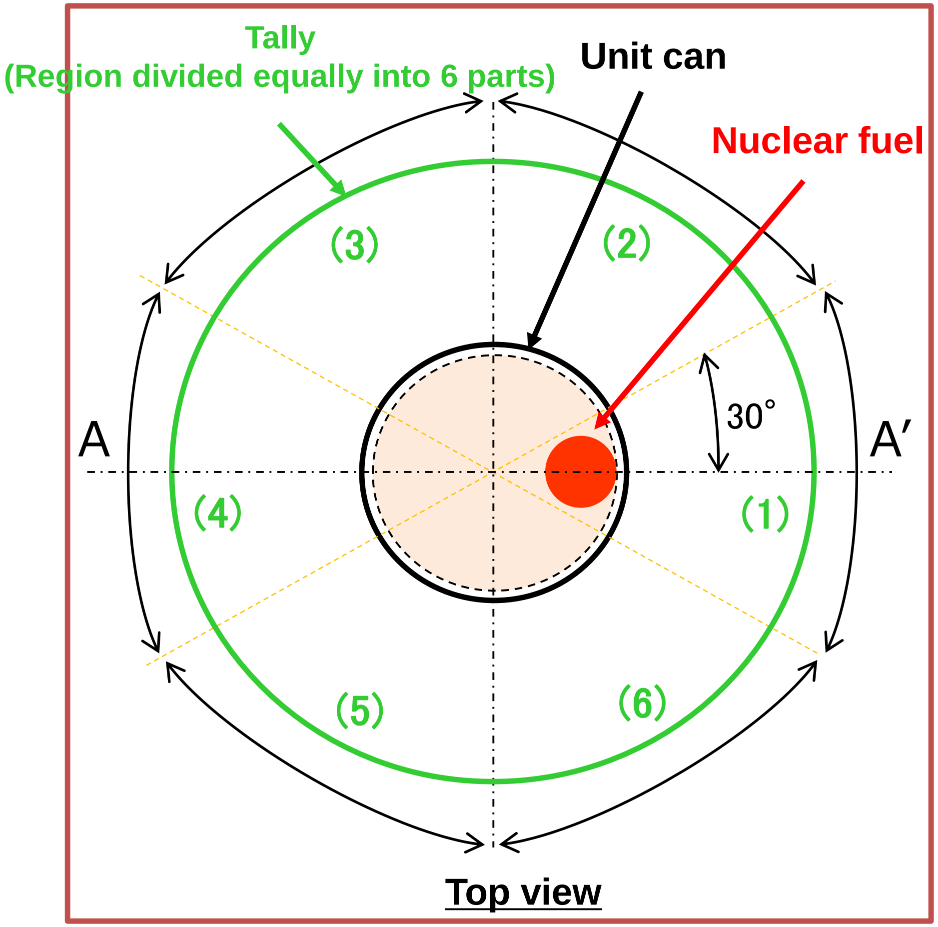
Other common conditions:
- Burn-up 23GWd/t
- FP emission rate: Standard
- Moisture content 1wt%
- Homogeneous model

- Amount of U and the entire incident flux had a positive correlation.
- The incident flux peaked due to the impact of the self-shielding effect caused by variations in fuel debris density (filling rate).
- **In the case of the canister (Φ220mm×H840mm),** since the detector was far away for the gamma rays coming from the top and bottom ends of the container, and since the canister had thick walls of 10mm, **the incident flux peaked further.**

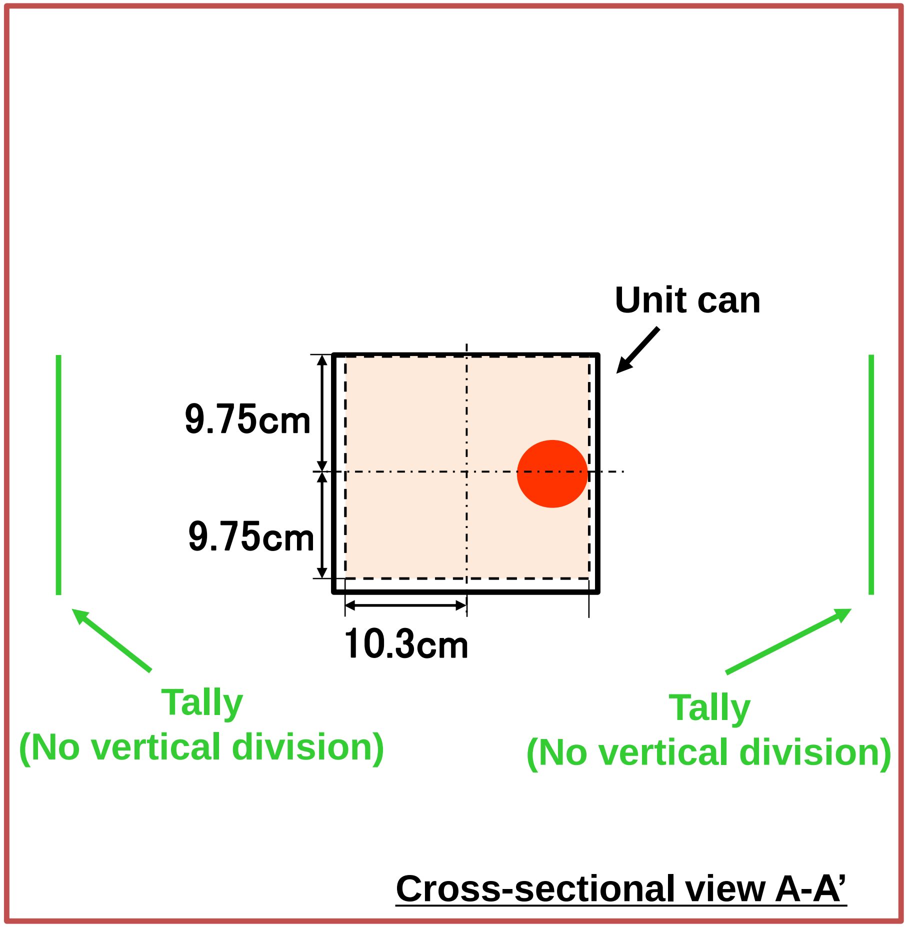
2.2.2 Passive gamma rays - Sensitivity analyses Uneven distribution (1/3)

Analysis by changing the method of filling fuel debris in the container

■Tally settings of the uneven distribution cases #The tally was divided into 6 parts for the horizontal direction (outer surface) cases only.



Top view



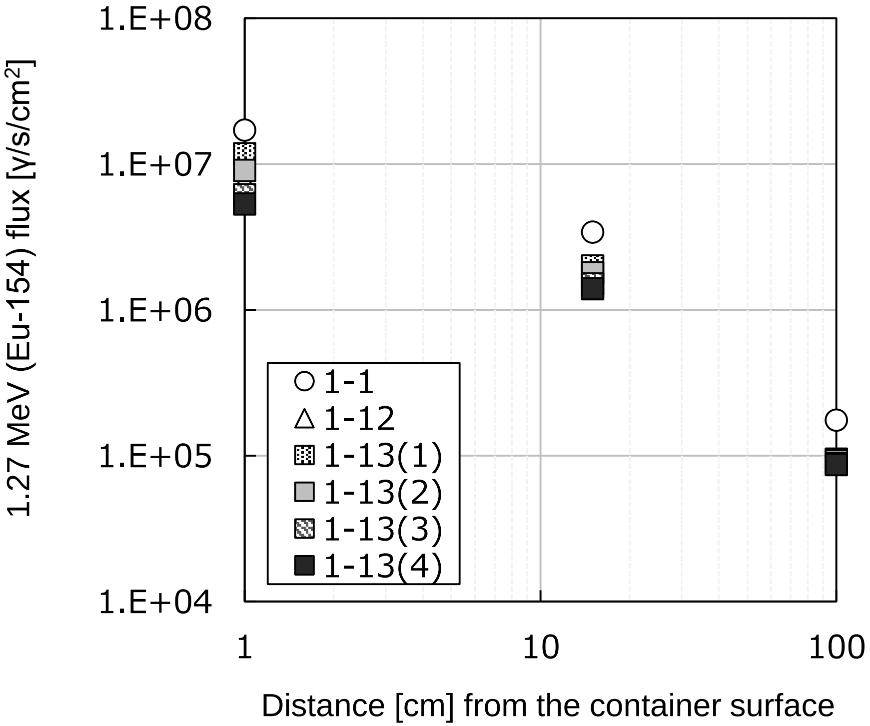
Cross-sectional view A-A'

The location and dimensions for installing the tally for the unit can are the same as described in slide No. 79.

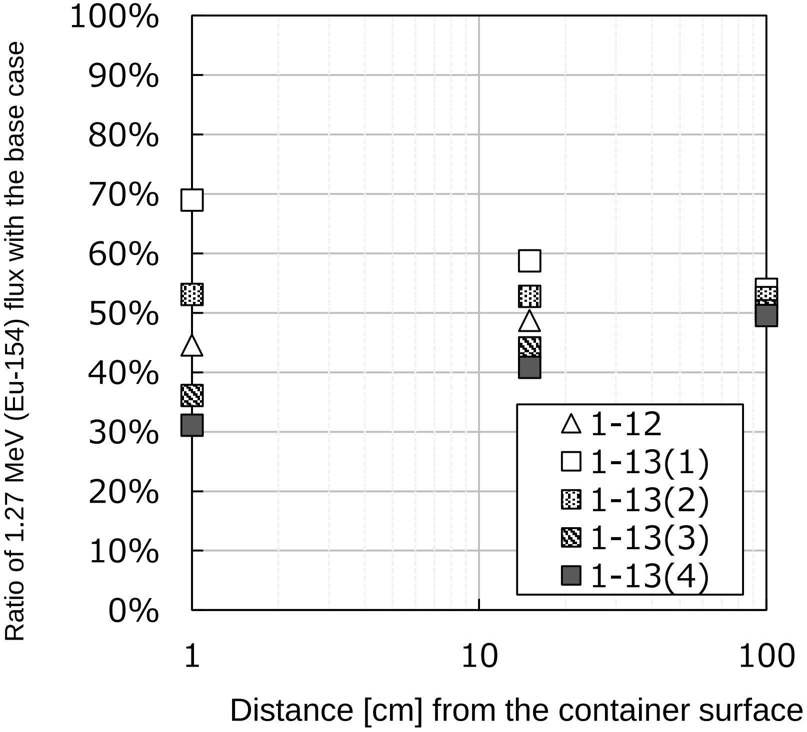
2.2.2 Passive gamma rays - Sensitivity analyses Uneven distribution (2/3)

■Case of uneven distribution of molten debris:1.27MeV flux analysis results
(For the uneven distribution cases, calculations were done by installing the tally at 1cm, 15cm and 100cm from the container surface.)

a) Case of uneven distribution with 1.27MeV flux



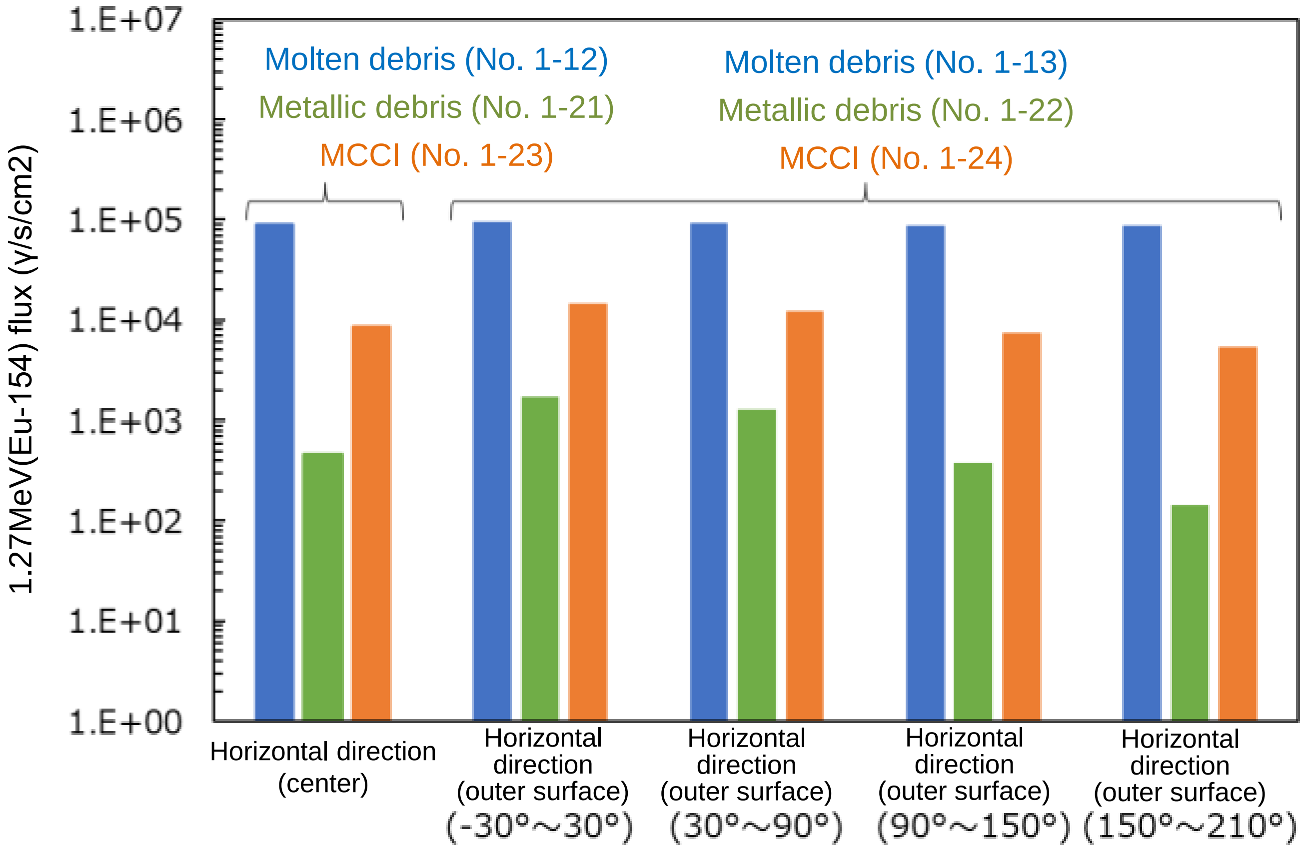
b) Case of uneven distribution with 1.27MeV flux



a) Flux was higher when the molten debris was uniformly present (1-1) throughout the container, than when there was uneven distribution (No. 1-12, 1-13).
b) The greater the distance from the surface of the container, the smaller was the impact of uneven distribution on the flux.

2.2.2 Passive gamma rays - Sensitivity analyses Uneven distribution (3/3)

■ Comparison of cases of uneven distribution of molten debris, metallic debris and MCCI (Molten Core Concrete Interaction): 1.27MeV flux analysis results



Since the proportion of material other than nuclear fuel (SUS, Concrete, etc.) was more in metallic debris and MCCI than in molten debris, if nuclear fuel was unevenly distributed in metallic debris and MCCI, the flux changed largely.

* The molten debris base case is used for other factors.

2.2.2 Passive gamma rays - Detector response (1/3)

Selection of prospective detectors and analysis conditions

■List of prospective detectors

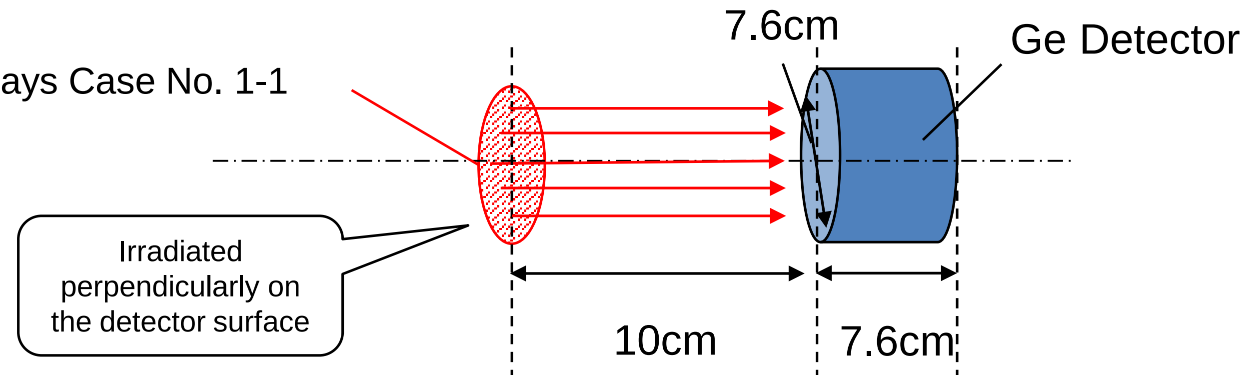
Prospective detectors	Material and shape	(Reference) Energy resolution	Remarks
Ge	Cylindrical (Diameter and thickness 7.62cm)	0.15%FWHM	Mirion Technologies (Canberra)
CZT	Cylindrical (Diameter 7.62cm and thickness 1cm)	0.8%FWHM	H3D (University of Michigan)
$LaBr_3$	Cylindrical (Diameter and thickness 7.62cm)	3.5%FWHM	ORTEC

■Analysis system

Assuming that a collimator will be installed in the actual system, gamma rays were made to fall perpendicularly on the surface of the detector.
(The impact of the thickness of the collimator, scattered rays, etc. is planned to be evaluated and studied in the future.)

Example) Ge Detector

Flux in Gamma rays Case No. 1-1

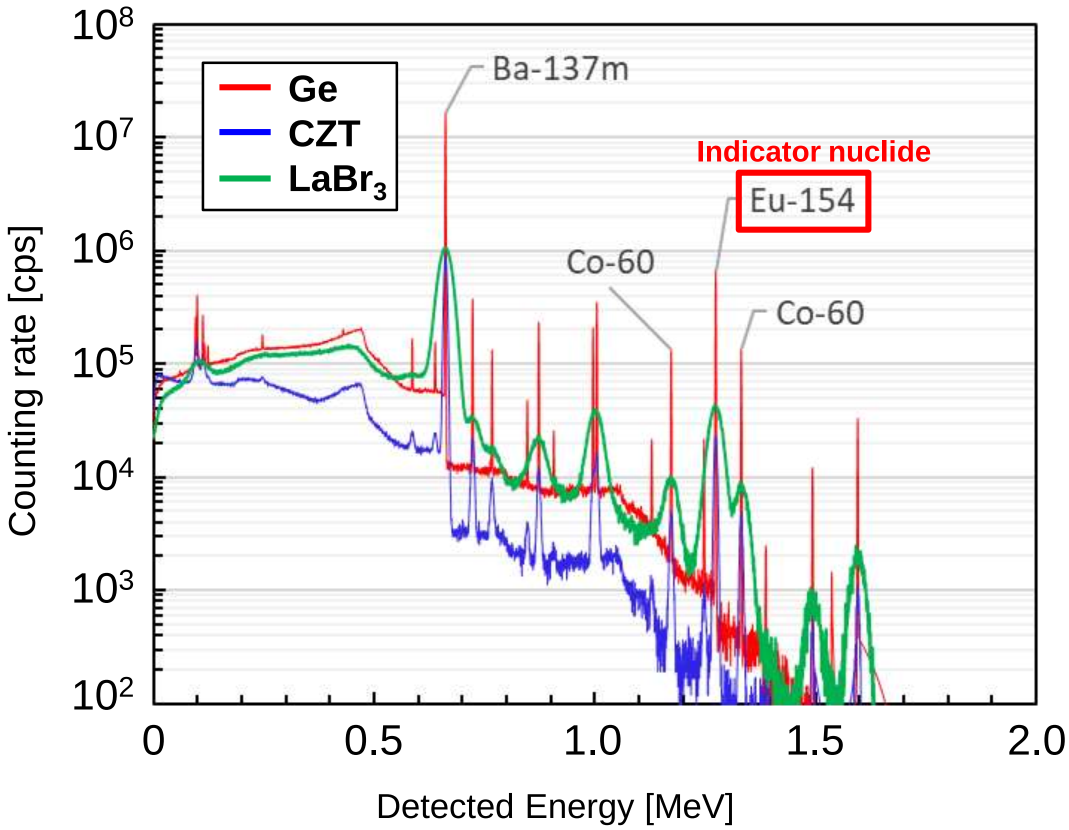


2.2.2 Passive gamma rays - Detector response (2/3)

Comparison of the response spectrum of prospective detectors

■Response of each prospective detector in the base case

Energy spectrum for each detector assuming the detector is 100cm from the container surface



- ➢ Ge and CZT were able to distinguish between 1.27MeV(Eu-154) and 1.33MeV (Co-60), but this distinction was difficult in the case of $LaBr_3$.

Total count rate and count rate at 1.27MeV peak

Prospective detector	Total count rate [cps]	1.27MeV count rate* [cps] (%)
Ge	2.2×10^8	2.2×10^6 (1.0%)
CZT	9.1×10^7	3.8×10^5 (0.4%)
$LaBr_3$	2.2×10^8	—

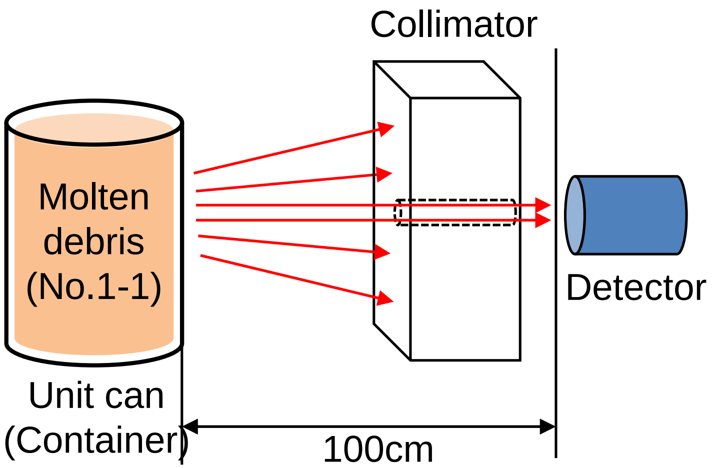
* Counting rate at the base region resulting from scattered rays is subtracted from that at the peak region resulting from gamma rays with 1.27MeV.

- ➢ The measurement time was estimated from the count rate at 1.27MeV peak.

2.2.2 Passive gamma rays - Detector response (3/3)

Estimation of measurement time for the prospective detectors

■Study of installation of every prospective detector (Assuming that the detector is installed at a distance of 100cm from the container surface)



- For a Ge detector with maximum count rate 25kcps[*1, 3], a collimator of diameter approx. 0.1cm was required (2.2×10^8→2.5×10^4cps)
- For a CZT detector with maximum count rate 450kcps[*2, 3], a collimator of diameter approx. 0.5cm was required (9.1×10^7→4.5×10^5cps)

[*1] Assuming that a gamma spectroscopy software of the same manufacturer was used.
[*2] Count rate limit of the H series detector of the same manufacturer.
[*3] Dead time due to pile-up was not considered.

■Estimation of the computation time of each prospective detector (Example: Assuming that the collimator is 20cm thick)

Prospective detector	Collimator diameter [cm]	Maximum count rate [cps]	Proportion of the count rate of 1.27MeV	Measurement time [seconds/round] (Time required to obtain 10^4 counts at the 1.27MeV peak)	Measurement frequency [Rounds / Container] (Translational scanning only)	Computational time for each container
Ge	0.1	2.5×10^4 [*1,3]	1.0%	40	500	5.5 hours
CZT	0.5	4.5×10^5 [*2,3]	0.4%	6	20	2 minutes

➢ In order to install a collimator for reducing the gamma rays incident upon the detector, measurement had to be performed while scanning the container. Hence the measurement frequency increased due to which the process took time. The collimator installation and measurement technique need to be improved.

2.2 Analysis results

2.2.2 Passive gamma rays - Additional sensitivity analyses (1/4)

Step 2 Analysis (1/4)

Five cases in which the peak count rate at 1.27MeV was less were analyzed taking multiple influencing factors into consideration.

■ Cases with a combination of fluctuations in 2 influencing factors

		Molten								Metallic	MCCI
		Fuel debris composition	MOX	Filling factor	Burn-up	FP emission rate	Cooling period	Uneven distribution	Container		
Molten	Fuel debris composition		-	△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)	△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)	× No change in Eu-154 peak	× Attenuation depending on half-life	△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)	×	-	-
	MOX			△ Flux increases/decreases with the increase/decrease in amount of MOX (Self-shielding effect present)	-	× No change in Eu-154 peak	× Attenuation depending on half-life	△ Flux increases/decreases with the increase/decrease in amount of MOX (Self-shielding effect present)	×	△	△
	Filling factor				△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)	× No change in Eu-154 peak	× Attenuation depending on half-life	△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)	×	△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)	△ Flux increases/decreases with the increase/decrease in amount of U (Self-shielding effect present)
	Burn-up					× No change in Eu-154 peak	× Attenuation depending on half-life	△ Self-shielding effect due to the form of the radiation source for uneven distribution is present	×	○	○
	FP emission rate						× Attenuation depending on half-life	× Expected to not be different than the uneven distribution in Step 1	×	× No change in Eu-154 peak	× No change in Eu-154 peak
	Cooling period							× Attenuation depending on half-life	×	× Attenuation depending on half-life	× Attenuation depending on half-life
	Uneven distribution								×	○	○
	Container									×	×
Metallic											-
MCCI											

Metallic debris and MCCI cases in which the burn-up and uneven distribution were changed were selected.

	Metallic debris	MCCI
Burn-up	Small: 1.3GWd/t	Small: 1.3GWd/t
Uneven distribution	At the center in the horizontal direction	At the center in the horizontal direction

4 cases
(Of these, 2 cases are redundant)

* The base case was used for other factors.

■Case in which the peak count rate at 1.27MeV was assumed to be the smallest

Filling rate	Burn-up	Uneven distribution
10vol% (UO_2: 5vol% / ZrO_2: 5vol%)	Small: 1.3GWd/t	At the center in the horizontal direction

1 case

Total
5 cases

2.2.2 Passive gamma rays - Additional sensitivity analyses (2/4)

Step 2 Analysis (2/4)

Five cases in which the peak count rate at 1.27MeV was less were analyzed taking multiple influencing factors into consideration.

■ Step 2 analysis cases

Case		**UO_2**	**ZrO_2**	**SUS**	**Concrete**	**Filling rate**	**Burn-up (GWd/t)**	**FP emission rate**	**Cooling period**	**Uneven distribution**	**Remarks** U content considered as the analysis condition	
1-21	Metallic debris Uneven distribution (center)	25vol%	25vol%	-	-	30vol%	23.0	Standard	20 years	**Uneven distribution (Center)**	0.0439kg	(Repeated)
1-25	Metallic debris Burn-up (low)	0.075vol%	0.075vol%	29.85vol%	-	30vol%	**1.3**	Standard	20 years	Uniform	0.0449kg	
1-23	MCCI Uneven distribution (center)	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	23.0	Standard	20 years	**Uneven distribution (Center)**	0.615kg	(Repeated)
1-26	MCCI Burn-up (low)	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	**1.3**	Standard	20 years	Uniform	0.615kg	
1-27	Molten debris Worst case	5vol%	5vol%	-	-	**10vol%**	**1.3**	Standard	20 years	**Uneven distribution (Center)**	2.93kg	

MCCI: Molten Core Concrete Interaction

2.2.2 Passive gamma rays - Additional sensitivity analyses (3/4)

Step 2 Analysis (3/4)

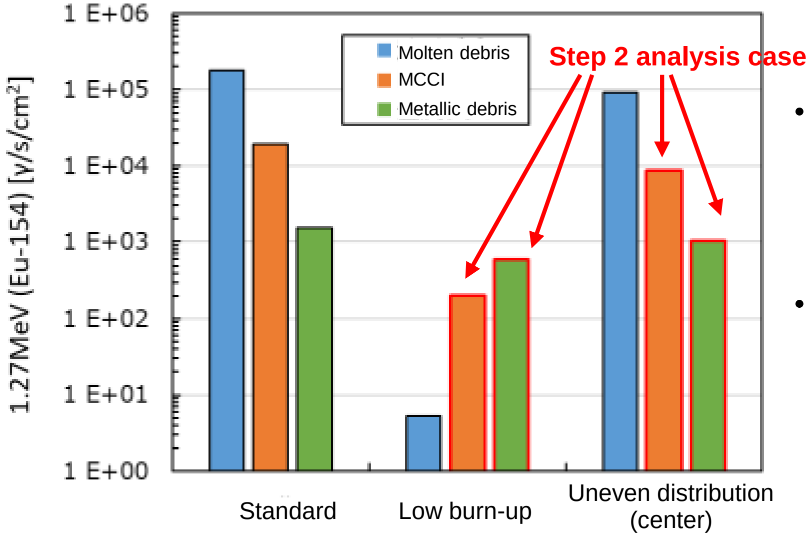
Five cases in which the peak count rate at 1.27MeV was less were analyzed taking multiple influencing factors into consideration.

■ MCCI (Molten Core Concrete Interaction) and metallic debris cases in which the burn-up and uneven distribution were changed

(Red frame: Step 2 analysis cases)

Case No.	Type of fuel debris	Variation parameters	Amount of U* (kg)	Total flux [γ/s/cm²]	1.27MeV peak [γ/s/cm²]	Proportion of 1.27MeV peak when compared with the standard case of each type of fuel debris (%)	Remarks
1-1	Molten debris	Standard	8.79	5.23×10^6	1.75×10^5	—	
1-6	Molten debris	Burn-up (low)	8.97	3.06×10^6	5.37×10^0	0.0030%	Comparison with 1-1
1-12	Molten debris	Uneven distribution (center)	8.79	2.61×10^6	9.08×10^4	52%	Comparison with 1-1
1-19	MCCI	Standard	0.615	2.90×10^6	1.92×10^4	—	
1-26	MCCI	Burn-up (low)	0.629	2.11×10^6	2.01×10^2	1.0%	Comparison with 1-19
1-23	MCCI	Uneven distribution (center)	0.615	2.54×10^6	8.67×10^3	45%	Comparison with 1-19
1-17	Metallic debris	Standard	0.0439	7.53×10^6	1.52×10^3	—	
1-25	Metallic debris	Burn-up (low)	0.0449	7.48×10^6	5.81×10^2	38%	Comparison with 1-17
1-21	Metallic debris	Uneven distribution (center)	0.0439	7.54×10^6	1.05×10^3	69%	Comparison with 1-17

*Amount of U = Total mass of Uranium isotopes



- The impact of burn-up was small in the case of MCCI and metallic debris as compared to molten debris
  →This is because the amount of U contained in MCCI and metallic debris is less.

- The impact of uneven distribution was about the same regardless of the type of fuel debris (around 40 to 70%)
  → Impact of disparity inside the container is higher than that of disparity in composition

2.2 Analysis results

2.2.2 Passive gamma rays - Additional sensitivity analyses (4/4)

Step 2 Analysis (4/4)

Five cases in which the peak count rate at 1.27MeV was less were analyzed taking multiple influencing factors into consideration.

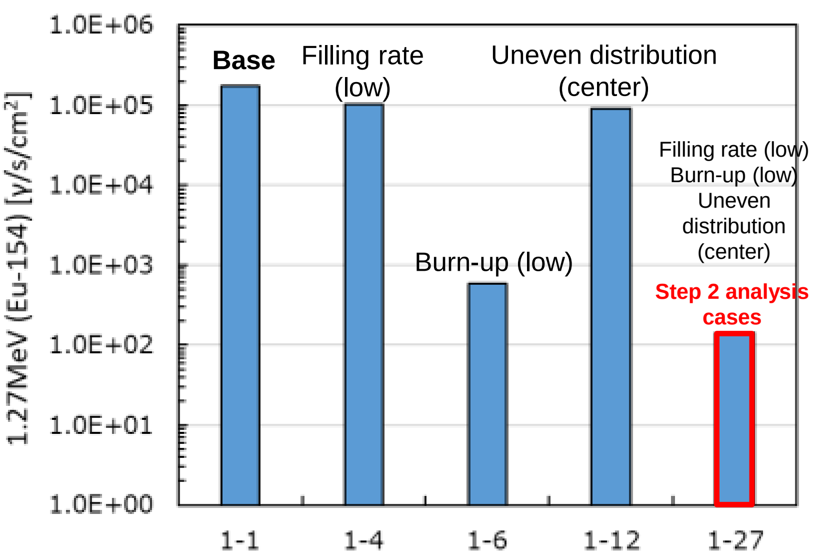
■Analysis of sensitivity to filling rate, burn-up, and uneven distribution in the case of molten debris

(Red frame: Step 2 analysis case）

Case No.	Type of fuel debris	Variation parameters	Entire debris (kg)	Amount of U* (kg)	Total flux [γ/s/cm²]	1.27MeV peak [γ/s/cm²]	Proportion of 1.27MeV peak when compared with 1-1 (-)	
1-1	Molten debris	Standard	15.8	8.79	5.23×10^{6}	1.75×10^{5}	—	
1-4	Molten debris	Filling rate (low)	5.28	2.93	3.40×10^{6}	1.03×10^{5}	5.90×10^{-1}	1.03×10^{-3} **
1-6	Molten debris	Burn-up (low)	15.8	8.97	3.06×10^{5}	5.92×10^{2}	3.38×10^{-3}	
1-12	Molten debris	Uneven distribution (center)	15.8	8.79	2.61×10^{6}	9.08×10^{4}	5.18×10^{-1}	
1-27	Molten debris	Filling rate (low), Burn-up (low), Uneven distribution (center)	5.28	2.99	7.28×10^{4}	1.42×10^{2}	8.12×10^{-4}	

*Amount of U = Total mass of Uranium isotopes

**Product of 1-1, 1-4 and 1-6



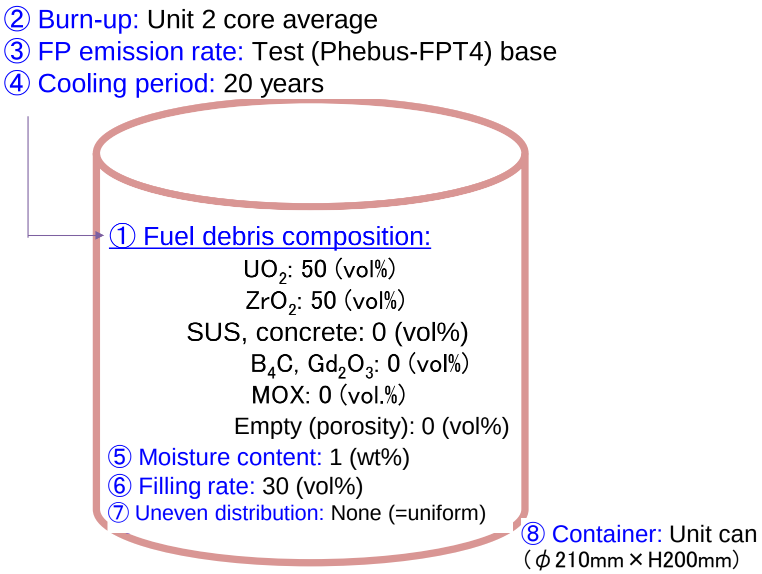
- Count rate of 1.27MeV peak decreased about 3 digits of magnitude as compared to the base case.
- It was about the same as the product of the cases of filling rate, burn-up and uneven distribution. Thus it is confirmed that all influencing factors linearly contributed to it.

→ The measurement time is expected to be extremely long based on the analysis of the detector response in the base case.

2.2.2 Passive gamma rays – Summary

➢ **Major findings obtained from the analysis:**

Impact	Influencing factor	Findings
Major	① Fuel debris Composition ② Burn-up ⑥ Filling rate ⑦ Uneven distribution ⑧ Container	・Even if only the fuel debris composition and filing factor are changed, as long as the burn-up remains constant, there is a possibility of being able to quantitatively evaluate the amount of U based on Eu-154, but **if the burn-up changes,** the correlation between Eu-154 and amount of U deteriorates. **[Refer to No. 88]** ・As a result of the **self-shielding effect** due to the shape of the container or the apparent density, the flux that is incident upon the detector changes. **[Refer to No. 93-95]** ・If a lot of material other than nuclear fuel is contained, and furthermore if nuclear fuel is unevenly distributed inside the container, the flux incident upon the detector changes.
Minor	③ FP emission rate ④ Cooling period (⑤ Moisture content*1)	・There is minor impact of FP emission rate rate on Eu-154. ・There is a possibility of being able to correct the cooling period by means of the retrieval time period and half-life.



② Burn-up: Unit 2 core average
③ FP emission rate: Test (Phebus-FPT4) base
④ Cooling period: 20 years

① Fuel debris composition:
UO_2: 50 (vol%)
ZrO_2: 50 (vol%)
SUS, concrete: 0 (vol%)
B_4C, Gd_2O_3: 0 (vol%)
MOX: 0 (vol.%)
Empty (porosity): 0 (vol%)
⑤ Moisture content: 1 (wt%)
⑥ Filling rate: 30 (vol%)
⑦ Uneven distribution: None (=uniform)
⑧ Container: Unit can
(φ210mm×H200mm)

*1 Not analyzed as change in the moisture content has only a minor impact on self-shielding due to the penetration power of gamma rays

Parameter values in the figure indicate base case conditions.

➢ **Study of the necessity of detailed analysis and consolidation of technical issues：**

- Analysis of the extent of impact of heterogeneity on the flux on the measuring surface
- There is a possibility of correcting the rate of change in flux by **correcting the impact of the burn-up** in fuel debris.
- If nuclear fuel is unevenly distributed in the container, the method of rotating the container and then carrying out measurement, or the method of measuring the distribution of material mixed inside the container by means of radioparency measurement, etc. and then correcting it, etc. are presumed to be effective. These methods are planned to be studied from next year onwards.

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

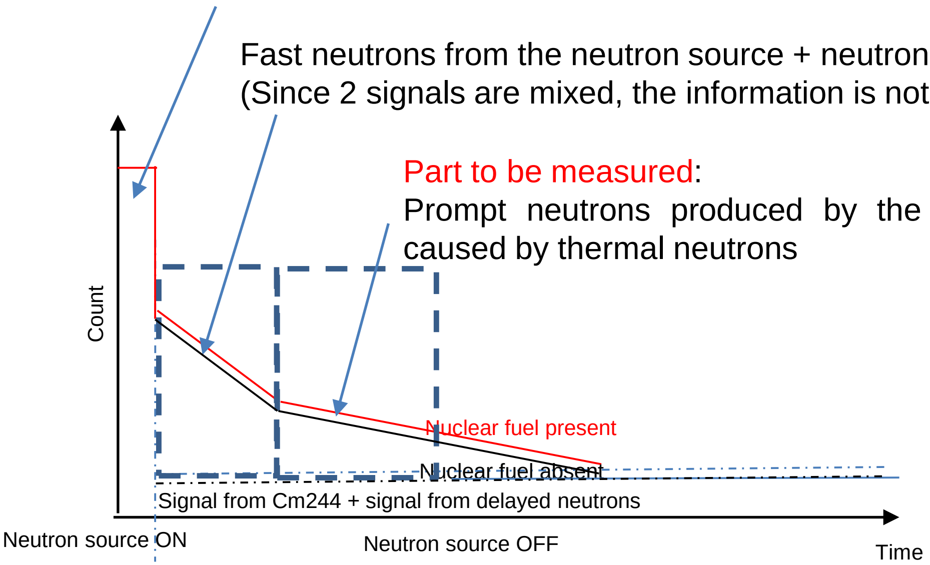
③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
  2.2.1 Passive neutrons
  2.2.2 Passive gamma rays
  2.2.3 Active neutrons
  2.2.4 Passive/active neutrons + passive gamma rays
  2.2.5 X-ray transmission measurement
  2.2.6 Cosmic rays scattering measurement

	① Fuel debris composition	Gd content	B content	MOX	② Burn-up	③ FP emission rate	④ Cooling period	⑤ Moisture content	⑥ Filling rate	⑦ Uneven distribution	⑧ Container	⑨ Irradiating radiation source	⑩ Detector
2.2.3 Active neutron	**No. 114 No. 128 to 130 No. 143 No. 144**	**No. 145**	**No. 145**	**No. 115**	**No. 122 to 124**	**–**	**No. 125 to 127**	**No. 119 to 121**	**No. 116 to 118 No. 144**	**No. 133 to 135**	**No. 146**	**No. 138 No. 147**	**No. 140 to 142**

2.2.3 Active neutrons - Measurement concept

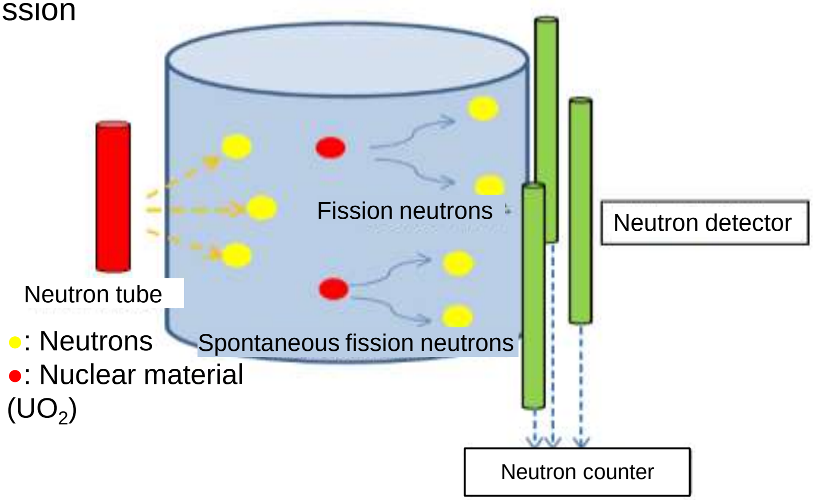
- Pulsed neutrons are irradiated from the neutron generator to the fuel debris, and neutrons produced by fissile nuclides (U-235, Pu-239, etc.) contained in fuel debris are measured.
- However, as the produced neutron flux is affected by the amount of nuclear material in fuel debris, the abundance of fissile nuclides attributable to burn-up, neutron absorption material (B, Gd, etc.),etc., there is variation in the neutron flux reaching the measurement surface.
- Based on the above, **the range to be measured was determined by means of analytical evaluation, and issues such as the measurement range of the detector required for the measurement system,the layout for measurement, etc. were identified.**



Fast neutrons from the neutron generator

Fast neutrons from the neutron source + neutrons produced by fast fission
(Since 2 signals are mixed, the information is not of much use.)

Part to be measured:
Prompt neutrons produced by the fission of U, Pu caused by thermal neutrons



●: Neutrons
●: Nuclear material (UO_2)

2.2.3 Active neutrons - Analysis model

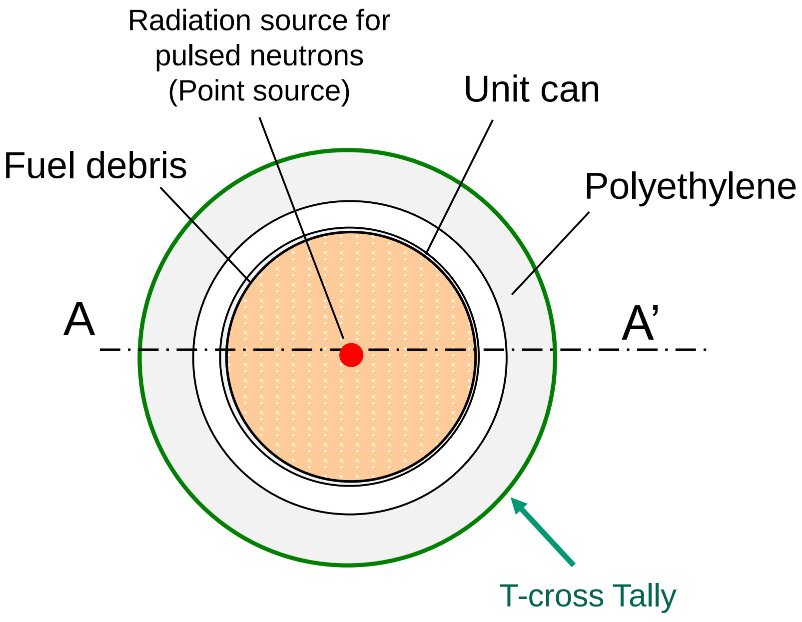
Radiation source for pulsed neutrons (Neutron tube ING031 manufactured by Russia's VNIIA is assumed)

Neutron energy: 14.1MeV, Neutron generation rate: 2x10^{8}n/s, Neutron generation direction: isotropic,

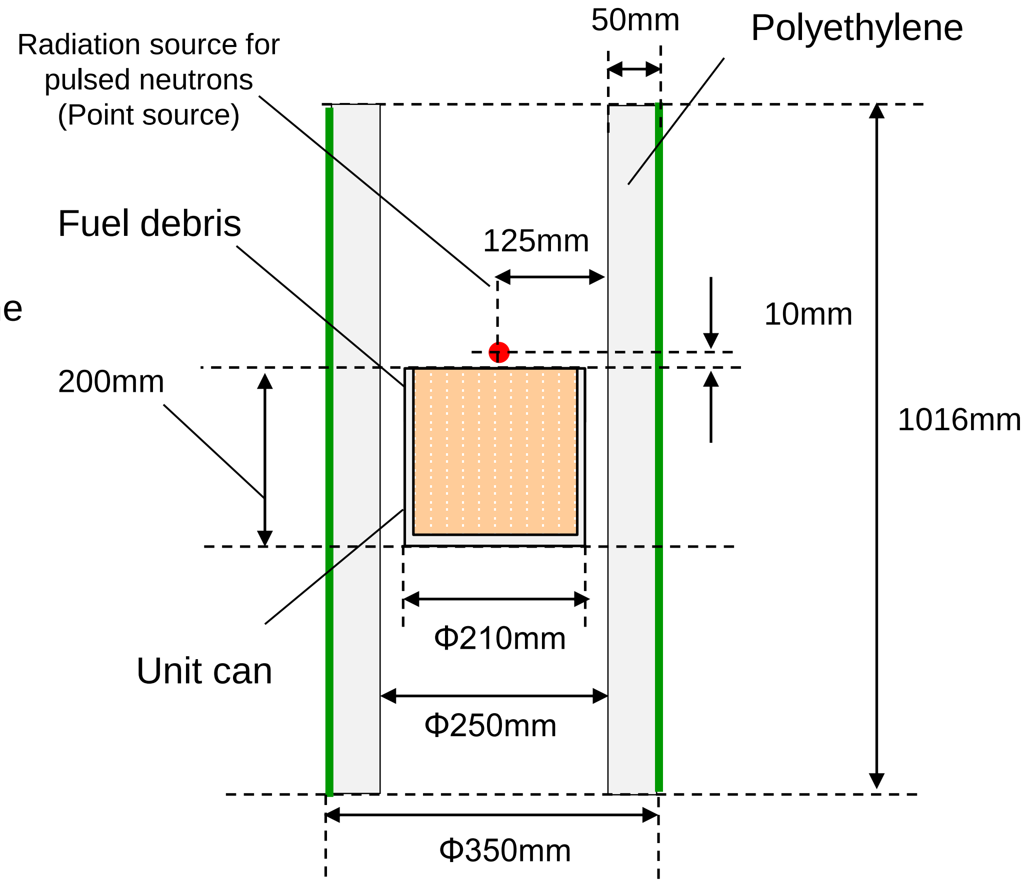
Pulse width: 1.2μs, Repetitive frequency: 100Hz

In order to scatter / moderate pulsed neutrons, polyethylene was installed around the unit can and the radiation source for pulsed neutrons.

→ Used for selecting the detector and studying the layout based on the changes in neutron flux (Total energy and 0.4eV or more (assuming that thermal neutrons are absorbed by Cd)) time.



Analysis model top view



Cross-sectional view A-A'

2.2 Analysis results

2.2.3 Active neutrons - Table listing the analysis cases (1/3)

- Considering the analysis conditions described in No. 3-1 as the base case, the analysis conditions that changed to influencing factors (No. 3-2 to 27) were assumed as the sensitivity analysis conditions. **All 27 cases**
- Influencing factors that changed from the base case under the sensitivity analysis conditions are highlighted blue. Here, the parameters that changed in association with the above-mentioned changes are indicated by yellow hatching.

Case No.	Composition inside the container *1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Irradiating neutron source	Changed parameter
	Type of fuel debris	Within the filling factor		Outside the filling factor							
		Composition	Total (filling factor)								
3-1	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Base case
3-2		**UO_2 : 7.5vol%(25vol%)** **ZrO_2 : 22.5vol%(75vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (UO_2, ZrO_2)
3-3		**MOX : 30vol%**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**0GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	MOX
3-4		UO_2 : 5vol%(50vol%) ZrO_2 : 5vol%(50vol%)	**10vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Filling factor
3-5		UO_2 : 25vol%(50vol%) ZrO_2 :25vol%(50vol%)	**50vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Filling factor
3-6		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**Gd_2O_3 : 3vol%** H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Gd content
3-7		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**Gd_2O_3 : 30vol%** H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Gd content
3-8		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**B_4C : 0.51vol%** H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	B content
3-9		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**B_4C : 10vol%** H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	B content
3-10		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**H_2O (Moisture content): 0.1wt%** Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Moisture content

2.2.3 Active neutrons - Table listing the analysis cases (2/3)

Case No.	Composition inside the container *1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Irradiating neutron source	Changed parameter
	Type of fuel debris	Within the filling factor		Outside the filling factor							
		Composition	Total (filling factor)								
3-11	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	**H_2O (Moisture content): 70vol%** Empty : 0vol%	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Moisture content
3-12		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**1.3GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Burn-up
3-13		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**51GWd/t**	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Burn-up
3-14		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	**30 years**	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Cooling period
3-15		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	**40 years**	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Cooling period
3-16		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal Direction (Center)**	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Uneven distribution
3-17		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal Direction (Outer surface)**	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Uneven distribution
3-18		UO2 : 15vol%(50vol%) ZrO2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	**Unit can (Φ220mm x H840mm, Thickness 10mm)**	D-T reaction (14.1MeV)	Container
3-19		**UO_2 : 0.48vol%[3.7kg] SUS : 10vol%(95.4vol%)**	**10.48vol%**	H2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	**Waste storage container (Inner container□Φ500mm x H300mm)**	D-T reaction (14.1MeV)	Container
3-20		UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	**D-D reaction (2.45MeV)**	Irradiating neutron source

2.2.3 Active neutrons - Table listing the analysis cases (3/3)

Case No.	Composition inside the container *1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Irradiating neutron source	Changed parameter
	Type of fuel debris	Within the filling factor		Outside the filling factor							
		Composition	Total (filling factor)								
3-21	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	**Accelerator based neutron source**	Irradiating radiation source
3-22	Uranium-rich	**UO_2 : 30vol%**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (type)
3-23	Metallic debris	**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (type)
3-24		UO_2 : 15vol%(25vol%) ZrO_2 : 15vol%(25vol%) **SUS : 30vol%(50vol%)**	**60vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (type)
3-25	MCCI	**UO_2 : 1.05vol%(3.5vol%)** **ZrO_2 : 1.05vol%(3.5vol%)** **SUS : 7.2vol%(24vol%)** **Concrete : 20.7vol%(69vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (type)
3-26		UO_2 : 15vol%(33.3vol%) ZrO_2 : 15vol%(33.3vol%) **Concrete : 15vol%(33.3vol%)**	**45vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (concrete)
3-27		UO_2 : 15vol%(25vol%) ZrO_2 : 15vol%(25vol%) **Concrete : 30vol%(50vol%)**	**60vol%**	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (concrete)

*1: Percentage inside the container. Percentage, when 100% is considered to be within the filling rate, is mentioned inside parentheses

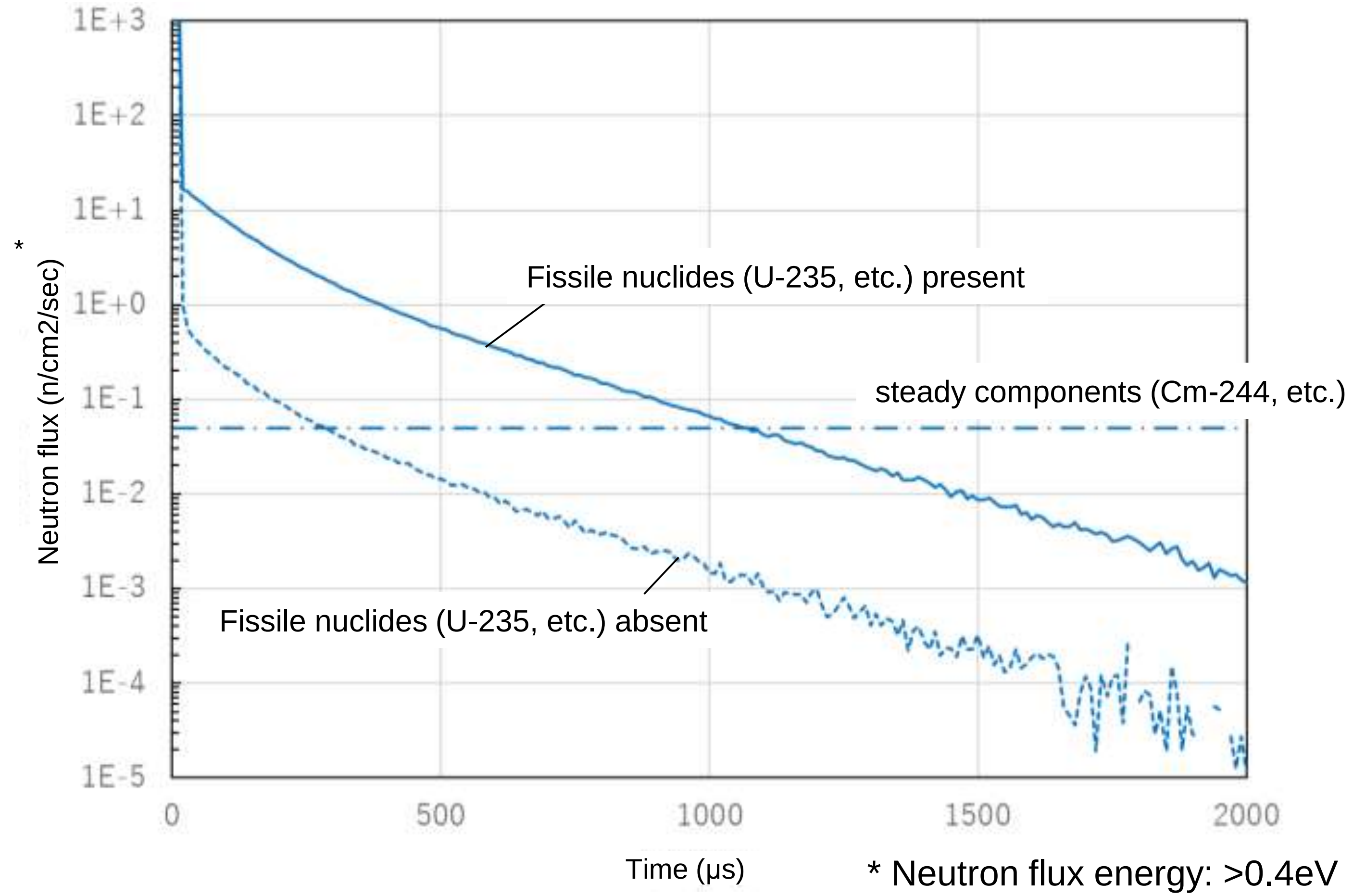
2.2.3 Active neutrons - Analysis results [Base case]

- Neutrons were irradiated to fuel debris, and it was verified that neutron flux time change due to the nuclear fission caused by fissile nuclides (U-235, etc.) can be obtained through analysis. Here, the neutron flux (after penetration of polyethylene) at the measurement surface was evaluated.
- Further, the flux from spontaneous fissile nuclides (Cm-244, etc.) that cause measurement noise was evaluated as well.

Analysis conditions (Base case)

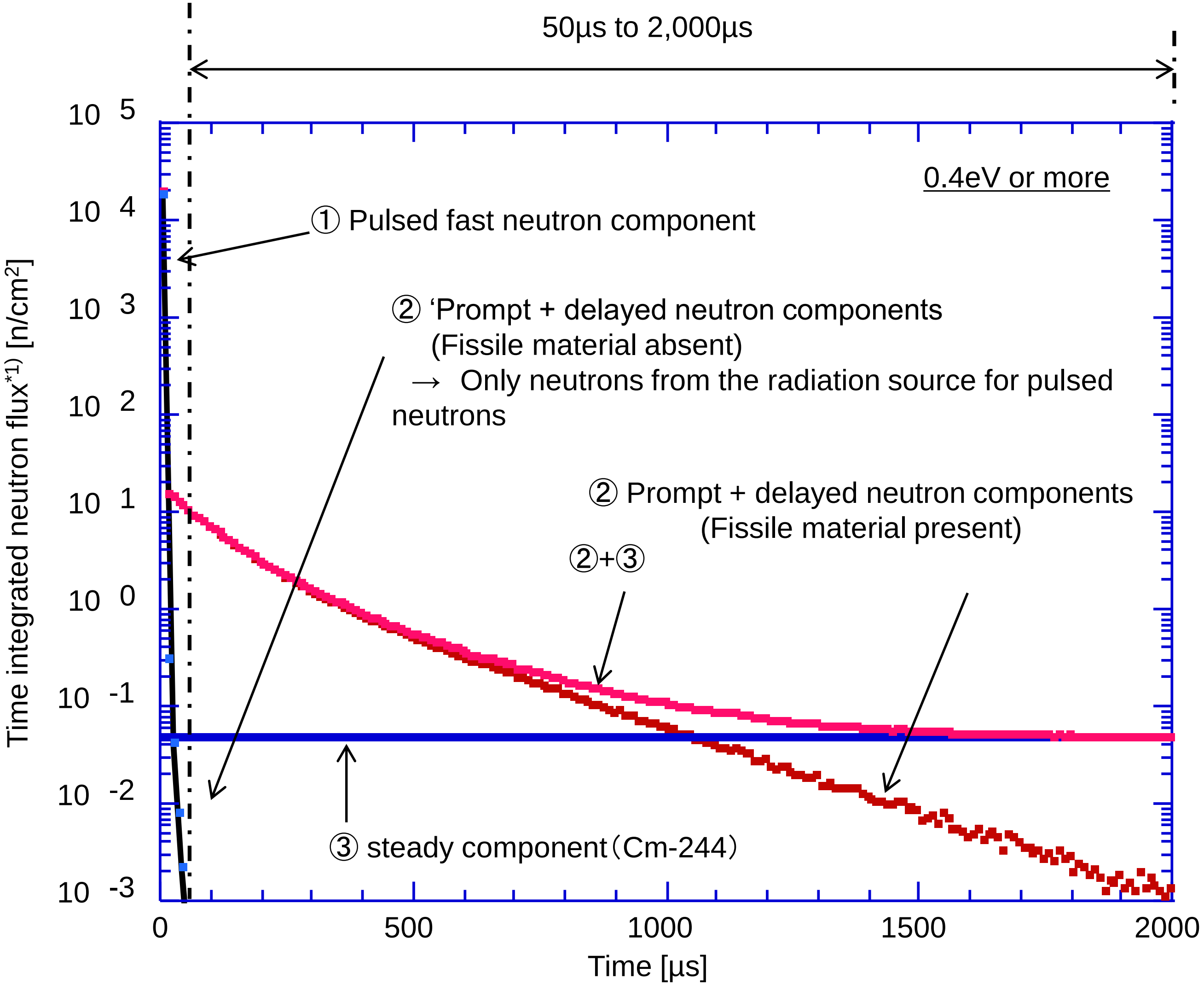
Neutron source:
- Energy: 14.1MeV
- Rate of incidence: 2×10^8 n/s
- Pulse width: 1.2μs
- Repetitive frequency: 100Hz

Fuel debris:
- UO_2: 15vol%
- ZrO_2: 15vol%
- Cooling period: 20 years
- Burn-up: 23GWd/t
- FP emission rate: Standard
- Moisture content: 1wt%
- Container: Unit can



* Neutron flux energy: >0.4eV

2.2.3 Active neutrons – Analysis details [Base case]



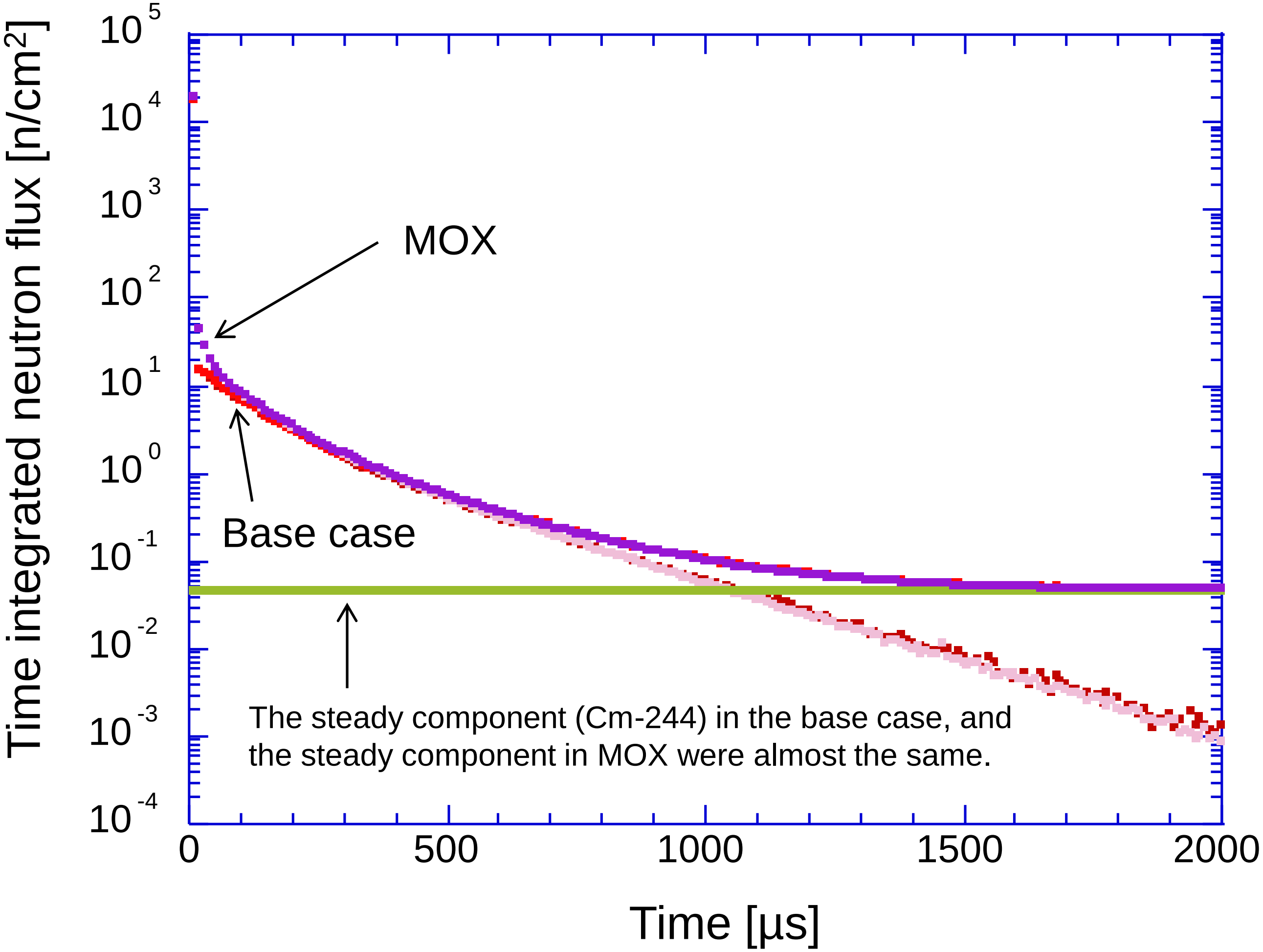
Evaluated using integrated value of ②, integrated value of ③, and integrated value of ②+③ at 50µs to 2,000µs

Component	Time integrated neutron flux*2) [n/cm²]
②	1.45E+02
③	9.47E+00
②+③	1.55E+02

*1) A value 100 times the integrated value between the time bins (10µs) for 1 pulse, considering a repetitive frequency of 100Hz.
*2) A value that is 100 times the integrated value between 50µs and 2000µs for 1 pulse, considering a repetitive frequency of 100Hz.

2.2.3 Active neutrons – Analysis results [MOX]

In the case of MOX fuel, the components of ② largely varied at an early time (100μs or less), but had almost the same value from 500μs onwards.



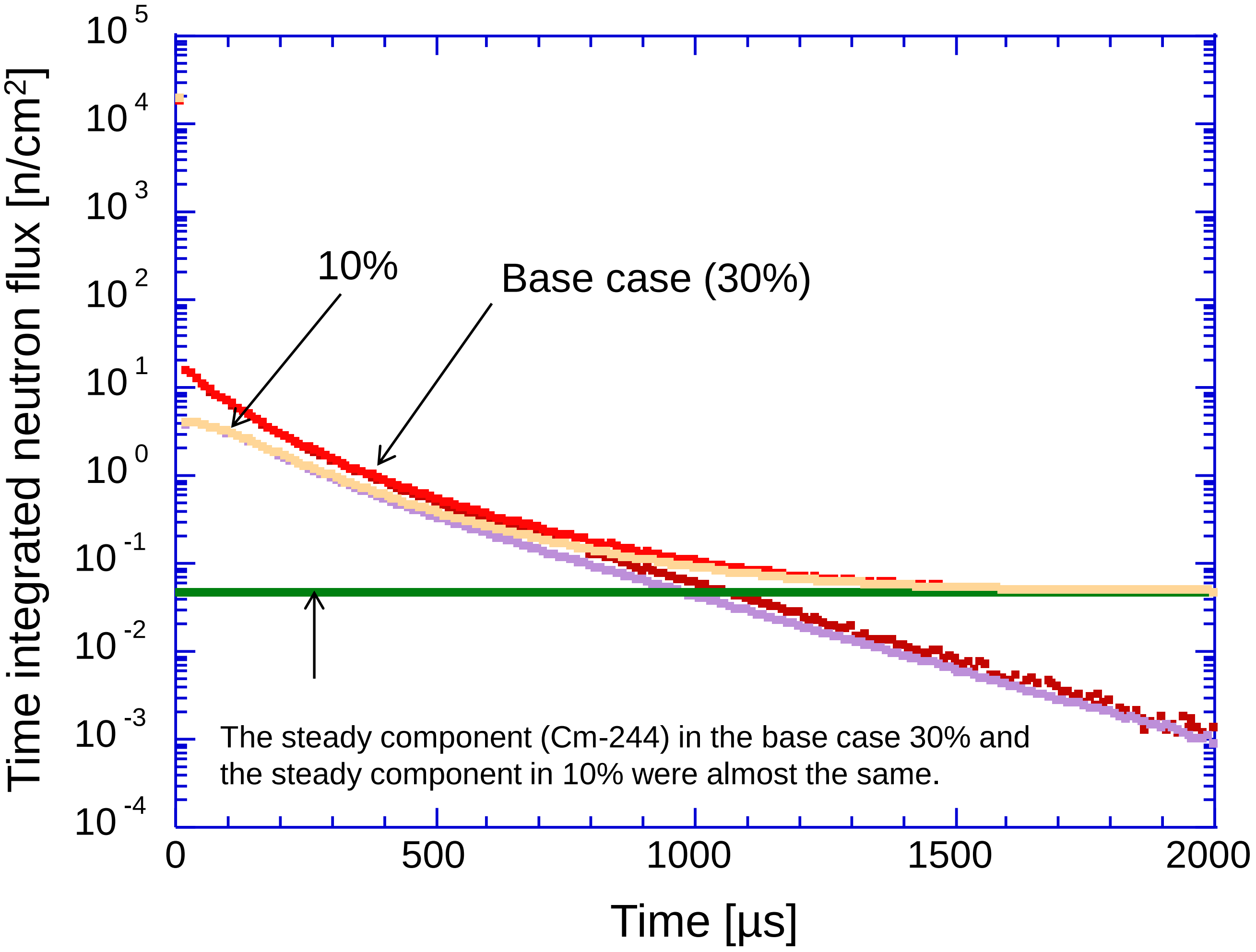
The steady component (Cm-244) in the base case, and the steady component in MOX were almost the same.

	Component	Time integrated neutron flux [n/cm²]
MOX	②	1.68E+02
	③	9.59E+00
	②+③	1.78E+02
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [Filling rate]

The steady component (Cm-244) of ③ almost did not change even if the filling rate (U mass) was changed.

Components of ② largely varied at an early time (100μs or less), but from 500μs onwards, the variation became almost constant.



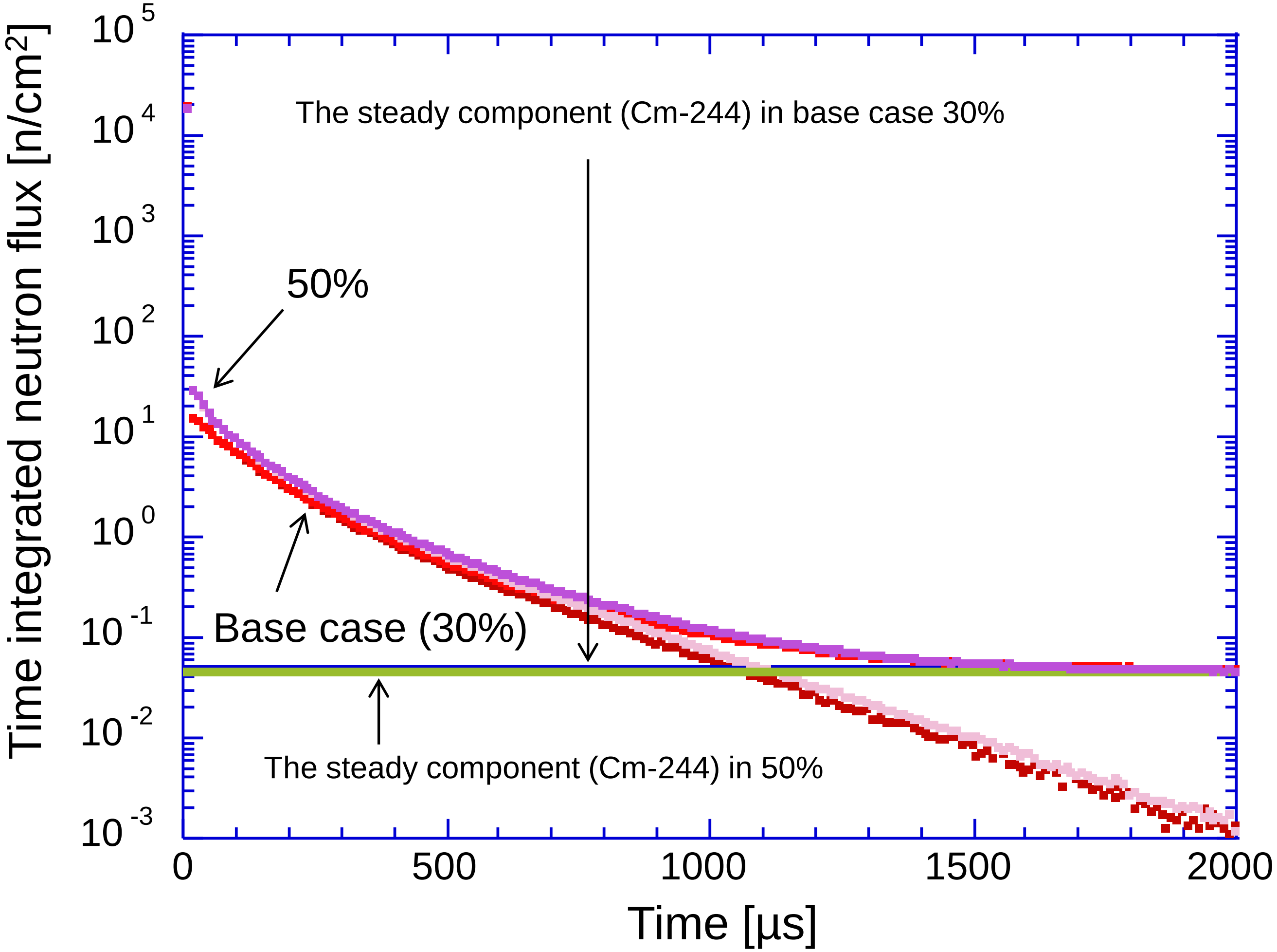
The steady component (Cm-244) in the base case 30% and the steady component in 10% were almost the same.

	Component	Time integrated neutron flux [n/cm²]
10 %	②	7.59E+01
	③	9.72E+00
	②+③	8.56E+01
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [Filling rate]

The steady component (Cm-244) of ③ almost did not change even if the filling rate (U mass) was changed.

Components of ② largely varied at an early time (100μs or less), but from 500μs onwards, the variation became almost constant.

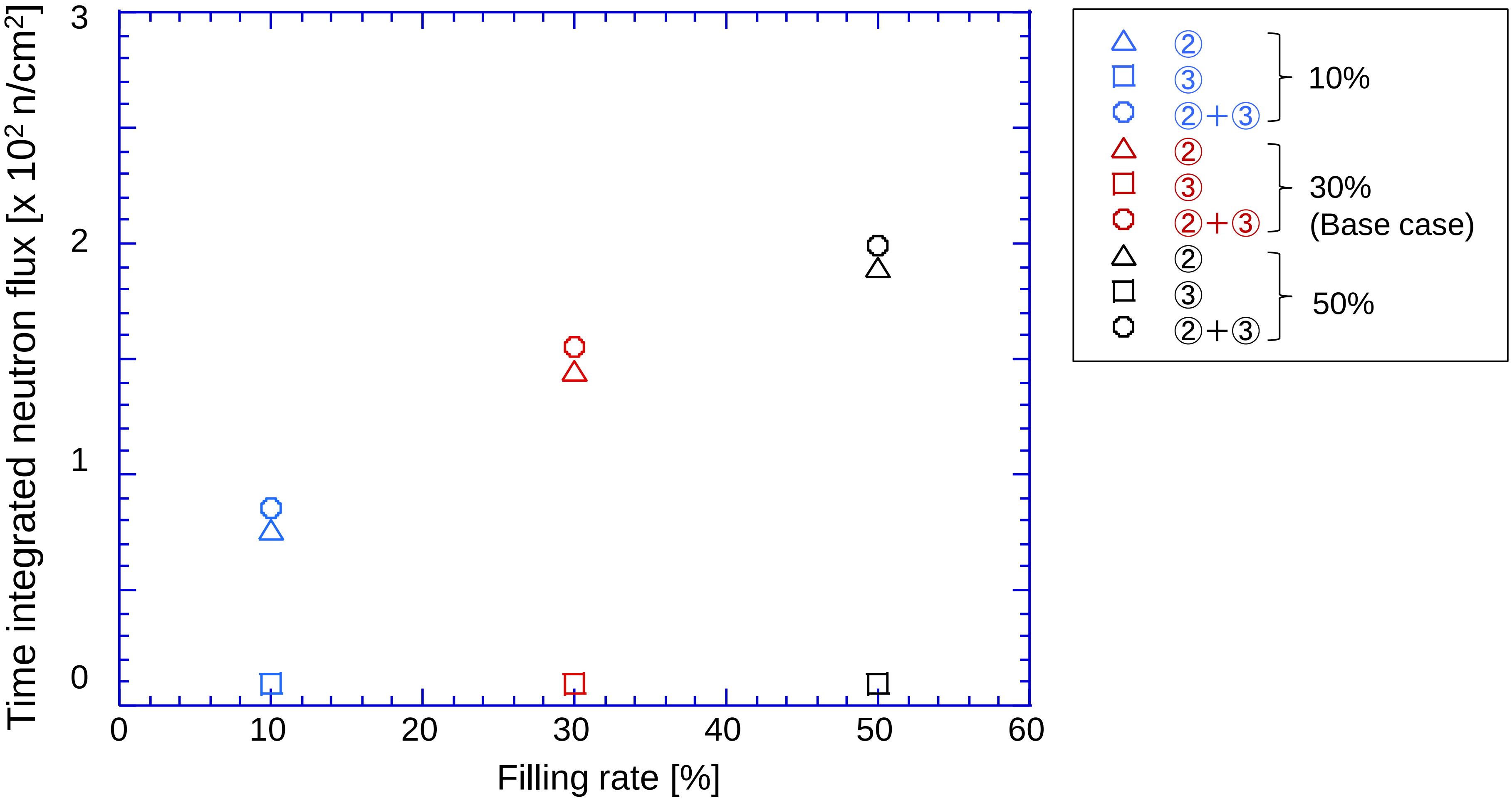


	Component	Time integrated neutron flux [n/cm²]
50 %	②	1.90E+02
	③	9.09E+00
	②+③	1.99E+02
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [Filling rate]

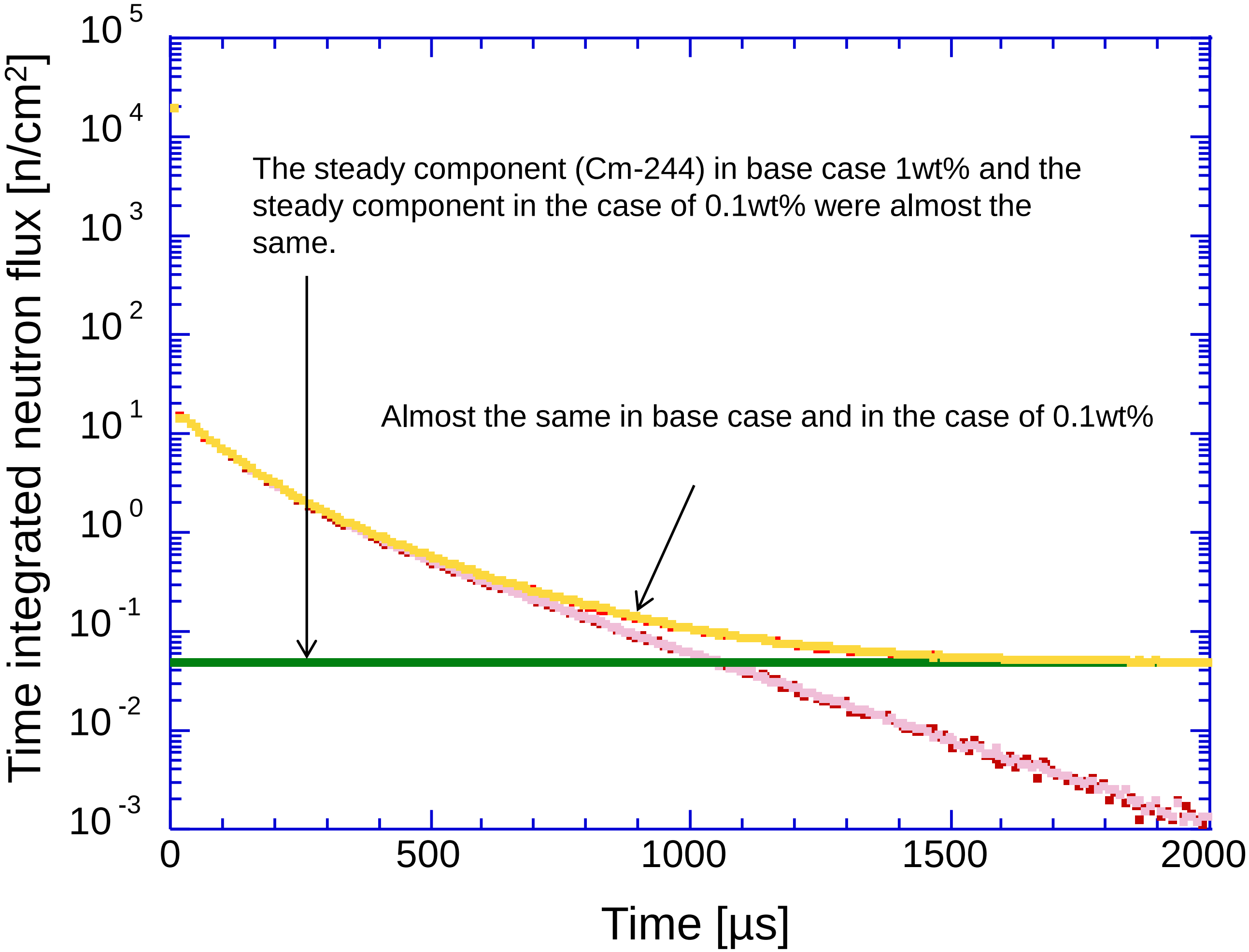
The steady component (Cm-244) of ③ almost did not change even if the filling rate (U mass) was changed.

The integrated value of ② was not linear with respect to filling rate (= U mas). It monotonically increased.



2.2.3 Active neutrons – Analysis results [Moisture content]

The components of ② and ③ had almost the same value in the base case (1wt%) and in the case of 0.1wt%.



The steady component (Cm-244) in base case 1wt% and the steady component in the case of 0.1wt% were almost the same.

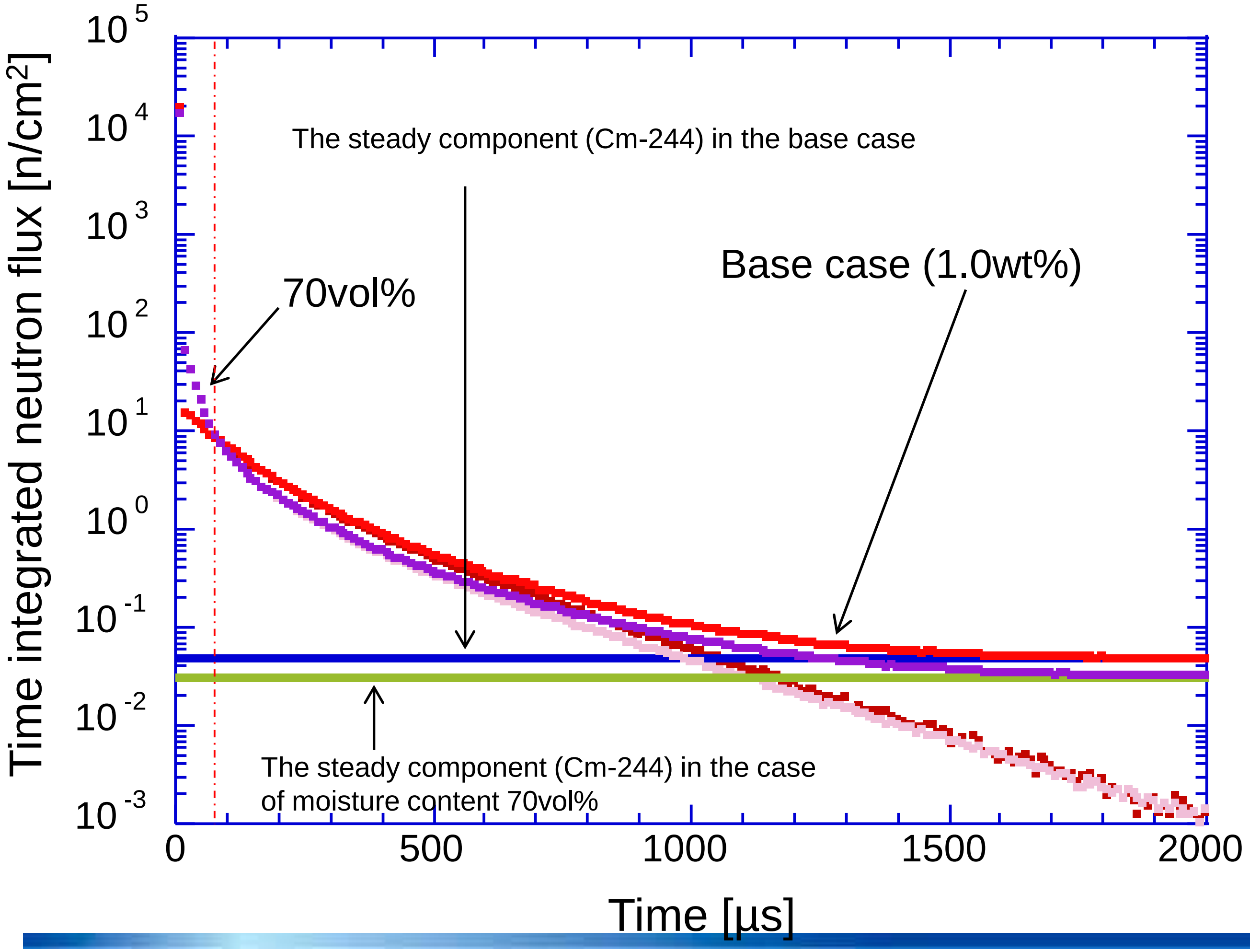
Almost the same in base case and in the case of 0.1wt%

	Component	Time integrated neutron flux [n/cm²]	(Reference) Integration interval 30 to 2,000μs
0.1 wt%	②	1.48E+02	1.73E+02
	③	9.63E+00	9.73E+00
	②+③	1.57E+02	1.83E+02
Base case	②	1.45E+02	1.70E+02
	③	9.47E+00	9.57E+00
	②+③	1.55E+02	1.80E+02

2.2.3 Active neutrons – Analysis results [Moisture content]

When the moisture content was 70vol%, at 80µs or less, the components of ② had a higher value than the base case, but 80µs onwards the value of the base case increased.

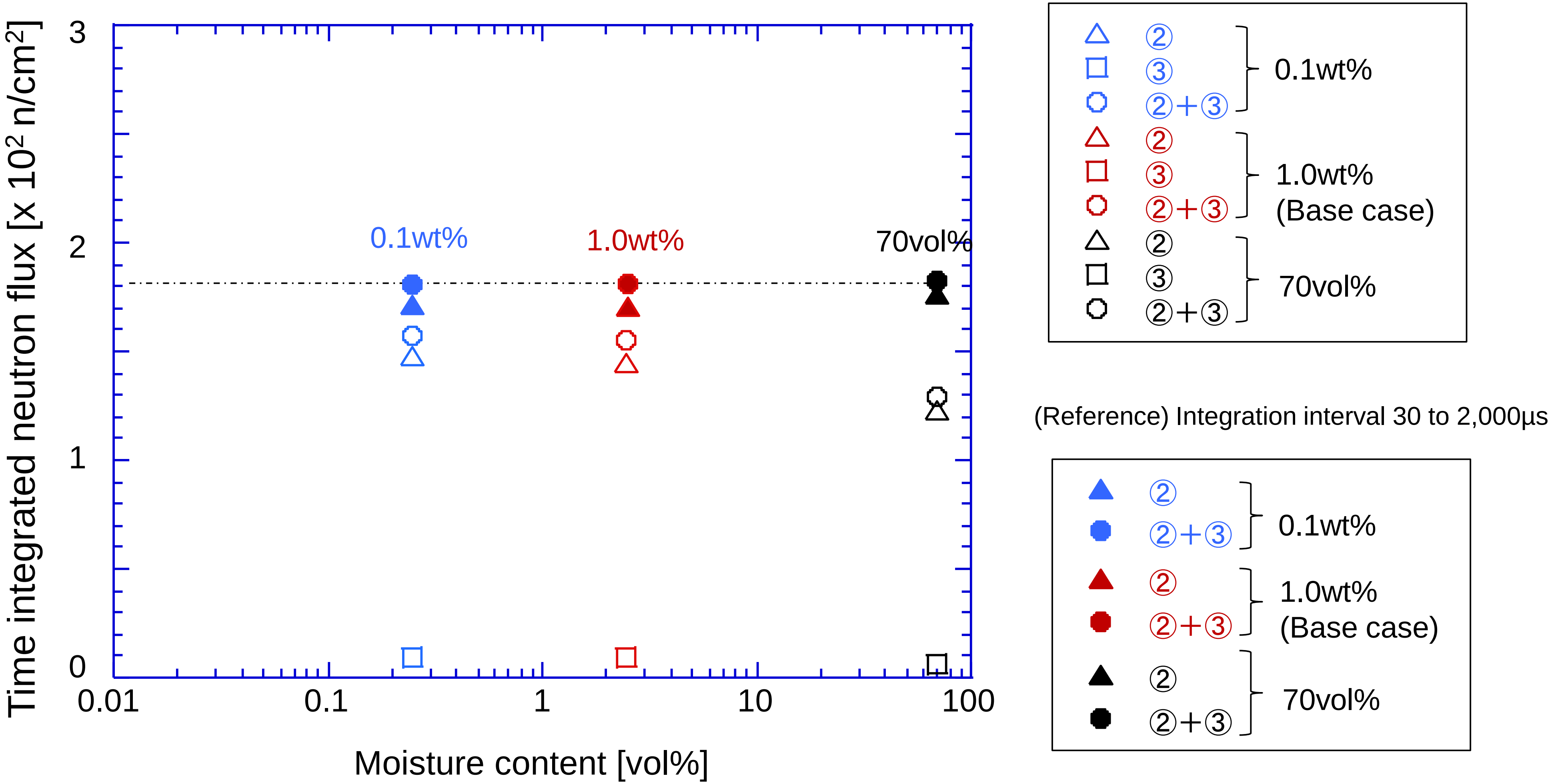
When compared with the integrated value in the interval of 30 to 2000µs, the value for the components of ② was almost the same for the base case and the case with moisture content 70vol%.



	Component	Time integrated neutron flux [n/cm^2]	(Reference) Integration interval 30 to 2,000µs
70 vol %	②	1.23E+02	1.75E+02
	③	6.19E+00	6.26E+00
	②+③	1.29E+02	1.81E+02
Base case	②	1.45E+02	1.70E+02
	③	9.47E+00	9.57E+00
	②+③	1.55E+02	1.80E+02

2.2.3 Active neutrons – Analysis results [Moisture content]

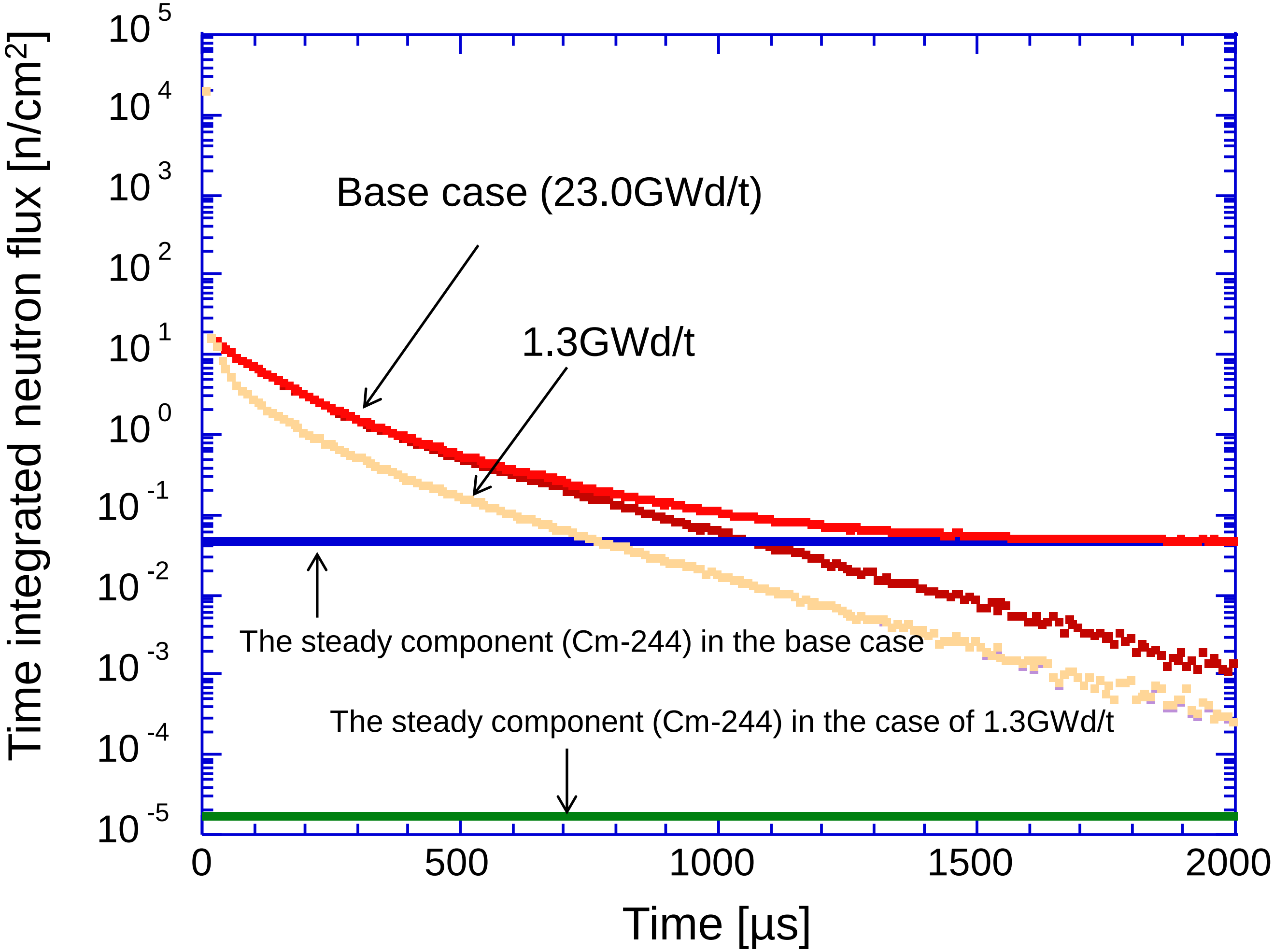
In the case of integration interval 50 to 2,000µs, when the moisture content became 70vol%, the neutron flux reduced, but if the integration interval was changed to 30 to 2,000µs, there was a possibility of being able to perform measurement without the influence of moisture content.



(Reference) Integration interval 30 to 2,000µs

2.2.3 Active neutrons – Analysis results [Burn-up]

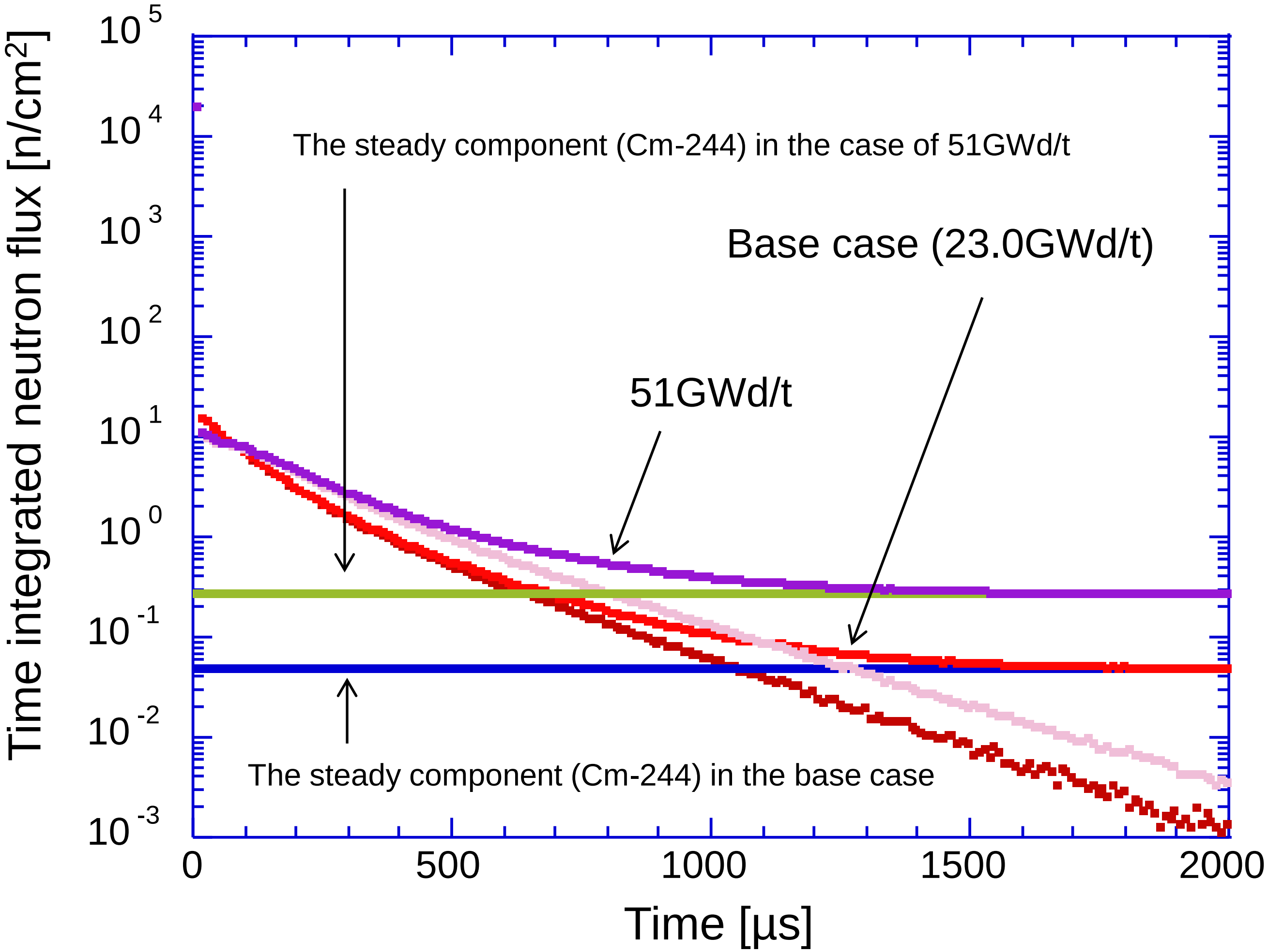
The value of steady component (Cm-244) of ③ in the case of 1.3GWd/t was about 4 digits of magnitude smaller than ②.



	Component	Time integrated neutron flux [n/cm^2]
1.3 GWd/t	②	5.45E+01
	③	3.41E-03
	②+③	5.45E+01
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [Burn-up]

The value of steady component (Cm-244) of ③ in the case of 51GWd/t was almost 5 times or more than the base case, but it was about 1/4 when compared with the steady components of ②.

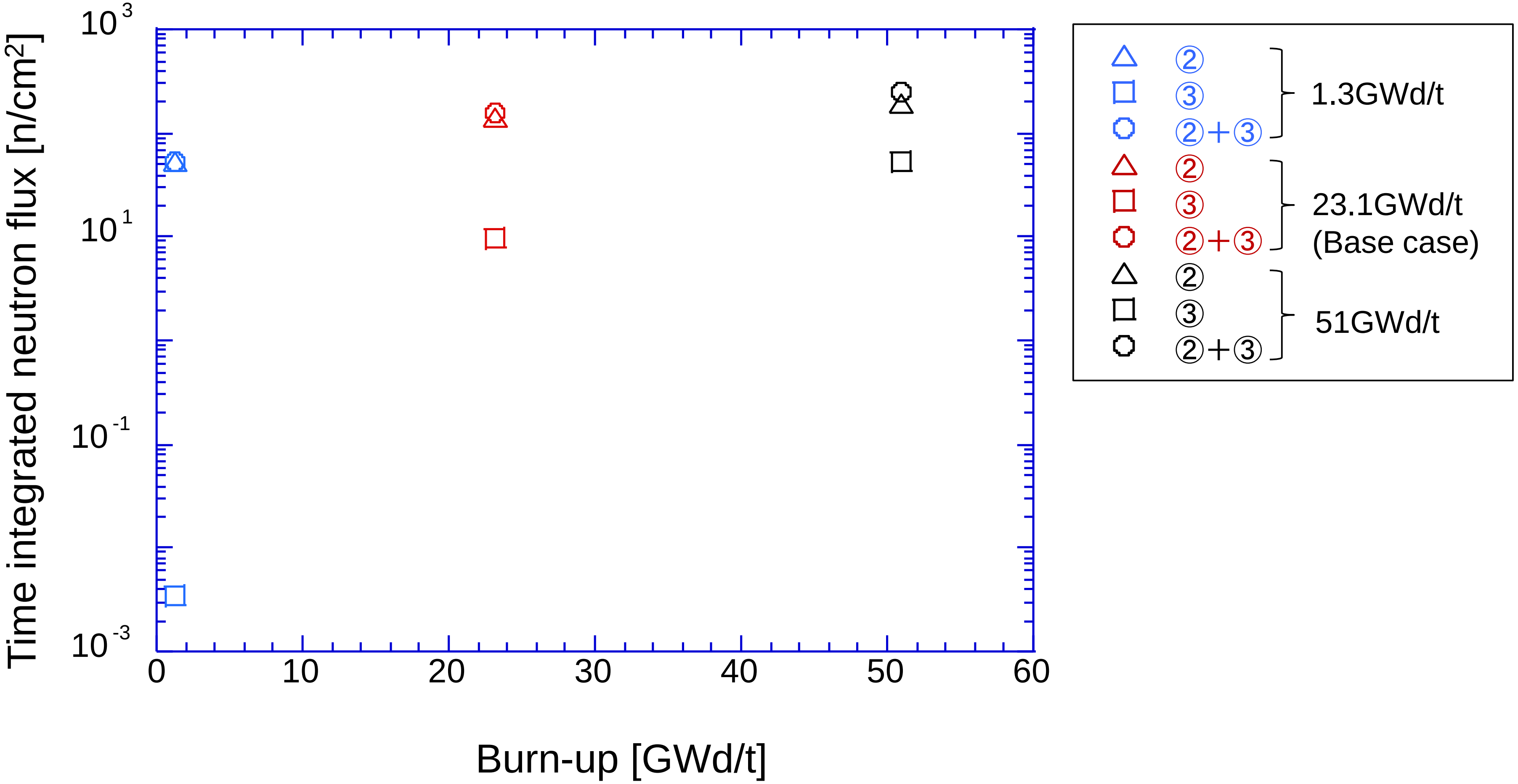


	Component	Time integrated neutron flux [n/cm²]
51 GWd/t	②	1.91E+02
	③	5.29E+01
	②+③	2.44E+02
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [Burn-up]

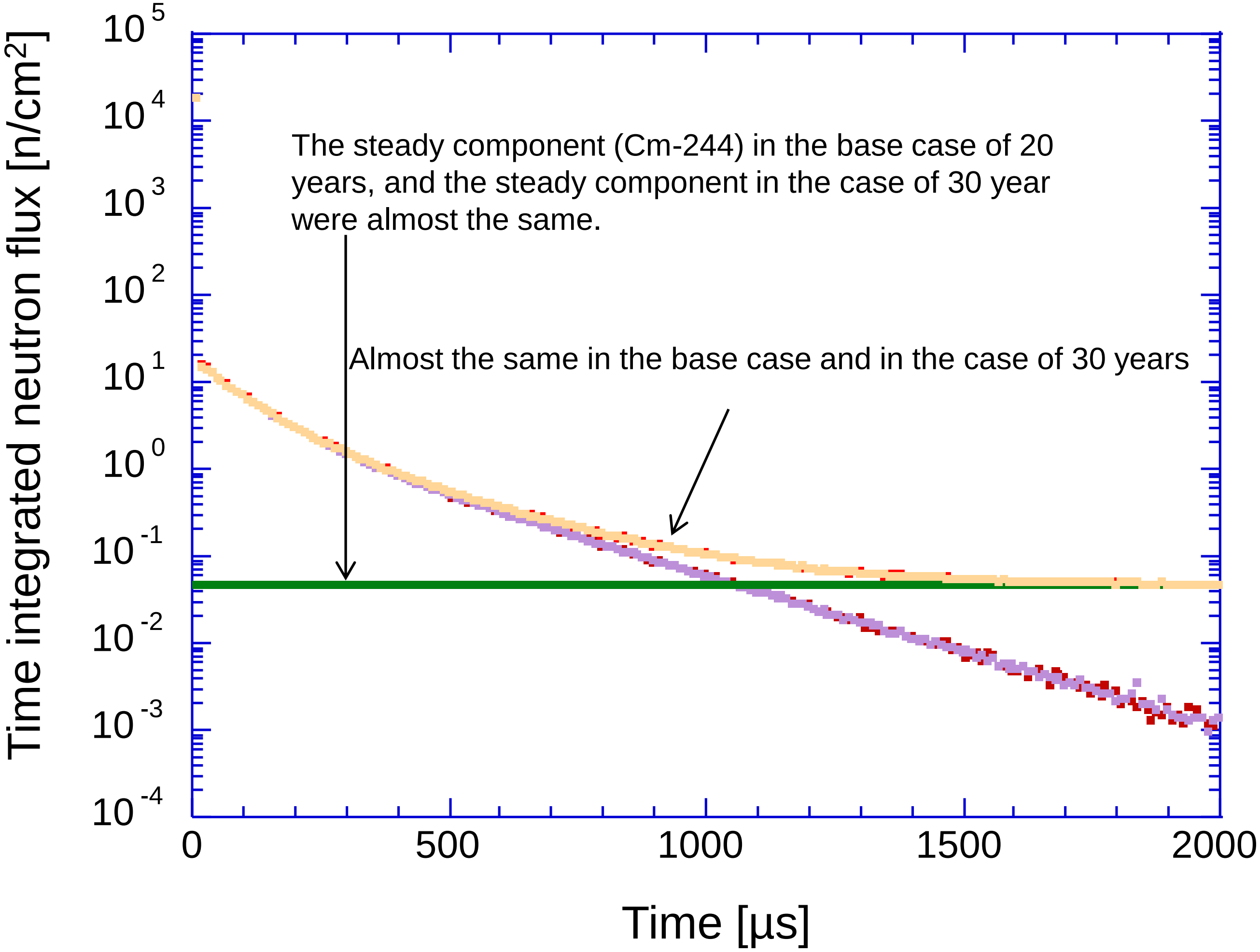
When burn-up increased, the integrated value of the components of ② of the neutron flux monotonically increased, but as the burn-up increased, the proportion of increase of the integrated value reduced.

The integrated value of the components of ③ sharply increased when the burn-up increased, but even in the case of 51GWd/t, it was about 1/4 of ②.



2.2.3 Active neutrons – Analysis results [Cooling period]

The cooling period had almost no impact on the time change pertaining to the components of ② and ③.



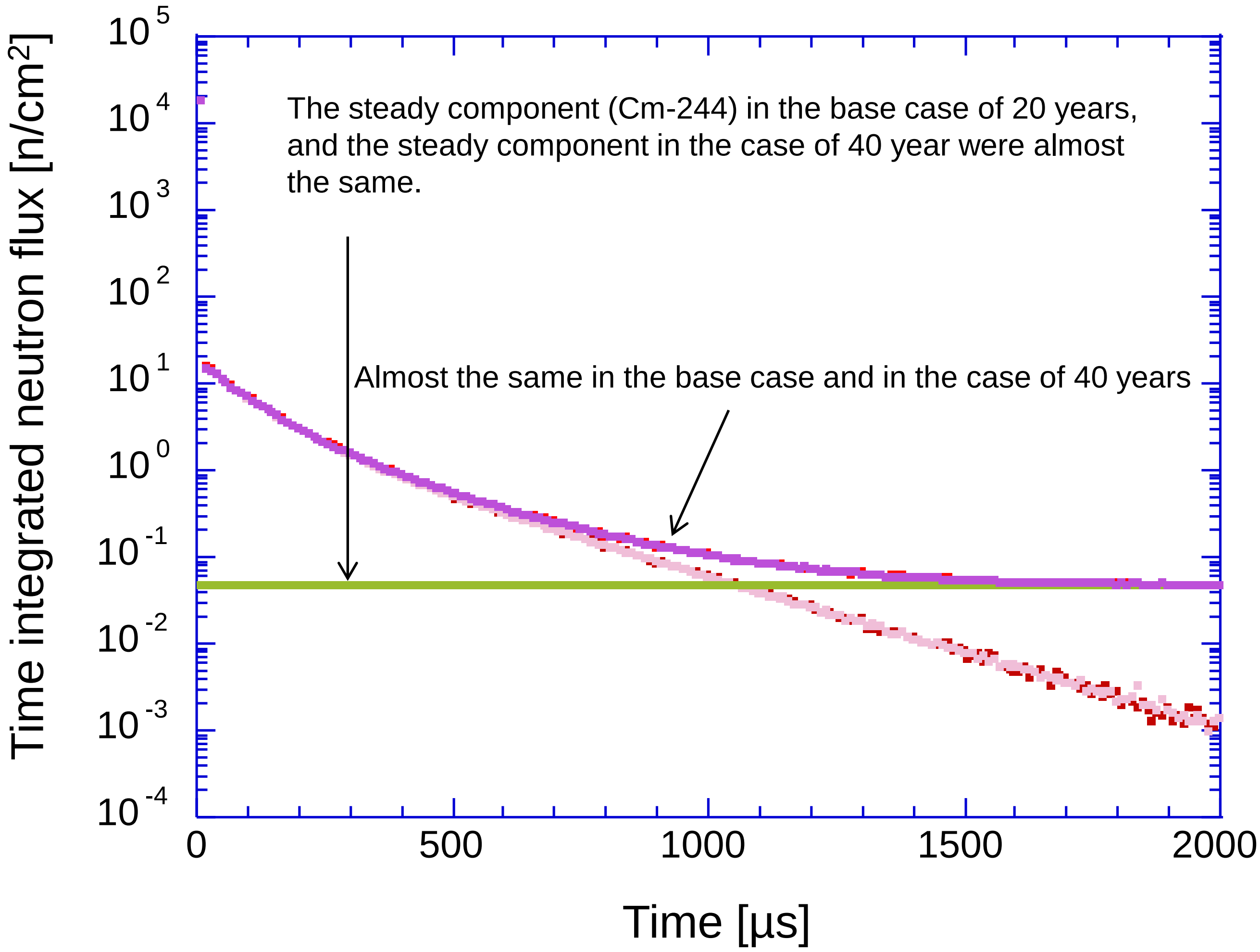
The steady component (Cm-244) in the base case of 20 years, and the steady component in the case of 30 year were almost the same.

Almost the same in the base case and in the case of 30 years

	Component	Time integrated neutron flux [n/cm^2]
30 years	②	1.43E+02
	③	9.47E+00
	②+③	1.53E+02
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [Cooling period]

The cooling period had almost no impact on the time change pertaining to the components of ② and ③.



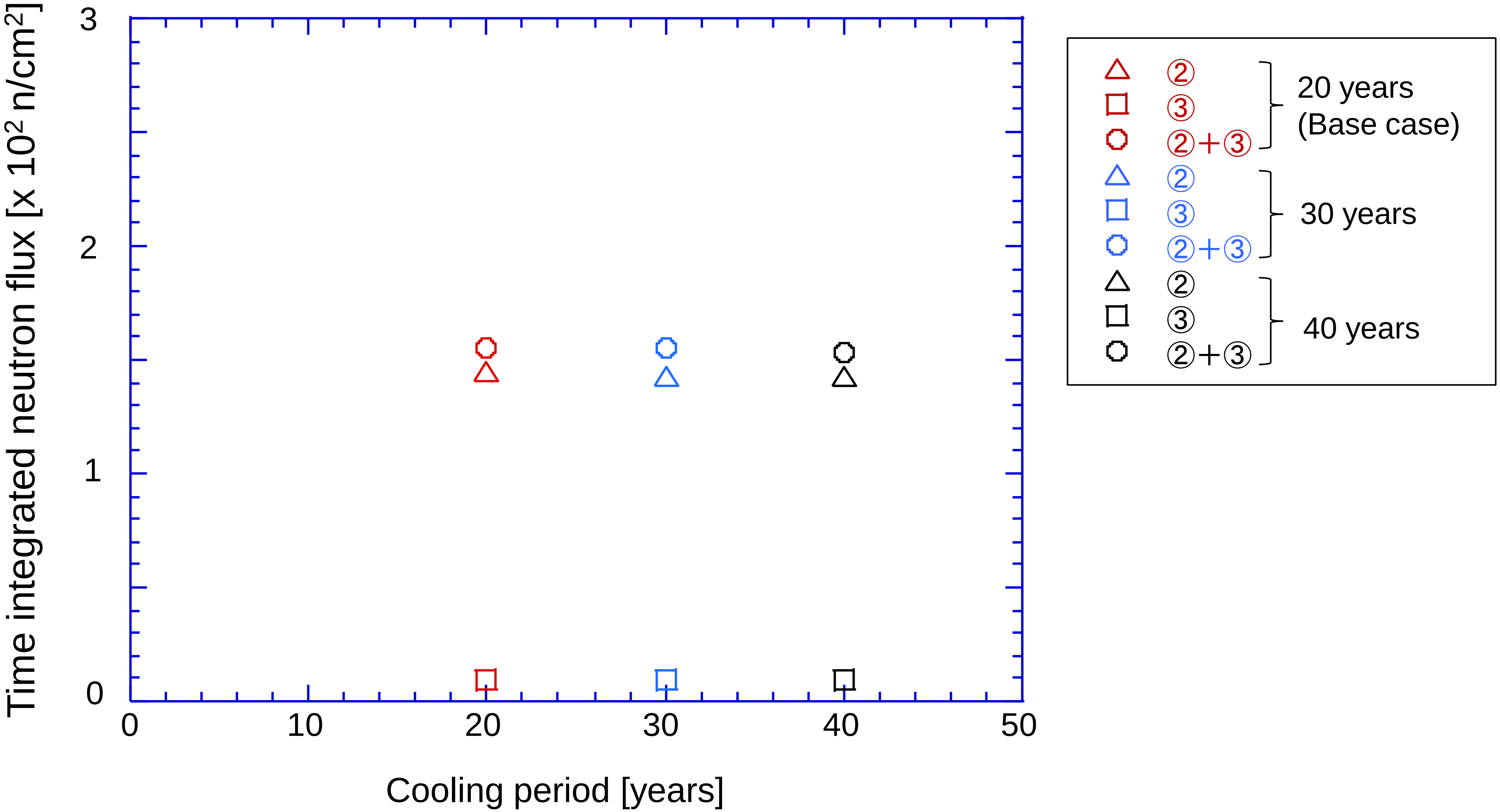
The steady component (Cm-244) in the base case of 20 years, and the steady component in the case of 40 year were almost the same.

Almost the same in the base case and in the case of 40 years

	Component	Time integrated neutron flux [n/cm²]
40 years	②	1.43E+02
	③	9.46E+00
	②+③	1.53E+02
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

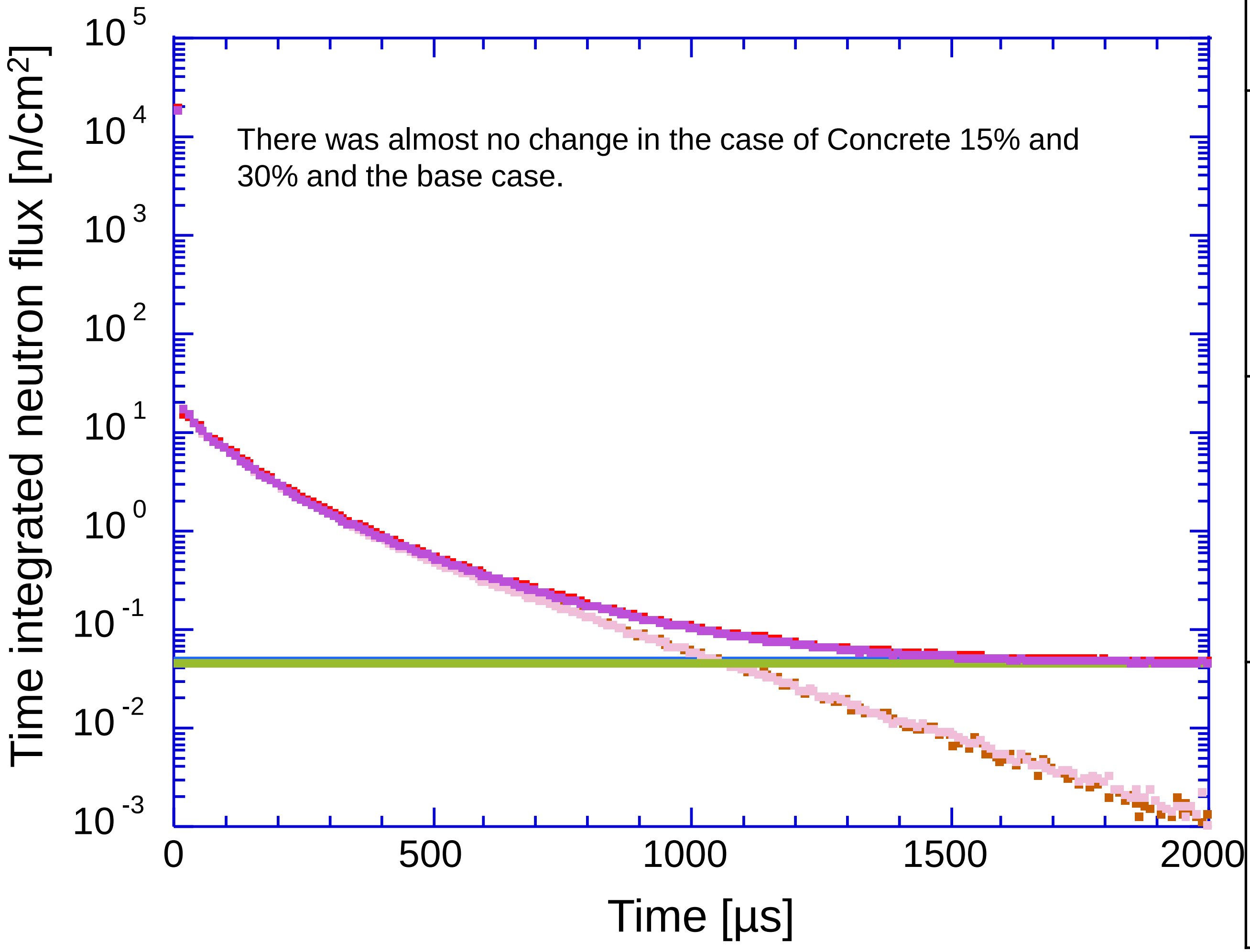
2.2.3 Active neutrons – Analysis results [Cooling period]

The cooling period had almost no impact on the integrated value pertaining to the components of ② and ③.



2.2.3 Active neutrons – Analysis results [MCCI]

There was almost no difference in the time change in the components of ② and ③ in the case of MCCI (Molten Core Concrete Interaction) and molten debris.



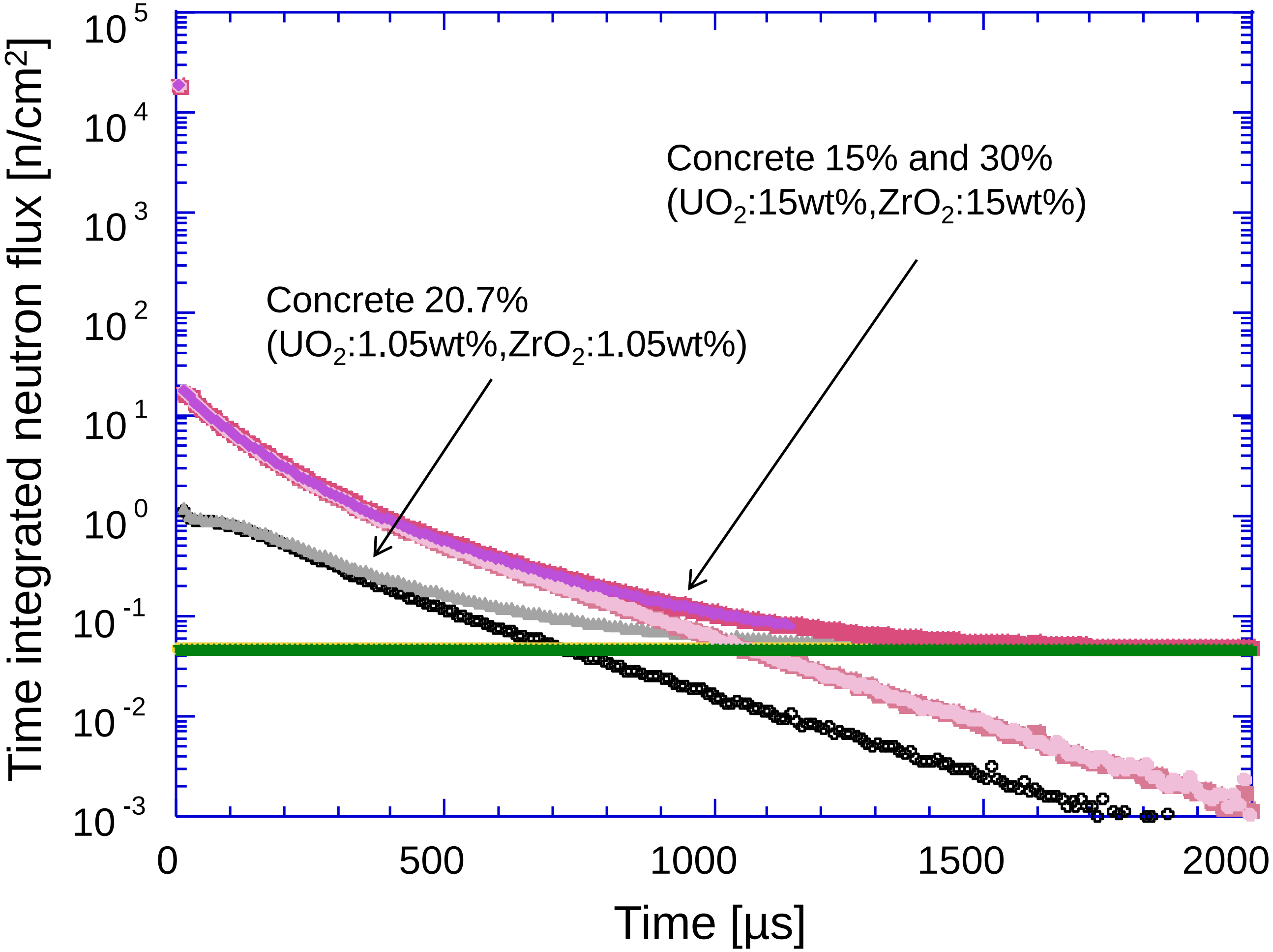
There was almost no change in the case of Concrete 15% and 30% and the base case.

	Component	Time integrated neutron flux [n/cm²]
Concrete 15 %	②	1.42E+02
	③	9.24E+00
	②+③	1.51E+02
Concrete 30%	②	1.39E+02
	③	9.00E+00
	②+③	1.48E+02
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

2.2.3 Active neutrons – Analysis results [MCCI]

When the amount of UO_2 and ZrO_2 was the same, there was almost no difference in the time change pertaining to the components of ② and ③, even if the amount of concrete changed.

When the amount of UO_2 and ZrO_2 was different, there was almost no difference in the time change pertaining to the components of ③, but in the case of components of ②, when the amount of UO_2 and ZrO_2 was approx. 1/15, the integrated value of the neutron flux was approx. 1/7.



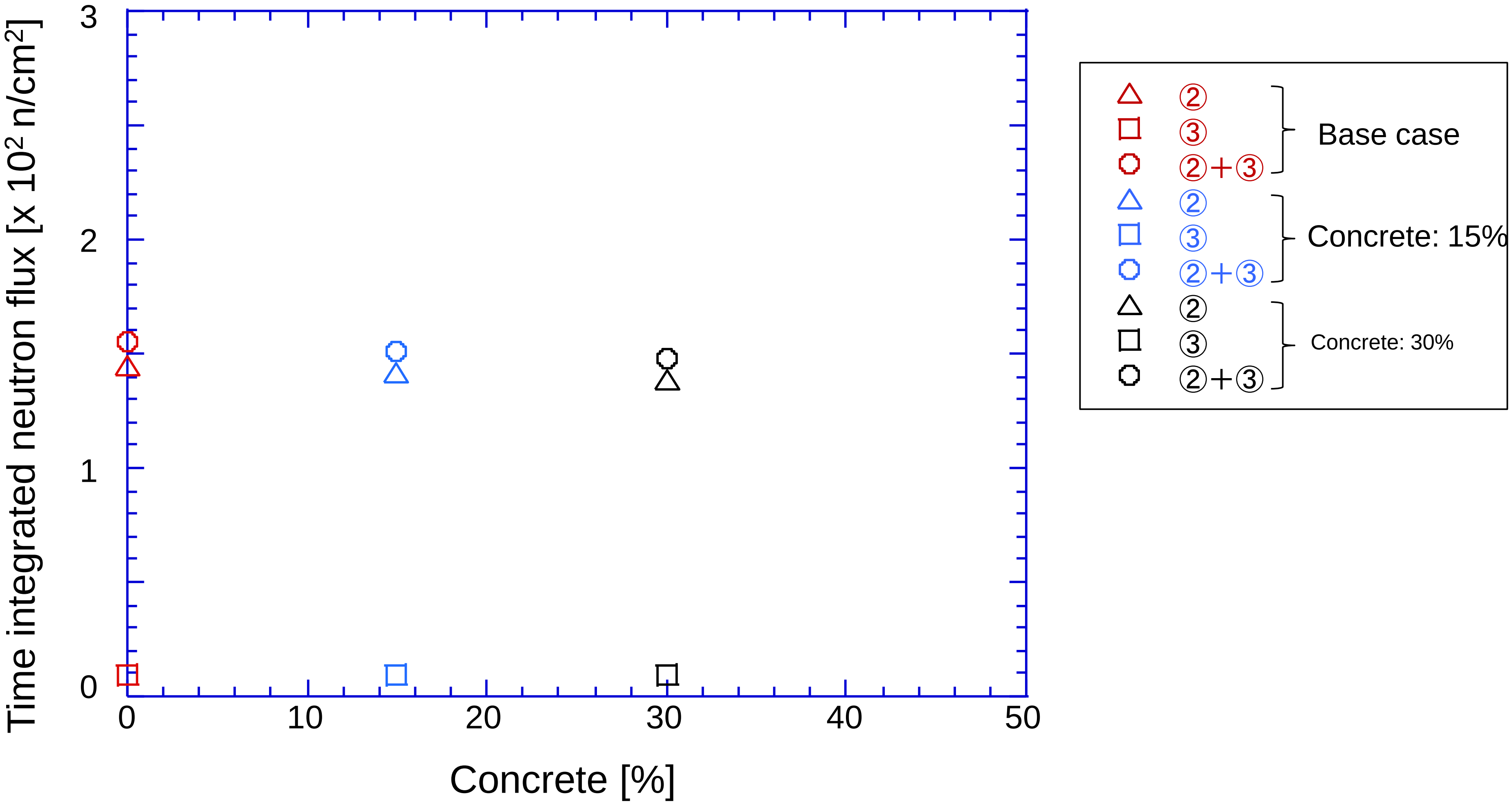
Concrete 15% and 30% (UO_2:15wt%,ZrO_2:15wt%)

Concrete 20.7% (UO_2:1.05wt%,ZrO_2:1.05wt%)

	Component	Time integrated neutron flux $[n/cm^2]$
Concrete 20.7 %	②	2.11E+01
	③	9.18E+00
	②+③	3.02E+01
Concrete 15 %	②	1.42E+02
	③	9.24E+00
	②+③	1.51E+02
Concrete 30%	②	1.39E+02
	③	9.00E+00
	②+③	1.48E+02

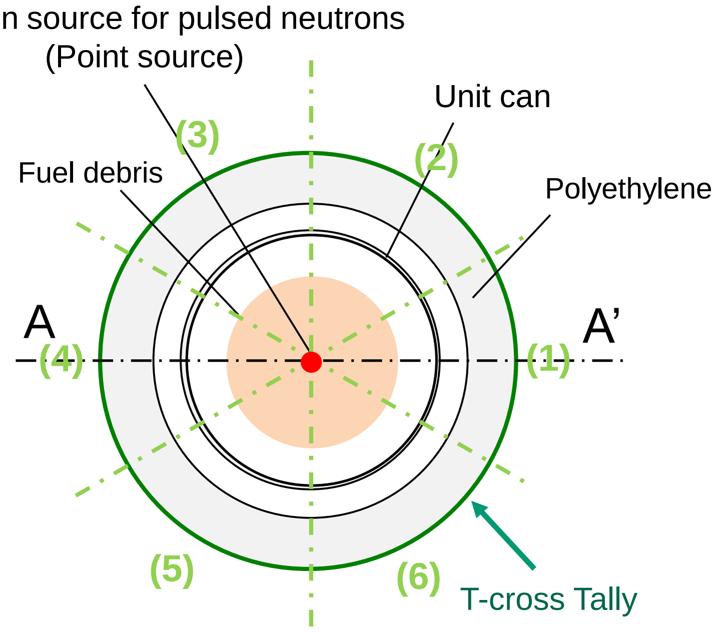
2.2.3 Active neutrons – Analysis results [MCCI]

There was almost no difference in the integrated value of the components of ② and ③ in the case of MCCI (Molten Core Concrete Interaction) and molten debris.

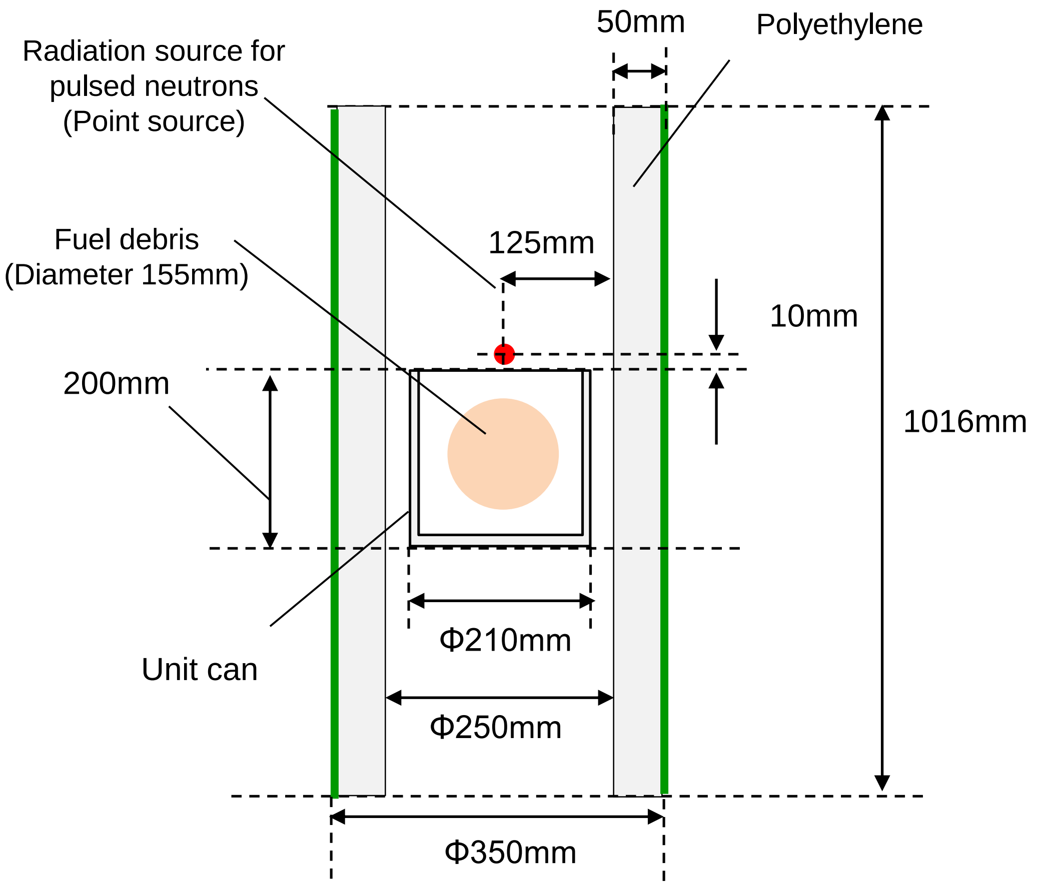


2.2.3 Active neutrons – Sensitivity analyses [Uneven distribution model (A)]

Tally
(Region divided equally into 6 parts)

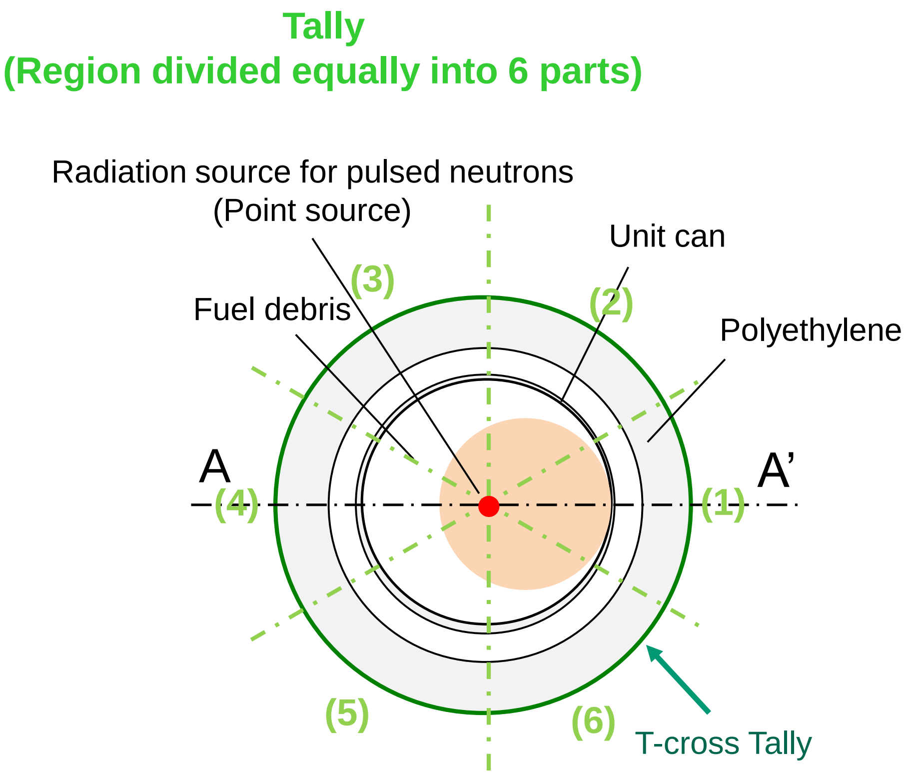


Analysis model top view

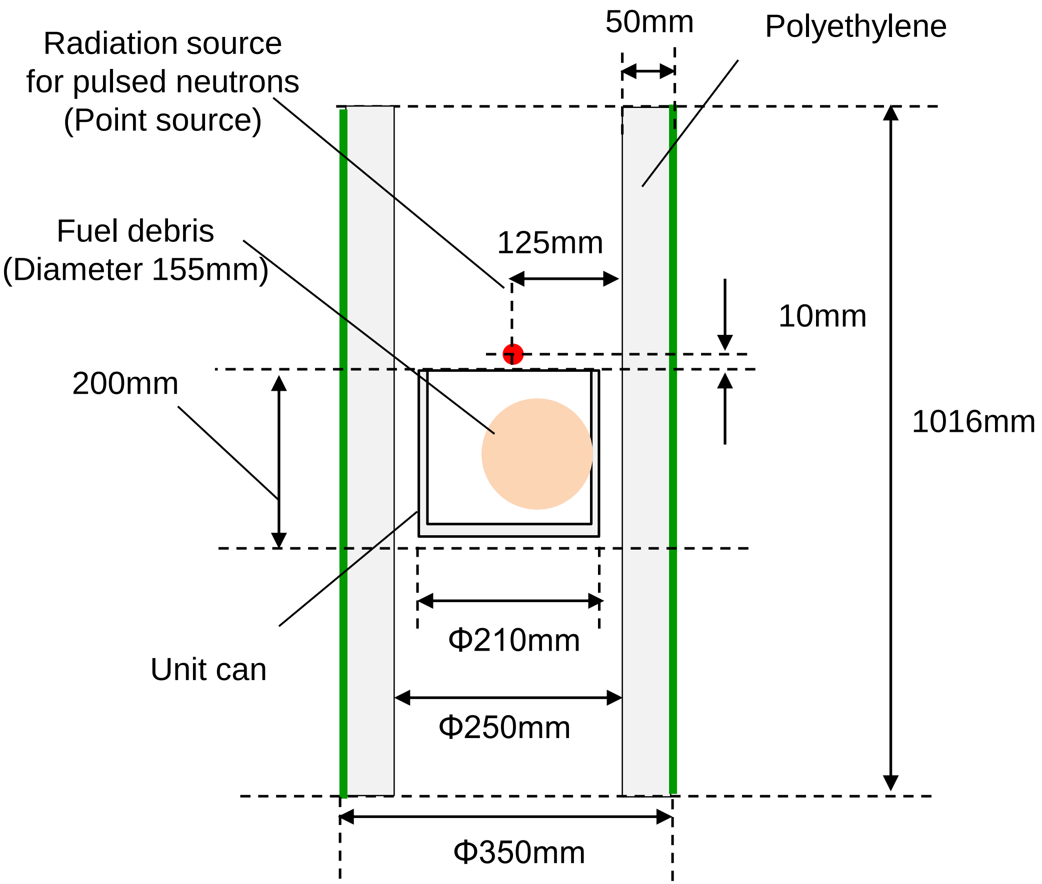


Cross-sectional view A-A’

2.2.3 Active neutrons – Sensitivity analyses [Uneven distribution model (B)]



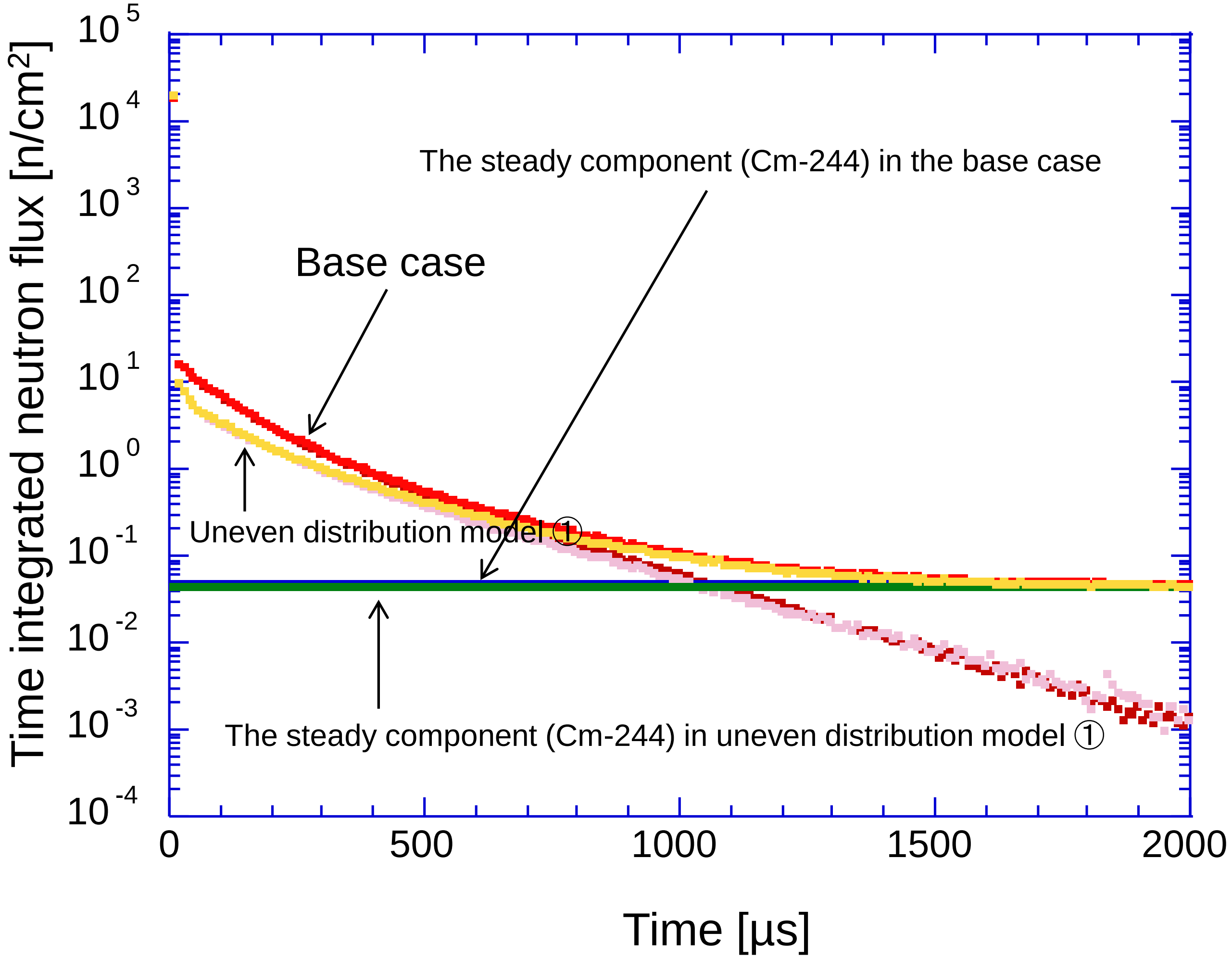
Analysis model top view



Cross-sectional view A-A’

2.2.3 Active neutrons – Sensitivity analyses [Uneven distribution model (A)]

The change in the component (Cm-244) of ③ resulting from uneven distribution was 10% or less. However, the components of ② largely changed early on (100µs or less) but the change was small 500µs onwards.

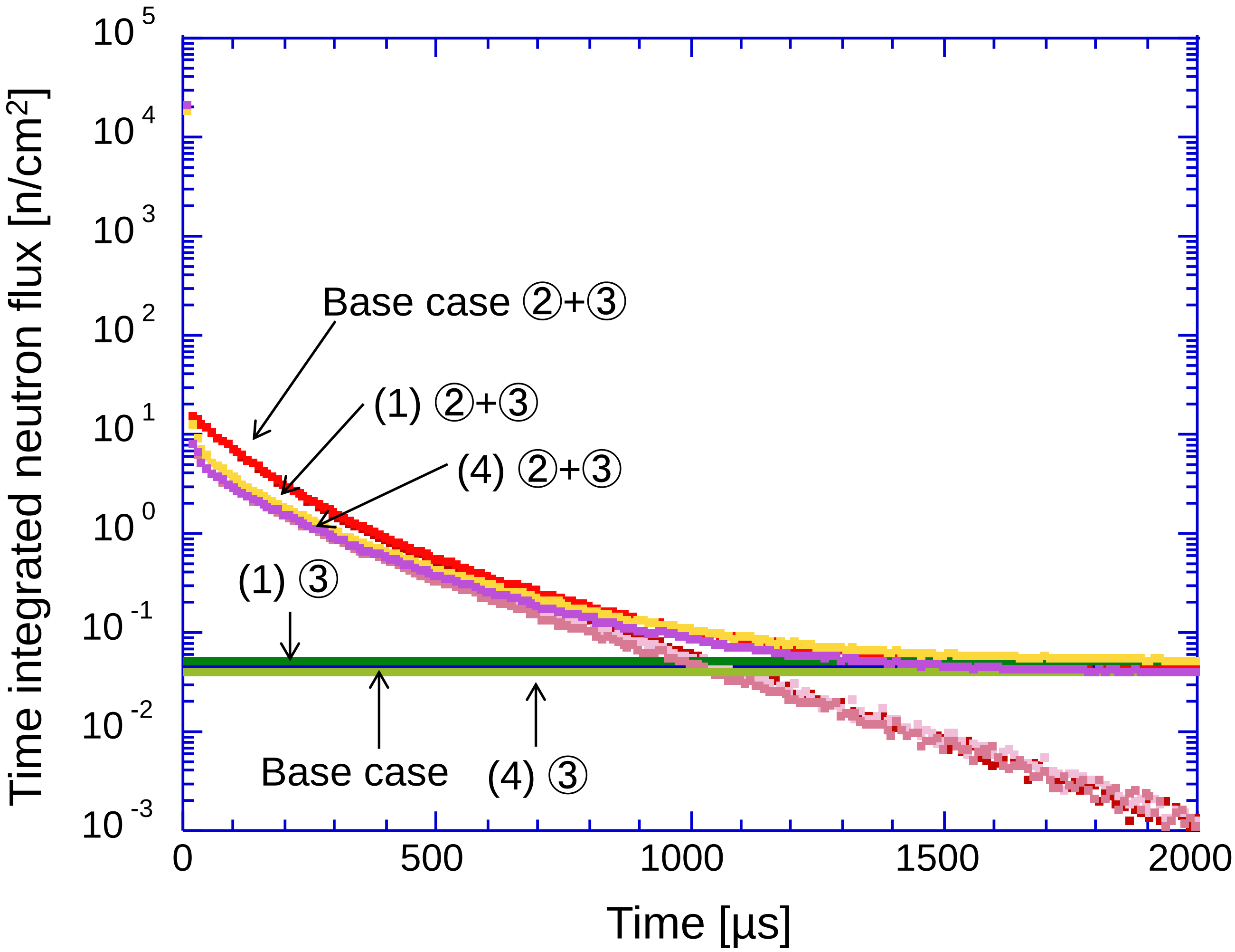


	Component	Time integrated neutron flux [n/cm²]
Uneven distribution model	②	8.07E+01
	③	8.86E+00
	②+③	8.95E+01
Base case	②	1.45E+02
	③	9.47E+00
	②+③	1.55E+02

In the uneven distribution model (A), the values of (1) to (6) were all the same.

2.2.3 Active neutrons – Sensitivity analyses [Uneven distribution model (B)]

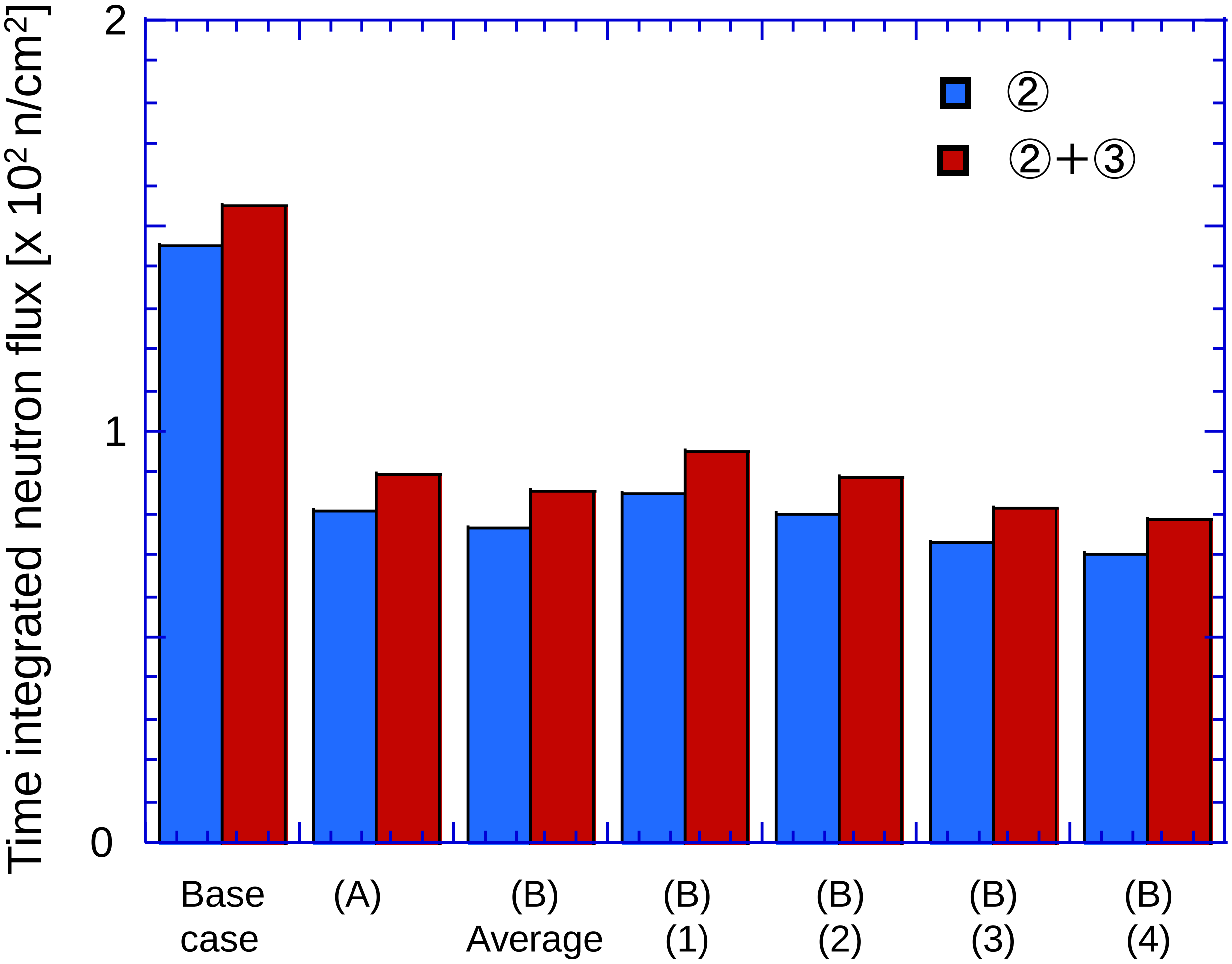
The change in the steady component (Cm-244) of ③ due to uneven distribution was 10% or less. However, the components of ② largely changed at an early time (100μs or less) but the change was small 500μs onwards.



		Component	Time integrated neutron flux [n/cm²]
Uneven distribution model (B)	(1)	②	8.49E+01
		③	1.03E+01
		②+③	9.52E+01
	(2)	②	7.97E+01
		③	9.33E+00
		②+③	8.90E+01
	(3)	②	7.28E+01
		③	8.14E+00
		②+③	8.10E+01
	(4)	②	7.04E+01
		③	7.77E+00
		②+③	7.82E+01
	Mean	②	7.67E+01
		③	8.84E+00
		②+③	8.56E+01
Base case		②	1.45E+02
		③	9.47E+00
		②+③	1.55E+02

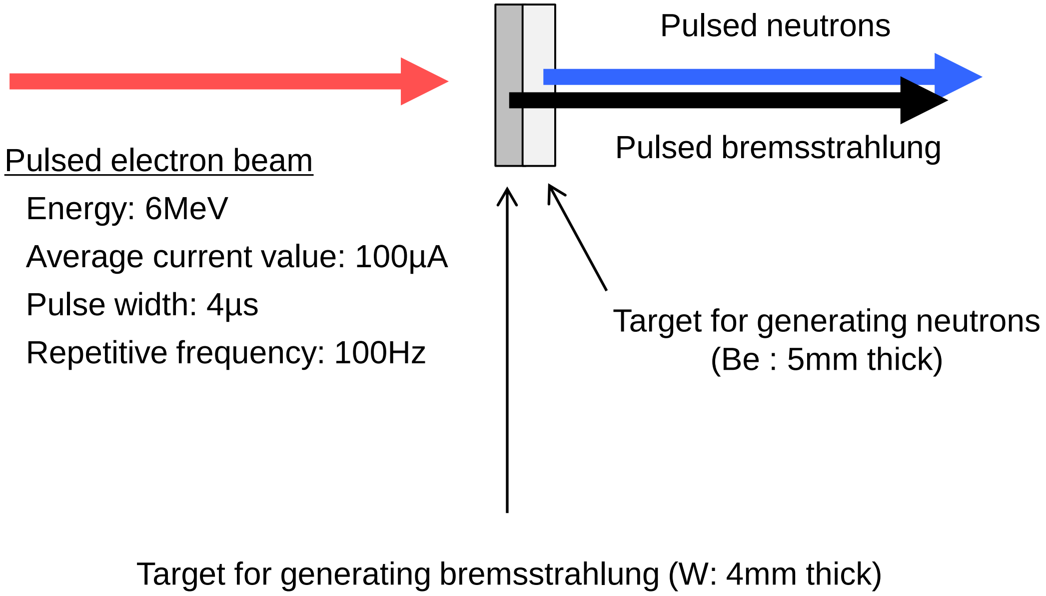
2.2.3 Active neutrons – Sensitivity analyses [Uneven distribution models]

There was a difference of less than 5% in the average value of the integrated values of the components of ② in uneven distribution models (A) and (B), but in the base case it was approx. double the values of the uneven distribution models (A) and (B).



2.2.3 Active neutrons – Other sensitivity analyses results

Accelerator based neutron source

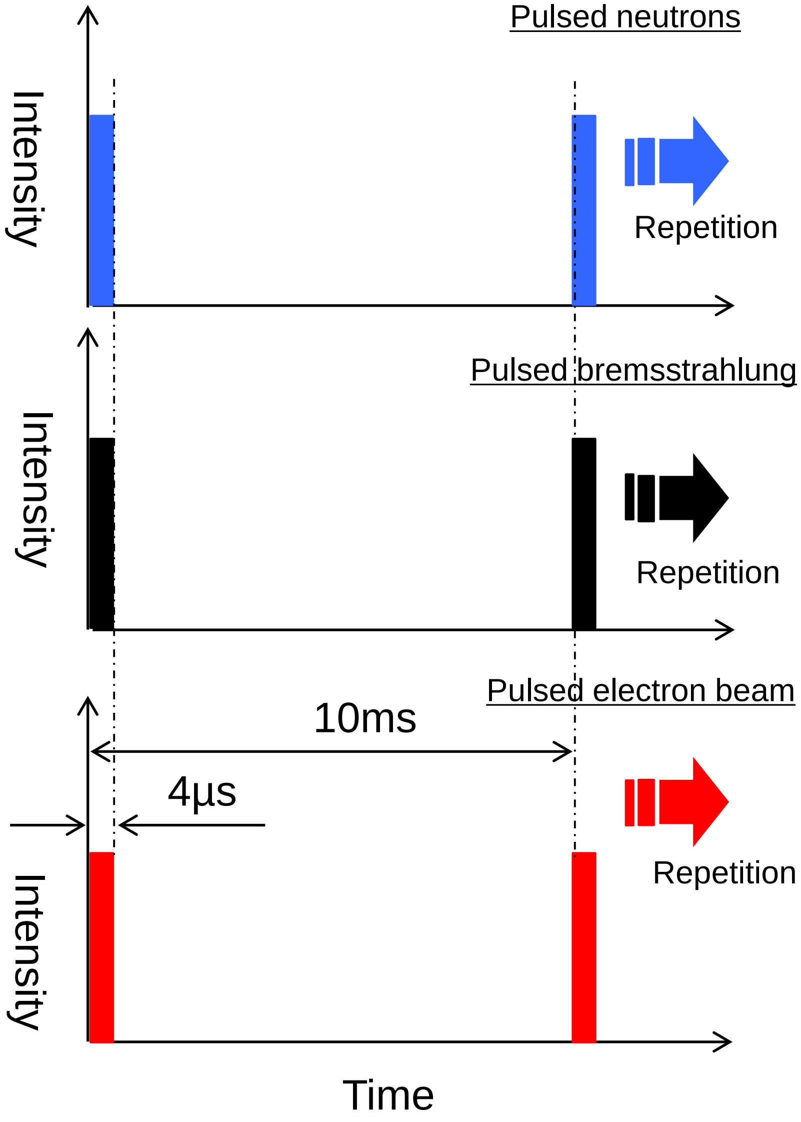


Pulsed electron beam

- Energy: 6MeV
- Average current value: 100μA
- Pulse width: 4μs
- Repetitive frequency: 100Hz

Rate of neutron generation: 4.5×10^8 n/s

Average neutron energy: 1.13MeV



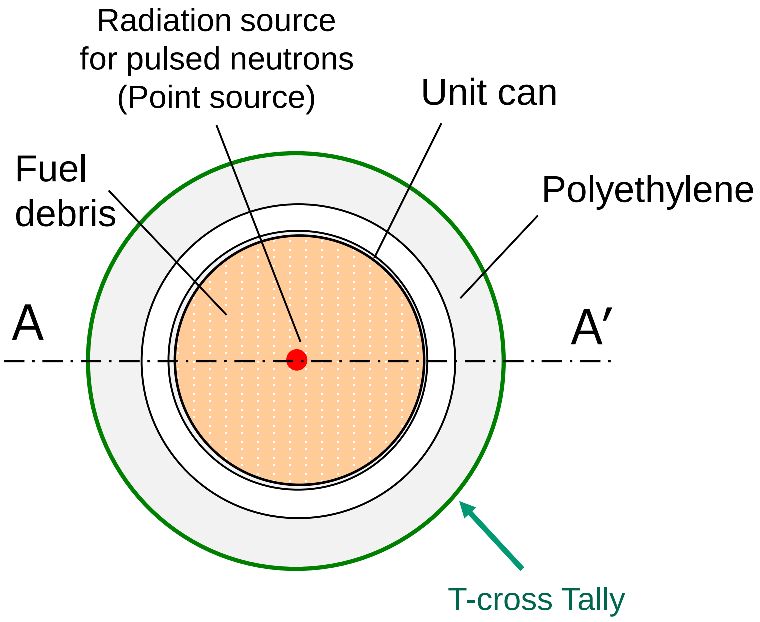
2.2.3 Active neutrons – Other sensitivity analyses results

Accelerator based neutron source

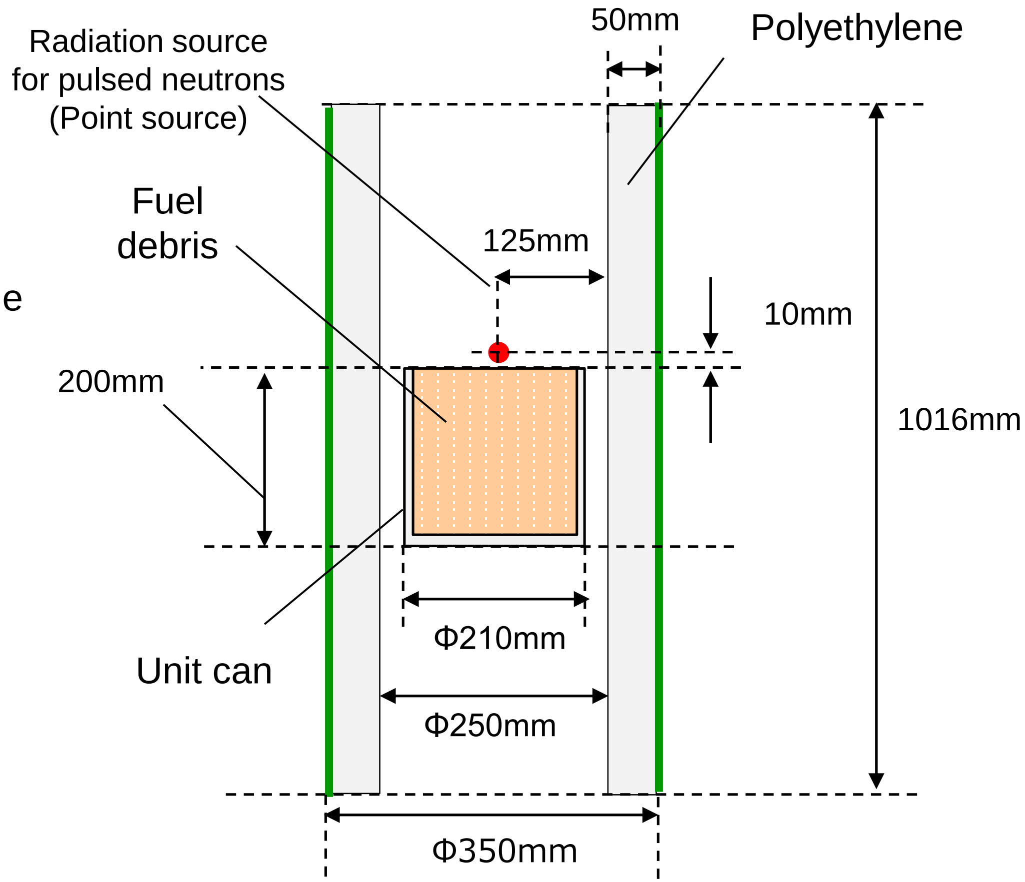
Neutron generation pulse width: 4μs

Rate of neutron generation: 4.5×10^8 n/s

Average neutron energy: 1.13MeV



Analysis model top view



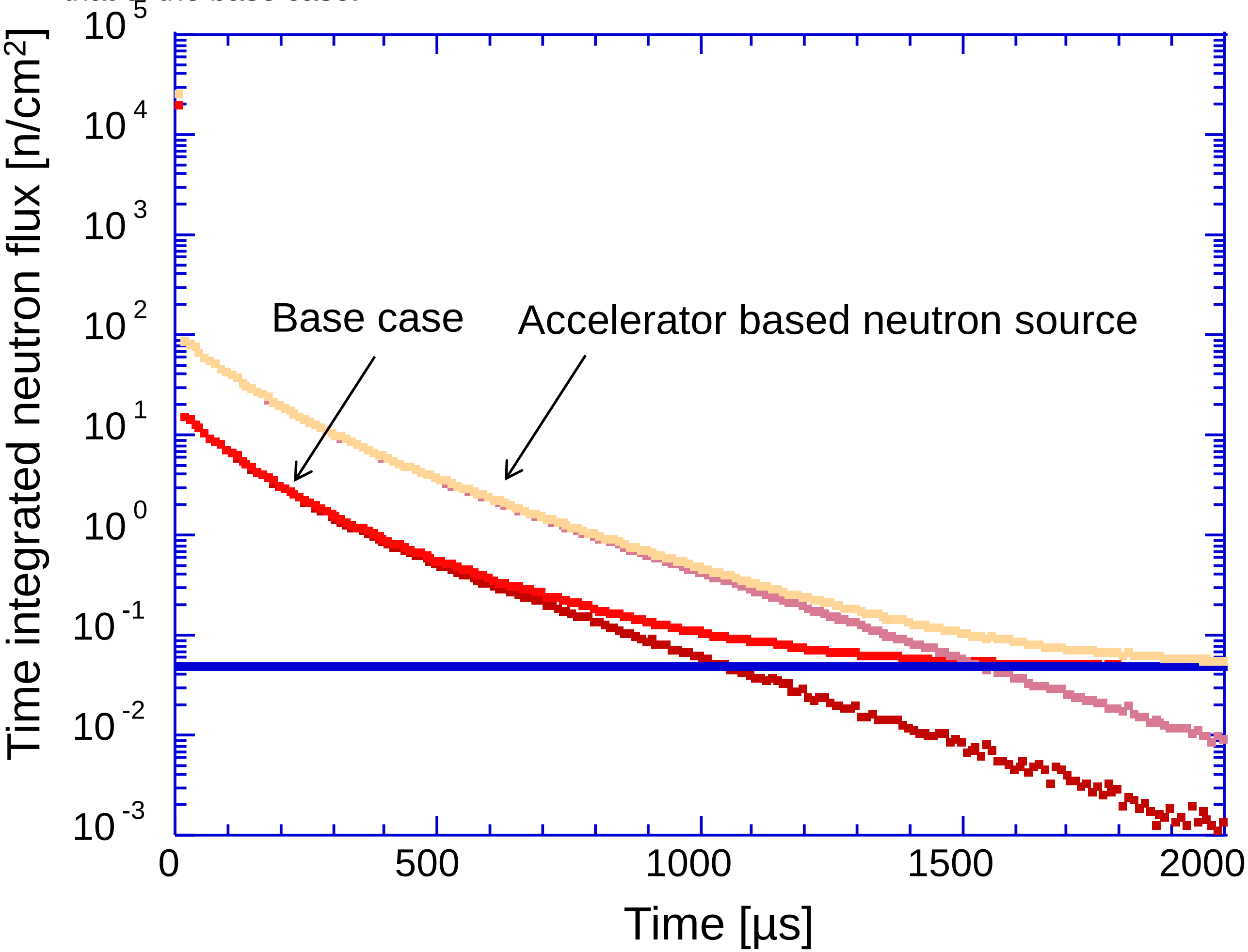
Cross-sectional view A-A’

2.2.3 Active neutrons – Other sensitivity analyses results

Accelerator based neutron source

(1) Rate of pulsed neutron generation: 4.5×10^8 n/s
(2) : 2.0×10^8 n/s
(When it is the same as the base case)

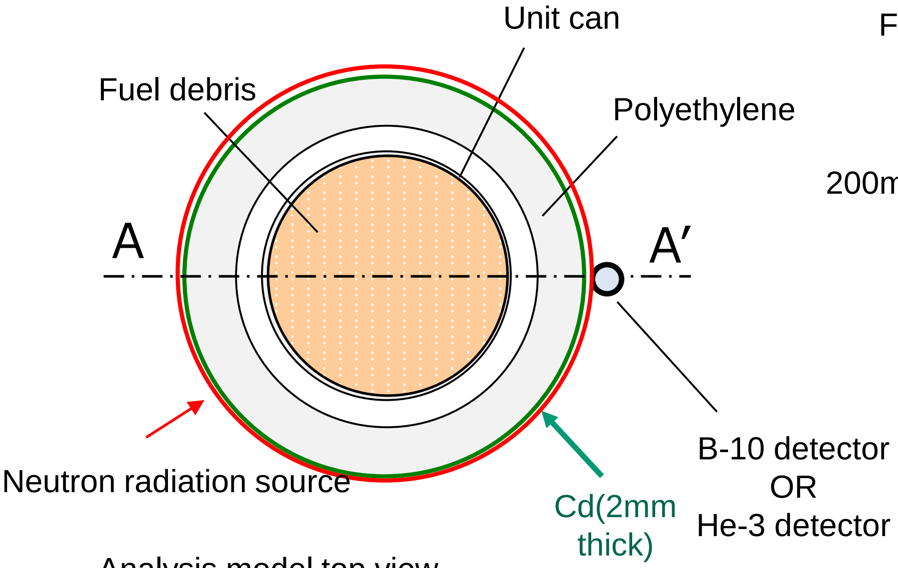
The integrated value of the components of ② per unit of the rate of neutron generation in the case of accelerator based neutron source was approx. 3 times that of the base case.



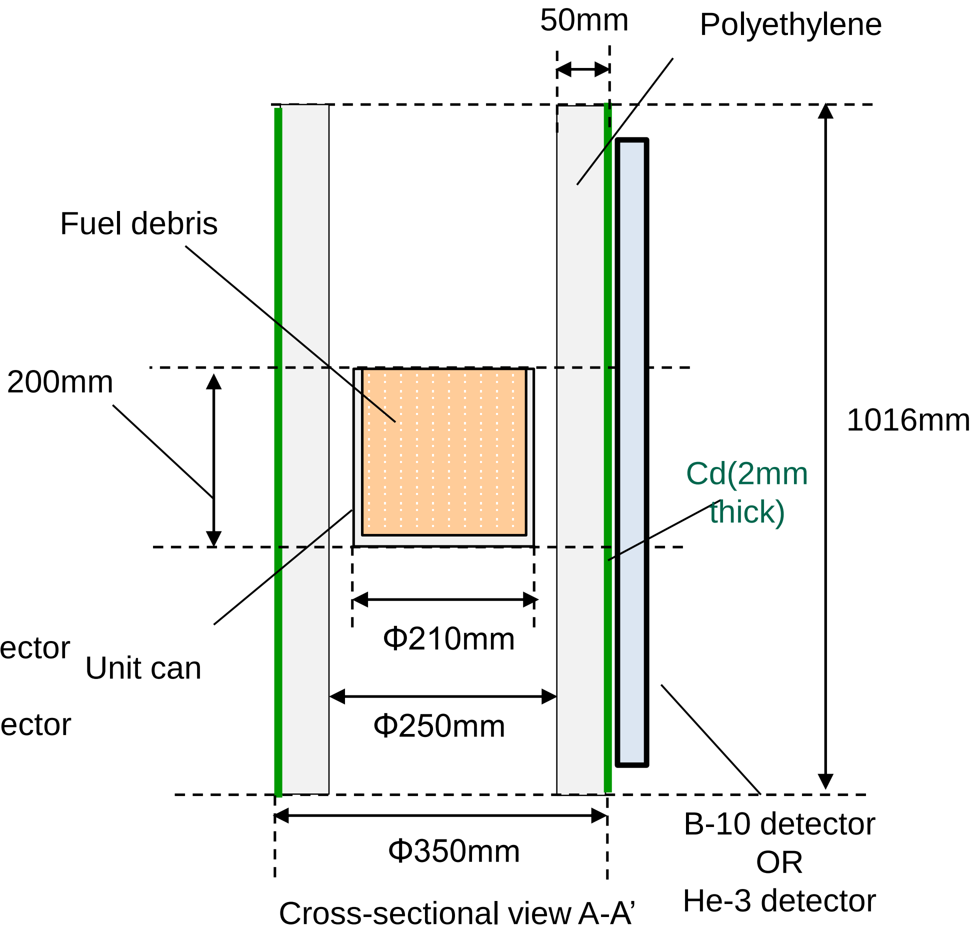
		Component	Time integrated neutron flux [n/cm²]
Accelerator based neutron source	(1)	②	9.15E+02
		③	9.47E+00
		②+③	9.25E+02
	(2)	②	4.07E+02
		③	9.47E+00
		②+③	4.16E+02
Base case		②	1.45E+02
		③	9.47E+00
		②+③	1.55E+02

2.2.3 Active neutrons – Other sensitivity analyses results

Response spectrum for a representative detector (System)



Analysis model top view

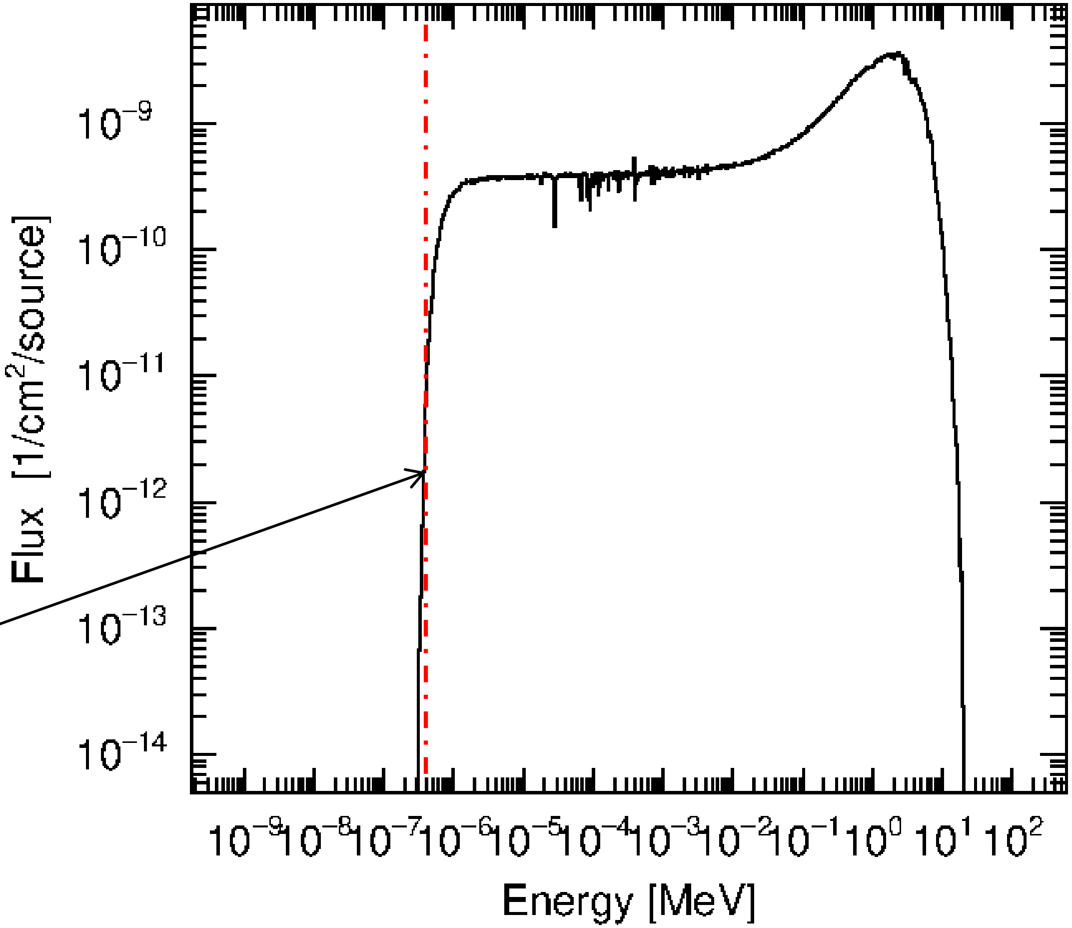


Cross-sectional view A-A’

2.2.3 Active neutrons – Other sensitivity analyses results

Response spectrum for a representative detector (Energy spectrum of the neutron radiation source)

Energy spectrum of the neutrons on the side of the outer cylinder of Cd in the base case
(Integrated value at the interval of 50μs to 2,000μs)



Cd cut neutrons with energy lower than 0.4eV.

2.2.3 Active neutrons – Other sensitivity analyses results

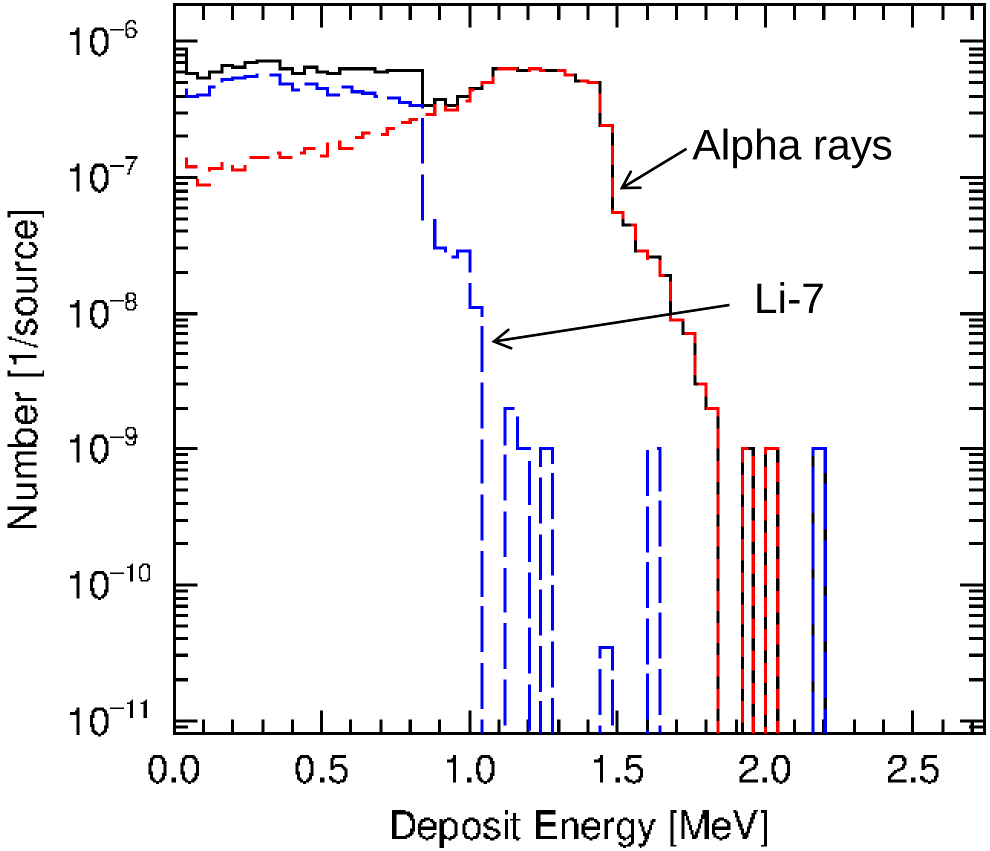
Response spectrum for a representative detector (B-10 detector)

B-10 detector: Diameter (inner diameter) 25.4mm, effective length: 1000mm

B-10 thickness 0.8547μm (=0.2mg/cm^2)

Ar gas pressure 0.3atm

Housing: 0.5mm thick SUS304



Count rate in the base case

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

→ 26.2cps

Time required for getting a 10,000 count: 382 seconds

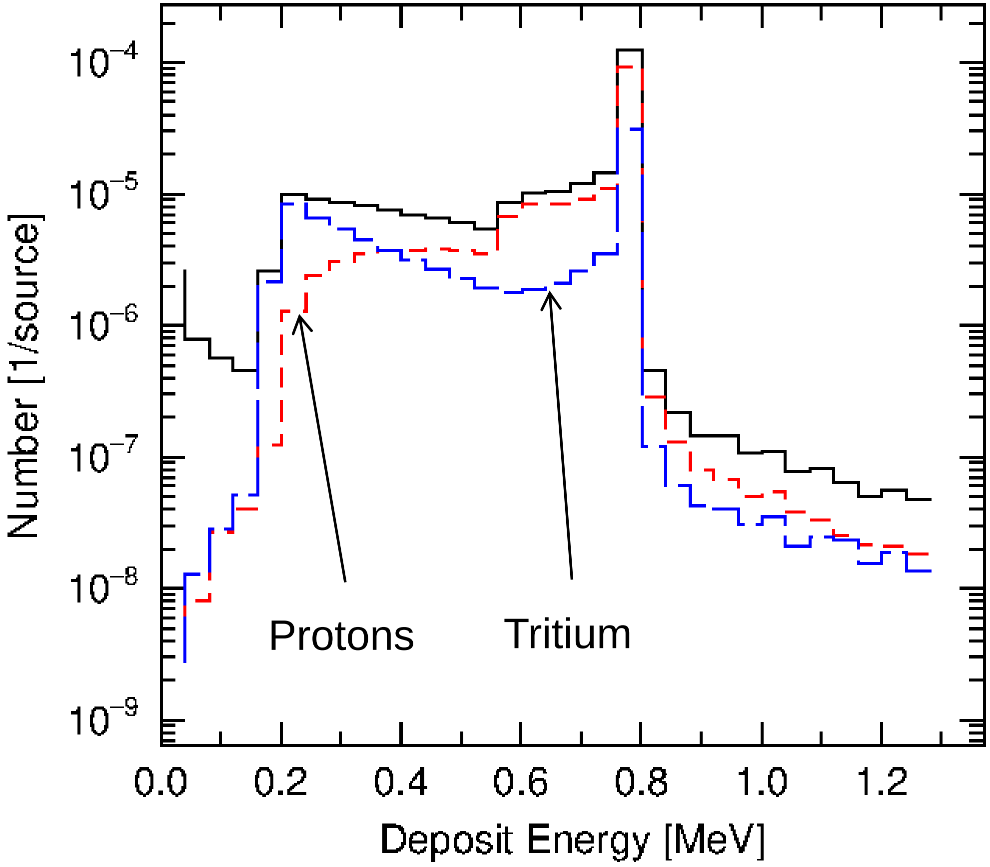
2.2.3 Active neutrons – Other sensitivity analyses results

Response spectrum for a representative detector (He-3 detector)

He-3 detector: Diameter (inner diameter) 25.4mm, effective length: 1000mm

Housing: 0.5mm thick SUS304

He-3 pressure 4atm



Count rate in the base case

Protons and tritium that impart 80keV or more energy were measured.

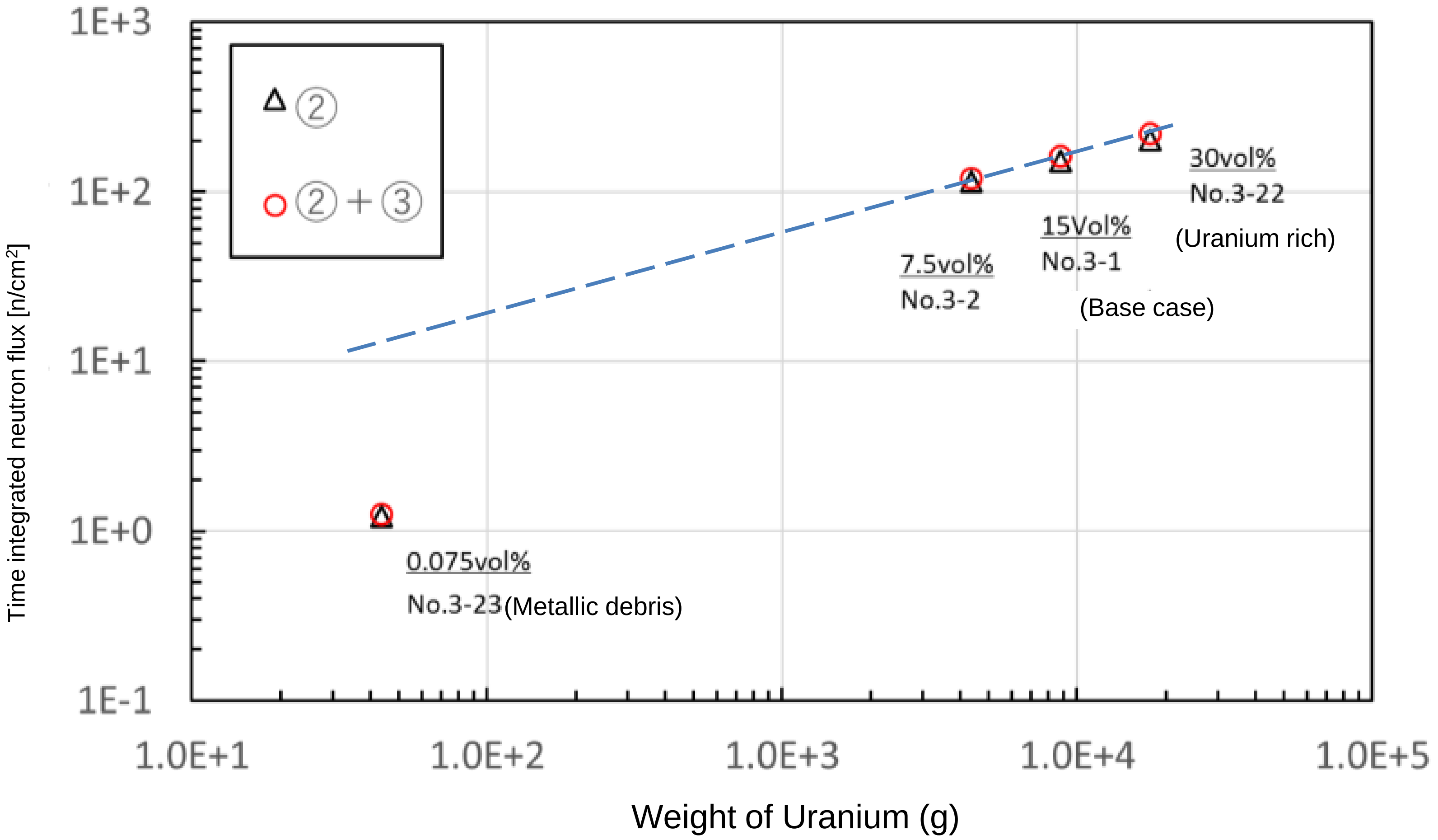
→ 326.7cps

Time required for getting a 10,000 count: 31 seconds

2.2.3 Active neutrons- Analysis results [Sensitivity Analysis]

✓ Sensitivity to the amount of Uranium (Influencing factor ①)

- The amount of Uranium and neutron flux has a proportional relationship.
- When the composition largely differed from molten debris such as in the case of metallic debris, etc., since the deceleration and level of thermalization of neutrons generated by the source for pulsed neutrons differed, the trend differed.



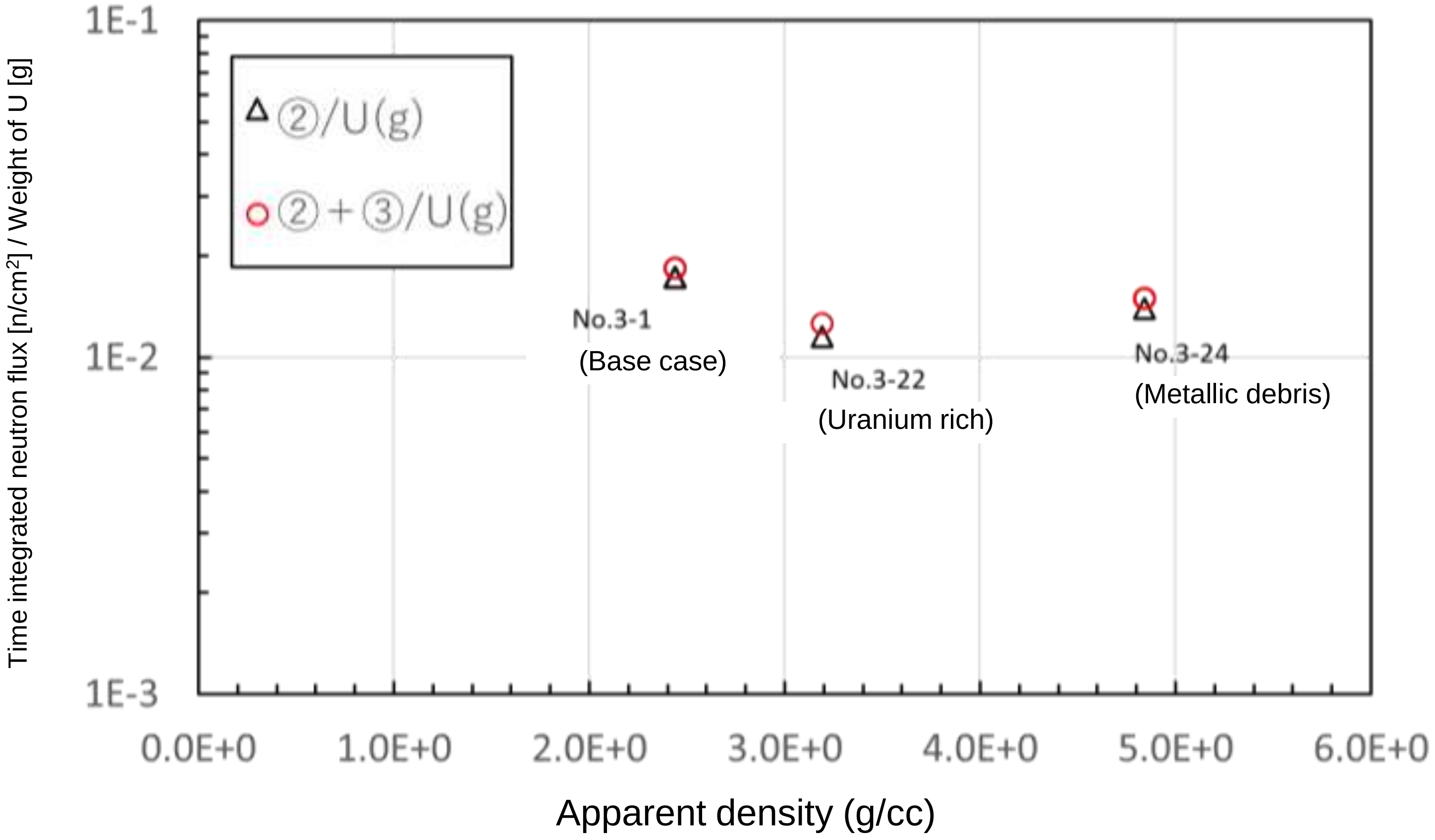
2.2.3 Active neutrons- Analysis results [Sensitivity Analysis]

✓ Sensitivity to apparent density (Influencing factors ① and ⑥)

・The difference in apparent density of fuel debris had a small impact on neutron flux.

(There was slight difference since the deceleration and level of thermalization of neutrons differs depending on the fuel debris composition.)

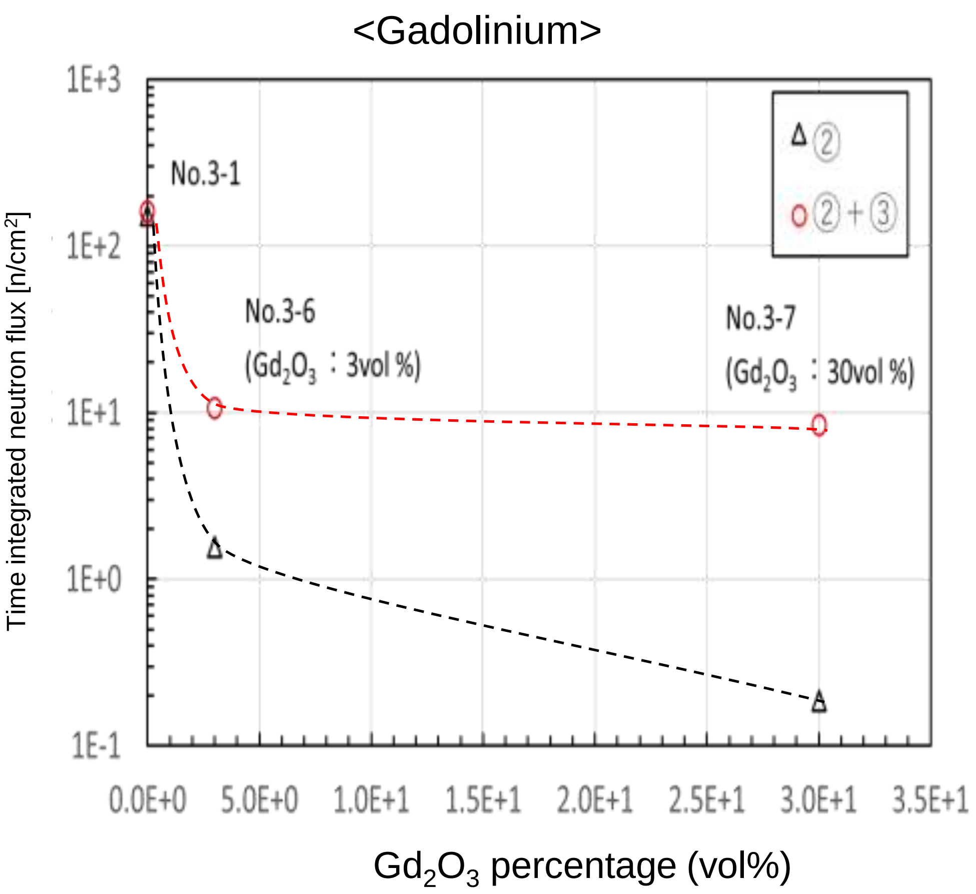
Case No.	Type of fuel debris	UO_2	ZrO_2	SUS	Concrete	Filling rate
3-1	Molten debris	15vol% (50vol%)	15vol% (50vol%)	0vol%	0vol%	30vol%
3-22	Uranium-rich	30vol%	0vol%	0vol%	0vol%	30vol%
3-24	Metallic debris	15vol% (25vol%)	15vol% (25vol%)	30vol% (50vol%)	0vol%	60vol%

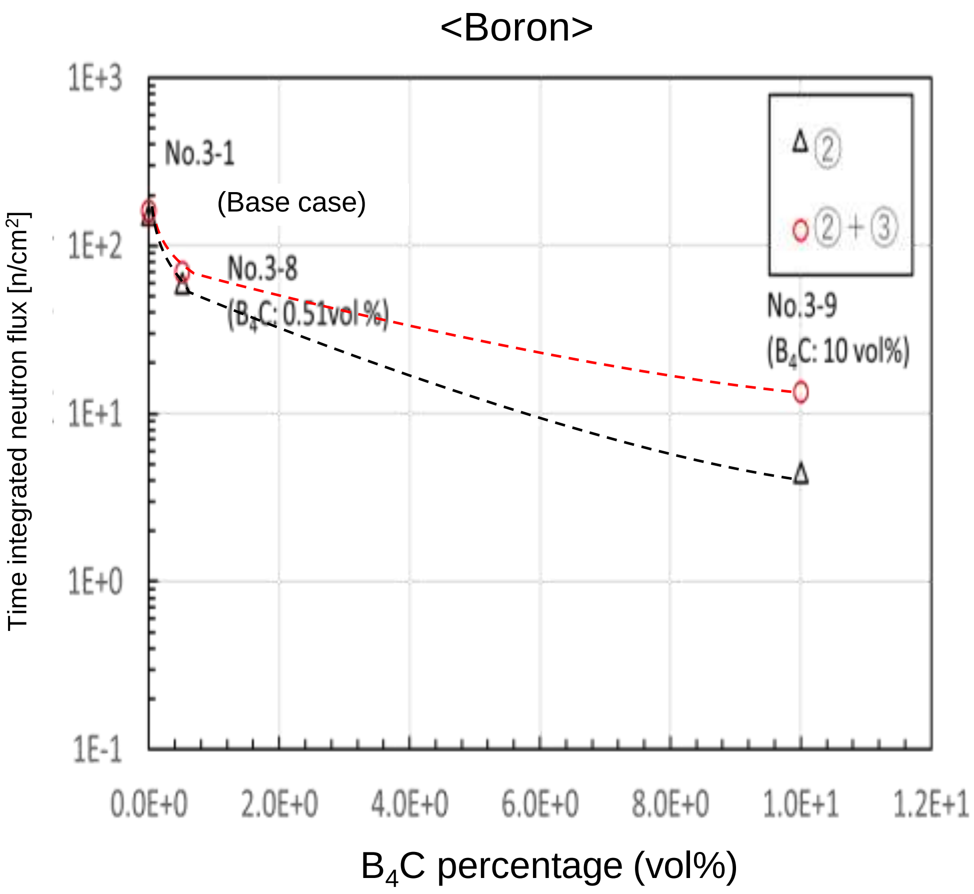


2.2.3 Active neutrons- Analysis results [Sensitivity Analysis]

✓ Sensitivity to the neutron absorption material (Influencing factor ①)

- The neutron flux reaching the surface of the detector reduced due to neutron absorption material such as Gd, B, etc.
- The larger the amount of neutron absorption material introduced, the more the reduction in neutron flux. (Almost all the neutron flux (③) was from the steady components (Cm-244, etc.) Particularly in the case of Gd.)

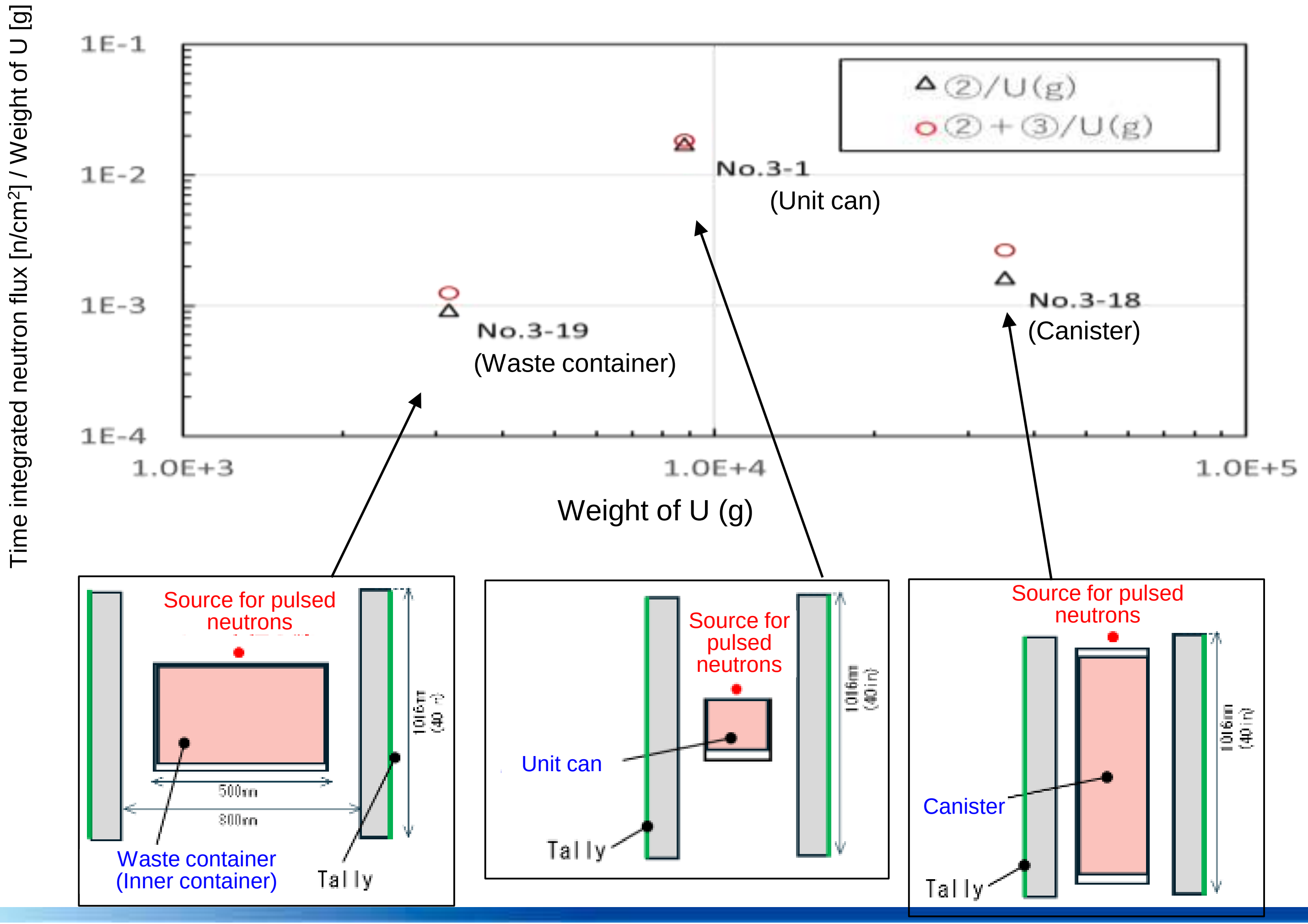




2.2.3 Active neutrons- Analysis results [Sensitivity Analysis]

✓ Sensitivity to the shape of container (Influencing factor ⑧)

・When the shape of the container was different, the amount of Uranium and neutron flux were not proportionate due to the impact of the measurement system.
(In the case of containers other than unit cans, a large number of neutrons from the source for pulsed neutrons leaked outside the system.)

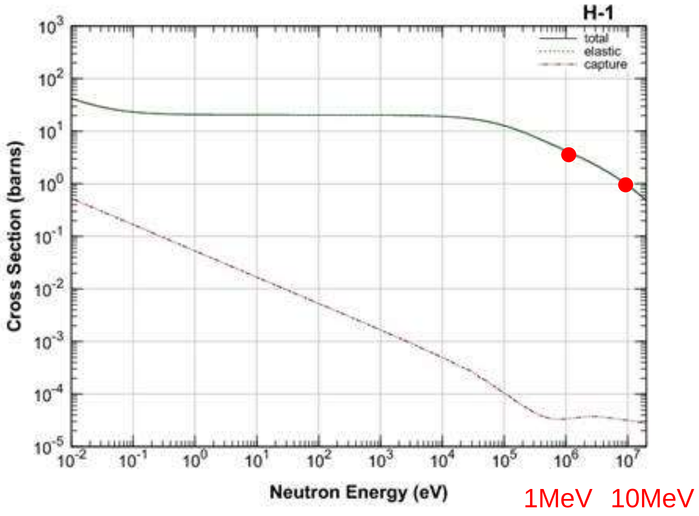


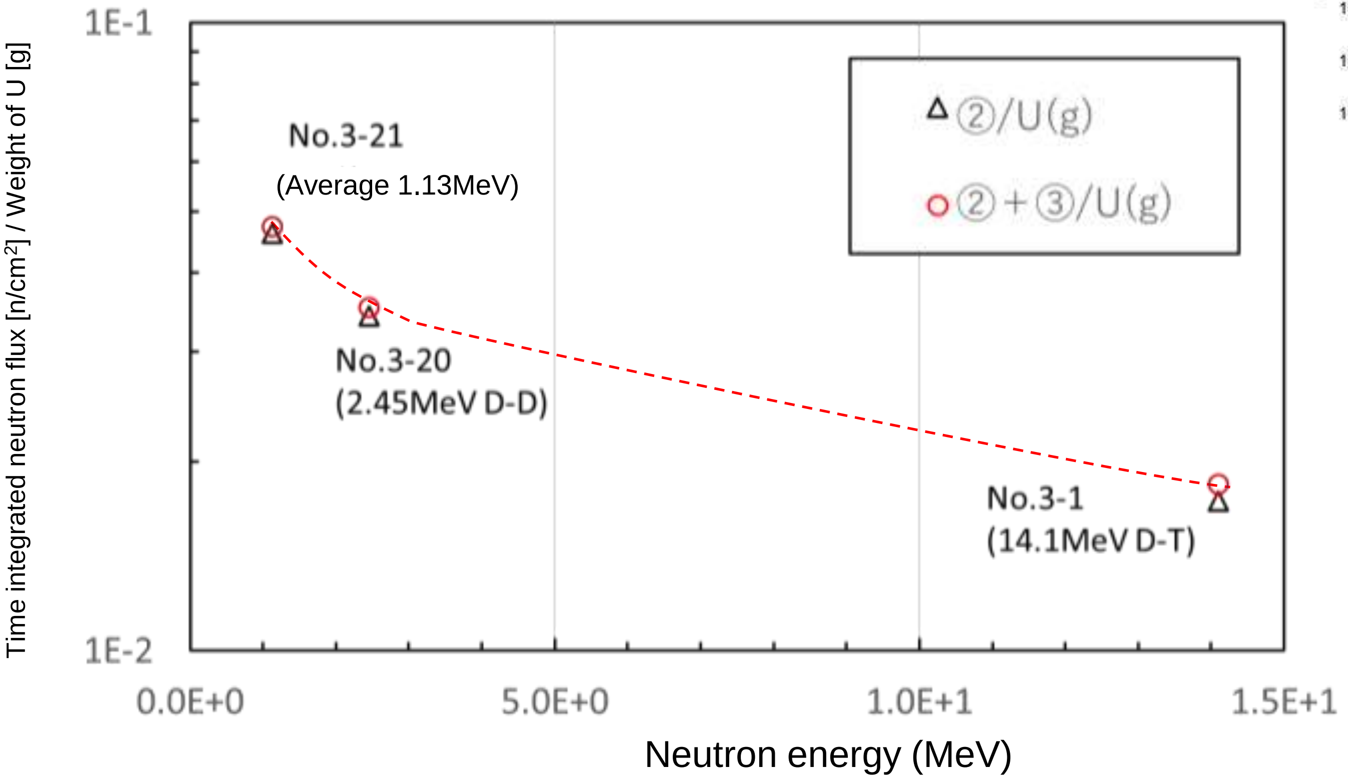
2.2.3 Active neutrons- Analysis results [Sensitivity Analysis]

✓ Sensitivity to the energy of neutrons from the accelerator based neutron source (Influencing factor ⑨)

・The lower the energy of the irradiated neutrons, higher was the neutron flux.

・This was because, when the neutron energy was low, together with the deceleration effect of polythylene, the neutrons decelerated and thermalized thereby inducing thermal neutron fission.
The cross-sectional area of H which forms polyethylene showed a difference of approx. 4 times between the case of 1MeV and 10MeV.
→ There is a possibility of increasing the neutron flux by improvising the deceleration system.



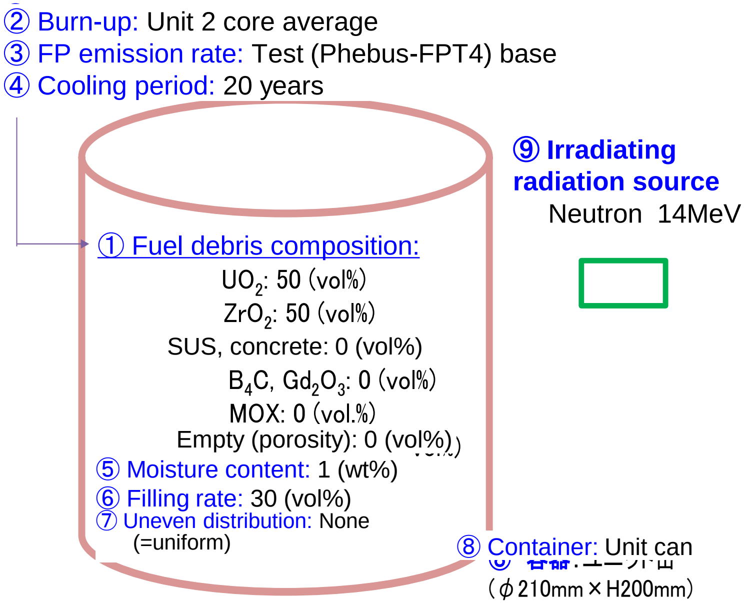


2.2.3 Active neutrons – Summary

- **Major findings obtained from the analysis:**

Impact	Influencing factor	Findings
Major	① Fuel debris composition: (Neutron absorption material) ② Burn-up ⑦ Uneven distribution ⑨ Irradiating radiation source	･**When the amount of neutron absorbing agent increases**, the amount of thermal neutrons in the unit can decreases and **the nuclear fission is suppressed.** **[Refer to No. 145]** ･**If the burn-up increases,** the amount of U-235 in fuel debris decreases, and since Cm-244, etc. that becomes a source of noise increases, **sensitivity reduces.[Refer to No. 122 - 124]** ･If the size of debris is around the same, the impact of uneven distribution is small, but if the debris is small, **sensitivity reduces.** ･There is a possibility of **being able to correct the impact of the energy of irradiated neutrons on sensitivity by optimizing the system.**
Minor	(③ FP emission rate[*1]) ④ Cooling period ⑤ Moisture content ⑥ Filling rate: ⑧ Container	･ Cooling period has a minor impact. ･ There is a possibility of being able to minimize the impact of moisture content. ･ The filling rate (apparent density) has a minor impact. ･ There is a possibility of being able to correct the shape of the container.

*1 ③ FP emission rate is the emission rate of gamma rays and does not have an impact on the measurement of neutron radiation.



② Burn-up: Unit 2 core average
③ FP emission rate: Test (Phebus-FPT4) base
④ Cooling period: 20 years

⑨ Irradiating radiation source
Neutron 14MeV

① Fuel debris composition:
UO_2: 50 (vol%)
ZrO_2: 50 (vol%)
SUS, concrete: 0 (vol%)
B_4C, Gd_2O_3: 0 (vol%)
MOX: 0 (vol.%)
Empty (porosity): 0 (vol%)
⑤ Moisture content: 1 (wt%)
⑥ Filling rate: 30 (vol%)
⑦ Uneven distribution: None (=uniform)
⑧ Container: Unit can
(φ210mm×H200mm)

Parameter values in the figure indicate base case conditions.

- Study of the necessity of detailed analysis and consolidation of technological issues
  - Combination of different measurement techniques (prompt gamma rays analysis, etc.) needs to be studied for **correcting the influence of neutron absorption material** contained in fuel debris.
  - There is a possibility of correcting the rate of change in flux by **correcting the impact of the burn-up** in fuel debris.

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

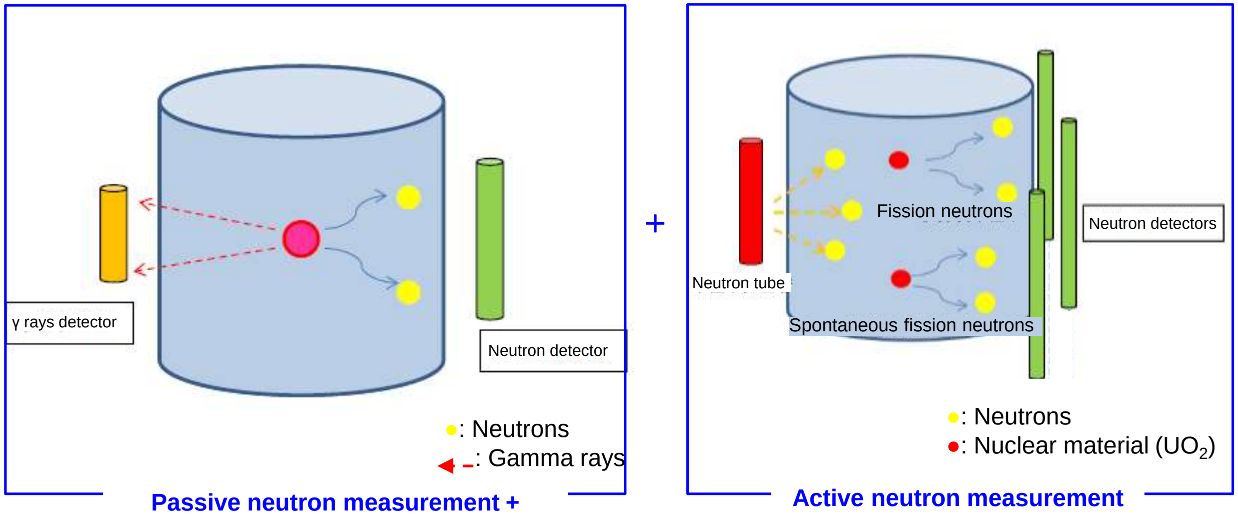
③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
  2.2.1 Passive neutrons
  2.2.2 Passive gamma rays
  2.2.3 Active neutrons
  2.2.4 Passive/active neutrons + passive gamma rays
  2.2.5 X-ray transmission measurement

	① Fuel debris composition	Gd content	B content	MOX	② Burn-up	③ FP emission rate	④ Cooling Period	⑤ Moisture content	⑥ Filling rate	⑦ Uneven distribution	⑧ Container	⑨ Irradiating radiation source	⑩ Detector
2.2.4 Combination	No. 156 No. 157	No. 157	—	—	No. 153 No. 157	—	—	—	No. 157	No. 156 No. 157	—	—	—

2.2.4 Passive/active neutrons + passive gamma rays - Measurement concept

- Fuel debris contains gamma ray emitting nuclides originating from fuel (Eu-154, etc.), and nuclides originating from fuel that emit neutrons (Cm-244, etc.) due to spontaneous fission. Hence neutron beams and gamma rays that are passive and originate from fuel can be measured. Also, by irrdiating neutrons, since neutrons from the fissile nuclides (U-235, etc,) contained in fuel debris are emitted, neutron beams that are active and originate from fuel can be measured.
- However, it was confirmed through analytical evaluation (2.2.1, 2.2.2, 2.2.3) of each measurement that measured values varied due to influencing factors, and such conditions (influencing factors and their fluctuation range) made measurement difficult.
- Based on the above, **analysis was conducted to find out whether or not measurement would be possible by combining measurement techniques to compensate for these conditions that render measurement difficult.**



Passive neutron measurement + Gamma rays measurement

Active neutron measurement

Figure Basic concept of the measurement principle for the Passive/active neutron beam measurement + γ rays measurement technology

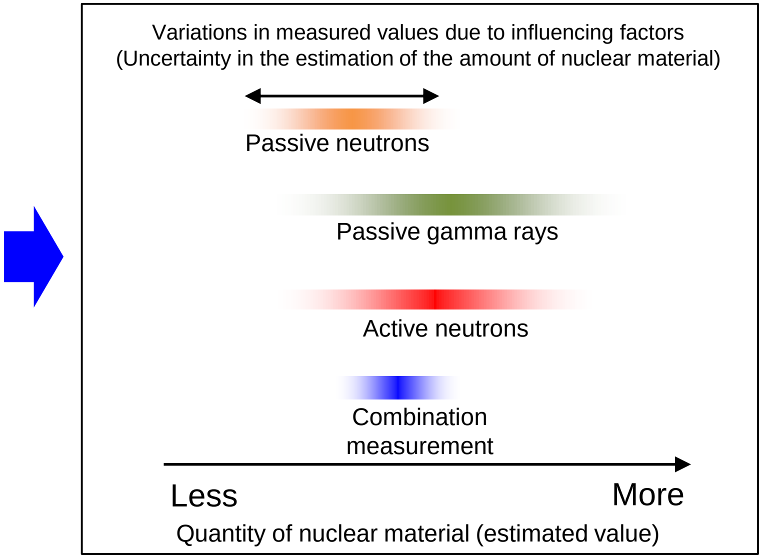


Figure Image illustrating approach towards sorting out the combination of measurement techniques

2.2.4 Passive/active neutrons + passive gamma rays – Concept of analysis

<Purpose>

- Based on past results of analyzing individual measurement techniques, ”Burn-up”, Self-shielding”, and “Neutron absorption material” were focused on as influencing factors due to which the variation in measured value increases. The possibility of compensating for the variation in measured values due to these influencing factors by combining measurement techniques was verified.

Findings based on results of analyzing stand-alone measurement technologies:

Measurement technique	Findings	Factors with a significant impact		State of fuel debris in which variations in measured values are presumed to be large	
		Item	Influencing factor	Measured value: Low	Measured value: High
Passive γ	･When burn-up changes the correlation between Eu-154 and amount of U deteriorates. ･As a result of the self-shielding effect , the flux that is incident upon the detector changes.	Burn-up	② Burn-up	Low burn-up (Eu154: small amount) + major self-shielding (Fuel debris composition: metallic debris + uneven distribution: center)	High burn-up (Eu154: large amount)
		Self-shielding of gamma rays	① Fuel debris composition ⑥ Filling rate ⑦ Uneven distribution ⑧ Container		
Passive n	･When burn-up changes the correlation between Cm-244 and amount of U deteriorates. (Flux changes by the order of magnitude) (･Moisture content has a minor impact(Note 1))	Burn-up	② Burn-up	Low burn-up (Cm244: Small quantity)	High burn-up (Cm244: Large quantity)
Active n	･When burn-up increases, sensitivity reduces. ･Fission gets suppressed due to the neutron absorption material.	Burn-up	② Burn-up	High burn-up + major neutron absorption (Gd, B: Large quantities)	—
		Neutron absorption material	① Fuel debris composition (Gd, B content)		

(Note 1) Impact is considered to be minor as based on the analysis of sensitivity to moisture content in active neutrons, the variation in steady components (Cm-224 of the passive neutrons) is small in systems wherein polyethylene has been provided

2.2 Analysis results

2.2.4 Passive/active neutrons + passive gamma rays – Findings based on the results of past analyses

- Based on results of past analyses, the possibility of compensating for the variation caused by individual influencing factors by combining 3 measurement techniques, was inferred. (Table below)

Conditions considered as factors having a significant impact (Note 1)					Analyzed cases	Rough comparison of the extent of variation of the influencing factors (Note 2) and the possibility of compensating for it (Note 3)					
Burn-up	Self-shielding of gamma rays			Neutron absorption material		Passive γ		Passive n		Active n	
	Fuel debris composition	Filling rate	Uneven distribution	Gd, B content		Variation	Possibility of compensating	Variation	Possibility of compensating	Variation	Possibility of compensating
Medium	Molten	Medium	-	-	**Base case**	-	○	-	○	-	○
Low	Molten	Medium	-	-	**Sensitivity analysis** (Burn-up)(Note 4)	Major	x	Major	x	Medium	○ (Since BG component is small)
High	Molten	Medium	-	-			☆		☆		△
Medium	Metallic	Medium	-	-	**Sensitivity analysis** (Fuel debris composition)(Note 4)	Medium	△	Minor	○	Minor	○
Medium	MCCI	Medium	-	-		Medium	△	Minor	○	Minor	○
Medium	Molten	Least	-	-	**Sensitivity analysis** (Filling rate)(Note 5)	Minor	○	Minor	○	Minor	○
Medium	Molten	Medium	Center	-	**Sensitivity analysis** (Uneven distribution)(Note 5)	Minor	○	Minor	○	Minor	○
Medium	Molten	Medium	-	Maximum	**Sensitivity analysis** (Gd, B content)(Note 5)	Minor (Not evaluated but is determined qualitatively)	○	Minor	○	Major	x

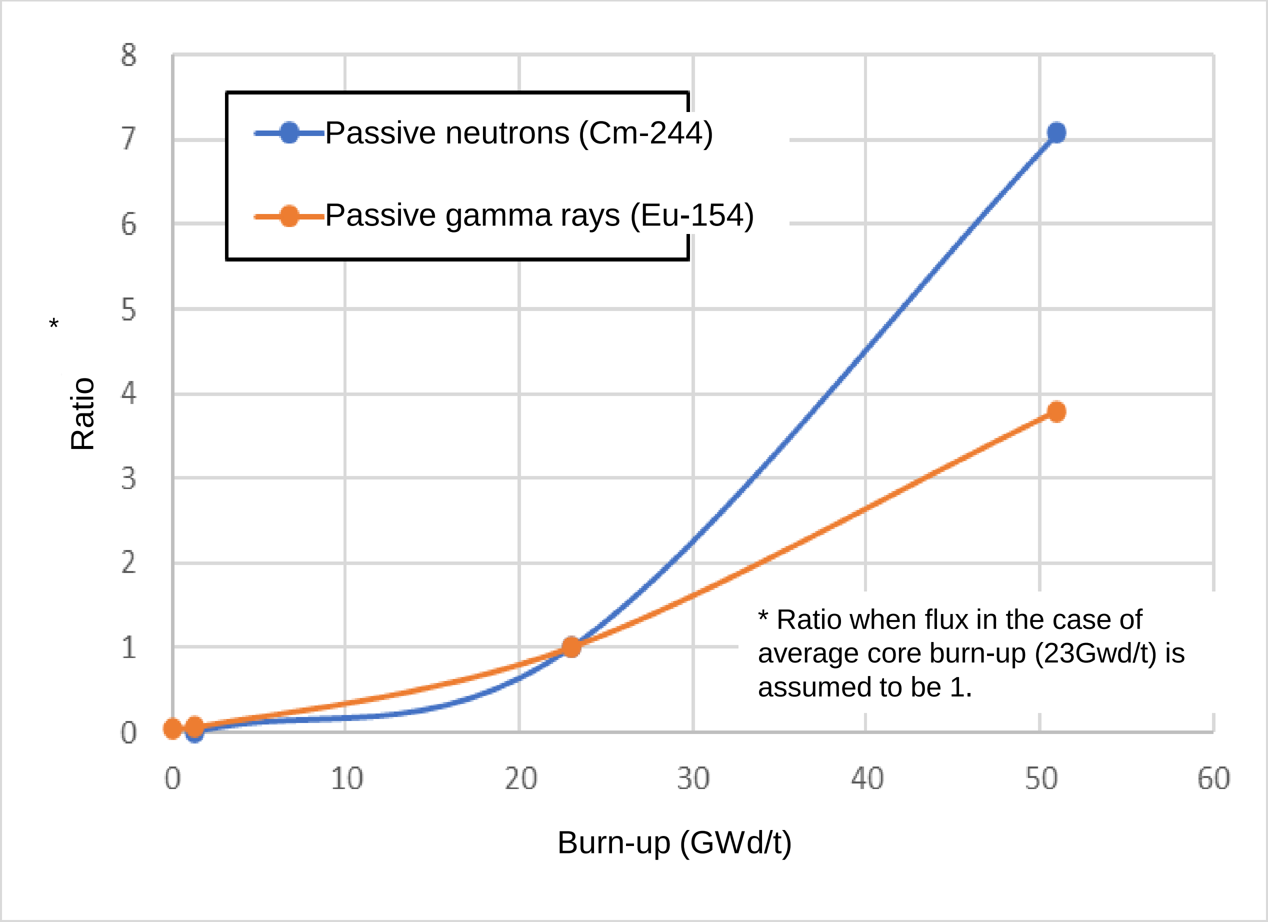
(Note 1) Base case conditions are indicated in **black.** Conditions that have changed from the base case are indicated in **blue.** Note that, conditions other than the factors mentioned here are all base case conditions.
(Note 2) When changes in flux per unit of the amount of U are about double or half: Small variation, about less than 1 order of magnitude: Moderate variation, 1 order of magnitude or more: Large variation
(Note 3) ○: Sufficient flux reaches the measurement surface, there is little variation and measurement is possible, △: Flux changes about 1 order of magnitude or less but can be corrected, etc., ×: Flux reduces extremely and hence measurement is difficult,
☆: Sufficient flux reaches the measurement surface, but based on the information obtained using the passive γ・n measurement technique, a mutually complementary relationship is required for estimating nuclear material.
(Note 4) Since conditions that lead to an increase in variations differ depending on the measurement technique, multiple conditions are set.
(Fuel debris composition: Metallic debris, MCCI debris, Burn-up: Low, high)
(Note 5) Only the conditions in which variations increase and flux decreases are consolidated. (Filling rate: least, Uneven distribution: center, Gd, B content: greatest)

2.2.4 Passive/active neutrons + passive gamma rays – Findings based on the results of past analyses

➢ Measures in response to variations due to burn-up

The fact that the tendency of Cm-244 (passive neutrons) and Eu-154 (passive gamma rays) to increase differs was focused on.

→ Based on the ratio of Cm-244 / Eu-154, measurement error due to burn-up can be corrected



* Ratio when flux in the case of average core burn-up (23Gwd/t) is assumed to be 1.

2.2.4 Passive/active neutrons + passive gamma rays – Analyzed cases

- The combination of factors having a large impact according to the results of past analyses, was studied and it was decided to verify the possibility of compensating by analyzing the following 3 cases (in the blue frame) as passive/active neutrons + passive gamma rays.

Conditions considered as factors having a significant impact (Note 1)					**Policy for setting up the analysis conditions**
Burn-up	**Self-shielding of gamma rays**			**Neutron absorption material**	
	Fuel debris composition	**Filling rate**	**Uneven distribution**	**Gd, B content**	
Medium	Metallic	Medium	Center	-	**Verification of the possibility of compensating for “self-shielding”** (large variation and low flux when **the passive γ measurement technique** is used) **by means of the passive n measurement technique** .
Low	Metallic	Medium	Center	-	**Verification of the possibility of compensating for “burn-up” and “self-shielding”** (large variation and low flux when **the passive γ･n measurement technique** is used) **by means of the active n measurement technique**.
High	Molten	Medium	-	Maximum	**Verification of the possibility of compensating** for **“neutron absorption material” and “burn-up”** (large variation and low flux when **the active n measurement technique** is used) **by means of the passive γ and passive n measurement technique** .
Low	Metallic	Least	Center	Maximum	**Verification of the possibility of compensating** for **“burn-up”, “self-shielding”, and “neutron absorption material”** (large variation and low flux when **3 measurement techniques** are used) **by means of a combination of the passive γ･n and active n measurement technique**.

(Note 1) Base case conditions are indicated in **black.** Conditions that have changed from the base case are indicated in **blue.** Note that, conditions other than the factors mentioned here are all base case conditions.

Since the condition in this case is high burn-up, it is presumed that the factor can be compensated by means of the passive γ, n measurement method. Hence this case has been excluded from the analysis.

2.2.4 Passive/active neutrons + passive gamma rays - Analyzed cases

- Analytical simulation models using individual measurement methods were used.
- Considering the analysis conditions described in No. 4-1 as the base case, the analysis conditions with changed influencing factors (No. 4-2 to 4) based on the policy for setting up analysis conditions mentioned on the previous page, were assumed as the sensitivity analysis conditions. **All 3 cases**
  (Base case has been analyzed using analytical simulation for individual measurement techniques)

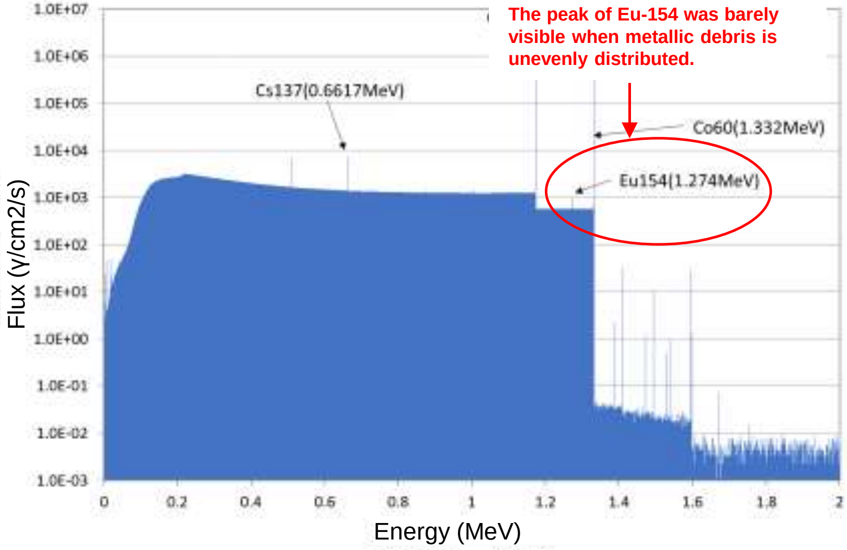
Case No.	Measurement technique *1	Composition inside the container*1				Burn-up	FP emission rate	Cooling period	Uneven distribution	Container	Irradiating neutron source	Changed parameter
		Type of fuel debris	Within filling factor		Outside filling factor							
			Composition	Total (Filling factor)								
4-1	Passive γ Passive η Active η	Molten debris	UO_2 : 15vol%(50vol%) ZrO_2 : 15vol%(50vol%)	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	Uniform	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Base case
4-2	Passive γ Passive η	Metallic debris	**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	23.0GWd/t	Standard	20 years	**Horizontal direction (center)**	Unit can (Φ210mm x H200mm)	-	Fuel debris composition (type) Uneven distribution
4-3	Passive γ Passive η Active η		**UO_2 : 0.075vol%(0.25vol%)** **ZrO_2 : 0.075vol%(0.25vol%)** **SUS : 29.85vol%(99.5vol%)**	30vol%	H_2O (Moisture content): 1wt% Empty: Remainder	**1.3GWd/t*3** 23.0GWd/t	Standard	20 years	**Horizontal direction (center)**	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (type) Burn-up, Uneven distribution
4-4	Active η		**UO_2 : 0.025vol%(0.25vol%)** **ZrO_2 : 0.025vol%(0.25vol%)** **SUS : 9.95vol%(99.5vol%)**	**10vol%**	**Gd2O3 : 30vol%** H_2O (Moisture content): 1wt% Empty: Remainder	**1.3GWd/t*3** 23.0GWd/t	Standard	20 years	**Horizontal direction (center)**	Unit can (Φ210mm x H200mm)	D-T reaction (14.1MeV)	Fuel debris composition (type) Filling factor, Gd content, Moisture content, Burn-up, Uneven distribution

*1 : Not analyzed here, if there are prospects of being able to conduct measurement using other measurement techniques, or if it is believed that qualitative measurement is difficult, based on sensitivity analysis of measurement techniques.
*2 : Percentage inside the container. Percentage, when 100% is considered to be within the filling rate, is mentioned inside parentheses.
*3 : UO2 and ZrO2 are assumed to have low burn-up (1.3GWd/t), and SUS is assumed to have base burn-up (23.0GWd/t).

2.2.4 Passive/active neutrons + passive gamma rays - Analysis results

<Metallic debris unevenly distributed at the center (Cases in which flux measured using the passive γ measurement technique decreased) [Analysis No. 4-2]>

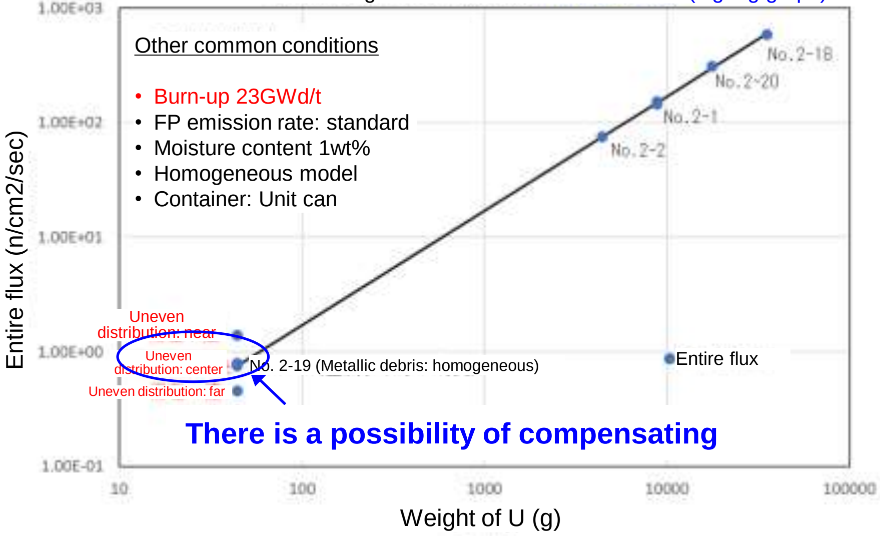
<Passive γ>



The peak of Eu-154 was barely visible when metallic debris is unevenly distributed.

<Passive n>

Relation between the weight of Uranium and the entire flux (log-log graph)



Other common conditions

- Burn-up 23GWd/t
- FP emission rate: standard
- Moisture content 1wt%
- Homogeneous model
- Container: Unit can

There is a possibility of compensating

(Note) As it was confirmed that measurement is possible with passive n, the analysis of active n was omitted.

For cases when measurement of nuclear material is expected to be difficult with passive γ (self-shielding effect: large), the possibility of compensating by measuring nuclear material originating from fuel using the passive n measurement method will be verified.

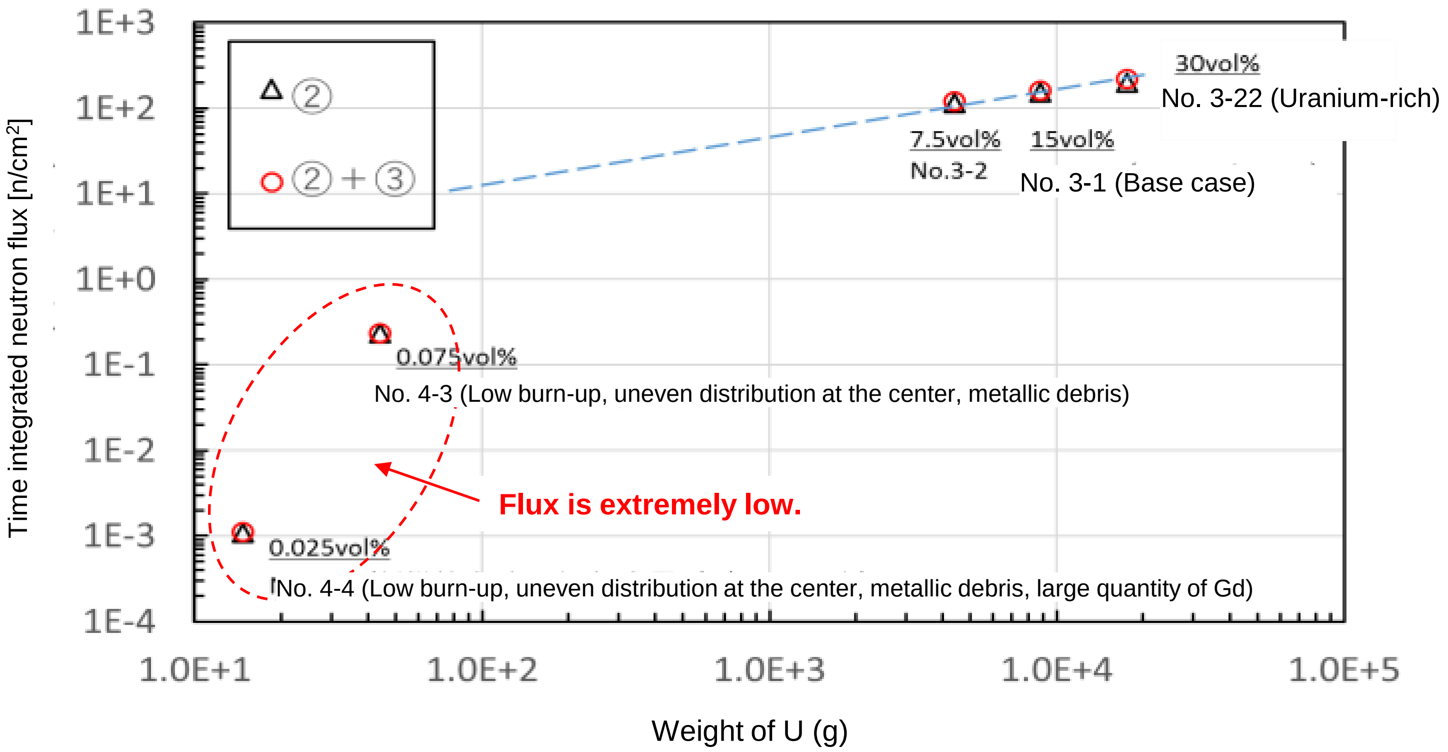
2.2.4 Passive/active neutrons + passive gamma rays - Analysis results

<Metallic debris unevenly distributed at the center and having a low burn-up (Cases in which flux measured using the passive γ･n measurement technique decreased) [Analysis No. 4-3]>

<Metallic debris unevenly distributed at the center and having a low burn-up (Large quantity of Gd) (Cases in which flux measured using the passive γ, passive n and active n measurement technique decreased) [Analysis No. 4-4]>

<Active n>

* Due to the low burn-up, it is difficult to measure nuclear material originating from fuel by measuring passive γ and passive n. (Based on past analysis results)



Flux is extremely low.

The measured value reduced substantially because of suppression of fission due to small quantities of nuclear material and due to the presence of neutron absorption material.

2.2.4 Passive/active neutrons + passive gamma rays – Summary

- Major findings obtained from the analysis:
  - When individual measurement techniques are used individually, “burn-up”, “self-shielding” and “neutron absorption material” are the influencing factors causing measurement errors.
  - When 3 measurement techniques are combined, it was confirmed that there is a possibility of reducing measurement errors (reduction in variation in the measured values).

Conditions under which measurement becomes difficult (Factors with a significant impact)		Measurement technique			
Item	**Influencing factor**	**Passive n**	**Passive γ**	**Active n**	**Combination**
Burn-up	Burn-up (low)	x	x	○	○
	Burn-up (high)	☆	☆	△	
Self-shielding of gamma rays	Fuel debris composition, filling rate, uneven distribution, etc.	○	△	○	○
Neutron absorption material	Gd, B content	○	○	x	○

○: Sufficient flux reaches the measurement surface, there is little variation and measurement is possible, △: Flux changes about 1 order of magnitude or less but can be corrected, etc., ×: flux reduces extremely and hence measurement is difficult.
☆: Sufficient flux reaches the measurement surface, but based on the information obtained using the passive γ･n measurement technique, a mutually complementary relationship is required for estimating nuclear material.

2.2.4 Passive/active neutrons + passive gamma rays – Summary

➢ Study of the necessity of detailed analysis and consolidation of technical issues

- The technique for correcting the influence of factors that have a significant impact needs to be studied (Following are typical examples).

  Burn-up: Correction based on the difference in the tendency of Eu=154 (passive γ) and Cm-244 (passive n) to increase.

  Neutron absorption material: Study of combination of different measurement techniques (prompt gamma rays analysis, etc.)

- Based on the results of analyses conducted this year, analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment.

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

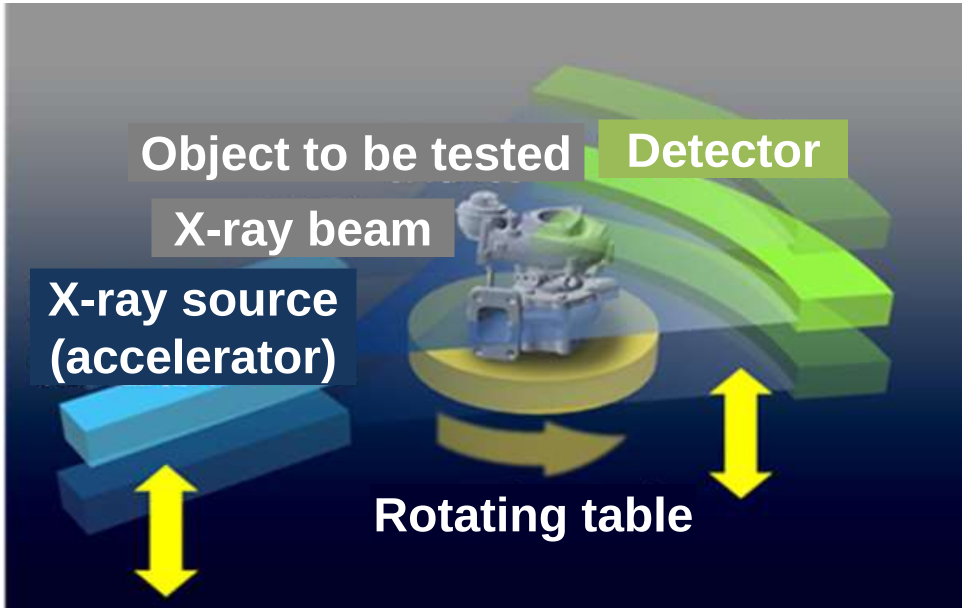
③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
  2.2.1 Passive neutrons
  2.2.2 Passive gamma rays
  2.2.3 Active neutrons
  2.2.4 Passive/active neutrons + passive gamma rays
  2.2.5 X-ray transmission measurement
2.2.6 Cosmic rays scattering measurement

	① Fuel debris composition	Gd content	B content	MOX	② Burn-up	③ FP emission rate	④ Cooling Period	⑤ Moisture content	⑥ Filling rate	⑦ Uneven distribution	⑧ Container	⑨ Irradiating radiation source	⑩ Detector
2.2.5 X-ray	No. 166 No. 167	–	–	No. 166 No. 167	–	No. 166 No. 167	–	–	No. 166 No. 167	No. 166 No. 167	No. 166 No. 167	No. 166 No. 167	No. 169 to 172

2.2.5 X-ray transmission measurement - Measurement concept

- **Measurement principle:** From amongst the X-rays that are irradiated while rotating the debris, the x-rays that penetrate the debris are measured, and a tomographic image is produced by means of computational image reconstruction using the data measured in all directions.
- **Measurement system:** Debris is placed between the accelerator based X-ray source and the detector tally
- **Radiation source conditions:** X-ray spectrum calculated from the EGS*
- **Detector response:** Total amount of X-ray energy for every pulse irradiated by the accelerator based X-ray source
- **Measurement time:** 10 to 15 seconds per image



Structure of the radioparency measurement (High energy X-ray CT method) equipment

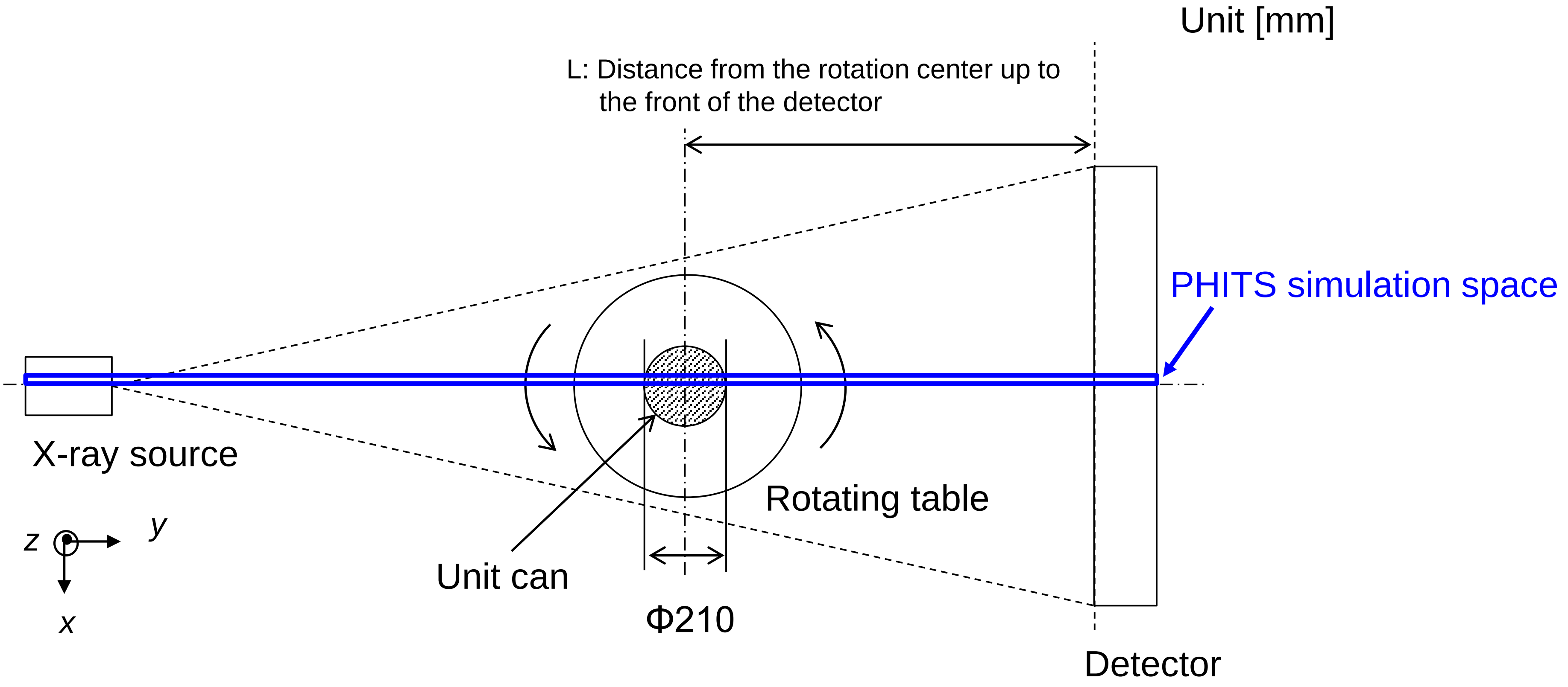
In the radioparency measurement equipment, the object to be measured placed on the rotating table is placed in such a way that the accelerator based x-ray source and the x-ray detector are on either sides, and by irradiating X-rays while turning around the rotating table once, radioparency data in all directions with respect to the measured object is obtained. A tomographic image including the inside of the object being measured is produced by performing computational image reconstruction using this radioparency data.

*Particle Transport Code: Electron Gamma Shower

2.2.5 X-ray transmission measurement – Analysis conditions

Analysis conditions (1/3) Analysis model

Flux evaluation system for radioparency measurement (High energy X-ray CT method)

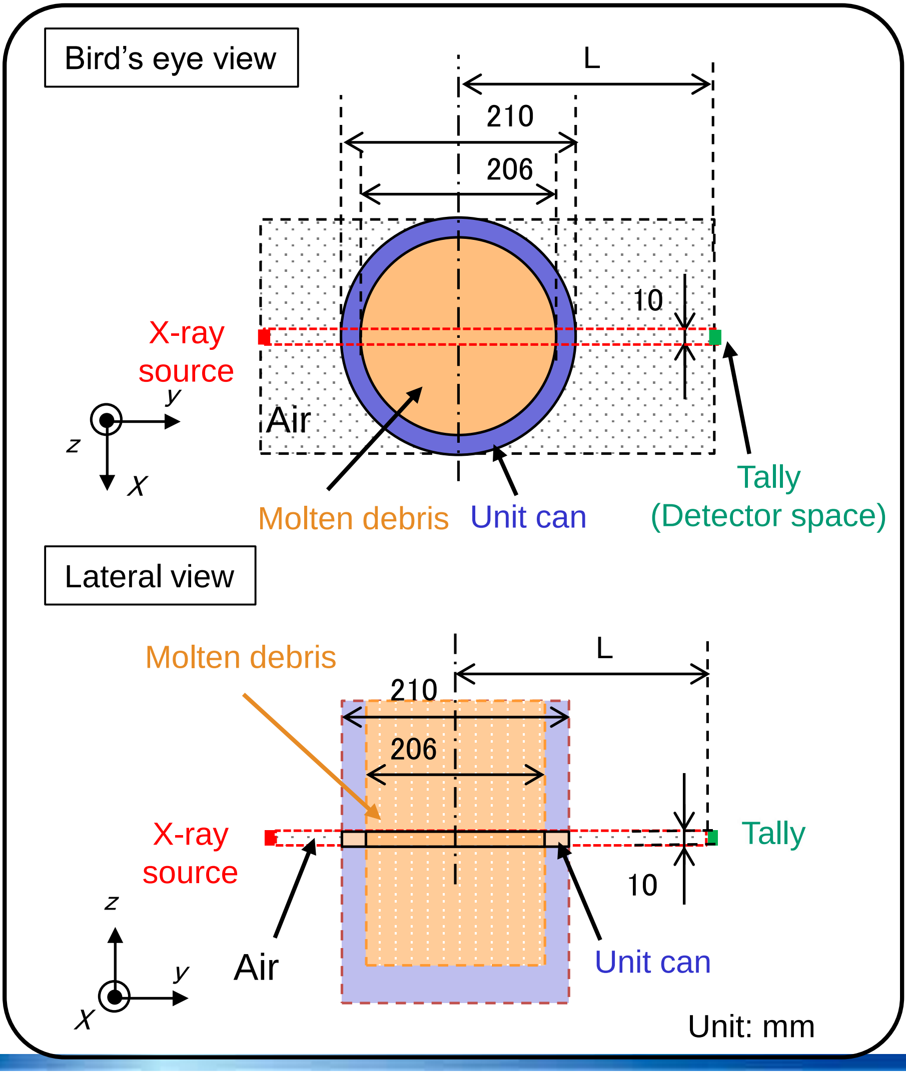


* Assuming that concrete is placed in front of the detector, the spatial width in the direction of the Z axis is set in accordance with the scanning pitch (1mm).

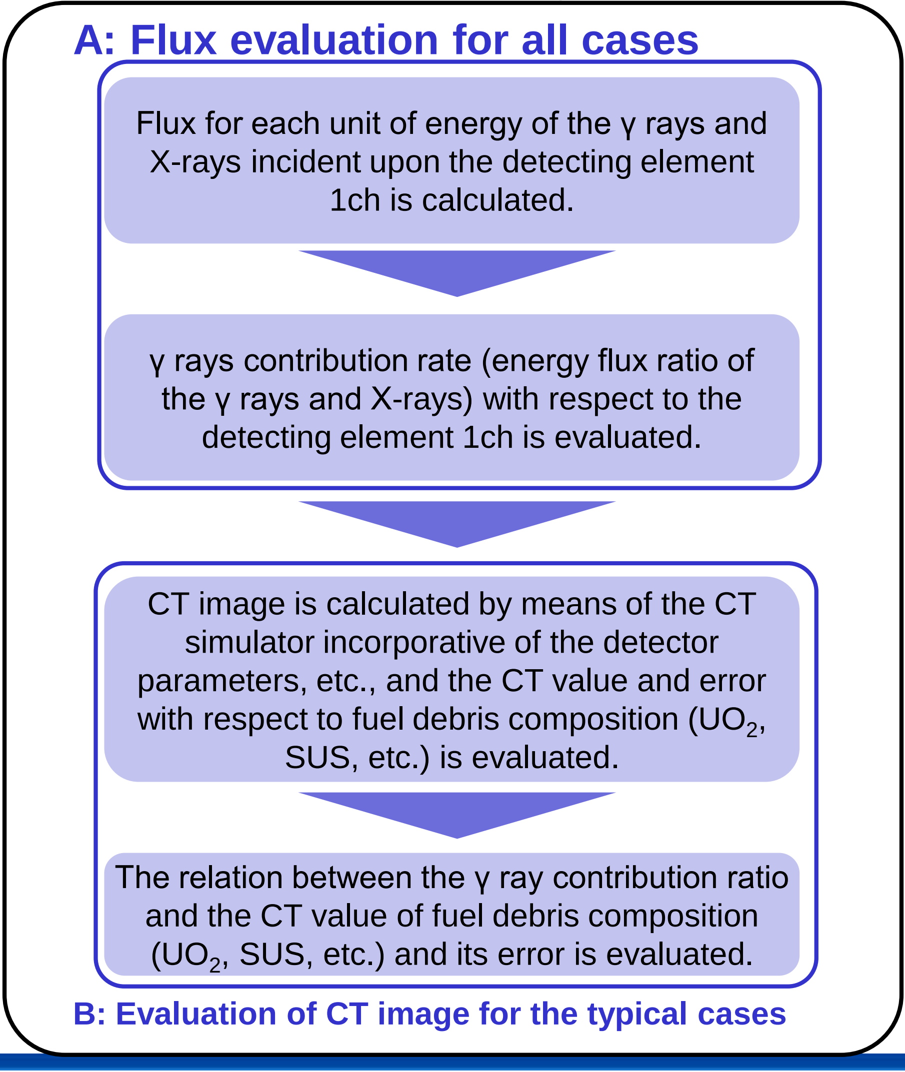
2.2 Analysis results
2.2.5 X-ray transmission measurement – Analysis conditions

Analysis conditions (2/3)   Flow of analysis

PHITS simulation system



Flow of analysis



A: Flux evaluation for all cases

Flux for each unit of energy of the γ rays and X-rays incident upon the detecting element 1ch is calculated.

γ rays contribution rate (energy flux ratio of the γ rays and X-rays) with respect to the detecting element 1ch is evaluated.

CT image is calculated by means of the CT simulator incorporative of the detector parameters, etc., and the CT value and error with respect to fuel debris composition (UO_2, SUS, etc.) is evaluated.

The relation between the γ ray contribution ratio and the CT value of fuel debris composition (UO_2, SUS, etc.) and its error is evaluated.

B: Evaluation of CT image for the typical cases

2.2.5 X-ray transmission measurement – Analysis conditions

Analysis conditions (3/3) Analysis cases

Of the 20 passive gamma rays cases, the cases pertaining to burn-up and cooling period were excluded, and 18 cases in which X-ray energy was added were analyzed.

Case		UO_2	ZrO_2	SUS	Concrete	Filling rate	FP emission rate	Uneven distribution	Container	X-ray energy
5-1	Base	15vol%	15vol%	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-2	Small amount of UO_2	7.5vol%	22.5vol%	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-3	MOX	30vol%	-	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-4	Filling rate	5vol%	5vol%	-	-	10vol%	Standard	Uniform	Unit can	9MeV
5-5		25vol%	25vol%	-	-	50vol%	Standard	Uniform	Unit can	9MeV
5-8	FP emission rate	15vol%	15vol%	-	-	30vol%	Zero emission	Uniform	Unit can	9MeV
5-9		15vol%	15vol%	-	-	30vol%	High emission	Uniform	Unit can	9MeV
5-12	Uneven distribution	15vol%	15vol%	-	-	30vol%	Standard	At the center in the horizontal direction	Unit can	9MeV
5-13		15vol%	15vol%	-	-	30vol%	Standard	Outer surface in the horizontal direction	Unit can	9MeV
5-14	Container	15vol%	15vol%	-	-	30vol%	Standard	Uniform	Canister	9MeV
5-15		0.5vol%	10vol%	-	-	10.5vol%	Standard	Uniform	Inner waste container	9MeV
5-16	Uranium-rich	30vol%	-	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-17	Metallic debris	0.075vol%	0.075vol%	29.85vol%	-	30vol%	Standard	Uniform	Unit can	9MeV
5-18		15vol%	15vol%	30vol%	-	60vol%	Standard	Uniform	Unit can	9MeV
5-19	MCCI debris	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	Standard	Uniform	Unit can	9MeV
5-20		15vol%	15vol%	0vol%	30vol%	60vol%	Standard	Uniform	Unit can	9MeV
5-21	X-ray irradiation energy	15vol%	15vol%	-	-	30vol%	Standard	Uniform	Unit can	6MeV
5-22		15vol%	15vol%	-	-	30vol%	Standard	Uniform	Unit can	15MeV

2.2.5 X-ray transmission measurement – Analysis results

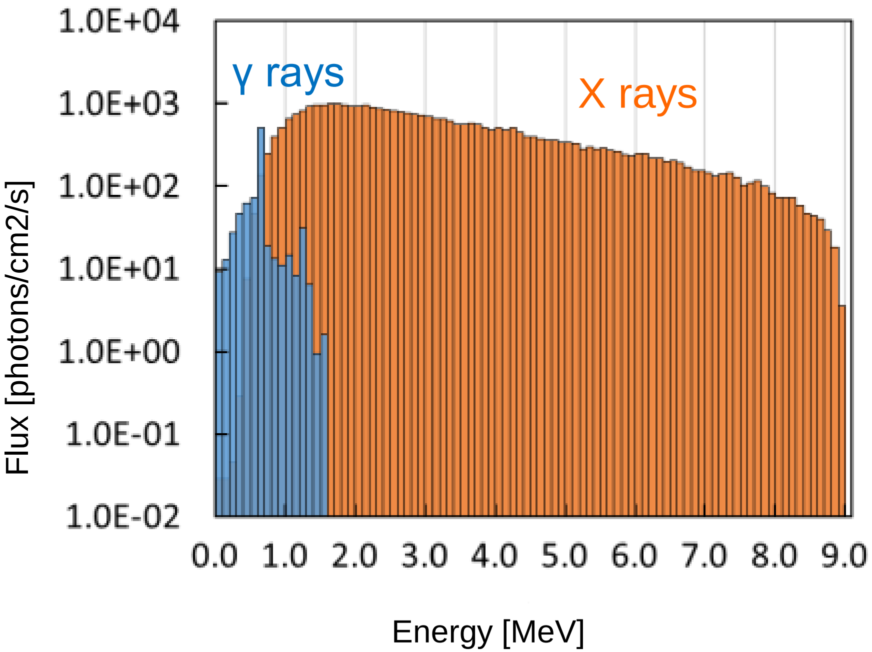
Analysis results (1/3) Flux evaluation of the base case

Base case analysis conditions in the radioparency measurement system

Case No.	Fuel debris Type	UO_2	ZrO_2	H_2O	Filling rate*	Entire fuel debris	Amount of U**
5-1	Molten debris	15vol%	15vol%	1wt%	30vol%	15.8kg	8.79kg

*Filling rate does not include H_2O, **Amount of U = Total mass of Uranium isotopes

Flux of energy from x-rays and energy from the γ rays in the radioparency measurement system



Results of base case analysis in the radioparency measurement system

	X-ray	γ rays
Total flux [photon/cm^2/s]	3.5×10^4	8.5×10^2
Average energy [MeV]	3.3	0.63

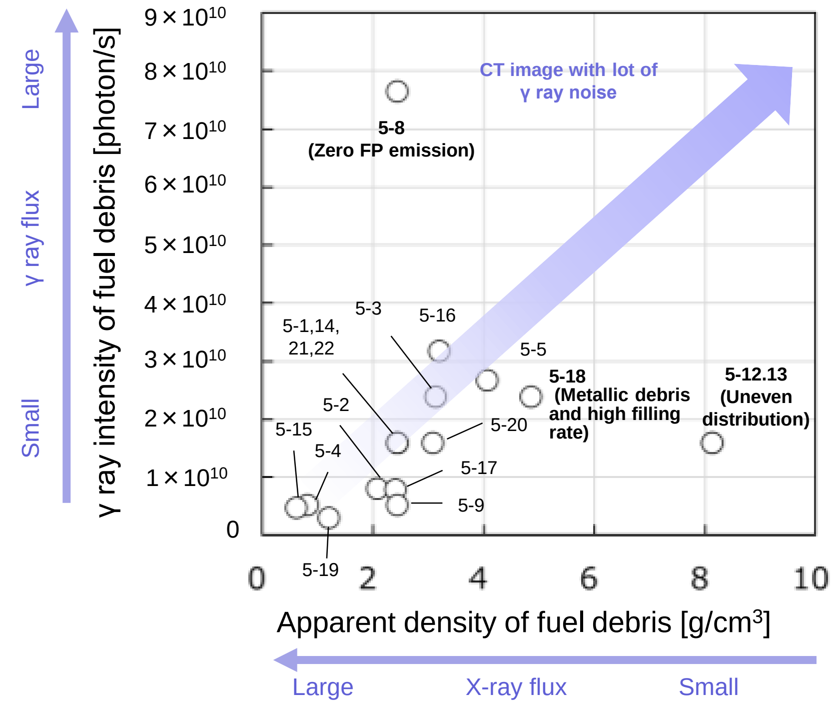
- Since as against x-rays, the total flux of γ rays was low (<3%), and the average energy was low, it is assumed that the impact of noise from γ rays on the CT image is low.

2.2.5 X-ray transmission measurement – Analysis results

Analysis results (2/3) Flux evaluation of all cases

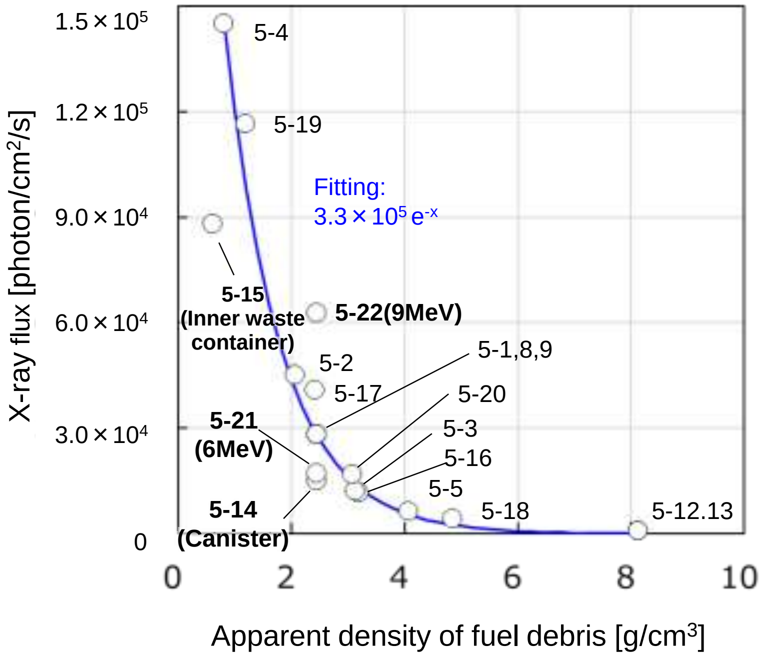
The γ ray and x-ray flux was calculated for all 18 cases（Since the analysis of γ rays is the same as passive gamma rays, it was omitted).
It was found that the x-ray flux reduces following an exponential function with respect to the apparent density of fuel debris.

■Analysis conditions：Apparent density of fuel debris and γ ray intensity



Flux evaluation

■Analysis results: X-ray flux with respect to the apparent density of fuel debris



- When the apparent density of fuel debris was large and intensity of γ rays was high, since the proportion of γ ray flux was larger than the x-ray flux, it is inferred that the γ ray noise in the CT image becomes bigger.

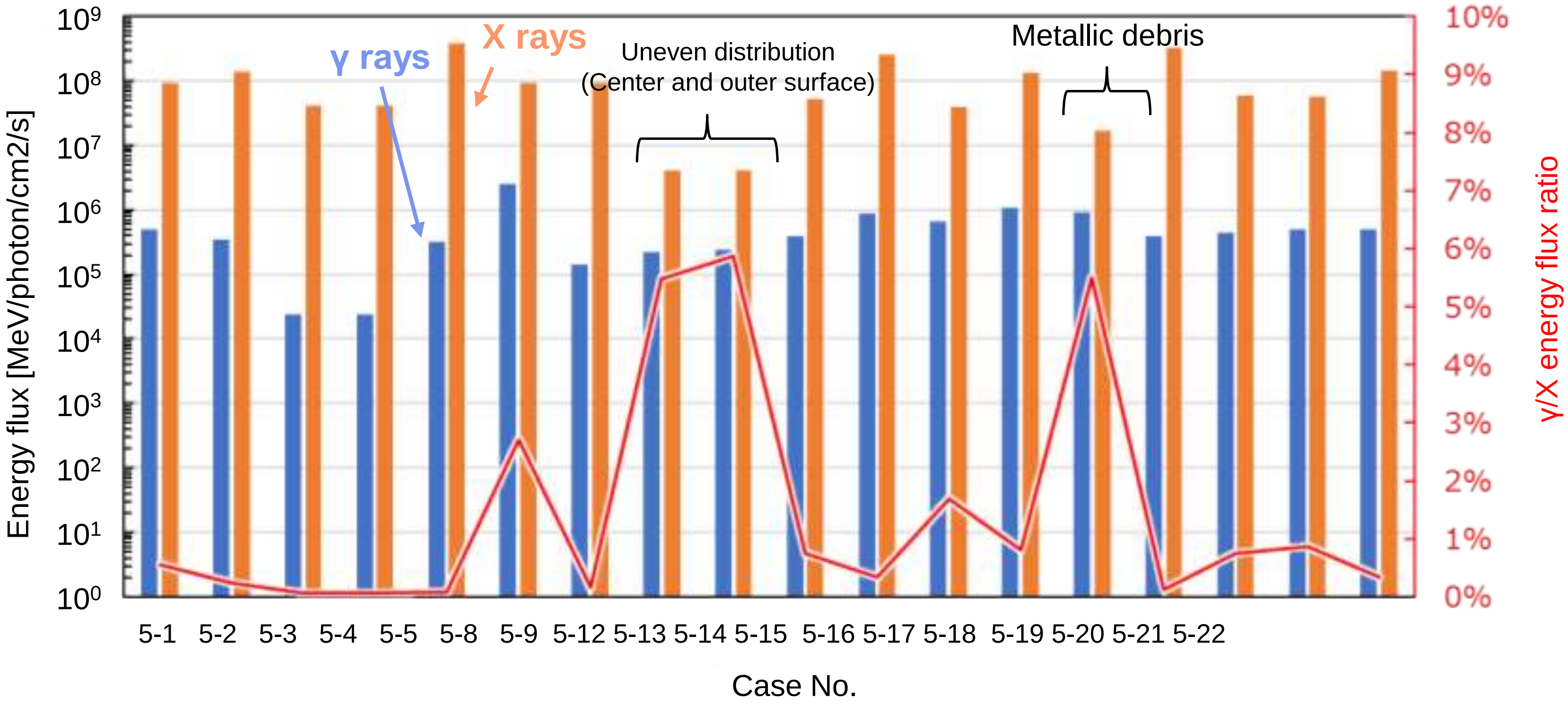
- X-ray flux reduced following an exponential function with respect to the apparent density of fuel debris.
- The values that deviated from the exponential function were values pertaining to the cases with containers that have no correlation with apparent density (5-14,15) or X-ray irradiation energy (5-21,22).

2.2.5 X-ray transmission measurement – Analysis results

Analysis results (3/3) Flux evaluation of all cases

In order to study the impact of γ ray noise on the CT image, the γ ray and X-ray energy flux（the value obtained by adding flux of each energy and the energy product) respectively was obtained, and the proportion of γ rays as against X-rays was calculated.

γ ray and X-ray energy flux (left vertical axis) and γ ray / X-ray energy flux ratio (right vertical axis)



- The maximum γ/X ray energy flux ratio was approx. 6%. The proportion of γ rays was large in uneven distribution (5-12,13) and metallic debris (5-18).
- In the CT image evaluation, in addition to the base case, uneven distribution and metallic debris will be added to the typical cases and analyzed.

2.2.5 X-ray transmission measurement – Analysis conditions

Analysis conditions　Selection of typical cases for evaluating the CT image

Four cases were selected in all, including the base case (5-1) and the cases in which γ ray noise is assumed to have a major impact on the CT image.

Case		UO_2	ZrO_2	SUS	Concrete	Filling rate	FP emission rate	Uneven distribution	Container	X-ray energy
5-1	**Molten debris (base case)**	**15vol%**	**15vol%**	**-**	**-**	**30vol%**	**Standard**	**Uniform**	**Unit can**	**9MeV**
5-2	Small amount of UO_2	7.5vol%	22.5vol%	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-3	MOX	30vol%	-	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-4	Filling rate	5vol%	5vol%	-	-	10vol%	Standard	Uniform	Unit can	9MeV
5-5		25vol%	25vol%	-	-	50vol%	Standard	Uniform	Unit can	9MeV
5-8	FP emission rate	15vol%	15vol%	-	-	30vol%	Zero emission	Uniform	Unit can	9MeV
5-9		15vol%	15vol%	-	-	30vol%	High emission	Uniform	Unit can	9MeV
5-12	**Uneven distribution**	**15vol%**	**15vol%**	**-**	**-**	**30vol%**	**Standard**	**At the center in the horizontal direction**	**Unit can**	**9MeV**
5-13		**15vol%**	**15vol%**	**-**	**-**	**30vol%**	**Standard**	**Outer surface in the horizontal direction**	**Unit can**	**9MeV**
5-14	Container	15vol%	15vol%	-	-	30vol%	Standard	Uniform	Canister	9MeV
5-15		0.5vol%	10vol%	-	-	10.5vol%	Standard	Uniform	Inner waste container	9MeV
5-16	Uranium-rich	30vol%	-	-	-	30vol%	Standard	Uniform	Unit can	9MeV
5-17	Metallic debris	0.075vol%	0.075vol%	29.85vol%	-	30vol%	Standard	Uniform	Unit can	9MeV
5-18	**Metallic debris (High filling rate)**	**15vol%**	**15vol%**	**30vol%**	**-**	**60vol%**	**Standard**	**Uniform**	**Unit can**	**9MeV**
5-19	MCCI (Molten Core Concrete Interaction)	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	Standard	Uniform	Unit can	9MeV
5-20	MCCI (High filling rate)	15vol%	15vol%	0vol%	30vol%	60vol%	Standard	Uniform	Unit can	9MeV
5-21	X-ray irradiation energy	15vol%	15vol%	-	-	30vol%	Standard	Uniform	Unit can	6MeV
5-22		15vol%	15vol%	-	-	30vol%	Standard	Uniform	Unit can	15MeV

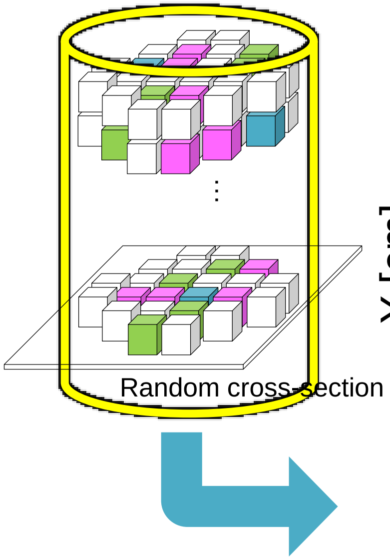
2.2 Analysis results

2.2.5 X-ray transmission measurement – Analysis results

Analysis results (1/5) CT image evaluation of typical cases

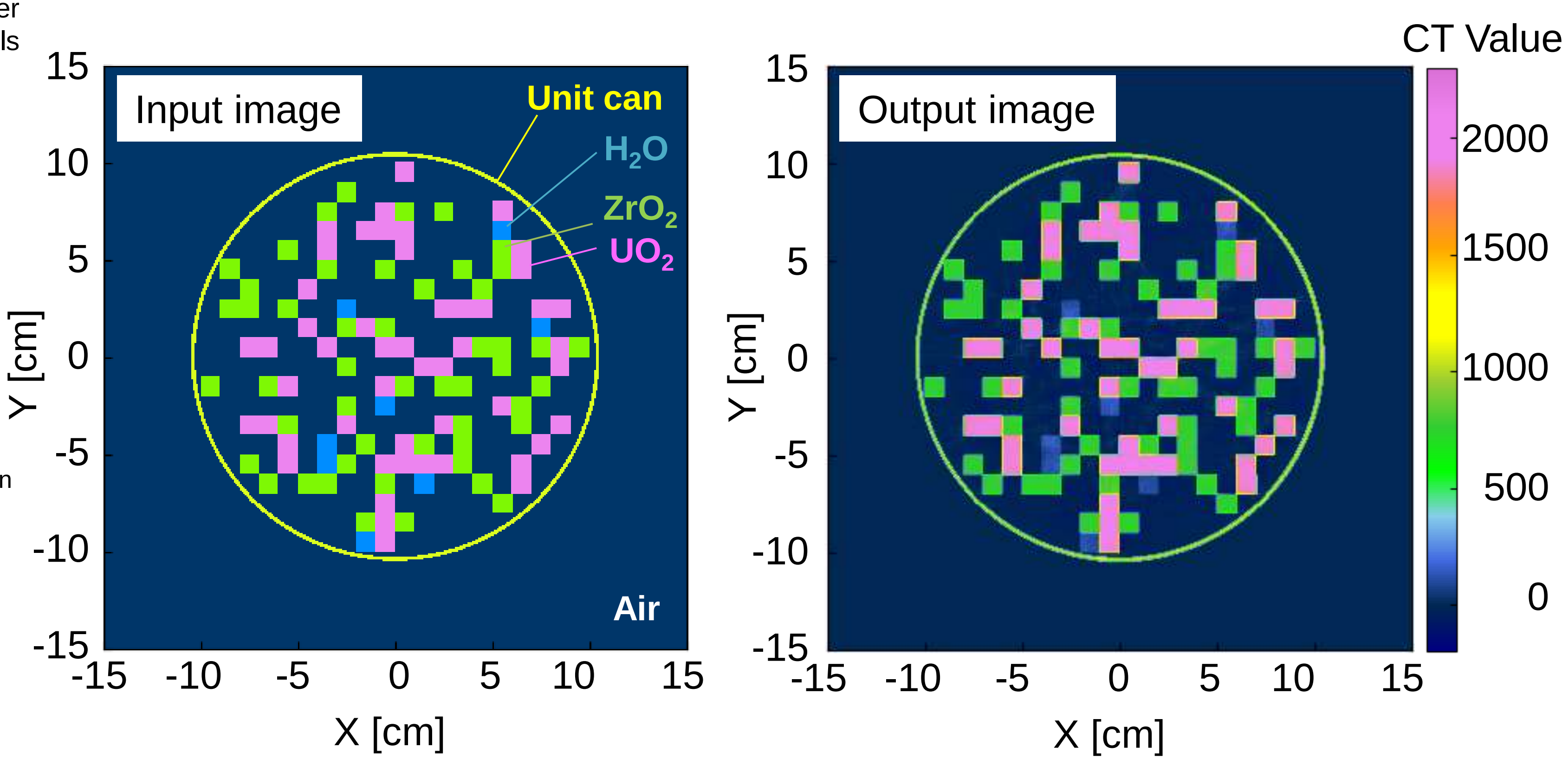
Based on the computational results of the CT simulator [1] incorporative of detector parameters, etc. equivalent to the actual equipment, the CT image was reconstructed.

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



Calculated assuming a cross section of an arbitrary location

Case 5-1: Molten debris (Base case) … UO_2: 15vol%, ZrO_2: 15vol%, H_2O: 1wt%



- It was possible to recognize UO_2, ZrO_2, and H_2O which are fuel constituent materials and the container

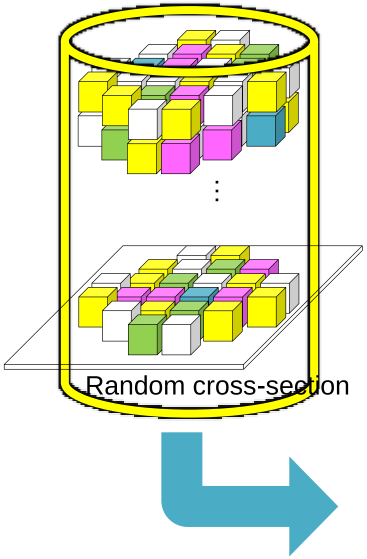
* CT value is computed considering average CT value of container (unit can) as 1000.
* CT value outside the container is set to 0

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

2.2.5 X-ray transmission measurement – Analysis results

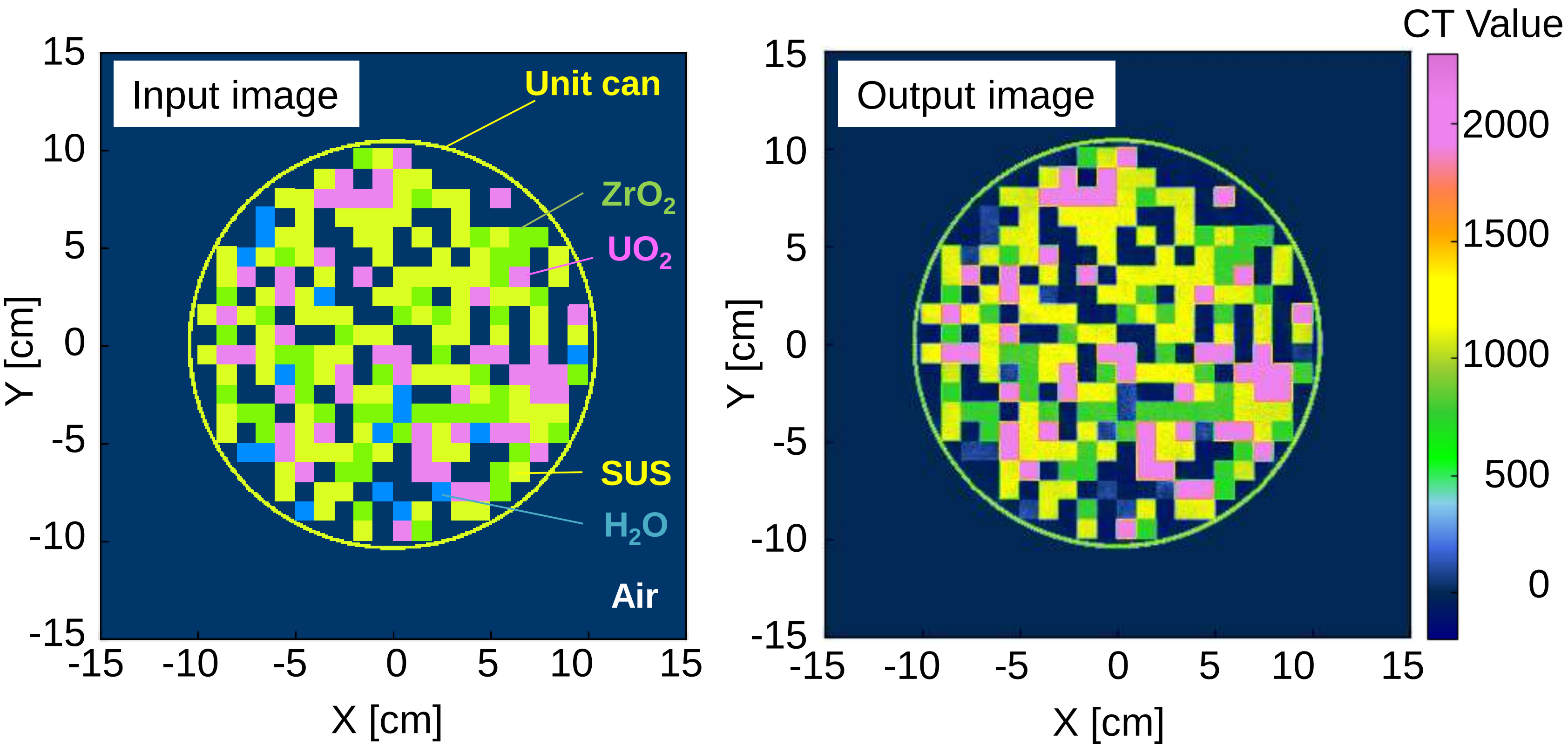
Analysis results (2/5) CT image evaluation of typical cases

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



Calculated assuming a cross section of an arbitrary location

Case 5-18：Metallic debris (High filling rate) … UO_2: 15vol%, ZrO_2: 15vol%, SUS: 30vol%, H_2O: 1wt%



- ➢ Even when there was lot of metal and the filling rate was high, it was passible to recognize each material.

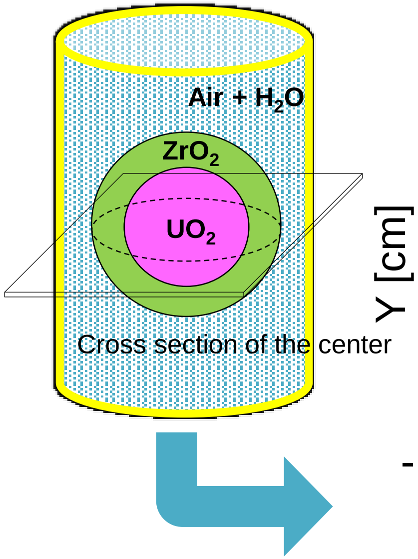
* CT value is computed considering average CT value of container (unit can) as 1000.
* CT value outside the container is set to 0

2.2.5 X-ray transmission measurement – Analysis results

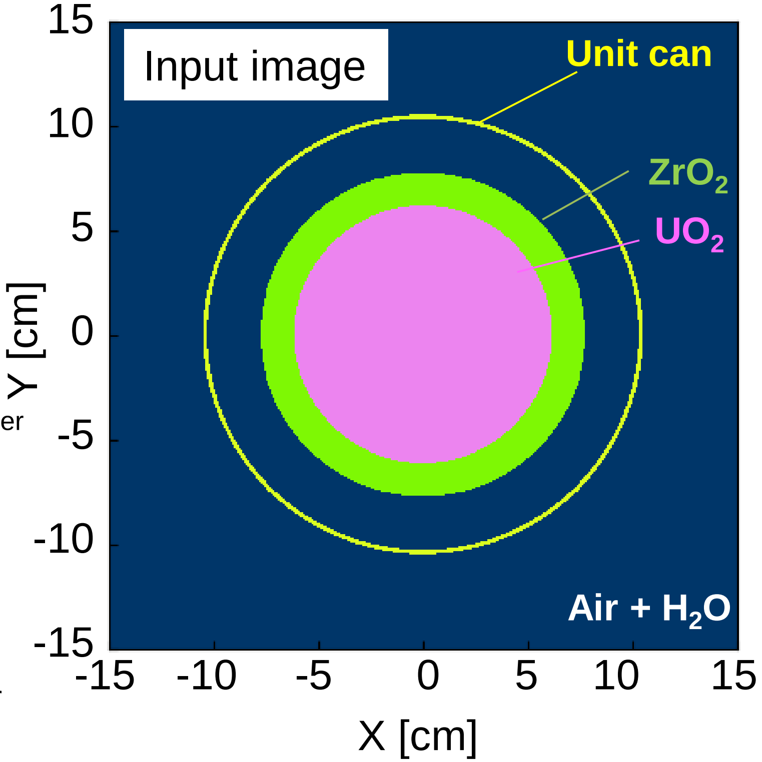
Analysis results (3/5) CT image evaluation of typical cases

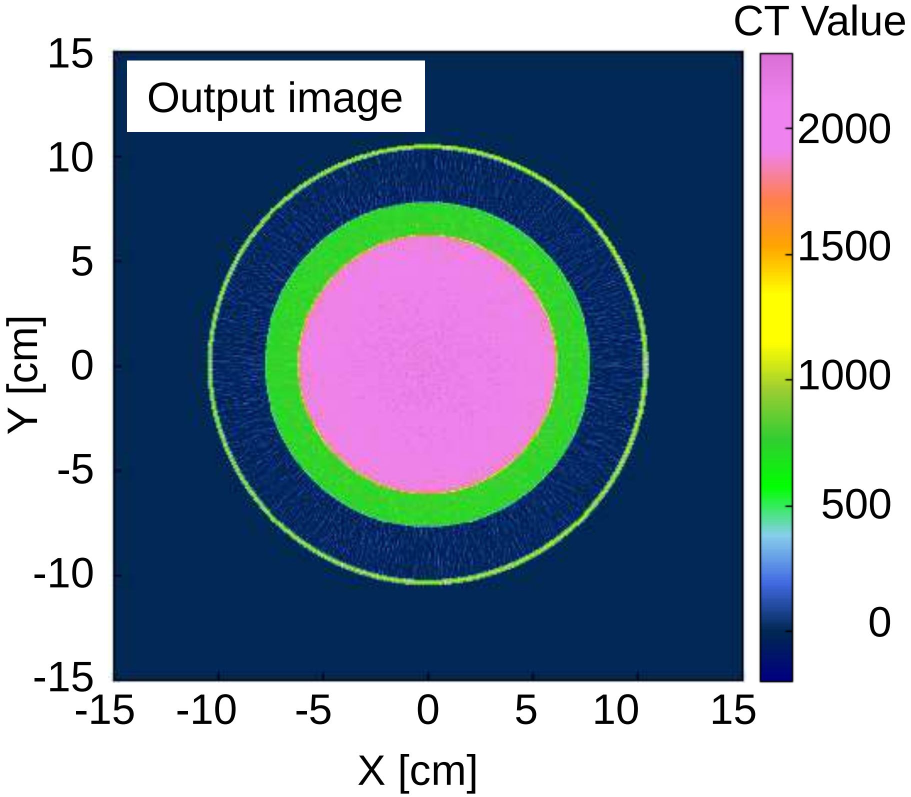
Case 5-12: Molten debris unevenly distributed (at the center in the horizontal direction) … UO_2: 15vol%, ZrO_2: 15vol%, H_2O: 1wt%

Uneven distribution model
Nuclear fuel (UO_2 + ZrO_2) unevenly distributed inside the container



Calculated assuming a cross section of the center of the container.





- It was possible to recognize UO_2 and ZrO_2 in the uneven distribution case as well.
- However, since the apparent density decreased as H_2O got mixed with water, H_2O could not be distinguished from air.

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

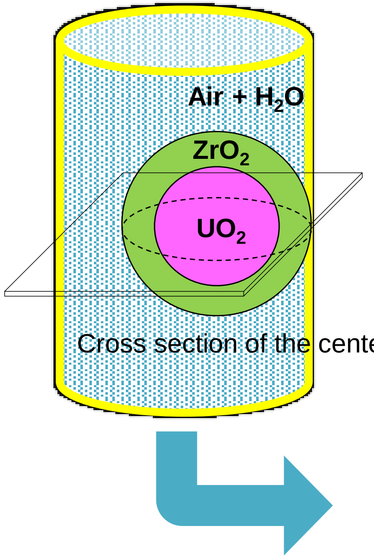
2.2.5 X-ray transmission measurement – Analysis results

Analysis results (4/5) CT image evaluation of typical cases

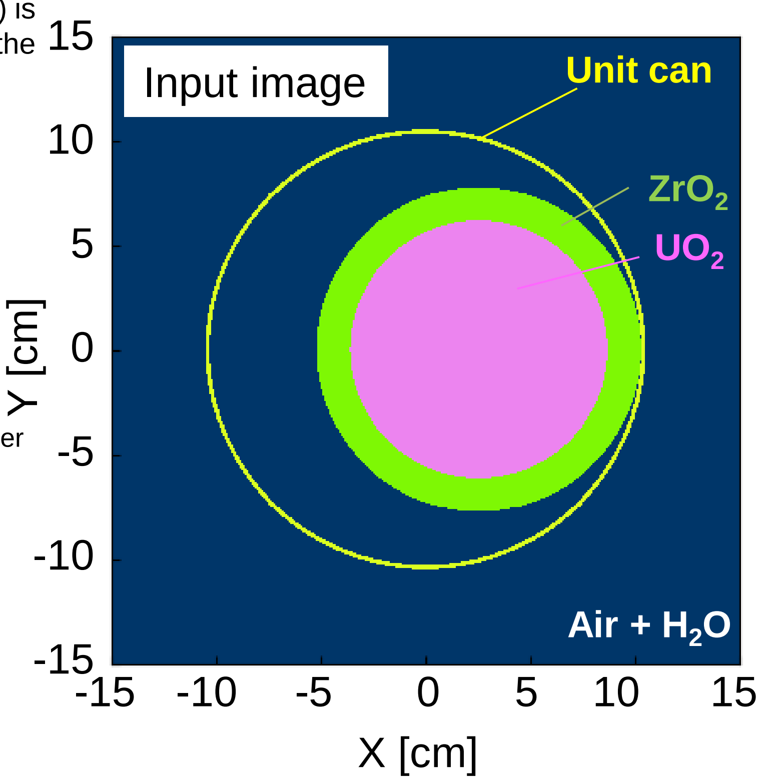
Uneven distribution model

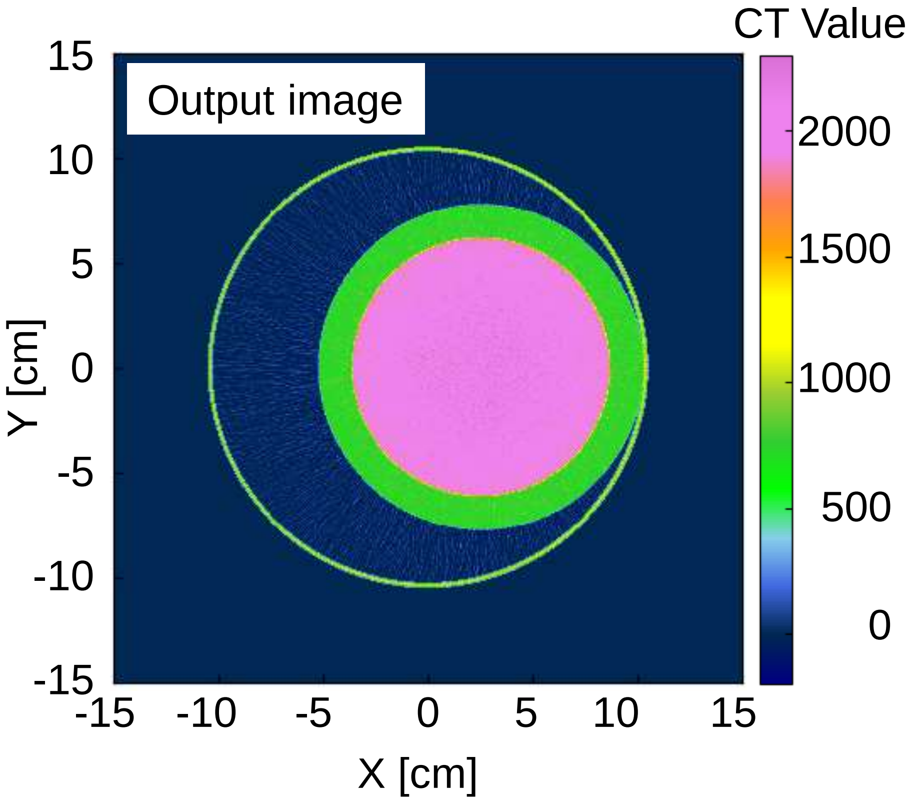
Case 5-13: Molten debris unevenly distributed (outer surface in the horizontal direction) … UO_2: 15vol%, ZrO_2: 15vol%, H_2O: 1wt%

Nuclear fuel (UO_2 and ZrO_2) is unevenly distributed inside the container



Calculated assuming a cross section of the center of the container.





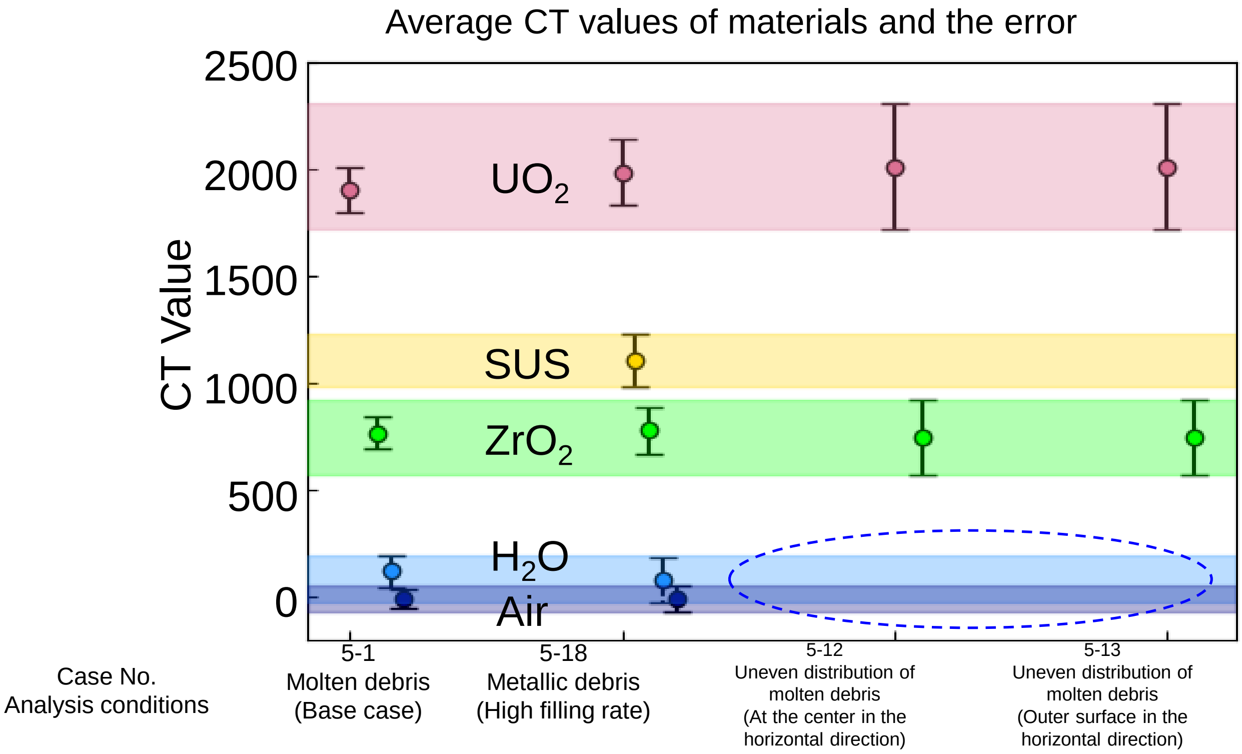
- Results were the same as case 5-12 with uneven distribution (at the center in the horizontal direction).

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

2.2.5 X-ray transmission measurement – Analysis results

Analysis results (5/5) CT image evaluation of typical cases

In order to evaluate the ability to distinguish material based on the CT value, the average of the CT values of material voxels and the error were evaluated.
(The CT values of material voxels excluding those that were at the border between materials were identified and error was calculated based on 3σ method.)



* Uneven distribution cases were excluded as H_2O and Air were mixed in those cases.

- ➢ As the CT value of UO_2 largely differed from other materials, it could be identified.
- ➢ Under the conditions this time, even SUS, ZrO_2 could be identified, however, if multiple influencing factors overlap, it is likely that these cannot be identified.

2.2.5 X-ray transmission measurement

Summary

■Major findings obtained from the analysis

- Flux evaluation for all cases :
  - γ/X ray energy flux ratio that serves as the indicator for γ ray noise in CT images was maximum approx. 6%. It was found that the proportion of γ rays was higher in the uneven distribution cases and metallic debris (high filling rate) cases.
- Evaluation of CT image from the typical cases :
  - From the evaluation of the CT image that was reconstructed based on the results of calculations using the CT simulator incorporative of detector parameters, etc. equivalent to the actual equipment, and assuming that the heterogeneous model is made up of 1 cm square voxels, it was confirmed that nuclear fuel (UO_2) and other materials can be identified.

■Study of the necessity of detailed analysis and consolidation of technical issues

- Flux evaluation for all cases :
  - The γ/X ray energy flux ratio that underwent sensitivity analysis in this project was maximum approx. 6%, which is low.
    → Cases in which multiple influencing factors are changed will be additionally analyzed, and the necessity of shielding γ rays will be studied.

- Evaluation of CT image from the typical cases :
  - If the apparent density of material changes (air mixes at a size that is lower than spatial resolution) it becomes difficult to identify material.
    → Assuming cases wherein the apparent density changes, the applicability of CT measurement using a different X-ray energy will be studied.
  - If multiple materials mix at a size that is lower than spatial resolution, it becomes difficult to identify the material.
    → Methods for evaluating the amount of fuel debris, etc. mixed at a size that is lower than spatial resolution will be studied.

2. Implementation Details

(1) Analytical evaluation of factors influencing measurement errors of prospective measurement technologies

① Selection of influencing factors

② Setting the fluctuation range of the influencing factors

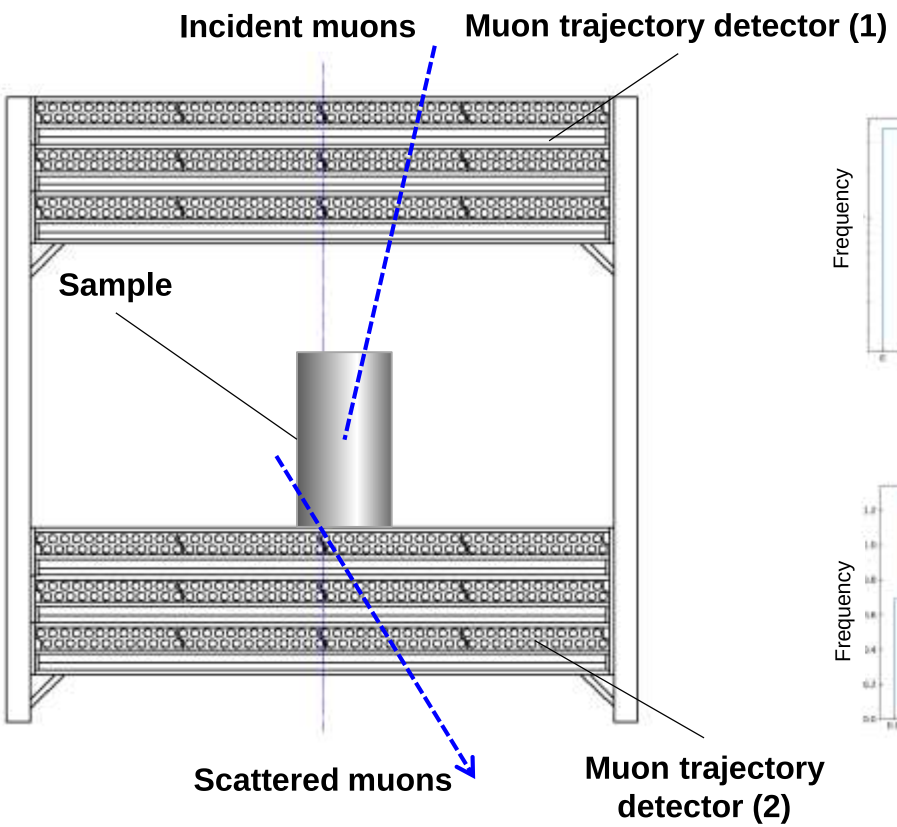
③ Analytical simulation

2.1Analysis conditions
2. 2 Analysis results
- 2.2.1 Passive neutrons
- 2.2.2 Passive gamma rays
- 2.2.3 Active neutrons
- 2.2.4 Passive/active neutrons + passive gamma rays
- 2.2.5 X-ray transmission measurement
- 2.2.6 Cosmic rays scattering measurement

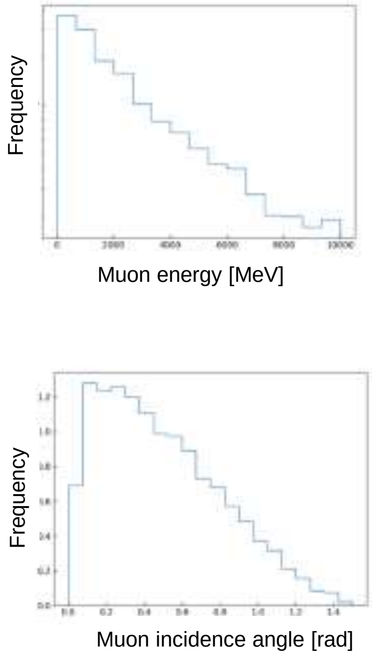
	① Fuel debris composition	Gd content	B content	MOX	② Burn-up	③ FP emission rate	④ Cooling Period	⑤ Moisture content	⑥ Filling rate	⑦ Uneven distribution	⑧ Container	⑨ Irradiating radiation source	⑩ Detector
2.2.6 Cosmic rays	No. 179 No. 184	No. 180	No. 180	No. 179	No. 181	No. 181	No. 181	No. 180	No. 179	No. 182	No. 183	–	All

2.2.6 Cosmic rays scattering measurement - Measurement concept

- **Measurement principle:** Measurement of changes in the trajectory of muons penetrating fuel debris
- **Measurement system:** Placement of muon trajectory detector above and below the sample
- **Radiation source conditions:** Setting of the muon energy and angle spectrum through EXPACS*
- **Detector response:** Muon scattering angle distribution (calculated from the changes in trajectory above and below)
- **Measurement time:** 1 hour (Conditions under which it is assumed that 10,000 or more valid events can be obtained)



Cosmic rays scattering measurement system

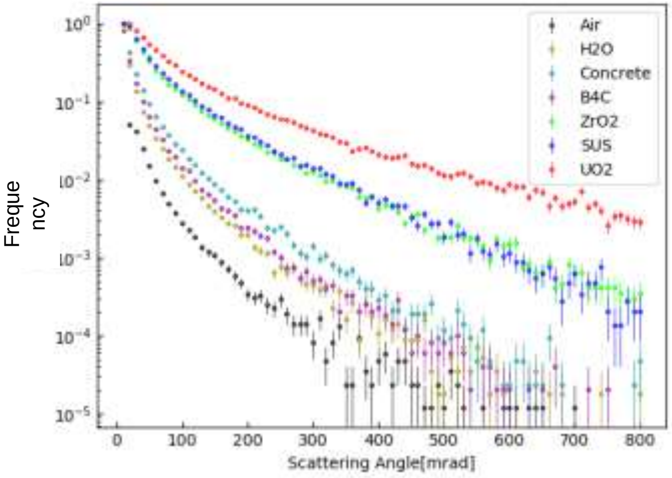


Conditions for incident muons

Muon scattering angle

$$\theta_0 = \frac{13.6}{\beta cp}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln\left(\frac{x}{X_0}\right)\right]$$

X_0: Radiation length (substance dependent)
x: Penetration distance
βcp: Energy

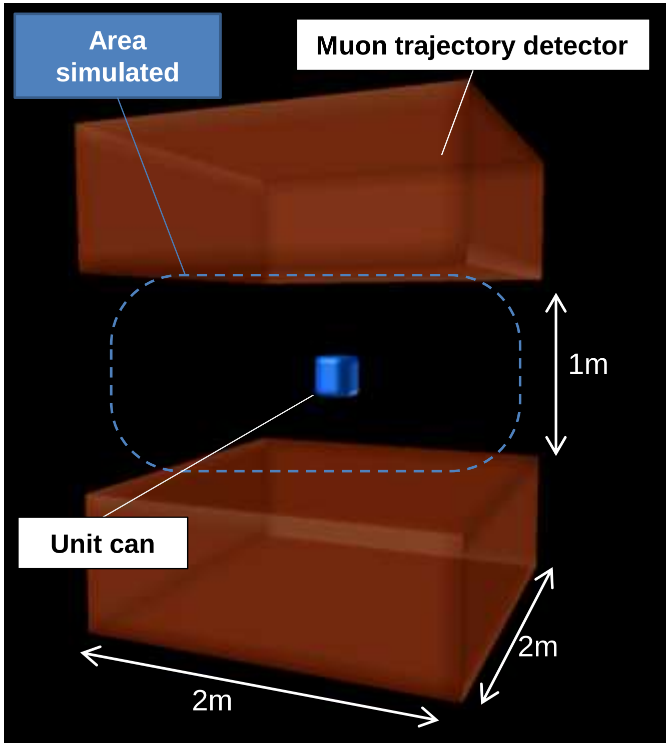


Muon scattering angle distribution

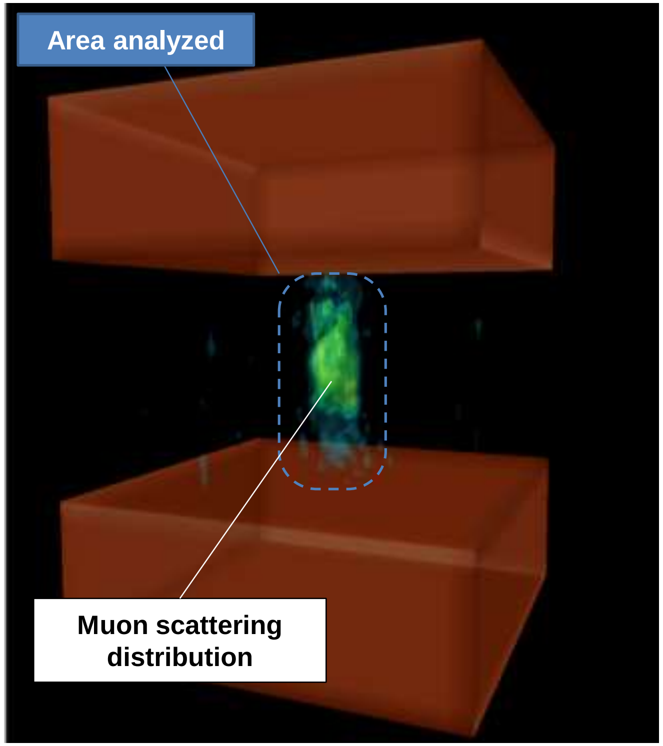
※EXPACS (https://phits.jaea.go.jp/expacs/jpn.html)

2.2.6 Cosmic rays scattering measurement - Analysis model

- **Scope of simulation:** The muon trajectory between the upper and lower detectors is reproduced by means of simulation
- **Scope of data analysis:** Identification of data on muon scattering around the sample
- **Data analysis technique:** As a primary evaluation, the muon scattering average angles (Total scattering in the area being analyzed / Total number of muons penetrating the area being analyzed) are compared.



Simulation system



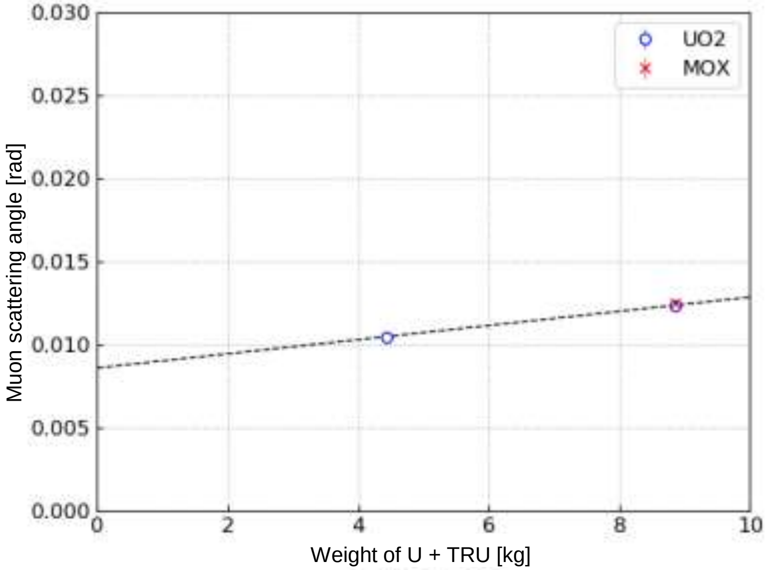
Simulation results
(Muon scattering distribution)

2.2.6 Cosmic rays scattering measurement - Analyzed cases

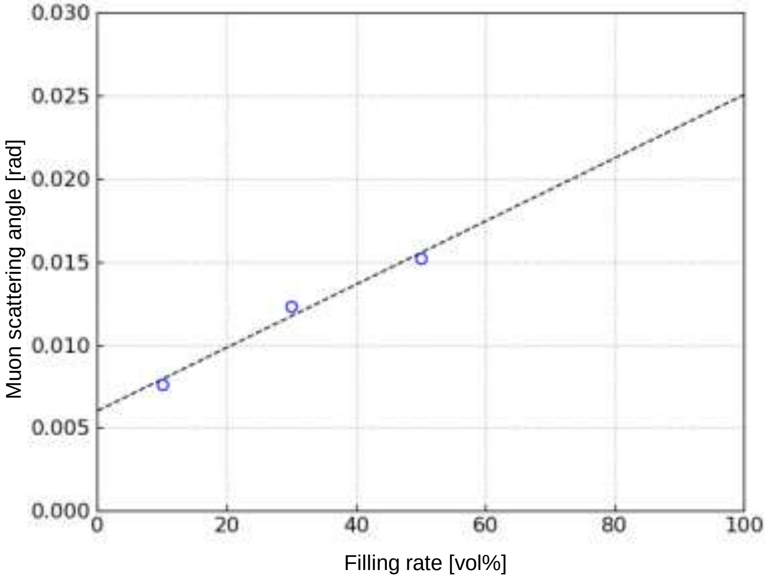
Case		UO_2	ZrO_2	SUS	Concrete	Total (Filling rate)	Burn-up (GWd/t)	FP emission rate	Cooling period (Years)
6-1	Molten debris	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-2	Molten debris (small quantity of U)	7.5vol%	22.5vol%	0vol%	-	30vol%	23	Standard	20
6-3	MOX	15vol% (MOX)	15vol%	0vol%	-	30vol%	0	Standard	20
6-4	Filling rate (low)	5vol%	5vol%	0vol%	-	10vol%	23	Standard	20
6-5	Filling rate (high)	25vol%	25vol%	0vol%	-	50vol%	23	Standard	20
6-6	Gd (low)	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-7	Gd (high)	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-8	B (low)	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-9	B (high)	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-10	Water content (low)	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-11	Water content (high)	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-12	Burn-up (low)	15vol%	15vol%	0vol%	-	30vol%	1.3	Standard	20
6-13	Burn-up (high)	15vol%	15vol%	0vol%	-	30vol%	51	Standard	20
6-14	FP emission rate (Zero emission)	15vol%	15vol%	0vol%	-	30vol%	23	Zero emission	20
6-15	FP emission rate (high emission)	15vol%	15vol%	0vol%	-	30vol%	23	High emission	20
6-16	Cooling period	15vol%	15vol%	0vol%	-	30vol%	23	Standard	30
6-17	Cooling period	15vol%	15vol%	0vol%	-	30vol%	23	Standard	40
6-18	Uneven distribution 1	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-19	Uneven distribution 2	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-20	Container 1	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-21	Container 2	15vol%	15vol%	0vol%	-	30vol%	23	Standard	20
6-22	Uranium-rich	30vol%	0vol%	0vol%	-	30vol%	23	Standard	20
6-23	Metallic debris	0.075vol%	0.075vol%	29.85vol%	-	30vol%	23	Standard	20
6-24	Metallic debris	15vol%	15vol%	30vol%	-	60vol%	23	Standard	20
6-25	MCCI debris	1.05vol%	1.05vol%	7.2vol%	20.7vol%	30vol%	23	Standard	20

2.2.6 Cosmic rays scattering measurement - Analysis results: (1) Amount of U, filling rate

- Evaluation of the correlation between the amount of U +TRU contained in fuel debris and muon scattering
- ➢ Parameters: U content, MOX fuel, filling rate



Molten debris with a different U content and MOX fuel (6-1, 6-2, 6-3)

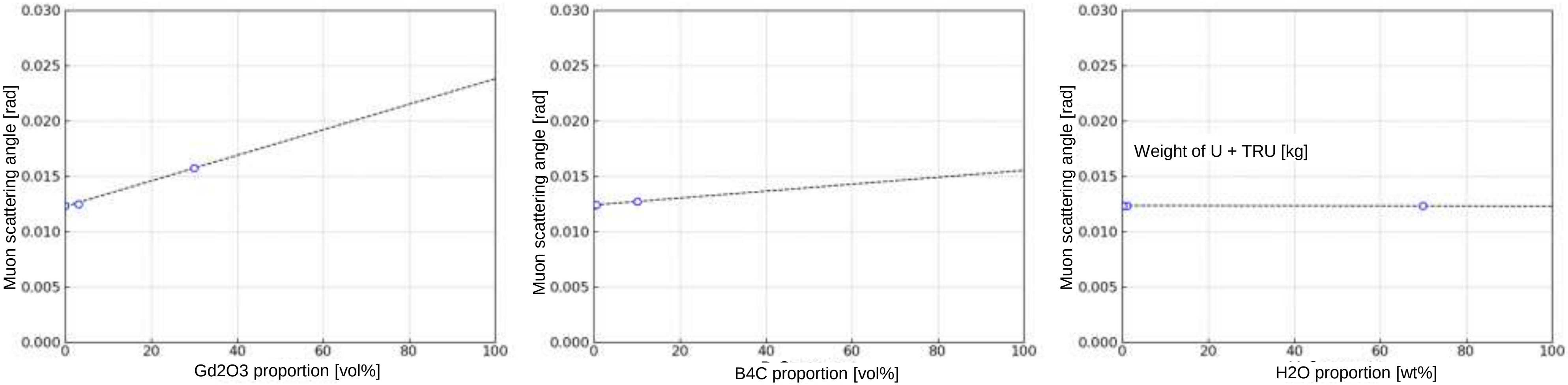


Changes in the filling rate of molten debris (6-1, 6-4, 6-5)

- The muon scattering value increased as the weight of U +TRU in fuel debris increased.
- When the composition was the same, scattering value increased with the filling rate.
- The difference between UO_2 fuel and MOX was small.

2.2.6 Cosmic rays scattering measurement - Analysis results: (2) Gd, B content

- Evaluation of the impact of the proportion of each component contained in fuel debris
- ➢ Parameters: Gd_2O_3, B_4C, Moisture content



Gd_2O_3 (Density: 7.41g/cm^3)
(6-1, 6-6, 6-7)

B_4C (Density: 1.76g/cm^3)
(6-1, 6-8, 6-9)

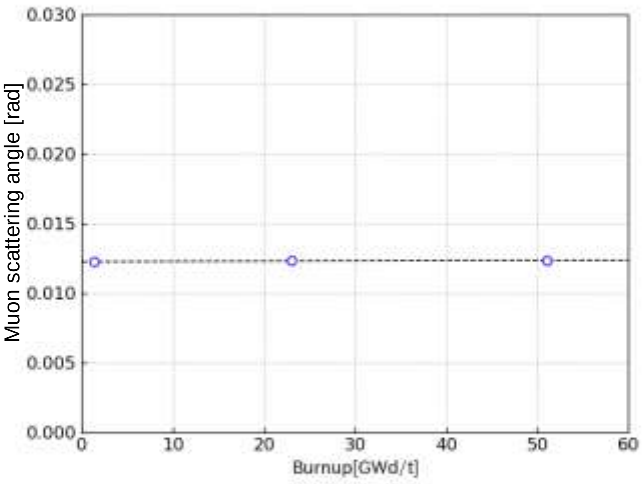
H_2O (Density: 1.0g/cm^3)
(6-1, 6-10, 6-11)

- The impact of the proportion of Gd_2O_3 which has comparatively higher density was large.
- The impact of B_4C and moisture content which have a lower density was small.

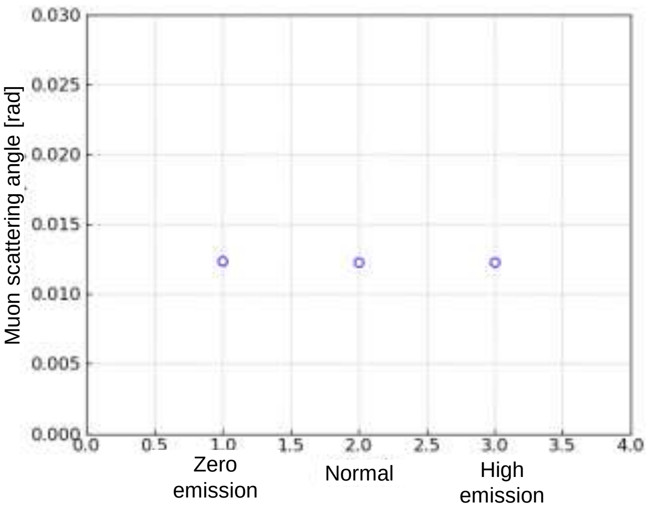
2.2.6 Cosmic rays scattering measurement - Analysis results (3): Burn-up, FP, cooling period

- Evaluation of impact of operating conditions and cooling conditions, etc.

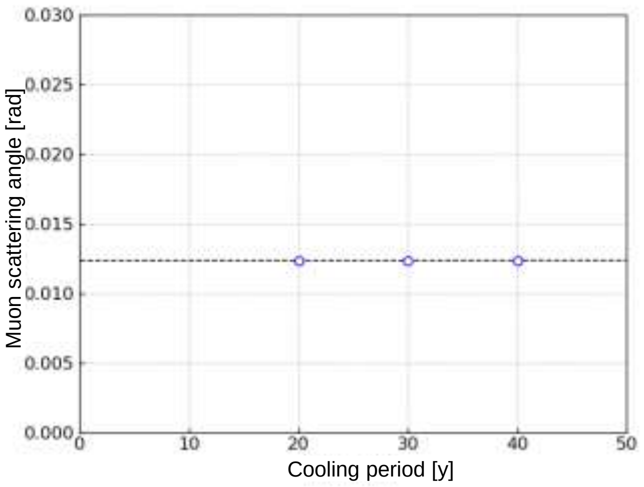
➢ Parameters: Burn-up, FP emission rate, cooling period



Burn-up
(6-1, 6-12, 6-13)



FP emission rate
(6-1, 6-14, 6-15)



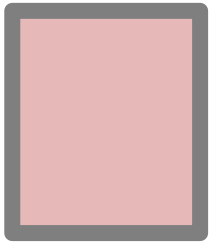
Cooling period
(6-1, 6-16, 6-17)

- Impact of burn-up, FP emission rate, and cooling period was small.
- Impact of difference in isotopes of the same element on muon scattering was small.

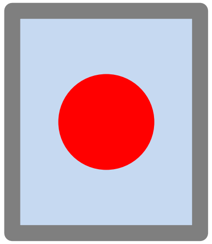
2.2.6 Cosmic rays scattering measurement - Analysis results: (4) Volume of fuel debris and uneven distribution

- Evaluation of impact of the volume of fuel debris and uneven distribution of its location
- The impact of different volumes, density and location in the base case and in cases with the same components and weight was evaluated.

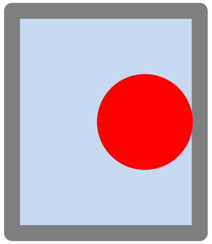
➢ Parameters: Volume, density and location



① Uniform distribution



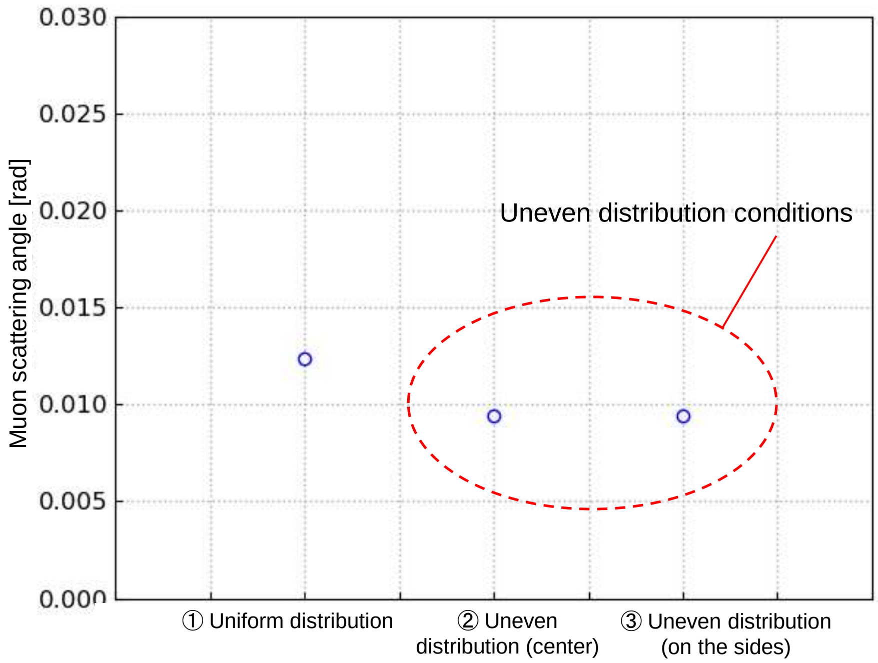
② Uneven distribution (center)



③ Uneven distribution (on the sides)

Volume: 6,500cm³
Density: 2.413g/cm³

Volume: 1,950cm³
Density: 8.0425g/cm³



Uneven distribution conditions
(6-1, 6-18, 6-19)

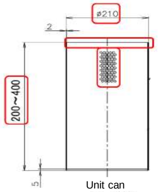
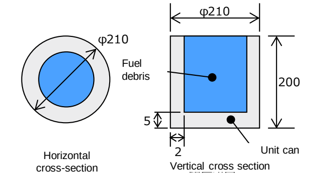
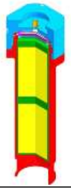
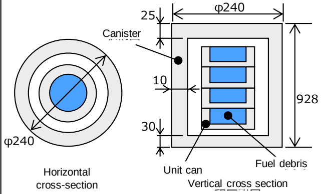
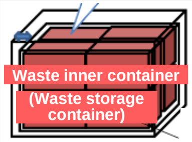
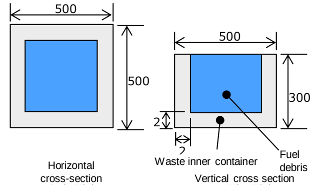
- When the weight remained the same but the volume changed, the muon scattering value changed.
- Impact of difference in location was small when the volume remained the same.

2.2 Analysis results

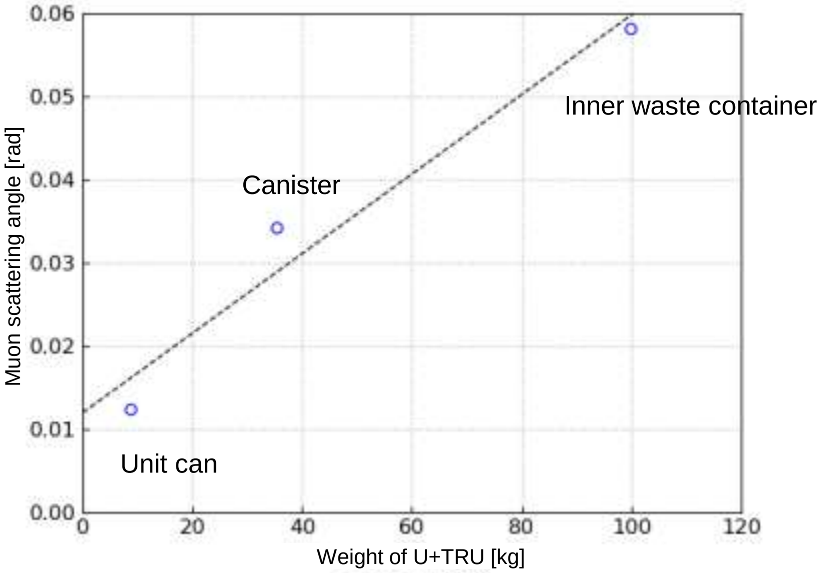
2.2.6 Cosmic rays scattering measurement - Analysis results: (5) Canister

- Evaluation of the impact of difference in the container in which fuel debris is collected
- The fuel debris composition was set to the same conditions as the base case, and the filling rate was set at 30% of the capacity of the container.

➢ Parameters: Shape of the container

Type of container	Shape of the container	Evaluation model (Unit: mm)
1. Unit can **φ 210mm x 200mmH** **Thickness 2mm** **[Reference: Fuel Debris Retrieval PJ*]**	 **Figure Proposed structure of the unit can** From the Subsidy Project of Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget - Development of Technology for Containing, Transfer and Storage of Fuel Debris Research Report (Final Report) March 2021	
2. Canister **Φ 240mm x 928mmH** **Thickness 10mm** **[Reference: Canister PJ**]**	 **Figure Proposed structure of canister (Simple installation structure / Inner diameter 220mm / without air feeder)** From the Subsidy Project of "Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget (Development of Technology for Containing, Transfer and Storage of Fuel Debris PJ" FY2020 Final Report dated June 2021	
3. Waste inner container **500mm☐x 300mmH** **Thickness 2mm** **[Reference: Treatment and Disposal PJ***]**	 Figure Proposed structure of the waste storage container From the Subsidy Project of "Decommissioning and Contaminated Water Management in the FY2018 Supplementary Budget (Research and Development for Treatment and Disposal of Solid Wastes)" FY2019 Accomplishment Report dated December 2020	

*Subsidy Project of Development of Technology for Fuel Debris Retrieval
**Subsidy Project of Development of Technology for Containing, Transfer and Storage of Fuel Debris
***Subsidy Project of R&D for Treatment and Disposal of Solid Waste

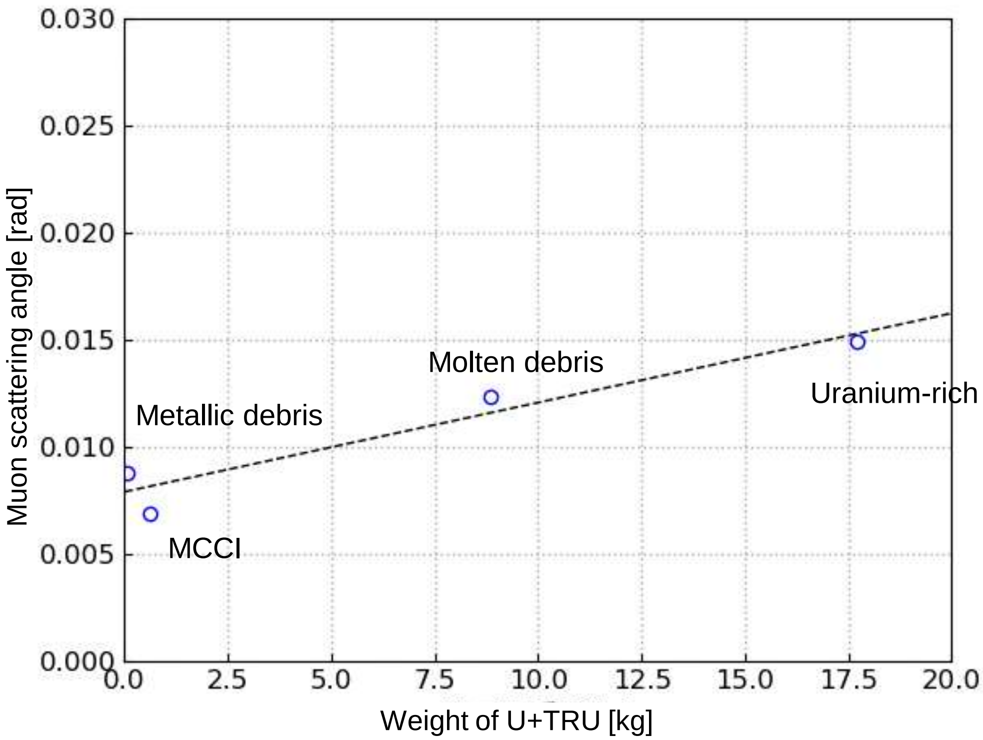


Unit can, canister, inner waste container
(6-1, 6-20, 6-21)

- Even if the type of container was different, the scattering value increased in accordance with the muon scattering angle and the weight of U+TRU.
- Parameter survey by container needs to be conducted for detailed evaluation.

2.2.6 Cosmic rays scattering measurement - Analysis results: (6) Type of fuel debris

- Evaluation of the impact of the type of fuel debris (molten debris, Uranium-rich, metallic debris, MCCI (Molten Core Concrete Interaction))
  - ➢ Parameters： Fuel debris composition

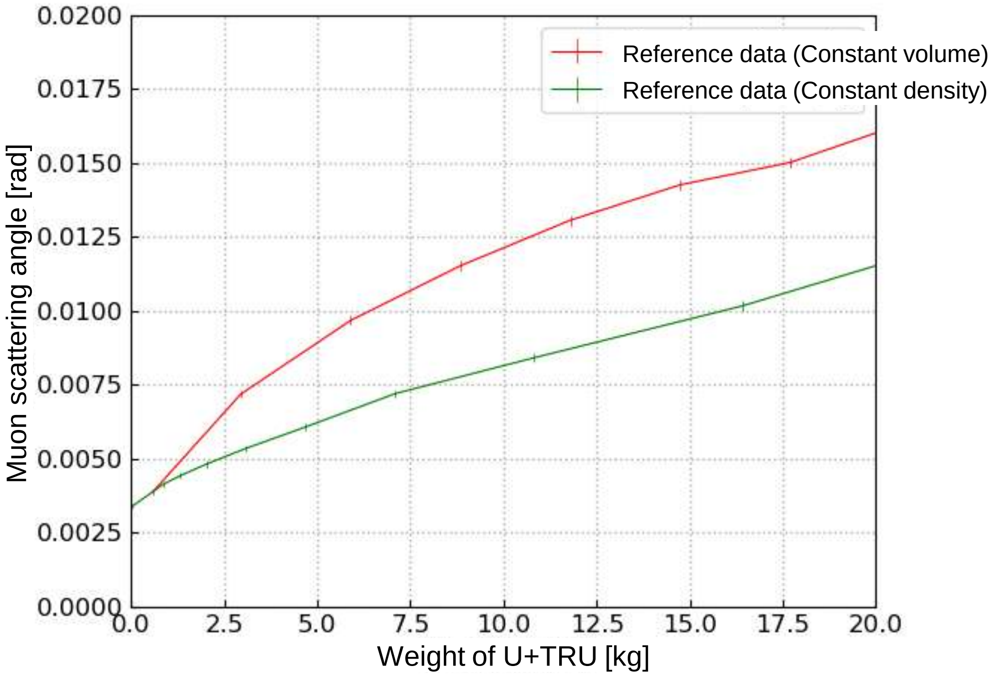


Molten debris, Uranium-rich, metallic debris, MCCI
(6-1, 6-22, 6-23, 6-25)

- The muon scattering value increased in accordance with the weight of U +TRU even when the fuel debris composition was different.

2.2.6 Cosmic rays scattering measurement - Analysis results: (7) Creation of reference data

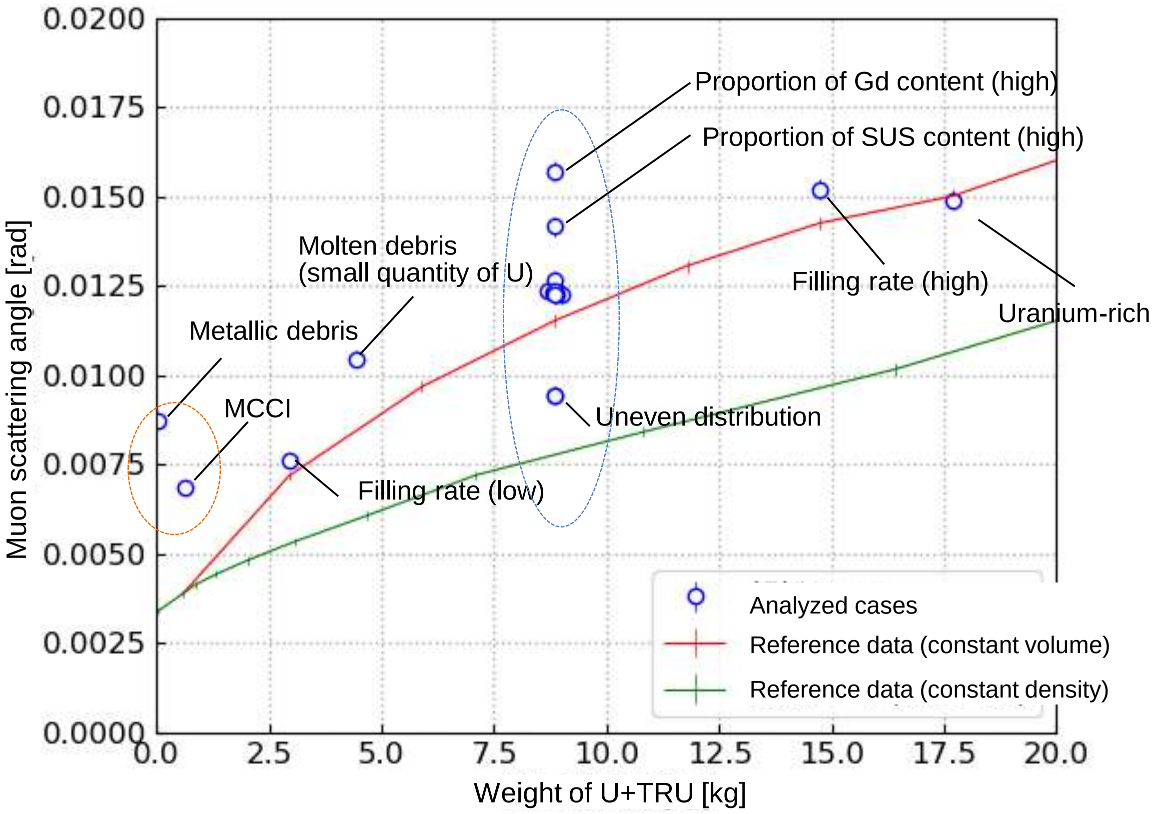
- Reference data
  - Evaluation of muon scattering angle with respect to the amount of U as reference data
  - Simulation was conducted with only UO_2 as the uniform component.
- ① Constant volume (Adjustment of the amount of U by changing the density):
  - Constant volume (unit can capacity), Density 0 to 10.525[g/cm^3]
- ② Constant density (Adjustment of the amount of U by changing the volume):
  - Constant density (10.525[g/cm^3]), spherical (radius 1 to 10[cm])



- The muon scattering angle differed in accordance with the weight of U which varies when the volume and density of fuel debris changed.

2.2.6 Cosmic rays scattering measurement - Analysis results: (8) Comparison with reference data

- **Evaluation of the overall trend by comparing the reference data and the analyzed cases**



① Variation in measured values
- Variation of ±30% when the weight was the same as the base case
- Largest when there was Gd content
- Smallest under high density conditions

② Lower limit for identification
- Even in the case of metallic debris and MCCI conditions where U content was less, scattering occurred above a certain level.
- If it is converted to the weight of U in the reference data it corresponds to approx. 2.5kg to 5.0kg

- The reference data evaluated based independently on UO_2 and the trend of the analyzed cases matched by and large.
- The scattering value increased due to the Gd and SUS content.
- The scattering value decreased in the case of uneven distribution (small volume, high density)

2.2.6 Cosmic rays scattering measurement – Summary

- Major findings obtained from the analysis:
  - A mutual correlation can be seen between the muon scattering value and the weight of heavy elements (U +TRU) present in fuel debris.
  - Scattering value increases due to SUS, Gd_2O_3 that have a high density.
  - Scattering value fluctuates depending on the volume of fuel.
  - Burn-up, FP emission rate, and cooling period have little impact.

- Approximation of measurement accuracy (Primary evaluation based on the average scattering angle value)
  - Variation in measured value: ±30%（Fluctuates depending on the conditions in the case of fuel with the same weight)
  - Lower limit for identification: 2.5kg to 5.0kg (Scattering occurs above a certain level even when there is no U or only minute quantity of U)

- Study of the necessity of detailed analysis and consolidation of technical issues
  - Detailed analysis of muon scattering angle
    - ➢ Study of the method of distinguishing between scattering caused by U, Pu, etc., and scattering caused by other material
    - ➢ Study of the techniques for analyzing muon scattering angle distribution
  - Evaluation of the impact of the volume and density of fuel
    - ➢ Study of the combination of data analysis and volume evaluation based on image analysis
  - Impact of radiation from fuel debris on the sensor
    - ➢ Verification of the radiation resistance of the sensor and study of improvement measures

2. Implementation Details

(2) Study of future research and development plans aiming for application of sorting technology to actual equipment

① Identification of technical issues for the purpose of practical application of the sorting technology

② Study of research and development plan (Contents, duration, conditions)

③ Goals of the main processes

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (1/9)

[Work procedures]

A common form was created for identifying issues by measurement technique.

- ✓ The step mentioned in section 2.(2)② at which action needs to be taken is listed here.

Note)

Development of technology for sorting fuel debris and radioactive waste
Identification of technical issues for the purpose of practical application

Target measurement technology: 1

No.	Classification			Items	Details	Response policy	Corresponding development step	Remarks
	Principle, conditions, etc.	Accuracy, efficiency, etc.	Device, equipment, etc.					
1-1								
1-2								

- ✓ Principle, conditions, etc.: Issues arising from the measurement principle or the conditions applied, etc.
- ✓ Accuracy, efficiency, etc.: Issues pertaining to measurement accuracy identified through analytical simulation
- ✓ Device, equipment, etc.: Issues related to equipment structure, placement, handling, etc.

- ✓ Development policy for resolving the issues is mentioned here
- ✓ Refined as much as possible to ensure it is captured in the research and development plan

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (2/9)

[Division of work]

・The companies responsible for each measurement technique are listed below (following the division of analysis work).

・Overall review is conducted by all organizations including JAEA.

No.	Prospective measurement technology	Division of work
1	Passive neutron measurement technology	Hitachi-GE, MHI
2	Passive gamma rays measurement technology	Hitachi-GE, MHI
3	Active neutron measurement technology	Hitachi-GE, MHI
4	Passive/active neutrons and passive gamma rays measurement technology	MHI
5	X-ray transmission measurement (High energy X-ray CT method)	Hitachi-GE
6	Cosmic rays scattering measurement (Muon scattering method)	Toshiba ESS

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (3/9)

[Consolidation of identification results]

・From among the issues identified, those considered to be "Key issues" from the following 3 viewpoints were marked.

(In the [Overview of identification results] described hereinafter, the identified key issues are indicated by a red frame.

Classification	View points on key issues	Example of identified issue
A	Issue concerning the principle - Unprecedented	Development of an algorithm for estimating the amount 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 technology	The properties of fuel 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.

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (4/9)

[Overview of identification results]

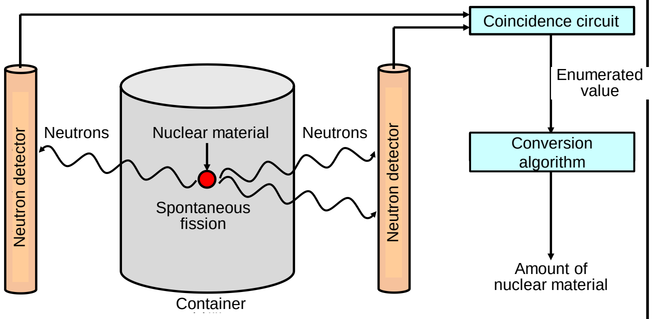
[Target measurement technique]：1. to 4. Passive/active neutrons and passive gamma rays

- **Based on the analytical evaluation in 2.(1), it was confirmed that sorting and measuring is possible by combining measurement techniques depending on the influencing factors.**
- **Assuming the concept of measurement by combining the measurement technologies described in 1 to 3, in addition to the issues pertaining to individual measurement techniques (1, 2, 3) that need to be resolved, the technical issues concerning combination measurement technique (4) were consolidated.**

1. **Passive neutron measurement technology**
2. **Passive gamma rays measurement technology**
3. **Active neutron measurement technology**
4. **Passive/active neutrons and passive γ rays measurement technology**

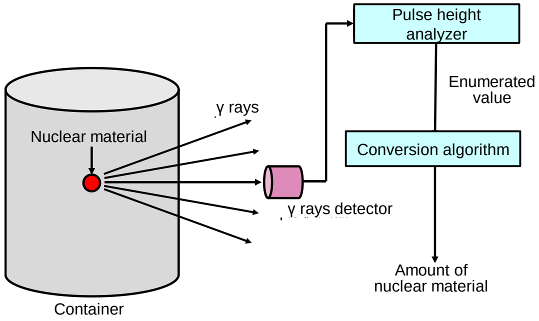
1. Passive neutron measurement technology

・ Neutrons produced by the spontaneous fission of fissile nuclides are measured.



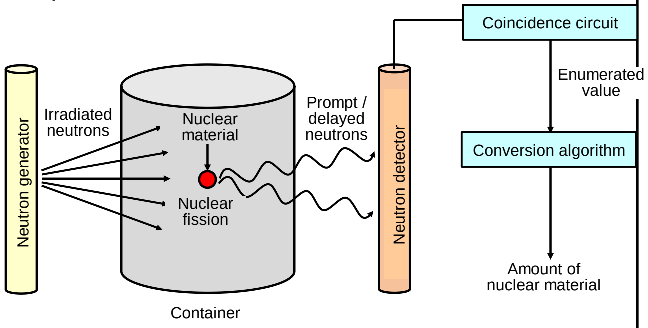
2. Passive gamma rays measurement technology

・ Gamma rays produced by the spontaneous fission of fissile nuclides are measured.



3. Active neutron measurement technology

・ Nuclear fission of fissile nuclides is induced by irradiating neutrons from the outside.
・ The prompt neutrons and delayed neutrons produced as a result, are measured.



2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (5/9)

[Target measurement technique]: 1. to 4. Passive/active neutrons and passive gamma rays

[Overview of identification results]

Note)

The key issues from among the technical issues identified with respect to each individual measurement technique (1, 2, 3) are consolidated.

No.	Items	Details	Response policy	Corresponding development step
1-3	Method of converting the measured value to evaluation value	State of co-presence of Cm244 and U is unknown	The analyst will be requested to verify the state of co-presence by conducting a sampling analysis of fuel debris.	2-① C
1-10	Algorithm (Estimation of the amount of nuclear material)	The method of converting the effective mass of Cm244 into amount of U/Pu, when fuel with different burn-ups is mixed, is yet to be determined.	The correlation between the number of spontaneous fission neutrons produced and the amount of U/Pu will be studied using a mixed simulation of fuel debris composition from the 3D nuclide inventory data.	2-③ A, B
1-13 3-11	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
1-14 2-15 3-14	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
2-2	Method of converting the measured value to evaluation value	The state of co-presence of Eu154 and U is unknown.	The analyst will be requested to verify the state of co-presence by conducting a sampling analysis of fuel debris.	2-① C
2-12	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
3-1	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.	The scope of application will be verified 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

Step 2 (Measurement concept / scenario development)
① Study of target performance value
② Development of the concept of the equipment 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 equipment
② Software development
③ Elemental technology verification test (ongoing)

Step 4 (Test manufacturing and comprehensive verification test)
① Test manufacturing of measuring equipment
② Demonstration test (Hot, etc.), improvement

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (6/9)

[Target measurement technique]: 1. to 4. Passive/active neutrons and passive gamma rays

[Overview of identification results]

Note)

No.	Items	Details	Response policy	Corresponding development step
4-1	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
4-2	Optimization of the placement of detector	Streamlined layout of the neutron generator, detector, shield, moderator, etc.	The equipment 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)
4-3	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)
4-4	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 assessment analysis.	2- ② (2-①, 2-⑤)
4-5	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**
4-6	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**
4-7	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	The phenomenon will be understood by comparing the simulation and the test.	2-②、2-③、2-⑤ **B**
4-8	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
4-9	Maintainability	Enhancement of the maintainability of the numerous detectors	A structure that enables direct maintenance from outside the cell	3-① onwards

Step 2 (Measurement concept / scenario development)
① Study of target performance value
② Development of the concept of the equipment 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 equipment
② Software development
③ Elemental technology verification test (ongoing)

Step 4 (Test manufacturing and comprehensive verification test)
① Test manufacturing of measuring equipment
② Demonstration test (Hot, etc.), improvement

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (7/9)

[Overview of identification results]

[Target measurement technique]: 5. X-ray transmission measurement (High energy X-ray CT method) 1/2

Note)

No.	Items	Details	Response policy	Corresponding development step
5-1	Measurement principle	･Since only information on density can be obtained from past radioparency measurements, a measurement technique that enables evaluation of the amount 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, that measurement technique will be studied.	2-① 2-② 2-③ 2-⑤ B
5-2	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 amount 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
5-3	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
5-4	Estimation of the amount of nuclear material Algorithm	･An algorithm for estimating the amount 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 technique 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 estimation of the amount of nuclear material using other measurement techniques, using the CT measured values, and performing evaluation will be studied.	2－③ 3- ② A, B

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (8/9)

[Overview of identification results]

[Target measurement technique]: 5. X-ray transmission measurement (High energy X-ray CT method) 2/2

No.	Items	Details	Response policy	Corresponding development step Note)
5-5	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
5-6	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
5-7	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
5-8	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
5-9	Maintainability	・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
5-10	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 equipment, 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.

2.(2) ① Identification of technical issues for the purpose of practical application of the sorting technology (9/9)

[Overview of identification results]

[Target measurement technique]: 6. Cosmic rays scattering measurement (Muon scattering method)

No.	Items	Details	Response policy	Corresponding development step Note)
6-1	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
6-2	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 under the measurement conditions.	2-① 2- ② 2-⑤ B
6-3	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 count rate.	・The correlation of the detector placement with the count rate of background radiation and the muon count rate will be evaluated. ・A measurement system that can sufficiently reduce the background radiation will be studied.	2- ② 2-④ 3-①
6-4	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 count 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
6-5	Detector specifications	The detector is made up of numerous sensors, and each individual sensor has dead time for a certain period after the incidence of gamma rays. The gamma rays count rate can be reduced by downsizing each individual sensor, but the cost increases.	・Sensor size and performance corresponding to the background conditions will be studied.	2-② 2-⑤ 3-① 3-②
6-6	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

Note) Indicates that the process of resolving the issue starts at the corresponding development step to get an idea of the prospects.

2. Implementation Details

(2) Study of future research and development plans aiming for application of sorting technology to actual equipment

① Identification of technical issues for the purpose of practical application of the sorting technology

② Study of research and development plan (Contents, duration, conditions)

③ Goals of the main processes

2.(2)② Research and development plan (Contents, duration, conditions) (1/11)

[Development steps and R&D items]

[Target measurement technique]: 1. to 4. Passive/active neutrons and passive gamma rays

(Step 1) Feasibility study of measurement (Analyzing the possibility) ⇐ This year's research
- ① Setting the purpose and target (shape, density, etc.) of measurement
- ② Nuclear material → Evaluating the behavior of radiation incident upon the detector
- ③ Identification, etc. of technical issues contributing to the concept of measurement

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios	Response to the identified issues
① Study of target performance value required for sorting (Temporarily set for about 1 year ＋ updated after ② to ④) Target performance value of the measuring equipment (measurement time, equipment size, lower detectable limit, error, radiation resistance, etc.) will be set.	1-3, 2-2, 3-1, 4-3, 4-4
② Development of the concept of the equipment by means of detector response analysis (about 2 years) Analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment and evaluating performance.	4-1, 4-2, 4-3, 4-4, 4-7
③ Study of method for evaluating nuclear fuel material, etc. based on the measured quantity (about 2 years) Evaluation method for estimating the amount of nuclear fuel material based on measured values will be developed (Including combination of measurement technologies).	1-10, 2-12, 4-5, 4-6, 4-7
④ Re-examination of sorting scenarios (Temporarily set for about 2 year ＋ updated after ① to ③) The applicable sorting/segregation scenarios, the location where the measuring equipment will be used, etc. will be studied.	
⑤ Elemental technology verification test using existing equipment, etc. (About 3 years: excluding permission and authorization) Applicability will be verified by means of elemental technology verification test using existing non-destructive measuring equipment, etc.	1-13, 1-14, 2-15, 3-1, 3-11, 3-14, 4-2, 4-3, 4-4, 4-7
(Step 3) Basic design and software development	
① Basic design of the equipment	4-8, 4-9
② Software development for estimating the amount of nuclear material	
③ Elemental technology verification test (ongoing)	
(Step 4) Comprehensive verification test using prototypes, simulated radiation source, etc. (Demonstration test using the hot laboratory, etc.)	
① Test manufacturing of measuring equipment	
② Demonstration test using spent fuel with a known composition or actual fuel debris ⇒ Improvement in software for estimating quantity of nuclear material ⇒ Improvement in placement of detector, error evaluation	

(Step 5) Fabrication of actual equipment ⇒ actual operation

2.(2)② Research and development plan (Contents, duration, conditions) (2/11)

[Development steps and R&D items]

[Target measurement technique]: 5. X-ray transmission measurement (High energy X-ray CT method)

(Step 1) Feasibility study of measurement (Analyzing the possibility) ⇐ This year’s research
① Setting the purpose and target (shape, density, etc.) of measurement
② Nuclear material → Evaluating the behavior of radiation incident upon the detector
③ Identification, etc. of technological issues contributing to the concept of measurement

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios	Response to the identified issues
① Study of target performance value required for sorting (Temporarily set for about 1 year ＋ updated after ② to ④) Target performance value of the measuring equipment (measurement time, equipment size, lower detectable limit, error, radiation resistance, etc.) will be set.	**5-1, 5-2, 5-3, 5-5**
② Development of the concept of the equipment by means of detector response analysis (about 2 years) Analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment and evaluating performance.	**5-1, 5-2, 5-3**
③ Study of method for evaluating nuclear fuel material, etc. based on the measured quantity (about 2 years) Evaluation method for estimating the amount of nuclear fuel material based on measured values will be developed (Including combination of measurement technologies).	**5-1, 5-3, 5-4**
④ Re-examination of sorting scenarios (Temporarily set for about 2 year ＋ updated after ① to ③) The applicable sorting/segregation scenarios, the location where the measuring equipment will be used, etc. will be studied.	
⑤ Elemental technology verification test using existing equipment, etc. (About 3 years: excluding permission and authorization) Applicability will be verified by means of elemental technology verification test using existing non-destructive measuring equipment, etc.	**5-1, 5-3**
(Step 3) Basic design and software development	
① Basic design of the equipment	**5-5, 5-7, 5-8, 5-9**
② Software development for estimating the amount of nuclear material	**5-4**
③ Elemental technology verification test (ongoing)	
(Step 4) Comprehensive verification test using prototypes, simulated radiation source, etc. (Demonstration test using the hot laboratory, etc.)	
① Test manufacturing of measuring equipment	**5-5, 5-6, 5-7, 5-8, 5-9, 5-10**
② Demonstration test using spent fuel with a known composition or actual fuel debris ⇒ Improvement in software for estimating quantity of nuclear material ⇒ Improvement in placement of detector, error evaluation	

(Step 5) Fabrication of actual equipment ⇒ actual operation

2.(2)② Research and development plan (Contents, duration, conditions) (3/11)

[Development steps and R&D items]

[Target measurement technique]: 6. Cosmic rays scattering measurement (Muon scattering method)

(Step 1) Feasibility study of measurement (Analyzing the possibility) ⇐ This year's research

① Setting the purpose and target (shape, density, etc.) of measurement
② Nuclear material → Evaluating the behavior of radiation incident upon the detector
③ Identification, etc. of technological issues contributing to the concept of measurement

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios	Response to the identified issues
① Study of target performance value required for sorting (Temporarily set for about 1 year ＋ updated after ② to ④) Target performance value of the measuring equipment (measurement time, equipment size, lower detectable limit, error, radiation resistance, etc.) will be set.	6-2
② Development of the concept of the equipment by means of detector response analysis (about 2 years) Analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment and evaluating performance.	6-2, 6-3, 6-5
③ Study of method for evaluating nuclear fuel material, etc. based on the measured quantity (about 2 years) Evaluation method for estimating the amount of nuclear fuel material based on measured values will be developed (Including combination of measurement technologies).	6-1, 6-6
④ Re-examination of sorting scenarios (Temporarily set for about 2 year ＋ updated after ① to ③) The applicable sorting/segregation scenarios, the location where the measuring equipment will be used, etc. will be studied.	6-3, 6-4
⑤ Elemental technology verification test using existing equipment, etc. (About 3 years: excluding permission and authorization) Applicability will be verified by means of elemental technology verification test using existing non-destructive measuring equipment, etc.	6-1, 6-2, 6-5
(Step 3) Basic design and software development	
① Basic design of the equipment	6-1, 6-3, 6-4, 6-5
② Software development for estimating the amount of nuclear material	6-5, 6-6
(Step 4) Comprehensive verification test using prototypes, simulated radiation source, etc. (Demonstration test using the hot laboratory, etc.)	
① Test manufacturing of measuring equipment	
② Demonstration test using spent fuel with a known composition or actual fuel debris ⇒ Improvement in software for estimating quantity of nuclear material ⇒ Improvement in placement of detector, error evaluation	

(Step 5) Fabrication of actual equipment ⇒ actual operation

2.(2)② Research and development plan (Contents, duration, conditions) (4/11)

[Approach towards the criteria for sorting]

- Sorting category and criteria (Tentative plan in accordance with the current approach)

Sorting category	Main purpose of sorting	Criteria (tentative)			
		(None of the conditions mentioned on the right are met)	*1 Concentration of U-235 in fuel debris: Lower than reactivity equivalent to 1.5wt%	*2 Quantity of nuclear material is equal to or lesser than 3.7kg/container	Quantity of nuclear material is equal to or lesser than the amount (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)	● **Enhancing retrieval throughput** ● **Reducing the scale of fuel debris storage**	–	○	–	–
c: Waste storage container (Control level)	**Ensuring criticality safety**	–	–	○	–
d: Waste storage container (Contamination level)	**Streamlining of storage and management of waste**	–	–	○	○

Will be updated at Step 2.

*1: According to results of past evaluations conducted under the Subsidy Project of Development of Technology for Containing, Transfer and Storage of Fuel Debris, if it is assumed that all fuel debris is 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. Hence, expecting some margin in this 1.7wt%, 1.5wt% will be set.

*2: Considering the placement and stacking while storing, the least critical mass (approx. 30Kg) will be set on the condition that it would be divided equally in 8 waste storage containers.

2.(2)② Research and development plan (Contents, duration, conditions) (5/11)

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

① Study of the values of performance objectives required for sorting (Temporarily set for about 1 year ＋ updated after ② to ④)

The values of performance objectives of the measuring equipment will be tentatively set so that the measurement concept for sorting and the sorting scenarios can be studied.

- The values of performance objectives of the measuring equipment will be set, depending on the measurement location (pretreatment building, storage facility, etc.) during the fuel debris retrieval process, and the target container, so that the measurement concept for sorting and the sorting scenarios can be studied.
- Following are examples of the performance objectives that will be set.
  - Measured quantity, evaluated quantity
  - Lower detectable limit, error, measurement time
  - Radiation resistance, equipment size, etc.
- These performance objectives (tentative) will be tentatively set as the preliminary proposal for about 1 year, and will be updated along with ④ after studying ② to ④ and incorporating the results.

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

② Development of the concept of the equipment by means of detector response analysis (for about 2 years)

Analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment and evaluating performance.

- A Monte Carlo simulation will be conducted for the stand-alone measurement technology studied in FY2021 based on the value of the performance objectives (tentative) in ① and the issues in the technologies identified in FY2021, and a tentative concept for the equipment will be proposed.
- The detector model here will take into consideration the placement of a reasonable detector, moderator, γ rays shielding material, etc., their radiation resistance, etc. as a system that assumes actual equipment.
- The performance of this equipment concept will be evaluated focusing on the fuel debris conditions based on the issues identified in FY2021 pertaining to each measurement technology, besides the common cases of typical fuel debris.
- For this performance evaluation, the amount directly measured using each method (for example, effective mass of Cm244 in the case of passive neutron method, etc.) will be used, rather than the evaluated value.

2.(2)② Research and development plan (Contents, duration, conditions) (7/11)

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

③ Study of the technique for evaluating the amount of nuclear fuel material, etc. based on the measured quantity (about 2 years)

The method for evaluating the amount to be evaluated (quantity of nuclear fuel material, etc.) based on the measured quantity will be studied.

- **The method for deriving the amount or properties to be evaluated from the measured quantity, in the case of the equipment concept studied in ② will be studied and a tentative plan will be created.**
- **The amount or properties to be evaluated are basically pertaining to the amount of U, but in order to discover a broad range of possibilities pertaining to each measurement technology (broad range of possibilities of the sorting scenarios), they will be considered as indicators, etc. related to the Pu quantity, fissile quantity, isotopic composition, moisture content, criticality risk, and the evaluated quantity that is believed to be applicable to sorting or nuclear fuel material control, including the relative values, will be studied.**
- **The method for derivation refers to setting dedicated algorithms or parameters for estimating the evaluation quantity, based on the property of the measured quantity to vary depending on the conditions of the objects to be measured, or on the correlation between measured quantity and evaluation quantity, and wherein multiple measurement methods are combined if required.**
- **In this study, test analysis and investigations will be conducted as required.**

2.(2)② Research and development plan (Contents, duration, conditions) (8/11)

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

④ Re-examination of sorting scenarios

(Temporarily set for about 2 years ＋ updated after ① to ③)

The applicable sorting/segregation scenarios will be studied, and prospective options will be proposed.

- During the process from retrieval to storage of fuel debris, possible sorting/segregation scenarios will be studied based on the results of ① to ③, and prospective options will be proposed.
- During this study, the practicality/ rationality of managing fuel debris and waste at the Fukushima Daiichi Nuclear Power Station as well as the feasibility of the proposed technology will be taken into consideration, and the location of measurement, measurement technology (multiple combinations are also possible), measured quantity, management method, etc. will be consolidated.
- A preliminary proposal will be tentatively set for about 2 years, and will be updated along with ① after studying ① to ③ and incorporating the study results.

2.(2)② Research and development plan (Contents, duration, conditions) (9/11)

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

⑤ Elemental technology verification test using existing equipment, etc.

(For about 3 years: excluding permission and authorization)

Applicability will be verified by means of elemental technology verification test using existing non-destructive measuring equipment, etc.

- **Assuming that existing non-destructive measurement equipment or newly installed small equipment will be used, in anticipation of measurement of actual nuclear fuel material in the future, by implementing simulation and preliminary tests (Refer to the next page for prospective existing equipment), verification tests for element technology will be conducted.**
- **The above-mentioned test plan will be created in FY2022 (including study of TMI-2 debris measurement). In addition, the permission and authorization required for implementing the elemental technology verification tests will be consolidated.**

2.(2)② Research and development plan (Contents, duration, conditions) (10/11)

[Target measurement technique]: 5. X-ray transmission measurement (High energy X-ray CT method)

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

① Study of target performance value required for sorting (Temporarily set for about 1 year ＋ updated after ② to ④)

Values of the performance objectives of the measuring equipment

- **Measurement time**
- **Equipment size**
- **Setting of lower detectable limit, error, radiation resistance, etc.**

② Development of the concept of the equipment by means of detector response analysis (about 2 years)

Analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment and evaluating performance.

- **The radioparency measurement method using different x-ray energies will be evaluated by means of analysis, and the applicability will be examined.**
- **The shielding, etc. for reducing gamma rays originating from fuel debris will be evaluated by means of analysis, and its need will be examined.**
- **The method of evaluating the amount of fuel debris, etc. mixed at a size that is lower than spatial resolution will be studied by means of analysis.**

③ Study of method for evaluating nuclear fuel material, etc. based on the measured quantity (about 2 years)

Evaluation technique for estimating the amount of nuclear fuel material based on measured values will be developed.

- **The stand-alone radioparency measurement method and its combination with other measurement methods, etc. will be studied by means of analysis.**
- **The algorithm for estimating and evaluating the amount of nuclear fuel material will be studied based on the results of studying ② and combinations of measurement methods, etc.**

④ Re-examination of sorting scenarios (Temporarily set for about 2 years ＋ updated after ① to ③)

The applicable sorting/segregation scenarios, the location where the measuring equipment will be used, etc. will be studied.

- **Considering the practicality/ rationality of managing fuel debris and waste at the Fukushima Daiichi Nuclear Power Station as well as the feasibility of the proposed technology, the location of measurement, measurement technology (multiple combinations are also possible), measured quantity, management method, etc. will be consolidated, and the sorting scenarios will be developed once again.**

⑤ Elemental technology verification test using existing equipment, etc. (About 3 years: excluding permission and authorization)

Applicability will be verified by means of elemental technology verification test using existing non-destructive measuring equipment, etc.

- **Tests will be conducted using simulated fuel debris (cold) test pieces, by means of existing radioparency measurement equipment that can irradiate different x-ray energies, and applicability to fuel debris will be verified.**

2.(2)② Research and development plan (Contents, duration, conditions) (11/11)

[Target measurement technique]: 6. Cosmic rays scattering measurement (Muon scattering method)

(Step 2) Development of the measurement concept and re-evaluation of the assumed scenarios

① Study of target performance value required for sorting (Temporarily set for about 1 year ＋ updated after ② to ④)

Values of the performance objectives of the measuring equipment

- **Measurement time**
- **Equipment size**
- **Setting of lower detectable limit, error, radiation resistance, etc.**

② Development of the concept of the equipment by means of detector response analysis (about 2 years)

Analytical simulation including the detector model will be performed with the purpose of developing the concept of the equipment and evaluating performance.

- **Creation of simulation model including the detector model**
  - **Evaluation of the correlation of the background radiation count rate resulting from detector placement, shielding, etc. and the muon count rate**
- **Study of required specifications of the detector corresponding to the measurement conditions**

③ Study of method for evaluating nuclear fuel material, etc. based on the measured quantity (about 2 years)

Evaluation method for estimating the amount of nuclear fuel material based on measured values will be developed.

- **Study of the method of evaluating the amount of U by combining muon scattering distribution and other measured values, etc.**
- **Imaging by analyzing the spatial distribution of muon scattering angles and development of a correction method depending on the shape of fuel debris**

④ Re-examination of sorting scenarios (Temporarily set for about 2 years ＋ updated after ① to ③)

Applicable sorting/segregation scenarios, the location where the measuring equipment will be used, etc. will be studied.

- **Study of combination with other techniques, division of work, etc.**
- **Study of optimization and positioning of this technique in the fuel debris sorting scenarios as a whole**

⑤ Elemental technology verification test using existing equipment, etc. (About 3 years: excluding permission and authorization)

Applicability will be verified by means of elemental technology verification test using existing non-destructive measuring equipment, etc.

- **Sample measurement test using existing muon measurement facilities**
- **Development of elemental technologies such as circuit, etc. and combination tests with existing facilities**

2. Implementation Details

(2) Study of future research and development plans aiming for application of sorting technology to actual equipment

① Identification of technical issues for the purpose of practical application of the sorting technology

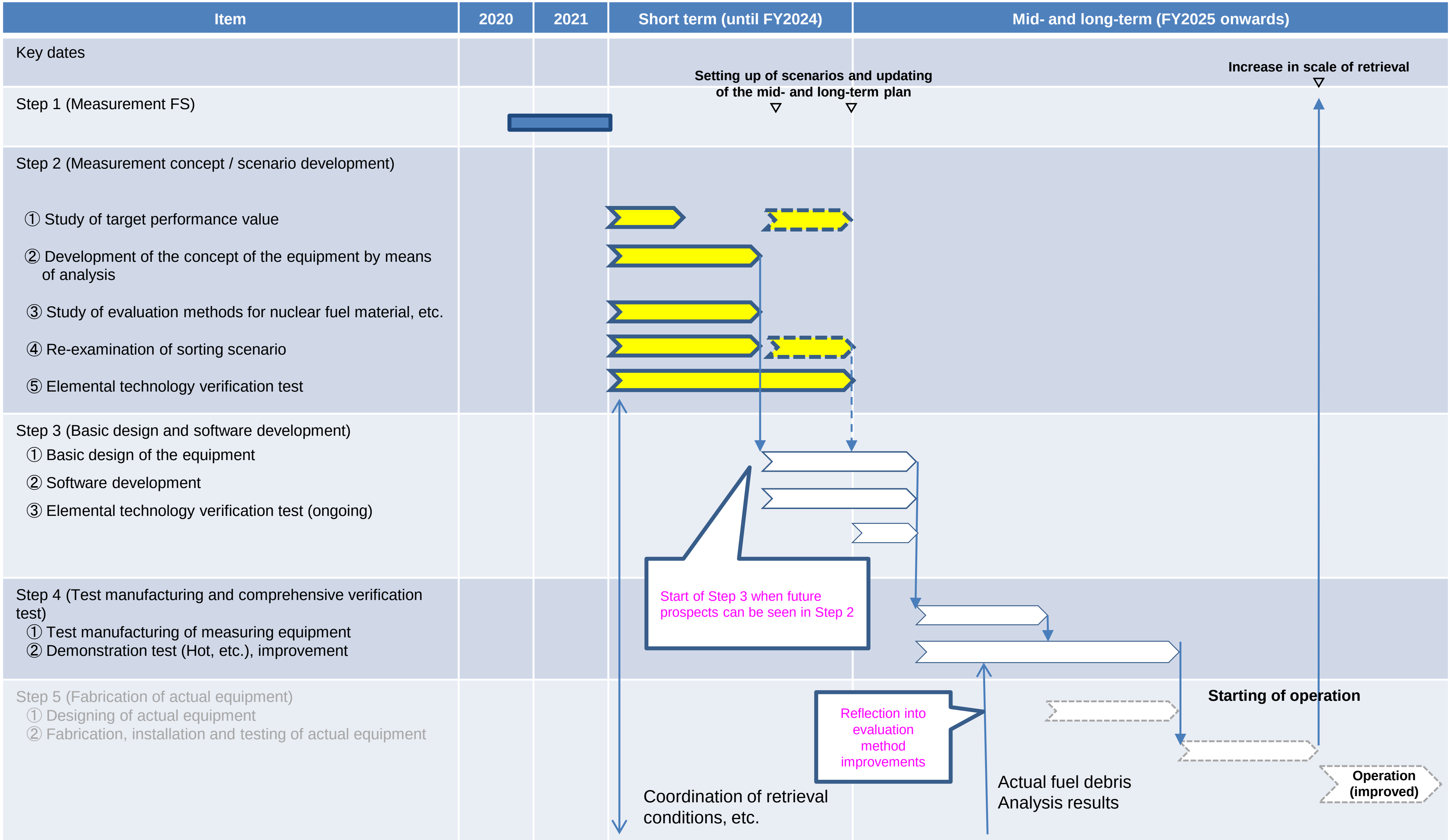
② Study of research and development plan (Contents, duration, conditions)

③ Goals of the main processes

2.(2)③ Goals of the main processes (1/3)

[Proposed development schedule]

[Target measurement technique]: 1. to 4. Passive/active neutrons and passive gamma rays



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 equipment 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 equipment

② Software development

③ Elemental technology verification test (ongoing)

Step 4 (Test manufacturing and comprehensive verification test)

① Test manufacturing of measuring equipment

② Demonstration test (Hot, etc.), improvement

Step 5 (Fabrication of actual equipment)

① Designing of actual equipment

② Fabrication, installation and testing of actual equipment

Start of Step 3 when future prospects can be seen in Step 2

Reflection into evaluation method improvements

Starting of operation

Operation (improved)

Coordination of retrieval conditions, etc.

Actual fuel debris Analysis results

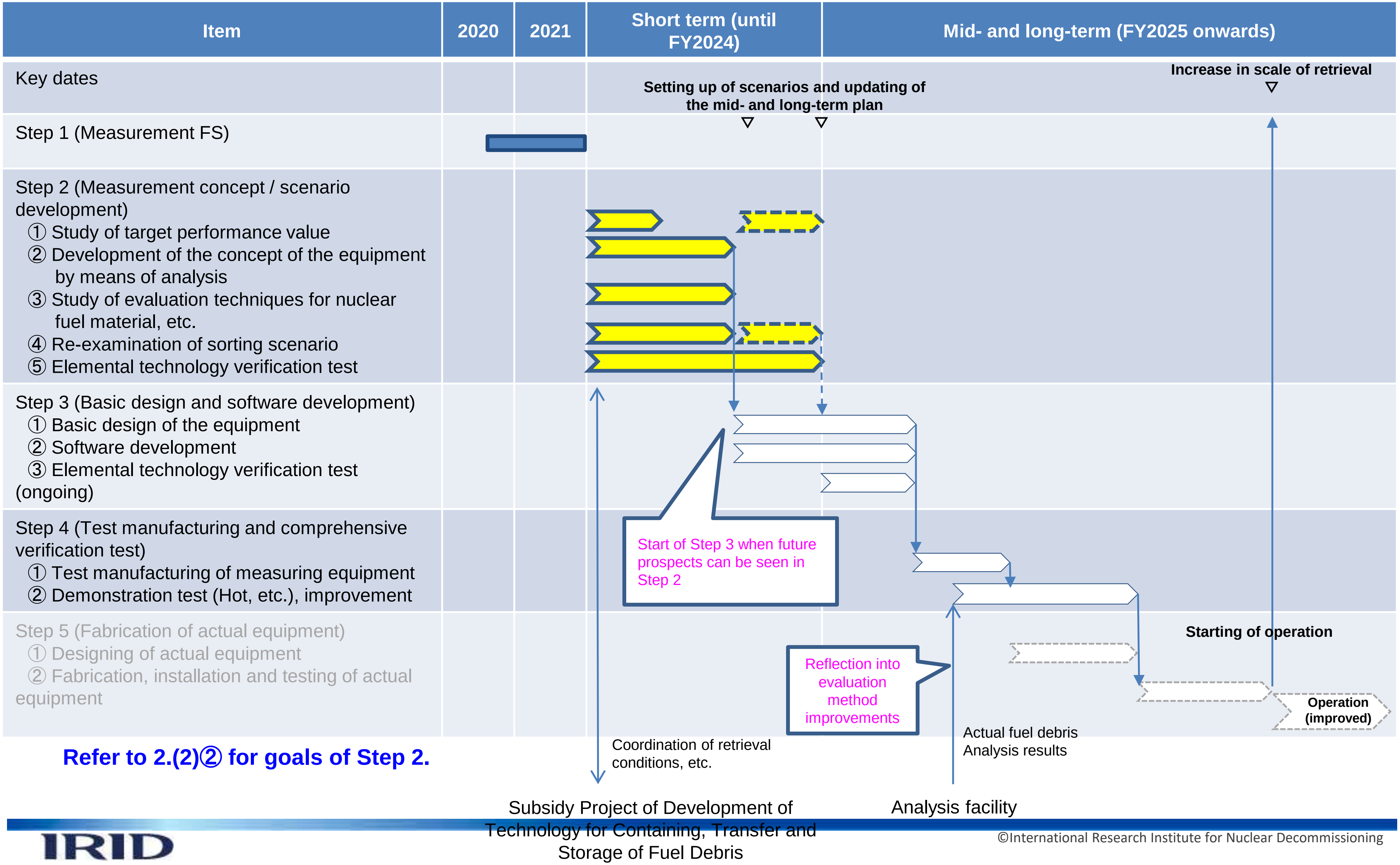
Analysis facility

Refer to 2.(2)② for goals of Step 2.

2.(2)③ Goals of the main processes (2/3)

[Proposed development schedule]

[Target measurement technique]: 5. X-ray transmission measurement (High energy X-ray CT method)



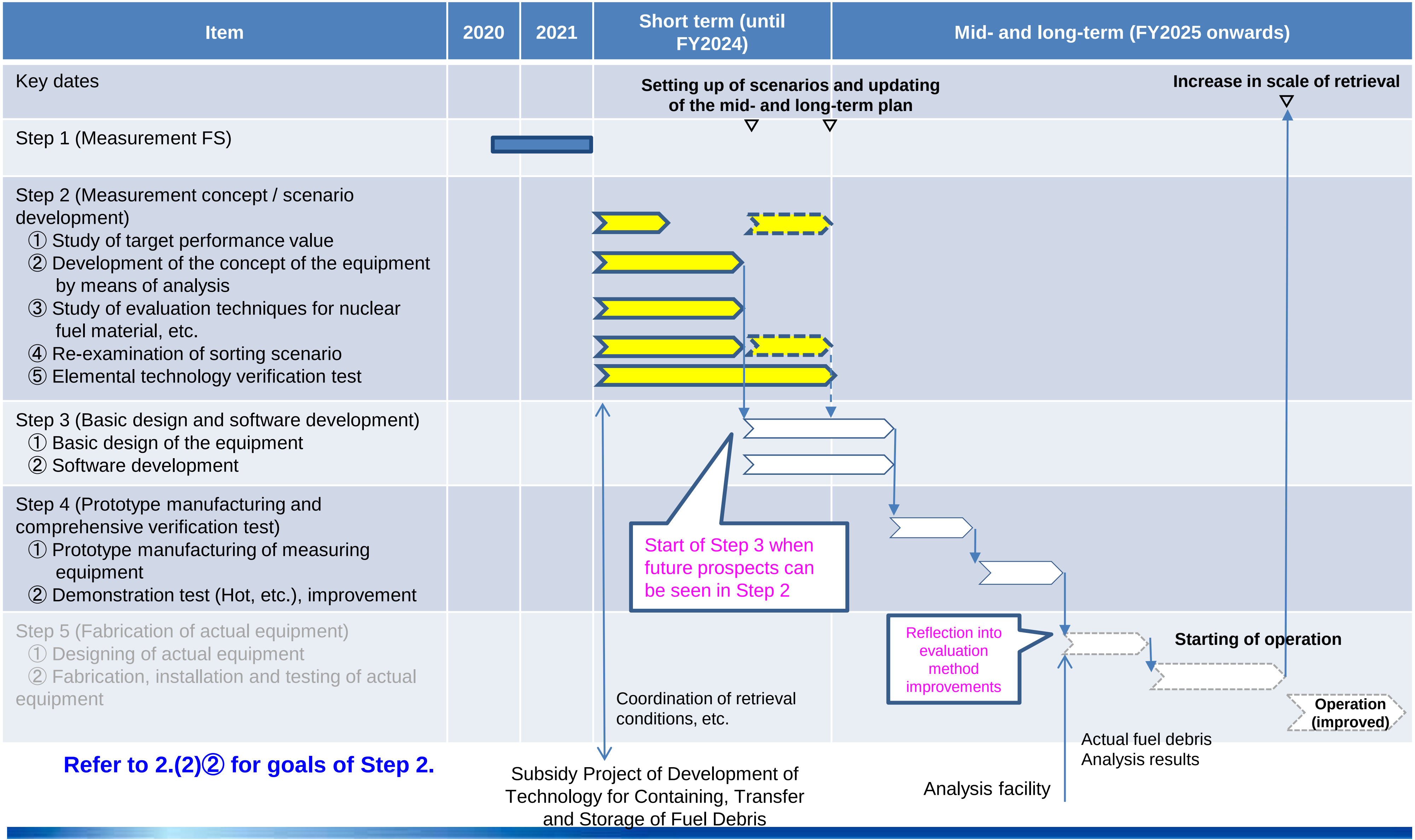
Item	2020	2021	Short term (until FY2024)	Mid- and long-term (FY2025 onwards)
Key dates				
Step 1 (Measurement FS)				
Step 2 (Measurement concept / scenario development) ① Study of target performance value ② Development of the concept of the equipment by means of analysis ③ Study of evaluation techniques 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 equipment ② Software development ③ Elemental technology verification test (ongoing)				
Step 4 (Test manufacturing and comprehensive verification test) ① Test manufacturing of measuring equipment ② Demonstration test (Hot, etc.), improvement				
Step 5 (Fabrication of actual equipment) ① Designing of actual equipment ② Fabrication, installation and testing of actual equipment				

Refer to 2.(2)② for goals of Step 2.

2.(2)③ Goals of the main processes (3/3)

[Proposed development schedule]

[Target measurement technique]: 6. Cosmic rays scattering measurement (Muon scattering method)



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 equipment by means of analysis ③ Study of evaluation techniques 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 equipment ② Software development				
Step 4 (Prototype manufacturing and comprehensive verification test) ① Prototype manufacturing of measuring equipment ② Demonstration test (Hot, etc.), improvement				
Step 5 (Fabrication of actual equipment) ① Designing of actual equipment ② Fabrication, installation and testing of actual equipment				Starting of operation Operation (improved)

Start of Step 3 when future prospects can be seen in Step 2

Reflection into evaluation method improvements

Coordination of retrieval conditions, etc.

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

Actual fuel debris Analysis results

Analysis facility

Refer to 2.(2)② for goals of Step 2.

3. Summary

Level of achievement of this project

Issues were identified for setting the required specifications contributing to the future research and development plan by conducting analytical simulation for the regions where existing technology cannot be applied.

1) Analytical evaluation of parameters influencing measurement errors of prospective measurement technologies	
① Analytical simulation	･The intensity, etc. of the impact of factors on measurement errors was evaluated for each measurement technology based on the correlation between the range of fluctuation of the factors and the changes in the measured flux, etc. in the direction of the measuring surface and information on the extent of impact was consolidated. (TRL: Level 2)
② Study of the need for detailed analysis and consolidation of technical issues[*1]	The need for further detailed analysis and the issues in reducing measurement errors were identified based on the results of analysis.
2) Study of future research and development plans aiming for application to actual equipment	
① Identification of technical issues for the purpose of practical application of the sorting technology[*1]	･The challenges in studying the measurement technologies required for sorting were identified based on the technical issues identified through analytical evaluation of parameters having an impact on the measurement error and the investigation of measurement technologies for sorting which was conducted in FY2019.
② Goals of the main processes involved in developing the sorting technology[*1]	･In addition to studying the contents of research and development, the development procedures, and development period for resolving the technical issues identified in the previous section, the approach towards the pre-conditions and judgment criteria required while examining the research and development plan were consolidated. ･The technologies to be adopted were narrowed down, and based on that the goals of the main processes involved in developing the sorting technology were organized.

*1：As identification and consolidation of issues in developing technologies, and organization of the goals, etc. are different than development items, the Technology Readiness Level (TRL) has not been set.