This is a report on the achievements of the Decommissioning, Contaminated Water and Treated Water Management Project (Development of Analysis and Estimation Technology for Ascertaining the Attributes of Fuel Debris) subsidized by METI Agency for Natural Resources and Energy that commenced in FY2025.

Analysis results for the fuel debris samples obtained during the first and second trial retrievals

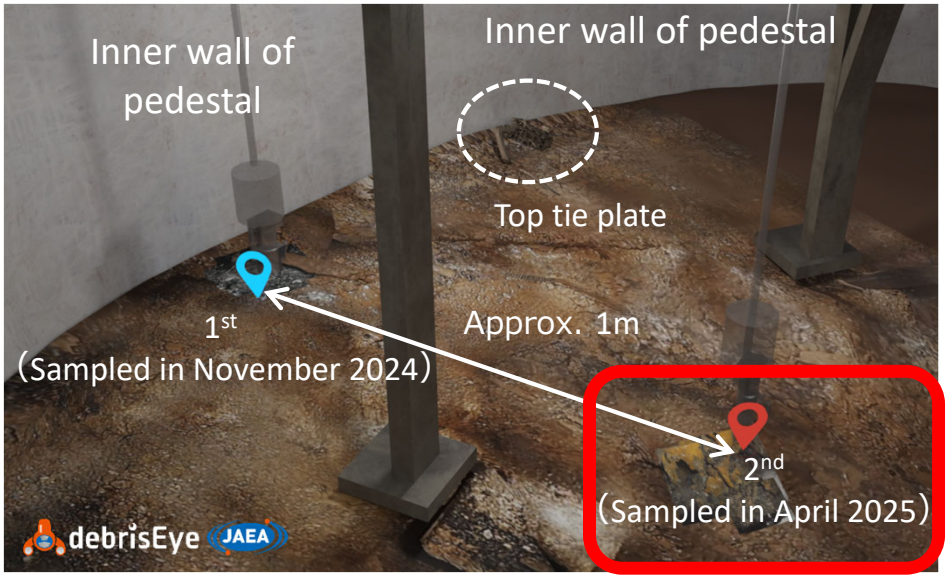
August 27, 2026

Japan Atomic Energy Agency

Tokyo Electric Power Company Holdings, Inc.

Achievements to date

- To date, Tokyo Electric Power Company Holdings, Inc. has taken two fuel debris samples from the bottom of the Unit 2 pedestal.
- The second fuel debris sample obtained through trial retrieval (hereinafter referred to on occasion as, “2nd fuel debris” (the same goes for the 1st fuel debris sample)) was delivered to JAEA Ooarai Nuclear Engineering Research & Irradiated Fuels Monitoring Facility (FMF) on April 25, 2025. [1] Thereafter, the sample was subject to non-destructive analysis, batching and sample transport through August 2025. The results of this process have already been reported. [2]
- This report focuses mainly on the results of detailed analysis performed thereafter.



Schematic of the sampling locations of fuel debris during a Unit 2 trial retrieval (Bottom of the pedestal)

✓ Completion of originally planned analyses [3]

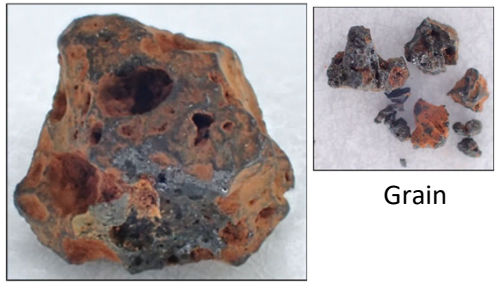
✓ Additional analyses implemented
⇒ **Refer to the reference materials in this report**

(Approx. 9mm×Approx. 7mm)

1st Fuel debris

✓ Non-destructive analysis and batching completed [2]

✓ **Completion of originally planned analyses**
⇒ **Reported on in this report**



Grain

Clump

(Approx. 5mm×Approx. 4mm)

2nd Fuel debris

External appearance of fuel debris samples and analysis progress status (after delivery to the JAEA FMF)

[1] JAEA, TEPCO HD, Fuel debris Sample (2nd) Non-destructive analysis results (Most recent data), Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (138th), May 29, 2025, document 3-3
[2] JAEA, TEPCO HD, Fuel debris Sample (2nd) Non-destructive analysis results (Most recent data), and batching results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (141st), August 28, 2025, document 3-3
[3] JAEA, TEPCO HD, Fuel debris Sample (1st) analysis results (Most recent data), Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (144th), November 27, 2025, document 3-3

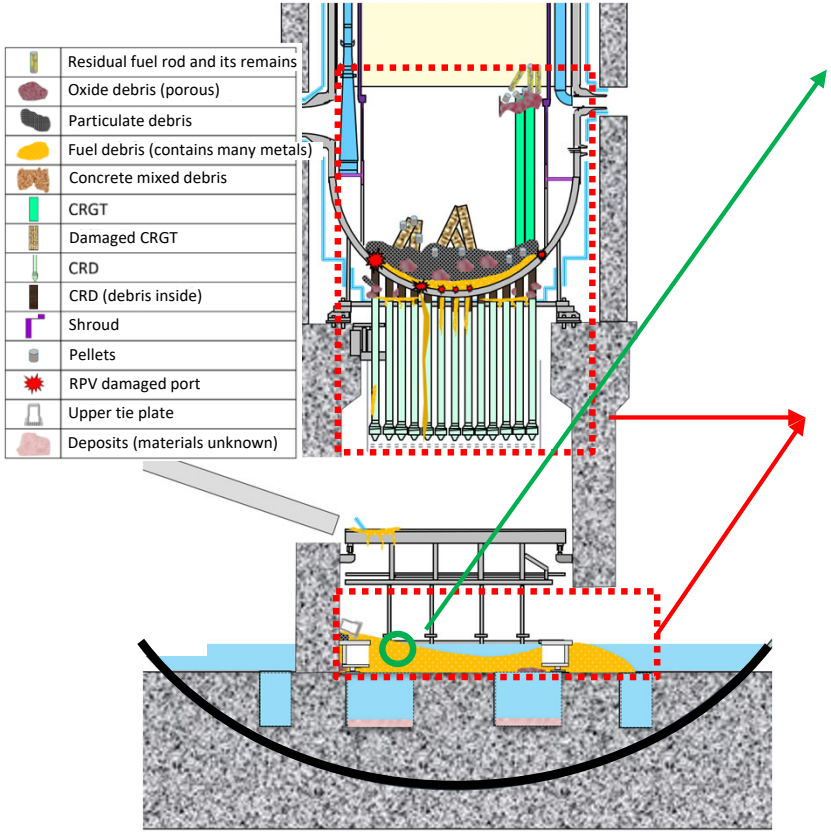
Analysis purpose of the fuel debris sample

- By analyzing the obtained sample, grasp the condition of the sampled area to estimate the formation process of the fuel debris.

⇒ More precise estimation of the condition inside the core will become the basis for review of full-scale fuel debris retrieval to safely retrieve fuel debris and realize thoroughly managed stable storage.

<Example of incorporating "estimation of the condition inside the core" into "review of fuel debris retrieval methods">

- Estimate hardness of fuel debris → select retrieval methods and tools
- Possibility of criticality of fuel debris → review safety measures and storage methods



Estimated drawing of the condition inside the core [1]

1. Grasping the condition of the sampled area

- Acquisition of **information tailored to decommissioning needs**
  - ✓ Grasp the type and concentration of major components (nuclide/element) in the sample and review the origin of each component
  - ✓ Grasp the content and distribution of fuel components in the sample

2. Estimation of formation process of fuel debris

- Estimation of fuel debris properties through **review of in-core environment during the accident**
  - ✓ Estimate the formation conditions of the sample based on microstructure, composition of constituent phases and crystal structure of phases including U in the sample.
  - ✓ Evaluate the surrounding of the sampled area based on the comparison of existing accident scenarios with the internal investigation results (evaluate based on the results of multiple future sample analyses)

[1] JAEA, FY2024 Report of the FY2023 Subsidized Project of Decommissioning, Contaminated Water and Treated Water Management (Development of Analysis and Estimation Technology for Grasping Fuel Debris Properties (3. Development of Technology for Estimating RPV damage status and fuel debris migration behavior inside the PCV)).

Analysis items and evaluation details of the fuel debris sample

1. Analysis for grasping the condition of the sampled area (Grasping the condition of fuel debris samples)

Analysis items	Analysis methods	Evaluation details	Examples of major applications for decommissioning
Basic information 【Already reported [1]】 ・External appearance, weight, dose rate, density distribution	・Exterior, weight, dose rate measurement ・Imaging plate (IP) ・X-ray CT	Organization of basic information	Basic information to review retrieval (existence and mount of pores, etc.)
Element content (1) (elemental composition)	・ICP-MS ・ICP-AES	Content of fuel components Origin of major components	Basic information to review safety measures at retrieval, such as criticality evaluation, and storage methods
Isotope ratio (2)	・TIMS ・SIMS	U isotope ratio	
Radioactive concentration (3)	・γ-ray spectrometry ・α-ray spectrometry ・β-ray spectrometry ・Liquid scintillation counter, etc.	Accompanied condition of U with focal nuclides Amount of radioactivity of nuclides targeted for analysis	Information to review technology development for non-destructive measurement at fuel debris retrieval Data required to deliberate treatment and disposal
Element and compound distribution (4)	・SEM-EDX ・SEM-WDX ・TEM-EDX ・XRD	Evaluation of distribution of elements and compounds (including pores)	Basic information to review retrieval methods and tools (estimation of hardness, toughness, etc.)

2. Analysis for estimation of formation process of fuel debris

Analysis items	Analysis methods	Evaluation details	Examples of major applications for decommissioning
Crystal structure and composition of phases including U (5)	・SEM-EDX ・SEM-WDX ・TEM-EDX ・Raman spectroscopy ・XRD ・μ-XRF/XRD/XAFS	Estimation of temperature and atmosphere when U particles, etc. are formed Oxidation state of U, etc.	Precise estimated drawing of the condition inside the core to review retrieval methods and internal investigation

[1] JAEA, TEPCO HD, Fuel debris Sample (2nd) Non-destructive analysis results (Most recent data), and batching results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (141st), August 28, 2025, document 3-3

Overall flow of the analysis of the fuel debris sample

- Detailed analysis of the 2nd fuel debris sample was carried out by four agencies in light of batching status and the amount required [for analysis].
- Additional analysis performed by the NDC was carried out using the 1st fuel debris sample.

【Fukushima Daiichi Nuclear Power Station Unit 2】

↓ Fuel debris transport

【JAEA Oarai Nuclear Engineering Institute】

Oarai Nuclear Engineering Institute (JAEA)
NSI: Nuclear Science Research Institute (JAEA)
NDC: MHI Nuclear Research & Development Co., Ltd.
NFD: Nippon Nuclear Fuel Development Co., Ltd.

- In order to assess the primary types and content ratios of crystal phases in the fuel debris, the NDC additionally analyzed the crystalline structure using XRD.
- A radioactivity analysis was also additionally performed by the NDC in order to add nuclide analysis targets

Additional analysis was conducted on the first sample.

Non-destructive analysis: X-ray CT; External appearance, weight, dose rate, IP; γ-ray spectrometry; SEM-WDX

	【JAEA Harima】 (SPring-8)	【JAEA NSI】	【NDC】	【NFD】
Solid analysis[1] (mechanical analysis)	μ-XAFS μ-XRF μ-XRD	SEM-WDX TEM-EDX SIMS	**XRD**	SEM-EDX TEM-EDX Raman spectroscopy
Liquid analysis[1] (chemical analysis)		ICP-MS Radioactivity analysis	ICP-AES TIMS Radioactivity analysis	ICP-MS ICP-AES Radioactivity analysis
Major analysis results	Micro crystal structure, Valence of U, etc.	Fuel component element, U isotope ratio, Element and compound distribution, Radioactive concentration	Major elemental composition, U isotope ratio, Radioactive concentration	Element composition U isotope ratio **Radiation concentration** **Crystal structure**	U Crystalline structure, Composition, Element distribution

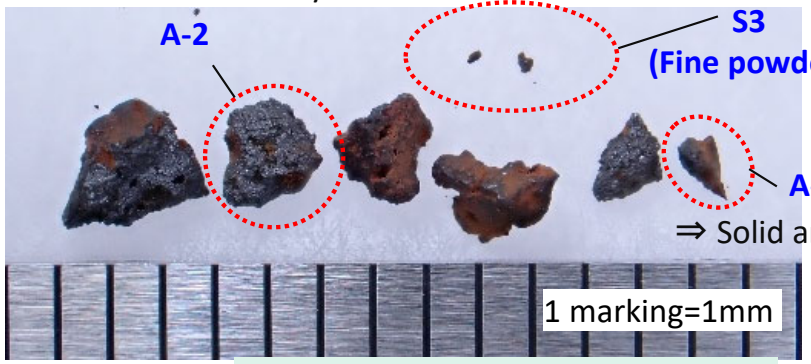
Fuel debris sample batching

- As with the 1st sample, clump samples were pulverized (struck with a stainless steel rod weighing approximately 250 grams) to separate the clump into chunks and powder.
- Based on the size of the sample and the amount required for analysis, four sample batches were created for four agencies.

Clump
(Prior to pulverization)

Pulverized

⇒ Solution analysis

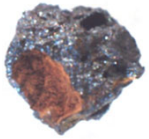


⇒ Solid analysis

Chunk + Powder ：Sample A

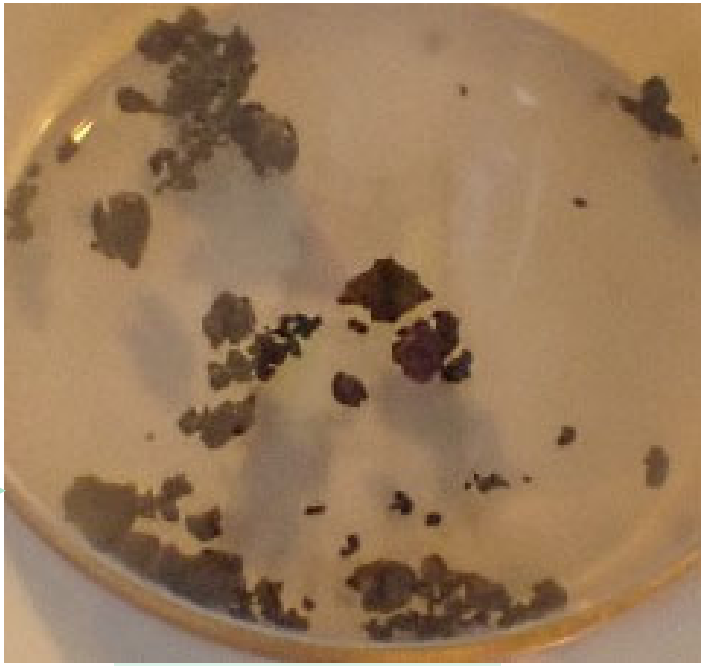
⇒ Solution analysis/Solid analysis at **JAEA Ooarai Nuclear Engineering Research**

Solid analysis at **SPring-8** （Fine powder ）



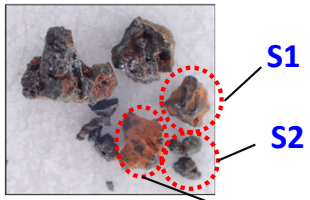
Chunk：Sample C

⇒ Solid analysis at **NFD**



Powder ：Sample B

⇒ Solution analysis at **JAEA Ooarai Nuclear Engineering Research**



Grains
(Grain-like fragments that accompanied the sample when it was received)

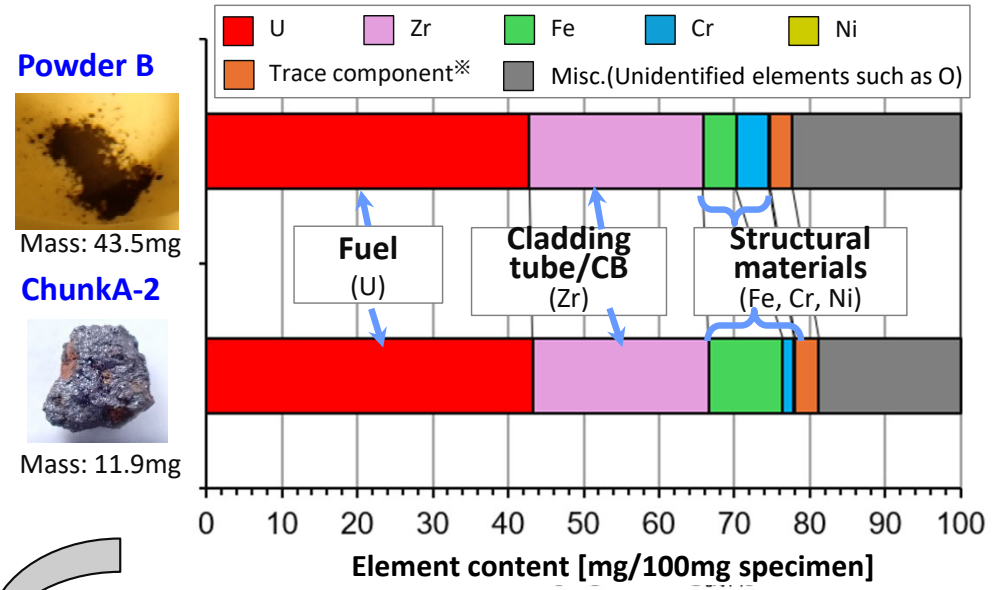
Fragment：Sample S1, S2, S4

⇒ Solid analysis at **SPring-8**

2nd Fuel debris pulverization and batching

※ The photos have been adjusted so that the samples match the same size scale

(1) Element content



※ Trace components of Pu, Nd, Gd, B, Si, Ca, Mg, S, Ti, Mn, Co, Cu, Zn, Mo, Ru, Rh, Pd, Ag, Sn detected (Each was less than 1% of the sample mass)

Figure 1 Primary elements of the 2nd Fuel debris sample

- As with the first sample, ratio of U to mass in the 2nd Fuel debris was the highest. (Figure 1)
- The ratios of U and Zr are higher than the 1st Fuel debris, but the ratios of structural materials, and Ni in particular, are lower. (Figure 2)
- In both the 1st and 2nd Fuel debris samples, the atomic ratio of Zr/U is close to the ratio of Zr/U that takes into consideration core cladding tubes and CB, etc. (Figure 2)

Converted to molar ratios of major elements

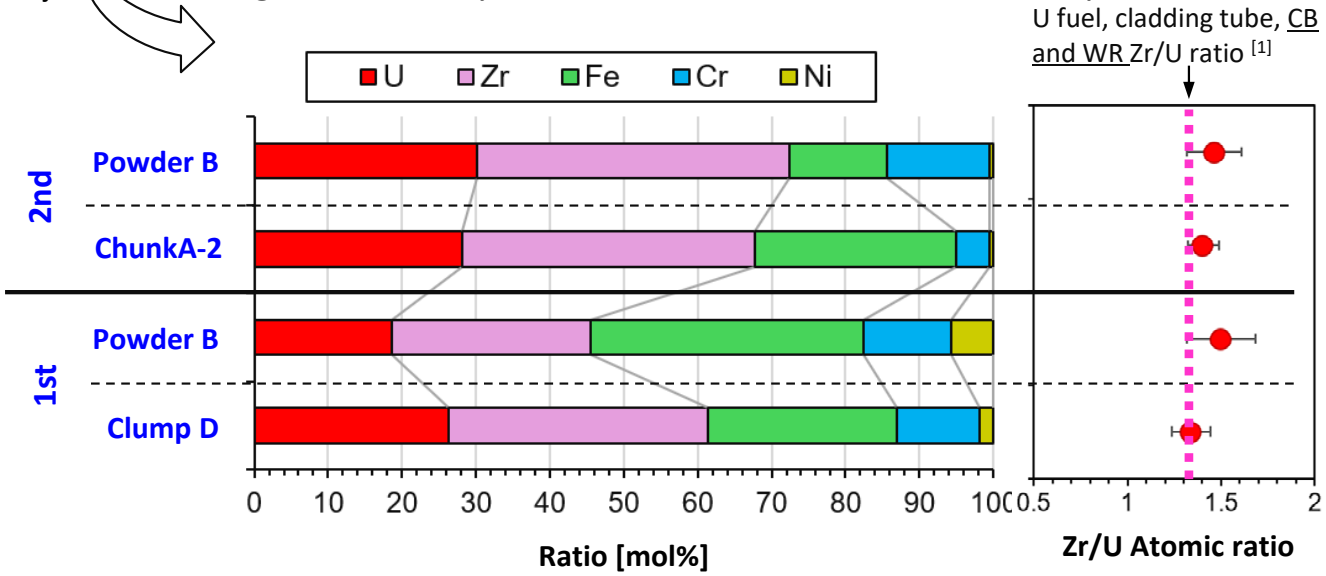


Figure 2 Comparison with 1st Fuel debris (Primary element ratio)

- ➢ It is assumed that both the 1st and 2nd Fuel debris samples comprise not just fuel, but also material from the cladding tubes and channel boxes, etc.
- ⇒ Can be used as reference data for U concentration range.

[1] Sato et al., Nucl.Eng.Des., 404, 112205. Calculated based on Table1 (CB: Channel box, WR: Water load)

(2) U isotope ratio

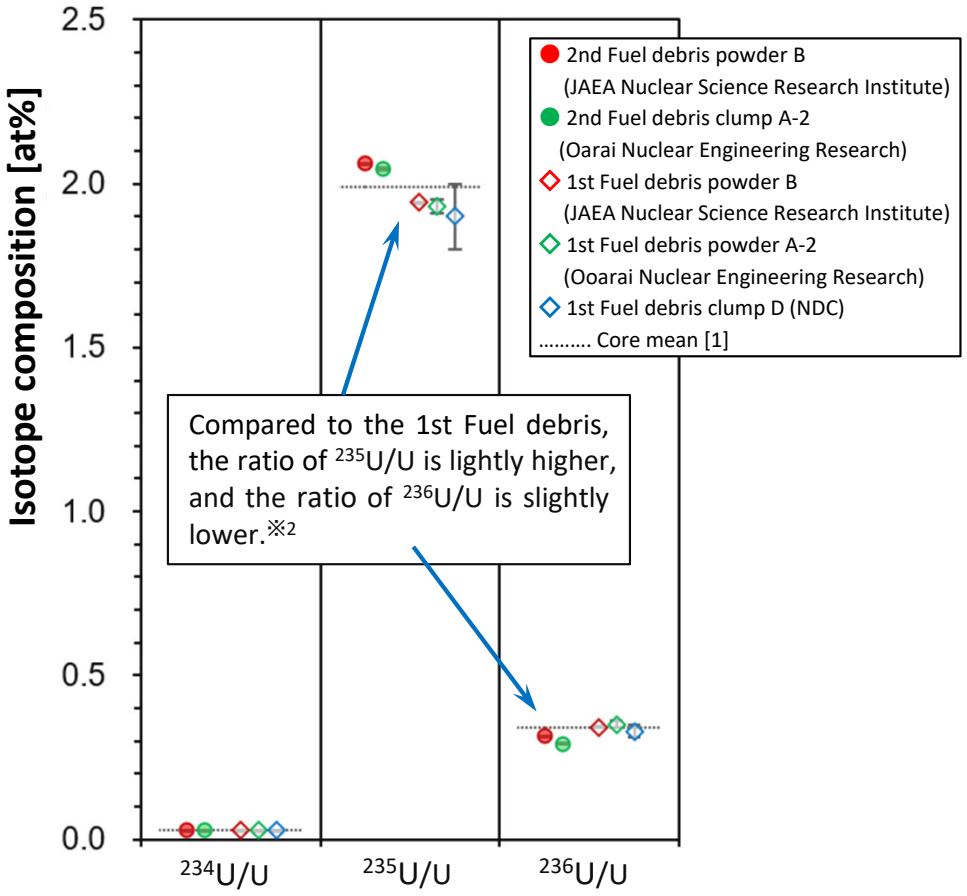


Figure 2nd Fuel debris U isotope composition and comparison with the 1st fuel debris sample

■ The ^{235}U/U ratio of the 2nd Fuel debris is 2.02–2.04wt% close to the core mean [1] of Unit 2 even though there is a slight difference compared to the 1st Fuel debris sample.

✓ The ^{235}U/U ratio in Unit 2 prior to the accident varies※1, but in both the 1st and 2nd samples, [the ratio] is close to the core mean.

➢ This suggests mixture over a fairly wide area and not just in the limited area of the core.

⇒ ^{235}U/U ratio trends of the fuel debris will be considered while deepening our understanding of how the accident progressed by looking at how the fuel debris was formed, and also while analyzing more of fuel debris samples taken from a wider area in the future.

※1 The ratio of ^{235}U/U (uranium concentration) in the core prior to the accident was between less than 1% to approx. 4%.

※2 As fuel is burned, ^{235}U is consumed, and ^{236}U is formed as it captured neutrons, so there is no contradiction.

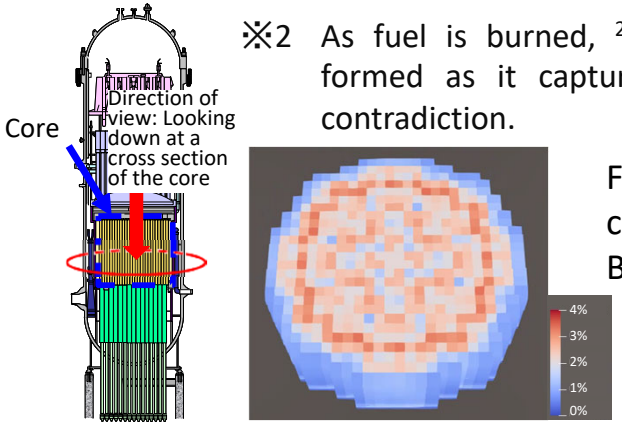


Figure Example of the uranium concentration distribution in a BWR reactor core [2]
(The redder the color the higher the concentration)

[1] Okumura et. al., Atomic Energy Society of Japan 2021 Spring Conference, 3B01.
[2] JAEA, TEPCO HD, Fuel debris Sample (1st) analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025, Document 3-3

(3) Radioactivity concentration

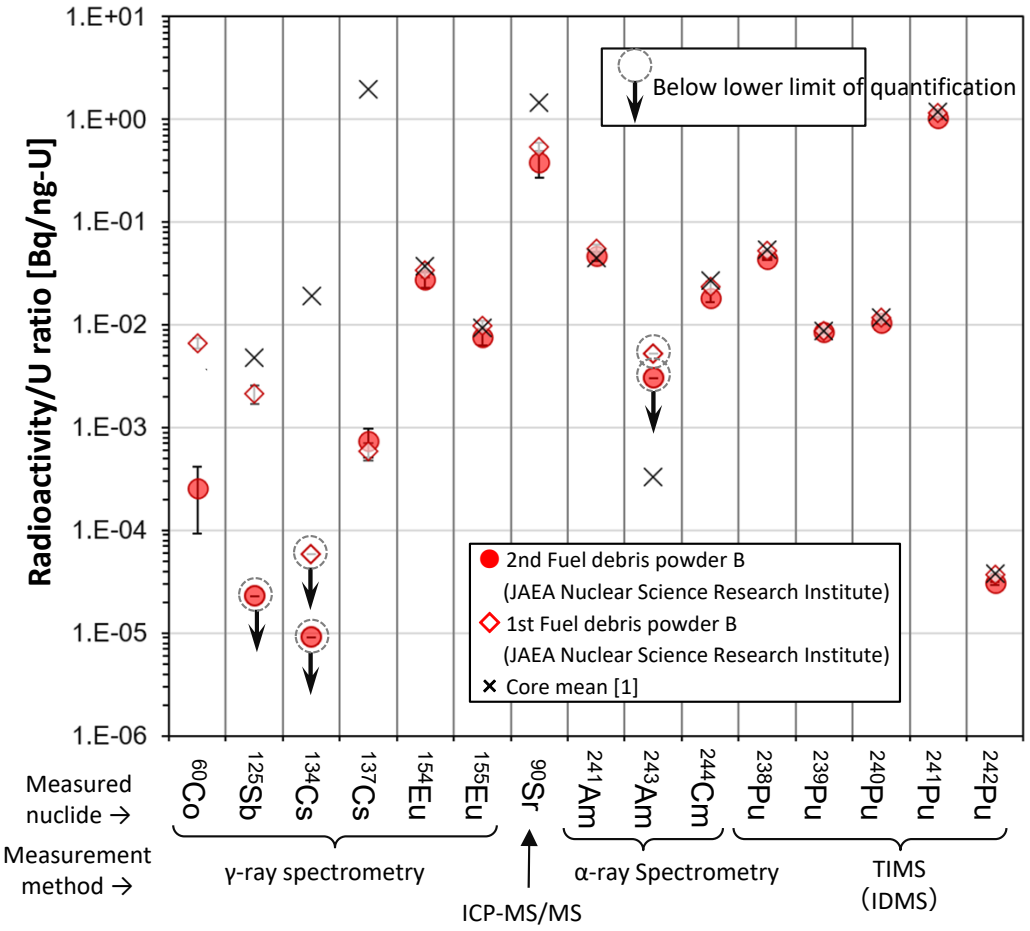


Figure Ratio of U mass to radioactivity for each nuclide in the 2nd Fuel debris sample and comparison with the 1st sample

Note: Radioactivity measurements were revised on June 30, 2026
Pu isotope radioactivity Was assessed using isotope composition obtained from TIMS (Thermal ionization mass spectrometry) and the Pu element Atomic weight measured with IDMS (isotope dilution mass spectrometry)

[1] Okumura et. al., Atomic Energy Society of Japan 2021 Spring Conference, 3B01.

■ The breakdown of radioactivity in the second fuel debris sample shows the same trends as the first sample with the exception that ^{60}Co and ^{125}Sb are scarce. (Left figure)

- ✓ The contribution from ^{90}Sr, α nuclides (^{241}Am, ^{244}Cm and Pu isotopes) and ^{154}Eu is large
- ✓ The contribution from ^{134}Cs and ^{137}Cs is small and small when compared to the core mean

➢ In both the 1st and 2nd samples, it is possible that cesium volatilized during the accident due to the high temperatures thereby forming a sample with low γ dose rates

■ The ratio between Eu, Am, Cm and Pu isotopes and U is close to the core mean in both the first and second samples.

➢ Association was confirmed between ^{154}Eu and ^{244}Cm,※ which are focused on as indicator nuclides for detecting fuel debris, and U between the locations where the 1st and 2nd samples were taken.

⇒ Data on the association with U will be provided to the non destructive measurement technology development project that is underway.

※ Known to usually associate with U in spent fuel

(4) Element and compound distribution

Region classification by cross-sectional observation

Chunk C

Through an optical microscope the metal phase appears white (looks bright)

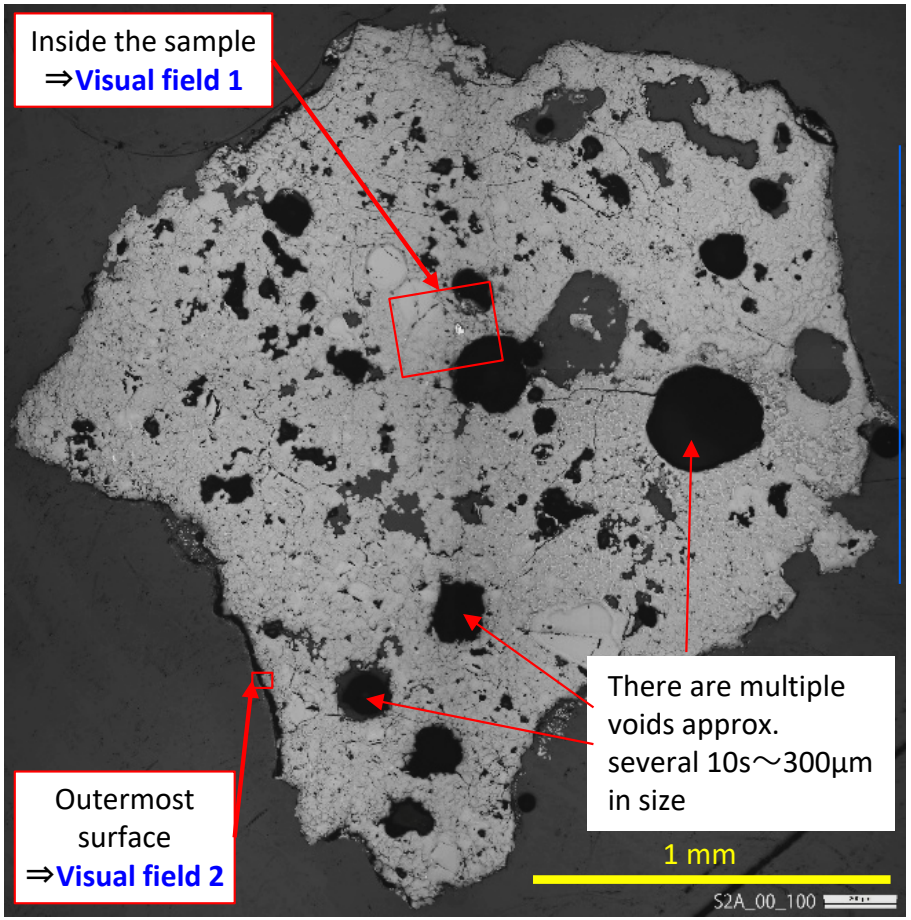
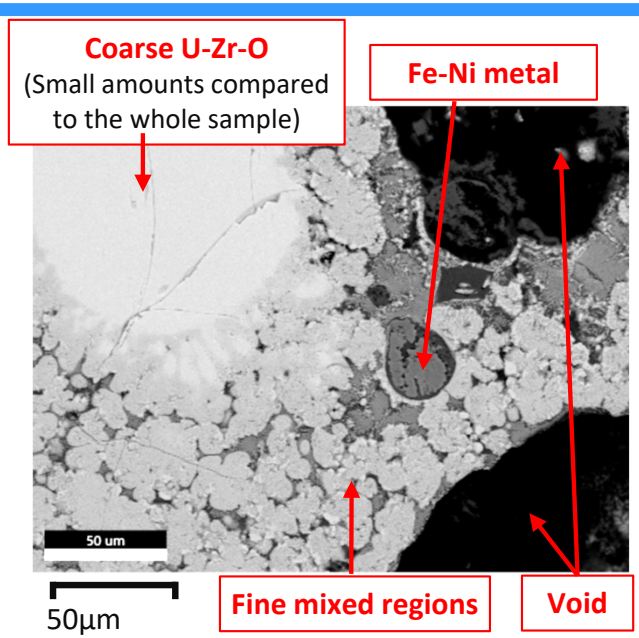
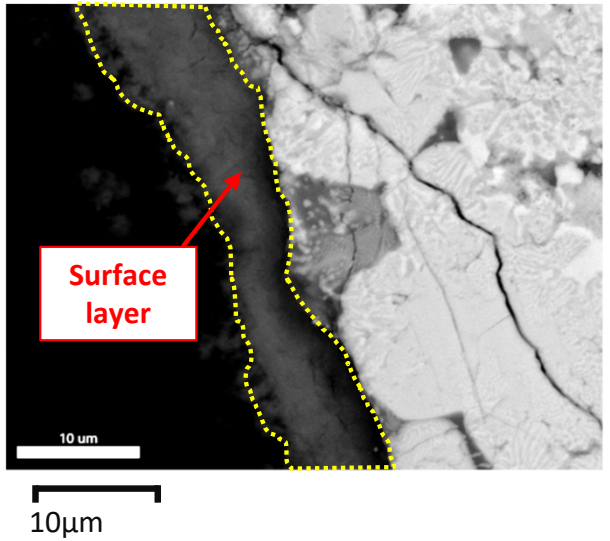


Figure 1 Optical micrograph of a cross section of the 2nd Fuel debris



Visual field 1：Inside the sample



Visual field 2：Sample Outermost surface

Figure 2 SEM Observation images of a cross section of the 2nd Fuel debris

- The 2nd Fuel debris sample was classified as having five major regions for the most part: a **Fine mixed region (Zr-U-Fe-Cr-O composite phase)**, a **Coarse U-Zr-O region**, a **Fe-Ni metal region**, **Voids**, and a **Surface layer (Ni-Fe-O). (Figures 1 and 2)**
- Compared to the first sample, there are very few Fe-Ni metal phases and the fine mixed region makes up the majority of the sample.
- There are voids distributed throughout the entire fine mixed region.

Reference Area ratio of each region (Image analysis of Figure 1) Units: area %

Fine mixed regions	Coarse U-Zr-O	Fe-Ni metal	Void
80	2	< 0.1	18

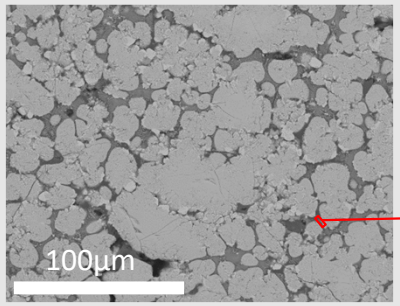
➢ Compared to the first sample the second sample was easier to pulverize

⇒ Basic data needed to deliberate retrieval methods and tools

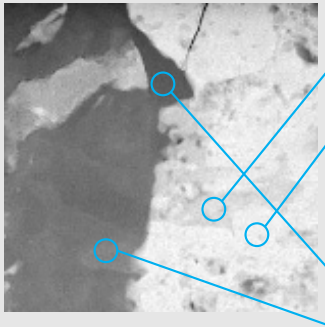
(5) Crystalline structure and composition of phases containing U (1/2)

For regions showing unique fine structures or elemental distributions, SEM-EDX and TEM-EDX analyses were used to identify oxide phases, metal phase composition, and crystalline structure, in order to form hypothesis about the process through which these regions were formed.

SEM image



Fine mixed region



TEM observation results

Tetragonal crystal $(Zr_{0.6}U_{0.4})O_2$

Cubic crystal $(U_{0.7}Zr_{0.3})O_2$

⇒ Mixed Zr-U-O phase that forms an island-like region approx. several 10s - Approx. 100μm in size

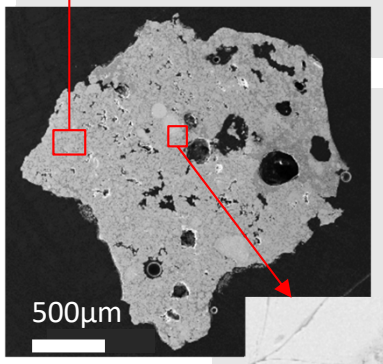
$FeCr_2O_4$

Fe_3O_4

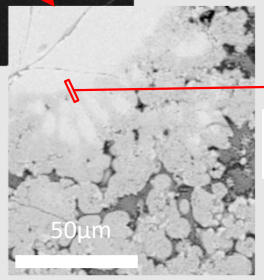
⇒ Fe/Cr oxides are mixed in almost like they filled the voids between Zr-U-O system

Fine mixed region: Occupies the majority of the cross section

- The fine structure observed shows characteristics consistent with the melting and solidification of Zr-U-Fe-Cr-O systems.
  - It is hypothesized that during the accident cladding tubes and CB, etc. and structural materials oxidized while they melted and mixed with the fuel after which they cooled and solidified

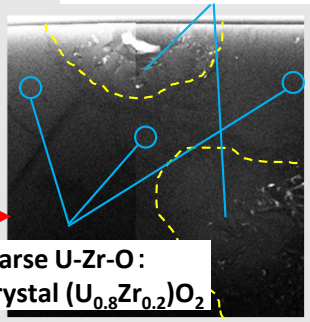


Chunk C
Complete SEM image

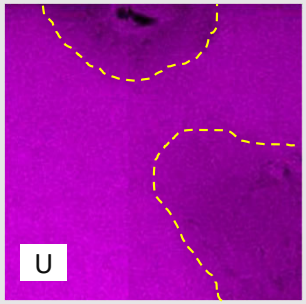


Enlargement of area near the Coarse U-Zr-O

Mixed phase with a slightly high concentration of Zr: $U_{0.6}Zr_{0.4}O_2$ + Cr-Fe-O



Coarse U-Zr-O : cubic crystal $(U_{0.8}Zr_{0.2})O_2$



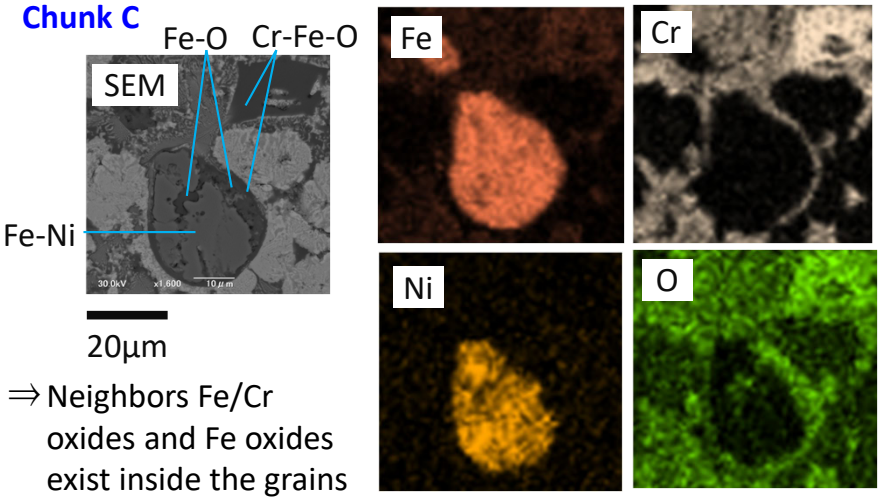
⇒ Since the crystals of the large cubic crystal $(U,Zr)O_2$ are touching the boundaries of phases around it with complicated shapes, it is assumed that there was interaction with the surrounding liquid phases, such as the intrusion of Zr, etc. from the surrounding area and crystal growth inside the liquid phase.

TEM observation results

Coarse U-Zr-O: Only a small amount exists in the cross section

- This is a large cubic crystal $(U,Zr)O_2$ that shows signs that it was touching the surrounding molten material
  - It is hypothesized that there was suspension consisting of the molten material and Coarse U-Zr-O

(5) Crystalline structure and composition of phases containing U (2/2)



⇒ Neighbors Fe/Cr oxides and Fe oxides exist inside the grains

Figure 1 Fe-Ni metal and surrounding elements distribution

Fe-Ni metal: Only a very small percentage of the content ratio

- The Fe-Ni metal phase is in contact with Fe_3O_4 and $(Fe,Cr)_3O_4$ (Figure 1). Fe_2O_3 was not observed, and resembles mixtures forming through oxidation caused by steam.

  - Out of all the elements coming from structural materials (Fe, Cr, Ni), Cr and Fe oxidized first due to the steam generated, leaving a metal phase with a high concentration of Ni.

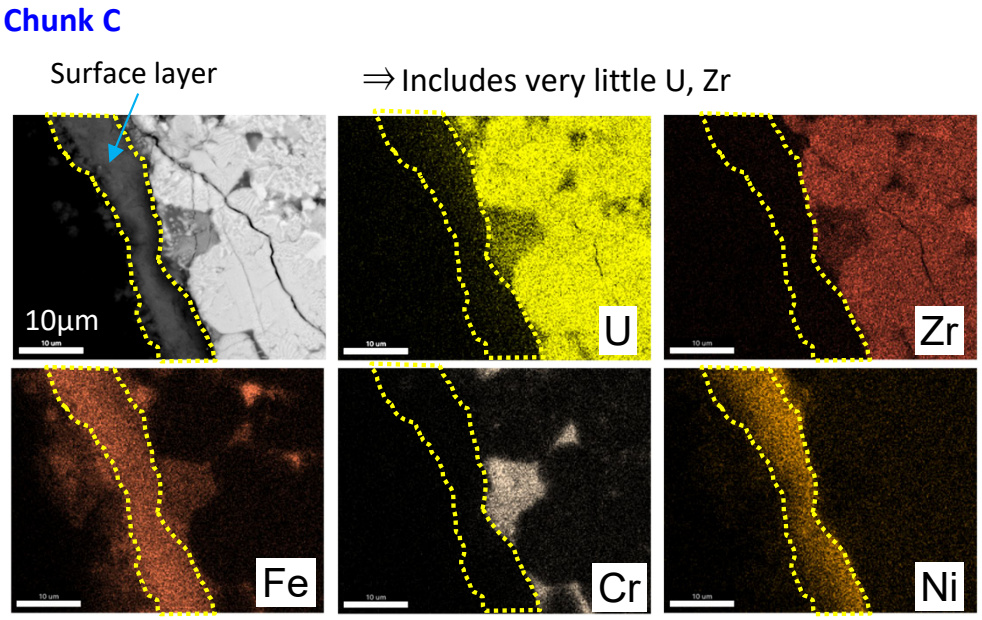


Figure 2 Primary element distribution near the outermost surface of the sample

Surface layer: Deposited to a thickness of approx. 10 - 50µm

- Comprised mainly of Ni-Fe-O. Similar layers were seen in fragments accompanying the clump, thereby suggesting it contains hydroxides.

  - It is assumed that after the most of the sample was formed through melting and solidification, this layer was formed as dissolved constituents in the cooling water precipitated onto the surface.

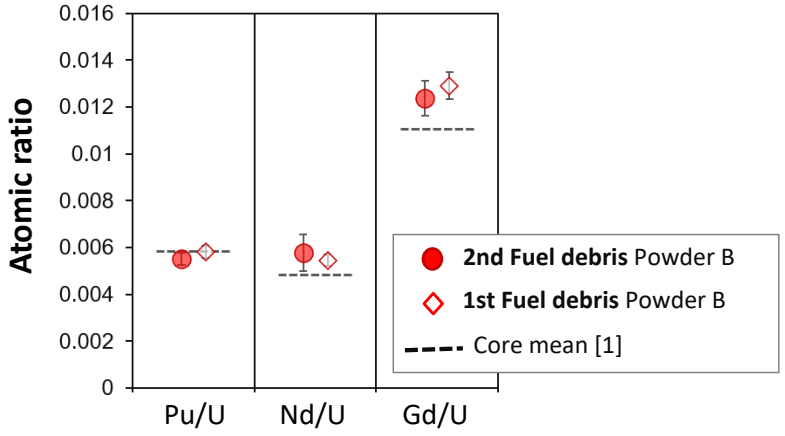
Sample formation process hypothesis based on the analysis results (1/4)

Mixing with elements originating from the core

- If we focus on U, Pu, Nd and Gd※, even though there is only a slight difference in the isotope composition of both the first and the 2nd sample, the values obtained are close to the core mean for both. (Figure 1)

※ The isotope compositions of U/Pu (actinoid nuclide) , Nd (fission product that indicates burn-up) and Gd (burnable poison) have distributions in the radial and axial directions consistent with the core prior to the accident.

- When the original molten material of the first and second samples was formed, it is hypothesized materials throughout a relatively wide of the core



Reference Ratio of U to Pu, Nd and Gd

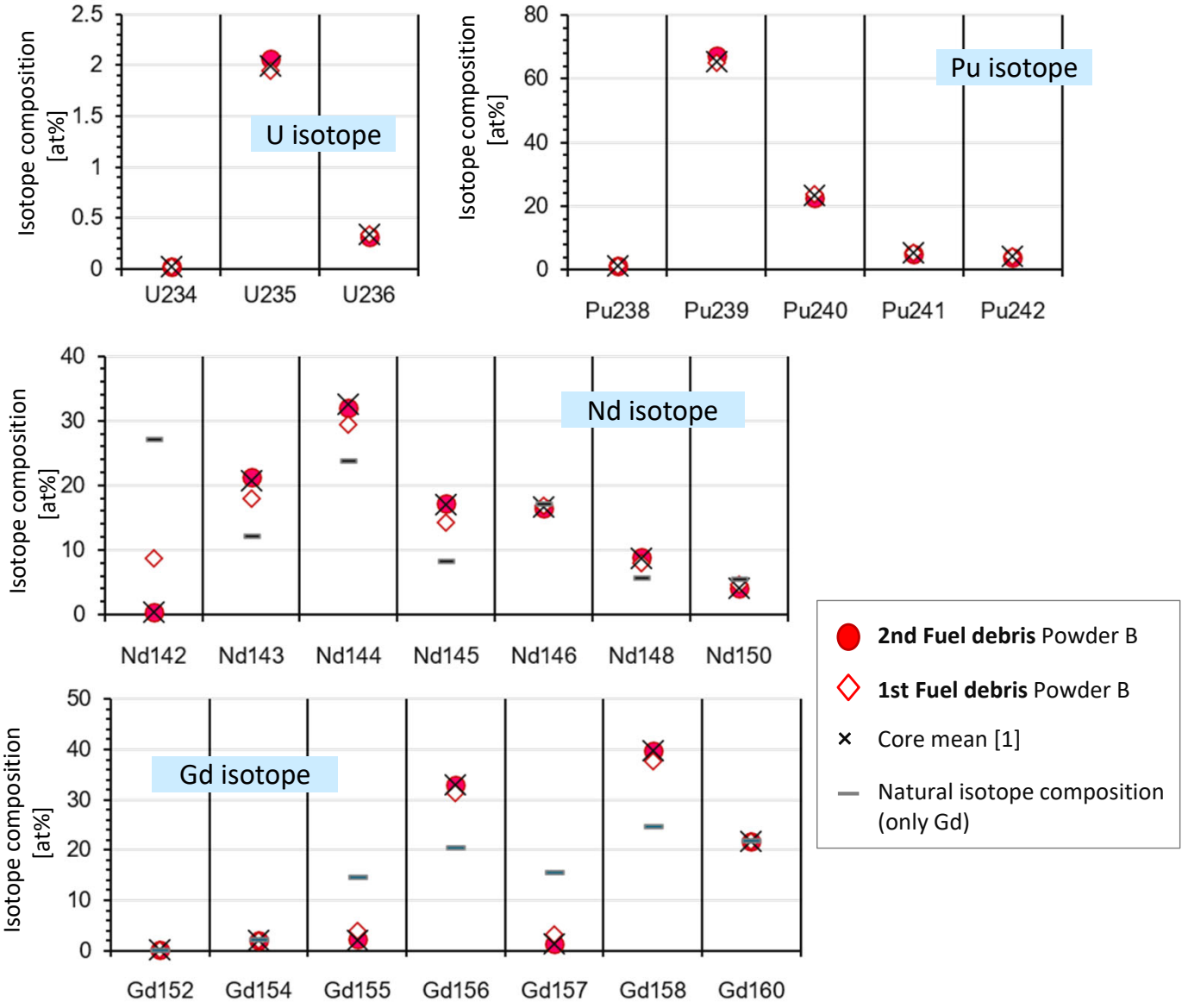


Figure 1 1st/2nd Fuel debris Pu, Nd and Gd isotope composition

(Comparison of TIMS analysis results from the JAEA Ooarai Nuclear Engineering Research)

[1] Okumura et. al., Atomic Energy Society of Japan 2021 Spring Conference, 3B01.

Sample formation process hypothesis based on the analysis results (2/4)

Entrainment of structural material elements

- The percentage of structural material elements in the first and second samples is larger than the average composition of the core prior to the accident （Figure 1）
  - Both samples suggest the possibility that as the molten material that formed in the core fell to the bottom of the RPV, it became entrained with structural material※1 elements at the bottom of the core.

※1 Lower tie plates, fuel support fixtures, etc.

- Compared with the first sample, the second fuel debris sample has almost no Ni and few metal phases. （Figure 2 ）
  - It is possible that the entrained structural material elements, such as stainless steel, oxidized and separated into Fe-Cr oxides and Fe-Ni metal phases, and the second fuel debris sample comprises this oxide phase (the metal remained in another fragment)
  - The second fuel debris sample has an angular shape, and most likely broke off of a larger fused solid.

- For both the first and second fuel debris samples, it is hypothesized that molten material was formed as the structural material elements at the bottom of the core became entrained after which they separated into oxide phases and metal phases thereby forming through different processes.

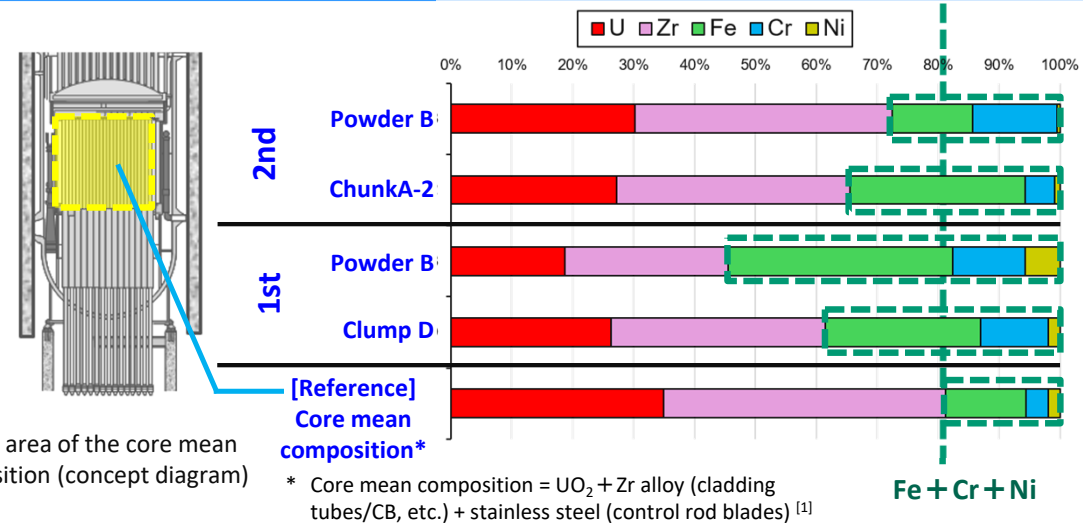


Figure 1 Solution analysis results (ratio of the primary five elements) and mean composition comparison

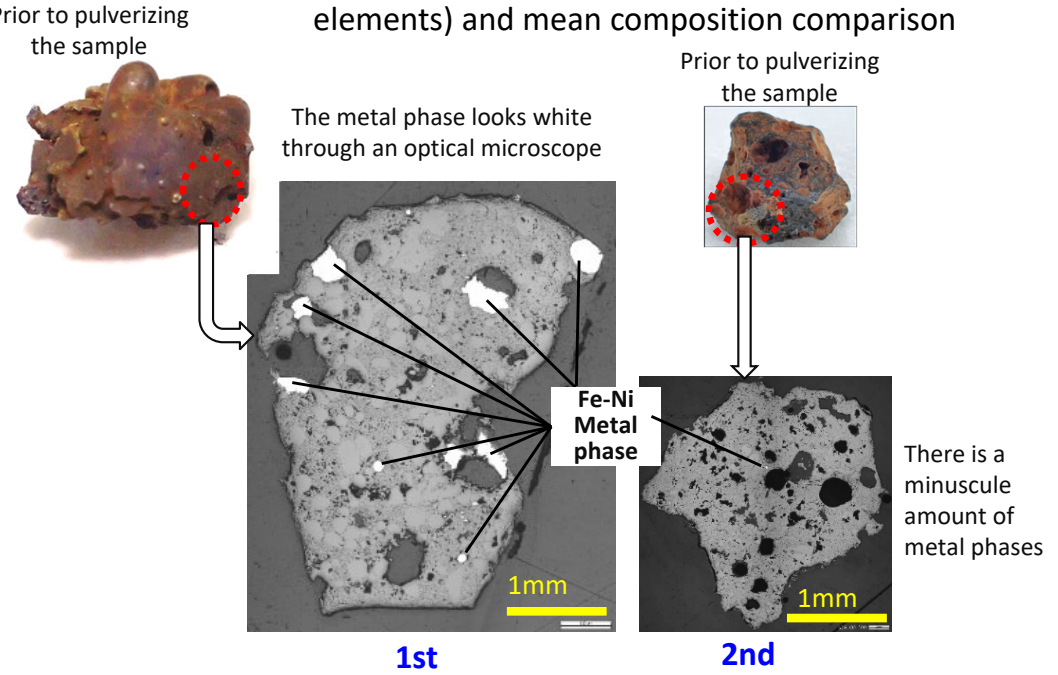


Figure 2 Observation of the cross-sections through an optical microscope

[1] Calculated based on Sato et al., Nucl.Eng.Des., 404, 112205. Table1

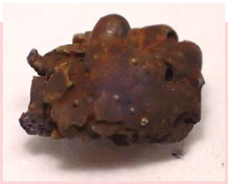
Sample formation process hypothesis based on the analysis results (3/4)

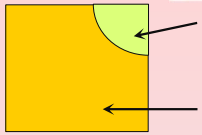
Hypothesis about the solidification process of the molten material

- Whereas there are differences in crystal growth progress and phase separation process between both the first and the 2nd fuel debris samples, The temperature range within which they melted and solidified is almost the same

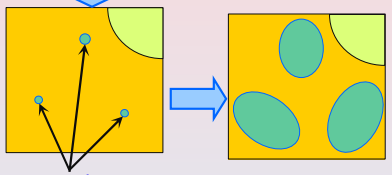
Temperature: High → Low

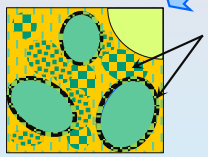
1st Fuel debris



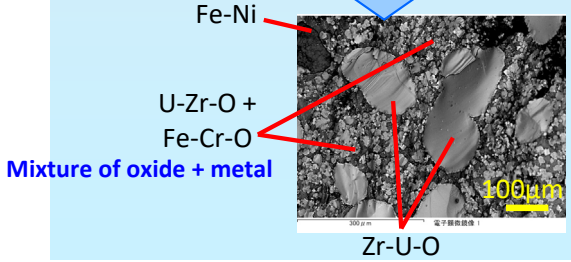


Approx. 1900～2400℃ (Temperature at which precipitation starts)





Approx. 1350℃～1550℃ (Temperature at which FeO and Fe_3O_4 precipitate)



i. Molten material formation

- ✓ It is estimated that molten material of the first and second samples contained almost the same elements (The materials that molten material entrained were the same)
- ✓ It is estimated that these materials were separated as the second debris changed from a molten material into a solid (Almost no Fe-Ni metal phases)

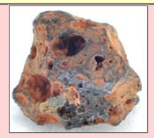
ii. Crystallization ～ Suspended state

iii. Progression of fine phase precipitation

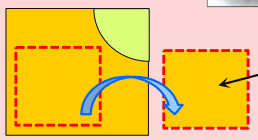
iv. Completion of solidification

- ✓ It is assumed that solidification completes with the precipitation of FeO or Fe_3O_4

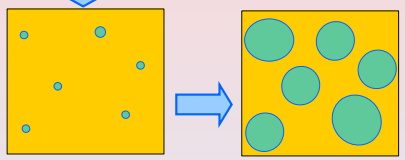
2nd Fuel debris

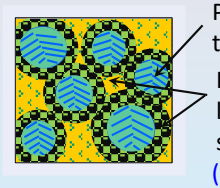


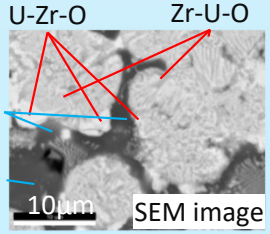
There are notes on the **Fine mixed region** that makes up the majority of the cross-section



Approx. 2200～2500℃ (Temperature at which precipitation starts)

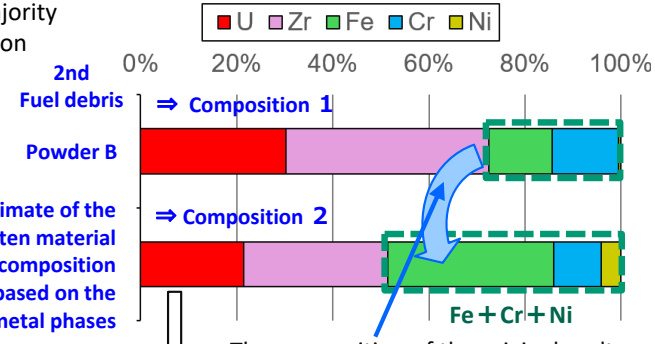




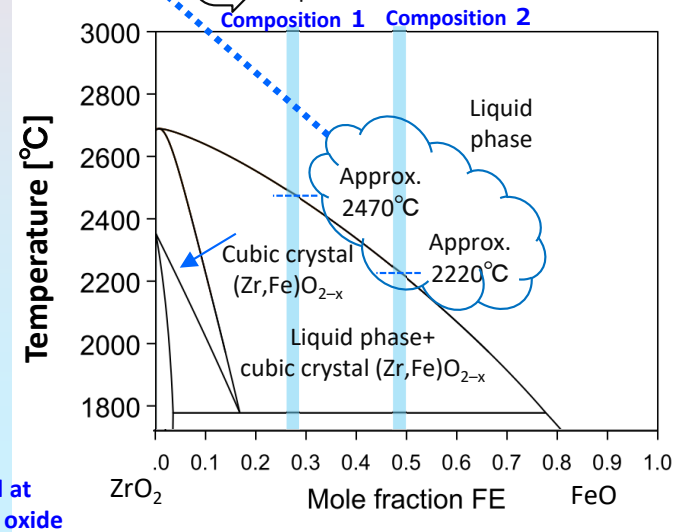


Structure formed at the center of the oxide

Composition estimates

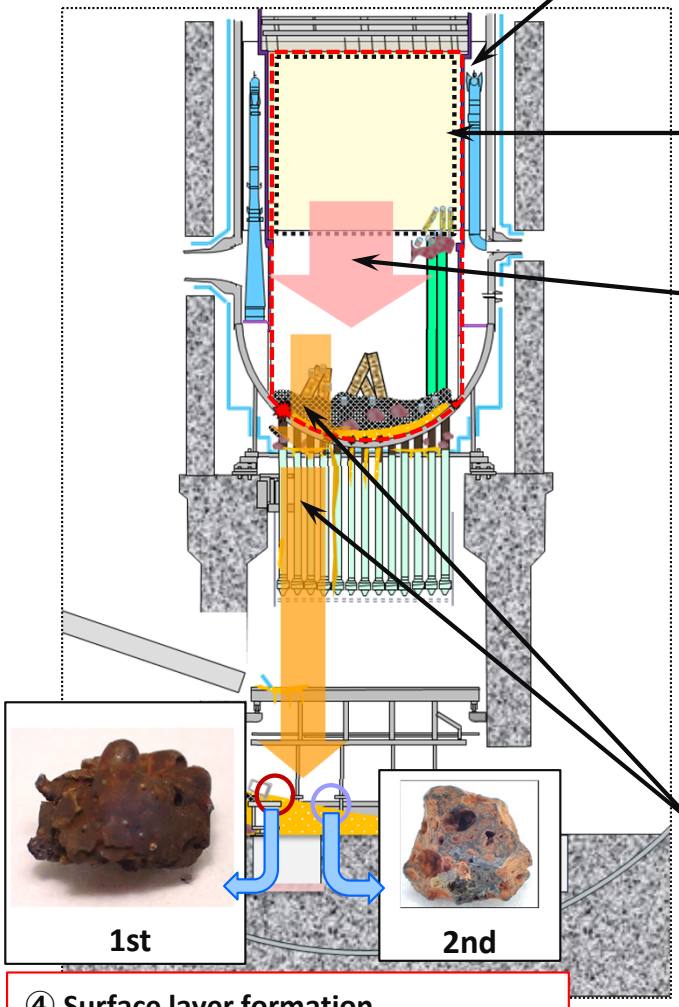


The composition of the original molten material was estimated by adding the contribution from Fe and Ni after back calculation of the composition corresponding to SUS304 assuming that all Cr in the 2nd Fuel debris sample had oxidized.



Rough estimate of melting temperature using the ZrO_2-FeO phase diagram

Sample formation process hypothesis based on the analysis results (4/4)



① Molten state inside the RPV

Exceeds approx. 1900℃

a. Fuel melts and mixes in core

- With both the first and second fuel debris samples it is assumed that a relatively wide area of fuel was mixed in while the channel boxes, etc. were being entrained. 【P7,8,13】

b. As the material migrates to the bottom of the RPV it becomes entrained with structural materials

- With both the first and second fuel debris samples it is assumed that part of the core support plates, bottom tie plates, and CRGT, etc., became entrained on the molten side. 【P7,14】

c. Oxidization of structural materials

- In both the first and second fuel debris samples, Fe_2O_3 did not oxidize, and it is possible that structural material elements, such as stainless steel, oxidized due to the steam generated, after which Cr and Fe, which oxidize relatively easily, oxidized in succession. 【P12】

② Suspended state

- The composition and range of temperature differ for the 1st and 2nd samples. 【P15】

③ Solidification

Below approx. 1350～1550℃

- FeO and Fe_3O_4 precipitates and solidification is completed. 【P15】

④ Surface layer formation

- It is assumed that the surface layer structure was formed after the majority of the sample is generated through melting and solidification.

Figure Rough estimate of the generation process of the 1st/2nd Fuel debris samples

Summary of hypothesis

■ Even though it is possible that the formation conditions, such as temperature, etc., differed slightly, the first and second fuel debris samples formed through mostly the same pathway (Left diagram①～④)

- By using analysis results to deepen our standing of the phenomena that actually occurred, we may be able to estimate conditions within the core that we are unable to see thereby enabling us to deliberate fuel debris retrieval methods and future internal investigations

⇒ Since these estimates are provisional, we will continue to engage in analysis and assessment with the intent of updating and refining them.

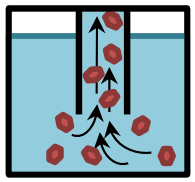
Result conclusions

- The fuel debris sample obtained through the second trial retrieval displayed the following attributes:
  - ✓ As with the first sample, the U weight ratio was high. It is assumed that Zr elements, cladding tubes and channel boxes, etc. were entrained along with structural material elements (FE, Cr, Ni).
  - ✓ The $^{235}U/U$ ratio of the sample was slightly different than the first sample, but close to the core mean. This suggests that fuel got mixed in not in a limited region of the core, but rather in a relatively wider region.
  - ✓ In regards to radiation concentration, although the concentration of radioactive cesium was low, as with the first fuel debris sample, the contributions from β-ray and α-ray emitting nuclides, such as ^{90}Sr and Pu isotopes, are large.
  - ✓ As with the first sample, there is a wide distribution of voids inside the sample, which is most likely why it was easy to pulverize.
  - ✓ Compared with the first fuel debris sample the percentage of Fe-Ni metal phases originating from structural material elements is low. During formation of the 2nd fuel debris sample the metal phase and the oxide phase separated, so it is possible that the metal phase migrated separately from the oxides. And, it is possible that the composition of the molten material prior to separation is similar to the first fuel debris sample. This does not contradict our assumptions to date, and gives us clues for estimating the behavior of fuel and structural materials during the accident and also the condition of the core.
- Even though the first and second fuel debris samples were taken from different locations, they are similar in terms of composition, structure, and the process through which they formed. No conclusions can be drawn about the conditions inside the core from these results alone, but it is possible that fuel debris that formed through a similar process exists in the vicinity of the location from which the second sample was taken.
- We will continue to analyze the sample in order to ensure safety during decommissioning and improve the accuracy of estimates about the conditions inside the reactor (refer to the next page for more information)

Result conclusions
– Leveraging the knowledge obtained through analysis for decommissioning –

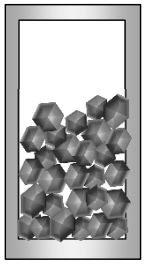
Understand the conditions inside the reactor → **Retrieval** → **Storage** → ・・・

Process into small fragments
(Clump-like Fuel debris)



Suction recovery
(Grain-like fuel debris)

Storage container



	Retrieve safely and store	Ensure work environment safety	Retrieval efficiently		Ascertain conditions inside the reactor
Needs					
Focal point	Can fuel elements containing uranium be handled safely?	Will several layers of protection be necessary because the materials emit intense radiation?	Is it easy to identify what materials contain a large amount of uranium?	Will the material be too hard to retrieve?	How will we address areas that are not directly visible?
Analysis results	A lot of structural material elements $^{235}U/U$ ratio is close to the mean	Little cesium, which is the primary source of gamma radiation	Europium and curium accompany uranium	The structure is non-uniform and has many voids	Temperature and atmosphere estimated from the process through which the samples formed
Knowledge gained from analysis	It is possible that the nature of fuel components changed as they melted and became mixed with the substances around them	Radiation sources that should be the focused targets of countermeasures, such as beta rays and alpha rays, etc., have been clarified	We have gained clues about how to identify uranium content by measuring gamma rays and neutrons	It is likely that the samples are easy to crush and recover because they have many voids	Deepening our understanding about the phenomena that occurred during the accident will enable us to predict fuel debris conditions
Leverage for decommissioning	⇒ Leveraged to deliberate safe handling methods and storage methods	⇒ Leveraged for exposure countermeasures	⇒ In the development of non destructive measurement technologies and retrieval device design		⇒ Leveraged to deliberate fuel debris retrieval and internal investigations

Analysis will enable us to deliberate handling technology that matches fuel debris conditions and design equipment, and this knowledge will be leveraged for decommissioning

Reassessment of the analysis results from the 1st fuel debris sample Summary

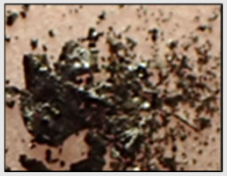
■ When analyzing fuel debris with unknown composition and non uniform attributes, there are cases where the conventional methods for analyzing spent fuel where the composition is very heterogeneous and unique pretreatment, such as alkali fusion, etc., is performed, cannot be applied. So, even after the analysis results that have already been reported [1][2] were publicly released (hereinafter referred to as, "initial report"), we continued to advance analysis methods based on discussions with external experts.

■ While using the analysis results to assess the attributes of the sample and the process by which it formed, we also compared analysis methods, matched nuclides, and inspected analysis conditions. As a result, we have found that there is room for improvement with conventional analysis methods in regards to the following three issues, and we have performed a reassessment of them.

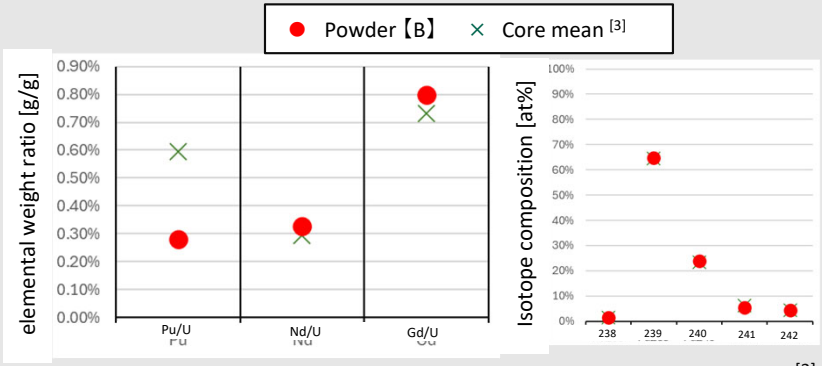
(1) U, Pu, Nd and Gd element concentration measured with isotope dilution mass spectrometry (IDMS)

Focal point

Approx. 0.1g



1st Fuel debris Powder【B】



The ratio of U to Pu, Nd and Gd in the initial report [1] [2]

Pu isotope composition [2]

✓ The ratio of Pu/U was approximately half the core mean. However, the ratios of Nd/U, Gd/U, and the Pu isotope composition, and the ratio of ^{241}Am/U※ were close to the core mean, and we have examined how well this aligns with these trends while also improving the methodology.

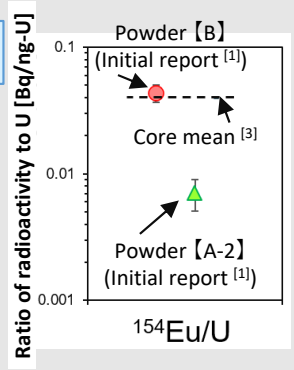
※ At current time it is assumed that the majority of ^{241}Am was formed from the decay of ^{241}Pu

(2) Radioactivity concentration by γ-ray/α-ray spectrometry

Focal point

Approx. 0.01g

1st Fuel debris Powder【A-2】



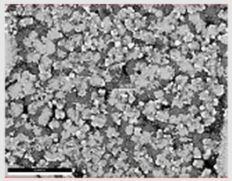
Radiation concentration comparison of the batched specimens
– ^{154}Eu/U ratio assessment example –
(Initial report value [1] used)

✓ There was a large difference in the radiation concentration between batched specimens so the cause of this was deliberated and methodology was improved.

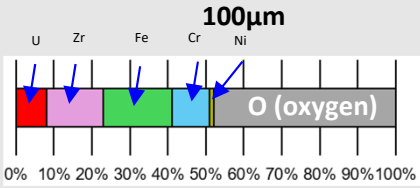
(3) Primary element ration from SEM-EDX surface analysis

Focal point

Fine mixed phase



1st Fuel debris Clump【C】



SEM-EDX surface analysis semi-quantitative results for the fine mixed phase

✓ Even though observation results show the majority to be oxides, we examined how well this aligns with the fact that oxygen concentration values are low.

Analysis methods have been improved to address these areas for improvement

[1] JAEA, TEPCO HD, Fuel debris Sample (1st) analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025, Document 3-3
[2] JAEA, TEPCO HD, Fuel debris Sample (1st) analysis results (update), Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (144th), November 27, 2025, Document 3-3
[3] Okumura et. al., Atomic Energy Society of Japan 2021 Spring Conference, 3B01.

Reassessment of the analysis results from the 1st fuel debris sample
Improvements made to analysis methodology

(1) Measuring U, Pu, Nd and Gd element concentration using isotope dilution mass spectrometry (IDMS)

① Improvements to pretreatment by revising the Pu valence control process（Pu）

- ✓ The analysis flow conventionally used for spent fuel has been revised and a chemical separation/pretreatment methodology suitable for alkali fusion specimens was introduced.
- ➢ During pretreatment, the valence is adjusted in consideration of hexavalent Pu in the specimen by adjusting the added reagents, thereby achieving chemical equilibrium with the Pu in the tracer solution. ⇒ This has been reflected in the procedure

② Concentration evaluation formula improvements（for U, Pu, Nd, and Gd）

- ✓ The evaluation formula for converting isotope composition to element concentration was revised.
- ➢ The density difference※ between specimens was reflected in the assessment of the tracer solution and added amount of measured specimen (fuel debris solution) used for the evaluation formula, and more strictly converted (applied) based on volume rather than mass.

※ Since highly concentrated nitric acid and a lot of alkaline flux is used during the analysis of fuel debris fuel debris, the density is higher than the tracer solution (primarily 1M nitric acid solution)

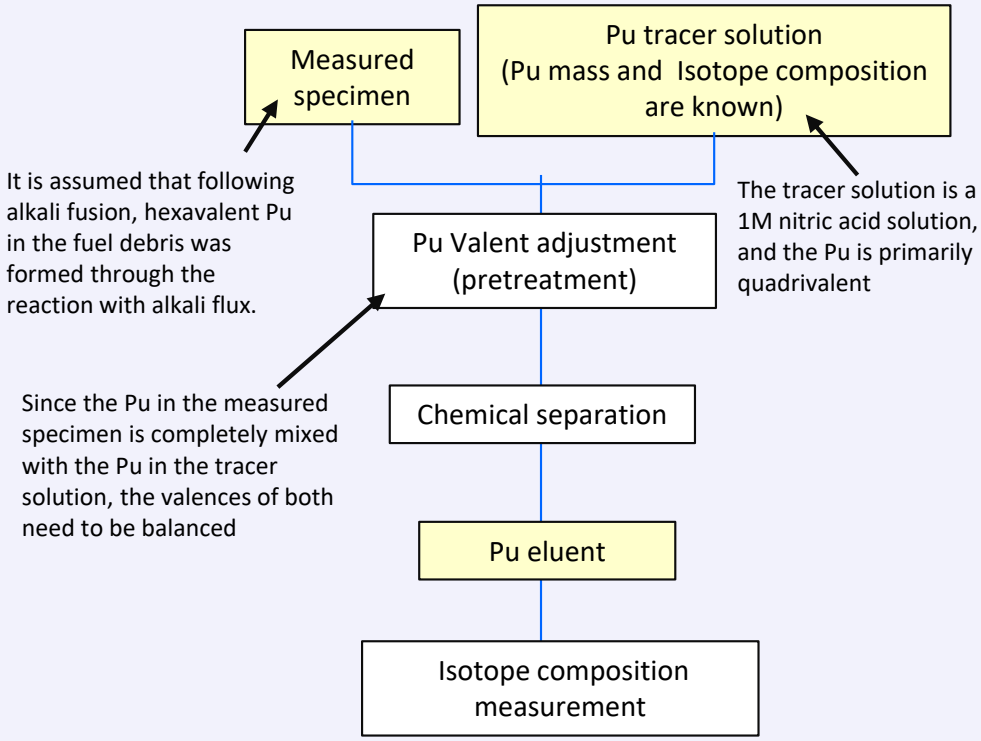


Figure Summary of Pu analysis flow using IDMS

(2) Measuring radioactivity concentration using γ-ray/α-ray spectrometry

- ✓ Spectrum analysis methodology and analysis conditions have been re-inspected
- ➢ Efficient calibration conditions for γ-ray and α-rays when measuring fuel debris were optimized

(3) Measuring primary element ratios from SEM-EDX surface analysis

- ✓ EDX spectrum analysis methodology and software settings were re-inspected
- ➢ Software setting conditions (stage tilt, etc.) when measuring fuel debris were optimized
- ➢ Attention was given to the accuracy of oxygen analysis results, which is inherently difficult to quantify, during assessment.

Measurements will be performed again as necessary in light of the improved analysis methodology, analysis results will be reassessed.

Reassessment of the analysis results from the 1st fuel debris sample
Reassessed results and the impact on attribute

Reassessed results

(1) Measuring U, Pu, Nd and Gd element concentration using isotope dilution mass spectrometry (IDMS)

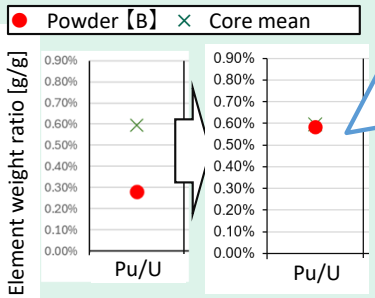
Powder【B】

Initial report value (Already reported[1] p.31)

	Analysis value [mg/100mg $_{specimen}$]
U	29.9 ± 0.2
Pu	0.084 ± 0.001
Nd	0.098 ± 0.001
Gd	0.239 ± 0.002

After reevaluation

	Analysis value [mg/100mg $_{specimen}$]
U	34.48 ± 0.64
Pu	0.201 ± 0.008
Nd	0.114 ± 0.005
Gd	0.294 ± 0.012



The Pu/U ratio is close to the core mean, and matches other data trends for ^{241}Am, etc.

⇒ Matches the assumption that fuel was mixed in over a relatively wide area

(2) Measuring radioactivity concentration using γ-ray/α-ray spectrometry

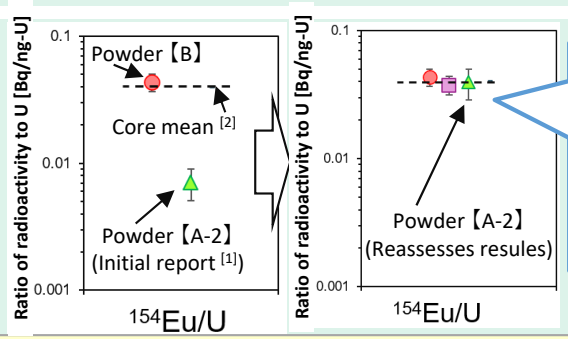
Powder【A-2】

Initial report value (Already reported[1] p.34)

Nuclide	Analysis value [MBq/g- specimen]
^{60}Co	2.0 ± 0.5
^{125}Sb	2.0 ± 0.5
^{137}Cs	0.6 ± 0.2
^{154}Eu	1.8 ± 0.5
^{241}Am	2.3 ± 0.6
^{242}Cm	0.02 ± 0.02
^{243}Cm+^{244}Cm	3.5 ± 0.2
^{241}Am+^{238}Pu	11.5 ± 0.4
^{239}Pu+^{240}Pu	4.8 ± 0.3

After reevaluation

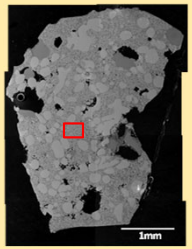
Nuclide	Analysis value [MBq/g- specimen]
^{60}Co	9 ± 2
^{125}Sb	6 ± 1
^{137}Cs	0.30 ± 0.09
^{154}Eu	10 ± 3
^{241}Am	13 ± 3
^{242}Cm	0.04 ± 0.03
^{243}Cm+^{244}Cm	8 ± 2
^{241}Am+^{238}Pu	25 ± 5
^{239}Pu+^{240}Pu	6 ± 1



Discrepancies between batch specimens have become clear

⇒ The assessment of nuclide associations has been improved by performing an assessment in light of the non uniformity of the samples

(3) Measuring primary element ratios from SEM-EDX surface analysis



Clump【C】

Initial report value (Already reported[1] p.42)

Primary element	Ratio of primary elements [at%]
O	48
Cr	10
Fe	18
Ni	1
Zr	15
U	8

After reevaluation

Primary element	Ratio of primary elements [at%]
O	74
Cr	4
Fe	8
Ni	< 0.5 (very little exists)
Zr	9
U	4

⇒ It has become easier to determine whether the main element is a metal or an oxide, and the accuracy of the assessment has been improved through the mutual comparison of solid analysis such as TEM observation, etc.

[1] JAEA, TEPCO HD, Fuel debris Sample (1st) analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025, Document 3-3
[2] Okumura et. al., Atomic Energy Society of Japan 2021 Spring Conference, 3B01.

Reassessment of the analysis results from the 1st fuel debris sample
Conclusions

■ Analysis accuracy was improved through the reassessment and there are no changes to the estimates※ pertaining to the fuel debris formation process, but some knowledge was reinforced.

※ Already reported assessment
- It is possible that fuel melted and mixed over a relatively wide area and structural materials from the bottom of the core were entrained
- Structural materials oxidized to an extent, but it is possible that they melted at temperatures between 1900 - 2400℃.

■ Data integration and checks to confirm that differing methodology align were continually implemented in order to assess the attributes of fuel debris. During the reassessment, the knowledge obtained through this process was reflected in improvements to analysis methodology, which led to improvements in fuel debris analysis accuracy and assessment reliability. Going forward we will continue to improve the accuracy of the analysis of fuel debris that is non-uniform and has unknown composition, and revise our assessment results as necessary.

- Revisions that were made to past reports in conjunction with the reassessment are as follows:

No.	Report	Page	Revision details	Reason for the revision
1	Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025, "Fuel debris sample (1st) analysis results"	p.7	Graph revision	Graph revised in conjunction with their reassessment of the U analysis values from IDMS
2		p.9	Graph revision	Graph revised in conjunction with their reassessment of the U and P analysis values from IDMS
3		p.31	Chart revision	Graph revised in conjunction with their reassessment of the U, Pu, Nd and Gd analysis values from IDMS
4		p.34	Chart revision	Chart revised in conjunction with a reassessment of the radioactivity concentration analysis values from γ-ray spectrometry and α-ray spectrometry
5		p.35	Chart revision	Revision of the Zr/U ratio and Gd/U ratio assessment values in conjunction with the reassessment of the analysis values for U and Gd from IDMS
6		p.42	Chart and Graph revision	Chart and graph revised in conjunction with a reassessment of the SEM-EDX semi-qualitative values and U analysis values from IDMS
7	Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (144th), November 27, 2025 "Fuel debris sample (1st) analysis results (update)	p.19	Graph revision and addendum added to report	Graph revised in conjunction with their reassessment of the U, Pu, Nd and Gd analysis values from IDMS, and addendum added to the report in conjunction with a revision of the Pu/U ratio
8		p.32	Same as Chart No. 1 in this report	Meeting materials from the 140th meeting quoted as reference
9		p.34	Same as Chart No. 2 in this report	Meeting materials from the 140th meeting quoted as reference
10		p.37	Same as Chart No. 6 in this report	Meeting materials from the 140th meeting quoted as reference

Revisions to portions of the initial report (No.1-7) noted in the reference materials

Reference materials

[Reference] 1st Fuel debris sample additional analysis results
Additional analysis details

◆ Radioactivity analysis

- In order to acquire information that will contribute to deliberations pertaining to treatment and disposal, the range of nuclides targeted for radioactivity analysis was expanded further than those analyzed in a conventional fuel debris sample.
- The nuclides targeted for analysis focused on β-ray emitting nuclides, for which hardly any data has been acquired from the fuel debris samples to date, while referencing the nuclides targeted for analysis in solid waste [1] (Refer to the chart on the right). In order to make effective use of the samples and in consideration of the analysis method, the first fuel debris solution (stored at the NDC) was used for the analysis.

Chart Nuclides targeted for radioactivity analysis by the NDC and measurement method

Nuclide	Measurement method
^{3}H, ^{14}C, ^{63}Ni, ^{79}Se	Liquid scintillation counter
^{36}Cl, ^{99}Tc, ^{90}Sr, ^{129}I	β-ray spectrometer or gas-flow counter
^{41}Ca	X-ray measurement
^{93}Zr, ^{93}Mo, ^{107}Pd	ICP-MS
^{126}Sn	γ-ray spectrometry（LE-Ge）
γ-ray emitting nuclide（^{137}Cs, ^{154}Eu, ^{241}Am, ^{60}Co）※	γ-ray spectrometry

※ Since data for these γ-ray emitting nuclides was obtained from batched specimens made from the first fuel debris sample[2], they were also subjected to additional analysis in order to deliberate differences between batched specimens

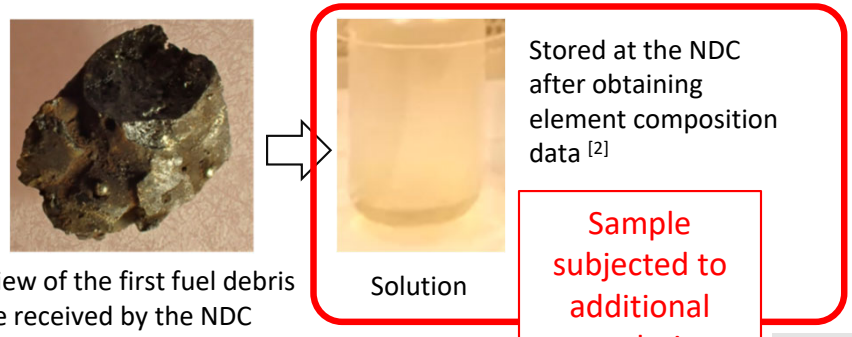


Figure Sample subjected to radioactivity analysis

◆ Assessment of phase conditions using SEM-EDX and XRD

- In order to further deepen our understanding of the process by which the first sample, which has a complicated shape, was formed, the phase status of locations with unique external appearances were assessed.
- Protrusions in the sample seen prior to pulverization (see the figure on the right) were chosen and the fine structure and crystalline structure/composition were compared to other regions in order to examine the differences in formation process between regions.

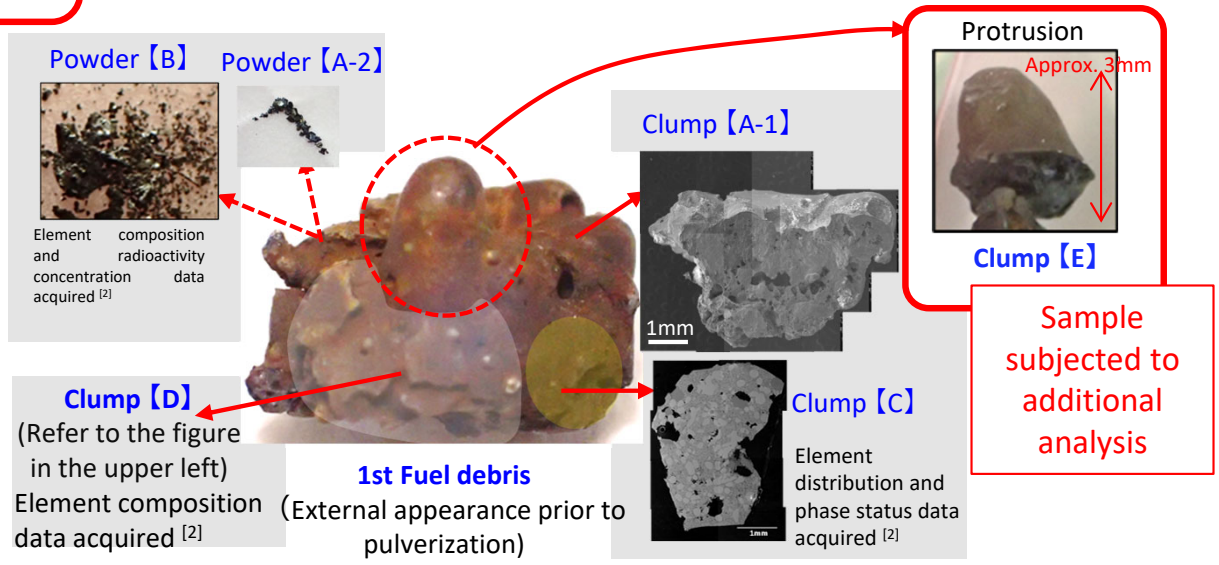


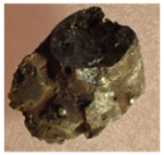
Figure 1st Fuel debris sample analysis status and additional analysis sample targets

[1] TEPCO HD, Selecting target nuclides for analysis during the analysis of solid waste from 1F, 23rd Technical Review Meeting on the Specified Nuclear Power Facility Implementation Plan, December 5, 2024, Document 2-1
[2] JAEA, TEPCO HD, Fuel debris Sample （1st) analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025, Document 3-3

◆ Analysis flow (summary)

■ A suitable amount of each nuclide was batched to make analysis specimens, and then subjected to pretreatment and analysis

1st Fuel debris Clump【D】

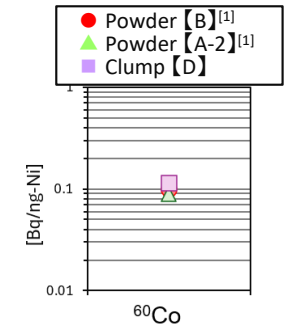


LSC : Liquid scintillation counter
GFC : 2π Gas-flow counter
ICP-MS : Inductively Coupled Plasma Mass Spectrometer

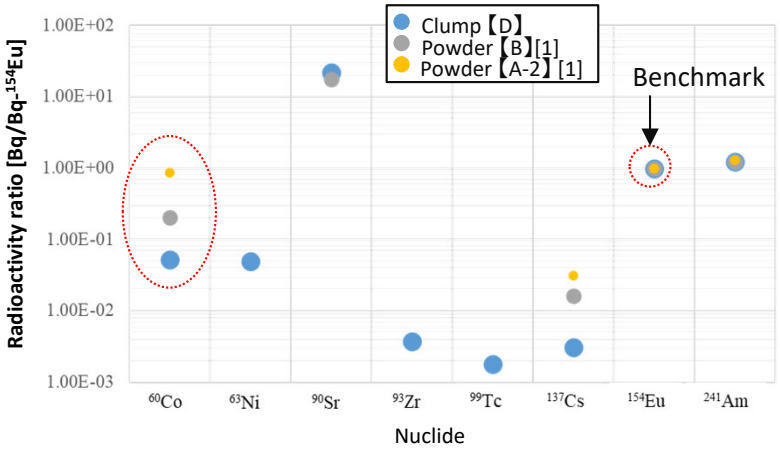
[Reference] 1st Fuel debris sample additional analysis results
Radioactivity analysis results

◆ Radioactivity concentration

- In addition to the γ-ray emitting nuclide targeted for analysis to date, ^{63}Ni and ^{99}Tc were also detected. (Chart 1)
- In regards to the concentration of γ-ray emitting nuclides, for which data has already been obtained from other batch specimens of the first fuel debris sample, ^{154}Eu, which is thought to be easily associated with U, was set as a benchmark nuclide for comparison. (Figure 1)
  - The difference in concentrations of ^{241}Am between samples is small, and it is assumed that it was easy for the nuclide to associate with U during formation of the sample. Whereas the differences in the concentration of ^{90}Sr between samples were also small, it was only slightly lower than the core mean.
  - Differences in the concentration of ^{60}Co between samples was seen. There were also differences in the concentrations of structural material elements (Fe+Cr+Ni) between batched specimens, and it is thought that it was also easy for this nuclide to associate. (The concentration of ^{60}Co is also noted using Ni as a benchmark nuclide for the sake of reference)
  - ^{137}Cs originated from fuel, but it is assumed that the majority volatilized during the melting process, and a minuscule amount remains in a non-uniform manner within the sample.



Reference ratio of ^{60}Co radioactivity to Ni weight



Revised on April 30, 2020

Figure 1 Radioactivity ratio using ^{154}Eu in the first fuel debris sample as a benchmark

[1] JAEA, TEPCO HD, Fuel debris Sample (1st) analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025, Document 3-3

1st Fuel debris Clump【D】

Chart 1 Radioactivity concentration assessment results (values on the date of measurement)

Expanded uncertainty: k=2

Nuclide	Radioactivity concentration [MBq/g specimen]	Lower limit of detection	Measurement date
^{3}H	ND	0.030	2026/4/21
^{14}C	ND	0.015	2026/4/21
^{36}Cl	ND	4.4×10^{-4}	2026/4/2
^{41}Ca	ND	0.38	2026/5/18
^{60}Co	0.86 ± 0.10	0.015	2025/10/4
^{63}Ni	0.77 ± 0.16	0.11	2026/4/3
^{79}Se	ND	0.018	2026/4/16
^{90}Sr	$(3.31 \pm 0.30)\times10^{2}$	0.25	2026/4/22
^{93}Zr	0.0577 ± 0.0066	9.5×10^{-4}	2026/5/8
^{93}Mo	ND	0.011	2026/5/18
^{99}Tc	0.0273 ± 0.0024	4.7×10^{-4}	2026/4/2
^{107}Pd	ND	4.8×10^{-5}	2026/5/12
^{126}Sn	ND	1.4×10^{-3}	2026/4/7
^{129}I	ND	4.9×10^{-3}	2026/4/14
^{137}Cs	0.0435 ± 0.0061	5.1×10^{-4}	2026/4/17
^{154}Eu	15.9 ± 2.5	0.039	2025/10/4
^{241}Am	18.8 ± 2.9	0.12	2025/10/4

ND: Not detected

Foundational data was attained that will enable us to enhance analysis as well as deliberate the mass relationship between various radionuclides as well as which nuclides should serve as benchmarks when doing so. Going forward we will continue to deliberate the nuclides targeted for analysis while accumulating data.

Reference aγ-ray spectrometry results　Clump【D】solution

■ ^{241}Am, ^{154}Eu, ^{155}Eu, ^{125}Sb, ^{137}Cs, ^{60}Co were the primary nuclides detected.

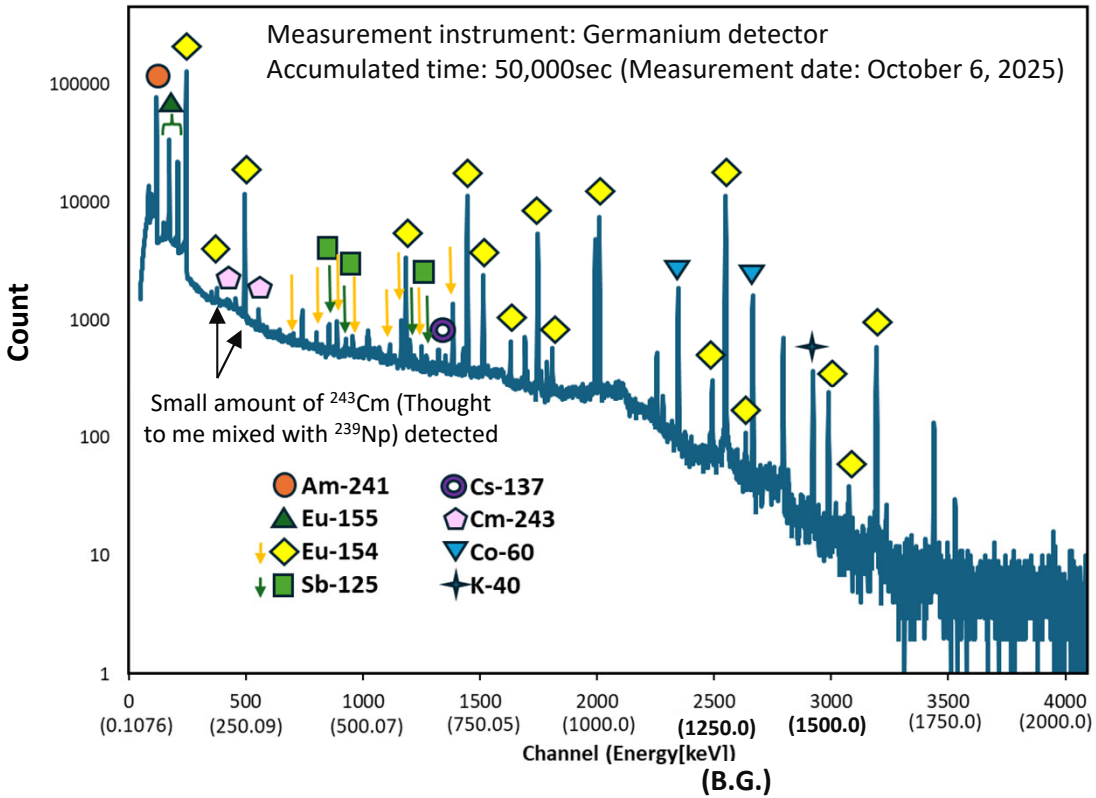
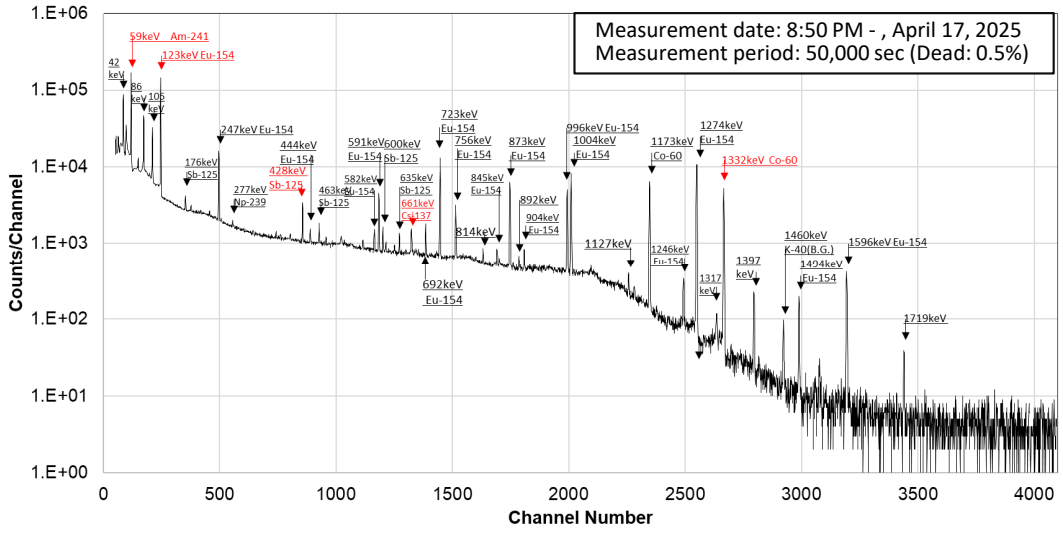


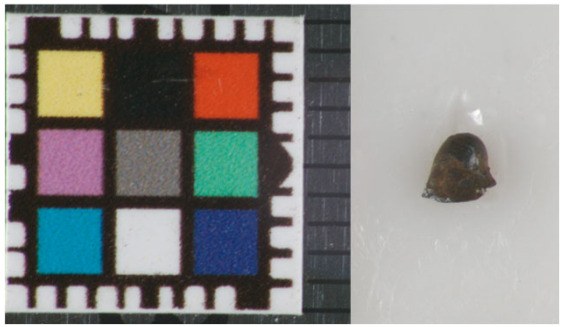
Figure　1st Fuel debris Clump【D】solution γ-ray spectrum



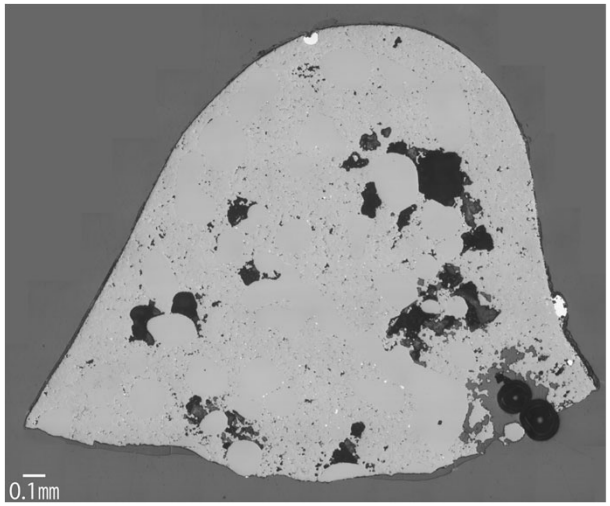
Reference: 1st Fuel debris
Powder【B】solution γ-ray spectrum

[Reference] 1st Fuel debris sample additional analysis results
Phase status assessment using SEM-EDX and XRD

◆ **Cross-sectional observation results**

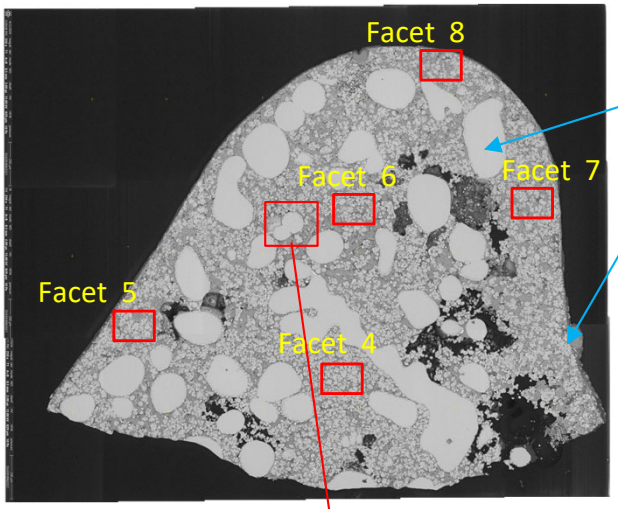


External view of the sample received by the NDC



1mm

Optical microscope image



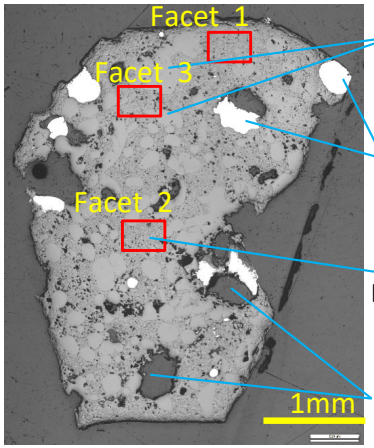
1mm

Zr-U-O

Fe-Ni metal （Very little in the cross-section）

Ni/(Fe+Ni)-0.7

SEM image (BSE image)



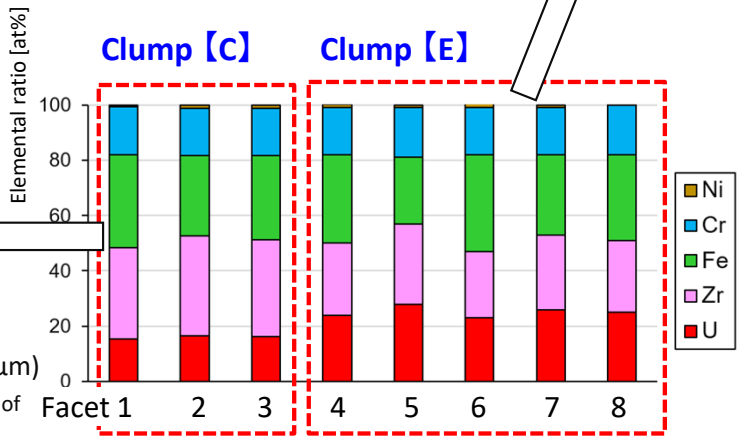
Zr-U-O phase
- The atomic ratio of Zr/U is approx. 2 （Almost constant regardless of grain）

Fe-Ni metal phase
- The atomic ratio of Fe/Ni is approx. 1～3 （Different depending on grain）

Fine mixed phase
- U-Zr-O, Zr-U-O, Fe-Cr-O, Fe-O mixed phase

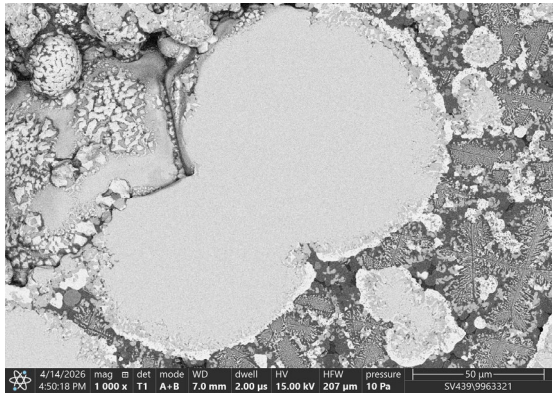
Void
(Several μm～several 100 μm)
- Approximately 20% of the area of the cross-section

Reference Clump【C】Optical microscope image of cross-section



Fine mixed phase SEM-EDX Surface analysis results

Zr-U-O phase



Zr/U-1.1

50μm

■ The protrusions on the first fuel debris sample (Clump【E】) showed the same trends as other areas when it comes to cross-section structure and the breakdown of Fe+Cr+Ni, but differences were also seen, such as a lower Zr/U ratio than that found in other regions.

[Reference] 1st Fuel debris sample additional analysis results
Phase state assessment using SEM-EDX and XRD

◆ **Cross-section observation results**

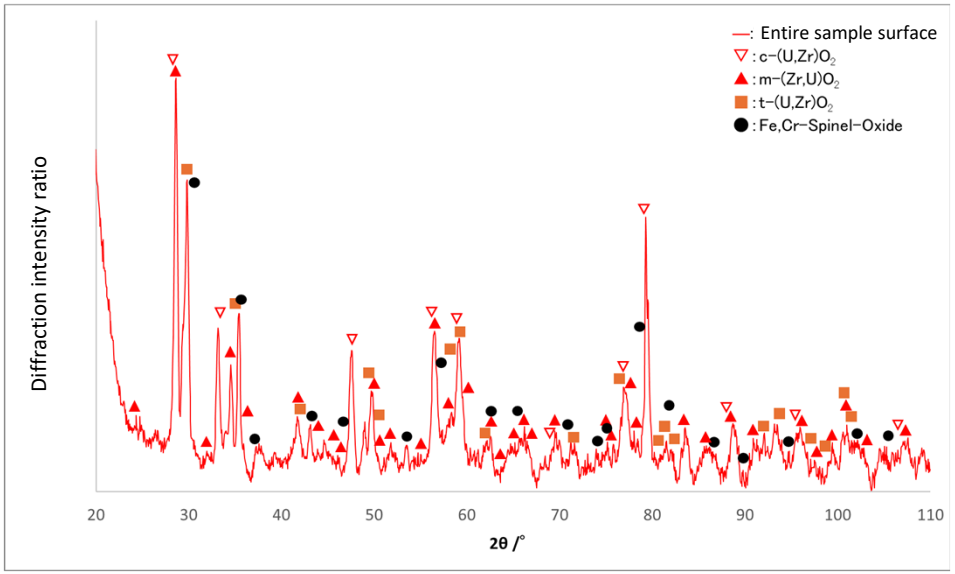


Figure 1 XRD measurement results for the entire cross section

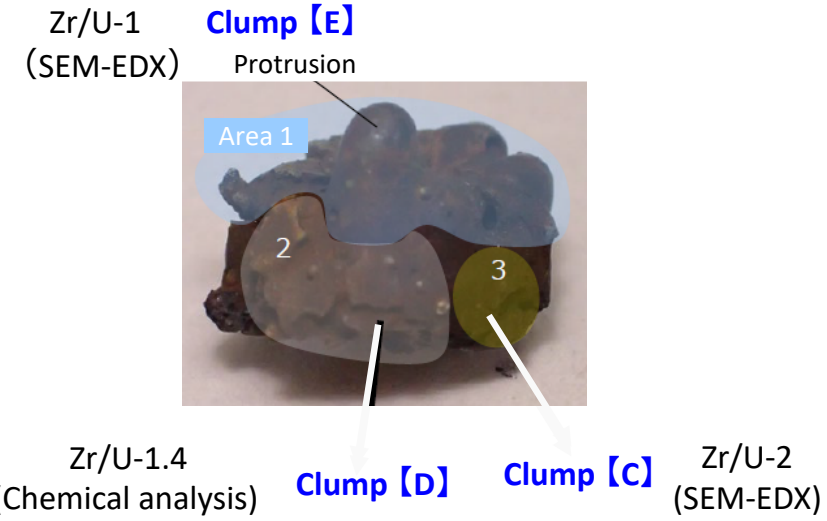


Figure 3 Composition of each region of the first fuel debris sample

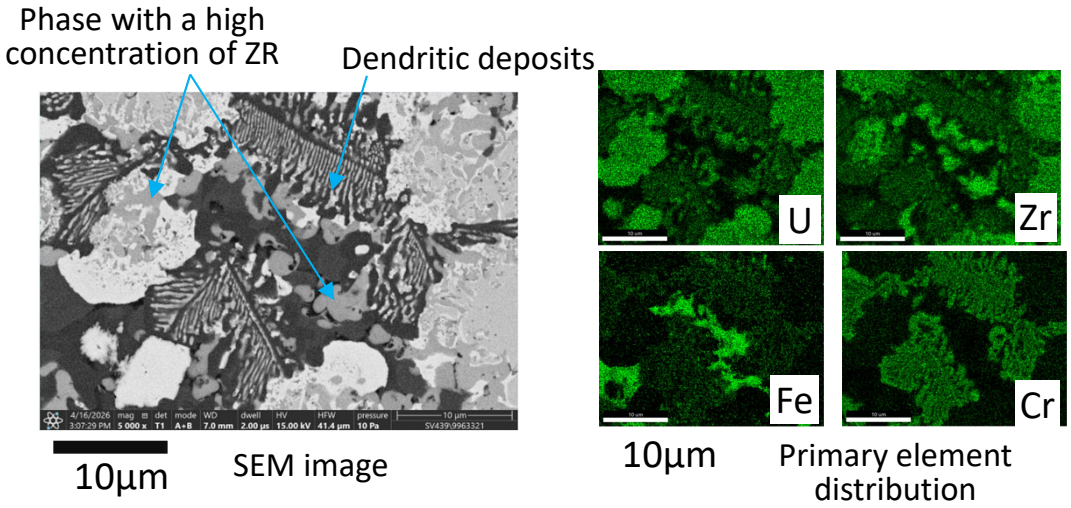


Figure 2 SEM-EDX analysis results for the fine mixed region

- XRD results from the cross-section identified cubic crystals $(U,Zr)O_2$ also seen through conventional TEM observation, as well as tetragonal crystals $(Zr,U)O_2$, Fe-Cr spinel phases, and monoclinic crystals $(Zr,U)O_2$ (Figure 1)

- Since SEM observations also found phases with high concentrations of Zr and dendritic deposits in the fine mixed phase (Figure 2), it is possible that the tetragonal crystals $(Zr,U)O_2$ and monoclinic crystals $(Zr,U)O_2$ identified with XRD correspond to these phases.

- It is assumed that these regions solidified from the same molten material as other regions in the sample, but since the composition is slightly different depending on region (Figure 3) it is possible that solidification occurred at a different time.

[Reference] 1st Fuel debris sample additional analysis results
Conclusions

- In order to expand the nuclides targeted for analysis, which will contribute to deliberating treatment and disposal, and also further deepen our understanding about the process through which the samples formed, the first fuel debris sample was subjected to additional radioactivity concentration and phase status analyses.
- During the additional radioactivity concentration analysis, nuclides that had not previously been targeted were added, and various analysis methods were applied. As a result, in addition to γ-ray emitting nuclides, β-ray emitting nuclides, such as ^{63}Ni and ^{99}Tc, were also detected.
  - Foundational data was obtained that will enable us to enhance analysis as well as deliberate the mass relationship between various radionuclides as well as which nuclides should serve as benchmarks when doing so.
  - During sample analysis in the future we will continue to deliberate the nuclides targeted for analysis while accumulating data.
- During phase status analysis, SEM-EDX was used to observe the cross-section, and XRD was used to assess the crystalline structure of protrusions that had not yet been analyzed. The results showed that whereas the structural phases of the cross section were the same as other regions, the ratio of Zr/U was lower than other regions.
  - It is assumed that these regions solidified from the same molten material as other regions in the sample, but since the composition is slightly different depending on region it is possible that solidification occurred at a different time.
  - Deliberation of the formation process will continue and such information will be reported at academic conferences and in academic papers

[Reference] 2nd Fuel debris solution analysis results
Element content/Isotope ratio/Radioactivity concentration

Chart Elements and nuclides focused on during solution analysis

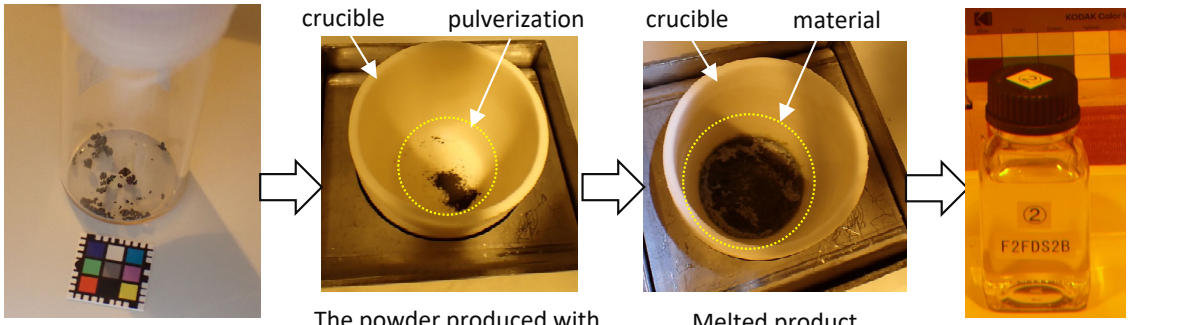
	Unit	Focused element/nuclide	Analysis method
Element content	mg/100mg $_{specimen}$ (Weight of each element per 100mg of the sample)	・U（Fuel）, Zr（Cladding tubes/CB） ・Fe, Cr, Ni（carbon steel, SUS, etc. ・Si, Ca, Al, Mg（Instrument materials, seawater, concrete, etc.） ・B (^{10}B), Gd (^{155}Gd, ^{157}Gd)（Neutron poison） ・Pb, Zn, Ti（Shielding, paint, etc.） ・Mo, Sb（Grease, instruments, FP, etc.） ・Other elements found during qualitative analysis or SEM	・ICP-AES ・ICP-MS ・IDMS
Isotope ratio	Molar ratio [-]	・U isotope： $^{235}U/^{238}U$ ration or $^{235}U/U_{total}$ ratio $U_{total} = {}^{234}U+{}^{235}U+{}^{236}U+{}^{238}U$	・TIMS ・ICP-MS
		・Pu isotope ・Nd isotope（Burn rate index） ・Gd isotope	・TIMS (The mass of the element was assessed using IDMS)
Radioactivity concentration	MBq/g (Radioactivity of each nuclide per sample weight)	・γ-ray emitting nuclide ・α-ray emitting nuclide ・^{90}Sr	・γ-ray spectrometry ・α-ray spectrometry ・ICP-MS/MS

◆Solution analysis at the JAEA Nuclear Science Research Institute (1/3)

○ **Element content** → Refer to the chart on the right

Analysis methods (summary)

1) Powder B specimen received by the JAEA Nuclear Science Research Institute, was pulverized for 30 minutes in a tungsten carbide (WC) vibratory ball mill.
2) The produced powder specimen was melted in an aluminum crucible with alkali flux※, and the resulting melted product was dissolved in heated nitric acid.
   ※ Alkali fusion: By heating and melting fuel debris, which is difficult to dissolve in acid, along with alkali flux (sodium peroxide), and converting it into a substance that can be easily dissolved in acid, we can obtain a uniform solution with no undissolved residue.
3) The total volume of the solution is visually inspected and diluted to volume of 250mm
4) The mass of elements in the solution is measured using the calibration curve method with ICP-AES, and the element content of the sample is assessed by deducting the weight of the specimen under test (43.5mg). Since the solution contains a lot of sodium originating from the alkali flux, during ICP-AES measurement, the matrix matching method is applied by which the same amount of sodium measured in the specimen is added to the control specimen.
5) In regards to U and Pu, each element in the solution obtained in 3) above was separated using UTEVA® resin and anion exchange resin, and the element volume of the obtained separated solution was measured using IDMS.



Specimen received by JAEA Ooarai Nuclear Engineering Research

The powder produced with the ball mill is added to an aluminum crucible

Melted product after alkali fusion

Solution produced from heated nitric acid

Figure Alkali fusion treatment

Chart Element content assessment results

Weight of the specimen under test: 43.5±0.4mg. Expanded uncertainty of k=2

Element	Element content※1 [mg/100mg specimen]	Notes
U	42.82 ± 0.78	Measurement with IDMS
Zr	23 ± 2	
Fe	4.4 ± 0.3	
Cr	4.3 ± 0.2	
Ni	0.16 ± 0.02	
B	0.08 ± 0.01	
Si	0.7 ± 0.06	Reference value※2
Ca	0.12 ± 0.01	Corrected mass of Ca in the flux
Al	N/A	Not included since it originates from the crucible
Mg	0.12 ± 0.02	Reference value※2
Na	N/A	Not included since it originates from the flux
S	0.11 ± 0.02	Reference value※2
Ti	0.03 ± 0.01	
Mn	0.41 ± 0.03	
Cu	0.11 ± 0.03	Reference value※2
Zn	0.08 ± 0.02	Reference value※2
Mo	<0.01	
Ru	<0.03	
Pd	0.10 ± 0.02	
Ag	0.05 ± 0.01	
Sn	<0.02	
Pu	0.237 ± 0.010	Measurement with IDMS
Nd	0.15 ± 0.02	
Gd	0.35 ± 0.02	
Ce	0.11 ± 0.04	
Co	0.35 ± 0.03	Assumed to originate from the WC used for pulverization
W	4.1 ± 0.3	Assumed to originate from the WC used for pulverization

※1 Analysis value uncertainty is a synthesis of the uncertainty associated with ICP measurement, specimen weighing, diluting to volume, calibration standard solution and dilution, and is represented as expanded uncertainty multiplied by a coverage factor (k=2)

※2 The concentration ratio of the procedural blank/solution exceeds 0.1 and is a reference value.

[Reference] 2nd Fuel debris solution analysis results
Element content/Isotope ratio/Radioactivity concentration

◆Solution analysis at the JAEA Nuclear Science Research Institute (2/3)

○ **Isotope ratios （U, Pu, Gd and Nd）** → Refer to the chart on the right

Analysis method (summary)

1) A suitable amount of the solution prepared in “Element content” on the previous page was batched and an eluent for each element was prepared using UTEVA® resin and anion exchange resin.
2) The prepared eluent was used for TIMS isotope ratio (Ex: $^{234}U/^{238}U$, etc.) measurement. During measurement, the total evaporation method※ that does not require mass fractionation correction was employed.
   ※ Total evaporation method: The specimen is painted onto a filament and totally evaporated to detect the isotope ions that are generated during this process. Mass fractionation correction is not required.
3) The following formulas were used to calculate isotope composition from the mean of the isotope ratio measurements (n = 3)

Isotope composition calculation formulas (U used as an example)

$$\begin{cases} {}^{234}U/U[at\%] = R_{234/238} / A \times 100 \\ {}^{235}U/U[at\%] = R_{235/238} / A \times 100 \\ {}^{236}U/U[at\%] = R_{236/238} / A \times 100 \\ {}^{238}U/U[at\%] = 1 / A \times 100 \end{cases}$$

$R_{234/238}$: $^{234}U/^{238}U$ isotope ratio (Measurement value)

$R_{235/238}$: $^{235}U/^{238}U$ isotope ratio (Measurement value)

$R_{236/238}$: $^{236}U/^{238}U$ isotope ratio (Measurement value)

$$A \equiv R_{234/238} + R_{235/238} + R_{236/238} + 1$$

Chart TIMS My stove composition analysis results

Weight of the specimen under test: 43.5±0.4mg. Expanded uncertainty of k=2

Element	Nuclide	isotope ratio ※1 [at%]
U	^{234}U	0.027 ± 0.001
	^{235}U	2.061 ± 0.001
	^{236}U	0.314 ± 0.001
	^{238}U	97.598 ± 0.001
Pu	^{238}Pu	1.264 ± 0.009
	^{239}Pu	67.159 ± 0.008
	^{240}Pu	22.763 ± 0.003
	^{241}Pu	5.072 ± 0.006
	^{242}Pu	3.743 ± 0.002
Nd	^{142}Nd	0.40 ± 0.01
	^{143}Nd	21.18 ± 0.01
	^{144}Nd	31.93 ± 0.02
	^{145}Nd	17.16 ± 0.01
	^{146}Nd	16.51 ± 0.01
	^{148}Nd	8.81 ± 0.01
	^{150}Nd	4.02 ± 0.01
Gd	^{152}Gd	0.11 ± 0.01
	^{154}Gd	2.05 ± 0.01
	^{155}Gd	2.23 ± 0.01
	^{156}Gd	32.96 ± 0.03
	^{157}Gd	1.24 ± 0.01
	^{158}Gd	39.69 ± 0.01
	^{160}Gd	21.73 ± 0.02

※1 Analysis value uncertainty was synthesized in accordance with the law of propagation errors during isotope composition calculation using the standard deviation from three repeated measurements, and is represented as expanded uncertainty multiplied by a coverage factor (k=2)

※2 Measurement period: U・Pu: May 2026, Nd/Gd: July 2026

◆Solution analysis at the JAEA Nuclear Science Research Institute (3/3)

○Radioactivity concentration → Refer to the chart on the right

Analysis method (summary)

- γ-ray emitting nuclides were measured by taking a 0.1mL of the solution (250mL) prepared in "Element content" on the previous pages, putting it in a 6mL vial with 2.9mL of nitric acid, and subjecting it to γ-ray spectrometry using a high purity germanium detector (Refer to the chart below)
- ^{241}Am and ^{244}Cm were measured by separating Am and Cm from the obtained solution with TRU resin, and measuring the radioactivity from the obtained separated solution with α-ray spectrometry.
- ^{90}Sr was measured by taking a portion of the obtained solution and adding a stable isotope Sr as a carrier, after which Sr resin was used to separate Sr and ICP-MS/MS Was used to measure the amount of ^{90}Sr in the obtained solution.

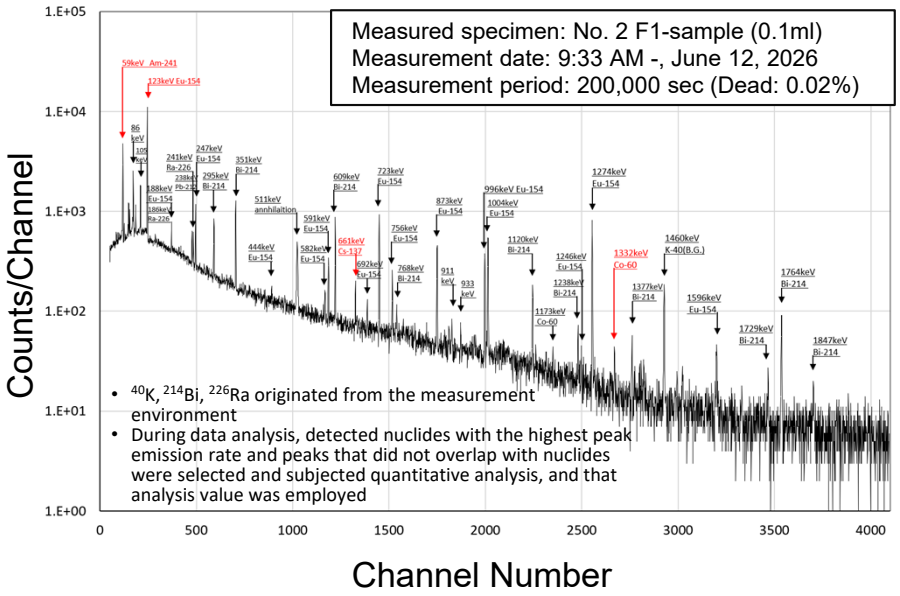


Figure γ-ray spectrum of the solution

Chart Radioactivity concentration assessment results

Weight of the specimen under test: 43.5±0.4mg. Expanded uncertainty of k=2

Analysis method	Nuclide	Radioactivity concentration※1 [MBq/g specimen]
γ-ray spectrometry	^{60}Co	0.11 ± 0.07
	^{125}Sb	<0.30
	^{134}Cs	<0.11
	^{137}Cs	0.32 ± 0.10
	^{154}Eu	12 ± 2
	^{155}Eu	3.3 ± 0.6
	^{241}Am	17 ± 2
α-ray spectrometry	^{241}Am	20 ± 2
	^{243}Am	<1.3
	^{244}Cm※2	7.9 ± 0.8
ICP-MS/MS	^{90}Sr	(1.7 ± 0.5) × 10^{2}

※1 Values as of the measurement date. Unity is a synthesis of the uncertainty pertaining to calibration, counting, γ-ray emission rate, batching, weighing, diluting to volume, and measurement system fluctuations, and is represented as expanded uncertainty multiplied by a coverage factor (k=2).

The dates for each analysis method are as follows:
- γ-ray spectrometry ： June 12, 2026
- α-ray spectrometry ： May 18, 2026
- ICP-MS/MS(^{90}Sr) ： April 8, 2026

※2 ^{244}Cm was solely assessed under the assumption that the amount of radioactivity from ^{244}Cm is sufficiently large even though the ^{243}Cm peak cannot be separated using α-ray spectrometry

◆JAEA Ooarai Nuclear Engineering Research Solution analysis (1/2)

○Element content → Chart 1

Analysis method (summary)

1) The analysis specimen (Chunk A-2:11.9mg) was dissolved in heated nitric acid (a very small amount of hydrofluoric acid was also added).
2) The solution was filtered through a PC membrane filter (pore diameter: 0.45μm) and the residue on top of the filter was recovered while the filtered liquid was diluted to volume to prepare the solution.
3) The calibration curve method was used with ICP-MS to measure the mass of the targeted nuclide in the obtained solution, and nuclide mass was converted to element mass using fuel composition[1] and natural isotope composition as references.
4) Since approximately 8% of the input mass ended up as undissolved residue (primarily Fe-Cr oxide), the element content was assessed using SEM-WDX/EDX and the mass of elements contained in the undissolved residue was estimated.
5) The element content of the sample was assessed by combining the element mass analysis value for the solution with estimated element mass in the undissolved residue.

Figure Dissolving with nitric acid and a small amount of hydrofluoric acid

Chart 1 Element content analysis values
Solution (ICP-MS) + Residue (SEM-WDX/EDX)

Weight of the specimen under test: 11.9mg. Expanded uncertainty of k=2

Element	Element content※1 [mg/100mg specimen]	Notes (Measured mass※2 etc.)
U	43.2 ± 0.9	Atomic mass: Total of 234, 235, 236, 238
Zr	23 ± 2	Measured mass:90
Fe	9.8 ± 0.6	Measured mass:57
Cr	1.52 ± 0.08	Measured mass:52
Ni	0.2 ± 0.1	Measured mass:60
Si	0.2 ± 0.1	Only detected in residue
Ca	2 ± 2	Measured mass:44. Below the quantitative limit
Al	0.07 ± 0.03	Only detected in residue
Mg	0.1 ± 0.1	Only detected in residue
Ti	0.10 ± 0.01	Measured mass:47
Mn	0.38 ± 0.04	Measured mass:55
Mo※3	0.02 ± 0.03	Measured mass:97
Nd※4	0.13 ± 0.01	Measured mass:146
Gd※4	0.4 ± 0.3	Measured mass:157

※1 Analysis value uncertainty is a synthesis of the uncertainty associated with ICP measurement, specimen weighing, diluting to volume of the solution, calibration standard solution and dilution, and is represented as expanded uncertainty multiplied by a coverage factor (k=2).

※2 Mass numbers that have no isobars or mass numbers that have been impacted very little by isobars based on the count before and after were selected.

※3 Mo is a reference value since it is assumed that the isotope composition differs from the natural isotope composition

※4 Nd and Gd were converted to element mass using fuel composition since the isotope ratio was close to the fuel composition of Unit 2

[Reference] 2nd Fuel debris solution analysis results
Element content/Isotope ratio/Radioactivity concentration

◆JAEA Ooarai Nuclear Engineering Research Solution analysis (2/2)

○ Isotope ratio （U） → Refer to Chart 1

- The nuclide mass of ^{234}U, ^{235}U, ^{236}U and ^{238}U in the solution batched and diluted from the original solution was measured using the ICP-MS and the calibration curve method, and calculated as a ratio of the total of these isotopes.

○ Radioactivity concentration

- γ-ray spectrometry → Refer to Chart 2
  - ^{60}Co, ^{125}Sb, ^{137}Cs, ^{154}Eu and ^{241}Am were detected in the solution. (Figure 1 above. The same nuclides as those in the non-destructive analysis results were detected)
  - The same nuclides were detected in the undissolved residue, but the relative intensity of ^{60}Co was high (Figure 1 below)

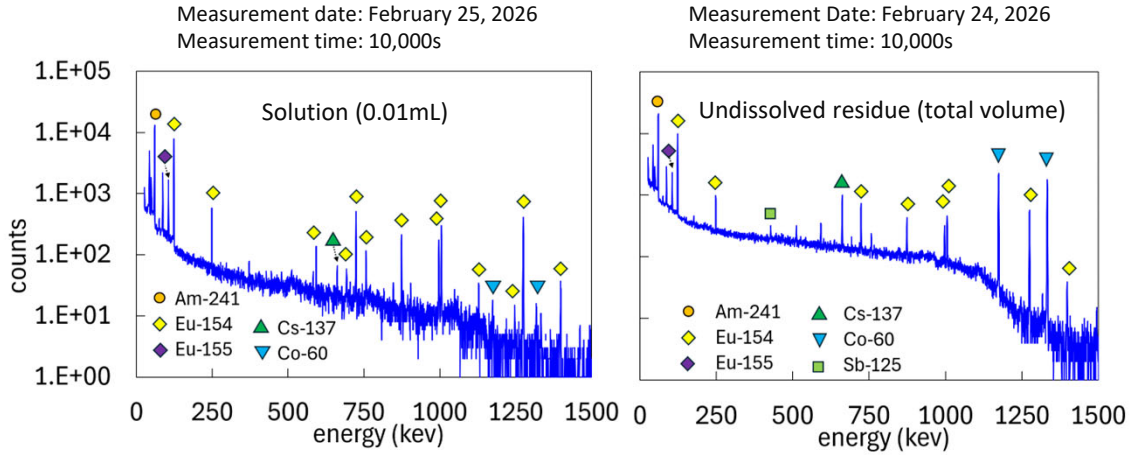


Figure 1 γ-ray spectrum Left: Solution Right: Undissolved residue

Chart 1 U Isotope composition analysis results

Expanded uncertainty of k=2

Nuclide	Isotope composition ※1 [at%]
^{234}U	0.027 ± 0.001
^{235}U	2.044 ± 0.004
^{236}U	0.29 ± 0.002
^{238}U	97.6 ± 0.2

※1 Ratio of U = $^{234}U+^{235}U+^{236}U+^{238}U$
Analysis value uncertainty is a synthesis of the uncertainty associated with the control liquid and calibration curve method, and is represented as expanded uncertainty multiplied by a coverage factor (k=2).

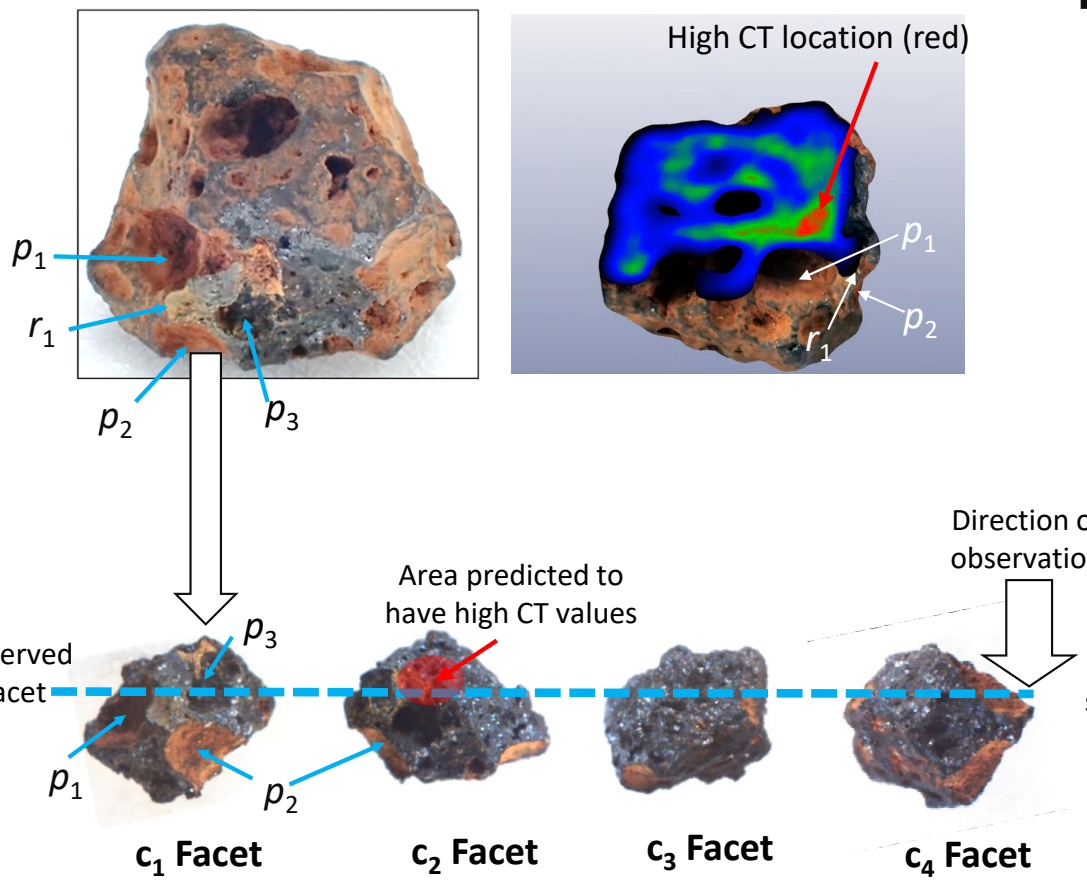
Chart 2 Radioactivity concentration assessment results

Weight of the specimen under test: 11.9mg. Expanded uncertainty of k=2

Nuclide	Radioactivity concentration※1 [MBq/g specimen]
^{60}Co	0.11 ± 0.03
^{125}Sb	<0.3
^{134}Cs	<0.2
^{137}Cs	0.19 ± 0.06
^{154}Eu	14 ± 4
^{155}Eu	4 ± 1
^{241}Am	20 ± 5

Observation location selection

【External appearance attributes used to ascertain the positional relationship】
p_1 - p_3 : Pit, r_1 : Ridge



After pulverization：**Chunk C**

Figure 1 General positional relationships of the second fuel debris sample prior to and after pulverization

- **Chunk C**, for which the positional relationship of the sample was relatively easy to ascertain prior to and after pulverization, was used for cross-sectional observation.（Figure 1）
- In consideration of the possibility that unmelted fuel (UO_2) may exist, an X-ray CT scan of the sample prior to pulverization was used to identify high CT locations, along which the fracture line of the cross-section was created, and that cross-section was observed（Figure 2 ）

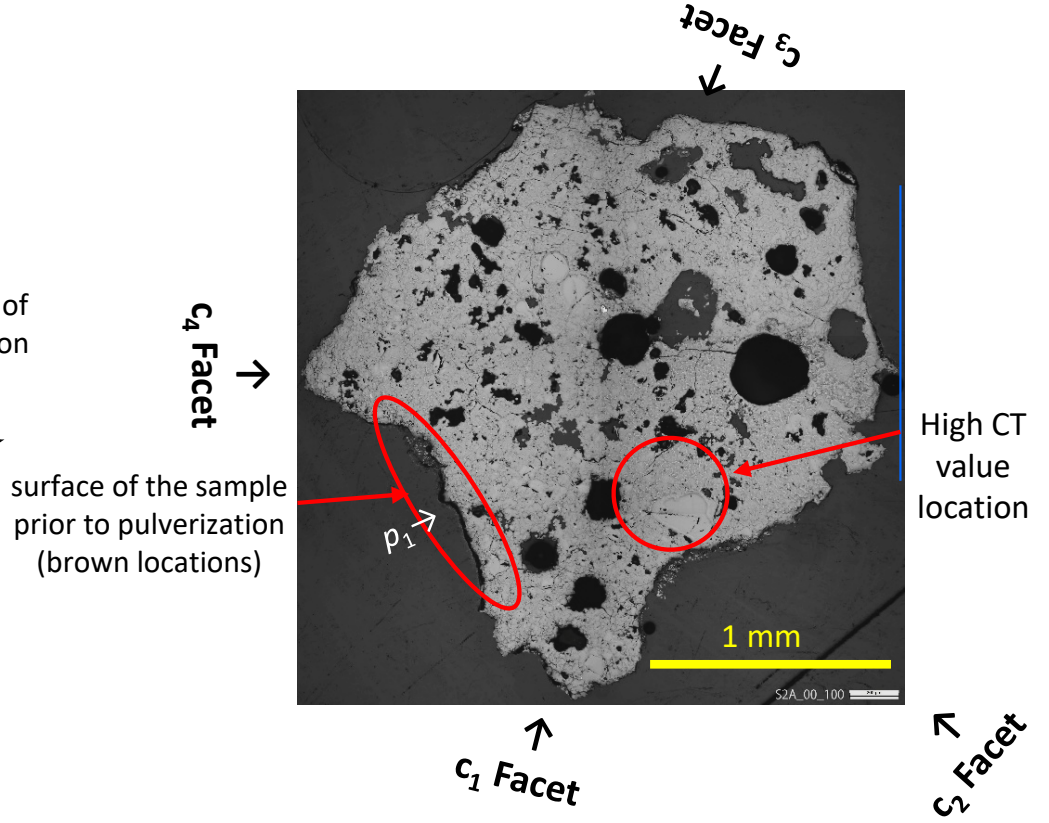
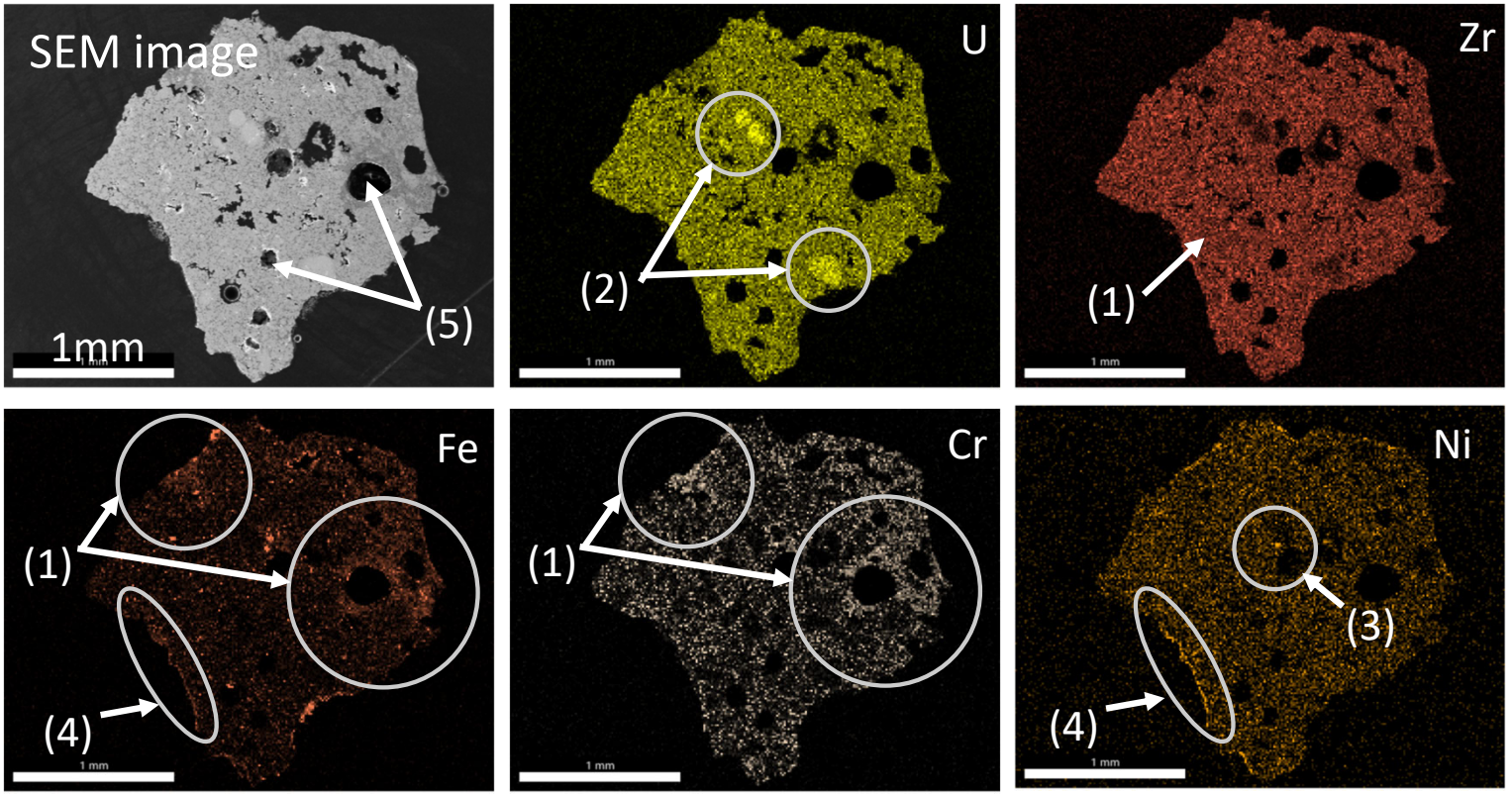


Figure 2 Optical microscope image of a cross-section of **Chunk C**

General region classifications based on cross-sectional observation and element distribution



- Define structure observation was conducted of regions that showed unique element distributions (1)-(5), and assessments were made about formation process of each region (Refer to the following pages)

Chunk C Element distribution of the entire cross-section (EDX element mapping)

【Classification results】

(1) Zr, and U are widely distributed throughout the entire sample and there is one Zr-U-O island less than several 10s - 100μm in size. Fe and Cr are distributed in the gap. There is an uneven distribution of Fe and Cr near the void. ⇒ **Fine mixed region**

(2) A clear region of highly concentrated U approximately 100μm in size is present in the high CT value area ⇒ **Coarse U-Zr-O**

(3) There is one small Fe-Ni near the center. ⇒ **Fe-Ni**

(4) There are relatively large amounts of Fe and Ni in the area that corresponds to the outermost surface of the sample. ⇒ **Surface layer**

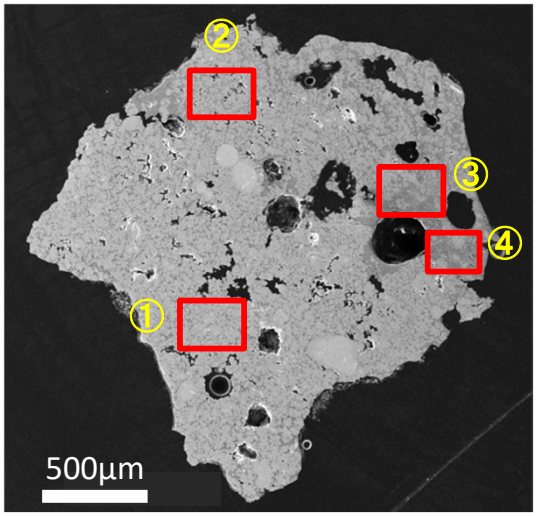
(5) There are voids of various sizes, shapes, and dimensions distributed throughout the entire cross-section ⇒ **Void**

[Reference] 2nd Fuel debris sample solid analysis results

Fine structure of each region and estimates about the formation process（3/9）

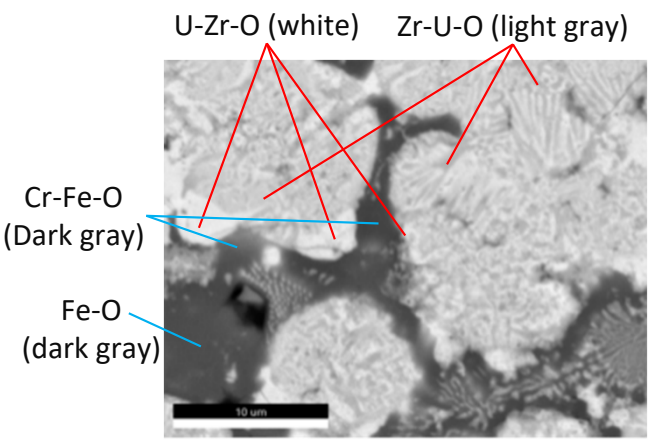
Fine mixed region

Chunk C



Complete SEM image

SEM image



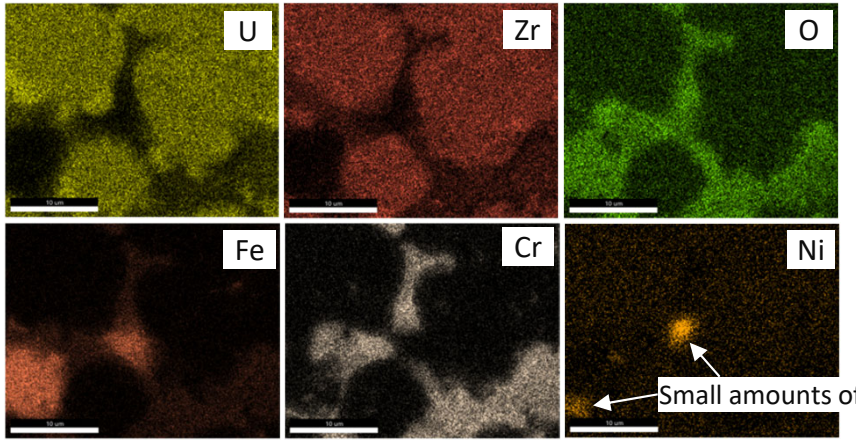
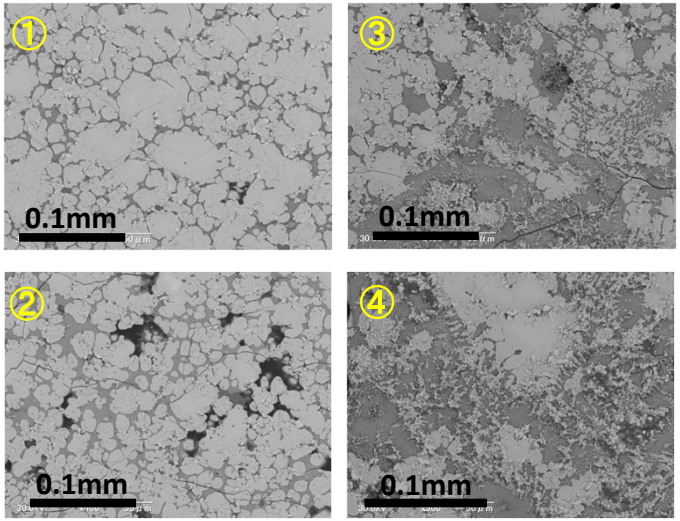


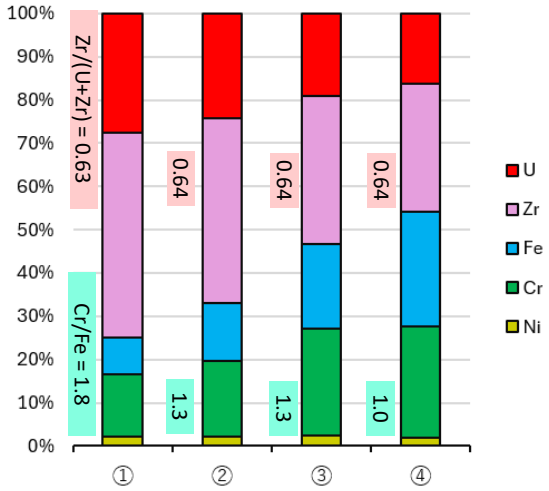
Figure 1　Typical example of fine mixed region element distribution



Region with a lot of U/Zr
(①②)

Region with a lot of Fe/Cr
(③④)

The Zr/(U+Zr) ratio Is fairly constant regardless of location, but the Cr/Fe ratio differs by location



Element composition of each visual field
(SEM-EDX Surface analysis results for each visual field)

Figure 2　Composition of each fine mixed region

- There are mainly 4 types of phases in the fine mixed region: Zr-U-O, U-Zr-O, Cr-Fe-O and Fe-O, but there is a mixture of various sizes from less than 1μm to several 10sμm（Figure 1）
- On a macro scale the sample can be divided into regions with a lot of U/Zr and regions with a lot of Fe/Cr（Figure 2 ）

➢ Since it is possible that temperature ranges within which each region formed differ, TEM was used to examine the structural phases of each region and make assessments about the differences in the formation process (See the next page)

[Reference] 2nd Fuel debris sample solid analysis results

Fine structure of each region and estimates about the formation process（4/9）

Fine mixed region（Region with a lot of U/Zr）

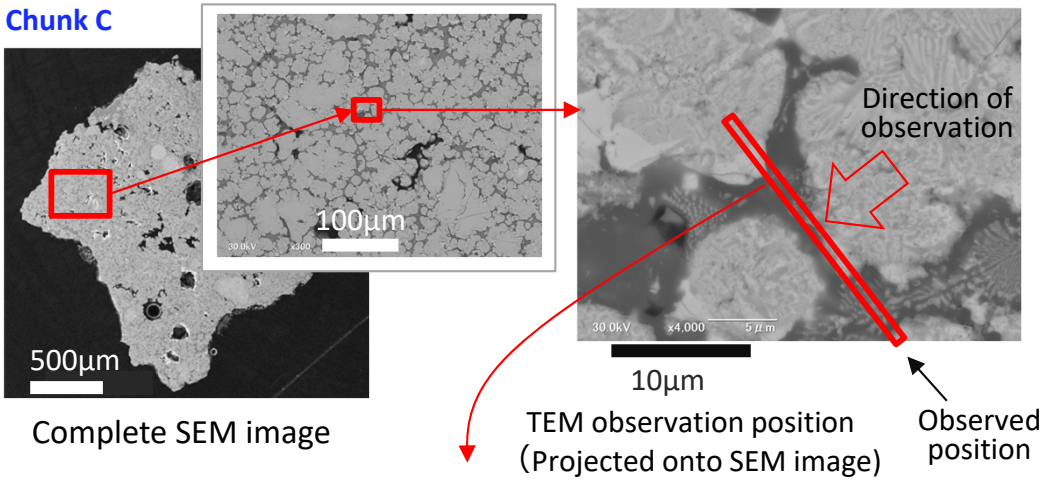


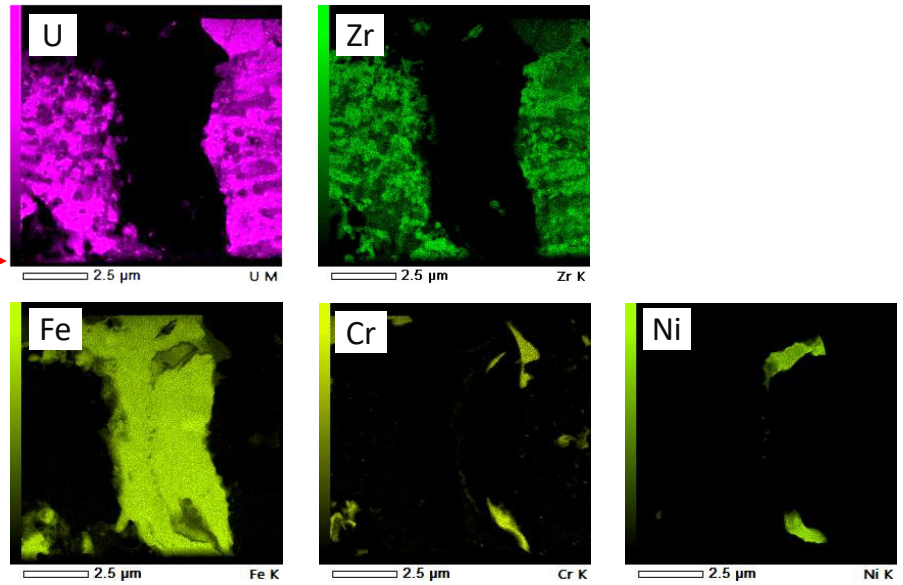
Figure Fine mixed region (region with a lot of U/Zr) structure phase (TEM analysis results)

- The Zr-U-O island several 10s μm in size seen under magnification was found through TEM observation to be a mixture of cubic crystals $(U,Zr)O_2$ and tetragonal crystals $(Zr,U)O_2$ less than approx. 1μm in size.

➢ The cubic crystal＋tetragonal crystal mixed phase, was either formed during solid phase separation or directly deposited from the molten material.

- There are Fe_3O_4 spinels and $FeCr_2O_4$ spinels around the Ni-Fe metal phase

➢ It is assumed that the aforementioned region was formed as Cr and Fe, which are elements in Fe-Cr-Ni structural materials (stainless steel, etc.) and which oxidize easily, oxidized in succession.

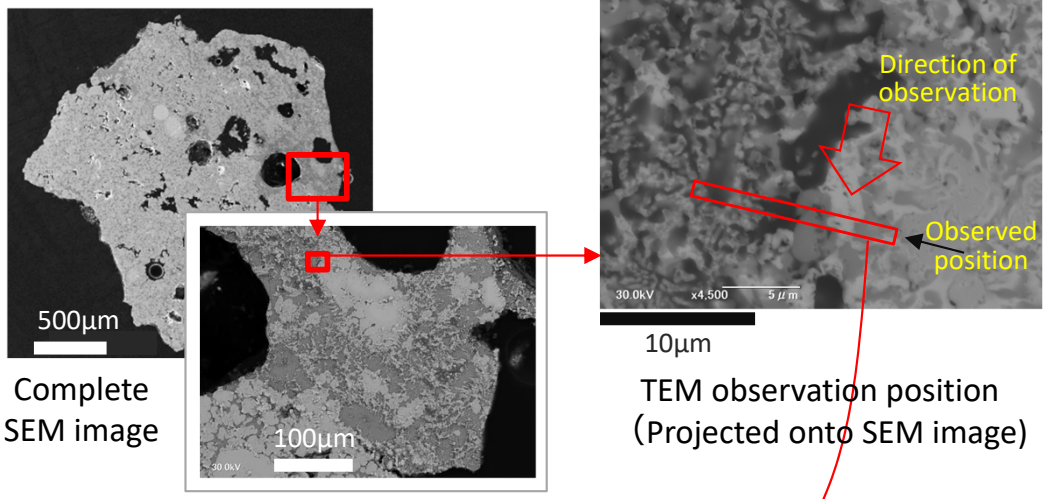


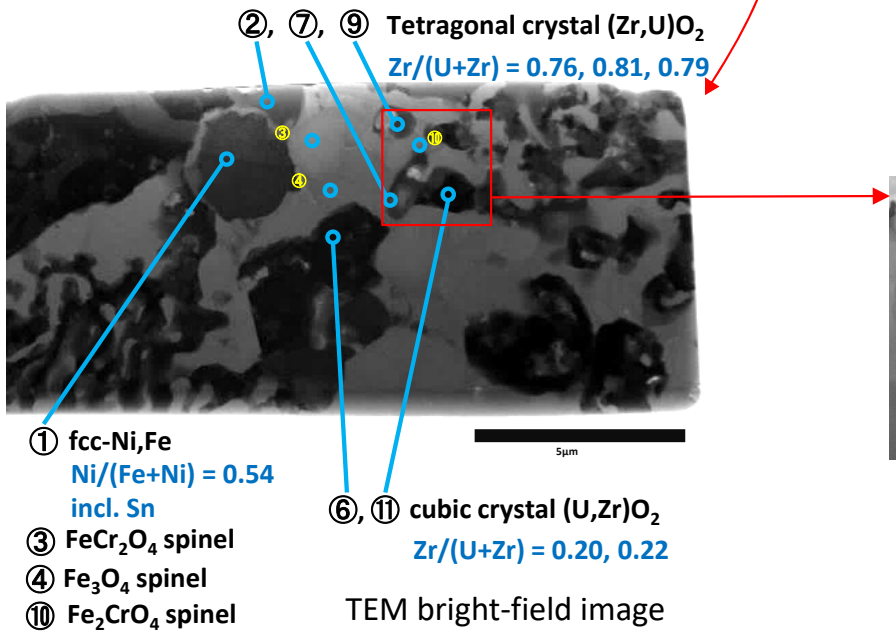
Primary element distribution (STEM-EDX surface analysis)

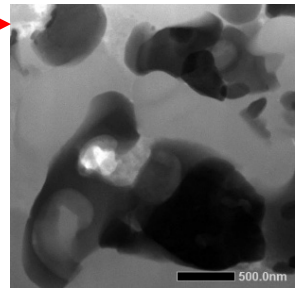
[Reference] 2nd Fuel debris sample solid analysis results
Fine structure of each region and estimates about the formation process（5/9）

Fine mixed region（Regions with a lot of Fe/Cr）

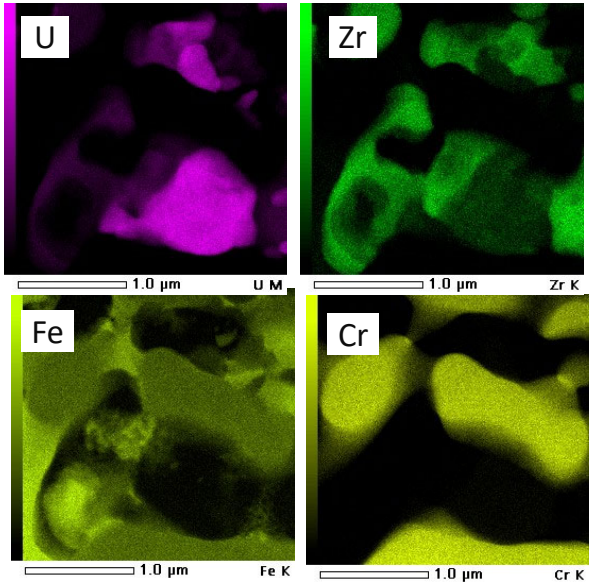
Chunk C







Enlargement of element distribution
(STEM-EDX surface analysis)



- The identified compounds were for the most part the same as those in areas with a lot of U/Zr (see the previous page) (Figure 1)
- Compared with regions that have a lot of U/Zr (See the previous page), there are large differences in the composition of material between the cubic crystals $(U,Zr)O_2$ and tetragonal crystals $(Zr,U)O_2$
  - ✓ Zr/(U+Zr) ratio of regions with a lot of U/Zr (refer to the previous page)

    Approx. 0.2–0.3 (cubic crystal) | Approx. 0.6–0.7 (tetragonal crystal)
  - ✓ Zr/(U+Zr) ratio of regions with a lot of Fe/Cr (refer to Figure 1)

    Approx. 0.2 (cubic crystal) | Approx. 0.8 (tetragonal crystal)

➢ It is possible that the aforementioned regions were formed in a temperature range that differs from areas with a lot of U/Zr.

Figure 1 Fine mixed region (region with a lot of U/Zr) structure phase (TEM analysis results)

Coarse U-Zr-O

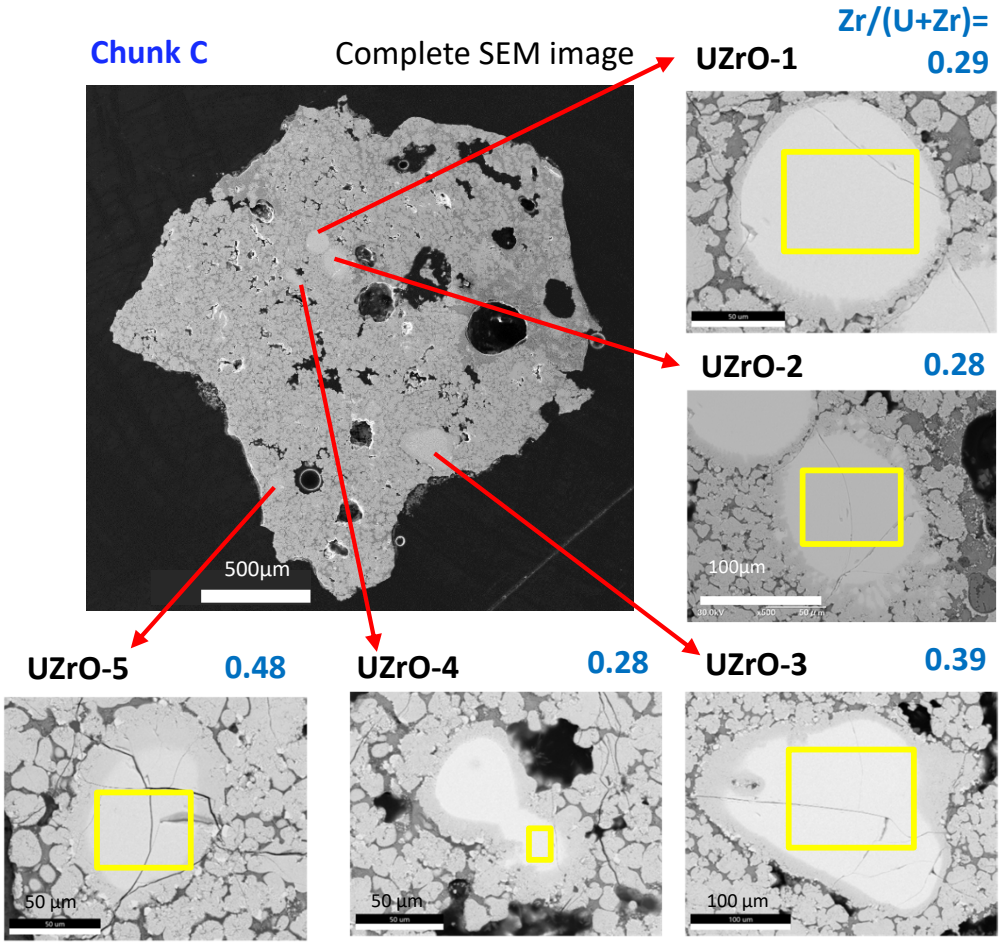


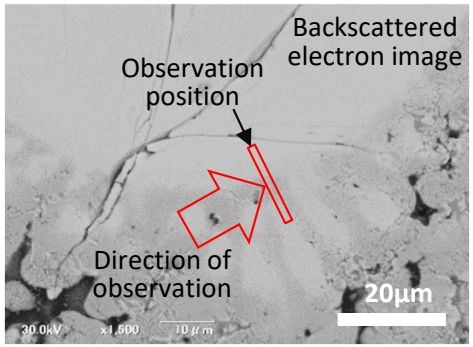
Figure SEM Observation results that focus on the coarse U-Zr-O phase

- There is a densely packed region of coarse U-Zr-O circles approx. 50- more than 100µm in size scattered throughout the fine mixed region
  - ✓ There is a fine mixed region separate from the phase with a high concentration of Zr in the periphery
  - ✓ The concentration of U in the phase is high. The Zr/(U+Zr) ratio near the center of each particle is between approx. 0.3–0.5, and differs depending on the particle
- It is assumed that when the course U-Zr-O formed, the surrounding fine mixed region was still in a liquid phase state.
- The U to Zr concentration ratio within each particle is almost constant, indicating that each particle most likely grew within approximately the same temperature range

➢ In order to examine the state of the molten material when coarse U-Zr-O formed, TEM was used to perform a detailed observation of the area bordering the fine mixed region (See the next page)

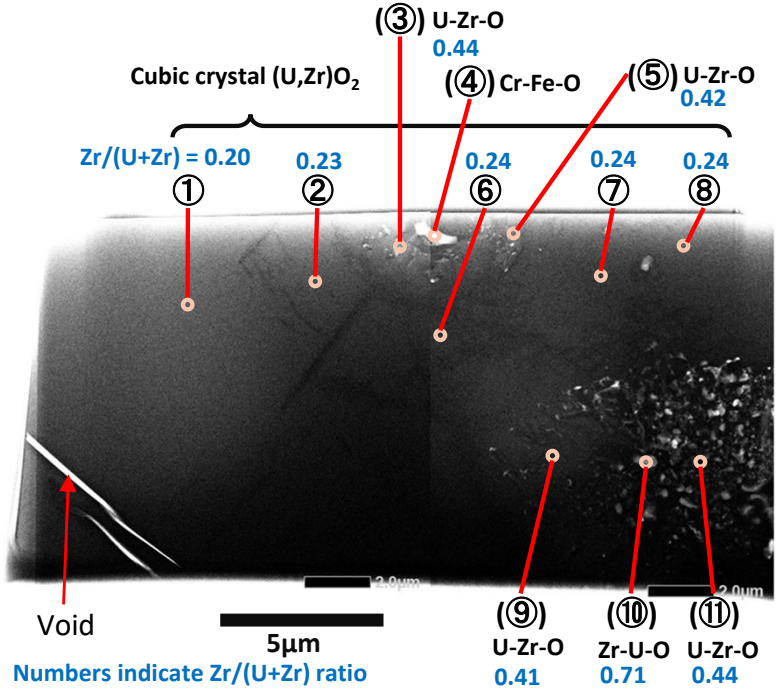
Coarse U-Zr-O

Chunk C



"UZrO-2," Which has a unique shape around the border of the fine mixed region, was focused on and a sample was taken near the boundary for TEM observation

TEM observation position
(Projected onto SEM image)



TEM Bright-field image of the coarse U-Zr-O

Figure 1 Coarse U-Zr-O structure phase
(TEM Analysis results)

- A cubic crystal $(U,Zr)O_2$ phase with a high concentration of U spreads out towards the edge in a dendritic pattern (Figure 1/Figure 2)
- It is possible that the dendritic part of the inside of coarse U-Zr-O is a monoclinic crystal (Figure 3). Surrounding phases consist of areas with slightly high concentrations of Zr between the dendritic shapes (Figure 1 ③, ④, ⑨~⑪)。

➢ It is possible that when the surrounding fine mixed region was melting, the crystal grew into a dendritic shape or there was Zr, etc. intrusion from the liquid phase.

A dendritic shape can be seen spreading from the inside towards the outer edge

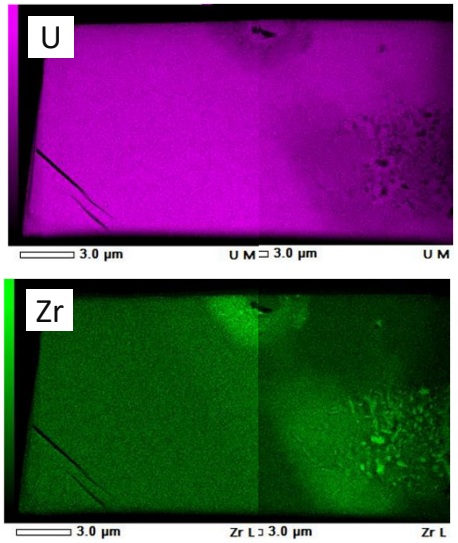
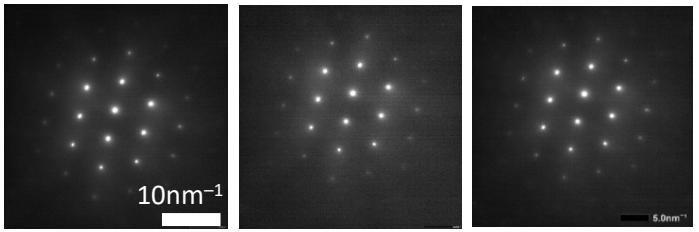


Figure 2 U/Zr distribution
(STEM-EDX surface analysis)

The diffraction patterns of positions ①, ②, ⑥, ⑦, and ⑧ indicate the same crystal system/ crystal direction, and it is possible that these are monoclinic crystals.



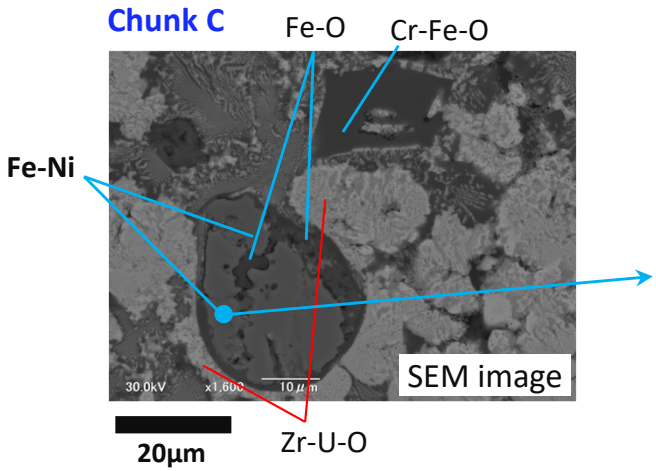
① Cubic crystal UO_2 Direction $[1\,1\,\bar{4}]$ ⑥ Cubic crystal UO_2 Direction $[1\,1\,\bar{4}]$ ⑧ Cubic crystal UO_2 Direction $[1\,1\,\bar{4}]$

Figure 3 Example of the electron diffraction pattern

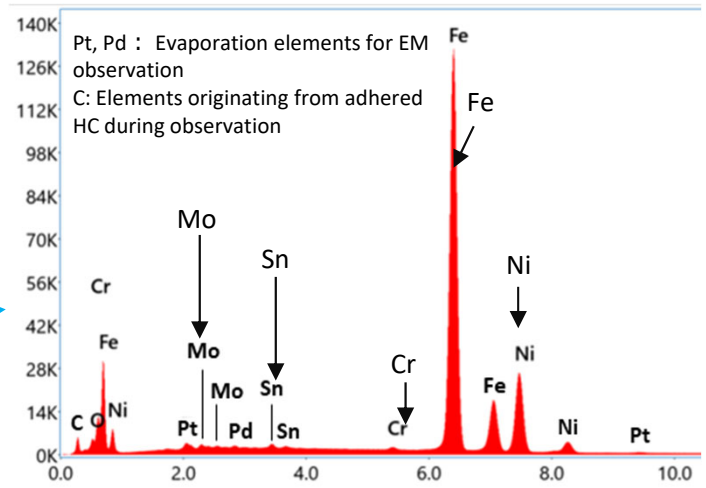
[Reference] 2nd Fuel debris sample solid analysis results

Fine structure of each region and estimates about the formation process（8/9）

Fe-Ni metal phase



EDX point analysis spectrum from above the metal phase



- Fe-Ni metal grains several μm-approx. 20μm in size are scattered throughout the flying mixed region and surrounded by Fe-O and Cr-Fe-O.
- Each grain has a different composition

Figure 1 SEM observation results from near the Fe-Ni metal phase

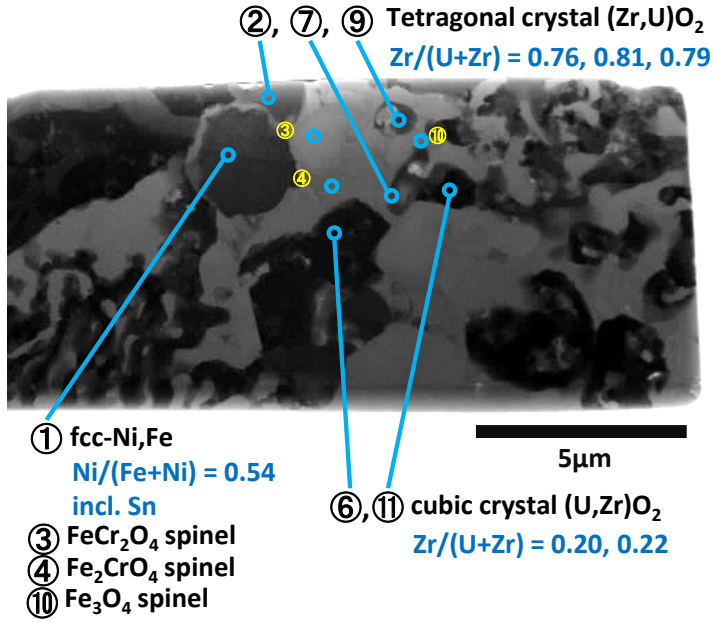


Figure 2 Fine mixed region TEM observation results
（Figure 1 is of area near a different metal phase）

- It is assumed that during the melting and solidification process, Cr and Fe, which are elements originating from structural materials (Fe, Cr, Ni), oxidized first thereby leaving a metal phase with a high concentration of Ni.

Surface layer

Chunk C

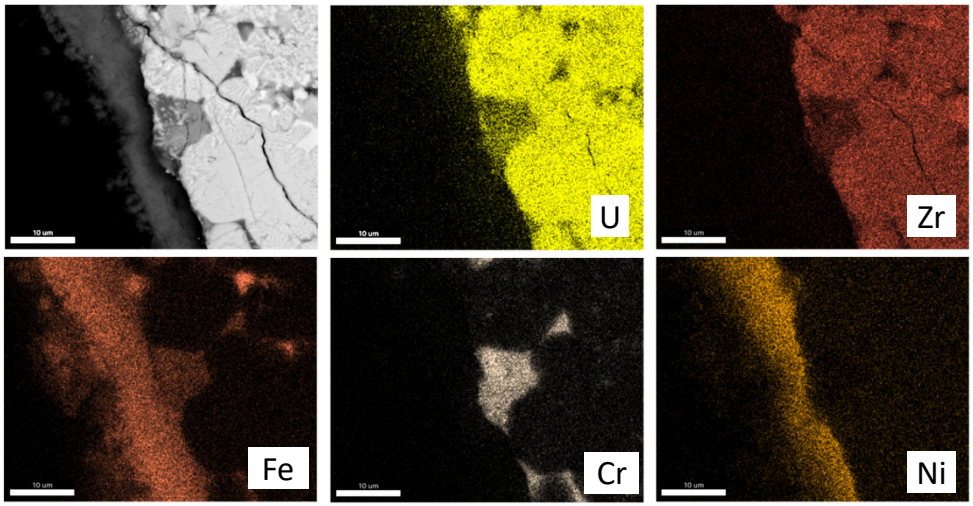


Figure 1 SEM observation from near the surface of the sample

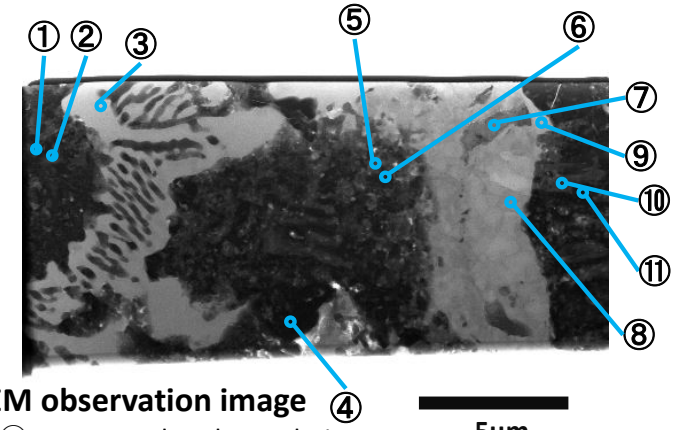
■ The outermost surface of the sample when received was formed from layers and deposits approximately approx. 10 - 50μm thick.

➢ After most of the sample was formed through melting and solidification, dissolved constituents in the cooling water were deposited on the surface of the sample thereby altering the surface

TEM fine structure assessment flow（1/2）

◆ Assessment of the element composition of each phase using STEM-EDX

Fine mixed region (regions with a lot of U/Zr)

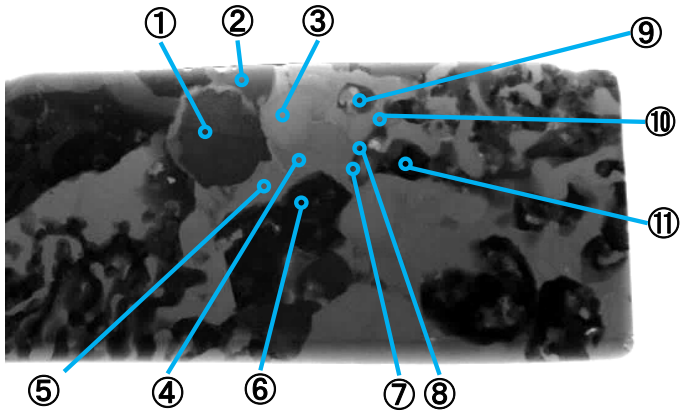


TEM observation image
(①～⑪ correspond to the analysis locations in the left graph)

The composition of each phase from STEM-EDX point analysis ※

at%	O	Al	Cr	Fe	Ni	Zr	Sn	Pb	U	U/(U+Zr)at%	Classification
①	63	n.d.	1	n.d.	n.d.	8	n.d.	n.d.	28	77	U-Zr-O
②	62	n.d.	1	n.d.	n.d.	24	n.d.	n.d.	13	36	Zr-U-O
③	58	L.O.Q.	30	12	n.d.	L.O.Q.	L.O.Q.	n.d.	n.d.		Cr-Fe-O
④	71	n.d.	L.O.Q.	n.d.	n.d.	9	n.d.	n.d.	20	69	U-Zr-O
⑤	76	n.d.	L.O.Q.	n.d.	n.d.	17	n.d.	n.d.	7	28	Zr-U-O
⑥	74	n.d.	n.d.	n.d.	n.d.	7	n.d.	L.O.Q.	19	74	U-Zr-O
⑦	3	n.d.	n.d.	30	67	n.d.	n.d.	n.d.	n.d.		Ni-Fe
⑧	64	n.d.	n.d.	36	n.d.	n.d.	n.d.	n.d.	n.d.		Fe-O
⑨	61	n.d.	27	12	n.d.	n.d.	n.d.	n.d.	n.d.		Cr-Fe-O
⑩	76	n.d.	L.O.Q.	n.d.	n.d.	15	n.d.	n.d.	9	37	Zr-U-O
⑪	73	n.d.	n.d.	n.d.	n.d.	8	n.d.	n.d.	19	71	U-Zr-O

Fine mixed region (regions with a lot of Fe/Cr)



TEM observation image
(①～⑪ correspond to the analysis locations in the left graph)

The composition of each phase from STEM-EDX point analysis ※

at%	O	Si	Cr	Fe	Ni	Zr	Sn	U	U/(U+Zr)	Classification
①	L.O.Q.	n.d.	n.d.	45	54	n.d.	1	n.d.		Ni-Fe
②	82	n.d.	L.O.Q.	1	n.d.	13	n.d.	4	24	Zr-U-O
③	70	n.d.	19	11	n.d.	L.O.Q.	n.d.	n.d.		Cr-Fe-O
④	76	2	L.O.Q.	20	n.d.	2	n.d.	L.O.Q.		Fe-O
⑤	75	2	L.O.Q.	21	n.d.	2	n.d.	L.O.Q.		Fe-O
⑥	75	n.d.	L.O.Q.	n.d.	n.d.	5	n.d.	20	80	U-Zr-O
⑦	85	n.d.	L.O.Q.	6	n.d.	7	n.d.	2	19	Zr-Fe-U-O
⑧	87	n.d.	L.O.Q.	1	n.d.	9	n.d.	3	24	Zr-Fe-U-O
⑨	84	n.d.	L.O.Q.	1	n.d.	12	n.d.	3	21	Zr-U-O
⑩	72	n.d.	6	20	n.d.	2	n.d.	n.d.		Fe-Cr-O
⑪	76	n.d.	L.O.Q.	n.d.	n.d.	5	n.d.	19	78	U-Zr-O

※ With the exception of elements for which it is noted n.d. or LOQ, the numbers reflect the percentage of each element from 100%.

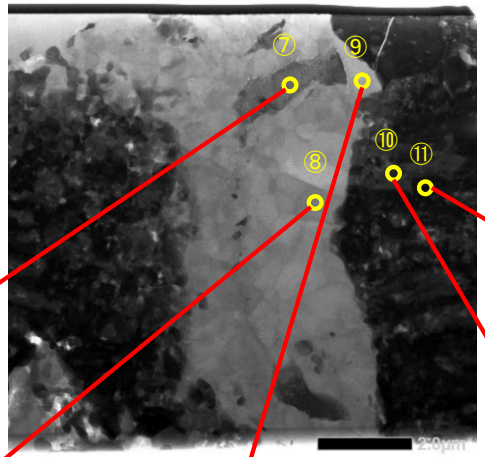
- n.d.: Indicates that no significant amounts were detected in the spectrum (“not detected”)
- L.O.Q.: Lower limit of quantification. Whereas a small peak was seen in the spectrum, it was determined that quantity was below the lower limit of quantification which is less than 0.5at%

[Reference] 2nd Fuel debris sample solid analysis results
TEM fine structure assessment flow（2/2）

◆ TEM electron diffraction pattern measurements and crystalline structure identification through Raman spectroscopy

- A TEM electron diffraction pattern was obtained for each phase position seen in the fine mixed region and the crystalline system was identified. Furthermore, estimates were made about the chemical form based upon the composition analysis results for each position mentioned on the previous page（Figure 1）
- In addition to the electron diffraction, Raman spectroscopy (Figure 2) was used as necessary to improve the accuracy of crystalline structure identification.

STEM image of the fine mixed region
（Right half of the region shown on the previous page）



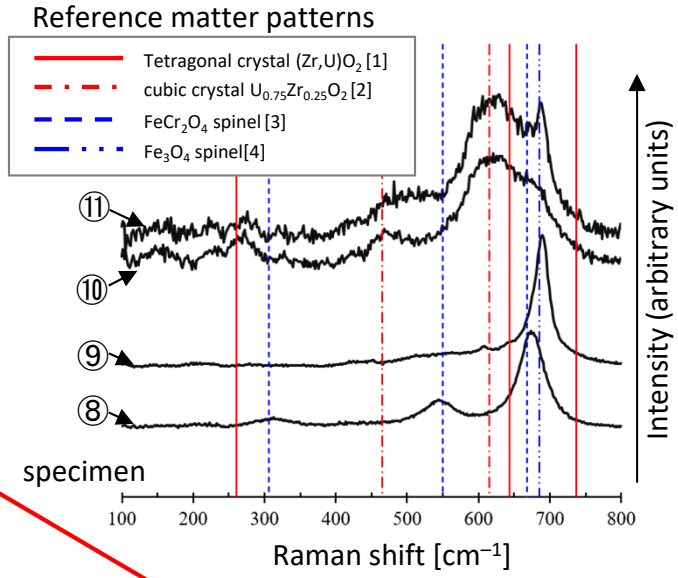


Figure 2 Raman spectroscopy results for each phase

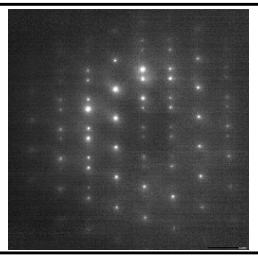
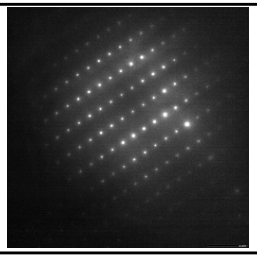
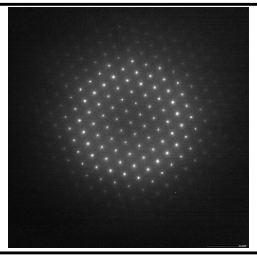
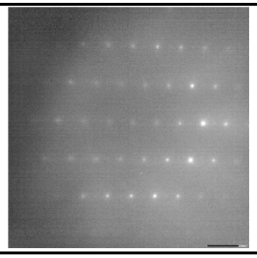
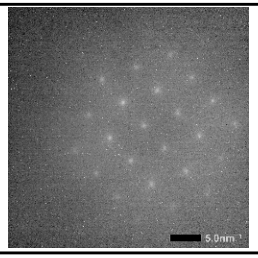
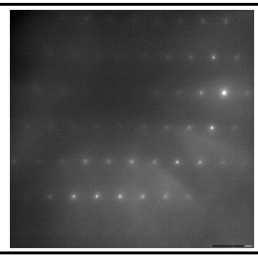
Position	⑦Ni-Fe	⑧Fe-O	⑨Cr-Fe-O	⑩Zr-U-O		⑪U-Zr-O
TEM Electron diffraction pattern						
Crystal system identification result	**fcc-(Ni,Fe) Direction $[0\ \bar{1}\ 1]$**	**Fe_3O_4 spinel Direction $[1\ \bar{1}\ 2]$**	**$FeCr_2O_4$ spinel Direction $[0\ 1\ \bar{1}]$**	**Tetragonal crystal ZrO_2 Direction $[\bar{3}\ 3\ 1]$**	**Tetragonal crystal ZrO_2 Direction $[1\ \bar{4}\ \bar{2}]$**	**Cubic crystal UO_2 Direction $[0\ 1\ \bar{3}]$**
Of chemical form made based on the composition analysis	**fcc-(Ni,Fe)**	**Fe_3O_4 spinel**	**$FeCr_2O_4$ spinel**	Tetragonal crystal $(Zr,U)O_2$		cubic crystal $(U,Zr)O_2$

Figure 1　TEM Electronic diffraction pattern for each analysis position and estimates of the chemical form based on composition analysis

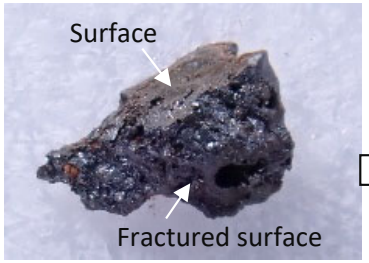
[1] Gibert-Mougel C, et al., J. Nucl. Mater., 295, (2001), 121–125.　[2] Kumagai Y, et al., J. Nucl. Mater., 625, (2026), 156553.
[3] McCarty KF and Boehme DR, J. Solid State Chemistry, 79, (1989), 19–27.　[4] Chicot D, et al., Mater. Chem. Phys., 129, (2011), 862–870.

[Reference] 2nd Fuel debris sample solid analysis results
The fine structure of other pulverized fragments （1/2）

◆ Comparison of multiple batched specimens

SEM and TEM Used to perform a detailed observation of not just Chunk C but the other batched specimens as well, and it was confirmed that they have the same element distribution and crystalline structure.

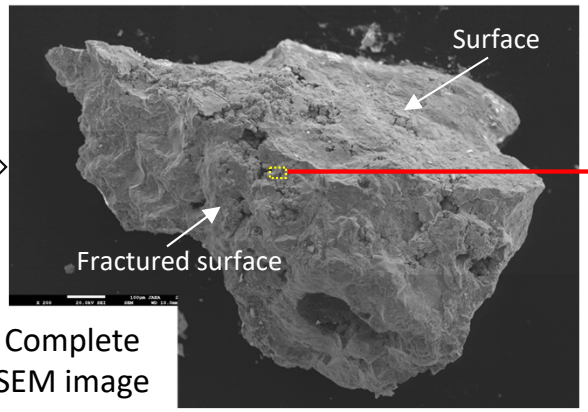
Chunk A-1



External appearance of pulverized fragment

500μm

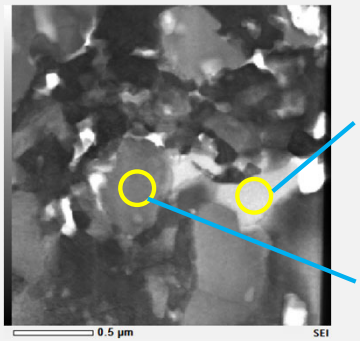
Observation of pulverized fragment



Complete SEM image

500μm

A thin film was fabricated from part of the fractured surface to prepare a specimen for TEM observation



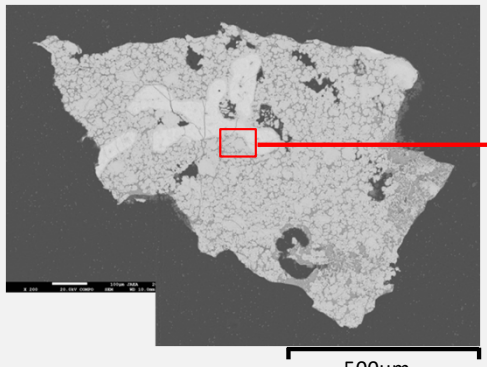
$(Fe,Cr)_3O_4$ spinel
Cr/(Fe+Cr)=0.71

Cubic crystal $(Zr,U)O_2$
Zr/(U+Zr)=0.60

0.5μm

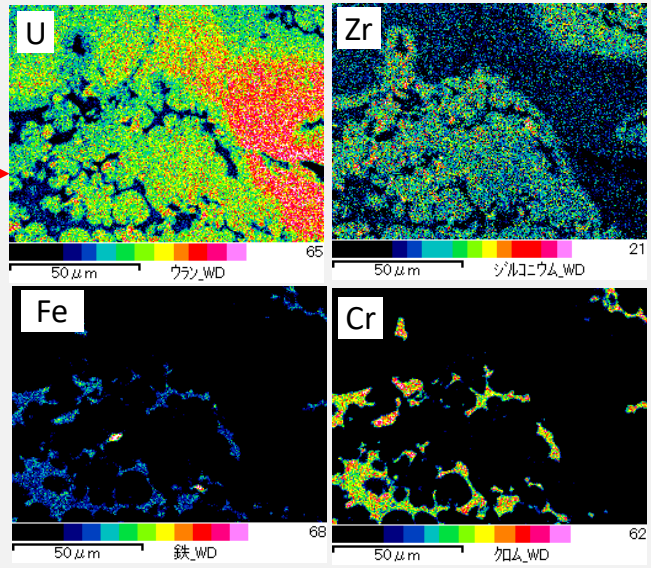
TEM image

A smooth surface was created in order to assess the element distribution over a wide area



SEM image of cross-section

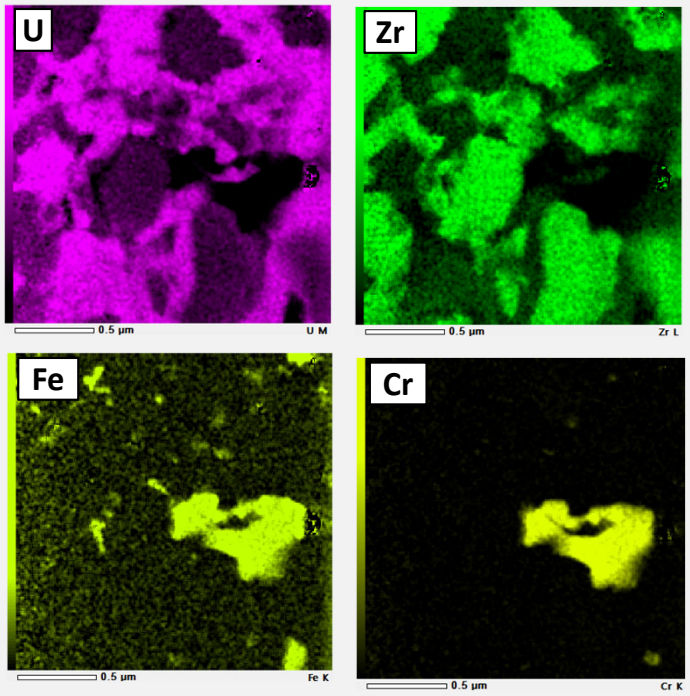
500μm



SEM-WDX mapping

A fine mixed region extends throughout the entire cross-section with sparsely scattered coarse U-Zr-O phases within (same attributes as Chunk C)

Element distribution in cross section of pulverized fragment （SEM-WDX）



STEM-EDX mapping

TEM observation results from thin film of cross-section

The fine structure of other pulverized fragments （2/2）

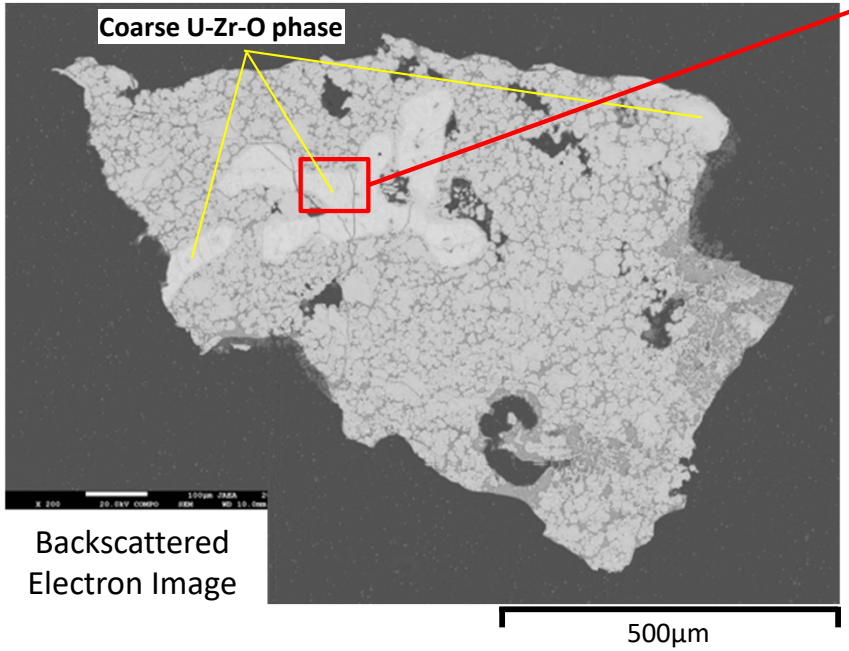
◆ SIMS assessment of localized U isotope ratio

SIMS was used to assess localized U isotope ratios in order to contribute to deliberations over the formation mechanism of the coarse U-Zr-O phase during the formation process of the second fuel debris sample.（Because if there is a remarkable difference between the isotope ratios of coarse U-Zr-O phase and the fine mixed region, it could be direct evidence that they have different origins)

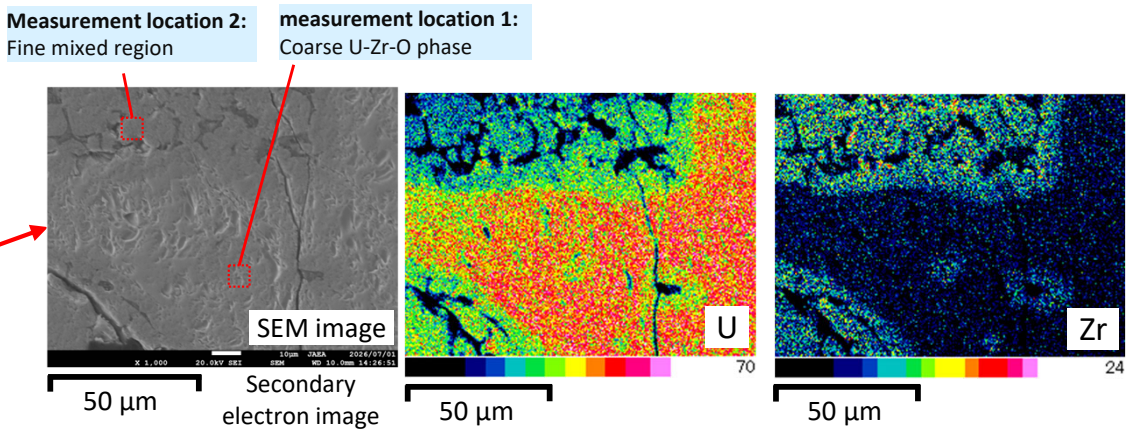
- No remarkable difference in the ratio of $^{235}U/^{238}U$ was found between the coarse U-Zr-O phase and the fine mixed region (both were approx. 2at%)
- No direct evidence about the origins of the coarse U-Zr-O phase was found at the measurement location, but we will continue to take measurements at other locations and analyze the sample in order to ascertain trends of localized isotope ratios.

ChunkA-1

Relatively small are in the fragment, but as with Clump C, the Coarse U-Zr-O phase is mixed with the Fine mixed region.

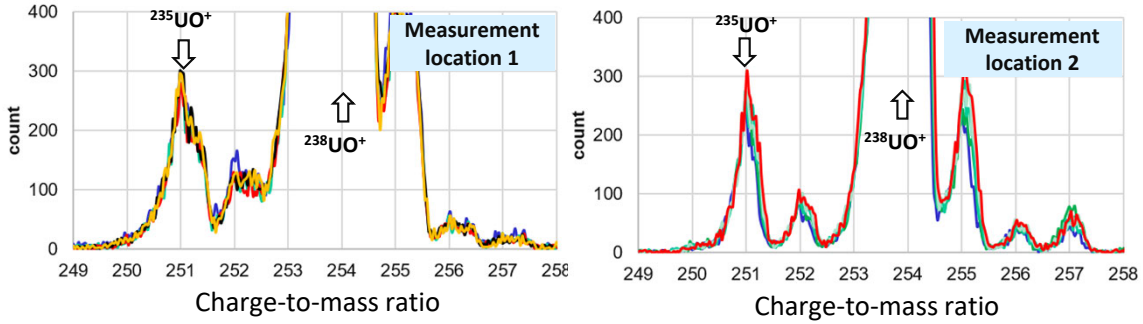


Chunk A-1 cross-section SEM image



Approximate location of SIMS measurements and element distribution in the surrounding（SEM-WDX）

※ Calculated from the intensity ratio of $^{235}UO^+$ and $^{238}UO^+$
（Measurements repeated five times）



Mass spectrum for each measurement location (SIMS measurement results)

[Reference] 2nd Fuel debris sample solid analysis results

Assessment of the chemical state of U, etc. using synchrotron radiation analysis（1/3）

◆ The aim of synchrotron radiation analysis:

To use μ-XRF/XRD/XAFS analysis that employs the High Intensity Synchrotron Radiation of Spring-8 to ascertain the primary constituent elements of the fuel debris sample as well as the distribution of those elements, as well as the chemical state of fuel elements, and crystalline structures

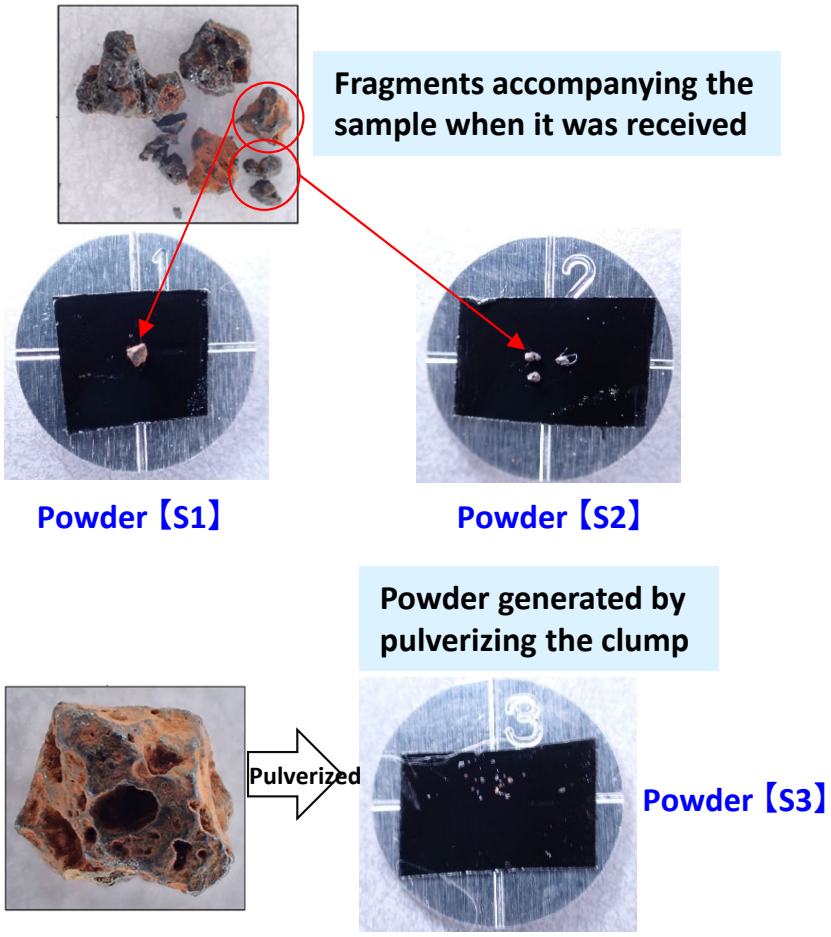
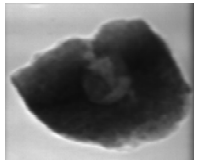


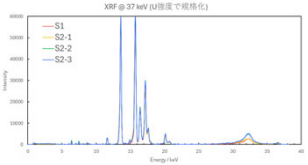
Figure The sample used for synchrony radiation analysis

Synchrotron radiation analysis (SPring-8) flow

Entire specimen analyzed using unfocused beam (2mm square)
（X-ray transmission image, XRF, XRD, XAFS）

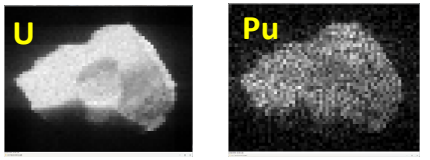
✓ General understanding of the attributes of the entire specimen
（Fine structure, constituent elements, crystalline structure, chemical state）


X-ray transmission image Powder【S2-2】


XRF example from unfocused beam

Constituent element of void distribution examined with μ-beam (1μm square) (XRF mapping)

✓ Constituent element void distribution examined
✓ Association between U and trace elements (Pe, etc.) found



Powder【S2-2】XRF mapping example

Crystalline structure and chemical state analyzed at specific specimen positions (μ-XRD, μ-XAFS point analysis)

✓ Ascertain crystalline structure and chemical state at specific specimen positions
✓ Ascertain phase differences between the surface and internal

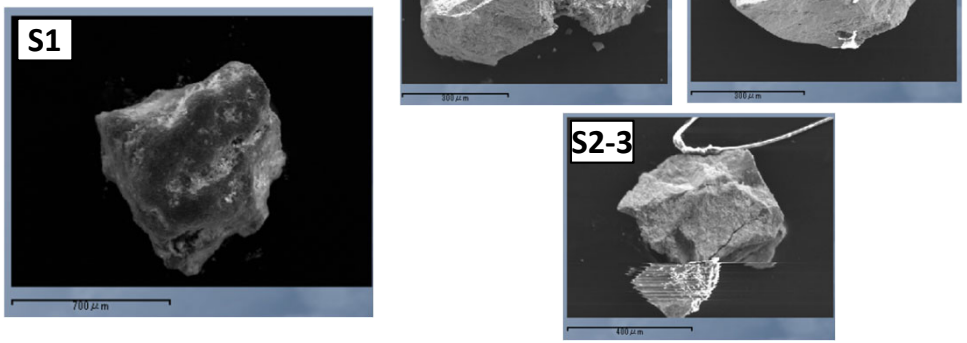
(※Use of imaging XAFS, and XRD mapping being deliberated)

[Reference] 2nd Fuel debris sample solid analysis results

Assessment of the chemical state of U, etc. using synchrotron radiation analysis（2/3）

◆ Ratio of primary elements in each sample

Fragments accompanying the sample when it was received



Powder generated during pulverization of the clump

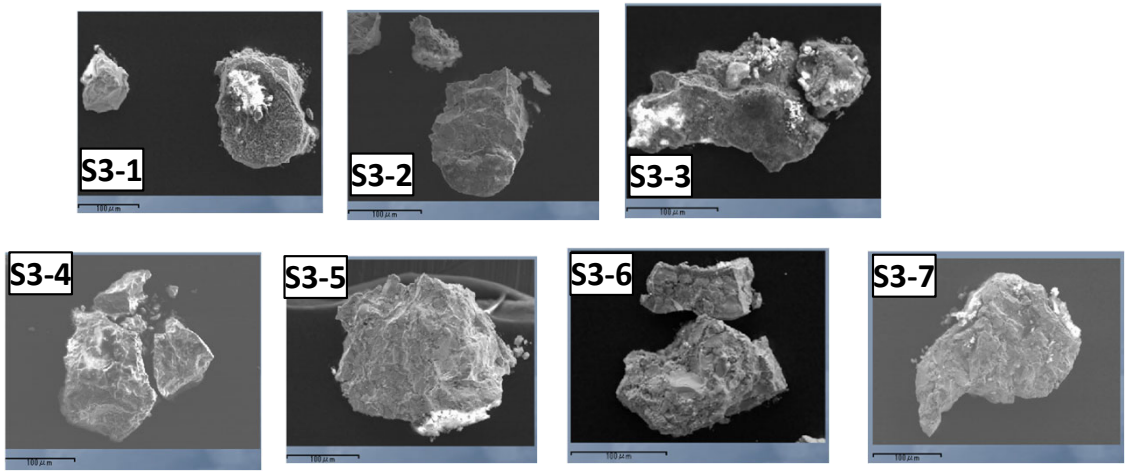
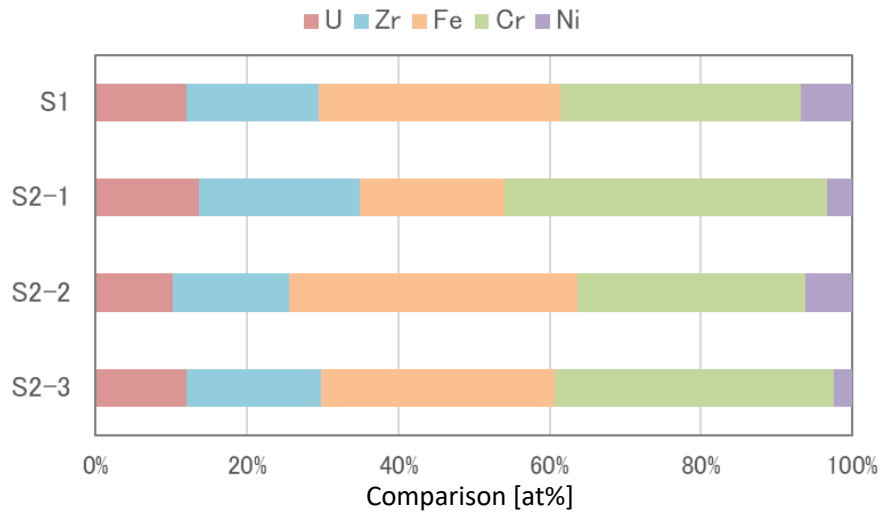
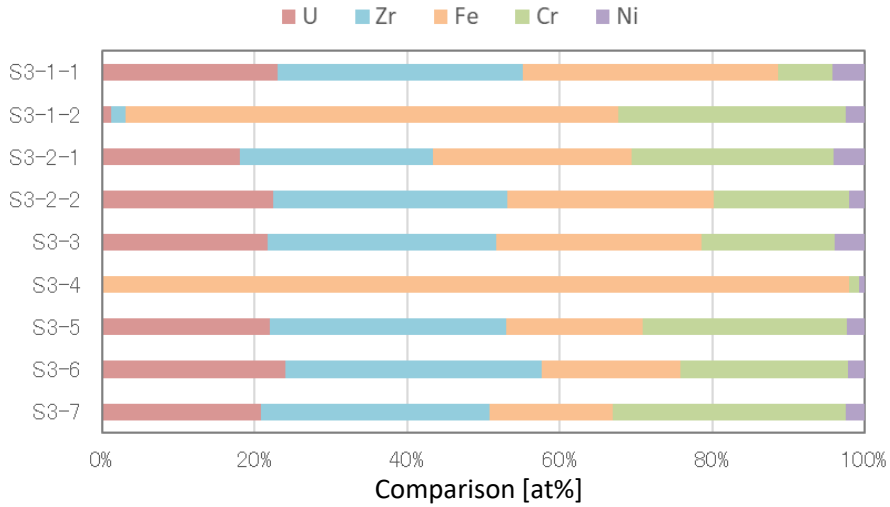


Figure 1 SEM image of sample used for synchrotron radiation analysis





※ Calculated by comparison the measurement results at 18.2 keV and 8.5 keV with the Control specimen
Data to a depth of several 10s μm from the surface is reflected in μ-XRF

Figure 2 Ratio of primary elements in each sample (XRF measurement results)

The Zr/U ratio between samples generally fluctuated between 1.4 and 1.8 (Refer to Figure 2). It is assumed that the clump and fragments sampled as part of the second fuel debris sample contain a mixture of U originating from fuel and Zr originating from cladding tubes, etc.

[Reference] 2nd Fuel debris sample solid analysis results

Assessment of the chemical state of U, etc. using synchrotron radiation analysis (3/3)

◆ Assessment of the chemical state near the surface

assessment of the element distribution, crystalline structure and valence, etc., of Powder S1, which has a clear position of relationship between the surface and the internal areas of the sample, were performed to examine the chemical state from the inside regions to the surface

- Regions with high concentrations of Fe/Ni exist near the surface (Figure 1). XRD analysis revealed a pattern resembling Fe oxide (Figure 2, P19 and P20), indicating that it may have formed after the accident.
- U valence at the same location is slightly high (figure 3, P19 and P20), and whereas XRD analysis revealed changes, such as a broadening of the cubic crystal UO_2 peak, higher order oxides such as U_3O_8 were not found.

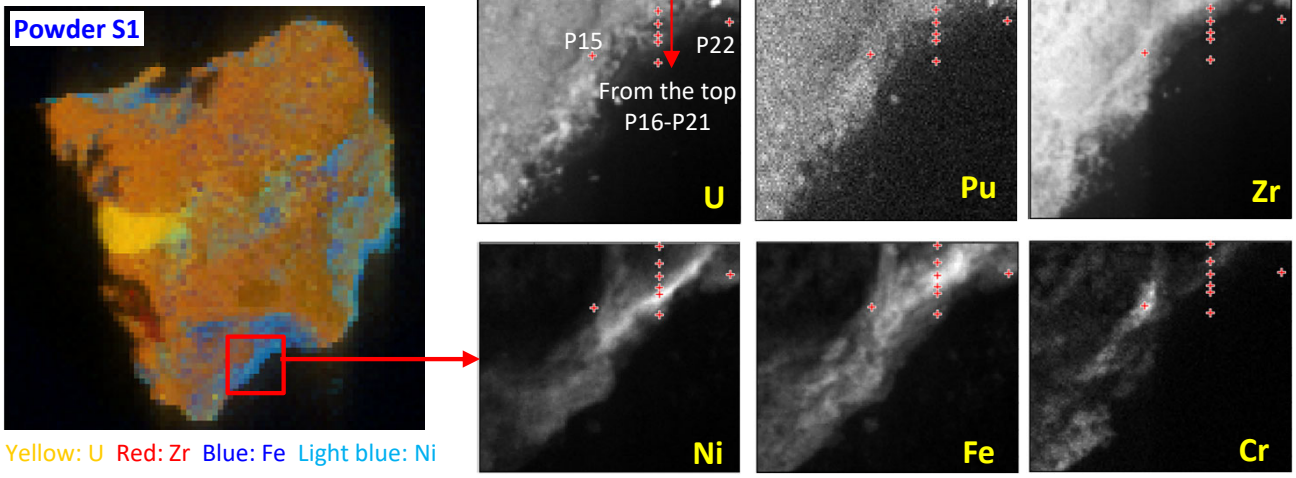


Figure 1 μ-XRF element distribution assessment

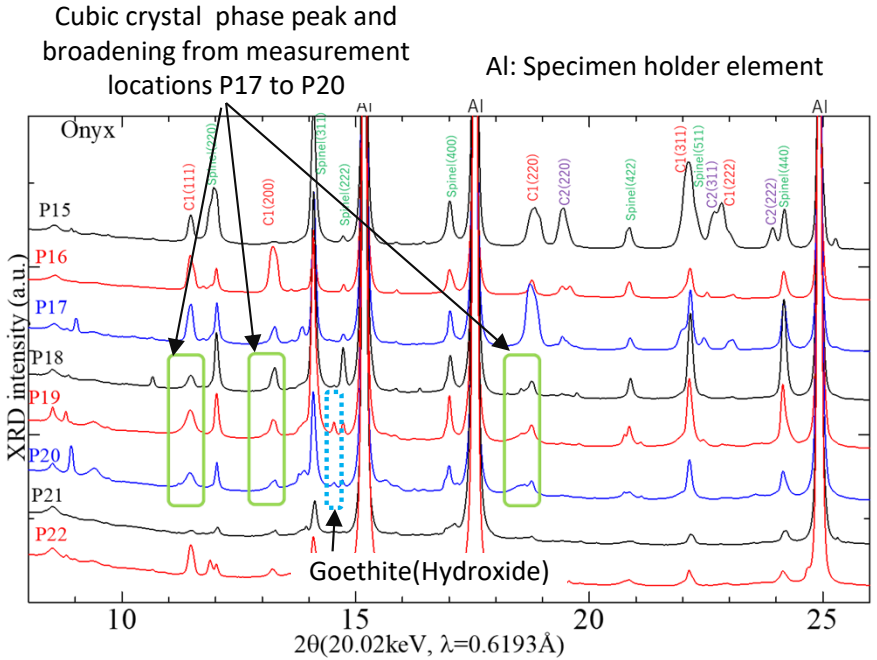


Figure 2 μ-XRD crystalline structure analysis

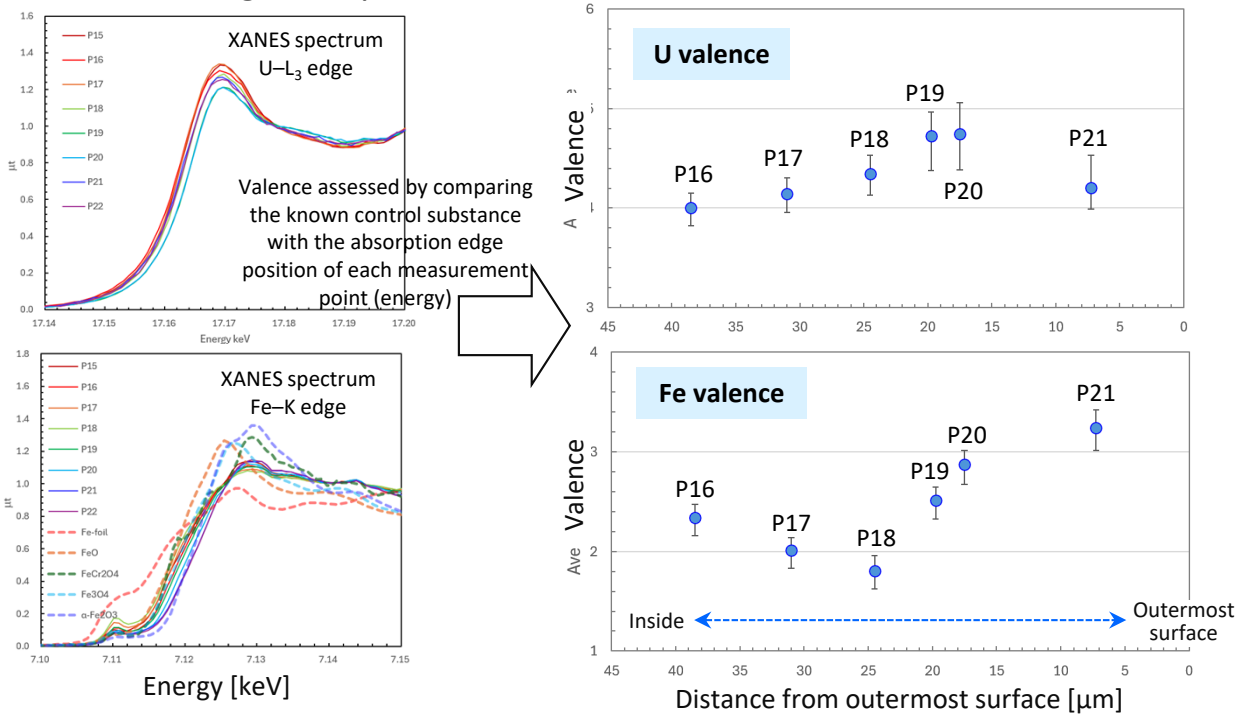
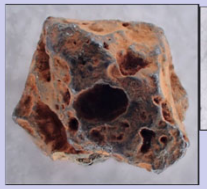
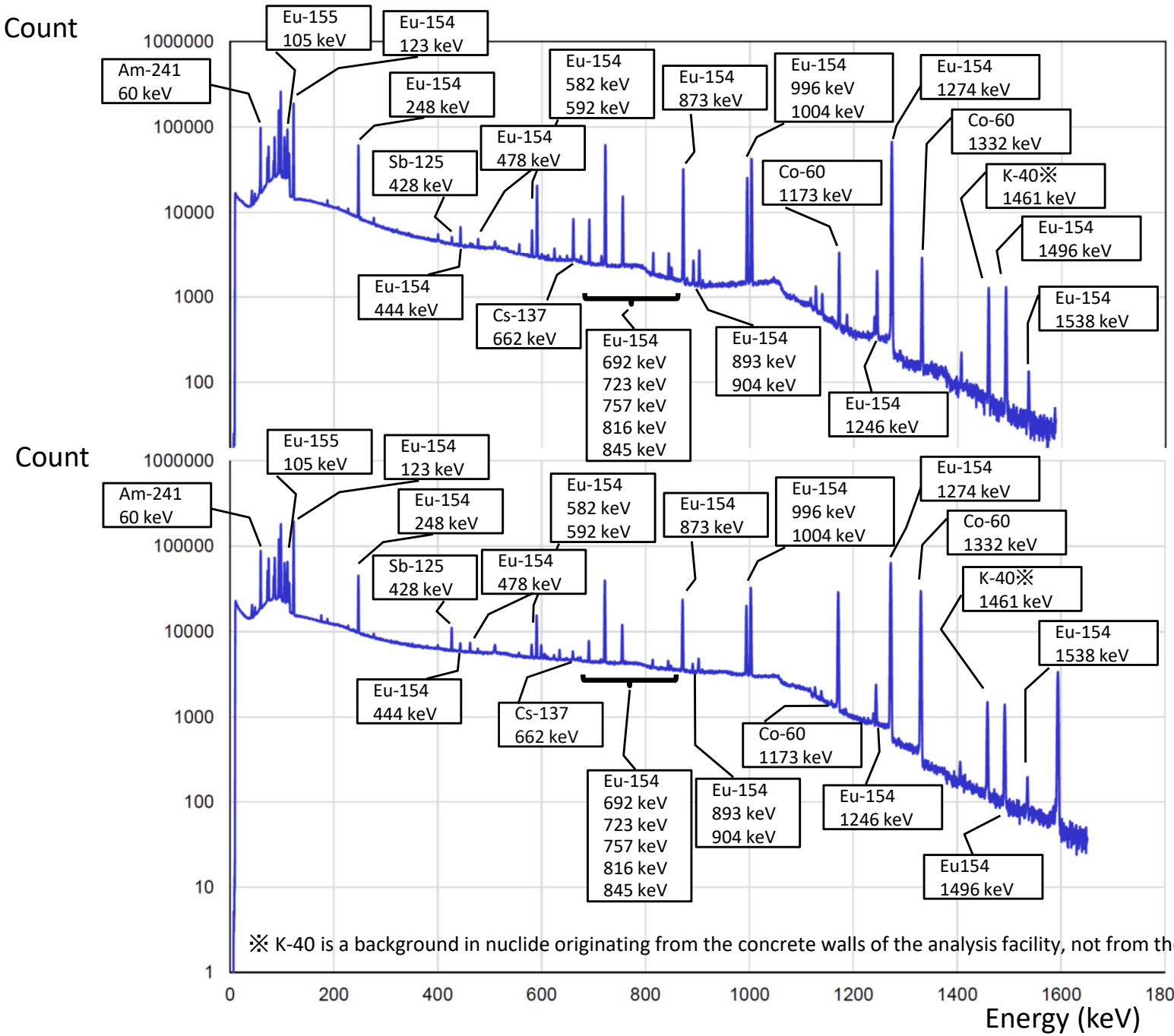


Figure 3 μ-XAFS oxidation state assessment

[Reference] 1st and 2nd Fuel debris analysis result comparison
Non-destructive analysis results

Items	1st Fuel debris	2nd Fuel debris	Notes
External appearance	 Reddish brown overall with black and glossy regions on the surface	 Clump  Fragments Brownish overall with black regions and holes on the surface	The areas of the 2nd sample that are brown (outermost surface layer) contain hardly any U, which may be why the color looks different
Mass	0.693g	0.187g (Total mass of the sample)	–
Size	Approx. 9mm×Approx. 7mm	Approx. 5mm×Approx. 4mm (Clump)	–
Dose rate	Approx. 8mSv/h (γ-ray)	Approx. 0.3mSv/h (γ-ray)	–
γ spectrometry	^{241}Am, $^{154, 155}$Eu, ^{125}Sb, ^{137}Cs, ^{60}Co detected	^{241}Am, $^{154, 155}$Eu, ^{125}Sb, ^{137}Cs, ^{60}Co detected	Same results
X-ray CT	CT values are non-uniform Distribution of low density areas assumed to be voids Volume: Approx. 0.1cm^3	CT values are non-uniform Distribution of low density areas assumed to be voids Volume: Approx. 0.026cm^3	Same results
Surface observations SEM-WDX	Si, Ca, Al, etc. detected in addition to U, Zr, Fe, Cr, Ni, O	U, Zr, Fe, Cr, Ni, O detected. Si, Ca, Al, etc. not detected	Second sample tends to be more homogeneous
Batching status	Pulverized by hand with a stainless steel rod	Pulverized by hand with a stainless steel rod	–

[Reference] 1st and 2nd Fuel debris analysis result comparison
Non-destructive analysis results (γ-ray spectrometry)

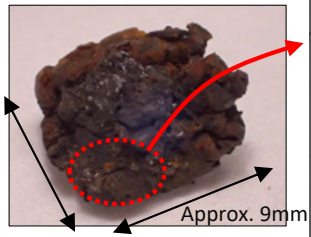
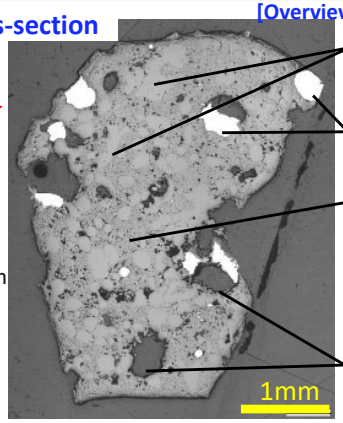
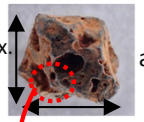
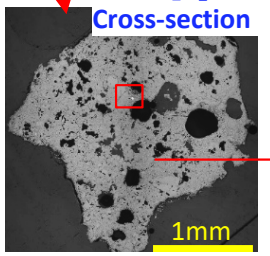
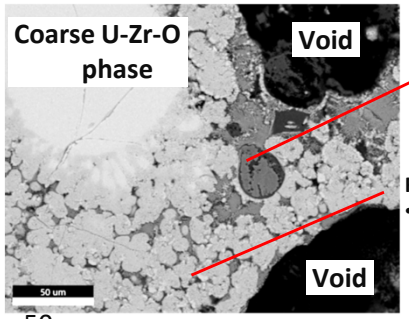


※ K-40 is a background in nuclide originating from the concrete walls of the analysis facility, not from the sample

2nd Fuel debris
Measurement time: 10,000s
Measurement date: April 30, 2025

1st Fuel debris
Measurement time: 10,000s
Measurement date: December 9, 2024

[Reference] 1st and 2nd Fuel debris analysis result comparison
Comparison summary

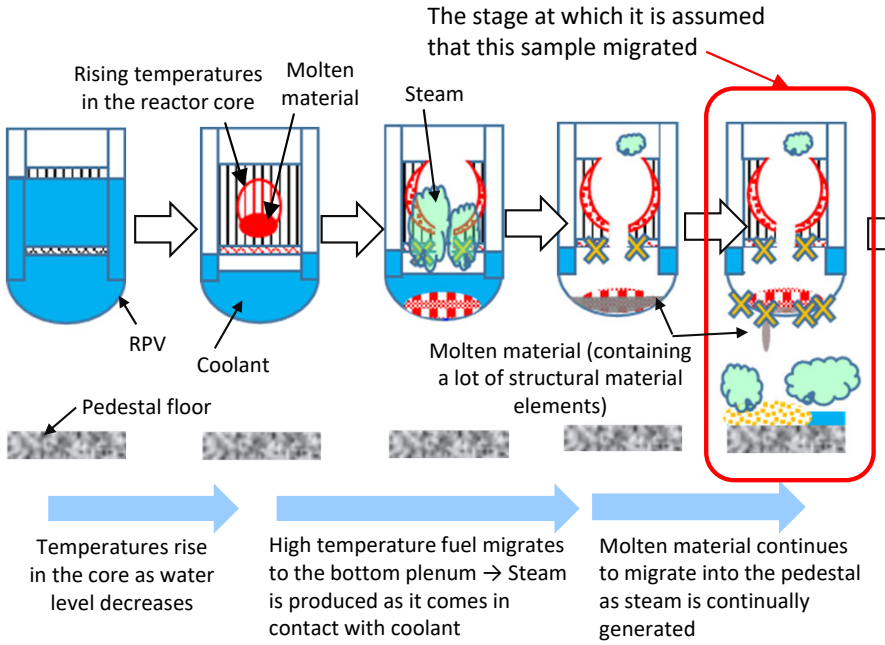
		1st Fuel debris	2nd Fuel debris
Hypotheses about the cross sectional structure and sample formation process		 External appearance of sample **Clump【C】cross-section** **[Overview of compositional phases]**  Optical microscope image **Coarse Zr-U-O phase** **Fe-Ni metal phase** **Fine mixed region** • U-Zr-O, Zr-U-O, Fe-Cr-O, Fe-O mixed phase **Void** • Size: Several - several 100s μm ✓ It is assumed that Cr and Fe out of the structural material elements (Fe, Cr, Ni) oxidized first. ✓ It is assumed that the sample formed inside the RPV as it solidified from a molten state (More than approx. 1900℃)	 External appearance of sample Approx. 5mm **Chunk【C】Cross-section**  Optical microscope image **[Overview of compositional phases]** (Backscattered electron image)  50μm SEM image **Fe-Ni phase** (Very little) **Fine mixed region** • U-Zr-O, Zr-U-O, Fe-Cr-O, Fe-O mixed phase ✓ It is assumed that Cr and Fe out of the structural material elements (Fe, Cr, Ni) oxidized first. ✓ It is assumed that the sample formed inside the RPV as it solidified from a molten state (More than approx. 2200℃)
Analysis results	Element content	• The percentage of structural material elements (Fe, Cr, Ni) is large compared to the core composition.	• The percentage of structural material elements (Ni, in particular) is larger than the 1st fuel debris sample.
	U isotope ratio	• Uranium enrichment: Approx. 1.9 wt% (^{235}U/U)	• Uranium enrichment: Approx. 2.0 wt% (^{235}U/U)
	Radioactivity concentration	• The concentration of Cs is low compared to the fuel composition prior to the accident, and the contribution from γ-ray emitting nuclides ^{154}Eu and ^{60}Co is high. • The concentrations of ^{154}Eu and ^{244}Cm are approximately the same as the fuel composition prior to the accident, and association with U was found.	• The concentration of Cs is low compared to the fuel composition prior to the accident • The concentrations of ^{60}Co and ^{125}Sb are lower than the 1st fuel debris sample.
	Element and compound distribution	• Comprised of primarily Coarse Zr-U-O phases, Fe-Ni metal phases, Fine mixed regions and Voids.	• Comprised primarily of Fine mixed regions, Coarse U-Zr-O phase and Voids. There are fewer Fe-Ni metal phases than the 1st fuel debris sample.
	Crystal structure and composition of phases that contain U	• Coarse Zr-U-O phase：cubic crystal $(Zr,U)O_2$ • Fe-Ni metal phase：Face-centered cubic structure Fe-Ni • Fine mixed region：Cubic crystal $(U,Zr)O_2$, cubic crystal $(Zr,U)O_2$, Tetragonal crystal $(Zr,U)O_2$ phase, spinel-shaped $(Fe,Cr)_3O_4$, and FeO cubic crystals exist • An amorphous phase of Ni-U-Fe-O systems has been deposited on the sample surface	• Fine mixed region：Cubic crystal $(U,Zr)O_2$ phase, tetragonal crystal $(Zr,U)O_2$ phase, spinel-shaped $(Fe,Cr)_3O_4$ exist. • Coarse U-Zr-O phase：Cubic crystal $(Zr,U)O_2$ • Fe-Ni metal phase • There are Ni-Fe-O system phases adhered to the surface of the sample (they contain very little U)

[Reference] Leveraging the analysis results to ascertain the conditions inside the reactor

In conjunction with deliberations to date, estimating how the accident progressed will enable us to ascertain conditions inside the reactor, such as fuel debris distribution, etc., and this information will be leveraged when deliberating fuel debris retrieval and internal investigations.

【Positioning of the sample analysis results】

From analysis of this fuel debris sample, we estimate that both the first and second fuel debris samples formed as structural material elements oxidized due to the steam created in the reactor pressure vessel as the material migrated into the pedestal



Unit 2 accident progression hypothesis [1]

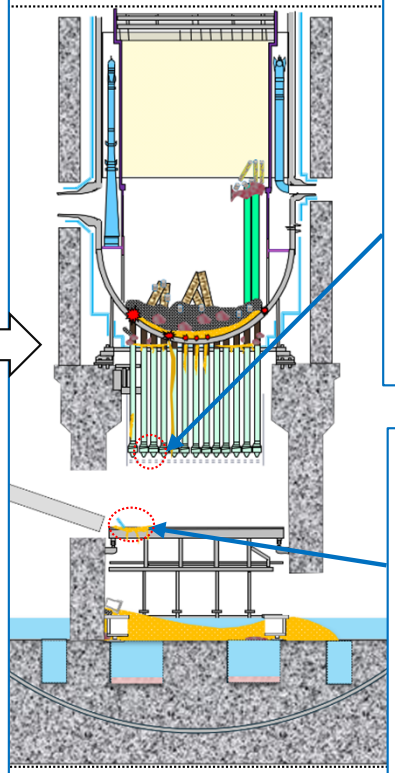


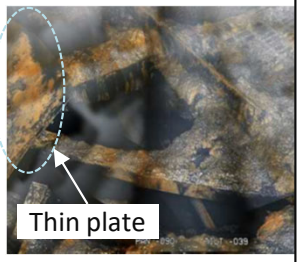
Diagram showing estimates about conditions inside the Unit 2 reactor [2]

【Knowledge gained from internal investigations】

No significant damage was found to the CRD housing supports
⇒ It is assumed that when the fuel debris migrated into the pedestal the temperatures did not largely exceed the melting point of stainless steel (Approx. 1450℃)

Photograph location F CRD housing supports

External appearance of CRD housing supports [3]
(Investigation period: January 2018)



Thin plates were found on top of the platform. A comparison with design schematics suggests the possibility that insulating material from directly below the RPV (aluminum alloy with a melting point of approx. 660℃) fell. [5]
⇒ It is assumed that insulation became entrained with the fuel debris as it migrated to the pedestal

External appearance of platform near the CRD rails [4]
(Investigation period: February 2017)

[1]Figure source: Excerpts from Yamashita et al. Annals of Nuclear Energy, 173 (2022) 109129. Additions were made
[2]JAEA, Decommissioning, Contaminated Water and Treated Water Management Project (Development of Analysis and Estimation Technology for Ascertaining the Attributes of Fuel Debris (Developing Technology for Estimating damage inside the RPV and the behavior of fuel debris as it migrated inside the PCV)) subsidized by METI Agency for Natural Resources and Energy that commenced in FY2025, FY2026 Final Report, October 2025
[3]TEPCO HD, IRID, Unit 2 Primary containment vessel internal investigation results. Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (50th), Document 3-3
[4]TEPCO HD, IRID, Unit 2 Primary containment vessel internal investigation. Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (39th), Document 3-3
[5]JAEA, Decommissioning, Contaminated Water and Treated Water Management Project (Development of Analysis and Estimation Technology for Ascertaining the Attributes of Fuel Debris (Developing Technology for Estimating damage inside the RPV and the behavior of fuel debris as it migrated inside the PCV)) subsidized by METI Agency for Natural Resources and Energy that commenced in FY2022, FY2022 Final Report, September 2023

[Reference] Materials inside the PCV

- Materials that might have been caught up in the creation process of the fuel debris sample due to the reaction to high temperatures during the accident and when the fuel debris migrated were identified and are useful for hypothesizing the fuel debris creation process.

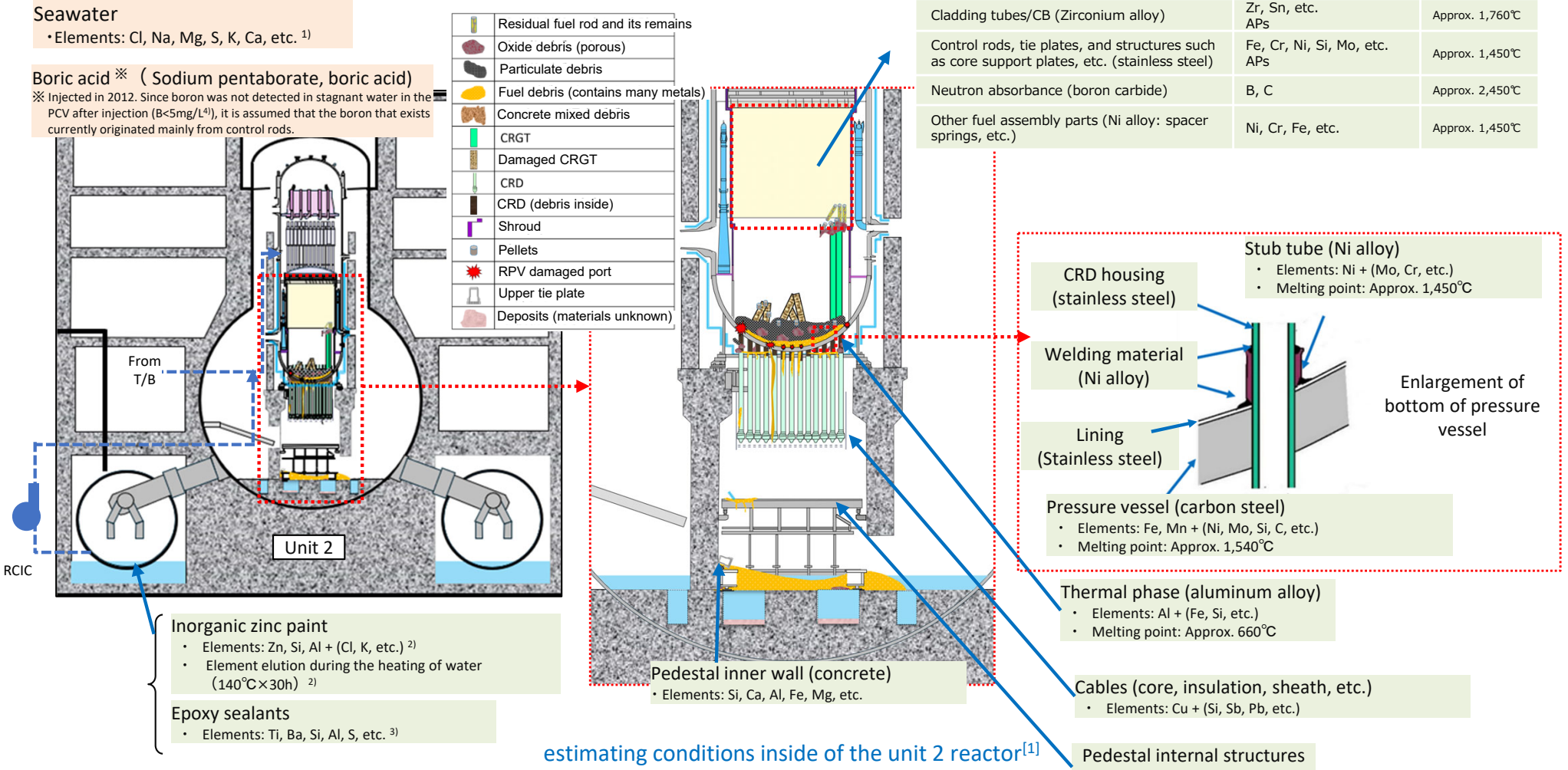
Light green: Materials that were originally present in the RPV and PCV

Light orange: Materials introduced following the earthquake

Major core materials	Major elements	Singular melting point
Uranium fuel	U, Gd, Pu, FPs, MAs	Approx. 2,800℃
Cladding tubes/CB (Zirconium alloy)	Zr, Sn, etc. APs	Approx. 1,760℃
Control rods, tie plates, and structures such as core support plates, etc. (stainless steel)	Fe, Cr, Ni, Si, Mo, etc. APs	Approx. 1,450℃
Neutron absorbance (boron carbide)	B, C	Approx. 2,450℃
Other fuel assembly parts (Ni alloy: spacer springs, etc.)	Ni, Cr, Fe, etc.	Approx. 1,450℃

Seawater
・Elements: Cl, Na, Mg, S, K, Ca, etc. [1)]

Boric acid ※ （Sodium pentaborate, boric acid)
※ Injected in 2012. Since boron was not detected in stagnant water in the PCV after injection (B<5mg/L[4)]), it is assumed that the boron that exists currently originated mainly from control rods.



estimating conditions inside of the unit 2 reactor[1]

1) Kirishima et al., J. Nucl. Sci.Technol. 52, (2015), 1240. 2) Nakamori, et al., Atomic Energy Society of Japan 2018 spring conference, 2M17.
3) TEPCO HD, Deliberations of TEPCO Fukushima Daiichi Nuclear Power Station Accident Analysis (28th meeting) Document 4-1. February 28, 2022 (SEM-EDX results)
4) IRID, JAEA, (39th) Secretariat of the Team for Countermeasures for Decommissioning, Contaminated Water and Treated Water Treatment, metrial3-4-4, February 23, 2017.(Analysis results of stagnant water in the PCV)

[1] JAEA, Decommissioning/contaminated water/treated water countermeasure project beginning in 2023 (development of analysis/estimating technologies for ascertaining the attributes of still debris) 3. The development of technologies for estimating RPV damage and the behavior of migrating fuel debris inside the PCV-Final report-.

[Reference] Overview and purpose of each item in debris analysis [1]

The following 3 types of analysis are used to analyze the fuel debris sample and identify its characteristics and how it was formed.

- **Non-destructive analysis**

  [Overview] Roughly grasp information, such as distribution of pores and high-density materials and contained components, without changing the state of the received sample as much as possible.

  [Purpose] Obtain basic information of the sample, and confirm the presence or absence of components derived from nuclear fuel (uranium, radioactive nuclides, etc.) early on. Additionally, review how to specifically proceed with the analysis, such as which area to focus on in the solid analysis and liquid analysis to be conducted later on and whether the location of the sample after fluctuation can be obtained.

  [Analysis methods] External appearance, weight, dose rate, IP, X-ray CT, γ-ray spectrometry, SEM-WDX (surface)

- **Solid analysis**

  [Overview] Confirm what kind of state uranium, zirconium and other components from the reactor are in (what the coexisting elements are, whether it retains its pre-accident state, whether it is oxidized, etc.), by fractionating parts of the sample and observing its cross section in detail.

  [Purpose] Obtain information on “how the sample was formed”, such as which materials reacted under what temperature or atmosphere* to form the sample.

  *The synchrotron analysis of SPring-8, which was newly added after the previous report, is considered to enable more accurate estimation of the temperature and atmosphere at the time of the accident, since more detailed data than the conventional observation method based on electron microscopes can be obtained such as three-dimensional distribution of elements in the sample and valence of uranium.

  [Analysis methods] SEM-EDX, SEM-WDX, TEM-EDX, SIMS, Raman spectroscopy, μ-XAFS, μ-XRF, μ-XRD

- **Liquid analysis**

  [Overview] Fractionate part of the sample and dissolve it in acid to measure the elements and nuclide content in the resulting dissolving solution.

  [Purpose] Obtain necessary information to review the process to safely retrieve and stably store fuel debris, such as uranium isotope ratio and radioactive nuclide concentration.

  [Analysis methods] ICP-MS, ICP-AES, TIMS, γ-ray spectrometry, α-ray spectrometry

Continuing the series of analyses will gradually identify the characteristics of fuel debris deposited in the core and contribute to safety evaluation and rationalization for fuel debris retrieval and storage.

[1] JAEA, TEPCO HD, Fuel debris Sample Non-destructive analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (138th), May 29, 2025.

[Reference] Abbreviation and overview of analysis methods [3]

Analysis method abbreviation	Analysis method name	Analysis method overview
ICP-AES	Inductively coupled plasma atomic emission spectroscopy	Qualitative and quantitative analysis method of elements by introducing atomized samples into high-temperature plasma and obtaining element-specific spectra by spectroscopy of the issued light.
ICP-MS	Inductively coupled plasma mass spectrometry	Method of measuring the concentration of elements and its isotopes by introducing atomized samples into high-temperature plasma, ionizing elements in the sample and measuring the number of ions in ion mass-to-charge ratio (m/z) by mass spectrometry.
TIMS	Thermal ionization mass spectrometry	Method of measuring the concentration of elements and its isotopes by applying samples onto metal filament, ionizing the atoms by heating under vacuum and measuring the number of ions in ion mass-to-charge ratio (m/z) by mass spectrometry.
IDMS	Isotope dilution mass spectrometry	Method for measuring the elemental mass (concentration) of a specimen targeted for analysis (analyte) by adding a known amount of a rare isotope with a totally different isotopic composition and measuring changes to the isotopic composition mass of the analyte before and after the changes and the amount of standard sample added. Isotopic composition is measured through mass spectrometry.
SEM	Scanning electron microscope	Device that can observe the sample surface by irradiating the surface with electron beams, and can also analyze elements by attaching an X-ray analyzer.
EDX	Energy dispersive X-ray spectroscopy	Method of elemental analysis and compositional analysis by detecting characteristic X-rays generated by electron irradiation and categorizing them by the energy of characteristic X-rays.
WDX	Wavelength dispersive X-ray spectroscopy	Method of elemental analysis and compositional analysis by detecting characteristic X-rays generated by electron irradiation and performing spectroscopy at the wavelength of characteristic X-rays.
TEM	Transmission electron microscope	Method of imaging electrons transmitted through the sample and scattered electrons for observation under high magnification by irradiating thinned samples with electron beams, and also conducting elemental analysis by attaching an X-ray analyzer. Crystal structure can also be obtained from the diffraction image.
SIMS	Secondary ion mass spectrometry	Method of measuring the concentration of elements and its isotopes by measuring the secondary ions generated by irradiating the sample surface with a beam of ions with a mass spectrometer and measuring the number of ions in ion mass-to-charge ratio (m/z) by mass spectrometry.
Raman spectroscopy	Micro Raman spectroscopy	Method of obtaining properties such as molecular structure, temperature, stress, electrical properties, orientation and crystallinity by irradiating the sample surface with light and dispersing Raman scattering light. Information on chemical form of micro-regions on μm order can be obtained by combining Raman spectroscopy with conventional optical microscopes.

[3] JAEA, TEPCO HD, Fuel debris Sample Non-destructive analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025.

[Reference] Abbreviation and overview of analysis methods [3]

Analysis method abbreviation	Analysis method name	Analysis method overview
X-ray CT	X-ray computed tomography	Method of obtaining density distribution of the sample interior by irradiating the sample with X-rays, capturing the transmitted X-ray intensity by a computer and scanning it three-dimensionally. Distribution of phases of different density can be obtained.
XAFS	X-ray absorption fine structure spectroscopy	Method of analyzing the internal structure of materials at the molecular and atomic level by irradiating the sample with X-rays and precisely observing the absorbed X-ray energy
XRF	X-ray fluorescence spectroscopy	Method of qualitative analysis of content of constituent elements by measuring the wavelength and energy of X-rays (X-ray fluorescence) generated according to the substance by irradiating the sample with X-rays
XRD	X-ray diffraction analysis	Method of analyzing the crystal structure, crystal orientation, crystal lattice size, etc. of the object by irradiating the sample with X-rays and measuring the resulting X-rays (diffracted X-ray)
IP	Imaging plate	Radiation image measuring instrument that detects radiation energy as stimulable luminescence. Dose distribution of the sample can be obtained.

[3] JAEA, TEPCO HD, Fuel debris Sample Non-destructive analysis results, Meeting of the Secretariat of the Team for Countermeasures for Decommissioning and Contaminated Water Treatment (140th), July 31, 2025.

JAEA

① Element content

TEPCO

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◆ In order to identify and quantify the elements contained in the fuel debris block [D] and particles [B] obtained through crushing, the specimens were fractionated, dissolved (approx. 0.1g each specimen), and analyzed.

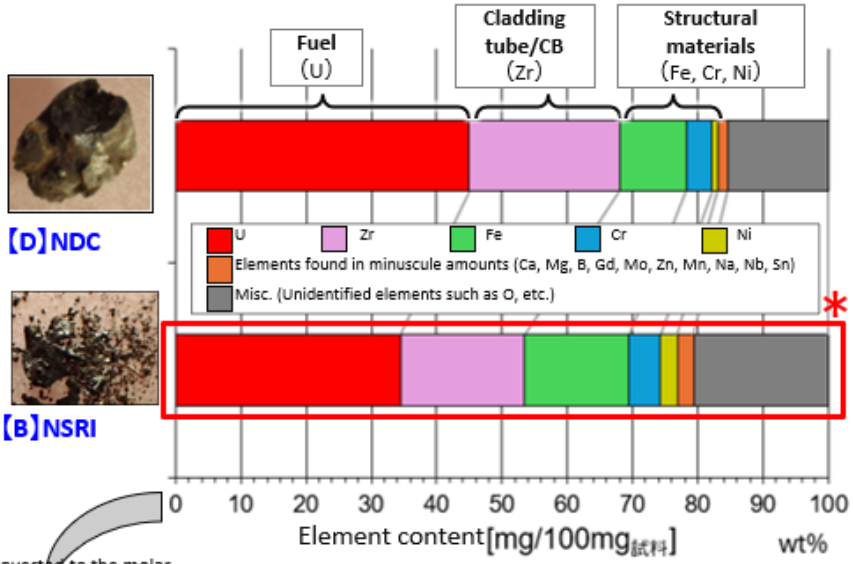

Figure 1 Elemental composition of the sample (ICP-AES and ICP-MS analysis results)

Converted to the molar ratio of primary elements

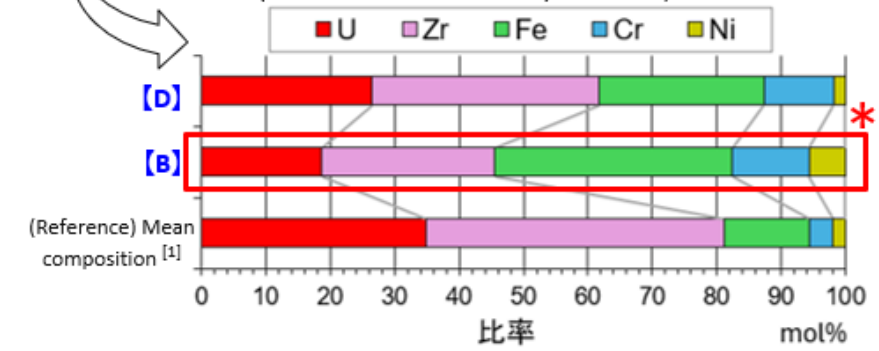

Figure 2 Ratio of major elements (U, Zr, Fe, Cr, Ni)

[1] Sato et al., Nucl.Eng.Des., 404, 112205. Converted to element mass based on Table1 fuel, cladding tube/CB and control rod blade material composition

- U、Zr、Fe、Cr and Ni were the primary elements in all samples. The ratio of U was highest compared to sample mass. (Figure 1)
- The ratio of structural material elements (Fe+Cr +Ni) was higher than the initial mean composition of fuel, cladding tubes/CB, and control rod blades in Unit 2. (Figure 2)

⇒ It is possible that after the fuel and cladding tubes, etc. melted in the core, these elements were generated as other materials got caught up in the molten material as it migrated to the PCV.

- The following elements were also found in minuscule amounts: Ca, Mg, B, Gd, Mo, Zn, Mn, Na, Nb, Sn. (All at amounts less than 1wt% of the sample mass)

⇒ In light of the structural materials inside the PCV and RPV as well as conditions during the accident, it is possible that these elements originate from seawater elements, as well as structural elements and the paint, etc. they were covered with.

- The ratio of fuel elements (uranium) differed in the parts of the sample that remained in block【D】and the parts that were turned to particles【B】during crushing (Figure 2).

⇒ 【B】suggests a larger ratio of the micro-mixed phase (Considering ④ Element, compound distribution)

Note: CB: Channel box, SUS: Stainless steel

＊ The graph was updated based on a re-evaluation of the analytical value for U on August 27, 2026.

③Radioactivity concentration

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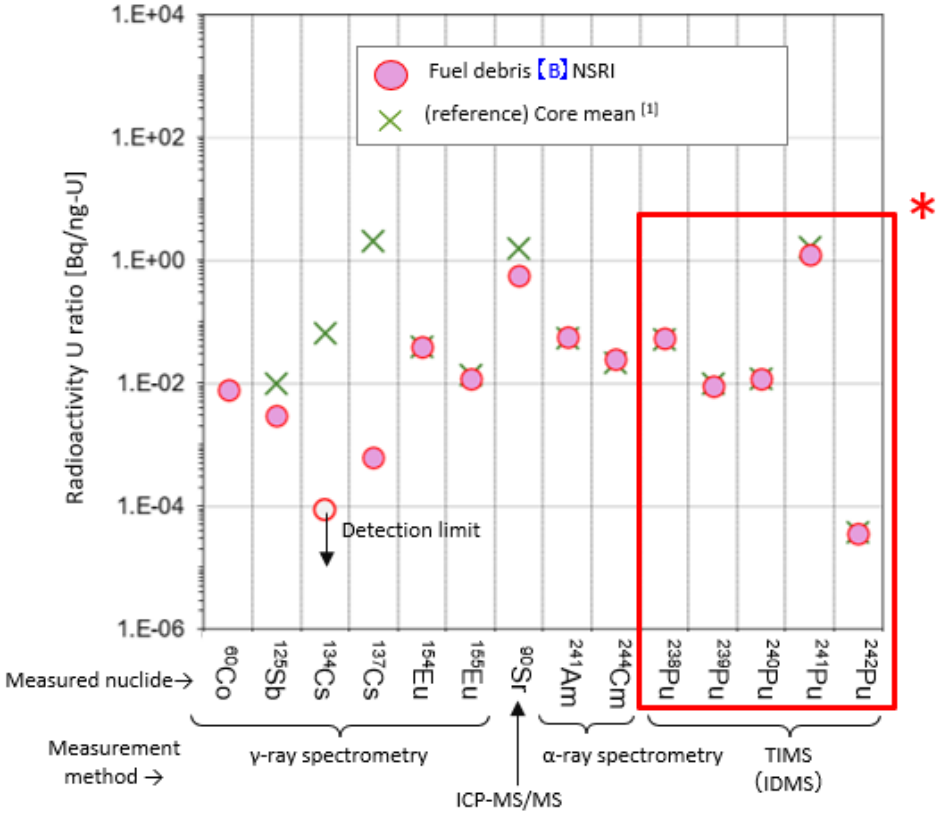
◆ In order to ascertain primary radioactive nuclides, fractionated specimens of particles【B】obtained through crushing were dissolved and the concentration of radioactivity in the solution was measured using γ-ray spectrometry and α-ray spectrometry, etc. In order to assess the association with uranium, which is the primary element in fuel, the ratio of nuclide radioactivity to uranium mass was calculated and compared with past samples and core means.



Ratio of each nuclide radioactivity to uranium mass

Note: Radioactivity has been corrected as of May 31, 2025 based on literature [1].
Pu isotope radioactivity was assessed from isotope composition obtained through TIMS (Thermal Ionization Mass Spectrometry) and the amount of Pu measured through IDMS (Isotope Dilution Mass Spectrometry).

[1] JAEA-Data/Code 2012-018.

○ Major radioactive nuclides

- ^{90}Sr, α nuclides (^{241}Am, ^{244}Cm, and Pu isotopes), ^{154}Eu and ^{60}Co contribute greatly to the radioactivity in fuel debris samples. (Left figure)
- The contribution of ^{134}Cs and ^{137}Cs is small, and less than core means.

⇒ It is possible that during the accident, radioactive Cs volatilized due to the high temperatures and formed fuel debris with low γ dose rates.

○ Accompanied condition of U

- The ratio of Sr, Eu, Pu, Am, Cm to U is very similar to core means.

⇒ ^{154}Eu and ^{244}Cm, which are searched※ for to detect fuel debris, were found to associate with U.

※Because they are known to associate with U after normal nuclear reactor operation.

＊ The graph was updated based on a re-evaluation of the analytical values for U and Pu on August 27, 2026.

JAEA

[Reference] Liquid analysis results — Element content ratio/isotope ratio/radioactivity concentration —

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◆ JAEA NSRI liquid analysis

○ Element content ratio → Chart 1

- Approx. 0.1g of particles【B】 was dissolved in an alumina crucible with alkaline flux※, and the resulting molten material was dissolved in hot nitric acid.
  - ※ Alkali melting: By taking fuel debris, which is difficult to dissolve in acid, and heating/dissolving it in alkaline flux (sodium peroxide) to convert it to a substance that is easily dissolved in acid, we can obtain a uniform solution without undissolved residue.
- The amount of the elements contained in the obtained solution was measured using ICP-AES to assess the element content ratio of the sample.
- U, Pu, Nd and Gd were separated from the solution using UTEVA ® resin and anion exchange resin after which IDMS was used to measure the amount of the elements in the separated solutions.

○Isotope ratio （U, Pu, Gd and Nd） → Chart 2

- The separated solutions of each element obtained in "Element content ratio" above were then measured using TIMS.

○ Radioactivity concentration → Chart 3

- For γ-ray emitting nuclides, a small amount was fractionated from the obtained solution to measure radioactivity with γ-ray spectrometry.
- For ^{241}Am and ^{244}Cm, TRU resin was used to separate Am and Cm from the obtained solution and α-ray spectrometry was used to measure the radioactivity of the separated solution.
- For ^{90}Sr, Sr resin was used to separate Sr from the obtained solution and ICP-MS/MS was used to measure the amount of ^{90}Sr isotopes in the obtained solution.

Chart 1 Element content ratio assessment results

k=2 Expanded uncertainty

Element	Element content ratio [mg/100mg Specimen] *	Notes
U	34.48 ± 0.64	IDMS measurement
Zr	19 ± 2	
Fe	16 ± 1	
Cr	4.8 ± 0.2	
Ni	2.6 ± 0.1	
Si※1	0.05 ± 0.01※1	Reference value ※1
Ca	0.29 ± 0.02	Revised value for the amount of Ca in the flux
Al		Excluded since it originates from the crucible
Mg※1	0.16 ± 0.01※1	Reference value ※1
B※1	0.05 ± 0.01※1 *	Reference value ※1
Gd	0.294 ± 0.012	IDMS measurement
Mo	0.21 ± 0.01	
Sb		Undetected by ICP-AES qualitative analysis
Pb		Undetected by ICP-AES qualitative analysis
Zn	0.08 ± 0.01	
Ti	0.02 ± 0.01	
Mn	0.43 ± 0.02	
Na		Excluded since it originates from the flux
Nb		Undetected by ICP-AES qualitative analysis
Sn	0.13 ± 0.01 *	
Pu	0.201 ± 0.008	IDMS measurement
Nd	0.114 ± 0.005	IDMS measurement

※1 In regards to the element concentration in the solution the concentration ratio of operational gaps to solution is 0.1 or higher, reference value.

*** The table was updated based on a re-evaluation of the analytical values for U, Pu, Nd, and Gd determined by IDMS on August 27, 2026.**

JAEA

[Reference] Liquid analysis results — Element content ratio/isotope ratio/radioactivity concentration

TEPCO

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◆ JAEA Oarai liquid analysis (cont.)

○ Radioactivity concentration

- γ-ray spectrometry
  - ^{60}Co, ^{125}Sb, ^{137}Cs, ^{154}Eu and ^{241}Am were detected. (Figure 1 top. Same nuclides that were detected during non-destructive analysis)
  - The same nuclides were detected in the undissolved residue, but the intensity of ^{60}Co was relatively high. (Figure 1, bottom)
- α-ray spectrometry
  - ^{242}Cm, ^{243}Cm+^{244}Cm, ^{241}Am+^{238}Pu and ^{239}Pu+^{240}Pu were detected in the solution

Chart 3 Radioactivity concentration assessment results *

k=2 Expanded uncertainty

Nuclide	Radioactivity concentration※1 [MBq/g-specimen]
^{60}Co	9 ± 2
^{125}Sb	6 ± 1
^{137}Cs	0.30 ± 0.09
^{154}Eu	10 ± 3
^{241}Am	13 ± 3
^{242}Cm	0.04 ± 0.03
^{243}Cm+^{244}Cm	8 ± 2
^{241}Am+^{238}Pu	25 ± 5
^{239}Pu+^{240}Pu	6 ± 1

※1 Values as of the date of measurement

* The table was updated based on a re-evaluation of the radioactivity concentration values obtained by gamma-ray spectrometry and alpha spectrometry on August 27, 2026.

- For ^{60}Co, ^{125}Sb, ^{137}Cs, ^{154}Eu and ^{241}Am, small samples were fractionated from the obtained solution and radioactivity was measured using γ-ray spectrometry. (Measurement date: April 17, 2025)
- For 242C, 243Cm+244Cm, 241Am+238Pu and 239Pu+240Pu, small amounts were taken from the obtained solution and smeared on a SUS plate after which α-ray spectrometry was used to measure the radioactivity of each nuclide. (Measurement date: May 13, 2025)

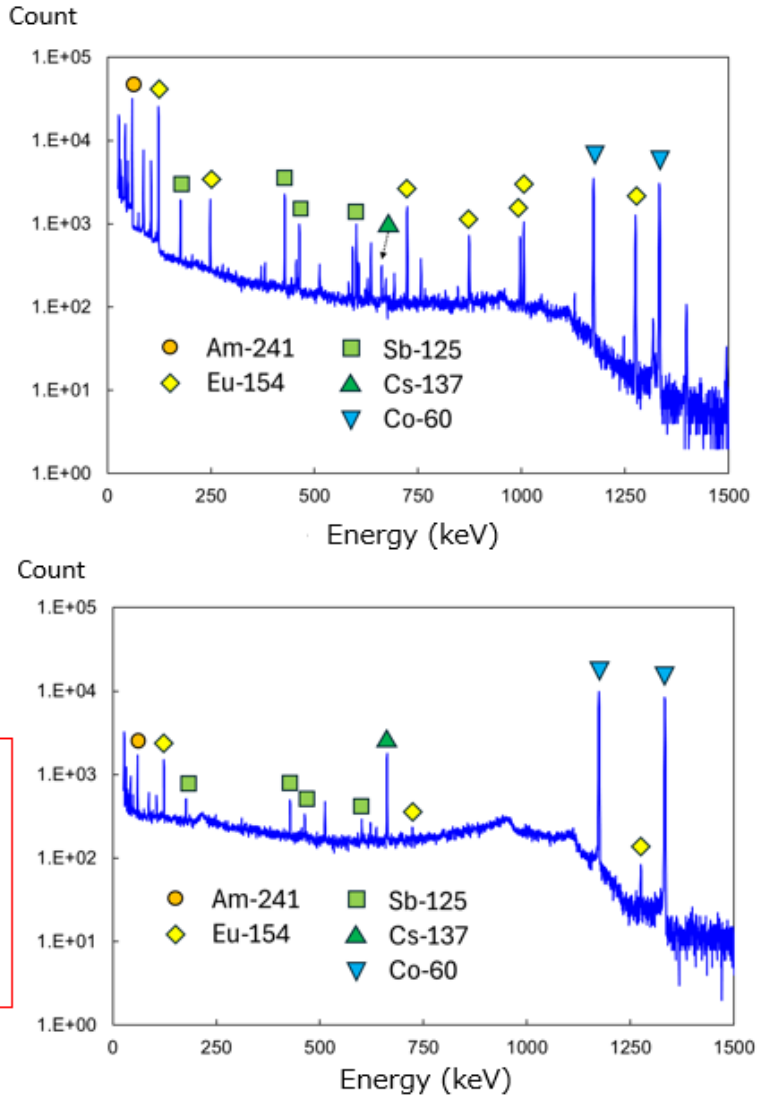

Figure γ-ray spectrometry Top: Solution, Bottom: Undissolved residue

Top: Measurement date: March 17, 2025, measurement time: 5,000 seconds, bottom: measurement date: March 18, 2025, measurement time: 10,000 seconds

[Reference] Liquid analysis results —Comparison with PCV penetration (X-6) sample—

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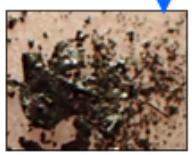
Material Adhesions to X-6 penetration investigation device

(Obtained in 2020)
Smear samples taken from the surface of the end of the investigation device.
A portion of the smear paper was cut into batches and subjected to liquid analysis.

Fuel debris sample

(Obtained in FY2024)
Sampled during first trial retrieval.
Crushed, fractionated and subjected to liquid analysis.

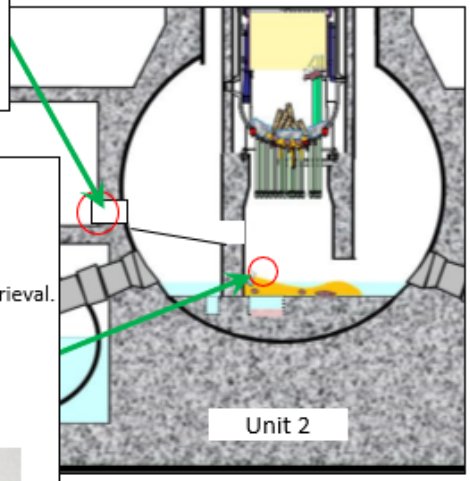
Obtained sample



Particles【B】

Block【D】

Particles【A-2】



- It is presumed that the PCV penetration (X-6 penetration) contains substances originating from fuel that migrated from the pressure vessel to the pedestal during the accident. Uranium isotopic composition and element ratio were compared for reference when generating a hypothesis about the process by which the fuel debris sample was created.
  - U isotopic composition: Same as the core mean (refer to page 8) and the X-6 penetration sample. (see the chart below)
  - Zr/U ratio (atomic ratio): Percentage of Zr is higher than the core mean (approx. 1.3. Refer to page 7) and the X-6 penetration sample. (see the chart below)
  - Gd/U ratio: Core mean is approx. 0.85wt%* of U weight while the measurement results from the fuel sample show approx. around 0.80wt%. (No quantitative data for the X-6 penetration sample)

Liquid analysis results (example of comparison between fuel debris sample and X-6 penetration sample)

Sample	U isotopic composition [at%]			Zr/U ratio (Atomic ratio)	Gd/U ratio [wt%]
	$^{234}U/U$	$^{235}U/U$	$^{236}U/U$		
Fuel debris sample					*
Particles【B】	0.027±0.001	1.943±0.002	0.342±0.001	1.4±0.2	0.85±0.04
Block【D】	0.026±0.002	1.9±0.1	0.33±0.002	1.33±0.08	0.9±0.1
Particles【A-2】	0.027±0.002	1.93±0.01	0.35±0.01	1.6±0.3	0.75±0.04
Material adhered to X-6 penetration investigation device (Data source: [1])					
Material adhered -2	0.03±0.03	1.91±0.03	0.34±0.03	1.03±0.02	No data since results Gd was not measured

Expanded uncertainty expressed as k=2

* The evaluation results of the Zr/U and Gd/U ratios were updated based on a re-evaluation of the analytical values for U and Gd on August 27, 2026.

[1] Ikeuchi et al., JAEA-Data/Code 2023-005.

[Reference] Solid analysis results

— Cross-section observations/composition assessment —

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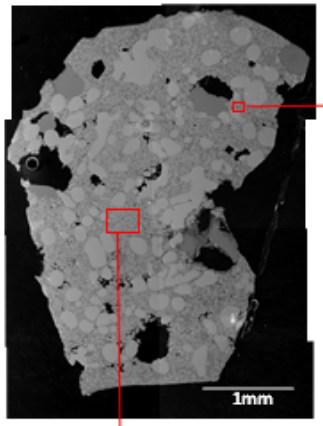
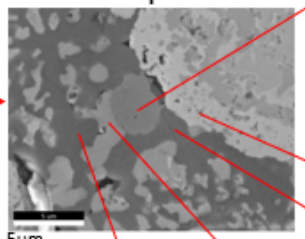
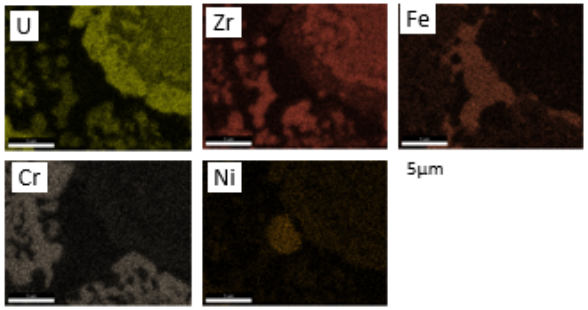
Block【C】: NFD

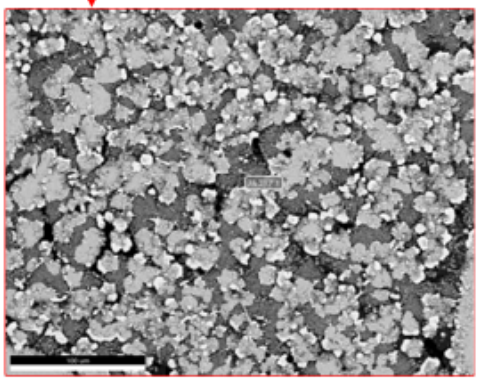
(C)Micro-mixed phase



Example of the inclusion of microscopic Fe-Ni metal phases





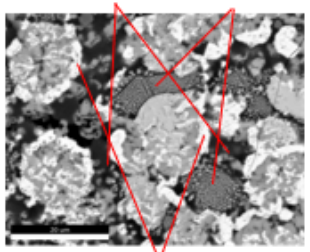


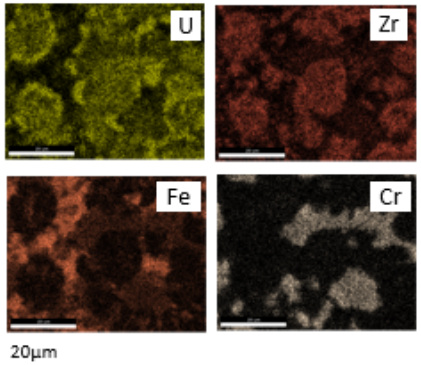
SEM-EDX facet analysis results of micro-mixed phase

at%

Major elements	Facet analysis *
O	74
Cr	4
Fe	8
Ni	<0.5 (Exist in small amounts)
Zr	9
U	4

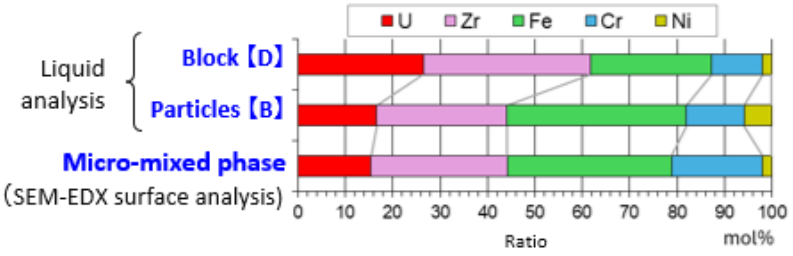
Example of microscopic oxide phase





- U-Zr-O phases, Cr-Fe-O phases, and Fe-O phases found mixed into micro-mixed phases in addition to small (~several μm) phases of Zr-U-O and Fe-Ni.

⇒ It is hypothesized that precipitation of the Zr-U-O phase continued and turned into molten oxide material with high concentrations of Fe and Cr, after which each phase split apart, cooled, and solidified.



Comparison of ratios of major elements

- The U:Zr:Fe:Cr:Ni ratio of the micro-mixed phase is close to the composition of particles【B h pulverization, indicating the possibility that powder was easily obtained through crushing.

*** The table and graph were updated based on the re-evaluation of the U analytical result for Powder [B] and the semi-quantitative result for Lump [C] on August 27, 2026.**

[Reference] Fuel element composition

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Reference) U、Pu、Nd、Gd isotope composition （mass spectrometry）

● Fuel debris【B】JAEA Nuclear Science Research Institute　× Core average value[1]　△ Natural isotope composition (Gd only)

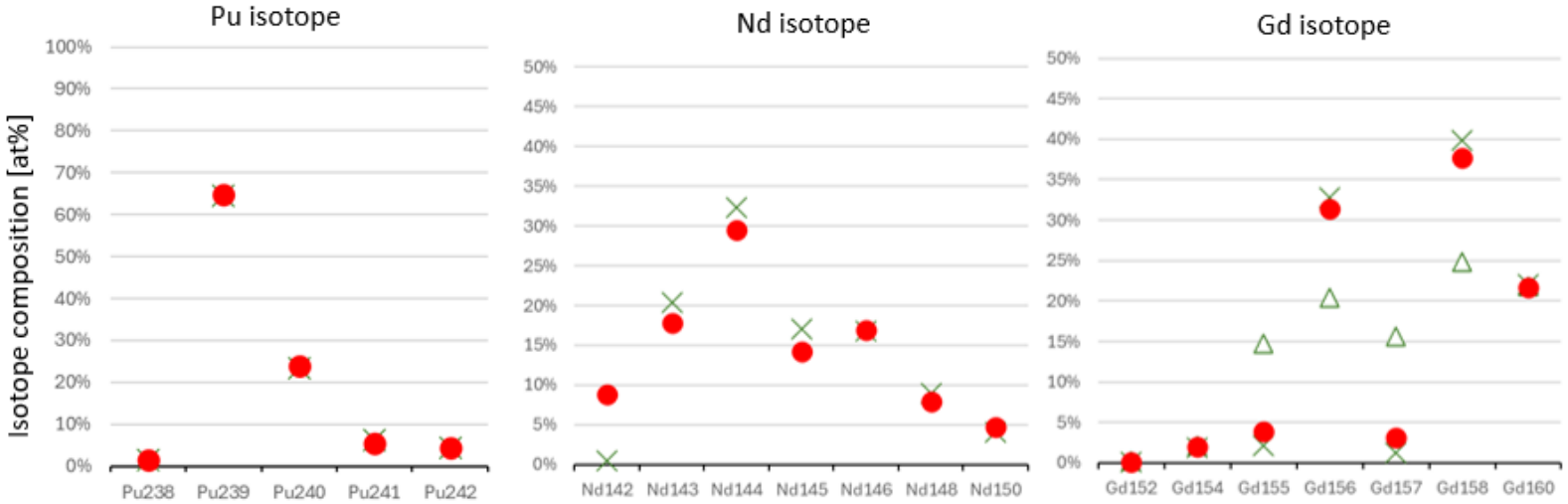
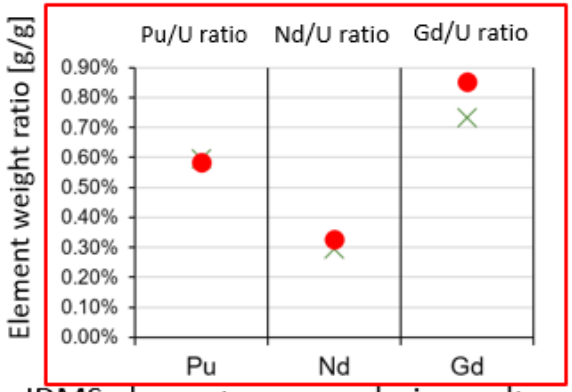


Figure 1　TIMS isotope composition analysis results (U has been omitted)



IDMS element mass analysis results
(compared to the ratio of U)

*

- The isotope composition is consistent with the average values for U, Pu, Nd, and Gd.
- Measurement of the element mass ratio to U shows that Gd/U and Nd/U are approximately the same as the average values, but the Pd/U ratio is approximately half of the average value.
- The chemical behavior of Pu depends greatly on the oxidation-reduction environment, so this provides a clue about the environment in which the fuel debris sample was formed.
- IDMS will be used to re-measure the Pu concentration in a standard solution in order to confirm the accuracy of the Pu analysis values. *
- Following the re-evaluation of the analytical results, a Pu/U ratio close to the average value was obtained as well.

[1] Okumura, et al., Atomic Energy Society of Japan 2021 Spring Conference, 3B01.

* **Based on the re-evaluation of the analytical values for U, Pu, Nd, and Gd by IDMS, the graphs showing ratios relative to U were updated and the relevant information was incorporated into the main text on August 27, 2026.**