Decommissioning Process **“Common Issues”**
Investigation Subject **“Measurement and analysis technology”**

Needs

1. Establishing a measurement and analysis technology for debris

Fuel Debris Retrieval：【Mid】

Desired state and reasons for it

- The “Inspection Guidelines on TEPCO Fukushima Daiichi NPS Reactor Facility Implementation Plan” focuses on the following risks: “Effects of radiation on the safety of the public”, Effects of radiation on the safety of the employees”, “Effects on safety assurance equipment, etc.”, “Effects on quality management”, “Effects on decommissioning project management”, “Effects on protective measures”. Therefore, it is required to have measurement and analysis technologies useful for overseeing these effects.
- Since fuel debris have the heterogeneity in terms of various physical property value, it occurs a wide range of uncertainty in the evaluation. Reducing the uncertainty range eliminates the need to include excessive margins in the safety assessment and safety measures, and improves the speed and rationality of decommissioning.

Current state against ideal

- After fuel debris removal started in 2021, analysis of samples containing fuel debris has been proceeded. It is desirable to use knowledge and information obtained from the sample analysis and survey on accident history examination (including amount of fuel and structural materials, FP adhesion, thermal history, equipment working status), retrieval method, transport／storing／storage, processing／disposal, and related worker safety and then, to promote the safe and efficient decommissioning through the entire processes from retrieval to processing and disposal.
- In order to utilize for the above matters, the data to be obtained from fuel debris analysis are broadly classified into “amount of nuclides and elements”, “shape and phase state”, “physical state (density and pore distribution)”, and “physical and chemical state on a micro scale”.
- As a methodology to obtain information on fuel debris for the purposes and matters mentioned above, it is anticipated to have both technologies and methods that can directly measure and analyze fuel debris existing inside the PCV and those that can transport and analyze in detail the debris at a hot laboratory, etc. after retrieval.
- In these cases, it is assumed that samples containing fuel debris exist in various states, and thus it is desirable to establish measuring and analysis technologies that have flexibility on the initial conditions of the samples and are applicable to various cases.

Issues to be resolved

- It should be noted that depending on the purpose of utilizing the analysis results (e.g., for fuel debris retrieval or for storing of fuel debris or otherwise), there may be different methods used for obtaining the same data using the same analysis method. Although some results can be obtained when analysis is performed, it is important that the analysis technology should include interpretation, analysis, and evaluation.

- In SEM, the location of observation is important. Since every sample is different, the approach to an unknown sample becomes an issue. It is important that the analytical technique including interpretation, analysis, and evaluation of the analytical results.
- In order to develop the measurement and analysis technology contributing to fuel debris retrieval, it is necessary to try to obtain data contributing to the maintenance of the safe conditions (criticality prevention／cool／hydrogen), confinement of alpha dust, etc. during cutting, the fuel debris segregation, methods and systems (including handling and workability for fuel debris), the understanding of the in-core status of the RPV, and in addition, information of indicators that may be useful for multiple of these data items (including fuel debris burn rate)
  - For criticality safety assessment, investigation is now underway on injecting boric acid based on conservative assumptions, preliminarily injecting non-soluble neutron absorbers, and overseeing work for subcriticality level based on neutron measurements. However, it is necessary to show the basis(e.g., compatibility of neutron absorbing materials with U, the amount of U, and neutron absorbing materials, etc.) for the existence／absence of possibility of fuel debris criticality in each unit and part through analysis of fuel debris samples and rational evaluation based on the analysis.
  - In heat generation and cooling countermeasures, the heat generation countermeasure can be evaluated analytically by evaluating changes in temperature distribution through on-site cooling water injection stop tests. However, when a temperature increase is observed in a specific part, it is important to obtain knowledge on the heat source, such as the U isotopic ratio and the FP composition. In the cooling countermeasure, on the other hand, it is important to evaluate the effect of a change in the chemical environment caused by changing the cooling method on the characterization of fuel debris and also evaluate changes in the surface and the deposition state of the fuel debris caused by the oxygen incorporation in the atmosphere during negative pressure control.
  - In the hydrogen generation countermeasure, it is necessary to evaluate the radiolysis of the cooling water by beta and gamma nuclides (especially, the influence of low energy radiation is large), which is considered to be a hydrogen generation source and the reaction between the cooling water and the unoxidized materials caused by the exposure of new surfaces during the fuel debris retrieval.
  - For the confinement of alpha dust, etc. during cutting, currently assuming laser cutting and mechanical cutting as cutting methods, rough evaluation of dust dispersions is in progress based on cutting simulation tests using simulated debris and past experience in hot cells. For laser cutting, it is important to evaluate changes in the oxidation degree caused by higher temperature of fuel debris (if the oxidation degree is low, low-order oxides may be formed, leading to a concern about re-evaporation) and the degree to which the volatile materials contained will be dispersed. For mechanical cutting, it is important to understand the mechanical properties (including hardness, brittleness, and melting point, etc.) and chemical properties (including average properties of a mixture or aggregate of phases and compounds) of fuel debris.
  - The handling of fuel debris needs to be investigated from the viewpoint of safety and workability and from the viewpoint of radiation dose. From the viewpoint of safety and workability, the handling of chemically active metallic debris, local chemical reactions and FP leaching caused by new surface exposure of fuel debris during retrieval work, and clarification of the persistence and precipitation of hard materials (residual B4C and borides) are the issues. In the case of air-cooling, fine particles adhering to the surface of the fuel debris may scatter, so it is necessary to take into account the surface adhesion during drying. As for the radiation dose, information on the dose rate of fuel debris is important as the basic data for the worker exposure control and the lifetime evaluation of the equipment

used. In addition, it is important to understand the source information necessary for occasional dose rate evaluation by analysis.

- In the investigation of a side access method for fuel debris retrieval, it is important to improve the accuracy of the evaluation of the condition inside the RPV, where a considerable amount of fuel debris remains. For this purpose, it is important to improve the evaluation accuracy of the fuel debris accumulation in the lower plenum of the RPV and the damage condition of the lower head, by the inverse problem analysis of the accident progression based on the analysis of samples containing fuel debris obtained from the pedestal, etc. The analysis items that are important in the inverse problem analysis are the chemical properties of the main components(including U, Zr, Fe, and B) of the fuel debris and deposits and the items related to their evaluation and among them, chemical properties of phases and particles containing U are specifically important.
- In the case where the concentration of U, Pu, burnable poison, FP radionuclides in the fuel debris is not known, for countermeasures such as criticality safety, cooling, and radiation shielding of transport／storage container of fuel debris, radiation resistance of equipment installed and hydrogen generation, the safety assessment is considered to be proceeded by assuming the maximum (or minimum) burnup and making conservative assumptions depending on the fuel debris handling such as no combustible Gd, no residual FP (or all FP remaining), etc.. Extremely conservative assumptions may delay the fuel debris retrieval with high handling volumes and may generate new risks. In order to allow for more reasonable conservative assessments, it is desirable to analyze burnup indices (148Nd (or alternative nuclides or elements) mass／U mass in fuel debris, and 235U mass／U mass in fuel debris).

● For the analysis related to storing and management of fuel debris, it is necessary to consider criticality safety, radionuclide／radioactivity, chemical stability／aging, and the rationalization of storing facilities.

- For the analysis of criticality safety in storing and management, it is important to understand the composition and isotope ratios of nuclear fuel materials in the fuel debris as basic data. In addition, it is necessary to have such basic information on the composition and isotopic ratios of major neutron absorbing materials, the density of fuel debris, and water content ratio, etc., and information on indicators for fuel debris analysis and evaluation, such as 148Nd, etc. is important in evaluating the contribution of FP. The heterogeneity should be taken into account because it is assumed that nuclear fuel materials with various compositions are heterogeneously mixed in the fuel debris.
- In the analysis of nuclides and radioactivity in storing and management, it is necessary to obtain information necessary for the evaluation of hydrogen generation amount and calorific value. For hydrogen generation, it is necessary to estimate the nuclides (alpha, beta, and gamma radiation sources) that may contribute to hydrogen generation and their radioactivity levels, the physical properties(including particle shape) of the radiation sources, and the water content ratio in packaged material or water amount in the storage container. As for the calorific value, it is necessary to have data on various radioactivity measurements of nuclides (137Cs, 90Sr) contributing to heat generation during the first decades after packaging, as well as data on the measurement of concentrations (vs. uranium) of actinide radionuclides in fuel debris.
- As for the analysis of aging during storing and management, the evaluation has been in progress so far on aging behaviors using simulated fuel debris, though in the future, it is important to demonstrate using actual fuel debris. Specifically, it is necessary to confirm and verify the characteristics of fuel debris (especially the presence and chemical state of key elements such as actinide elements) and the verification of physical, chemical, and biological

mechanisms (including weathering due to temperature changes, leaching due to contact with water, and microbial degradation).
  - For chemical stability during storing and management, it is important to collect knowledge and information on corrosion evaluation of the storage container. It is desirable to analyze the pH, chloride ion concentration, and nitrogen oxide concentration in the liquid phase in and around the fuel debris.
  - As for the rationalization of the storing facility, it is desirable to analyze the nuclides and their radioactivity of the fuel debris to be packaged, evaluate the calorific value of the storage canister, and confirm the cooling capacity.
- The analysis related to the processing and disposal of fuel debris must include the analysis of an inventory of radionuclides contained in the fuel debris, criticality safety assessment and leaching characteristics of the fuel debris, influential and environmental substances contained in the fuel debris, thermal and mechanical properties of the fuel debris, and hydrogen generation characteristics and effects on corrosion, etc.
  - The inventory of radionuclides in the fuel debris and the values of radionuclide migration parameters are used to assess the safety of processing and disposal. The analytical research facility in Okuma is planning to analyze 38 nuclides that are considered important for disposal (3H, 14C, 36Cl, 41Ca, 60Co, 59Ni, 63Ni, 79Se, 90Sr, 93Zr, 94Nb, 93Mo, 99Tc,107Pd, 126Sn, 129I, 135Cs,137Cs, 151Sm, 152Eu, 154Eu, 233U, 234U, 235U, 236U, 238U, 237Np, 238Pu, 239Pu, 240Pu, 241Pu, 242Pu,241Am, 242mAm, 243Am, 244Cm, 245Cm, 246Cm).
  - In the safety assessment of disposal, in order to understand the variation of environmental conditions achieve a highly reliable assessment, it is important to understand the chemical composition and amount of the contained substances (influence substances) that affect a criticality safety assessment of the fuel debris, the leaching characteristics of radionuclides from the fuel debris (including the waste body after processing), the environmental conditions for disposal (liquid properties affecting radionuclide migration parameters (including solubility, sorption distribution coefficient of the barrier, and a diffusion coefficient, etc.)), and various properties of the engineered barrier. In addition, along with understanding those influence substances, it is also important to understand the chemical composition and amount of the of hazardous substances that affect the environment.
- In order to design an appropriate waste body and disposal facility, it is important to understand the characteristics of the waste. In particular, in the case of fuel debris, it may have thermal effects on the surrounding disposal environmental conditions, and therefore it is important to evaluate those effects.
- Advance (streamline and improve accuracy) the technologies utilized in 1F decommissioning by applying AI／Machine learning.
  - Example 1 Application to radiation measurement technology : In the decommissioning of 1F, unlike the decommissioning of an existing nuclear plant, the contamination situation is unknown. Therefore, it may be difficult to analyze the radioactivity concentration of each nuclide with radiation measurement results (e.g., spectra), and more detailed measurement and analysis are required, which is an enormous task. Thus, it should be developed a technology to analogize true values from measurement results for unknown materials by having AI machine-learn the measurement results and simulation results for known materials. If this becomes possible, the work and time required for analysis can be greatly reduced.
  - Example 2 Application to radioactive waste and fuel debris analysis technology : Radioactive wastes whose contamination situation is unknown. Fuel debris which is composed of various dissolved materials. Since the distribution of contamination, components, and

concentrations are non-uniform and inhomogeneous, total analysis, rather than sample analysis, is required to accurately understand the totality of the contamination. By introducing AI into this process, it is aimed to analyze the entirety with high accuracy from few samples. If this becomes possible, the work and time required for analysis can be significantly reduced, and the amount of secondary waste generated can also be significantly curbed.

- The above is just one idea for an example of AI application, though it is expected that other AI applications will contribute to solving issues in 1F decommissioning.
- To this end, it is important to clarify issues and needs in 1F decommissioning, and to collaborate and co-create between the needs of 1F decommissioning and the seeds of AI technology.

2. Establishing a measurement and analysis technology for waste

Processing/Disposal/Environment Remediation：【Long 2】

Desired state and reasons for it

- In the processing and disposal of radioactive waste, it is necessary to assess the long-term safety after disposal. Therefore, it is desirable to establish measurement and analysis technologies contributing to the characterization of the nuclides and substances contained in the waste.
- Since solid wastes have diverse properties and large volumes, it is necessary to develop analytical facilities and train analytical personnel, as well as use analytical and evaluation methods that can efficiently determine the properties of solid wastes.

Current state against ideal

- The measurement of difficult-to-measure nuclides involves difficulties. Such nuclides are carbon and iodine. For example, iodine tends to become a gas, so it is necessary to examine a pretreatment method in consideration of the original state of the material.
- JAEA's Okuma Analysis and Research Center Laboratory-1 started operation in 2022, and construction of the second building is scheduled for completion in FY2026. For the time being, it is important to improve the accuracy of the model to obtain evaluation data based on the limited analytical data. Therefore, in the inventory evaluation using an analytical method, it is important to study the concept of a system to set and update the radioactivity inventory by comprehensively evaluating the analytical data and analyzed sites, as well as a method to reflect the variation of analytical data.

Issues to be resolved

- As a way to promote efficient decommissioning, implementation of characterization using rapid measurement (in-situ analysis and on-site analysis) by spectroscopic methods should be investigated, in addition to radiochemical analysis, so it is expected to promote necessary R&D for this purpose.

3. Establishing a technology for measuring radiation dose inside and outside the building

Fuel Debris Retrieval：【Mid】

Desired state and reasons for it

- In order to reduce the risk of exposure to workers, it is desirable to have the technology to analyze and measure the properties of the target nuclides in the work area and the surrounding dose.
- It is desirable to evaluate the diffusion of radioactive dust into the building as the result of access to the inside of the PCV for fuel debris retrieval.
- It is desirable to have a technology for discriminating and measuring alpha from U and Pu particles, gamma ray background, and beta ray, etc. with high efficiency and low detection limit.
- Analysis of soil, vegetation, etc. is desirable to enable environmental monitoring to understand environmental recovery and changes in environmental recovery within and near the site.

Current state against ideal

- For the examination of the status inside the reactor and building at the 1F decommissioning site, the performance and functionality of generally productionized radiation measurement devices are limited.
- For waste during fuel debris removal, workability can be improved if it can be quickly confirmed whether or not U is contained in the adhered materials on damaged supports, pipes, etc. We are conducting technological development using laser-Yuki breakdown spectrometry as a simple (in-situ) analysis technique that does not require separate facilities／equipment or sample transfer.

Issues to be resolved

- Decommissioning work on the 1F is subject to much higher radiation than working environment in other nuclear facilities. Therefore, decommissioning work must be done remotely. It is required to develop miniaturized measurement sensors, electronic circuits, and systems that have radiation resistance to high doses and can be operated remotely. For example, there are issues such as in a dry-up area on the basement floor, detecting alpha ray by penetrating a small alpha camera through a hole of 10 to 20 cm in diameter and to have a small camera that can go inside and shoot the images of basement floor.
- In the development of high radiation-resistant sensors and circuits, etc. in high-dose fields, research is required such as the basic mechanism of radiation damage to materials. As a specific example of development of sensors, etc., measurement device is required that in the background of high gamma ray can actually achieve the measurement of neutron from the viewpoint of criticality prevention, etc., the real time measurement of alpha ray from the viewpoint of fuel debris identification, and the measurement of gamma ray with high energy resolution from the viewpoint of nuclides estimation, along with satisfying various needs, such as radiation resistance, noise immunity, size (small size), counting rate and response, high dose rate capability, energy discrimination, spatial resolution (source localization), operability, and maintainability.
- Technological developments such as visualization of dose fields, contamination status, etc. based on information such as source strength and source direction using radiation measurement results, and clarification of fuel debris profiles will also be effective support tools for decommissioning work.
- Furthermore, it is the effective support tool for proceeding with the decommissioning work that the technology is developed to visualize dose field and contamination status based on

information such as source strength and source direction using the results of radiation measurements and to clarify the profile of fuel debris.

- In order to accurately estimate the environmental dynamics, it is also necessary to develop a monitoring technology for accurately understanding the contamination status and an analysis technology for simulating the migration behavior of radioactive materials. As for monitoring technologies, it is expected to have a remote and long-term continuous measurement technology, and mapping and behavior understanding technologies that utilize the big data from the measurement. As for the simulation technologies, it is desirable to develop a new model for analyzing the unique behavior in shallow underground (including the effect and kinetics of unsaturated layer) and an estimation technology using the code.
- Measurement and analysis technologies for liquids and gases are also important. In the case of liquids, it would be especially good to be able to monitor low-concentration seawater, and if tritium would have been discharged in the future, needs would grow for continuous measurement technology. In the case of gases, it would be especially good to have an alpha dust monitor that can remove the natural background contribution and measure the respiratory concentration limit of alpha ray, which is in the order of 10-7, at short intervals.

Relevant Issues

- CWM-101 “Understanding current status of contamination source”
- CWM-302 “Measuring alpha and difficult-to-measure nuclides”
- FDR-101 “Understanding status of fuel debris”
- FDR-106 “Understanding contamination status inside buildings”
- DRB-101 “Assessing conditions inside reactor and buildings (for dismantling)”
- DRB-202 “Establishing sorting criteria by alpha, beta and gamma contamination”
- TSR-101 “Characterization”
- PDR-101 “Characterization”
- PDR-103 “Material accountancy”
- PDR-205 “Verification and analysis method on waste body”