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ARTICLE

Applying Orano's Experience in High-Level Radioactive Material Handling to the Fukushima Daiichi Decommissioning Program

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Since Fuel Debris (FD) extracted from Fukushima Daiichi (1F) reactors are expected to contain unsealed high level radioactive materials, its handling from transportation to safe storage will pose several challenges in terms of safety and process feasibility. Three main design requirements are expected to apply to future FD handling facilities or equipment on 1F: ensuring the safety of the public and the workers operating these facilities, guaranteeing the remote operation and maintenance of FD handling facilities over the long term and providing analysis capabilities to collect data on FD properties. Through the design, operation, and maintenance of its nuclear fuel reprocessing plants, Orano cumulated long experience in the transportation, processing, storage and characterization of radioactive materials. The following technologies and practices used in Orano's reprocessing plants and which comply with the above requirements could be implemented by TEPCO in future FD facilities: shielded airtight container for High-Level Waste (HLW) transportation, remotely operated shielded airtight hot cells, contamination management inside hot cells and with HLW storage/transportation containers, and the implementation of a rational analysis strategy and the use of specific analysis technologies to measure and characterize the FD.

KEYWORDS: Fukushima, decommissioning, fuel debris, hot-cells, remote operations, contamination management, analysis

I. Introduction

The extraction and safe long-term storage of Fuel Debris (FD) generated by the meltdown of Fukushima Daiichi Nuclear Power Station (hereafter referred as "1F") Units No.1 to 3 reactor cores is one of the key parts in the overall nuclear power plant decommissioning process. As specified in TEPCO's 2024 Mid-and-Long-Term Decommissioning Action Plan,[1)] the strategy consists of starting the extraction of FD on a small scale, then by accumulating knowledge and experiences, to reach an industrial scale for all three Units.

FD extracted from 1F Primary Containment Vessels (PCV) are expected to be a mixture of unsealed radioactive materials (corium), reactor structural materials and concrete. For this reason, FD handling, including its safe transportation from the reactor to a dedicated facility, and as it can be assumed, its processing, characterization, conditioning in a dedicated canister or container, and safe storage will pose several challenges in terms of safety and process feasibility.

Orano, a leading international group in the nuclear energy sector and specialized in the nuclear fuel cycle, has been facing similar challenges throughout several decades in the design, operations, and maintenance of safe and reliable facilities handling unsealed nuclear materials such as La Hague Reprocessing Plants. This paper focuses on how Orano's cumulated experience in high level radioactive waste handling and characterization could be leveraged to benefit TEPCO in the design of future FD handling facilities on 1F.

II. Overview of Anticipated Requirements for Upcoming FD Handling Facilities

Since FD may contain unsealed high level radioactive materials, similar requirements for the design of high-level radioactive waste (HLW) handling facilities are expected to apply to future FD handling facilities or equipment. This first section lists up three main requirements (safety, operability/maintainability, and analysis capability) that one could assume for future FD handling facility and equipment on 1F.

1. Safety

The first requirements when designing HLW handling facilities is to ensure the safety of the public and the workers operating these facilities. The main safety functions which FD transportation equipment and handling/storage facilities will need to fulfil are expected to be the following:

- The protection of facility workers, the public and the environment against ionizing radiation
- The containment of radioactive materials
- The control of hydrogen generation from radiolysis and prevention of its accumulation
- The control of the subcriticality of handled fissile materials
- The evacuation of the thermal power produced by the radioactive materials.

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2. Operability/Maintainability

Since HLW cannot be handled at contact, the use of remote operations equipment will be required to operate FD handling facilities. Selected equipment will need to be designed to handle FD in a safe manner while giving the operators sufficient visibility on the object to be handled.

In addition, since FD extraction process is expected to last several years according to TEPCO's decommissioning action plan, maintainability of the FD facilities will be a key point to ensure safe reliable long-term operations. In order to minimize as much as possible the impact of radiations on workers (ALARA principle), maintenance of HLW handling equipment must be performed remotely. Besides, contamination spread from radioactive materials will need to be carefully managed inside HLW handling confined spaces to increase the reliability and durability of the equipment and facility.

3. Analysis capability

FD are expected to be a mixture of solidified melted materials including fuel assemblies, control rods, and some other materials. In the first step of FD extraction program, it will be necessary to understand the properties of FD for efficient and appropriate extraction operations, processing, storage and further disposal of the FD. The definition of an analysis strategy is essential to find the best way to characterize FD and to identify the best reconditioning strategy. It will especially contribute to the selection of relevant analysis methods and equipment to be used to characterize FD.

III. Orano's Relevant Experience for the Design of Future Fuel Debris Handling Facilities

This section introduces technologies and practices used by Orano for decades in its reprocessing facilities to handle, store and characterize radioactive materials and which could be implemented to comply with the requirements listed in the previous section when handling FD on 1F.

1. Shielded Airtight Container Design for High Level Radioactive Material Transportation

In Orano's La Hague nuclear fuel reprocessing facility, various shielded airtight containers are used to transport radioactive materials. One example is the PADIRAC shielded container developed by La Calhene[2)] which is used to transport radioactive waste on-site such as radioactive waste generated during the operation of the reprocessing facilities and contaminated tools. PADIRAC is a qualified, reliable and simple solution for moving small quantities (up to a few kg) of HLW while maintaining confinement, and with shielding against radiation. Radiation protection is ensured by lead shield and sliding shielded door. The product to be transported is loaded in an airtight DPTE container, which is loaded inside the shielded PADIRAC. The DPTE solution is an airtight transfer double door system allowing to avoid a breach of containment during product transfer between the container and any containment structure equipped with a DPTE docking port such as hot cells as shown in **Fig. 1**. A protection cover can also be used to prevent damage from a PADIRAC drop or collision during transportation. In case of short-term transportation of a low quantity of HLW, heat removal and radiolysis hydrogen generation inside an airtight container are not expected to be a significant concern for safety. However, to increase the confidence in the design regarding hydrogen management inside the container, a high-performance sintered metal filter could be installed on the DPTE container (see the section about Contamination management for more details on filters for hydrogen management) to allow hydrogen release while maintaining the confinement of radioactive materials. Sub-criticality can be managed by limiting the mass of the HLW transported.

Based on the above, the shielded PADIRAC with DPTE container is thought to be a reliable solution for the safe transportation of small quantities of FD from one confinement structure (e.g. air-tight cell connected to the PCV) equipped beforehand with a docking port to a FD handling facility for instance.

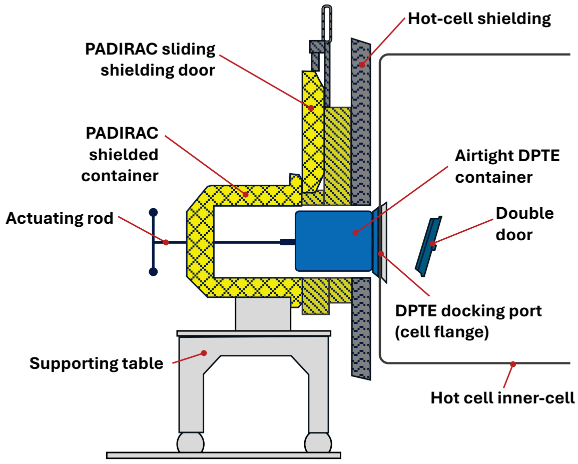

Fig. 1 PADIRAC shielded container and DPTE container docked to a containment structure (hot-cell inner cell)

2. Shielded Airtight Hot Cell Design for High Level Radioactive Naterial Handling

Hot cell is one of the main contributor for safe handling radioactive materials in Orano's reprocessing facilities. Hot cells use specific elements to achieve sufficient protection against gamma/beta radiations and neutrons (concrete or a combination of steel/polymer). Concrete is usually used for large process cells embedded in the building structure which offers high seismic resistance while steel/polymer is preferred for compact hot cells. Compact hot cells are used for instance on La Hague reprocessing plant process control laboratory to perform several types of analysis such as the composition of plutonium and uranium in process solutions or powders, or radioactive waste treatment (**Fig. 2**).

When handling radioactive materials, hot cells inner walls (stainless steel liner or stainless-steel inner cell surrounded by shielding walls) need to be designed to be sufficiently airtight providing a primary static containment (case of radioactive source unsealed in the cells) to avoid the spread of radioactive materials outside the cells. Secondary containment should be also provided by the room surrounding primary containment cells in order to ensure at least two barriers between radioactive materials and the environment.

Fig. 2 Shielded hot cells in La Hague reprocessing facility process control laboratory

To prevent the release of radioactive materials, each containment area should be classified by an appropriate nuclear zoning classification standard, depending on both the area radiation level and radioactive contamination level during normal operations and accidental contaminating situations. Nuclear zoning classification regarding radioactive contamination level results in ventilation requirements for each containment. For hot cells as described above, both primary and secondary containments must have a dynamic confinement provided by a ventilation system, which applicable provisions for the design and operation are specified in ISO standards as in[3]. In practice, ventilation maintains a negative pressure inside the cells (primary containment) compared to the pressure outside (secondary containment or working area) to limit the spread of radioactive material in the event of failure of the primary static containment. Ventilation can also be used to create a differential of pressure between different cells, as explained further in the dedicated section related to contamination management. The containment is extended on the ventilation ducts on which one or several High-Efficiency Particulate Air (HEPA) filters should be installed on series at the cell air intake and exhaust for filtering before discharge to the environment, depending on each cell radioactive contamination potential. An example of a shielded hot cell structure with a ventilation system is shown on **Fig. 3**.

Hydrogen management and heat removal in hot cells is ensured through cells ventilation. Subcriticality can be managed by limiting the mass of radioactive materials handled in the cells and/or the geometry of containers handled in the cells.

Shielded hot cells are used widely on Orano's reprocessing plants, and comply with all the main safety requirements assumed for the handling of FD. Such confinement shielded structure operated remotely appear to be also necessary on 1F if FD need to be processed and analyzed before being loaded in canisters or containers for further storage.

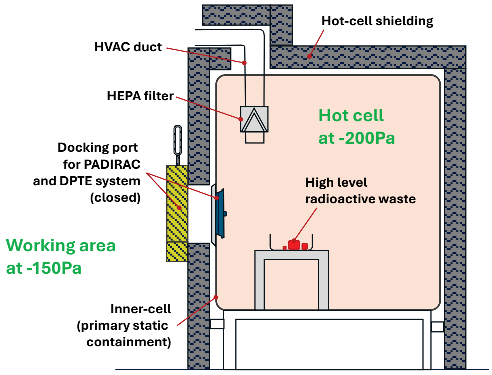

Fig. 3 Example of a shielded hot cell structure with a ventilation system

3. Remote Operation Equipment

In Orano's reprocessing facilities, the operation and maintenance of hot cells can be done remotely with mechanical and robotic remote manipulator arms which extend the operator's ability to manipulate objects in a radioactive environment. One example of manipulator used for decades on Orano's La Hague reprocessing plants is the Master – Slave Manipulator (MSM) with articulated arms as shown in **Fig. 4**. Operators operate the master arm outside the cell to handle objects of a weight up to a few tens of kilograms, perform maintenance of equipment and recover and pack waste with the slave arm on the inside of the cell.

Fig. 4 Operator using MSM for maintenance operations at La Hague vitrification facility

Depending on the nature of the operations, MSM can be operated with direct vision through a shielded window or using cameras in the cell. MSM are installed with leak airtight sleeves to guarantee the confinement.

Computer-assisted manipulators can also be used to be remotely controlled from the control room (such as on HLW vitrification facilities in La Hague) to allow a decrease of cells shielding requirements (decrease of operator exposure due to permanent operations close to the cell). In addition, repeated operations can be performed more efficiently and reliably compared to a standard MSM (e.g. automatic non-contamination control of a container).

In addition to manipulators, a wide range of hot cell handling equipment, such as trolleys and cranes, can be specifically designed to be able to remotely handle heavier objects in high radioactive environment.

Fig. 5 Computer assisted manipulator used to operate La Hague vitrification facility

4. Contamination Management

Contamination management inside and outside HLW handling containment is crucial to ensure the safety of workers and the public regarding the risk of internal radiation exposure. It is expected to be one of the major challenges on 1F site from the extraction of FD up to its safe storage.

(1) Contamination Management Inside Hot Cells

To manage the contamination inside hot cells, the cells can be separated and classified as indicated above according to their expected level of airborne contamination during normal operation and abnormal contaminating situations, which depends on the operation performed in the cell (type of radioactive materials containers (airtight or not) moved in the cells, radioactive materials processing, analysis, etc.). To manage contamination dispersion between the cells, dynamic confinement is provided by a ventilation system, creating an airflow from areas of low levels of contamination towards areas with higher levels of contamination by setting a negative pressure cascade between the cells as shown in **Fig. 6**. The pressure difference in adjacent cells with different level of contamination can be set to 50Pa, for instance.

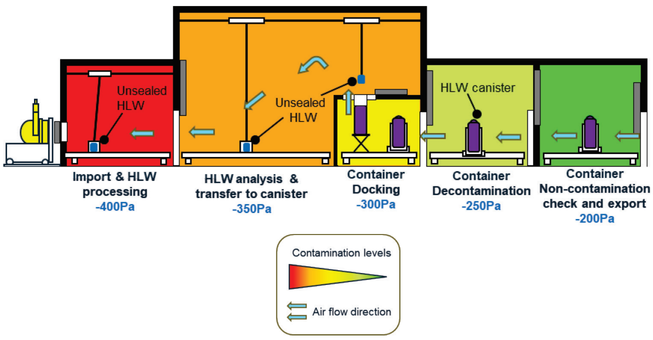

Fig. 6 Example of pressure management in a line of hot-cells handling HLW

Detection means can also be implemented to monitor cells contamination atmosphere (depending on contamination potential inside the cells, continuously or only prior to opening cell for exceptional maintenance).

Contamination can also be monitored to detect a leakage from the cells towards the working area (outside the cells). For example, airborne contamination in the working area is monitored with continuous air sampling at each MSM workstations and potential other crossing or penetrations to ensure the safety of operators.

(2) Storage or Transportation Container External Contamination Management using Airtight Docking

If FD are to be loaded in a canister or a container for future safe storage, proper management of contamination of the external surface of the canister/container should be considered. This can be achieved first with an airtight docking of the canister/container to the hot cell handling the HLW to be loaded.

In addition to the Padirac/DPTE solution as mentioned above, the HLW canister/container head can be designed to be flat to allow the largest machined connection surface as possible between the canister/container and the docking port of the cell. A ventilation system can be used to adjust the pressure differential across the docking port to limit the leakage rate towards the clean area. This kind of docking is used often on Orano's La Hague reprocessing plant to load or unload safely radioactive materials from containers, such as on T0 facility (Spent Fuel dry unloading facility) where casks container spent fuel assemblies are discharged.

The Mobile Equipment Replacing Cask (MERC) technology is another specific solution used by Orano to evacuate safely process equipment used in high-radioactivity environments at reprocessing facilities when subject to regular inspections or failures (**Fig. 7**). The safe transfer of the contaminated equipment from the cell to the cask is ensured by a tight docking using multiple seals between the cell, a hatch and the cask itself, and a dynamic confinement (depressurization inside the cask) thanks to a connection between the cask and the ventilation system.

Fig. 7 Mobile Equipment Replacing Cask (hatch type)

(3) Ensuring Both Hydrogen Management and the Confinement of Radioactive Materials in Containers

Another challenge related to the safe storage of HLW such as FD is to ensure the design of the storage canister or container ensures both the confinement of radioactive particles and radiolysis hydrogen release. Similar challenge has been encountered on La Hague reprocessing plant when designing a standard stainless-steel container for the packaging of compacted high activity metallic pieces (such as fuel cladding named “hulls” which remain as metallic waste after the shearing of spent fuel assemblies and the dissolution of fuel pellets) into stainless steel canister called UC-C (Universal Canister for Compacted waste) for safe interim storage and final disposal.

Two complementary solutions can be used for safe hydrogen risk management: limit sources of hydrogen emission (water, organic materials etc.) and/or control hydrogen release to avoid its accumulation inside canisters/containers.

To limit sources of hydrogen emission in the case of HLW stored in UC-C canisters mentioned above, metallic pieces are dried before compaction in order to limit the moisture content of the waste and thus limit the hydrogen generation through radiolysis inside the canisters. The drying process specifications are selected depending on project requirements and constraints i.e. type of materials to be dried, necessity or not to perform drying in inert atmosphere, drying temperature etc. FD extracted from 1F reactors will be most likely wet and will require drying before being loaded in a storage canister or container to limit hydrogen generation during storage and the risk of corrosion inside the canister. Attention should be paid to the risk of ignition leading to fire hazard associated with the pyrophoricity of zirconium, especially when drying low granulometry materials containing zirconium such as powder or dust/fines, which may be included in the extracted FD. Measures such as using an inert gas atmosphere during the drying operations and limiting the temperature of drying below the minimum ignition temperatures of zirconium powders can be used to prevent a risk of ignition.

High-performance sintered metal filters can also be welded on the canister lid to allow hydrogen release from the canister/container while ensuring proper ventilation of the storage cell. Poral® sintered metal filters are used by Orano on UC-C canisters to keep the compacted HLW storage cell free of contamination while allowing the release of radiolysis hydrogen from the canisters (**Fig. 8**).

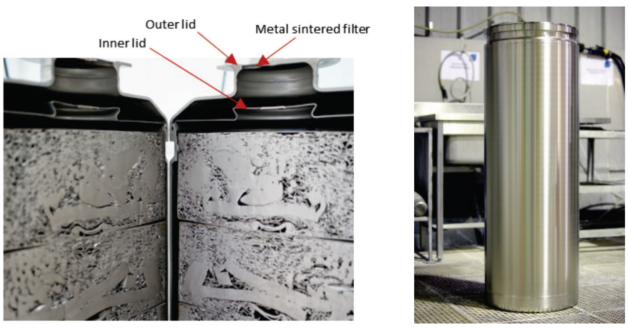

Fig. 8 UC-C canister with sintered filters welded on outer lid

For instance, filtration performance can be up to 99.9% for particles with a diameter above 0.5μm for a grade 03 Poral® stainless steel sintered filter.[4)] The use of such high-performance filter is highly recommended on future potential FD storage canister/container on 1F.

(4) Surface Contamination Control

To ensure a canister or container radioactive surface contamination is within specific standards when being transported outside a radiological controlled area, surface contamination control is necessary. In Japan for example, the law specifies the non-fixed surface contamination of an object leaving a radiological controlled area should be below 0.4 Bq/cm^2 for alpha emitters and 4.0 Bq/cm^2 for other nuclides.[5)]

For shielded containers, surface contamination control may be done directly at contact by an operator with necessary control device and protection equipment (gloves, mask etc…). However, in the case of high activity waste canister such as the UC-C canister introduced in the previous section, contamination control within a shielded hot cell using remote device such as a robot or a computer assisted manipulator is necessary. The robot or manipulator can be programmed to automatically scrub the canister or container surface to be controlled with a smear, transfer the smear to a control machine equipped with two control chambers (one for beta/gamma rays, the other for alpha contamination) and finally transfer the smear to the smear bin.

In the event contamination is found on the surface of the canister/container, decontamination in a separate cell is recommended to keep the cell where contamination control is performed as much as possible free of contamination.

5. Analysis Capability

Orano’s reprocessing and waste storage facilities are equipped with a wide range of analysis equipment to quantify the amount of fissile materials dissolved after spent fuel assemblies shearing, monitor chemical processes, control end products, characterize radioactive waste etc. Such experience in analyzing nuclear materials could be used on 1F to understand the characteristics of FD.

(1) Analysis Strategy

The definition of an analysis strategy will be essential to find the best way to characterize FD and to identify the best reconditioning strategy.

The first step is to determine which parameters will need to be analyzed to address the objectives of HLW characterization. Then appropriate analysis method and type of measuring equipment will be selected for each parameter. Some of the expected analyses to characterize and measure the FD and examples of equipment used by Orano to achieve such analyses are below:

- Activity measurement for transportation and storage purpose: gamma and neutron dose rate measurement instruments
- Hydrogen generation rate measurement (only done for qualification purposes in La Hague facilities): gas chromatography
- Elemental composition determination: X-Ray Fluorescence spectrometry (XRF; non-destructive

analysis for U and Pu) or Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES; destructive analysis)

- Anions & cations compositions to manage the corrosion risk: High Pressure Ion Chromatography (HPIC)
- Organic content measurement to select the waste conditioning method: Total Organic Carbon (TOC) meter
- Measurement of fissile materials: Active Neutron Interrogation (ANI; see the next section for more information).

The followings will need also to be defined to guarantee the analyses objectives and performance are achieved:

- the specification of the waste package
- the number of measuring stations to be implemented
- the definition of appropriate radiological reference spectra and the use of representative analyses of waste in order to qualify the analysis equipment
- implementation of special measures to carry out analyses in a radioactive environment such as nuclearization of analysis equipment or shielding around the measurement chamber to reduce radiation background etc.

(2) Example of the ANI Technology to Determine HLW Properties

ANI is a non-destructive measurement technology used at La Hague reprocessing plant, for instance, to determine the residual masses of fissile materials (U and Pu) in metallic fuel cladding (hulls) HLW packages as explained in.[6] This technology is essential for non-destructive measurement of fissile materials in waste containers, which will most certainly be required for the quantification of fissile materials in FD extracted from 1F reactors, not only for sorting before interim storage, but also for nuclear safeguards and Nuclear Material Control and Accountability (NMCA).

Orano has a long experience in ANI technology developed with the French Alternative Energies and Atomic Energy Commission (CEA), not only with historical measuring stations, but also through continuous improvement (upgrade with internal monitors and transmission measurement) which allowed to significantly reduce uncertainties and improve measurement accuracy. Several improved ANI measurement stations are currently operating in La Hague reprocessing plants (shearing & dissolution facilities, compaction facility, legacy waste retrieval facility…) as shown in **Fig. 9**.

Fig. 9 Left: ANI station in La Hague compaction facility Right: Newly installed ANI station in the Orano La Hague Waste retrieval HAO Cell

III. Conclusion

Fukushima-Daiichi Fuel Debris Retrieval is probably the most complex decommissioning challenge in the world since it combines the problematics of back-end fuel cycle facility operations and waste management, at a very large scale and with many unknowns. This paper gave an overview of the expected main requirements in terms of safety, operability/maintainability, and analysis capability which are expected to apply to future FD handling facility or equipment. Through the design, operation, and maintenance of its spent fuel reprocessing plants, Orano cumulated long experience and know-how to safely handle and store HLW: shielded airtight containers, remotely operated shielded hot cell, contamination management, nuclear measurement etc. In the view of similar challenges faced in the handling of FD retrieved from 1F reactors in the future, Orano's experience and best-practices from lessons learned can be leveraged to benefit TEPCO in the design of its technical solutions to overcome these challenges.

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