# MANAGEMENT OF RESEARCH AND TEST REACTOR ALUMINUM SPENT NUCLEAR FUEL – A TECHNOLOGY ASSESSMENT

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## ABSTRACT

The Department of Energy's Environmental Management (DOE-EM) Program is responsible for the receipt and storage of aluminum research reactor spent nuclear fuel or used fuel until ultimate disposition. Aluminum research reactor used fuel is currently being stored or is anticipated to be returned to the U.S. and stored at DOE-EM storage facilities at the Savannah River Site and the Idaho Nuclear Technology and Engineering Center. This paper assesses the technologies and the options for safe transportation/receipt and interim storage of aluminum research reactor spent fuel and reviews the comprehensive strategy for its management. The U.S. Department of Energy uses the Appendix A, Spent Nuclear Fuel Acceptance Criteria, to identify the physical, chemical, and isotopic characteristics of spent nuclear fuel to be returned to the United States under the Foreign Research Reactor Spent Nuclear Fuel Acceptance Program. The fuel is further evaluated for acceptance through assessments of the fuel at the foreign sites that include corrosion damage and handleability. Transport involves use of commercial shipping casks with defined leakage rates that can provide containment of the fuel, some of which are breached. Options for safe storage include wet storage and dry storage. Both options must fully address potential degradation of the aluminum during the storage period. This paper focuses on the various options for safe transport and storage with respect to technology maturity and application.

## INTRODUCTION

The Department of Energy's Environmental Management (DOE-EM) Program is responsible for the receipt and storage until ultimate disposition of aluminum research reactor spent nuclear fuel that was used in research and test reactors worldwide and contains U.S. origin and certain non-U.S. origin enriched uranium [1]. Spent fuel from domestic research reactors is also consolidated by the DOE at its U.S. storage sites.

The foreign and domestic research reactor fuel is primarily aluminium-based, aluminium-clad, that is being stored in L-basin, a water basin at the Savannah River Site (SRS). Additionally, aluminium fuel, the majority of which originated from the Advanced Test Reactor, is in dry storage at facilities at the Idaho Nuclear Technology and Engineering Center (INTEC) at the Idaho National Laboratory.

This paper assesses the technologies specific to aluminium-based research reactor fuel for safe transportation, condition assessment for receipt, and continued interim storage in either “wet” or “dry” storage systems. The practices involved in its safe management with a focus on the technical bases for their application are summarized.

## DISCUSSION

The return of research reactor spent nuclear fuel for interim storage involves several major functions shown pictorially in Figure 1. These functions include site assessments of the spent fuel and spent fuel characterization, transport of spent fuel from the reactor location to the DOE sites, and extended interim storage at the DOE sites.

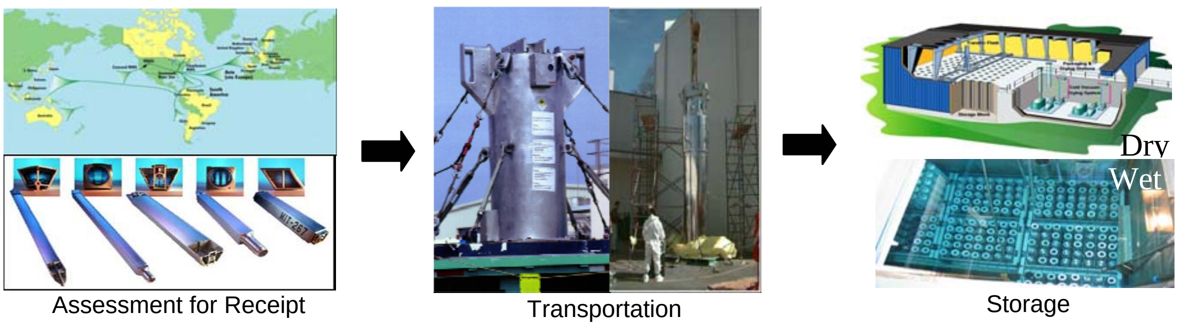


Figure 1. Aluminum-based, aluminum-clad spent nuclear fuel from research reactors worldwide is being transported to the U.S. and stored in L-basin at the Savannah River Site. Additional aluminum fuel is in dry storage at the Idaho Nuclear Technology and Engineering Center.

The following sections summarize the steps in management of spent nuclear fuel, highlighting the key technologies involved in providing for its safe management.

### Fuel Condition Following Irradiation and At-Reactor Basin Storage

Water basin or pool storage at the reactor site is used to provide cooling and shielding of the fuel following discharge from the reactor. Aluminum fuel is particularly susceptible to corrosion attack in low quality water. The three primary forms of corrosion observed in aluminum spent fuel when stored in poor quality water include pitting corrosion i.e. localized corrosion, crevice corrosion which typically occur in crevices formed at joints, and galvanic corrosion which occur when dissimilar metal contact each other. Figure 2, shows an example of a fuel assembly of Materials Test Reactor design (multiple fuel plates in a “box” assembly) that has minimal corrosion attack following its use in reactor and basin storage; Figures 3A and 3B show examples of fuel assembly that have undergone corrosion attack via several corrosion modes.

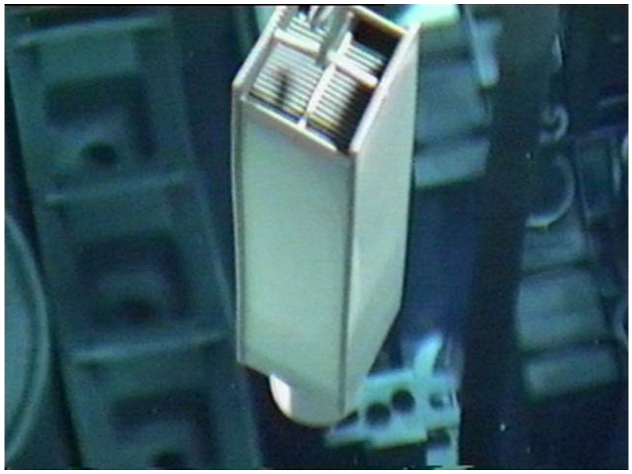

Figure 2. Aluminum-based, aluminum-clad spent nuclear (plate) fuel assembly in a good physical condition, post-irradiation and storage in a basin with good water quality.

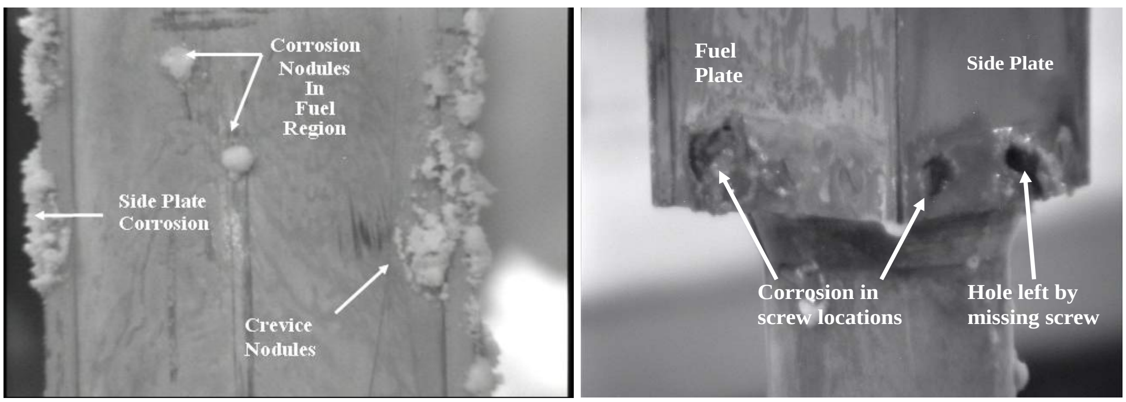


Figure 3. Aluminum-based, aluminum-clad spent nuclear fuel in moderately degraded condition post-irradiation and storage in a basin with poor water quality and storage conditions. (a) evidence of pitting corrosion attack and crevice corrosion attack is the corrosion products and (b) evidence of galvanic attack due to stainless steel-aluminum alloy couple at the location of stainless steel screws is shown

The irradiation of the fuel elements and at-reactor storage alters the fuel from its initial condition. Due to the various irradiation and fuel storage conditions at the sites, the characteristics of the fuel inventory are at a range of physical and isotopic conditions.

## Spent Nuclear Fuel Characteristics

Spent Nuclear Fuel (SNF) characteristics information is needed for transport, storage and disposal systems for evaluation of system operation, safety, and environmental impact. Characteristics information for each spent nuclear fuel assembly to be received at and stored in pool storage at the U.S. Department of Energy (DOE) Savannah River Site (SRS) is compiled in an “Appendix A” document for the fuel [2-3]. The Appendix A document for a fuel assembly (collection of the fuel elements, e.g., plates into a fuel unit or assembly) aims to provide the accurate and pertinent information concerning the post-reactor-operation characteristics of the fuel assembly.

The Appendix A document includes a detailed description of each element, rod or plate, that makes up a fuel assembly as well as a detailed description of the assembly as a whole. This includes geometric and mass information including fuel meat mass, composition, and geometry for each element that comprise a full assembly. Cladding material mass, composition, and geometry are also included for each element. The full assembly description includes geometric and mass information on additional materials, such as spacers, dummy plates, thermocouples, fittings, etc., that are included in the full assembly.

## Spent Nuclear Fuel Transportation

Shipment of radioactive materials, including spent nuclear fuels, is subject to national and/or international radioactive material transportation requirements documents [4-5]. These requirements address structural integrity, criticality control, radiation shielding, thermal analysis, and containment analysis of the shipment. Structural integrity is primarily a function of cask and basket design. The light-weight aluminum spent fuel assemblies do not challenge standard shipping cask designs. Criticality control for the enriched uranium assemblies is generally addressed by geometry of the fuel baskets that limit the redistribution of spent fuel plates within a given cask. Radiation shielding is provided by integrated shields in the shipping cask. The thermal response of the cask is a function of the heat dissipating capacity of the cask and the heat generating rate of the radioactive material in the cask. Typical shipments of aluminum spent fuel assemblies are sufficiently delayed as to allow for the decay of the shorter lived fission products and commensurate reduction in assembly thermal load. Interactions of fuel materials with the canister materials are considered in reference [6] for the special case of a disposal canister for the fuel.

Aluminum-clad nuclear fuel stored in water basins is subject to corrosion attack if the water quality and storage conditions are aggressive to aluminum and approximately 7% of the number of fuel assemblies are expected to contain through-clad penetrations [7]. Containment during shipment of breached aluminum-based spent nuclear fuel without canning can be demonstrated through the implementation of a methodology that incorporates the fuel/clad structure and material corrosion behavior of the fuel using fuel-specific performance data including laboratory experiments and phenomenological modeling [8]. This methodology was adapted from ANSI 14.5 [9] and NUREG-6487 [10], which provides guidance on the implementation of the regulatory requirements for the shipment of commercial spent nuclear fuel.

## Interim Wet Storage

Interim wet storage in a water basin is one of the two options for the storage of spent fuel awaiting ultimate disposition. It requires maintenance of good water quality and storage conditions of the aluminum fuel to avoid its corrosion-induced degradation. Figure 4 shows an example of a basin for spent nuclear fuel storage.

Elements of a management strategy for basin storage include water quality limits, methods to clean-up water, monitoring of water quality, and implementation of a corrosion surveillance program.

Corrosion surveillance is also required to provide an early warning that degradation is not occurring under the storage conditions. Periodic inspection of the fuel and storage system materials is useful to validate the surveillance results and demonstrate safe fuel sotrage.

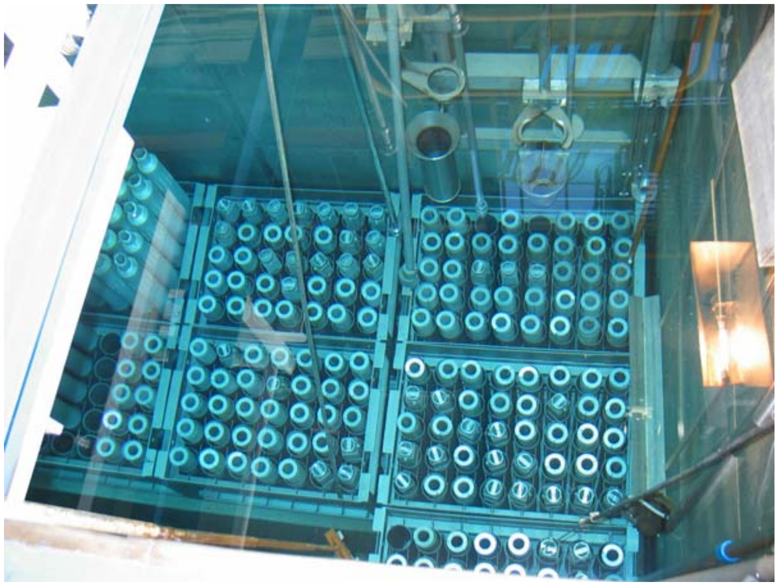

Figure 4. A typical water basin for aluminum spent nuclear fuel storage (courtesy of the Australian Nuclear Science and Technology Organization (ANSTO))

***Water Quality***

Aluminum materials in water are susceptible to corrosion attack, especially if the water conditions are of poor quality. A recent publication by the IAEA, that included the fuel storage experience at the Savannah River Site, provides guidelines for avoiding excessive corrosion through water quality management [11]. The IAEA publication on practices recommended for water quality [11] includes protocols for corrosion surveillance. The purpose of a corrosion surveillance program (CSP) in a research reactor facility is to provide early detection of corrosion of components, structures and/or the nuclear fuel in contact with the water.

***Storage of Breached Fuel in Water Basins***

Breached fuel can release radioactivity from the fuel into the basin water. The basin activity is dominated by the concentration of $^{137}Cs$ in the basin water as determined by chemical analysis of basin water samples. Therefore, modeling radiation release rates from breached aluminum fuel into the basin water depends on the release rate of $^{137}Cs$. The methodology to evaluate the effect of breached fuel on basin activity was established in Reference [12]. The activity concentration of the basin is directly related to the pumping rate through the water clean-up system (deionizers) and the release rate of $^{137}Cs$ from the existing basin sources and from the fuel meat material exposed by the through clad penetration. The long-term steady-state activity concentration in the basin will be proportional to these parameters. Due to the finite, slow corrosion rate of the exposed fuel, the L-basin with its water clean-up system can tolerate a fairly large quantity of breached fuel and yet maintain water activity levels within safe limits

### *Mitigating Severely Breached Fuel in Wet Storage*

The DOE complex has had a long history of handling a wide variety of damaged fuel types. Placing the damaged fuel assembly in an isolation canister has been a common solution to contain the radionuclide activity that can be released from breached-cladding (primarily Cs-137). Experience has shown that canisters with special design features may be needed dependent on the fuel type and condition.

Isolation canisters for damaged SNF are designed to allow underwater storage of the highly damaged fuel while containing the radionuclide activity that can be released from it. Containing the released activity is important from the standpoint of radiological protection of basin operations personnel and reducing waste generated by more frequent regeneration/replenishment of basin deionizer resin beds. A common design feature in the SRS-design OS canisters was an inverted J-tube in the lid of the canister. The inverted J-tubes act as gas traps to separate the internal water environment from bulk basin water. Gases released from damaged SNF build up at the top of the can and into the inverted J-tube. Figure 5 shows that, with the opening at the top of the canister, very little gas buildup is needed to separate the two water environments.

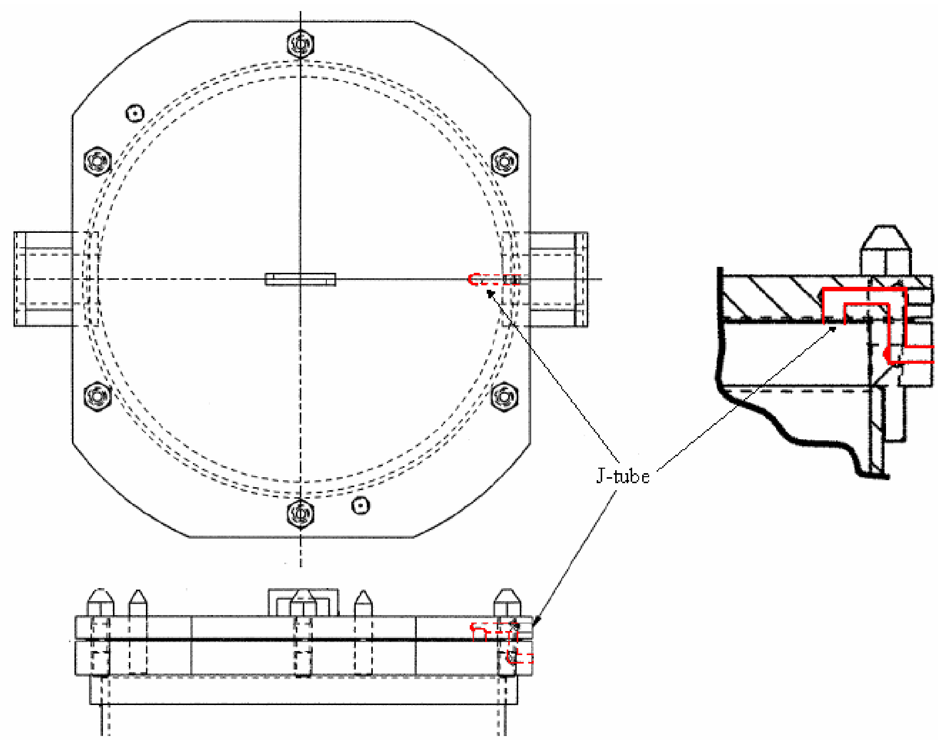


Figure 5. Later J-tube design on damaged-fuel storage can.

The open design of the original J-tubes made them susceptible to silt buildup and pluggage. Valved couplings were added to avoid this problem, but this restricted the free flow of gas from the canisters. To minimize the potential for pluggage of the tube with debris, changes in the J-tube design were made. In employing isolation canisters for the storage of damaged/degraded spent nuclear fuel, the canister provides the necessary and critical design features that were once performed by the fuel structure and cladding. The DOE has implemented many improved versions of such isolation canisters at the L-basin at SRS [13].

Historically, SRS chose isolated storage in water for the significantly damaged and cut fuel, separating it from the remainder of the basin water by loading it into large water-filled canisters. The method of storing damaged fuel underwater was to place fuel pieces in small diameter canisters (some aluminum and some stainless steel) which were grouped with others and placed in larger aluminum vessels referred to as over-sized (OS) canisters (Figure 6).

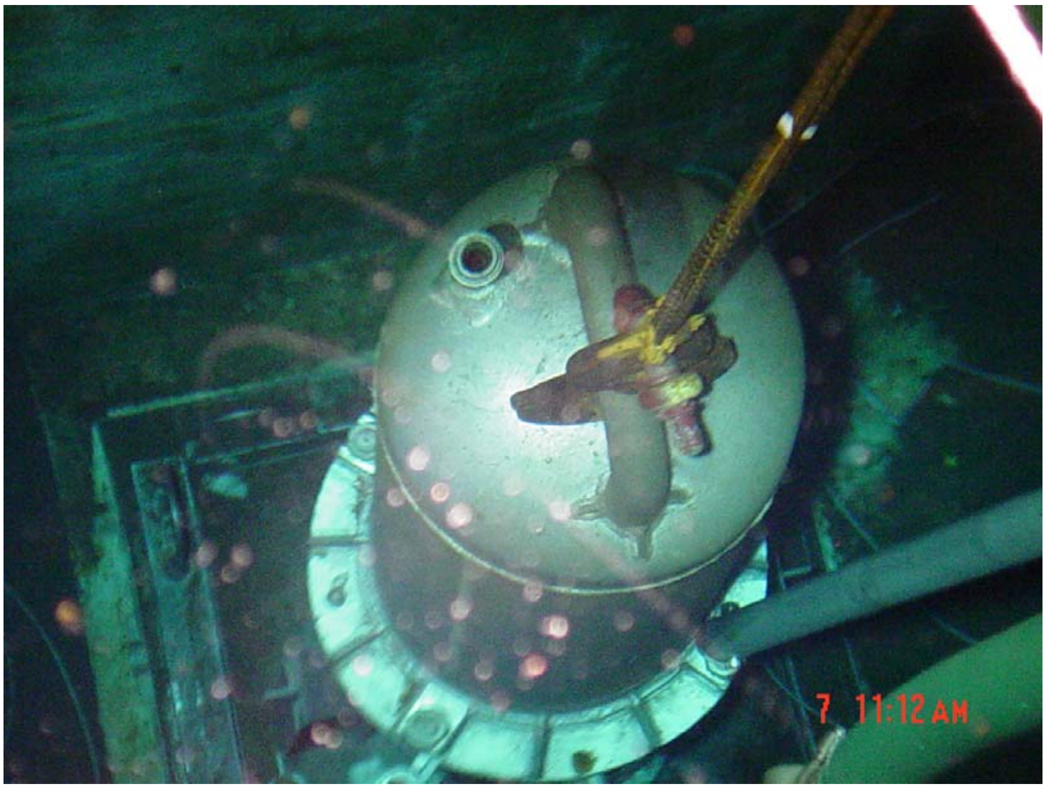


Figure 6. An oversized aluminum storage canister used for damaged-fuel (at -9.14 m) in RBOF

The SRS experience with these oversized isolation canisters illustrates the benefit and the potential liability with the employment of isolation canister technology. The isolation canister effectively isolates the bulk basin water from the water within the isolation canister. However, the water within the isolation canister may become increasingly more contaminated with fission products from the ongoing fuel degradation process. This becomes significant if there comes a need to open the isolation canister as in the case of the SRS oversized isolation canisters. To mitigate the highly contaminated water and minimize the impact on the bulk basin water activity upon opening the OS canisters, SRS developed and employed a technology to clean the water within the isolation canister through a filtration and deionization system.

The oversized isolation canisters that required recovery were 3.96 m tall right circular cylinders with an interior diameter of 0.33 m, made in two halves with flanges in the center of the long axis. They were designed with an exterior access tube from the bottom of the vessel and a J-tube at the top. Gas emanating from the fuel could be vented out of the OS can through the J-tube if desired. Couplings were affixed to the end of both of these tubes, isolating the contents of the OS cans from the basin, but providing a path to flush water through the vessel or take water samples. The required parts of the submersible deionizer in its simplest form were: a pump and motor, filter, and an ion-exchange column (Figure 7). The space allotted for the system was approximately 1 $m^2$ on a basin shelf at 4.6 m below the water's surface. The basin engineer recommended 28.3 l of cation resin for the system, which bracketed system flow between 7.6 and 37.9 lpm to achieve the greatest ion exchange efficiency. The remainder of the system was sized accordingly. Positive displacement gear pumps (redundant) were powered by non-lubricated air motors, allowing variable speed operation and protection against locked-rotor situations. The water-lubricated pump(s) drew water from the oversized can(s) through a 100 micron wire mesh filter. The filter cartridge mesh size was chosen to protect the pumps and keep material from plugging the resin column. The design was checked for code compliance, fabricated, and fully tested before delivery to RBOF. Below is a sketch of the system.

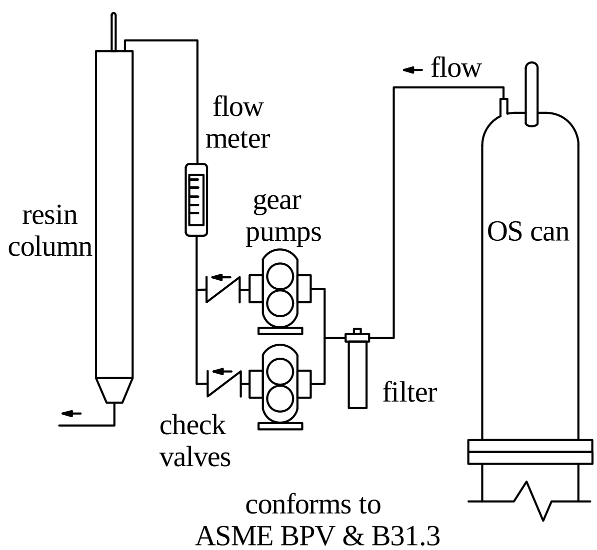


Figure 7. RBOF Underwater Deionizer Sketch

The redundant pumps and their corresponding motors were fixed to a 0.71 x 0.91 m skid and plumbed together with stainless steel pipe, having a common suction from the filter. Each pump was followed by a check valve before joining to a common flow meter. The check valves allowed either pump to operate singly, without recirculating water to the suction, or simultaneously, if desired. The filter housing sat in a notched tubular receptacle which kept it from rotating and allowed it to be removed and replaced easily as a unit. The ion exchange column was aligned with its discharge pipe and held in position with parallel vertical guide rails. Other than the fixed piping on the skid, all liquid transfer was accomplished with reinforced rubber hose. Below is a photograph of the underwater deionizer as it was positioned in the SRS RBOF basin, 4.6 m below the surface of the water.

The site Spent Fuel Project organization personnel planned, and RBOF Operations performed, OS canister flushing using the submersible deionizer with excellent results.  Oversized cans were designed in 2 pieces with a pipe connection to the bottom half and a J-tube vent at the top of the upper half.  The J-tube vent was connected to the deionizer allowing low activity basin water to be drawn into the storage can with pump suction to bring high activity water into the deionizer (Figure 8).  Some of the storage can's inlets were restricted or plugged with particulate so Basin Operations personnel loosened the OS can flange to allow basin water to be drawn into the can through the flange opening for purging.

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Figure 8. RBOF underwater deionizer with empty oversized canister halves

Oversized can water activity was monitored using a submerged probe attached to a radiation monitor.  Dose rates in the general basin water never exceeded the limit of 0.02 mGy/hr. The internal volume of each OS can was approximately 416 l and flow through the ion-exchange resin was maintained at 15.1 lpm. The deionizer removed cesium from OS canister water allowing damaged fuel to be moved into more modern stainless steel storage containers with an improved J-trap and designed to fit the racks in the destination facility.

## Interim Dry Storage

The second option for the storage of aluminium spent fuel pending disposition is that of Interim Dry Storage. The requirements for dry storage are based on providing for safe, retrievable storage of the aluminum fuel. Safe retrievability is directly related to limiting degradation of the fuel in a storage system to an acceptable level. Limits to acceptable degradation of the fuel during the drying and the storage period are needed to ensure post-storage handleability, criticality safety, radionuclide confinement by the fuel/clad system, and a full range of ultimate disposal options.

Removal of the aluminum fuel from basin water and placement in a dry storage system does not totally preclude corrosion unless the fuel/canister system is completely dry and in a sealed storage system. In addition, other degradation mechanisms that can potentially affect the integrity of aluminum-clad spent nuclear fuel over long term storage need to be considered. Other mechanisms become important since the fuel temperature in a dry system would be higher than in wet storage due to removal of water as a cooling media and consolidation of fuel to reduce a storage system footprint.

### *Degradation in Dry Storage*

Maintaining changes to the fuel condition within acceptable degradation is consistent with the requirements for dry storage of commercial spent nuclear fuel given in Title 10 of the U.S. Code of Federal Regulations, Part 72, paragraph h [14] which allow no large breach of the cladding during storage and subsequent handling. Limits for acceptable degradation of aluminum fuel during fuel drying and a dry storage period of 50 years were developed and reported [15].

Two distinct types of dry storage systems are envisioned: a “sealed system” which would store fuel assemblies in fully-sealed containers and a “non-sealed” system which would store assemblies in non-sealed containers or holders open to the environment of the facility.

### *Sealed Dry Storage*

The approach to avoid excessive degradation in a sealed system is to dry the contents of water remaining in the fuel/container to-be-sealed, for both free and bound waters, to a level such that if the water is consumed by corrosion of the fuel, acceptable degradation of the fuel is maintained; and also that the production of hydrogen does not pose a threat. Gases produced may overpressure containers, embrittle materials, reach flammable concentrations, accelerate corrosion, or form pyrophoric species that would impact safe post-storage retrieval. As an example, severe corrosion attack can occur with a combination of air, water, and the attendant radiation of a fuel. In laboratory tests in which aluminum cladding alloys were placed in a sealed capsule with air and water and placed in a gamma cell, rapid corrosion occurred relative to the cases with no radiation [16]. In addition, corrosion occurred at all values of relative humidity (no threshold) as compared to the case with no radiation. The mechanism of the attack was attributed to a lowering of the pH of the water by radiolysis of the air [16].

### *Non-sealed Dry Storage*

A non-sealed system is one in which fuel would be in contact with the ambient air in a dry storage facility (e.g. outside air temperature and relative humidity conditions). Since the corrosion of aluminum exposed to ambient air progresses at a slow rate, even at high humidities (up to 100%) at near room temperatures, safe storage in a non-sealed system can be achieved. One caution is non-sealed storage in "dirty" atmospheres (those containing low chloride and sulphate compounds). As mentioned, a non-sealed system would be subject to demonstration of confinement in storage of breached fuel.

## CONCLUSIONS

Technologies have been established to safely transport research reactor aluminum spent fuel from reactor locations and store aluminum-based, aluminum-clad spent nuclear fuel in a water basin and/or dry storage systems at U.S. DOE sites. Methodologies to evaluate the fuel condition and characteristics, and systems to prepare fuel, isolate damaged fuel, and maintain storage conditions have been established.

The aluminum fuel storage experience to date, supported by the understanding of the effects of environmental variables on materials performance, demonstrates that storage systems that minimize degradation and provide full retrievability of the fuel up to several decades can be achieved in wet storage and vented or non-sealed dry storage. A recent IAEA workshop showed examples of wet and dry storage practices that resulted in maintaining fuel with minimal degradation, and those that caused significant degradation. A guide for practices for wet and dry storage systems from this workshop is also being developed by the IAEA to facilitate technology transfer amongst member nations [17].

Continued storage that provides full retrievability up to 100 years will require establishment of environmental limits with firm technical basis of the fuel/storage system configuration with vigilance in maintaining environmental limits of acceptable storage. Continued surveillance and evaluation of the fuel and storage system materials to verify the predicted impact of the environment on materials behavior would also be needed to demonstrate reliable safe storage throughout the storage period.

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