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Inspection of Aluminum SNF Subject to Corrosion Under Extended Basin Storage – 21218

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ABSTRACT

Approximately 7 MTHM comprising 12,000 assemblies of aluminum-clad spent nuclear fuel (ASNF) owned and managed by the U.S. Department of Energy, Office of Environmental Management is stored in the L Basin at the Savannah River Site (SRS). The predominant design of the ASNF stored in L Basin is the Materials Testing Reactor (MTR) equivalent design, a plate fuel design. A special inspection program to provide a characterization of corrosion degradation of selected MTR assemblies following decades of wet storage has been completed. The details of the inspection program and the inspection results are described.

A total of 10 ASNF assemblies (9 of MTR design, 1 of involute design), stored in the L Basin for 18 to 21 years, following a prior storage history at foreign research reactor sites, were visually examined using a remote underwater camera with controlled lighting on a custom-design Fuel Inspection Table to provide reproducible imaging conditions. Predominant types of corrosion of aluminum fuel cladding material observed on the fuel include pitting, crevice, galvanic, and end-grain attack.

The inspection results, including comparison to previous inspections on-site at Foreign Research Reactors, demonstrate that the water quality and storage configuration in L Basin do not cause additional aggressive corrosion degradation of the fuel. Recommendations were made to re-inspect selected fuel in 5 years to trend changes in corrosion degradation. The inspection of the fuel is part of the overall Augmented Monitoring and Condition Assessment Program (AMCAP) that develops the inspection apparatus and executes programs to enable condition assessment of spent nuclear fuel and of storage containers in L Basin using remote inspection to demonstrate safe storage of SNF pending its retrieval for ultimate disposition.

INTRODUCTION

The L Basin facility (concrete water basin of 3.8 million gallon capacity) at the Savannah River Site (SRS) had a historic mission of cooling fuel discharged from the L production reactor. With the de-inventory of the Receiving Basin for Offsite Fuel (RBOF) completed in 2003, and with its fuel transferred to L Basin, all spent nuclear fuel at SRS has been stored in L Basin. The mission of L Basin over the past two decades has been to support nuclear non-proliferation programs associated with Foreign Research Reactors (FRR) and Domestic Research Reactors (DRR) with fuel receipts and continued safe storage of the fuel in L Basin pending it final disposition.

The aluminum-clad spent nuclear fuel (ASNF) in the L Basin inventory is primarily of the Materials Testing Reactor design, an assembly of fuel plates with aluminum alloy cladding on fuel cores of an aluminum matrix. Approximately 12,000 of these assemblies are stored in aluminum "bundles" or tubes with 3 to 5 assemblies per tube or approximately 3000 bundles stored vertically in the L Basin in storage racks.

Control of water quality is of paramount importance to avoid corrosion degradation of the aluminum fuel. In transition from production reactor mission to fuel receipt and extended storage mission, the L Basin went through several upgrades in its water purification systems from portable deionizers to permanent, redundant cation and anion exchange systems. Sand filters were replaced with new sand filters. Sludge on the basin floor was removed by vacuuming. New importance was placed on the target parameters for maintaining an enduring good water chemistry program. The fuel that has been received and stored in L Basin since that time has been stored in water with quality typically within operating limits. The operating limits are within the IAEA guidelines for good water chemistry [1]. These limits are intended to minimize the corrosion attack to both the aluminum fuel cladding and the aluminum structural components over an extended storage period in a spent fuel water storage basin.

The L Basin conductivity from recent years trended between 0.5 to 2 μS/cm for an average of 1.25 μS/cm. Over the last 20 years, and especially in the early part of those years, trends of conductivity were generally lower at around 0.1 to 1.1 μS/cm or an average of 0.5 μS/cm. The L Basin trends for pH were typically centered on pH 6.0 within a range of 0.5 over the last 20 years. The pH and conductivity are monitored every week using sampling methods. Chlorides and metal ions including iron and aluminum ions, were typically less than 0.2 ppm over the last 20 years. Copper and mercury are also closely monitored. These parameters are monitored every 6 months using sampling methods.

The fuel received in L Basin had incidence of corrosion from prior water storage facilities that did not have conditions conducive to corrosion minimization. The fuel was received with some corrosion damage and placed in bundled storage in L Basin.

The Augmented Monitoring and Condition Assessment Program at the SRS has as overall goal to support the technical demonstration of continued safe storage of SNF in L Basin. The AMCAP MTR Fuel Inspection Program goal is to determine the condition of aluminum-clad spent nuclear fuel stored long term in L Basin through visual examination of the fuel. A special inspection program was set up to interrogate the condition of these fuels with visual examination to evaluate: 1) if the storage conditions in L Basin promoted new corrosion incidence; and 2) if the storage condition in L Basin arrested or mitigated the existing corrosion damage. This paper outlines the types of corrosion that can attack aluminum materials in water storage, describes the selection of 10 ASNF assemblies for inspection, describes the visual examination of the assemblies, and presents the results of the inspection.

ASNF FUEL INSPECTION – FUEL SELECTION

Types of Corrosion Typical for ASNF in Basin (Wet) Storage

A brief summary of the types of corrosion observed on the inspected fuel is provided in this section as a basic orientation to the factors involved in the corrosion phenomena that could occur to aluminum even in good water quality.

General corrosion is a thermodynamic chemical process of aluminum corrosion in water. Recent work done by SRNL for the U.S. NRC [2] suggests that, based on the low temperature and good water quality conditions of L Basin, the general corrosion rate should be bounded by approximately 0.1-0.2 mils per year. This corrosion rate would be further reduced specifically for aluminum spent nuclear fuel (ASNF) placed in the reactor core due to a high-temperature oxide that forms during reactor operation.

The observed types of localized corrosion, typical for ASNF stored in basin water, are crevice, pitting (on-plate surface and on-edge of plate), galvanic-induced, and end grain attack (or end grain pitting).

The localized corrosion of aluminum in basin storage water is an electrochemical process which is impacted by a balanced surface potential between aluminum oxidation and the reduction of oxygen that occurs at the surface remote from the immediate site of the aluminum oxidation.

Crevice corrosion is a form of corrosion that occurs on a metal surface at locations where two surfaces are joined together, such as the joint of the side and fuel plates of the MTR fuel. Under-deposit corrosion, which results from debris that accumulates on a metal surface, is a form of crevice corrosion. The crevice allows a generally stagnant micro-environment to form, which leads to the initiation of corrosion from changes in the crevice chemistry, which will differ significantly from the bulk water chemistry. These changes include oxygen depletion in the crevice, acidification of the crevice solution, and a build-up of aggressive species such as chloride.

Pitting corrosion is a localized corrosion of a passive metal surface that initiates at a point location, then takes the form of varying sized, drill-like cavities with time. The formed pits may be open and uncovered or covered with a semi-permeable membrane of corrosion products (i.e. nodules). For aluminum, the ready formation of aluminum oxide contributes to both oxide within a pit as well as a nodule over the pit. Factors that impact the initiation and progression of pitting corrosion include:

- Metal composition and surface characteristics – presence of surface defects (second phase/intermetallic particles, grain boundaries, etc.)
- Environment – pH, halide concentration, especially chloride, bulk and in-pit oxygen availability, bulk solution conductivity

Pitting at the edge of a side plate end can be described as "edge corrosion" to highlight the prevalence of pitting at this location. Factors contributing to pitting near an edge may be associated with more surface defects associated with the formation of an edge including the ability to physically passivate a shape angular structure like an edge of a plate.

Galvanic Corrosion (*or Galvanic-Induced Corrosion*) results from the electrical contact of two dissimilar metals such as two different aluminum alloys or aluminum and stainless steel, in the presence of a conductive electrolyte. In these couples, the less noble material (i.e., aluminum) will become the anode of this corrosion cell and tend to corrode at a higher or accelerated rate, compared with the uncoupled condition. The more noble material (i.e., stainless steel) will act as the cathode in the corrosion cell.

End Grain Attack (End Grain Pitting) is another type of edge/pitting corrosion that occurs selectively on the cut surface or cross section that is normal to the rolling or fabrication direction. The presence of impurities (stringers) or second phase/intermetallic particles on this surface enhance the localized corrosion due to differences in surface potential as discussed for galvanic corrosion. If the attack progresses along a grain boundary or flow lines aligned in the rolling or fabrication direction, the attack can occur at a faster rate. The factors impacting the other forms of localized corrosion also affect end grain attack.

Selection of ASNF for Inspection

The fuel assemblies selected, as shown in TABLE I, all have aluminum cladding with mostly uranium-aluminum fuel cores. Variances in the selected fuel cores extend to an assembly with a blended core that contained uranium oxide and uranium silicide fuel.

The fuel selection basis was limited to foreign or domestic sourced, Material Test Reactor (MTR) assemblies with existing observable corrosion or suspected corrosion pre-cursors. There were 10 assemblies selected from five countries and from a total of six irradiation facility/reactor sites within those countries. Nine of the assemblies selected contained High-Enriched Uranium (HEU) fuel.

Physically most assemblies were of the box-type, mostly square, slightly rectangular cross- sectional shapes. One of the selected assemblies was round with inner and outer inert holding tubes with involute fuel fastened between the tubes. Most of the other fuel assemblies were of the box type and included side plates. The length of each assembly varied but most assemblies inspected had a singly or doubly cropped end(s) resulting in an inspected assembly length of 25 to 30 inches. Nozzle ends had been cropped previously. In most cases stainless steel screws were removed by slightly cropping the inert section of the opposite fuel end to the nozzle. Seven of the ten selected assemblies had curved fuel plates sandwiched between two side plates. The aluminum alloy used in the materials of construction was mostly 1100 aluminum or alloy of similar composition. There were few variances in side plates towards 6061 aluminum or the international standard near equivalent to it. Most sides plates were 1100 aluminum.

All assemblies selected were stored in L Basin in Expanded Basin Storage (EBS) Bundles with nearly half of the selected assemblies stored in bundles in L Basin for over 20 years. Most of the assemblies inspected have been stored in wet storage between the original facility and Savannah River Site (SRS) L Basin in excess of 30 years. Some of the assemblies have been reactor discharged in excess of 50 years. The total years of storage include the time at the reactor storage facility and time in the Savanah River Site (SRS) Spent Fuel L Basin storage and were as of CY2020.

TABLE I. Selection of Fuel Assemblies.

Reactor & Fuel Assembly No.	Plate Geometry	Current Corrosion	Total Years of Storage	Burnup (KWd/assy)
RA-3 S-113	curved	moderate	33	5.4
ENEA Galileo GA 84X	flat	moderate	40	1.0
RA-3 160	curved	moderate	45	8.6
IEA-R1 IEA-79	curved	high	56	0.6
ENEA Galileo 71-GA67	flat	moderate	40	16.7
RA-3 30	curved	moderate	48	24.4
HIFAR UED 1567	involute	moderate	50	45.6
RA-3 236	curved	moderate	42	72.3
ENEA ISPRA 3-9-IX	curved	moderate	47	77.4
HFR Petten F950	curved	low	24	211.8

The primary consideration which formed the basis for inspected fuel selection was prior knowledge or records of fuel degradation at the time of receipt into the basin. A variation of fuel type and burnup was then emphasized in order to expose what, if any, correlation could be drawn between these parameters and corrosion susceptibility. Older fuels were then prioritized as these would be expected to exhibit the most impact from wet storage, all other things being equal. Lastly, a single outlier assembly, HFR Petten F950, was chosen from a bundle featuring a high “cobweb” severity specifically to investigate potential microbial corrosion. Barring any cladding surface effect from these cobwebs, this assembly was otherwise known to have excellent storage history and could serve as a pristine baseline condition.

ASNF-MTR Fuel Inspection Table

A special table to control lighting and positioning repeatability was designed for the remote (underwater) visual examination. The Fuel Inspection Table (Figure 1) features double and adjustable intensity LED light banks on the corner of the inspection table, backstop rest for the inspected fuel, accommodations to receive rectangular box MTR fuel or round fuel, 8 camera slots for optimized basin underwater camera viewing and camera zooming, a symmetrical ruler for fuel positioning on the table, accommodations for up to a 36 inch fuel length, and adjustable inspection table legs.

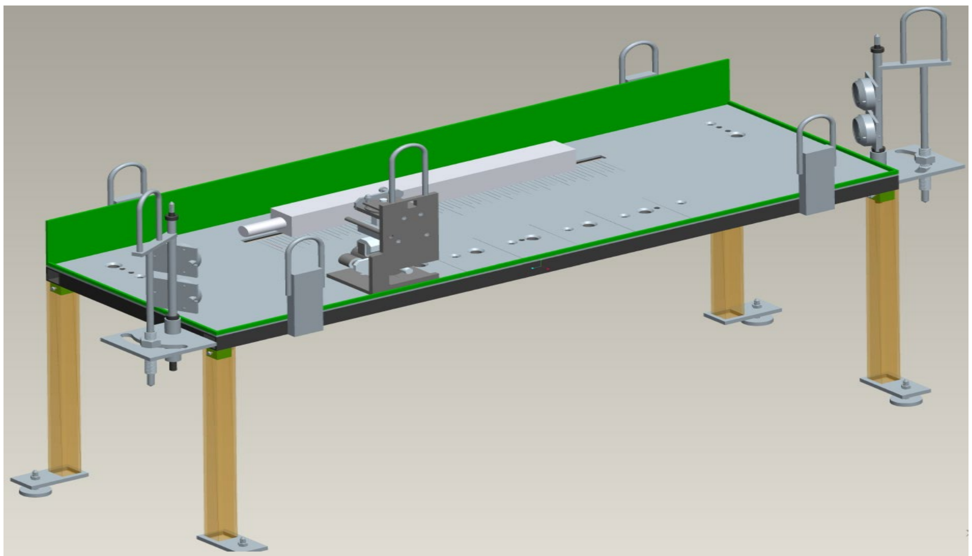

Figure 1. The L Basin MTR Fuel Inspection Table isometric.

The Inspection Table consists of 8 distinct camera locations designated Slots 1 through 8. Once a slot is occupied, the camera can pan and tilt to investigate anomalies and regions of interest. The camera angle must first be centered following relocation to a new slot in order to provide a full viewed snapshot of each 6” segment of the fuel. The locations are marked by slots in which to drop the camera holding tool.

Remote controlled LED lights are also included in the inspection table design (Figure 2). These lights can be toggled on/off alternately throughout the procedure to provide optimal viewing conditions of certain regions of the fuel. The LED lights are also adjustable individually as two or just one light banks(s) with and without the use of the basin underwater camera lighting.

A visual aid gauge is provided to assist the inspectors in characterizing the surface area of flaws such as pits, nodules, and general corrosion. This tool can be placed overtop the target assembly to overlay a calibrated semi-transparent grid on the camera view. The grid line pitch is 2 mm or approximately 1/12”. A visual aid gauge was used and placed over the fuel but there was no attempt to measure the surface area of anomalies, the focus was capturing observations during inspection of the fuel resting on the inspection table.

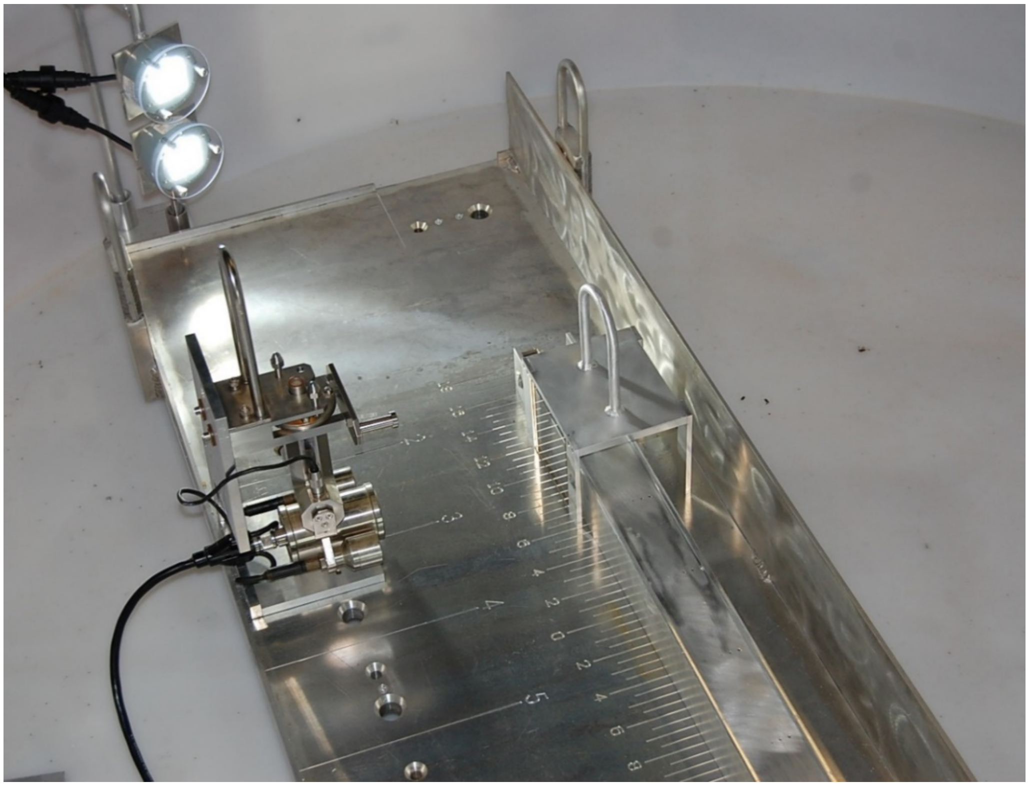

Figure 2. Inspection table showing LED light bank on, camera with fixture and fuel assembly area gauge.

INSPECTION RESULTS AND RECOMMENDATIONS FOR REINSPECTION

Four inspection campaigns comprised the special (one-time) inservice inspection. The four campaigns were set up to provide confidence in the handling of the fuel as the enrichment and burnup of the assemblies increased with each inspection campaign.

The summary table (TABLE II) below catalogs and summarizes the types of corrosion found for the 10 inspected assemblies. Typical corrosion seen on the fuel include: 1) side plate edge corrosion; 2) crevice corrosion at the interface of exterior fuel plates and side plates with pitting and/or raised nodules with irregular shapes; 3) dense populations of pitting corrosion clusters of raised nodule colonies over part or the whole fuel meat region of exterior fuel plates; 4) sparse populations or single occurrences of pronounced raised nodule pitting corrosion; 5) irregular dark discolorations over the entire fuel meat region or on the edges of a fuel meat region face; and 6) end-grain attack on cropped edges of fuel assemblies-one or both top/bottom edges. Some light discolorations over exterior fuel plates or outer dummy fuel plates was noted. The definitions used in the table with respect to corrosion found during the inspections are the following:

<u>A) Occurrence Frequency:</u>
Sparse (Spar) – Appearance is intermittent over the surfaces
Localized (Local)- Feature present at various locations over the surface
Pervasive (Per)– Features occurring broadly over the surface
<u>B) Severity:</u>
Superficial (Sup)– Minor, not pronounced
Moderate (Mod)– Feature pronounced
Severe (Sev)- Extensive corrosion attack

TABLE II. Types of Corrosion Found in the 10 Inspected Assemblies.

Reactor (fuel plate shape)	Edge corrosion	Crevice corrosion	High density nodules/ pits	Sparse pronounced nodules/ pits	Dark discoloration over fuel meat region	Potential microbial settlements	End-grain attack
	side plates	fuel plate interface	fuel plate/ fuel meat	fuel plate/ fuel meat	fuel plate/ fuel meat	interior fuel plate ends	top and bottom fuel ends
IEA-R1 (curved)	A) Per B) Sev	A)Per B)Mod	A) Local B) Mod	A) Per B) Sev (some discoloration)	None	A) Spar B) Sup (isolated)	A) Local B) Mod
RA-3 (curved)	A) Local B) Mod	A)Local B)Mod	A) Local B) Mod	A) Local B) Sup/ Mod	A) Local B) Mod (full or partial)	None	A) Spar B) Sup
ENEA Galileo (flat)	A) Spar B) Sup	None	A) Spar B) Sup	A) Local B) Mod (trailing effect/ w/ tails)	None	None	None
ENEA ISPRA (curved)	A) Per B) Sev (w/ pitting)	A)Per B)Sev (w/ pitting)	None	None	None	None	A) Per B) Sev (w/ pitting)
HIFAR (involute)	N/A	N/A	A) Local B) Mod (outer tube, not fuel)	A) Local B) Mod (outer tube, not fuel)	None	None	A) Spar B) Sup
HFR Petten (curved)	None	None	A) Local B) Mod	A) Spar B) Sup	None	None	None

Based on the observations as noted in the table, common types of corrosion observed for fuel stored in L Basin are crevice corrosion at the side plate/external fuel plate joint, edge corrosion on the side plates of the assembly, end-grain corrosion, especially at cropped ends, and pitting corrosion. While these are the common types of corrosion, essentially all corrosion was initiated at the origin facility and not in L Basin, with the possible exception of the end-grain corrosion.

The following paragraphs provide a snippet of typical still images, from video records of the campaigns, showing the inspection results and provide the recommendations for reinspection of selected assemblies in 5 years. Re-inspection of these assemblies would strengthen the posture that the observed types of localized corrosion are not progressing under L Basin storage conditions.

Two of the fuel assemblies in the present inspection are not recommended for re-inspection due to the minor amount of corrosion damage observed. This includes one of the two ENEA Galileo fuel assemblies and the HFR Petten Assembly.

For the RA-3 fuel it is recommended two of the four assemblies be re-inspected in 5 years. This includes the first RA3 assembly, S-113, a control assembly with stainless steel guides, and the last inspected RA3 assembly, 236, which was a high burnup standard assembly with unique exfoliated/spalled oxide formations and stainless steel screws. All RA-3 assemblies showed similar corrosion features in the same places for edge corrosion, crevice corrosion, fuel meat corrosion both pits and nodules and end-grain corrosion on the ends of the assemblies, as seen in Figure 3. Additionally, there was a standard assembly 138, within the first inspection assembly bundle, that had complete dark discolorations over one face of the fuel meat region of an exterior fuel plate that is also recommended for inspection. Three RA-3 assemblies are recommended for future fuel inspections.

Figure 3. RA-3 S-113 Concave outer fuel plate showing edge pitting corrosion, crevice corrosion, pitting corrosion and discoloration.

The two inspections associated with the Italian ENEA Storage Facilities' Galileo fuel showed minimal corrosion. The moderate corrosion profiles associated with this MTR fuel are bounded by other more severe found on inspections of other AMCAP MTR Fuel inspections. However, there were unique corrosion characteristics on the second Galileo fuel assembly, 71-GA67, that warrant a repeat inspection to monitor condition of the assembly over L Basin storage time. This second Galileo inspected fuel is recommended for re-inspection.

The ENEA ISPRA Reactor fuel assembly 3-9-IX is also recommended for reinspection. It has some severe crevice and side plate corrosion, seen in Figure 4, and gross end-grain corrosion with corrosion products on the ends of the assemblies, as seen in Figure 5. It will be interesting to reinspect for a future campaign to determine a worsening condition. It is also recommended that a high burnup assembly be selected from in the same bundle and inspect it (Assembly 3-51-VI). Assembly 3-9-IX has a 30% burnup and 3-51-VI has a 60% burnup for the fuel assembly.

Figure 4. ENEA ISPRA Assembly 3-9-IX showing side plate edge and fuel plate pitting corrosion, crevice corrosion, and end grain attack.

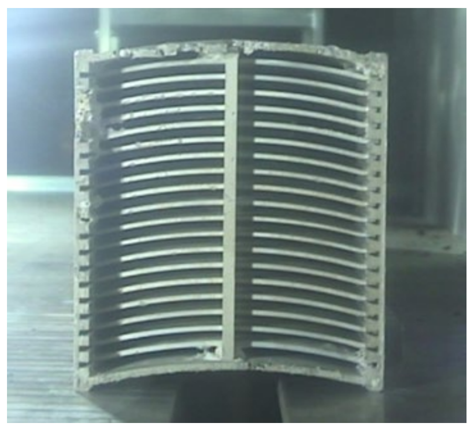

Figure 5. ENEA ISPRA Assembly 3-9-IX showing end grain attack.

The IEA-R1 reactor assembly IEA-79 is also recommended for reinspection. This assembly contained pits in the fuel meat region, as seen in Figure 6, that appeared to indicate decladding and fuel failures, in addition to a number of other corrosion phenomena, which in many cases were some of the most severe of the ten assemblies inspected. It was a low burnup assembly. It is also recommended that a high burnup assembly IEA-77 (in an adjacent stored fuel bundle, same rack) also be added for the next fuel inspection. This higher burnup fuel selection for inspection is contingent on the availability of previous facility inspection data that can be used for comparisons.

Figure 6. IEA-R1 Assembly 79 concave outer fuel plate showing nodular pitting and crevice corrosion.

The inspected Australian Mark III fuel UED 1567, Figure 7, had limitations for inspecting fuel plates. Since the outer tube was only aluminum and one of the ends had a fuel ID plate installed, which prevented the ability to view one end of the fuel plate ends, the only useful fuel inspection information observed was one end view of the involute fuel plates. Based on previous facility inspection data, outer fuel plates with numerous varying surface area pits indicate a potential corrosion path to the outermost assembled involute fuel plate. However, even if both ends were exposed, it would be difficult to ascertain the fuel plates condition. There were many pictures of HIFAR inspection assembly UED 1567 taken at the time of the previous facility fuel inspection. Additionally, there was a careful inspection sheet formulated to go along with previous fuel inspection pictures. The results of the AMCAP MTR fuel inspection for assembly UED 1567 indicated no increase in corrosion than that found at the origination facility. If a Mark IV assembly was selected or another Mark III, the same observations limitations would exist for observing fuel condition (i.e., only one end of the fuel plates could be observed). Although the HIFAR assembly has limited fuel inspection value a reinspection of the assembly would be good to check on regular aluminum corrosion rates within a stored bundle, focusing on the exterior aluminum tube condition over storage time.

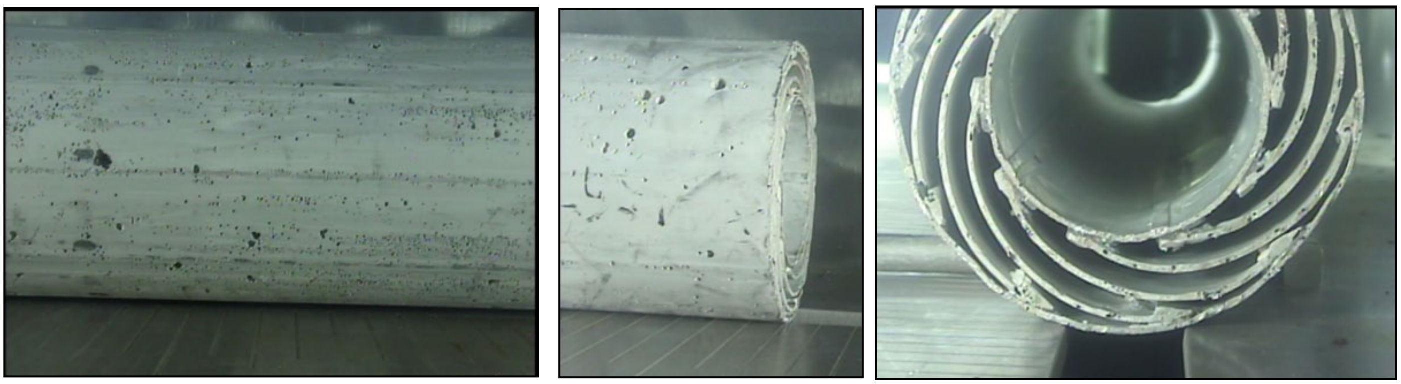

Figure 7. HIFAR UED 1567 (left two pictures) outer casting (non-fuel) showing pitting attack. Right picture, bottom view of HIFAR UED 1567 showing crevice corrosion and end grain attack.

SUMMARY AND CONCLUSIONS

The AMCAP MTR Fuel Inspection Program provides information on the physical condition of aluminum-clad spent nuclear fuel stored long term in L Basin through direct visual examination of the fuel. Demonstration of continued safe storage of the fuel is achieved by showing no continued gross corrosion attack under L Basin storage conditions. The program consists of an initial special inspection of the fuel, serving as a "baseline examination," followed by re-inspection after a 5-year additional storage period to evaluate whether corrosion degradation was active and significant to impact the ability to continue to store the fuel.

The special inspection program to inspect 10 assemblies was successfully completed. Corrosion damage typical for aluminum in poor quality water was observed. The results of corrosion damage were compared to the results of inspections made at the basin of origin, or upon initial receipt in L Basin, as available. The AMCAP inspection team was able to convert original inspection video from previous facility inspections and records to provide sufficient detail to enable comparisons to the present inspection results following an approximate additional 20-year storage period in L Basin.

It is concluded that the water quality and the bundled storage configuration for ASNF in L Basin did not cause aggressive (new incidence of) corrosion degradation of the fuel. It is further suggested that mitigation of the prior corrosion damage of the fuel also appears to have been achieved with the good water quality conditions of L Basin. No significant corrosion attack would be expected in 5 years additional storage, to be verified by the re-inspection.

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