Examination of Aluminum Containers for Extended Wet Storage of Non-Aluminum-Clad Spent Nuclear Fuel

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ABSTRACT

Approximately 20 MTHM comprising 2000 elements of non-aluminum-clad spent nuclear fuel (NASNF) is owned by the U.S. Department of Energy and is managed in wet storage in the L Basin at the Savannah River Site. The NASNF claddings are primarily zirconium/zircaloy or stainless steel. These fuel elements are stored in one of the following configurations: i) directly within a thin-wall (0.052"-thick) aluminum tube with a 5" diameter, and either 12' or 14' in length, or within a square tube of 0.125"-thick aluminum in a 5" square, 12' in length; ii) within small aluminum cans that are stacked and stored in the tubes; or iii) direct fuel or fuel within the small cans that are placed in thick (0.148") aluminum oversize storage canisters (OSCs) 8" in diameter. These fuel containers must remain intact for safe handling and to maintain configuration for criticality control. This storage configuration could cause inside-out corrosion attack due to galvanic couple or sediment-induced corrosion. To verify the condition of the fuel containers under long-term storage, container interrogation using non-destructive examination (NDE) methods is being performed under the Augmented Monitoring and Condition Assessment Program (AMCAP) at Savannah River Site.

The NDE methods selected to provide the condition assessment are visual testing (VT) and ultrasonic testing (UT) that are adapted to tooling for remote underwater examination of the containers. The system for examination using the VT method was readied in a mockup to demonstrate the video recording cameras were capable and robust for in-situ deployment with tubes in the Vertical Tube Storage (VTS) racks to examine 90% or more of surfaces of the tubes. This required that the camera withstand water and radiation exposure, and that the camera deployment mast would fit within the narrow gap between the tube and rack. The cameras were tested at various dose rates and ultimately to failure in the SRNL ^{60}Co irradiator. Five vulnerable bundles have been visually examined. The engineering development for the inspection and the inspection results are reported in this paper. The engineering development for a system for remote, underwater examination using an automated-scan UT method is in progress, and deployment in L Basin is targeted for 2023.

INTRODUCTION

The goal of the Augmented Monitoring and Condition Assessment Program (AMCAP) program is to provide a condition assessment of the storage containers for non-aluminum-clad spent nuclear fuel (NASNF) in L Basin and demonstrate continued safe storage of all NASNF pending retrieval for ultimate disposition. The storage configuration of NASNF is vulnerable to inside-out corrosion attack including galvanic corrosion at touch points of the NASNF cladding against the aluminum containers, and from sediment-induced corrosion of the aluminum containers.[1]

The approach being used in AMCAP is to develop and deploy engineered systems for examination methods for remote, in-situ inspection of the bundle storage in VTS and for OSC storage in the OSC racks.[1] A system for the Visual Testing (VT) method using video-recording cameras was readied as part of the full-scale mockup development, and was deployed in L Basin for a visual examination (VE) to provide an initial condition assessment.[2] This report describes the development and the deployment of the VT system for inspection of selected bundles in L Basin.

The first deployment of the VT system was for visually examining five spent fuel bundles. Bundles were chosen based on their vulnerability in terms of inner fuel contents, history, storage duration, storage configuration, and possibility of inside-out corrosion due to galvanic coupling of fuel cladding with the aluminum bundle wall.

- Bundle 4302 contains Elk River Reactor (ERR) fuel within a GP tube. The ERR bundles were heavily loaded with multiple fuel rods, creating multiple areas where fuel rods touch the inner bundle wall. Each of these touch points creates a possible area for galvanic corrosion.
- Bundles 1056 and 0845 both contain Heavy Water Components Test Reactor (HWCTR) fuel within L bundles. Bundle 1056 also contains multiple fuel rods, creating multiple areas for potential galvanic corrosion within the bundle. Bundle 0845 contains one fuel rod which was possibly cut before placing it into the bundle for storage.
- Bundle 7999 contains HWCTR fuel that was loaded into an aluminum A can, which was then loaded into a GP tube. The fuel was cut before being loaded into the can, creating potential for hydrogen production if the fuel were to come in contact with water.
- Bundle 1051 also contains HWCTR fuel that was loaded into nine cans, which were then loaded into an L bundle. The various fuel and can configurations allow for possible fuel degradation and for possible inner can failure.

The condition assessment provided by the visual examination of the bundles was limited to an assessment of the corrosion attack on the external surfaces. Additional examinations to assess the corrosion attack to the bundles from the inside is pending completion of the ultrasonic examination system. The inspection team used engineering judgment that the corrosion features observed were non-threatening to immediate continued storage and handling in the near-term (several years' timeframe). However, calculation of the structural capacity to withstand all anticipated handling loads is being performed. This calculation will be issued prior to removal of the bundles outside of the storage rack for augmented examination to determine the cause of the features observed on one bundle in the March 2021 examination.

Dry runs were performed before in-situ execution in L Basin. A full-scale mockup of a portion of an L Basin EBS rack was created and staged at Savannah River National Laboratory (SRNL). A special 3x2 section of water-filled rack was loaded with full-size L bundles and GP tubes, to allow for simulated testing of tooling and cameras (Figure 1).

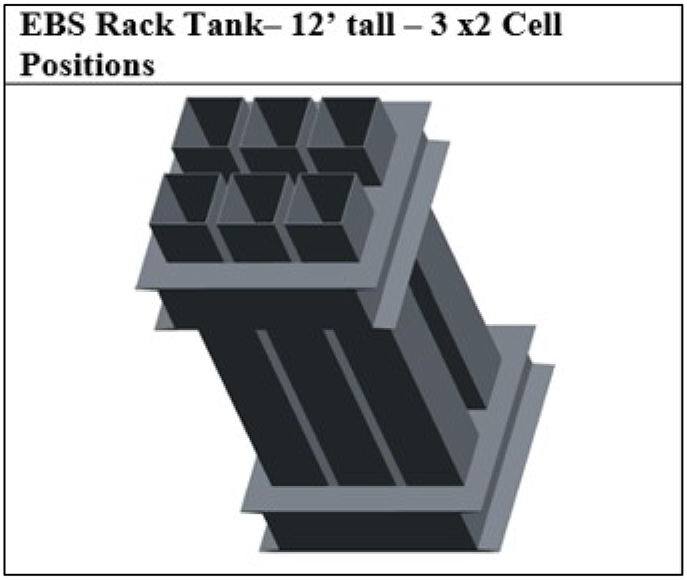

Figure 1. Full Scale Rack for Mockup

Selected Fuel and Fuel Container - Attributes and History

Five bundles were selected for the visual examination, which contained two different types of NASNF. Four of the bundles contained HWCTR fuel and one bundle contained fuel from the ERR. The ERR bundle and two of the HWCTR bundles have direct loaded fuel, while the fuel in the other two HWCTR bundles were packed into cans prior to bundling. One bundle contained a single long aluminum "A" can and the other had multiple "K" and "E" cans. This bundle housed the only "E" cans stored in L Basin.

The HWCTR was a non-defense related test reactor utilized to test candidate fuel designs for use in the civilian power industry. The reactor, located in SRS B-Area, operated from 1962 until 1964 and was retired in place in 1965. A large portion of the irradiated fuel assemblies were disassembled or cut and shipped to Savannah River Laboratory (SRL) for destructive examinations in the lab's "High Level Caves". The heavily shielded "High Level Caves" allowed chemical and metallurgical equipment studies on highly radioactive materials. The remaining assemblies were shipped to the spent fuel basins in R, P and H [Receiving Basin for Off-site Fuels (RBOF)] areas for storage. Upon completion of the examinations, the cut assemblies were canned and shipped to RBOF. After R-reactor was shutdown in 1964, the intact and canned assemblies in R-Basin were shipped to P Basin before being shipped to RBOF for final disposition. Since almost all the HWCTR fuel contains zirconium-based metals, it was excluded from processing in the canyons due to economic reasons. The fuel was instead shipped to L Basin for continued interim storage as part of the RBOF deinventory mission.

Intact ERR assemblies were received at RBOF in the late 1960's. In late 1978 and early 1979, ERR fuel assemblies were disassembled (cropped) and consolidated into 38 GP tube to increase available storage space in RBOF. Each GP tube was loaded with 125 ERR rods, the equivalent of five ERR assemblies. The ERR rods could be stacked vertically with a maximum of two rods in the vertical direction. The fuel rod core is pelletized UO_2 – ThO_2 cladded in stainless steel with welded end plugs. The rods are approximately half inch in diameter and 63.5 inches long.

Almost of all the rods loaded into GP tubes were intact, except for a few rods that were either already broken or were broken during the repackaging process. A total of 5 ERR GP tubes contain broken fuel rods including bundle 4302. Bundle 4302 was loaded with three broken rods which broke into 6 pieces. The broken rods were placed in an aluminum tube, crimped shut, and then placed in the GP tube. Despite the broken rods, historical documentation indicates that none of the ERR GP tubes contain loose fuel pellets.

Between October and November of 2002, all ERR GP Tubes were shipped to L Basin for RBOF deinventory. Bundle 4302 was shipped to L Basin on 10/30/2002. Prior to shipment, an engineering analysis determined the GP Tube lid bails were inadequate for the loading conditions and the lids were replaced in RBOF. The fuel weight in the bundles, approximately 408 pounds, exceeded the bundle payload design weight.

The concern for this bundle was inside-out corrosion caused by galvanic coupling between the numerous points where the fuel rod ends touch the thin walled, aluminum GP Tube.

Most of the HWCTR fuel is a round, tubular design with fuel packed between a nested inner and outer tube and a hollow internal moderator region. Most of the HWCTR fuel is clad with Zircaloy-2, but some fuel is clad with Zircaloy-4. Both claddings can form a galvanic couple with the aluminum bundles. HWCTR fuel with a U metal core will expand and form an oxide if exposed to water.

L Bundle 1056 contains fourteen (14) intact HWCTR Segmented Metal Tubes (SMT). The SMT fuel core is naturally enriched U metal. SMT fuel tubes are 1.7 inches in diameter and 11.25 inches long with 0.022-inch-thick Zircaloy-2 cladding. The intact fuel tubes were stored in RBOF bucket storage before being repackaged into L Bundle 1056 for RBOF deinventory in early 2003. An oxide containment plate (OCP) was placed at the bottom of the bundle prior to loading the fuel tubes. The bundle had to be loaded with multiple tubes per stacked layer using an EBS Fuel Loader. The loaded fuel height can be estimated to be between 25 to 50 percent of the bundle height, as they were loaded in RBOF, horizontalized for shipping and verticalized for placing in EBS rack storage in L Basin. L Bundle 1056 was shipped to L Basin on 3/5/2003.

L Bundle 0845 contains one intact (1) Thorium Metal Tube (TMT) over 2.5 inches in diameter and roughly 118 inches long. The TMT fuel core is mostly thorium metal with 1.5% U metal. The TMT fuel cladding is about 50% thicker than the SMT fuel cladding at 0.030 inches. The fuel tube was stored in RBOF row storage before being repackaged into an L bundle. L Bundle 0845 was shipped to L Basin on 6/14/2001.

The primary concern for these bundles is galvanic corrosion from the fuel contacting the bundle inner walls. A secondary concern exists for degraded U metal fuel reacting with water if the cladding has failed or if the fuel has been cut. In this case, there is a potential for degraded fuel to fall to bottom of the bundle and accumulate in the bottom crevice region. Bundle 0845 may contain cut fuel.

GP Tube 7999 houses an aluminum A can loaded with two cut pieces (75-inch piece and a 14-inch piece) of HWCTR Restraint Metal Tube (RMT). RMT has a naturally enriched U metal core with 0.06 inch-thick Zircaloy-2 cladding. It is assumed the smaller 14-inch cut fuel piece has one exposed end and the larger cut piece has two exposed ends based on available records. This GP Tube has a removable lid which allowed for inspection of the aluminum A can in RBOF.

L Bundle 1051 houses a total of 9 aluminum cans filled with six distinct types of HWCTR fuel. The cans were stored in RBOF bucket storage before being repackaged into bundle 1051 for RBOF deinventory. During repackaging a visual inspection was performed on all cans and all cans were deemed structurally sound. The seven K cans stored in the bundle were originally stored in P-Area and are technically designated as "PK" cans. One item of note was that cans originally stored in P-Area had a higher amount of surface corrosion. A few of the K cans were packed with more than one type of cut HWCTR fuel and the two E cans were loaded wet with cut pieces of HWCTR Insulated Metal Tube (IMT) fuel, which is mostly U metal with a 1.5% molybdenum adder. L bundle 1051 was shipped to L Basin on 2/19/2003.

The concern for these bundles is degraded fuel leaving the inner cans and accumulating elsewhere, namely as sediment on the bottom of the bundle. A secondary concern is a bulged inner can exerting enough force to deform or split the bundle. The K cans and E cans in bundle 1051 are loaded similarly to the Z cans in RBOF which split due to the U metal fuel reacting with water. This reaction is assumed to have formed an oxide and expanded enough to split the can open and allow material to leave the can.

VISUAL EXAMINATION EXECUTION

A Bundled Fuel Visual Examination Guide was created to aide in consistent, routine reporting for the bundles within this report, as well as for future AMCAP visual inspections. This guide is available in Appendix A. Initial actions involve ensuring that all camera equipment and viewing and recording devices are functioning appropriately. The Mini 13© camera was first deployed for bundle sidewall surface area examination. Upon lowering the camera into position, the camera was placed over the top of the bundle to get a clear reading of the number and to verify the original bail position before starting inspection. If the tabs were present while deploying the camera, it would also be noted in the examination. The camera was encased in the wedge tooling to have a consistent view from the camera to the side wall in each corner. The wedge also kept the camera from overly scratching the bundles and allowed for easier camera deployment without as much binding between the tooling and the bundle or rack (Figure 2).

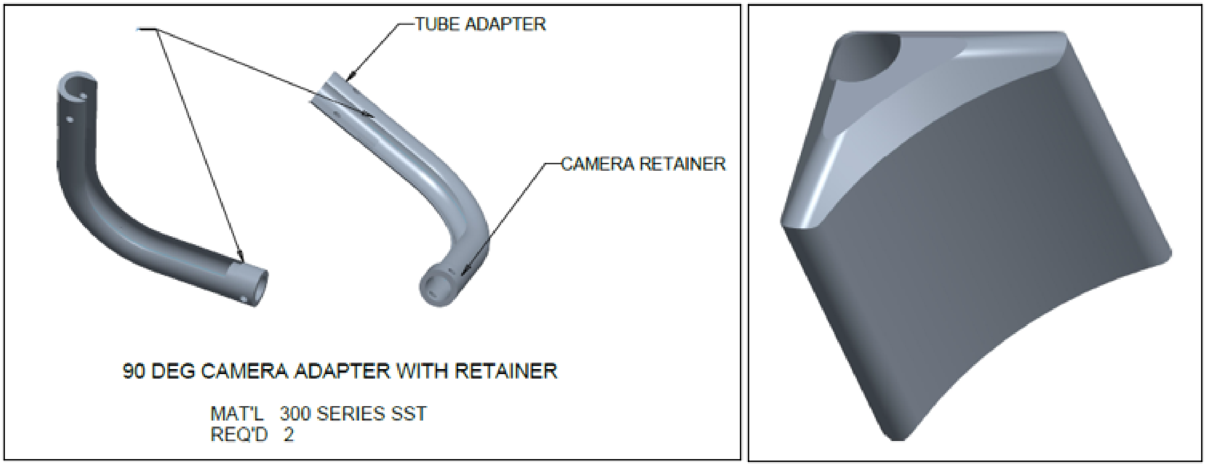

Figure 2. L bracket (left) to view bundle bottoms and camera wedge (right) to hold camera for sidewall imaging.

After noting the bail position with relation to the northern direction within the rack, visual examination was initiated in the northeast corner, then each subsequent corner was examined in a clockwise direction around the bundle (Figure 3). All bundles were examined and rotated in a clockwise direction to eliminate the possibility of inadvertently loosening the bundle lids with a counterclockwise rotation. These first viewed corners are denoted as 0° position corners. The bundle was then rotated clockwise 45° and each corner was examined. This allowed for the previously obscured surface area to be viewed and gave images of 90% or more of the total bundle surface area. The corners viewed after rotation are denoted as 45° position corners.

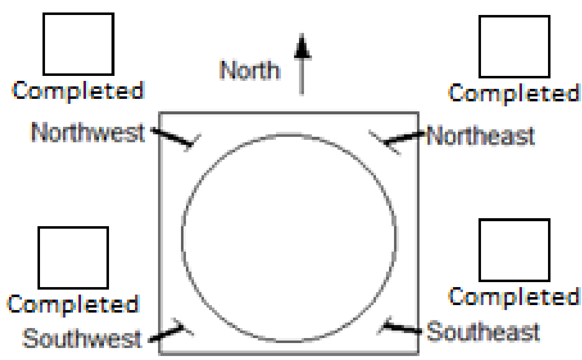

Figure 3. Visual Examination Inspection Diagram

Once the bundle sidewalls were fully examined, the bundle was lifted to allow visual examination of the bottom of the bundle. The FF side view camera attached to the L bracket tooling was deployed down one corner of the bundle, and then turned into place under the bundle to view upwards toward the bottom of the bundle (Figure 4). Bundles were only lifted high enough to deploy the camera underneath and to allow for appropriate focal distance for the camera to give optimal view of the bundle bottom. This was typically a lift of six inches or less per bundle to adequately view the bottom.

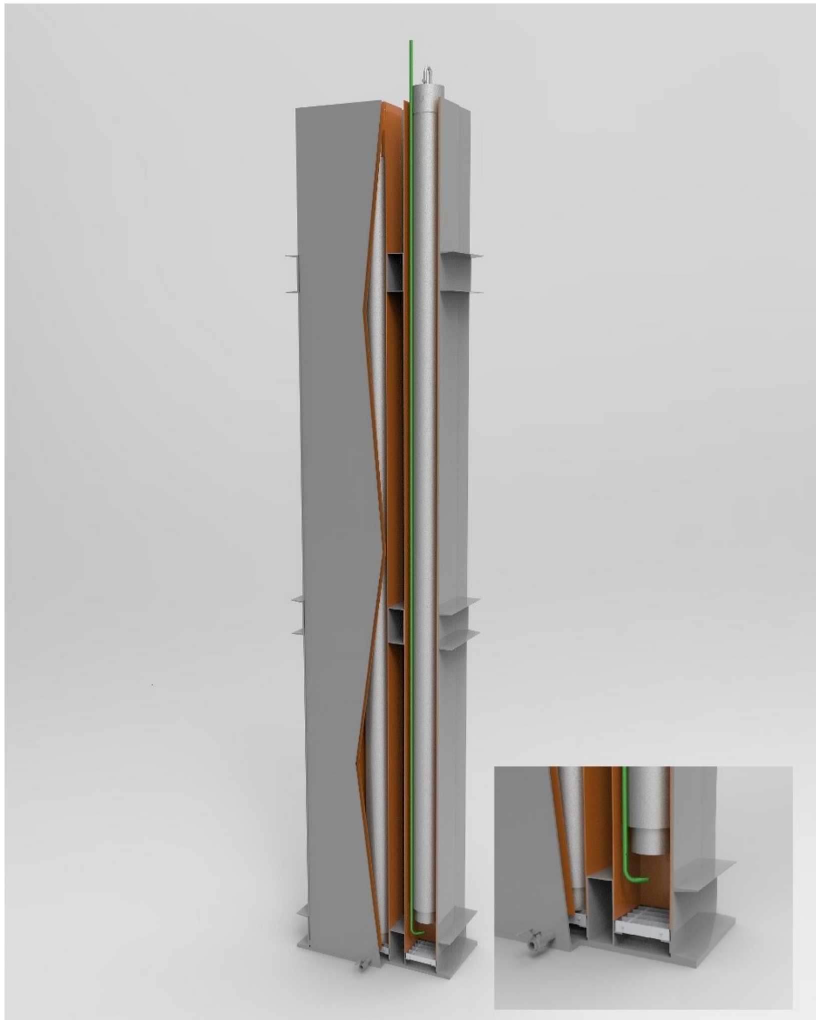

Figure 4. L Bracket Deployment for Bottom of Bundle View.

RESULTS AND PRELIMINARY CONCLUSIONS

The development of a system for examination using the Visual Test method, and its deployment for a condition assessment of selected bundles in L Basin was successfully completed, and the condition assessment of the bundles using the inspection results is reported.

The cameras used for the inspection were rigorously evaluated in terms of radiation tolerance and water compatibility. The results from the work show the primary camera to provide good images and utility for the inspection of NASNF containers.

The bundles exhibited an incidence of outside-in corrosion attack that was expected with the storage history in RBOF and L Basin. None of the attack was significant in terms of threatening structural integrity to continue to safely handle and move the fuel. The following are the primary conclusions from the condition assessment.

- All bundles showed general corrosion in many forms of aluminum oxide nodules, probable aluminum chloride nodules, scaling corrosion, and pitting. While these features were present, it is unknown whether the corrosion initiated in L Basin or if it were present before the bundles were placed within the basin. None of this minor general corrosion was deemed deleterious to the integrity of the bundle (Figure 5).

Figure 5. Corrosion nodules.

- Two bundles (7999 and 0845) exhibited corrosion along the sidewall edge near the weld at the bottom of the bundle. While the weld regions of both bundles were intact on the bottom, this sidewall to weld interface may be the most vulnerable point for inside out corrosion susceptibility. This would be especially important for bundles with potential for degraded fuel inside. The degraded fuel would gather in the inner crevice and corrode the thinner heat affected zone of the aluminum sidewall before any noticeable corrosion were seen on the underside of the thicker bottom portion of the bundle.

- All bundles contained scratches, scrapes or abrasions on their sidewalls. Many were clearly created before the bundle was placed in the basin and perhaps before the bundle was loaded with fuel. Circumferential scratches with associated orange or brown corrosion is most likely due to turning the bundles on steel racks, leaving a steel deposit on the aluminum surface. None of these features were currently deleterious to the bundle integrity (Figure 6).

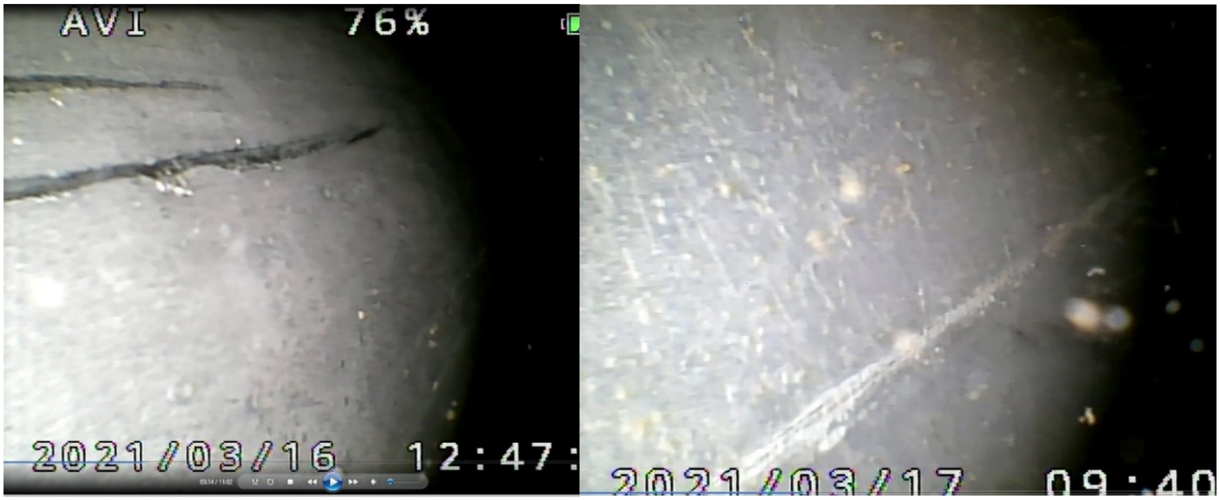

Figure 6. Abrasions on bundle sidewalls.

• L bundle 4302 had one small and unique anomaly on the sidewall at the bottom near the weld. It appears to be protruding from the bundle, with an associated pale yellow orange color. This bundle was overloaded with fuel beyond the design limit, but no conclusion could be made about whether there was any definitive protrusion from this bundle.

• GP tube 7999 had a noticeable bulge at the bottom on one side. The bottom of the bundle had a dent on the side associated with the bulge. As noted by an issued calculation, bundles will bulge if dropped instead of tearing open.5 While the bundle is slightly deformed, the fuel currently remains contained within the bundle.

• Small black features of different sizes were noted at many areas on most bundles. The cause of the black features was not definitively identified. Potential causes could be patches of dark-colored oxide, shadowing from raised nodules, or local penetration. An additional examination is planned for August on L bundle 0845 with supplemental lighting. The in-progress calculation on bundle integrity shows the high tolerance of the bundles with through-bundles defects against all handling loadings (Figure 7).

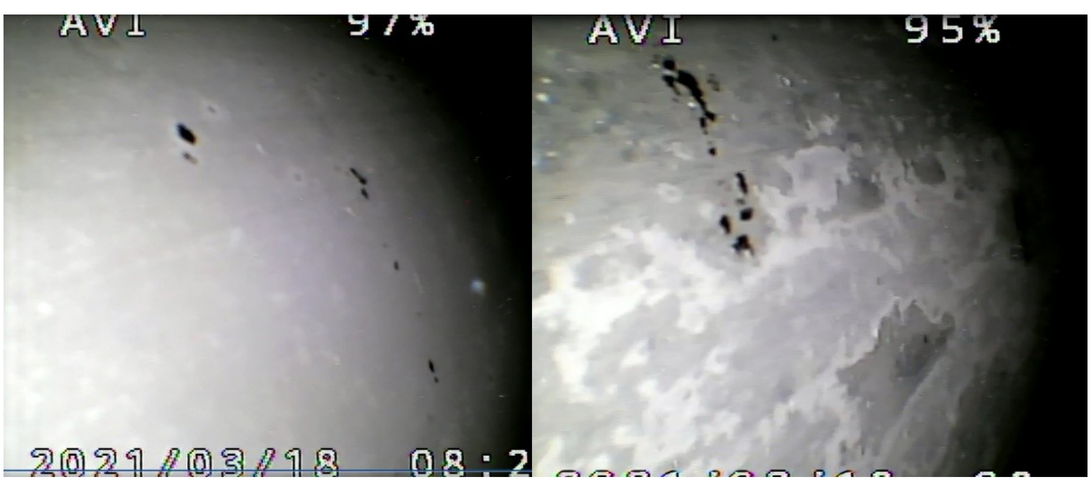

Figure 7. Black features on bundle sidewalls.

- There was debate over whether particulate and sediment in the basin would affect the visual examinations. The particulate was generally dependent on the detritus that was dislodged from the bundle. More associated microbial growth or corrosion on the bundle created more particulate in the water. The sediment at the bottom of the rack was nearly non-existent. While there was noticeable red-brown sediment, it was very minimal. Neither the particulate nor sediment had any negative effect in completing the visual examinations.

- L bundle 0845 exhibited pale green nodules. There is no direct conclusion that can be made on these nodules without some form of chemical analyses to determine its molecular composition. There is a belief that these nodules are iron sulfate, which would be potential evidence for a corrosion product from microbially induced corrosion (MIC). While all bundles showed some form of microbial growth, there was no direct evidence of MIC, and no large mass cobweb growth or biofilm was visible in the regions around the pale green nodules. While there is still the potential for MIC, there was no distinctly associated corrosion near areas of cobweb microbial growth.

- GP tube 4302 exhibited microbial growth inside the bundle, which was housed under a missile shield. This clearly shows that microbial eradication will be difficult within the basin. Microbial growth in the basin is prevalent and thriving.

- There seems to be a connection with bundles loaded with inner cans and gas emanation. While no direct conclusions can be drawn about what gas arose from the bundles, it will be important to look for gas emanation in bundles that contain cans in L Basin or for bundles that may be received in the future. Given the handling and decades of storage, and the consideration of the joint (weak protection against in-leakage), our "best speculation" is that the bubbles were an agglomeration of hydrogen that was from the corrosion reaction of the low alloy uranium.

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