

Strategy for Managing the Long Term Use of BORAL® in Spent Fuel Storage Pools

2012 TECHNICAL REPORT

Strategy for Managing the Long-Term Use of Boral® in Spent Fuel Storage Pools

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Product Description

BORAL® is a neutron poison material commonly used in spent fuel pool storage racks. This report examines the performance of BORAL® based on evaluation of surveillance coupons, identifies the degradation mechanisms for BORAL® in spent fuel pools, and evaluates the impacts of degradation. The report also develops a defense-in-depth strategy for managing BORAL® degradation for long-term use and suggests areas of research for further refinement of the BORAL® management strategy, including a recommended long-term corrosion test program.

Background

For improved efficiency of the area available for wet storage in nuclear power plants, various neutron absorber materials have been employed to maintain criticality safety within a reduced space. Some of the neutron absorber materials have experienced various levels of degradation and have in some instances had an impact on criticality safety. One neutron poison material commonly used in spent fuel pool storage racks is BORAL®. An aluminum boron carbide cermet, BORAL® is formed by hot rolling aluminum and boron carbide powder inside an aluminum ingot to produce a composite sheet with a porous inner core surrounded by an aluminum cladding. The composite sheet material is installed in a spent fuel storage rack for criticality control, exposing BORAL® to the spent fuel pool environment. Degradation of BORAL® has been observed in spent fuel pool applications in the form of blisters as well as general and localized corrosion. By understanding the amount of degradation, the mechanisms that lead to degradation, and the resultant impact, a strategy can be developed for long-term management of BORAL® in spent fuel pool applications.

Objective

 To develop a strategy for managing the long-term use of BORAL® in spent fuel storage racks.

Approach

The goal of the long-term management strategy is to be capable of detecting the onset of BORAL® degradation and to allow timely initiation of mitigation measures in order to offset any possible loss or redistribution of boron carbide.

Results

While the performance of BORAL® has generally been very good, some degradation has been observed for BORAL® in spent fuel pools. In specific, blistering of the aluminum cladding on the BORAL® sheet could lead to operational issues related to fuel handling. It is important to note that the corrosion observed to date has not led to any significant loss or redistribution of B-10, nor have any mechanisms been identified that would lead to either of these conditions. However, to avoid any unexpected conditions in the future, a strategy for managing the long-term use of BORAL® has been developed to include surveillance, measurement, and mitigation activities.

Applications, Value, and Use

BORAL® is a widely used neutron poison material for criticality control in spent fuel pool storage racks. The defense-in-depth strategy developed in this report for the long-term management of BORAL® provides methods for surveillance and monitoring to detect any unexpected changes that could influence the in-service performance and function of BORAL®. These surveillance measures should be more than adequate to detect the onset of material changes that could influence the in-service integrity of BORAL® before such changes become an issue.

Keywords

BORAL® Criticality Degradation Neutron Absorber Materials Spent Fuel Pool Used/Spent Fuel Storage

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Section 1: Introduction and Objectives

When the current generation nuclear plants were constructed, the spent fuel pools were fitted with spent fuel storage racks with a capacity of one and a third to two cores. The fuel discharged from the reactor was to cool for a few years to allow the residual decay heat to diminish. Subsequently, it was to be shipped for reprocessing. The fuel in storage was maintained safely subcritical by separating adjacent fuel assemblies by a sufficient distance so as to preclude neutronic coupling. Fuel storage racks with fuel storage cells that maintained a distance of 12 to 20 inches between adjacent assemblies were typical.

When nuclear fuel reprocessing was abandoned in this country, the utility industry was faced with an accumulation of permanently discharged fuel in the spent fuel pools whose storage capacity was limited. To remedy this situation, "high density" or "maximum density" spent fuel storage racks were introduced. In these fuel racks, neutron absorber materials were placed between fuel assemblies allowing the storage of fuel in close proximity to one another. The purpose of the neutron absorber materials is to preclude neutronic coupling between adjacent fuel assemblies and to maintain the fuel in storage in a subcritical condition. In "maximum density" fuel storage rack designs the separation distance approaches physical limits as imposed by the envelope dimensions of the fuel. In BWR fuel rack design, the minimum center to center spacing of adjacent fuel assemblies is about 6.0 inches. In PWR fuel rack designs, the minimum spacing is about 9.0 inches.

Various neutron absorber materials have been used in maximum or high density fuel storage racks. A comprehensive review of these materials and their in-service performance has been previously documented [1]. BORAL®, an aluminum/boron carbide cermet has been used extensively for this purpose both in the U.S. and around the world. To date the performance of this material in its service environment has, from all indications, been satisfactory.

The maximum and high density fuel storage racks that have been put in service in the U.S. typically have a design service life of 40 years. Some of those racks placed in service in the 1970s are now approaching 40 years of service. With plant life extension, these fuel storage racks will be relied on for at least another 20 years of service while the extended operating license is in effect. At the expiration of the operating license, fuel storage racks may be used for the storage of spent fuel for an extended period of time until the final disposition of spent nuclear fuel. These considerations suggest that BORAL® may be relied on for 80, or as many as 100 years, to control the reactivity of spent fuel assemblies in

storage. This length of time for an aluminum matrix material in a warm aqueous environment is well beyond the equivalent time for which this material has been subject to corrosion testing.

This project has as its prime objective the development of a strategy for managing the long-term use of the neutron absorber material, BORAL®, in spent fuel storage racks. The strategy that has evolved is a defense-in-depth approach capable of detecting the onset of BORAL® degradation and timely initiation of mitigation measures to offset any possible loss or redistribution of boron carbide.

Section 2: Background

BORAL® was formerly produced by Brooks and Perkins, Inc. Brooks and Perkins had developed the manufacturing process for BORAL® and held several patents on specific elements of the process that have since expired. Brooks and Perkins was subsequently acquired by AAR Manufacturing and for an interim period was known as AAR Brooks and Perkins. Subsequently, they were known as AAR Advanced Structures, AAR Cargo Systems, and finally as AAR Manufacturing.

In July 2006, the BORAL® product and certain manufacturing equipment were acquired from AAR by Ceradyne. The production of BORAL® has been moved to a 75,000 sq. ft. manufacturing facility in Chicoutimi, Quebec, Canada. The new facility and the production of BORAL® by Ceradyne are discussed in Reference 1-1. Virtually all of the BORAL® currently in spent fuel pools was produced by Brooks and Perkins or AAR Manufacturing.

BORAL® is a hot-rolled composite sheet consisting of (1) a core of uniformly mixed and distributed boron carbide and alloy 1100 aluminum particles; and (2) a surface cladding, on both sides of the core, serving as a protective barrier. Figure 2-1 is a micro photograph of the edge of a BORAL® sample showing the core and cladding region. BORAL® has been produced with the core containing anywhere between 35 w/o and 65 w/o boron carbide. The latter represents a practical upper manufacturing limit as with 70 w/o boron carbide there are insufficient aluminum particles between the boron carbide particles to sinter and form a bonded core matrix and a sufficiently strong bond between the core and the cladding. The level of boron carbide normally in the core is greater than 50 w/o.

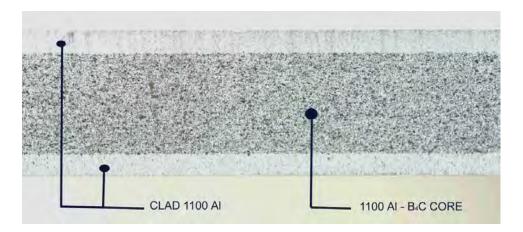


Figure 2-1
Microphotograph of the Trimmed Edge of BORAL® [1]

The core of BORAL® is somewhat less than maximum theoretical density and can contain varying amounts of porosity (1 to 8%). This porosity can have varying degrees of interconnectivity potentially allowing water ingress into the core. Subsequent corrosion of the inside surfaces of pores and the production of hydrogen can cause the clad to separate from the core as discussed subsequently.

2.1 BORAL® Use in Spent Fuel Storage Racks

BORAL® is used in spent fuel racks in rectangular plate or sheet form typically 5.50 inches to 8.0 inches in width, 0.040 inches to 0.100 inches thick and with a length corresponding to the active fuel length (typically 144.0 inches). Either one or two plates are used between each storage cell depending on the reactivity of fuel in storage and the storage rack design. Figure 2-2 is a cross section of a typical PWR Region 1 fuel rack for high reactivity, unburned reload fuel. This design provides for two plates of absorber between each cell separated by a flux trap water gap. The latter provides for thermalization of neutrons, thus increasing the effectiveness of the neutron absorber. The absorber plates are positioned on all four faces of the stainless steel cell walls that form a storage cell and retained there by a thin gage cover plate. The cover plate is generally tack-welded to the cell wall. The individual cells are generally connected at the corners (not shown) and to a base plate containing leveling feet to form a rack.

Figure 2-3 shows the cross section of a typical Region 2 PWR rack. This rack is used to store fuel of lower reactivity that has achieved a specified level of exposure. In this design, there are half as many stainless steel structural cells and resultant cells are formed by one wall of each four adjacent cells. There is only one plate of absorber between each fuel assembly in this design. The absorber plates are part of the structural cell walls in a manner similar to the Region 1 rack. As in the Region 1 design, the individual cells are connected by welding at the corners, and welded to a base plate to form a rack.

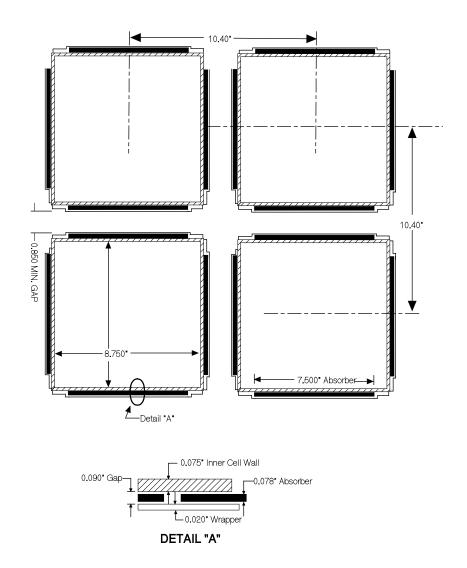


Figure 2-2 Cross Section of a Typical PWR Region 1 Storage Cell [1]

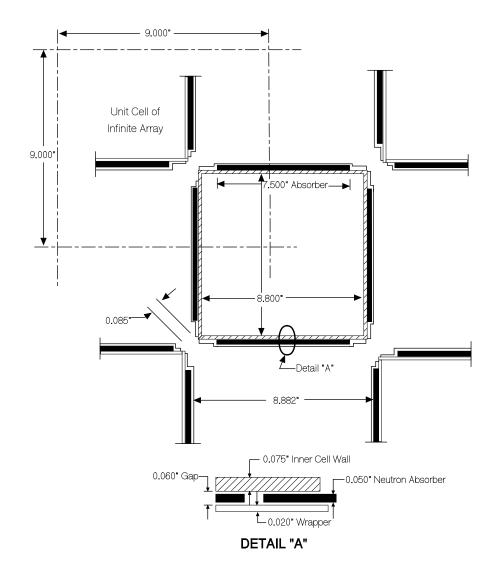


Figure 2-3
Cross Section of a Typical PWR Region 2 Storage Cell [1]

The Region 2 type rack design is also used to store BWR fuel assemblies; however, the cells have different dimensions. In the BWR design, the storage cell is approximately 6.0 inches square and the cells are positioned at a center-to-center spacing of slightly greater than 6.0 inches.

Most of the BORAL® supplied by Brooks and Perkins and AAR was supplied as sheet to the rack manufacturer who incorporated this material in the rack structure. However, during the late 1970s and in the 1980s, Brooks and Perkins produced individual spent fuel storage modules (SFSMs). Spent fuel storage modules consisted of concentric inner and outer square metal shrouds that

integrally encapsulate four BORAL® plates. The shrouds provided structural characteristics for use in spent fuel racks. The individual spent fuel storage modules were sold to rack fabricators who assembled the individual components into finished fuel racks.

The inner and outer shrouds were constructed of either aluminum or stainless steel U elements that were seam welded along the entire length to form square tubes. The inner shroud and outer shroud were assembled with four panels of BORAL® between the shrouds on each face. The assembled shrouds containing the BORAL® were then placed in a special hydro sizing fixture. The fixture was 25 feet long and weighed 30 tons. In the fixture a hydrostatic bladder was placed inside the concentric shroud and the shrouds were expanded against a die for final sizing by hydrostatic pressure. During sizing, the shroud walls were plastically deformed and convex stiffening indents were formed in the walls to provide additional strength as shown in Figure 2-4. After sizing, the shrouds were seal-welded top and bottom providing a sealed structure that was intended to isolate the BORAL® from the pool water.

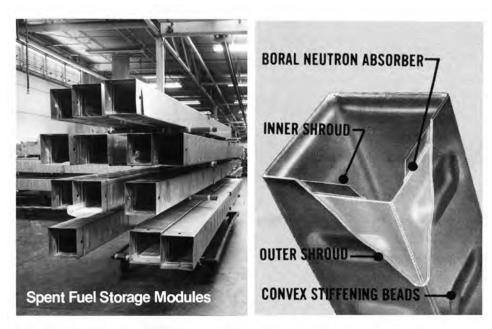


Figure 2-4
Brooks & Perkins Individual Spent Fuel Storage Modules [1]

Rack assemblies fabricated from individual spent fuel storage modules were installed in several pools, some of which are still in service today. Failure of some of the seal welds caused water to contact the BORAL® in some cells after installation. This produced the corrosion product hydrogen, and caused the module walls to deform and interfere with the fuel in storage. Brooks and Perkins subsequently ceased producing SFSMs and all rack designs are now vented to prevent deformation. The installed BORAL®, thus, is routinely in contact with the pool water.

In most spent fuel storage rack designs, once the BORAL® is placed in the rack during manufacturing, it is fixed in the rack structure and cannot be removed. A small number of racks in the U.S. have removable absorber assemblies.

As such, the majority of the installed BORAL® cannot be readily inspected for any signs of deterioration. Accordingly, many utilities have installed a series of surveillance coupons in their spent fuel pools. The surveillance coupons may be encapsulated in a manner replicating the way the BORAL® is housed in the racks or, in some cases, not encapsulated at all. The coupons are attached to one or more surveillance assemblies which are placed in vacant storage cells in the racks. Periodically, one or two coupons are removed from the spent fuel pool and sent to a qualified lab for inspection and testing to verify the in-service performance of the BORAL®.

As an alternative to surveillance coupon testing, a non-destructive test method can be applied to the BORAL® in the fuel storage racks to assess its in-service performance. This method was originally developed to monitor the degradation of another neutron absorber, Boraflex. The method has been used for fuel racks utilizing other neutron absorbers including BORAL®.

2.2 Population of U.S. Spent Fuel Pools with BORAL® Spent Fuel Racks

BORAL® was first used in a U.S. commercial reactor at Yankee Rowe in 1964. While that plant has now been decommissioned, BORAL® has been used in some 60 U.S. pools in spent fuel pool storage racks. It has also been used in several research reactors.

A survey has been conducted of the spent fuel pools in the U.S. to determine which pools contain fuel racks with BORAL® neutron absorbers. The participating utilities were also queried as to practices for BORAL® surveillance and the frequency for surveillance coupon tests and inspections. The survey data was supplemented with data from NETCO's Fuel Store Database. Table 2-1 contains a complete listing of all U.S. plants that are known to have at least one rack that uses BORAL® as the neutron absorber material. Some of the plants in Table 2-1 have a full complement of fuel racks with BORAL®. Others originally used Boraflex racks and subsequently were partially reracked with BORAL® racks so that about half of the racks in the pool now utilize BORAL®. Others have one removable rack module that resides in the cask loading area of the pool in between dry cask loading campaigns.

Table 2-1 also identifies the rack manufacturer, the date the racks were installed as well as whether a coupon surveillance program is in place. Where available, the frequency for coupon testing is included.

Table 2-1 Spent Fuel Pools in the U.S. with BORAL® Spent Fuel Storage Racks

Plant	Surv. Prog.	Freq.	Date Installed	Rack	Comments
BWR A	N			Holtec	
PWR A					Pool B Only
PWR B				Holtec	932 Cells
PWR C	N		1999	Holtec	
PWR D1 & D2	Y	2, 5, 8, 11 then @ 5 yr	1993	Holtec	
PWR E	Υ	Visual Every 2 yr	2004	Holtec	Region 1 Only
PWR F	Υ	Visual Every 2 yr	2004	Holtec	Region 1 Only
PWR G	Υ	5 yr	1989	UST&D	
BWR B	Υ	10 yr	1981	PAR	
BWR B	Υ	5 yr	1992/99	Holtec	
BWR C	Υ	2 yr – var	2001/2005	Holtec	Also uses Boraflex and METAMIC racks.
PWR H	Υ		1998	Holtec	
BWR D	N		1989	NES	
BWR D	N		2000	Holtec	
BWR E	Υ	5 yr	1980		METAMIC racks added in 2007.
PWR J1 & J2	Υ	5 yr/10 yr	2000	Holtec	
PWR K1 & K2	Υ	5 yr/10 yr	2000	Holtec	
PWR L	Y	1 st 5 cycles	1992/2003	Holtec	
PWR M1 & M2	Y	4 yr	1993	Holtec	Plant is being decommissioned.

Table 2–1 (continued) Spent Fuel Pools in the U.S. with BORAL® Spent Fuel Storage Racks

Plant	Surv. Prog.	Freq.	Date Installed	Rack	Comments
BWR F	Ν			NES	
BWR G	Υ	10 yr			
BWR H	Υ	10 yr			
BWR L	Υ	6 yr	1992	Holtec	
BWR M	Y	Opt. no recent test	Mid 90s	Holtec	
BWR N	Y	Opt. no recent test	Mid 90s	Holtec	
BWR P	Y (10)	3 yr	2000	Holtec	BORAL® racks added.
BWR Q	Y	1c, 3c	2001, 2007	Holtec	Original Boraflex racks in place.
PWR N	Y	5 yr	Early 90s, 2002	Holtec	
PWR P	Ν		2002	Holtec	
BWR R	N		1986	PAR	
BWR S	Υ	5 yr	1979	GE	
PWR Q	Ν		1997	PAR	
PWR S	Y	5 yr/10 yr	1980	GE	
PWR T	Υ	5 yr/10 yr	1980	GE	
BWR T	Υ	10 yr	1980/83	PAR	
BWR U	Υ	10 yr	1980/83	PAR	
PWR U	Ν		1999	Holtec	
BWR V					
BWR W					

Table 2–1 (continued) Spent Fuel Pools in the U.S. with BORAL® Spent Fuel Storage Racks

Plant	Surv. Prog.	Freq.	Date Installed	Rack	Comments
BWR X					
PWR V					
PWR W					
BWR Y				Holtec	
PWR X				ENC/Hol tec	
PWR Y				ENC/Hol tec	
PWR Z				Holtec	
PWR AA				W	About half the racks are BORAL®.
PWR BB				Holtec	About half the racks are BORAL®.
BWR Z				Holtec	All but 2 Boraflex rack modules.
BWR AA				Holtec	
BWR BB					
PWR CC				Holtec	1 rack (131 cells) only.
PWR DD				Holtec	1 rack (131 cells) only.
PWR EE				Holtec	1 rack only.
PWR FF				Holtec	1 rack only.
PWR GG					

Section 3: Coupon Surveillance Programs

Generally, once BORAL® is installed in fuel racks, it is not accessible for direct inspection to determine its in-service performance. Accordingly, utilities have often initiated a coupon surveillance program when new racks were installed.

In many cases, a coupon surveillance program consists of a series of small coupons either in a shroud simulating the manner in which the BORAL® is encapsulated in the racks or bare. The coupons are generally attached to a surveillance assembly, which is placed in a storage cell in a rack module. The surveillance assembly is generally surrounded by recently discharged fuel assemblies to accelerate the rate at which the coupons accumulate gamma exposure. Prior to placing the assembly in service, the coupons are generally characterized with respect to:

- Visual condition
- Dry weight
- Dimensions
- Specific gravity and density
- B-10 areal density

Periodically, coupons are removed from the surveillance assembly and sent to an independent laboratory for testing. The post-irradiation tests generally mirror the pre-irradiation testing. As the surveillance coupons are prepared from BORAL® cut from panels taken from the same production lot(s) used in the racks, the performance of the coupons is considered to be indicative of the performance of the material in the racks. Section 3.1 describes the surveillance coupon inspections and tests that are used to indicate the performance of BORAL® in spent fuel storage racks.

Many original installation racks and early vintage re-racks have Final Safety Analysis Report (FSAR) requirements for routine surveillance coupon removal and physical characteristic measurement; i.e. weight, length, width, thickness. A number of re-rack projects performed in the 1990s and early 2000s have no licensing requirements for BORAL® surveillance. This was based upon the NRC's confidence of BORAL® performance as reflected in the long service history and positive surveillance coupon results up to that point. Thus, a number of operating BORAL® racks have no surveillance coupon program. Recent (mid-2000s on) re-rack projects have been required to have surveillance coupon

programs that include not only routine coupon physical characteristic measurements but also B-10 areal density tests of those coupons. As plants pursue license renewal, the NRC has required utilities to "...demonstrate in their specific spent fuel pool environment for their specific material(s) that degradation has not occurred in a manner that could adversely impact the material's intended function." [2] Further, the NRC guidance states, "The loss of material and the degradation of the neutron-absorbing material capacity are determined through coupon testing, direct in situ testing, or both. Such testing includes periodic verification of boron loss through areal density measurement of coupons or through direct in situ techniques, such as measurement of boron areal density, measurement of geometric changes in the material (blistering, pitting, and bulging), and detection of gaps through blackness testing." [2]

3.1 Surveillance Programs Range of Spectrum of Practices

A review of EPRI member utility practices and NETCO research noted the following utility range of practices with respect BORAL® coupon surveillance programs.

- No formal program and no surveillance coupons.
- No formal program and any existing surveillance coupons have been abandoned in place in the spent fuel pool.
- Some programs have encapsulated coupons in the spent fuel pool replicating the manner in which BORAL® is captured in racks.
- Some programs have bare or un-encapsulated coupons in the spent fuel pool.
- Degree of coupon pre-characterization has been widely variable.
- Limited degree of archive material is available and the characterization data is limited.
- Variable post-irradiation surveillance coupon testing:
 - On-site coupon inspection/testing (coupon size measurement, weighing) and subsequently the coupons are returned to the spent fuel pool.
 - Sent to outside laboratory:
 - o visual and high resolution digital photography
 - dimensions
 - o as received weight
 - o drying
 - dried weight
 - density
 - o B-10 areal density
 - o blister size characterization
 - o microscopy

- cladding pit depth
- cladding pit size

3.2 Coupon Surveillance Test Scope

In the cases where utility surveillance coupons have been sent to an external laboratory for detailed examination, an overview of BORAL® performance is available based upon a wide variety of spent fuel pool environments encompassing in-service times of as little as one year to over twenty-eight years. Typically, a laboratory characterization of surveillance coupons contains the following elements:

- Length, Width, and Thickness Measurements
- Coupon Drying and Subsequent Weight Measurements
- Density Measurements
- B-10 Areal Density Measurements
- Microscopic Analysis
- Localized Degradation Characterization (Upon Request)
- Characterization of Material Anomalies (Upon Request)

It should be noted that a significant fraction of the lab coupon testing database utilizes information from BORAL® coupons that were removed from the spent fuel pool, tested, returned to the spent fuel pool and then subsequently removed again for testing. This practice introduces a variable in that the coupon does not exactly replicate the performance of the in-service panels, which remain wetted throughout their service life.

3.3 Lab Test Summary - General Corrosion

The matrix of BORAL® and alloy AA 1100 is highly corrosion resistant compared to other matrices that use other alloys of aluminum. BORAL® that is exposed to de-mineralized water, as in a BWR spent fuel pool, develops a more or less uniform oxide film. Once formed, the films serve to passivate the surface against further corrosion. In a 2,500-ppm boric acid solution, as in a PWR spent fuel pool, generalized corrosion does not occur. Figure 3-1 shows BORAL® coupons that have been exposed to de-mineralized water and a boric acid solution at a concentration of 2,400 ppm boron. The coupon exposed to de-mineralized water has a uniform light grey color characteristic of the oxide; whereas the coupon exposed to boric acid solution has an appearance characteristic of mill finish BORAL®.

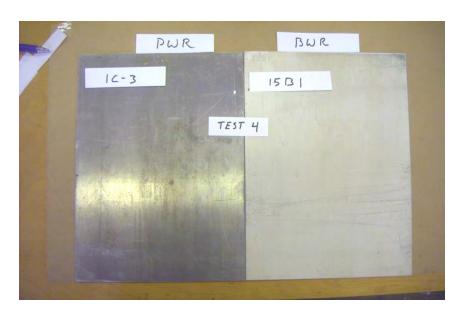


Figure 3-1
Appearance of BORAL® Exposed to Boric Acid Solution and De-mineralized Water [3]

The difference in corrosion behavior in de-mineralized water and boric acid is attributable to the pH of the solution. De-mineralized water typically has a pH in the range of 6.0 to 7.0 whereas the boric acid solution is at a pH of 4.0 - 4.5. Figure 3-2 contains weight loss measurements for aluminum alloy 3004 exposed to distilled water at various pHs for one week. The pH of the water was adjusted with HCl and NaOH. These test results show that oxide formation is a minimum in the pH range of 4.0 to 4.5 and is more significant at a pH of 6.0-7.0.

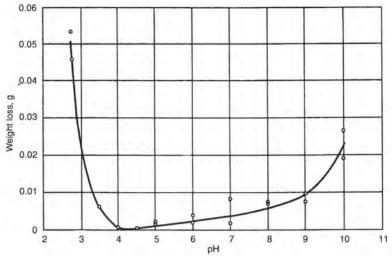


Figure 3-2 Corrosion Test Results for Aluminum Alloy 3004: Weight Loss vs. pH [4]

Generalized corrosion as reflected in surveillance coupon thickness was characterized by review of the BORAL® coupon examination data as accumulated by NETCO.

Coupon changes in thickness were calculated via spreadsheet and normalized using the respective in-service time for each coupon. After distinguishing between PWR and BWR it is noted that there is a significantly greater population of values for the PWR data set. A separate analysis of PWR and BWR measurements is performed to produce maximum departures from the pre-irradiation values of -2.4% per year and +3.3 % per year, respectively. The maximum departure from pre-irradiation values for the PWR corresponds to a net shrink rate, while the BWR maximum departure corresponds to a net growth rate. This is consistent with experimental data as well as prior observations of general corrosion having an increased early corrosion rate, especially in the BWR environment, until a tenacious self-passivating oxide layer is formed. Further, it was noted above, that aluminum in the PWR environment exhibits little evidence of formation of an oxide layer.

3.4 Lab Testing Summary – Localized Corrosion and Pitting

Localized corrosion and pitting of BORAL® can occasionally occur in either the BWR or PWR pool environments. In the BWR environment, localized corrosion can occur at weak spots in the passivating oxide film. In the PWR environment, localized corrosion can occur at sites of surface imperfections and/or residual surface contaminants left from the manufacturing process. The localized corrosion can take the form of pitting corrosion, crevice corrosion, galvanic corrosion, intergranular corrosion or exfoliation corrosion. Some of the most extensive localized corrosion has been observed in PWR surveillance coupons clad in stainless steel capsules.

Figures 3-3 and 3-4 are macro-photographs of the front and back side of a PWR surveillance coupon with localized corrosion. This extreme example of localized corrosion is thought to be pitting corrosion initiated by residual contaminants on the surface of the BORAL® and/or impurities in the core. The local pitting corrosion was likely amplified by galvanic effects as the coupon and capsule represent two dissimilar metals separated by an electrolyte (boric acid).



Figure 3-3
Macro-photograph of BORAL® Coupon with Localized Corrosion – Front Side [1]



Figure 3-4 Macrophotograph of ${\it BORAL}^{\it @}$ Coupon with Localized Corrosion – ${\it Back Side}$ [1]

The pits are characterized by through-cladding penetrations surrounded by heavy white oxide deposits. A mirror image of the deposits on the coupon appear on the inside surface of the stainless steel capsules suggesting an anodic/cathodic transfer mechanism characteristic of galvanic corrosion.

Other photomicrographs of corrosion pits and deposits are shown in Figures 3-5 and 3-6. Corrosive attack of the open edges of BORAL® have been observed in other coupons, as shown in Figure 3-7 and Figure 3-8. The edge of the coupon in Figure 3-7 appears characteristic of exfoliation corrosion that develops along the boundaries of long thin grains (caused by the rolling processing) parallel to the flat surface of BORAL®. The rust deposits in Figure 3-8 may suggest the presence of iron impurities in the core of the BORAL®.



Figure 3-5
Corrosion Pits and Corrosion Deposits [1]

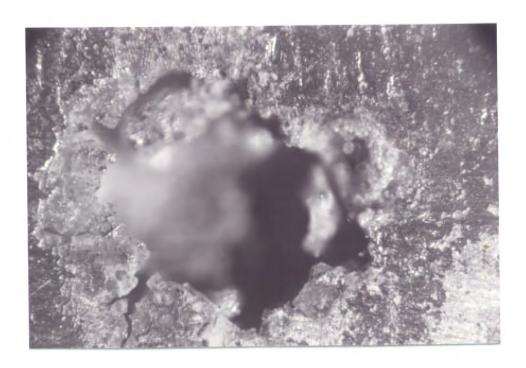


Figure 3-6 Through-Cladding Corrosion Pit [1]



Figure 3-7 Oxidized Edge of BORAL® [1]



Figure 3-8
Oxidized Edge of BORAL® with Rust Deposits [1]

NETCO has measured pit depth of pits observed on surveillance coupons.[5] Figure 3-9 contains a plot of pit depth versus time of exposure to pool water for BORAL® pits in both PWR and BWR surveillance coupons. As the nominal cladding thickness of BORAL® is typically 10 mils (0.01 inches), a number of the measured pits have penetrated through the cladding into the core of the BORAL®. It is noted that the pit depth versus time appears to be bounded by a function of the form $kt^{1/3}$.

PITTING CORROSION ON BORAL COUPONS

PIT DEPTH vs.TIME

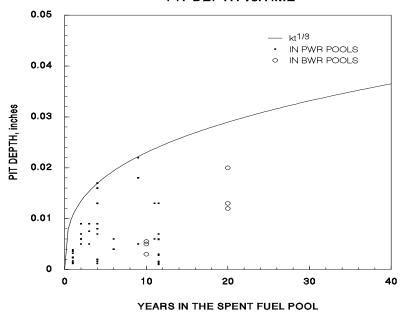


Figure 3-9
Pitting Corrosion on BORAL® Coupons [1]

The localized corrosion described above appears to be significant. The data points to the need for controlling impurities in both the aluminum powder and boron carbide used to manufacture BORAL®. Further, it identifies the need for complete cleaning of the surface of BORAL® after rolling to ensure that all residual oil used in the rolling process is removed. Current manufacturing processes have incorporated these improved process controls.

It should be noted that while corrosion has been observed on BORAL® surveillance coupons, to date, this in-service localized corrosion has been restricted primarily to the cladding and has not resulted in any measureable decrease in B-10 areal density. It is therefore concluded that the 1100 alloy matrix continues to serve as an effective matrix to retain the boron carbide.

3.5 Lab Testing Summary - Blister Formation

Blisters have been observed in the cladding of BORAL® used in both BWR and PWR pools since it was first used in a commercial reactor at Yankee-Rowe in 1964. While blistering can create possible plant operational issues, they have not been found to cause any loss or relocation of the boron carbide in BORAL® plates and, therefore, do not constitute a significant criticality safety concern.

Blisters have occurred in both surveillance coupons and in BORAL® racks. When blistering is severe, it can cause cell wall deformation in the spent fuel rack. Blisters are characterized by a local area where the cladding separates from

the core and the cladding is plastically deformed outward away from the BORAL® core. The appearance of a blister suggests its mechanism of formation is related to a local pressure buildup in the core causing cladding/core delamination and subsequent clad plastic deformation. To date, approximately 40% of coupons examined by NETCO exhibited blistering.

A postulated mechanism for blister formation is based on water entering the BORAL® through open porosity at the edges where the material was trimmed to size. Water in contact with the internal surfaces of interconnected pores causes internal corrosion and the production of Al_2O_3 and H_2 gas. The volume change associated with the formation of Al_2O_3 from Al causes the pores to close thus sealing H2 corrosion product and water in the core of the BORAL®. Subsequent formation of H2 and/or heating of trapped hydrogen and/or water by gamma energy from spent fuel causes an internal pressure buildup in the core. Figure 3-10 is illustrative of edge BORAL® blistering from a BWR pool.

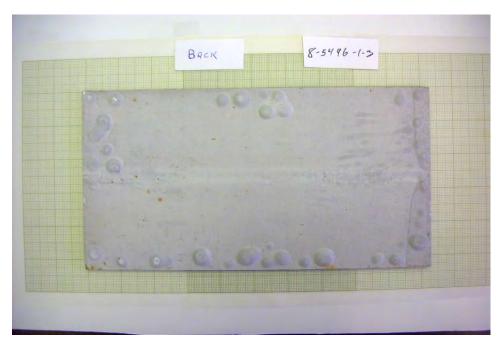


Figure 3-10
Blister in a BWR BORAL® Coupon Manufactured in the 1970s [1]

The size and location of blisters shown in Figure 3-10 would suggest water migration in the core is restricted close to the edge of the material. This might be the case if the internal porosity was relatively low and not well interconnected.

In addition to coupons that develop blisters while in the pool, coupons that were received without blisters have been observed to develop blisters when they are dried at an elevated temperature. To determine whether coupons have sustained any weight change, AAR recommended sequential drying for four hours each at 175°F, 300°F and 500°F. Some coupons that did not develop blisters in-pool do develop blisters after drying at 300°F. This is further evidence of trapped

hydrogen or moisture in the BORAL® core. For coupons that developed blisters in the pool, drying at temperature tends to increase the size and number of blisters. The EPRI BORAL® performance database [6] indicates blister height increases, peaking near 0.050 inches and later tapers off after approximately 15 years. Similarly, the area of individual blisters increases and later peaks near 0.210 square inches after approximately 18 years.

In general, blisters are more likely to occur in coupons subjected to demineralized water than those exposed to boric acid. Further, blisters that form in coupons subjected to boric acid tend to be fewer in number and smaller than those exposed to de-mineralized water. This would tend to support that corrosion product hydrogen is one factor contributing to blister formation. In the early years, AAR conducted a series of tests with powdered aluminum in demineralized water and boric acid and measured the value of hydrogen generated. Figure 3-11 contains a plot of hydrogen generation versus time in solutions of de-mineralized water and various solutions of boric acid. This result also tends to support the conclusion that generalized corrosion is reduced in PWR pools water relative to BWR pool water.

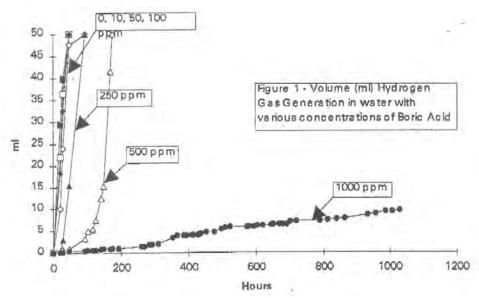


Figure 3-1 1 Hydrogen Generation from Aluminum Powder in Boric Acid [1]

3.6 Effect of BORAL® Manufacturing Date

The size of blisters and the location where they form appear to depend on when the BORAL® was manufactured and, by inference, the chemistry and process controls that were used during that period. For material manufactured in the 1970s, it has been observed that a series of relatively small blisters often formed within one inch from a cut edge of BORAL® as shown in the macro-photograph in Figure 3-10. The blisters shown in Figure 3-10 can be compared with blisters

that occurred in a coupon from the same BWR pool with BORAL® manufactured in the 1990s (Figure 3-12). In this case, blisters formed along edges and in the center of the coupon as well.



Figure 3-12
Blisters in BORAL® Coupon Manufactured in the 1990s [1]

The observation of blistering central to the BORAL® coupon would indicate that water can either migrate to the central region of the coupon core or possibly reach the core after localized corrosion has penetrated the aluminum cladding. This would indicate that the porosity of this sample is more open and well interconnected as compared to that of BORAL® made in the 1970s as illustrated in Figure 3-10.

3.7 Effect of Rack Design Features vs. Coupon Capsule Design

The majority of in-service spent fuel storage racks that utilize BORAL® as the neutron absorber have a design similar to that illustrated in Figures 2-2 or 2-3. The BORAL® is captured against the rack cell by a thin wall stainless steel wrapper plate. This wrapper plate is vented to the spent fuel pool. Venting the BORAL® wrapper plate was either done as part of the spent fuel storage rack original design and fabrication or subsequently done while the racks were inservice after observation of wrapper plate deformation.

It is intuitive that when creating a surveillance coupon program for a spent fuel pool storage rack, the optimal coupon is one that reflects or mimics the in-service BORAL® panel conditions. There are, however, conflicting considerations in play. Bare or un-encapsulated coupons have the advantage of the plant operator being able to directly observe the visual condition of the coupon without

removing it from the spent fuel pool environment. The encapsulated coupon has the advantage of creating the more restricted pool water flow environment that the in-service BORAL® is experiencing. Considering all other elements (i.e. surveillance coupon location, irradiation history, removal schedule, test elements, etc.) of a coupon surveillance program being equal, a surveillance program where the BORAL® coupons are enclosed in a capsule that replicates the enclosure material and water flow environment of the rack is judged to yield a better indicator of in-service BORAL® performance.

3.8 Effect of Radiation Energy Deposition on Local Water Temperature

For most metals, including aluminum, an increased environmental temperature produces an increased potential for corrosion. While gamma and neutron irradiation as experienced in a commercial light water reactor spent fuel pool, does not measurably have an effect on the material properties of BORAL®, the local energy deposition and the resultant increase in metal and coolant temperature does have the potential to effect the corrosion rate. Therefore, when utilizing coupons to represent the otherwise inaccessible in-service BORAL® panels, the surveillance coupon holder should be in a rack irradiation environment that represents or bounds that of the in-service BORAL®. It is therefore suggested that when practical, freshly discharged fuel be placed adjacent to the surveillance sample coupons.

3.9 Conclusions: BORAL® Use in Wet Storage

While BORAL® is subject to both generalized corrosion and local corrosion in spent fuel pools, the overall performance to date has been satisfactory. This conclusion is based on the data from utility coupon surveillance programs which have shown no reduction in B-10 loading due to these effects.

Similarly, in-pool blistering of BORAL® has, to date, proven to primarily affect the operational aspects of the storage racks by impacting fuel assembly dimensional clearances. The blistering may also have some effect on the rack's criticality because of the displacement of some moderating water, but these changes have been shown to be very small.

It has been noted that, in a few instances, rack cell wall deformation has occurred making it difficult to remove fuel. With plant life extension now the norm at most LWRs in the U.S., some BORAL®, which originally had a design service life of 40 years will be in service 60 years or more. Continued surveillance as part of an overall plant material aging management program is prudent such that the onset of any safety or operational issue may be detected early enough to allow appropriate review and implementation of mitigation measures.

Section 4: Boral Degradation Mechanisms

4.1 Clad Blistering and Operational Considerations

While blisters have not been observed to alter the neutron absorption properties of BORAL® as measured areal B-10 density, there is a potential operational issue with respect to BORAL® blisters in spent fuel storage racks. In BWR racks, as well as in PWR Region 2 racks, blisters in the BORAL® that occur under the thin gage wrapper plate (Figure 2-3) can cause the wrapper plate to locally deform and intrude into the fuel storage cell reducing the fuel assembly clearance in the cell. Should blisters occur in more than one BORAL® panels in the cell at a coincident axial elevation, the condition becomes enhanced and could make fuel removal from cells with blistered BORAL® difficult. BORAL® clad blistering is only one of a number of causes for fuel assembly binding in spent fuel storage racks. Fuel assembly bow and twist, irradiation induced growth of higher burnup fuel assemblies (axial and radial growth), accumulated fuel handling damage to the thin gage wrapper plate, new fuel design external envelop changes, changes to location of assembly features (such as grid straps or fuel channel buttons or channel corner thickness), rack fabrication tolerances and installation related distortion of cells can of themselves, or in combination with BORAL® panel blistering, cause fuel handling difficulties with respect to the fit of fuel assemblies in spent fuel storage racks. Destructive examination of a number of documented BORAL® cells with operational issues would be required to determine the actual role of BORAL® panel blistering with respect to fuel fit in a spent fuel storage rack cell.

4.2 Blistering/Corrosion and Safety Considerations

Blistering

BORAL® cladding blisters may have an effect on Region 1 PWR fuel racks (Figure 2-2). The formation of intact and water tight BORAL® blisters can create voids which causes water to be displaced from the flux trap region between storage cells. Since the water in the flux trap region is used to thermalize neutrons, making the neutron absorber more effective, BORAL® blisters may result in an increase in the reactivity of the fuel/rack configuration.

General Corrosion

The clad and core matrix of BORAL® is composed of, or contains, alloy AA 1100 which is one of the more corrosion resistant alloys of aluminum. The observed general corrosion of BORAL® surveillance sample coupons to date has not revealed significant loss of the cladding layer or the core material. Thus, general corrosion of BORAL® is highly unlikely to be a path for the loss of reactivity hold down capability.

Corrosion Pitting

Corrosion pitting of the BORAL® clad has been observed in surveillance sample coupons. Section 3.4 described the appearance and morphology of BORAL® pitting. As noted in section 3.4, localized corrosion (pitting) has not resulted in any measureable decrease in B-10 areal density. However, given the projected long-term use of the racks, this mechanism must be monitored in the future to insure continuing full efficacy of the BORAL®.

4.3 Mechanisms Leading to B₄C Loss or Redistribution

Neutron attenuation is BORAL's® primary function and is fundamental to maintaining sub-criticality in spent fuel pools. Therefore, the B-10 areal density change is the most important attribute for consideration when evaluating the material performance of BORAL®. Given the wide range of uncertainty in the preliminary B-10 data, it is sometimes difficult to characterize a net change. Some pre-characterization measurements provided by utilities do not list an associated fabrication uncertainty. Occasionally, coupon measurements indicate an increase in areal density as compared to the accompanying pre-characterization data.

Analysis of the NETCO BORAL® measurement data shows a maximum loss of -0.86% of areal density per year for the PWR data set and a maximum loss of -0.04% of areal density per year for the BWR data set. It is important to note that a considerable number of the measurements in these data sets are values that are compared to measurements made on archive coupons, as opposed to a precharacterization measurement of the actual surveillance coupon. Thus, the measured losses may be more of an artifact of the measurement basis than the actual loss of B-10. B-10 areal density measurement uncertainty in NETCO tests typically ranges from ±0.0001 to ±0.0005 g/cm².

Depletion of B-10 in spent fuel storage racks from neutron irradiation is not considered a viable loss or redistribution mechanism due to the very low neutron fluence experienced by the absorber panels. Mechanical wear of the BORAL® core material may also be dismissed as a mode for B₄C loss or redistribution in that BORAL® has an aluminum cladding and the BORAL® panels in spent fuel storage racks are further encapsulated by a stainless steel wrapper plate. There also is no identified mechanism for frequent or continual fuel bundle movement in the racks that could cause fretting or abrasion type damage.

Corrosion of the core BORAL® material is the most credible mechanism for causing B_4C loss or redistribution in BORAL®. There are three aspects of BORAL® corrosion that may lead to B_4C loss or redistribution: general corrosion, localized or pitting corrosion and blistering.

General corrosion is an unlikely mode of B_4C loss or redistribution in that 1100-series aluminum used in the cladding and the core matrix is corrosion resistant in typical pool environments. The BORAL® cladding thickness is typically 10 mils. No evidence of general corrosion breach of the BORAL® cladding has been noted in any of the NETCO measured surveillance coupons. While general corrosion performance should continue to be monitored as part of a BORAL® aging management program, it does not appear to be a significant factor leading to B_4C loss or redistribution.

Pitting corrosion, as discussed in section 3.4, has in certain cases been observed to be sufficiently severe to have caused small penetration in the cladding. By its very nature, pitting corrosion is especially localized. Close examination of the pits in surveillance sample coupons do not identify growth of the pit below the clad. Further, B-10 areal density tests performed on surveillance sample coupons do not indicate any loss of material or reduction of neutron absorber efficacy. Pitting corrosion is a more likely mode of B₄C loss or redistribution than general corrosion; but to date, no surveillance sample coupon tested has exhibited a diminution of BORAL®'s primary function of neutron attenuation. Monitoring pitting corrosion should be part of a BORAL® aging management program to track the ongoing evolution of pitting corrosion in BORAL®. Such a monitoring program could include a range of activities including laboratory testing, analytical modeling of variables, and conducting an industry wide coupon examination program. By approaching such a program on an industry-wide coordinated basis, a wide range of operating plants could benefit from a much reduced scope of effort.

BORAL® blistering is described in section 3.5. Blistering as noted in fuel pool neutron absorber surveillance coupons is not a direct mechanism for B₄C loss or redistribution. The effects of blistering are described in sections 4.1 and 4.2. A potential indirect mechanism for the loss or redistribution of B₄C would be the breach of the clad material that forms the blister and the subsequent wetting of the core material. This may lead to corrosion of the core material below the blister, much like in the case of pitting corrosion. The core substrate contains 1100-series aluminum and as such is highly resistant to corrosion. The B₄C captured in the aluminum is unlikely to travel since the corrosion rate is low and the blister, even if breached, would tend to retain any loose material in the blister. A mechanical damage event due to fuel handling could serve to allow loose material in the blister to be expelled. Currently, there is no plant inspection or laboratory evidence supporting such a scenario. However, since BORAL® blistering has been noted, increases in blister size and number over time as noted by industry surveillance data should be reviewed as part of a BORAL® aging management program. There is some testing data that suggests that blister size does not continue to grow after a period of about 15 to 18 years of pool service.

Summary

Overall, from a review of the data from over 25 years of operating surveillance experience, there is a high confidence in BORAL's® ability to retain both the amount and distribution of B-10 in the form of boron carbide. Although some measurements have indicated a very small loss, the decrease is routinely within the typical uncertainty for an areal density measurement.

Section 5: Defense in Depth Strategy

From its introduction, BORAL® was perceived as an effective, trouble-free neutron absorber material. So much so that in the early 2000s, a major spent fuel storage rack provider was able to support station licensing of pool re-racks utilizing BORAL® that did not require BORAL® performance surveillance programs. This perception of BORAL® by the NRC changed with the release of Information Notice 2009-26, "Degradation of Neutron-Absorbing Materials in the Spent Fuel Pool." This perception was spurred by dry storage testing of BORAL® by ENSA in Spain in the early 2000s. Spent fuel pool coupon test results that exhibited blistering received increased scrutiny by the NRC as noted in the Information Notice. Further, as nuclear power stations renew operating licenses, the NRC now requires a material aging management plan that provides surveillance of BORAL® performance in spent fuel pools. Consistent with the "defense in depth" philosophy of nuclear power plant design, a multi-level strategy has been developed to address the potential of degradation of BORAL® in spent fuel storage racks.

In the previous chapters, test related data and observations were summarized and discussed. The information reviewed suggests a number of situations where BORAL® performance as indicated by the surveillance sample coupons can have an impact on spent fuel pool operations and safety. "Operations" in this context refers to fuel storage and handling in and around the spent fuel pool. "Safety" in this context refers to criticality safety or the ability to maintain and demonstrate sufficient margins to prevent criticality.

The concepts and overall strategy discussed in this section focus on the nuclear safety consequences of BORAL® degradation. While operational considerations (fuel handling) are not to be ignored; the safety issues (criticality) of are paramount importance and the strategy developed in this report focuses primarily on degradation effects that are criticality safety related, that is the loss or redistribution of B-10.

A prerequisite for the implementation of this strategy is an understanding of the design margin that exists for a particular station's spent fuel storage racks. The design criticality analyses and the resultant criticality margin must be reviewed and assessed with respect to the current requirements and expectations of the NRC as noted in DSS-ISG-2010-01 "Staff Guidance Regarding the Nuclear

Criticality Safety Analysis for Spent Fuel Pools." This review and assessment may increase or decrease the criticality margin based upon the methods and assumptions used in the original analysis.

5.1 Surveillance Programs - First Level of Defense

The first level of defense should address one or more of three elements:

- 1. Use of spent fuel storage rack surveillance sample coupons
- 2. Tracking the industry operating and testing experience with BORAL®
- 3. Sampling and evaluating the spent fuel pool water chemistry

Should the results of first level surveillance measures indicate acceptable performance, the need to perform activities associated with the second level of defense is minimal. However, regulators and oversight organizations may require first and second level activities to be performed concurrently in some cases such as operations in the extended operating period associated with plant license renewal.

Spent Fuel Storage Rack Coupons

Many reactor spent fuel pools have an existing commitment for coupon surveillance. Section 3.1 noted the variability that exists among operating plants. An effective coupon surveillance program must address the performance issues that exist for BORAL®. These include ensuring the coupon surveillance program collects data on the general corrosion, localized corrosion, blistering and areal density of the coupons. For many plants, this would require a change in their surveillance test procedures and data requirements.

For plants with coupons and no surveillance program (abandoned or never implemented), there is an opportunity to bring the surveillance coupons into a state that can be considered representative by placing the coupon holder in a location that represents the highest radiation dose and highest local temperature. In practice, this would involve putting freshly discharged fuel adjacent to the coupon holder(s) after each refueling outage.

For plants with surveillance coupons, another key consideration is the availability of the total number of coupons and the manner that the coupons are to be used (i.e. inspected once and discarded or returned to the spent fuel pool after examination/testing). Consideration also must be given to station plans for license renewal and the continued availability of coupon testing to support the extended operation timeline. Plant operators that have surveillance coupons should consider the following questions when developing a long-term BORAL® aging management strategy:

- Should the original removal schedule for non-returning coupons be maintained or should the removal interval be lengthened? While maintaining the original removal schedule provides more frequent checks on BORAL® performance earlier, there may be little or no coupon performance information later in the spent fuel rack's operational life.
- Assuming that the coupon removal interval would be changed, what is the optimum surveillance frequency? Should a coupon(s) be available for testing at the end of plant licensed life?
- Can the individual site surveillance sample coupon be integrated with a larger industry-wide program? What generic or broad-based BORAL® performance issues can be addressed while maintaining adequate site-specific surveillance?

For plants with no surveillance program and no coupons, these considerations are a moot point.

Tracking Industry BORAL® Operating and Testing Experience

Knowing how other BORAL® plants are performing can act as a harbinger of one's own BORAL® performance. Plants with BORAL® racks can do a number of things to gather industry operating experience. Member utilities can rely on EPRI and the associated Neutron Absorber Users Group as a forum for BORAL® performance information exchange. The plant can independently establish information exchange relationships with peers to share data. Plants can rely on the Institute of Nuclear Power Operations' Operating Experience Reports to gather potentially adverse operating information regarding BORAL®. Utilities can also participate in individual or industry R&D efforts to gain test data, formulate performance models and improve test and surveillance techniques.

Pool Water Chemistry Analysis

Most plants follow the EPRI water chemistry guidelines with respect to pool chemistry maintenance and sampling. Generally, these sampling and operational guidelines are aimed at managing the corrosion performance of nuclear fuel and the reactor internals since spent fuel pool water may intimately mingle with that of the reactor coolant during refueling outages. As such, the operating assumption is that meeting fuel and reactor internals corrosion control limits bounds the performance requirements of components such as the spent fuel storage racks.

For example, as part of Boraflex degradation monitoring, power plants with Boraflex neutron absorber material tracked and trended the silica concentration in spent fuel pools. For many plants, this was relatively simple to incorporate into their spent fuel pool rack performance monitoring program since silica was a parameter to monitor and control as part of their fuel warranty requirements.

It is reasonable that a BORAL® performance monitoring program would sample and evaluate the elements and compounds that would indicate BORAL® degradation or detect chemistry conditions that would lead to degradation. The constituent elements in BORAL® include aluminum, boron and carbon. The key questions of such a monitoring program include the potential efficacy of such a sampling program and what actions, based on sample results, are viable and appropriate. This is discussed more detail as an area for further research.

5.2 B-10 Assays and Measurements – Second Level of Defense

Should any of the elements in the first level of defense indicate significant degradation of BORAL® performance, the plant operator would then consider implementation of a second level of defense. This involves quantitative testing of the in-rack BORAL® and a determination of the B-10 areal density of the material. The results of these inspections and tests would be compared to the current design and licensing basis for criticality control in the spent fuel pool. This can be accomplished in two ways:

- 1. Removal, examination and testing of a representative in-service BORAL® neutron absorber panel
- 2. In-rack measurement of BORAL® B-10 areal density

Removal and Examination of an In-service BORAL® Absorber Panel

The majority of BORAL®-poisoned racks incorporate BORAL® as an integral part of the rack structure (see Figures 2-2 and 2-3). Since the BORAL® is generally enclosed by a wrapper plate, direct examination is problematic. However, the station may choose to remove a BORAL® plate from the rack as part of a revised material aging surveillance program. Depending on the plant SAR and plant safety operations review committee, this activity may be considered part of periodic plant maintenance or as a one-time special test. Selection of a representative or bounding BORAL® absorber panel could be part of a potential research activity discussed in Section 6.

Although costly and time consuming, the technology exists to cut into a wrapper plate and expose an upper section of a BORAL® panel. Further, special removal grapples may be required to retrieve the BORAL® panel from an opened wrapper plate. The specific plant rack design may facilitate or hinder panel retrieval. Further consideration should be given to replacement of the BORAL® panel and re-closure of the wrapper plate. Prior to any such an activity, the cells adjacent to the panel to be removed should be emptied of fuel and considered inoperable. Once retrieved, a number of inspections can be performed at the plant site and at a remote lab to assess the in-service BORAL®. These inspections and tests are similar to that which would be performed on surveillance sample coupons.

Plant site surveillance test activities:

- Document general appearance and overall integrity of the BORAL® panel
- Measure the dimensions of the panel and compare them with the asdesigned and as-built records
- Measure the width and thickness of the panel at a number of locations and compare with the as-designed or as-built records
- If laboratory tests are to be performed, cut surveillance size coupons from the upper, middle and bottom of the panel (minimum size 2"x4"; maximum recommended size 6"x12") and package them for shipment to a testing laboratory

Lab surveillance test activities:

- Visual Inspection and High Resolution Digital Photography
- Coupon Drying (three step drying process)
- Dimensions
- Dry Weight
- Density
- Blister Size Characterization
- Microscopy for pit size and depth
- Neutron Transmission and B-10 Areal Density

In-rack measurement of BORAL® B-10 areal density

Quantitative in-situ measurement of in-rack BORAL® B-10 areal density can be accomplished by using an EPRI developed method called BADGER (Boron Areal Density Gage for Evaluating Racks). This system utilizes a californium neutron source located in one BADGER probe head and an array of neutron detectors located in another probe head. The source and detector heads are maneuvered on either side of the BORAL® panel to be tested. The entire panel is scanned by moving the source and detector heads simultaneously along the length of the BORAL® panel in the spent fuel storage rack. To minimize the radiation noise during the scan of the panel, a 3x3 fuel storage cell array centered on the detector head cell is required to be empty of fuel. BADGER provides panel average B-10 areal density measurements and identifies gaps in the neutron absorber panel of a size comparable to the step size of detector head travel. This technology was originally developed for the testing of Boraflex but has been adapted for use with BORAL®. To date, large amounts of data have been generated for Boraflex racks but only limited data for BORAL® racks.

5.3 Mitigation Measures - Third Level of Defense

The first and second levels of defense represent what a number of utilities have either implemented or are in the process of evaluating. Generally, the implementation of the first and second levels of defense can be accomplished through existing plant processes and do not require a plant license change. Further, if the results of the tests and surveillances of the first and second levels of defense indicate adequate BORAL® performance, activities associated with the third level of defense would not be necessary. The implementation of specific mitigation measures are expected to require major time and effort and would normally involve additional analyses, plant modifications, an operating license amendment, additional administrative controls and very large expenditures as compared to first and second level of defense activities. Examples of third level mitigation measures include:

- 1. Revision of the spent fuel storage rack criticality analysis
- 2. Installation of retrofit neutron absorber inserts
- 3. Accelerate deployment of dry cask storage, usually in conjunction with added administrative controls on rack fuel loadings
- 4. Re-rack of the spent fuel pool

Revision of the Spent Fuel Storage Rack Criticality Analysis

As noted in the beginning of Section 5, a clear understanding of the current licensing and design basis is essential. Improved methods may provide the potential for additional margin; however, compliance with NRC expectations regarding spent fuel pool criticality analyses as expressed in DSS-ISG-2010-01 "Staff Guidance Regarding the Nuclear Criticality Safety Analysis for Spent Fuel Pools" is likely to consume any margin gains through the use of improved methods. Practically, this mitigation measure would be used in conjunction with the physical plant changes associated with the other third level of defense activities.

Installation of Retrofit Neutron Absorber Inserts

Neutron absorber inserts can be designed and installed to replace or augment the degraded in-situ neutron absorber capability. The utilization of neutron absorber inserts can be an activity that:

- Restores criticality control of nuclear fuel storage racks with degraded neutron absorber materials
- Maintains or improves the total fuel storage capability by recovering cell locations rendered inoperable due to identified neutron absorber panel degradation
- Maintains or improves storage flexibility of the existing spent fuel storage racks by ensuring all effected locations have the same reactivity hold down capability

• Extends the enrichment capability of existing fuel racks permitting the storage of fuel with higher initial enrichments

Inserts have been successfully deployed and are in the process of being implemented at a number of sites. The installation of retrofit neutron absorber inserts have the potential to reduce costs and resource expenditures associated with complex spent fuel storage management strategies, and allow the continued use of existing spent fuel storage racks avoiding the cost of new rack design, fabrication, installation and old rack disposal. Similarly, the dose and potential contamination associated with insert implementation is considerably less than that of re-rack or accelerated dry storage. However, the plant operator should consider the following costs and issues associated with the use of retrofit inserts:

The use of retrofit inserts for spent fuel storage racks require a complete understanding of the spent fuel storage rack cell mechanical configuration to ensure proper design and fit of the insert to the rack. For inserts that become part of a fuel assembly, such as PWR inserts that are installed in the guide tubes, a complete understanding of the target fuel assembly mechanical configuration is required to ensure proper design and fit of the insert to the fuel assembly. The use of inserts will require engineering review, criticality analysis and a license amendment. For all inserts, the design of the insert and the associated operational and licensing impacts must be fully understood by the plant operator. Below are listed a number of issues to be considered by the plant operator when choosing an insert technology:

Fuel Assembly Inserts (PWR Only)

- Compatibility with the plant fuel storage design basis (seismic, assembly cooling, insert reactivity credit)
- Compatibility with the existing or anticipated dry cask storage/transportation design and licensing basis (eventual disposal issue)
- Ability to be re-installed in pool-located assemblies after the original recipient assembly has been transferred to dry cask storage/transport
- Ease of insert installation and removal
- Ease of fuel handling; i.e. use of existing fuel handling grapple and procedures with insert installed
- What controls will be used to insure that inserts cannot be inadvertently removed

Rack Inserts

- Method of insert installation some inserts must be installed with the fuel already in the rack cell, other insert designs must have the rack storage cell empty
- Some insert designs are dynamic in use in that inserts must be removed to move fuel and later installed at the new fuel location

- Some insert designs are installed once and become a static or integral part of the rack
- The available free space in the storage cell is reduced by the presence of the insert

Accelerate Deployment of Dry Cask Storage

This mitigation measure does not directly address the degradation of the in-rack neutron absorber. However, it does address a method that may reduce the required in-pool modification of the spent fuel storage racks and is a method to manage the consequences of neutron absorber panel degradation. The plant operator should weigh the overall cost of either initiating a dry cask storage project earlier or if an Independent Spent Fuel Storage Installation (ISFSI) already exists, accelerating the purchase of dry casks as compared to direct mitigation options.

This activity involves the purchase, deployment and loading of dry cask storage sufficient to allow plant operations that support refueling, vessel servicing and enhanced fuel pool security. The spent fuel storage rack locations need to provide adequate fuel storage for discharged fuel cooling time to meet the loading requirements of the cask system deployed, provide adequate storage of new reload fuel (if new fuel is staged in the fuel pool storage racks prior to refueling), and maintain full core offload capability (this may be either a license requirement, station commitment to the NRC or plant operational policy). Further, a revised spent fuel pool criticality analysis is required to demonstrate that a lower density storage of spent and new fuel meet the design basis reactivity margin requirements. Along with a pool operation strategy to maintain a 3 out of 4 or 2 out of 4 loading of the spent fuel pool, administrative and physical measures would be required to ensure that the new design and licensing basis are met. Physical measures are likely to include rendering spent fuel storage rack cells that are not to be used permanently inaccessible by fuel. If the blocking of fuel storage cells is necessary as part of the licensing of the new spent fuel storage rack configuration, consideration must also be given to ensuring continued compliance with enhanced pool security requirements for natural convection cooling. Thus, while a physical block for particular spent fuel storage rack cells may be required, sufficient natural convection flow capability through these blocked cells may need to be ensured. Also, an existing ISFSI's offsite dose model will require a review to determine if a revision to station's 10CFR72.212 report is required due to possible changes in the operational and off-site dose.

Re-rack

For many plants with fuel pool storage issues such as neutron absorber performance or inadequate fuel storage capacity; re-rack is a base case consideration. Re-rack or rack addition was the best solution in the 1980s through the early 2000s to address inadequate pool storage capacity. Until the early 2000s, especially for BWRs, re-rack was the preferred solution for the many plants that needed to perform neutron absorber degradation mitigation.

Considerations and issues, other than cost, associated with re-rack that need to be made as part of the option review process of re-rack includes:

- The fuel storage capacity of the plant to empty at least one rack module so that it can be removed and replaced with a new rack module
- Re-rack modification schedule interface or interference with plant operations, refueling outages and the associated outage preparation such as new fuel receipt
- On-site processing and off site transportation for disposal of the removed racks
- Design of re-rack modules meets the current and anticipated fuel reactivity design and licensing basis

Section 6: Candidate Research and Development Activities

The role of research and development regarding long-term use of BORAL® is to position utility personnel for success in implementing a cost-effective defense-indepth program. R&D should provide the basis for reasonable assurance of continued neutron absorber efficacy for the operational life of the spent fuel storage rack. The activities described in this section will serve to reduce or eliminate operational surprises when performing site-specific surveillance. The results of the R&D activities noted below should further support; or, if necessary, revise the defense-in-depth strategy outlined in Section 5.

Each of the R&D activities noted below address specific aspects of BORAL® performance and may serve to provide confirmatory or new performance information regarding BORAL®. The challenge for the industry is to assess the range of candidate R&D activities and determine which ones can be expected to yield meaningful results, which can be done in a reasonable period of time, and which can be done at an affordable cost.

6.1 Long-Term Accelerated Corrosion Testing

The objective of long-term corrosion testing of BORAL® is to provide data that can assist in predicting the expected long-term performance of BORAL®. The results from this experimental work are expected to provide guidance to utilities as they implement the first two levels of the BORAL® management strategy as part of their defense in depth efforts. The corrosion testing program is envisioned to be carried out over a 5 year period.

This program has been designed to test and evaluate, in an accelerated manner, the effects on BORAL® caused by very long-term exposure to a spent fuel pool environment. The way the tests will achieve the accelerated data is by conducting the tests at elevated temperatures. The targeted time that the accelerated tests will be trying to replicate are those in-service times similar to that which BORAL® would experience during extended operation in the nuclear fuel storage pools considering operating license renewal and decommissioning operations.

A preliminary corrosion test program is described in detail in Appendix A of this report.

6.2 Dose Calculations to Identify Highest Duty BORAL® Panels

As part of the Boraflex degradation management project sponsored by EPRI, NETCO created RACKLIFE to monitor and trend key performance parameters of that neutron absorber material. Similarly, a software tool can be developed to determine the highest duty BORAL® panels based upon fuel assembly location history. This tool can serve to point the user to representative or bounding BORAL® panels to perform in-situ testing as part of the second level of defense as described in Section 5.2.

6.3 Detailed In-Situ Measurement of BORAL® Panels

The operating pools can be reviewed and candidates for the performance of an extensive BADGER test can be identified. The review criteria can include service life, fuel discharge exposure and storage strategy (i.e. discharge core to same location each outage). A representative population of the most severe duty can be the object of an industry sponsored BADGER test program. This examination can serve as a benchmark for in-situ testing and also help determine the quantitative limits of in-situ type examination equipment.

6.4 Destructive Exam of Long Service Life, High Duty BORAL® Panels

It would be beneficial to provide benchmarking data between surveillance coupon data and an actual panel from an in-service rack. This can be performed by finding a host plant to allow opening and removal of an in-service BORAL® panel wrapper plate. This panel can then be subjected to detailed visual and dimension examination and comparison to rack fabrication records as well as the data from surveillance coupons. A vital part of this examination would be destructive coupon cutting from the in-service panel such that these coupons may be subject to neutron transmission testing in a laboratory to measure the areal density of representative sections of the panel. This data may be compared to the Safety Analysis Report minimum required areal density, the areal density of the surveillance coupon and the nominal as-built measured areal density.

6.5 Retrieve Non-NETCO BORAL® Coupon Data

While NETCO has performed the majority of the plant BORAL® surveillance coupon testing for the nuclear industry, there is a small but significant body of data that would supplement and complement the growing EPRI BORAL® performance data base [6]. EPRI participating plants are recommended to review the proprietary information release requirements for this non-NETCO generated data and consider releasing it to be added to the EPRI BORAL® performance database.

6.6 Collect and Evaluate Spent Fuel Pool Water Chemistry

An additional BORAL® performance surveillance method may be the sampling and analysis of spent fuel pool water for the presence of aluminum (as aluminum or aluminum oxide) and boron (as boron or boron carbide). Should utilities opt for spent fuel pool water chemistry monitoring to potentially detect the onset of B₄C loss or redistribution, it is necessary to develop action levels and follow-on actions similar to that guidance that exists in the EPRI water chemistry guidelines. To determine these metrics, or indeed see if these metrics even exist, model baths with different size BORAL® breaches due to simulated open blisters and clad penetrating corrosion pits should be created to determine, in a controlled environment, that degradation products can be detected and in what form and at what concentrations. This can be evaluated by the Neutron Absorber Users Group to determine if a chemistry monitoring program could be effective.

6.7 Evaluate the Effect of BORAL® Cladding Bonding on Blistering

A study on the role of porosity in BORAL® blister formation noted the bonding of the BORAL® cladding to the core material has been found to be significantly variable from production lot to production lot [7]. While the clad bonding variability phenomenon was noted, it was not investigated.

6.8 Develop BORAL® Blister Prediction Methodology

EPRI research has identified porosity as one of the key parameters in the formation, location and size of blisters. It has been speculated that clad bonding may have a role in blister formation. Further research can be performed to identify the key variables in blister formation and develop a methodology for predicting blister formation and growth.

6.9 Develop BORAL® Localized Corrosion Prediction Methodology

EPRI research has identified localized corrosion and the associated pitting as one of the means by which BORAL® may degrade. Review of existing test data and additional research can be performed to identify the principal elements that lead to localized corrosion and pitting and develop a methodology for predicting localized corrosion and pit growth.

6.10 Investigate the Correlation between BORAL® Surveillance Sample Coupons and In-Rack Measurements

In a number of formal and informal meetings, the NRC has speculated regarding the correlation between surveillance sample coupons and in-rack performance. In many cases, the NRC has required utilities seeking plant operating license renewal to perform an in-situ test of in-service neutron absorber panels to

benchmark the two. As data becomes available from plants that have gone through this exercise, a detailed comparison of the surveillance sample coupon results and in-situ measurements can be performed.

Section 7: Summary and Conclusions

7.1 History

The NRC has identified performance concerns regarding a number of boron-containing spent fuel pool neutron absorbers (Boraflex, Carborundum and BORAL®). The operational performance history of these absorbers makes it necessary to fully understand and pay strict attention to neutron absorber materials to ensure their long-term efficacy.

As the likelihood increases for the storage of spent fuel beyond that originally envisioned, increased focus must be given to the long-term performance of the absorber material that is currently in use in our spent fuel storage systems.

Although performance to date has been very good for BORAL®, introduced some 25 years ago, work should be undertaken to identify and understand all possible degradation mechanisms, develop monitoring techniques, identify the variables that effect degradation, and build surveillance databases. This total accumulation of knowledge can then be used to establish a high confidence in the long-term use of BORAL® and identify any possible degradation issues in advance of the actual problem.

7.2 BORAL® Current Performance

Possible BORAL® performance issues can be divided into two main classes: A) Safety (criticality safety) relative to the functionality of the B-10 in the core material; and, B) Operational as characterized by blistering of the BORAL® surface where the aluminum cover material (cladding) separates from the core Boron containing material thus potentially effecting fuel handling.

BORAL® has successfully met all the criticality safety performance requirements for over 25 years of service as demonstrated by the following considerations:

- There have been no surveillance data or observed cases where there has been significant loss or redistribution of B-10 from BORAL®.
- No mechanisms have been identified or observed that would lead to severe degradation of the BORAL® core material.
- No mechanisms has been identified that would lead to a sudden loss or reconfiguration of the BORAL® core material.

One consideration with BORAL® that might have an effect on criticality safety is if there were, after an extremely long service life, a situation developed that caused major corrosion in the BORAL® core material. One possible scenario that might lead to such corrosion is if severe localized pitting corrosion occurred in the BORAL® aluminum cladding. If such pitting were severe enough, the cladding could be penetrated and significant amounts of the inner core containing B-10 may be exposed to the pool environment. This would be a situation not unlike the cut edges of the BORAL® that are routinely exposed to pool water. To date, no significant loss of core B-10 has been observed from these bare edges from exposure to pool water. It should also be noted that the very nature of pitting corrosion in the cladding is such that it is highly unlikely that large surface areas of core material would become exposed to the pool environment.

7.3 BORAL® Management Strategy

A comprehensive "defense in depth" strategy is proposed to insure that no unexpected safety issues arise with the long-term use of BORAL®. Such a strategy recognizes and incorporates features that address the fact that the inservice life of BORAL® is now expected to be 60 years or greater.

The strategy focuses primarily on the B-10 safety related factors with secondary priority given to the operational considerations, such as blistering. In some ways, it is fortuitous that many of the more complicated technical aspects of BORAL® (manufacturing techniques, date of manufacture, porosity, trace chemical impurities, clad to core bonding strength, etc.) are much more related to the phenomena of clad blistering as opposed to the loss or redistribution of B-10 material from the core of the BORAL®.

The overall BORAL® management strategy provides a "defense-in-depth" approach for those plants that have BORAL® in the spent fuel pools to insure that there will always be adequate margins for prevention of criticality. The key factors in this approach are discussed in Section 5 and include:

- Surveillance Programs
- Assays and Measurements
- Mitigation Measures

The strategy also includes an approach by the nuclear industry that brings together the data from the various industry surveillance programs and shares all the BORAL® performance experience between plants. From the analyses of this data, R&D activities are identified that have the potential for providing needed test data, supporting modeling of BORAL® performance, and bringing additional understanding to the possible BORAL® degradation mechanisms. These coordinated industry-wide activities are likely to provide early identification of any unexpected BORAL® performance issues that may occur as

a result of the very long service life now planned for BORAL®. A discussion of possible R&D activities that have already been identified is provided in Section 6 of this report with the highest current priority being placed on the accelerated corrosion testing of BORAL®.

In the previous sections of this report, the changes that BORAL® experiences in its service environment have been reviewed. These changes relate primarily to the slow and gradual conversion of the base material aluminum to the oxide. It has been determined that when this conversion occurs, the boron carbide particles remain tightly bound in the resulting oxide layer resulting in absolutely no loss of boron carbide. These observations lead to the following conclusions:

- The changes which BORAL® undergoes in its service environment are gradual, occurring over long periods of time.
- These changes involve the gradual conversion of aluminum to the oxide and result in no loss or redistribution of boron carbide.

Based on these conclusions a defense in depth strategy for BORAL® surveillance and monitoring has been crafted to detect any unexpected changes in the material that could influence the in-service performance of this material and its functions. It is believed that these surveillance measures are more than adequate to detect the onset of material changes that could influence the in-service integrity of BORAL® before such changes become an issue.

Section 8: References

- 1. Handbook of Neutron Absorber Materials for Spent Nuclear Fuel Transportation and Storage Applications, 2009 Edition. EPRI, Palo Alto, CA: 2009. 1019110.
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- 4. Davis, J.R. (Editor), "Corrosion of Aluminum and Aluminum Alloys, ASM International, Materials Park, OH, August 1999, 27.
- 5. Boraflex Working Group Workshop No 18, Presentation Material, Washington, DC, May 2, 3, 2002.
- 6. Overview of BORALTM Performance Based Upon Surveillance Coupon Measurements. EPRI, Palo Alto, CA: 2010. 1021052.
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Appendix A: Project Plan—Long-Term
Accelerated Corrosion Test
Program for BORAL®
Aluminum Carbide Cermet

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1.0 Objectives

BORAL® is an aluminum metal matrix cermet that contains boron carbide which has been used extensively for fuel storage racks and dry storage baskets. A cermet is produced from an ingot that consists of an aluminum container filled with a homogenous mixture of boron carbide powder and atomized aluminum powder. When the ingot is heated and subsequently hot rolled to plate form, the aluminum particles sinter at the rolling temperature and under the pressure caused by the rolling process. However, the sintering process is not complete in that the core of the final product contains some porosity.

BORAL® was formerly produced by Brooks and Perkins, Inc. Brooks and Perkins had developed the manufacturing process for BORAL® and held several patents on specific elements of the process that have since expired. Brooks and Perkins was acquired by AAR Manufacturing and for an interim period was known as AAR Brooks and Perkins. Subsequently, it was known as AAR Advanced Structures, AAR Cargo Systems and finally as AAR Manufacturing.

In July 2006, the BORAL® product and certain manufacturing equipment were acquired from AAR by Ceradyne.

The objective of long-term corrosion testing of BORAL® is to estimate the in-service performance of BORAL® as part of a defense in depth effort in aging management of a key material component of a nuclear power plant spent fuel storage system.

This program has been designed to test and evaluate, in an accelerated manner, the effects on BORAL® caused by very long-term exposure to a spent fuel pool environment. These are conditions similar to that which BORAL® would experience during extended operation design service life in the nuclear fuel storage pools considering operating license renewal and decommissioning operations.

In the context of this project plan the following terms should be defined:

- 1. "Core" in reference to BORAL®, is the aluminum and B_4C mixture in the middle of the BORAL® composite plate. See Figure 1-1.
- 2. "Clad" in reference to BORAL®, is the outer 1100 series aluminum layer of the BORAL® composite plate. See Figure 1-1.
- 3. "Encapsulation" in reference to BORAL®, is the capture of the BORAL® composite plate within a stainless steel enclosure such as a spent fuel pool plate wrapper or coupon holder/capsule.

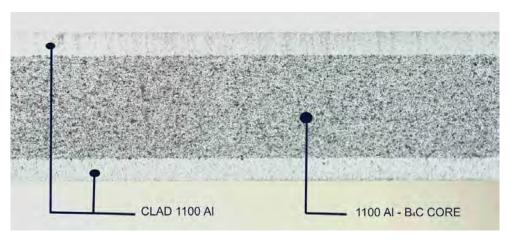


Figure 1-1
Definition of Core and Clad – Edge View of BORAL® Sheet [3]

2.0 Project Overview

As prime contractor, NETCO will provide project management and perform test services. All BORAL® coupon measurements and environmental testing will be conducted at NETCO's laboratory in Lake Katrine, NY. Pre-test and post-test characterization of B-10 areal density of the coupons will be performed at NETCO's Penn State laboratory. The Neutron Beam Laboratory at the Penn State Breazeale Nuclear Reactor will be used for neutron attenuation testing and B-10 areal density characterization. Neutron attenuation testing will be conducted by NETCO personnel. The Breazeale reactor staff will operate the TRIGA Test Reactor. Test data will be evaluated and the results documented by NETCO personnel at the company's Lake Katrine, NY offices.

Under the long-term corrosion performance program, material coupons will be gathered from participating utilities and purchased from Ceradyne and tested. A total of 180 BORAL® coupons of rectangular shape and 10 utility supplied BORAL® coupons will be subjected to two test environments, designed to simulate spent fuel storage conditions, namely, BWR and PWR spent fuel pools. Within the test categories, individual coupons will be subjected to pre-test and post-test characterizations. As deemed appropriate, coupon characterizations may include: visual inspection, high resolution photography, scanning electron microscopy, neutron attenuation as well as measurement of: thickness, dry weight and density.

Under this program, NETCO would demonstrate, on a five-year schedule, projected long-term performance of BORAL® under wet nuclear storage service conditions. The two test environments above correspond to storage conditions as shown in Table 2-1, below. The table also relates the test environment to the simulated storage condition.

Table 2-1
Storage Condition/Test Category/Test Environment

Storage Condition	Test Category	Test Environment
BWR Spent Fuel Pool	Accelerated Corrosion	195°F for five years* in demineralized water
PWR Spent Fuel Pool	Accelerated Corrosion	195°F for five years* in boric acid solution

^{*} This corresponds to approximately 90 years of in plant service performance.

3.0 Special Engineering Procedures

Documented Special Engineering Procedures (SEPs) serve to specify and control each test procedure as well as coupon inspection, measurement and data handling procedures. Procedures fall into three categories: test procedures, coupon characterization procedures and data handling procedures.

	Test Procedures
SEP-300013-01	Procedure for Long-Term Corrosion Testing of BORAL® Coupons
	Coupon Characterization Procedures
SEP-300013-02	Procedure for Pre-Test Characterization of Long-Term Test of BORAL® Coupons
SEP-300013-03	Procedure for Post-Test Characterization of Long-Term Test of BORAL® Coupons
	Data Handling Procedures
SEP-205-09	Procedure for Recording, Storage, Retrieval and Evaluation of Coupon Qualification Test Data

SEP-300013-01 through SEP-300013-03 are NETCO proprietary documents, and as such MAY NOT BE COPIED FOR EXTERNAL DISTRIBUTION. The SEPs will be made available for on-site review for purposes of participant utility or EPRI audit and/or source surveillance.

It is important to note that as appropriate, the SEPs incorporate pertinent industry standards. These include the following ASTM standards:

ASTM G 1 Standard Practice for Preparing, Cleaning and

Evaluating Corrosion Test Specimens.

ASTM G 31 Standard Practice for Laboratory Immersion

Corrosion Testing of Materials.

Specific instances of standard application are described in the SEPs.

4.0 Scope of Testing

The BORAL® Qualification Program includes 180 BORAL® production coupons and 10 utility archive samples of rectangular shape.

To simulate service conditions and to accommodate test requirements two distinct types of BORAL® coupon test configurations have been prepared. Configurations and the test environment to which each configuration is to be subjected are outlined in Table 4-1. As part of pre-test characterization, the surface of each coupon will be indelibly inscribed with a unique alphanumeric identification number, such that the identification will be preserved during testing. The identification number will be recorded in the coupon record. The record will become integral to the project database and will be used to establish correspondence and traceability between coupon type, test configuration, test performed and results obtained.

Un-encapsulated rectangular coupons will provide a baseline performance indication. Special purpose encapsulated rectangular coupons will be fashioned to simulate corrosion and flow stagnation conditions, namely galvanic and encapsulation. Note that all of the utility supplied coupons will be encapsulated. The encapsulated coupons will be used to simulate BORAL® contact with stainless steel. Further, the encapsulated coupons will simulate stagnation and reduced flow conditions of wet storage within the rack stainless wrapper plate.

Ceradyne will provide AAR BORAL® production material that it has stored since its acquisition of the AAR BORAL® intellectual property.

Ceradyne will provide BORAL® material produced with oil which corresponds to the AAR method used to control powdered aluminum combustion/detonation during the mixing of the BORAL® core material that is in service in most US spent fuel pools. Ceradyne will also provide the non-oil production BORAL® as part of the project. This should demonstrate the role of the production oil in corrosion (general & pitting) and blistering.

Table 4-1 BORAL® Coupon Type/Test Matrix

Coupon Type/Test	1 year	2 year	3 year	4 year	5 year
BWR/PWR					
Un-encapsulated AAR	V	V	√	V	√
Un-encapsulated Ceradyne – AAR process	V	V	√	V	V
Un-encapsulated Ceradyne – Ceradyne process	\checkmark	V	V	V	V
Encapsulated AAR	\checkmark	\checkmark	√	V	√
Encapsulated Ceradyne - AAR process	V	V	V	V	V
Encapsulated Ceradyne – Ceradyne process	V	V	V	V	V
Encapsulated Utility Archives					√*

^{*} Utility Archive samples are those provided by EPRI utility members and encapsulated in stainless steel

5.0 Project Plan: Long-Term Corrosion Tests

5.1 General

The long-term corrosion test program has been designed to determine the susceptibility of BORAL® to general (uniform) and localized (pitting) corrosion in PWR and BWR spent fuel pools. Two sets of coupons will be corrosion tested; one set in deionized water, simulating BWR pool conditions and one set in deionized water containing 2500 ppm boron as boric acid, simulating PWR pool conditions. Both test sets will be run at 195°F (90.5°C) to accelerate any corrosion effects for approximately 5 years (60 months). The corrosion is accelerated by conducting the tests at elevated temperatures relative to typical temperature in the plant service environment. Typically, spent fuel pools are operated in the temperature range of 80°F to 100°F (27°C to 38°C) with short-term excursions to 130°F (54°C) during refueling outages.

The test condition for accelerated corrosion test has been selected at 195° F which represents a temperature much more severe than normal pool conditions $(80^{\circ} - 100^{\circ} \text{ F})$ yet a temperature for testing when water evaporation rates in the test chambers are not so great or require continual make up of evaporated water.

It is generally accepted that corrosion rates follow an Arrhenius equation of the form:

$$\lambda = Ce^{-Q/RT}$$

where λ = reaction rate, C is a pre-exponential constant and Q is the activation energy for the reaction, R is the ideal gas constant, and T is the absolute temperature. In the following discussion, the above equation is used to determine corrosion rates at projected in-service conditions (80° – 100° F).

The activation energy of the reaction is critical to determining the Arrhenius reaction rate. While many factors can influence the exact activation energy for a given environment, an estimate can be made by considering the corrosion test results for aluminum alloy AA-1200 in very hot water. Godard [1, 2], et al. provides the following data:

$$\lambda_1 = \text{Ce}^{-Q/RT}_{1} = \text{SJ} \left[\frac{0.1 \, inch}{year} \right] \frac{sec}{meter} \ @ 323.15 \text{K}$$
 $\lambda_2 = \text{Ce}^{-Q/RT}_{2} = \text{SJ} \left[\frac{1.3 \, inch}{year} \right] \frac{sec}{meter} \ @ 473.15 \text{K}$
1 yr @ 195°F \Rightarrow 18.8 gr @ 80°F.

Therefore, a 5-year corrosion test at 195°F is equivalent to 94 years at more typical pool temperatures (80°F).

The test will be conducted in accordance with SEP-300013-01, Procedure for Long-Term Corrosion Testing of BORAL® Coupons. The coupons will be precharacterized in accordance with SEP-300013-02, "Procedure for Pre-Test Characterization of Long-Term Test BORAL® Coupons." Post-test

characterization for accelerated corrosion will be performed in accordance with SEP-300013-03, "Procedure for Post-Test Characterization of Long-Term Test of BORAL® Coupons."

5.2 Test Matrix and Coupon Description

The test matrix for the long-term corrosion test is shown in Table 5-1. A total of 180 Ceradyne BORAL* rectangular coupons will be tested; 90 in deionized water and 90 in water containing 2500 ppm boron as boric acid.

(Note: Dimensions of the rectangular shape coupons to be subjected to corrosion testing are 2 in. x 4 in.) 10 utility provided archive coupons will be tested as noted in Table 5-1.

Table 5-1
Coupon Test Matrix for Accelerated Corrosion Testing

Coupon Type	Deionized Water	Boric Acid Solution
Un-encapsulated AAR	15	15
Un-encapsulated Ceradyne – AAR process	15	15
Un-encapsulated - Ceradyne process	15	15
Encapsulated AAR	15	15
Encapsulated Ceradyne – AAR process	15	15
Encapsulated Ceradyne – Ceradyne process	15	15
Encapsulated Utility Archive	10*	10*

^{*} Utility supplied BORAL® coupons.

Un-encapsulated Coupons

The purpose of these coupons is to determine the rate at which a uniform oxide film forms. The rate of oxide build-up will be determined by changes in the coupon weight and thickness. The coupons will be subject to precision weighing prior to testing and precision weighing after drying upon removal from the test bath.

Encapsulated Coupons

Rectangular coupons encapsulated in stainless steel capsules have been included to simulate the semi-stagnant conditions around the neutron absorber which would prevail in fuel racks. The capsules are formed from three pieces of stainless steel as shown in Figure 5-1. The capsules are basically two flat plates of stainless steel which form a sandwich with a third "picture frame" configured stainless steel piece. The three pieces are held together by four stainless steel machine

screws and nuts. The coupon resides in the volume created inside the picture frame. The inlet and outlet slots are sized to simulate the fluid exchange rate (between inner volume around the coupons and bulk pool volume) as expected in a spent fuel rack condition. For this test a minimum exchange rate of ~0.1 volumes per day was conservatively selected.

The coupon encapsulation in 304L stainless steel will also act as a bimetallic couple. Inspection of the encapsulated coupons will be via optical microscopy.

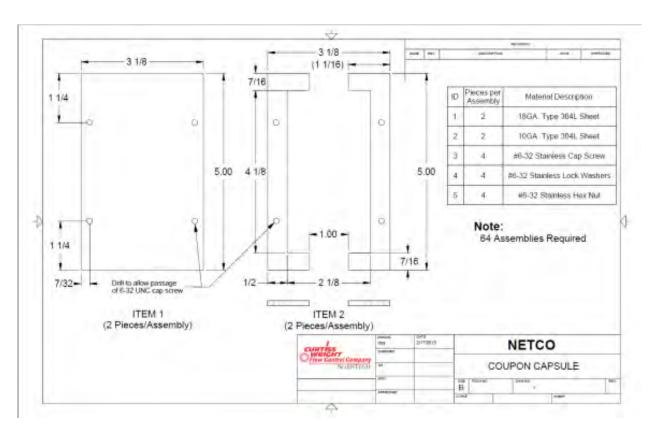


Figure 5-1 Coupon Capsules (used with permission)

5.3 Schedule for Long-Term Corrosion Testing

The long-term corrosion testing will be conducted at 195°F. The elevated temperature test environment is expected to accelerate corrosion effects relative to typical spent fuel pool conditions (80°F to 100°F). Corrosion effects are generally governed by an Arrhenius function of temperature.

Initially, all five test batches will be placed in the corrosion test environment (1-year, 2-year, 3-year, 4-year and 5-year test batches). The test plan includes the pre- and post-test characterization of all coupons included in each of the annual test batches. The results of this characterization are to be presented as a progress report as part of the EPRI NAUG annual meeting. The testing and evaluation of all five test batches will be formally reported in an EPRI report after the completion of post-test characterization of the final batch of test coupons at the end of five years.

5.4 Inspection and Tests

Table 5-2 contains the un-encapsulated and encapsulated coupon tests and inspections to be conducted for pre-test characterization and post-test characterization.

5.5 Control of Test Conditions

The demineralized water used for preparation of the corrosion test environment will be prepared in the laboratory using mixed bed resins similar to those used at spent fuel pools. The water will be chemically tested for chloride, pH and conductivity. The boric acid solutions will be prepared using this demineralized water and reagent grade boric acid. Periodically, and at a frequency to be determined by the NETCO Project Manager, samples from both water volumes will be taken and analyzed for chloride (BWR only), boron (PWR test only), pH and conductivity. The frequency for water sampling will be determined by initial measurement results and the range of variability encountered.

The constant temperature baths will be maintained at $195^{\circ}F$ ($90.5^{\circ}C$). Circulators (performance specification \pm 0.2°F) are provided to maintain uniformity of water temperature. Bath temperatures will be monitored with a thermometer with 1°C resolution and \pm 1°C accuracy and/or thermocouples. The corrosion baths will be fitted with gabled stainless covers to minimize evaporation. Makeup for evaporative losses will be made with deionized water. Records of the date, time and volume of makeup water added will be maintained. Water chemistry will be routinely monitored and necessary chemical makeup performed.

Test	Pre-Test Characteriza- tion	Post-Test Characteriza- tion		
Visual Inspection	•	•		
High Resolution Photography	•	•		
Dimensions	•	~		
Dry Weight	•	•		
Neutron Attenuation	•	•		
Surface characterization via Metallography for:				
Oxide Film	•	•		
Pit Size and Depth	•	•		

Table 5-2 Scope of Tests for Long-Term Accelerated Corrosion Testing (Un-encapsulated Coupons and Encapsulated Coupons)

6.0 Data Recording, Storage, Retrieval and Evaluation

Data recording, storage, retrieval and evaluation will be facilitated through the use of Microsoft ACCESS. This widely used commercially available software is ideally suited to efficiently and reliably support most phases of data handling for the BORAL® long-term accelerated corrosion performance project.

A relational database (e.g. BORAL.mdb) will be developed to meet the specified data handling requirements of the BORAL® long-term accelerated corrosion performance project. The use and structure of the various ACCESS database objects (i.e. tables, queries, forms and reports) within BORAL.mdb are set forth in SEP-205-09, Procedure for Recording, Storage, Retrieval and Evaluation of Coupon Qualification Test Data. The database is structured to maintain relational correspondence between coupon ID, test type and test results.

A coupon registry table will be incorporated into BORAL.mdb. Within the registry each coupon will be identified using a set of four alphanumeric characters, classified according to type and assigned to pre-specified testing. The coupon alphanumeric identification will function as an ACCESS key parameter and will be used to link coupon registry with the coupon test results.

At the time of measurement, laboratory data will be transferred directly to the BORAL.mdb database. Data transfer will be facilitated through the use of test specific ACCESS data entry forms, formatted to accept the particular data being

measured. For example, the automatic data entry form, which will be used to record pre-test caliper determined dimensional measurements for rectangular coupons and to transfer the data directly to BORAL.mdb is shown in Figure 6-1 below. Detailed procedures to gather and verify test data for the various coupon tests and coupon types are described in SEP-205-09.

SEP-205-09 requires that data be recorded both electronically and on hard copy. Hard copy data for each coupon will be developed from laboratory measured data using specifically formatted ACCESS report forms. Printed copies will be retained as backup. Additionally, electronic data will be stored on a local (at the laboratory) computer hard drive and will be transmitted electronically to NETCO's headquarters in Lake Katrine, NY after each test session. Further, at the completion of each measurement session, the Curtiss-Wright intranet will backup all files. All stored data will be password protected and available as read-only.

Selected data objects in the BORAL.mdb database will be exported to Microsoft EXCEL for statistical analyses and/or the generation of graphical displays.

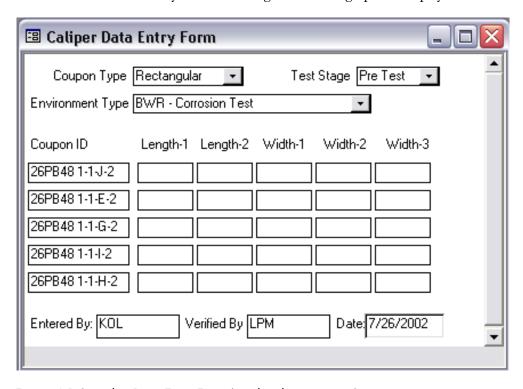


Figure 6-1 Sample - Data Entry Form (used with permission)

7.0 Project Schedule and Reporting

The project test coupon fabrication, capsule fabrication, pre-characterization and test bath preparation may begin within 90 days of project authorization by EPRI. The results of the test program are to be presented as a progress report as part of

the EPRI NAUG annual meeting. The testing and evaluation of all five test batches will be formally reported in an EPRI report after the completion of post-test characterization of the final batch of test coupons at the end of five years.

8.0 Quality Assurance

8.1 General

As is required for all safety related nuclear applications, relevant criteria of the Nuclear Regulatory Commission (NRC) 10CFR50 Appendix B – Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants – will be applied throughout the BORAL® long-term corrosion test program. Table 8-1 shows the NRC quality assurance requirements which will be applied to the BORAL® long-term corrosion test program and relates these requirements to corresponding sections of the NETCO quality assurance handbook.

Table 8-1
Relation of 10CFR50 Appendix B Requirements to NETCO
QA Handbook

Quality Assurance Topic	10CFR50 Appendix B Section	NETCO QA Handbook Section
Procurement Document Control	IV	QAD-H-2.6
Instructions, Procedures and Drawings	V	QAD-H-2.7
Document Control	VI	QAD-H-2.8
Control of Purchased Material, Equipment and Services	VII	QAD-H-2.9
Identification and Control of Material, Parts and Components	VIII	QAD-H-2.11
Inspection	Х	QAD-H-2.12
Test Control	XI	QAD-H-2.13
Control of Measuring and Test Equipment	XII	QAD-H-2.14
Handling, Storage and Shipping	XIII	QAD-H-2.15
Inspection, Test and Operating Status	XIV	QAD-H-2.16
Non-conforming Materials, Parts and Components	XV	QAD-H-2.17
Corrective Action	XVI	QAD-H-2.18
Quality Assurance Records	XVII	QAD-H-2.19
Audits	XVIII	QAD-H-2.20

8.2 BORAL® Long-Term Corrosion Test Program

Planned and systematic actions will be undertaken to assure that the BORAL® long-term corrosion test program proceeds in accordance with sound engineering practices and in conformance with all specified requirements are described below. The NETCO QA Manager is responsible to plan and oversee implementation of the QA program. The QA Manager reports directly to the NETCO Director, is independent of production pressure and has sufficient authority to execute applicable provisions of the NETCO QA Handbook throughout all phases of this project. It should be noted that quality control will be applied by NETCO personnel to the implementation of the qualification program and not to the manufacturing of BORAL® coupons provided by Ceradyne or utilities. The NETCO QA program also conforms to 10CFR21 notification requirements.

Procurement Document Control

As appropriate equipment and service procurement documents will be subject to formal review and sign-off by the Project Manager. As specified by QAD-H-2.6, it will be assured that all appropriate project and regulatory requirements are reflected in procurement documents.

Instructions, Procedures and Drawings

The test programs will be conducted as described in Sections 5.0, 6.0 and 7.0 of this Appendix. All pre-test characterization and post-test characterization of coupons as well as testing will be conducted per the series of Special Engineering Procedures (SEPs) described in Section 3.0 above. All procedures will be prepared in accordance with QAD-H-2.13 and QAD-H-2.7. Members of the project team are responsible to implement procedures in conformance with approved SEPs.

Document Control

All important documents associated with this project will be reviewed, approved, reproduced and distributed consistent with QAD-H-2.8. The NETCO directive further requires that document revisions or changes be subject to the same treatment and further, that only the latest revisions are utilized at the point of actual document referral. The NETCO Director and the QA Manager are to assure that all work is performed consistent with contract requirements.

Control of Purchased Material, Equipment and Services

Purchase of calibration for gage blocks, standard masses, load cells, etc. will be in compliance with the requirements of QAD-H-2.9. NETCO shall audit suppliers' quality programs to ensure compliance with the applicable requirements of 10CFR50 Appendix B. All calibrations shall be NIST traceable with accompanying certification to verify traceability. Vendor qualification will be performed consistent with NETCO procedure.

Identification and Control of Materials, Parts and Components

Consistent with QAD-H-2.11, all BORAL® coupons are to be inscribed with a unique alphanumeric identification. Unique identification will provide traceability of test results and help to preclude or to detect possible: data attribution to unintended coupon, the performance of improper coupon testing or incomplete coupon characterization. A coupon registry incorporated into the project database will function to control correspondence between coupon identification number, test sequences and test results.

Inspection

As per QAD-H-2.12, all work will be inspected in process to assure conformance with Special Engineering Procedures (SEPs) described in Section 3.0 above. Hold points will be imposed if requirements are not met. Work will not resume until all requirements are satisfied and verified by reinspection.

Test Control

Consistent with QAD-H-2.13, Special Engineering Procedures (SEPs) described in Section 3.0 above provide documented step by step test instructions including test prerequisites and test acceptance criteria.

Control of Measuring and Test Equipment

All measuring equipment used for this project is to be serialized, calibrated, controlled and documented. This applies to NETCO test instruments, such as gage blocks, weights and thermometers. QAD-H-2.14 sets the requirements to assure proper unexpired calibration of all equipment.

Handling, Storage and Shipping

The handling, storage and shipping of BORAL® coupons will be under the direct supervision and surveillance of NETCO personnel per QAD-H-2.15.

When not being subjected to evaluation, inspection or testing, the BORAL® coupons will be stored with access strictly controlled by the NETCO Project Manager. At the completion of testing, all BORAL® coupons will be retained and stored by NETCO for possible future reference.

Inspection, Test and Operating Status

Special Engineering Procedures (SEPs) described in Section 3.0 above require that a clear and accurate record be established and used to designate the test status of each coupon. QAD-H-2.16 provides means for additional assurance to confirm coupon test status and to preclude inadvertent test by-pass and the possible misuse of pre-test data.

Non-conforming Material, Parts and Components

QAD-H-2.17 requires that non-conforming items be clearly marked and segregated and prevented from inadvertent use. The non-conformity will be documented as will be the approved disposition (e.g. re-test, discard, accept with qualification, etc.) of the affected item.

Corrective Action

QAD-H-2.18 requires that all non-conformities be identified and corrected. Corrective actions are to be documented so that implementation may be proven. If in the judgment of the QA Manager, a non-conformity is determined to be significant or recurring, then the root cause must be determined to preclude recurrence and a report must be made to the NETCO Director as to cause and effectiveness of corrective actions.

Quality Assurance Records

QAD-H-2.19 requires that the Project Manager see to the identification, indexing and retention of all project related QA records. NETCO will retain all NETCO generated BORAL® long-term test QA records for a period of five years. The records will include the results of reviews, inspection, tests, audits, material analysis and monitoring of work performance. Records will also include qualification of procedures and equipment. Quality assurance records will be complete, legible and traceable.

Audits

All phases of the quality assurance program of the BORAL® long-term corrosion test program shall be subject to audit. Audits are to be conducted by the NETCO QA Manager, consistent with requirements of QAD-H-2.20. All open audit items are to be closed prior to completion of this project.

9.0 References

- 1. Godard, Jepson, Bothwell and Kane, The Corrosion of Light Metals, John Wiley and Sons, Inc., NY 1967; Pg. 124.
- 2. Godard, Jepson, Bothwell and Kane, The Corrosion of Light Metals, John Wiley and Sons, Inc., NY 1967; Pg. 15.
- 3. Handbook of Neutron Absorber Materials for Spent Nuclear Fuel Transportation and Storage Applications, 2009 Edition. EPRI, Palo Alto, CA: 2009. 1019110.

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