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Accelerated Corrosion Tests to Evaluate the Long-Term Performance of BORAL® in Spent Fuel Pools

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ABSTRACT

Fixed neutron absorber materials are used to increase storage capacity in spent fuel pools (SFPs) while maintaining criticality safety margins. BORAL® is a commonly used neutron absorber material for both wet and dry storage (SFPs and casks, respectively). In the United States, about 50% of the plants use BORAL® as neutron absorber material in SFPs [1]. BORAL® is also used in nuclear plants in Mexico, South Korea, Taiwan, and other countries [1, 2].

EPRI's accelerated corrosion test project started in 2013 as a five-year project. For this project, different vintages of BORAL® were placed in test baths representing PWR and BWR water chemistry and test were conducted at elevated temperatures. Furthermore, to evaluate the corrosion under worst conditions, the protective cladding material was intentionally removed for some of the coupons. Every year, a number of coupons had been removed and analyzed to determine long term performance. The areal density results from each year showed no indication of degradation, more clearly, statistically significant absorber loss. In this paper, an overview of EPRI's accelerated corrosion test project and results from the Year 1 to Year 5 of the test results will be presented.

INTRODUCTION

BORAL® is a neutron absorber material commonly used in spent fuel pools (SFPs) to increase storage space while maintaining criticality safety margins.

BORAL® is a metal matrix composite containing a mixture of boron carbide (B_4C) and Al-1100 [1]. The aluminum (Al) cladding, which is on both sides of the core, serves as a protective barrier, as shown in Figure 1. Al cladding is susceptible to corrosion, which can lead to blisters between the core material and the cladding over time [1]. Based on operational experience to date, in addition to blisters, pits also have been observed.

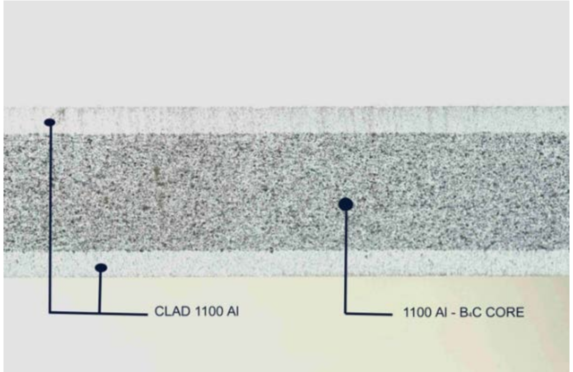

Figure 1. Microphotograph of BORAL®

The operational experience to date, based on significant number of coupons from numerous SFPs worldwide, showed no loss of efficacy for BORAL® [2]. However, given the plant and SFP lifetime is increasing, EPRI initiated several rojects to evaluate the long-term performance of neutron absorber materials and monitoring approaches. The focus of this paper is the five-year accelerated corrosion test project that started in 2013. The objectives of this project include the following:

- Evaluate BORAL® in-pool performance for extended service life
- Determine the long-term corrosion rate of BORAL®
- Determine the change in the corrosion rate for different types of BORAL®

The goal was to evaluate and determine if there is any gross degradation that could cause potential concern for criticality safety of the SFPs in the long term, beyond 60 years. For this purpose, over 200 coupons representing different vintages and encapsulation conditions were placed in the test baths at elevated temperatures to simulate corrosion effects representing more than 60 years of operation. In this paper, the description of the test and results from the accelerated corrosion test coupons are presented.

DESCRIPTION OF THE ACCELERATED CORROSION TESTS

Over time, there have been changes in the BORAL® manufacturing process and subsequently, this led to the availability and use of different vintages of BORAL® for storage. As part of this project, different vintages of BORAL® coupons, with multiple coupons for each type, were collected. These coupons were placed in test baths simulating pressurized water reactor (PWR) and boiling water reactor (BWR) water chemistry. The normal operating temperature for spent fuel pools ranges from 27°C to 38°C (80°F to 100°F). The tests are conducted at an elevated temperature of 91°C (196°F) to accelerate the corrosion and determine long-term performance, beyond 60 years.

A unique identification number for each coupon was etched on the corner of coupons. To understand and evaluate the differences in behavior, bare coupons with no stainless steel (SS) jacket and SS encapsulated coupons were placed in test baths. Around 100 coupons were placed in each test bath. Prior to placement into the PWR and BWR test baths, each coupon was characterized in detail so they can be compared against the results after residing in the test bath. The bare and encapsulated coupons in one of the test baths are shown in Figure 2.

Figure 2. Bare (front) and SS encapsulated (back) BORAL® coupons in a test bath.

Although it is not clearly visible in the picture, for a few coupons the Al cladding was removed (hereafter referred to as clad-removed) to determine the behavior for the worst-case scenario since the boron carbide core material is directly exposed to water chemistry at elevated temperatures.

The coupon analyses included visual inspection, high-resolution photography, measurement of dimensions and weight of coupons, and most importantly areal density measurements. At the end of each year, coupons representing different vintages were removed from both test baths and analyzed. In addition to the pre-insertion characterization, if available, blister and pit analyses were performed after removal from the test bath. The remaining coupons were left untouched and carry forward to the next year of the study. It should be noted that the Al clad-removed coupons were reinserted into the test baths for future analyses. The pre-test and post-test characterization parameters are summarized in Figure 3.

Test	Pre-Test Characterization	Post-Test Characterization
Visual Inspection	√	√
High Resolution Photography	√	√
Dimensions	√	√
Dry Weight	√	√
Density	√	√
Neutron Attenuation	√	√
Surface Characterization via Metallography for:		
Blister Characterization		√ *
Oxide Film		√ *
Pit Size and Depth		√ *

Figure 3. The summary of characterization parameters for the coupons

Areal density for each coupon was measured at the Penn State Breazeale Nuclear Reactor prior to placement into the test baths and after removal for comparison purposes. The water chemistry was monitored at regular intervals and maintained according to EPRI water chemistry guidelines for PWR and BWR SFPs. As part of the water chemistry, the pH, conductivity, sulfate, chloride, fluoride, aluminum levels for both PWR and BWR test baths, and boron levels (for PWR bath) were measured and maintained according to guidelines. However, during Year 1, due to issues with the water purification system, the sulfate levels for PWR test bath were significantly higher than the recommended levels. EPRI water chemistry guidelines recommend keeping sulfate levels below150 ppb; however, during the first year, sulfate levels for PWR test baths were up to 1500 ppb. The issue was addressed and starting from year 2, sulfate levels returned to recommended levels.

RESULTS

In this paper, the areal density results are primarily presented, as they are the most important parameter for performing the intended safety function as a neutron absorber material in SFPs. The previous year's results (Years 1-4) from the accelerated corrosion coupon results were also presented in References [3-5].

Areal Density Values for Bare and Encapsulated Coupons

The areal density values as characterized prior to placement in the test baths and after immersion in test baths for Year 1 (left) and Year 2 (right) coupons are presented in Figure 4. The areal density values as characterized prior to placement in the test baths and after immersion in test baths for Year 3 (left) and Year 4 (right) coupons are shown in Figure 5. Finally, the areal density values for Year 5 coupons are presented in Figure 6. In these figures, the coupons are ordered according to coupon identification numbers. In these figures, error bars show 3σ values.

The key for coupon labeling is:

- P (PWR); B (BWR)
- E (Encapsulated in SS Jacket); G (General, bare with no SS jacket)
- A (manufacturer A); C (manufacturer C); O (manufacturer O)
- The first number indicates the designated year of the coupon analysis
- For each year, three coupons of each types were immersed in test baths to identify if there are variations in degradation within the same type when exposed to the same conditions for the same amount of time. Subsequently, the last number indicates the coupon number within that batch.

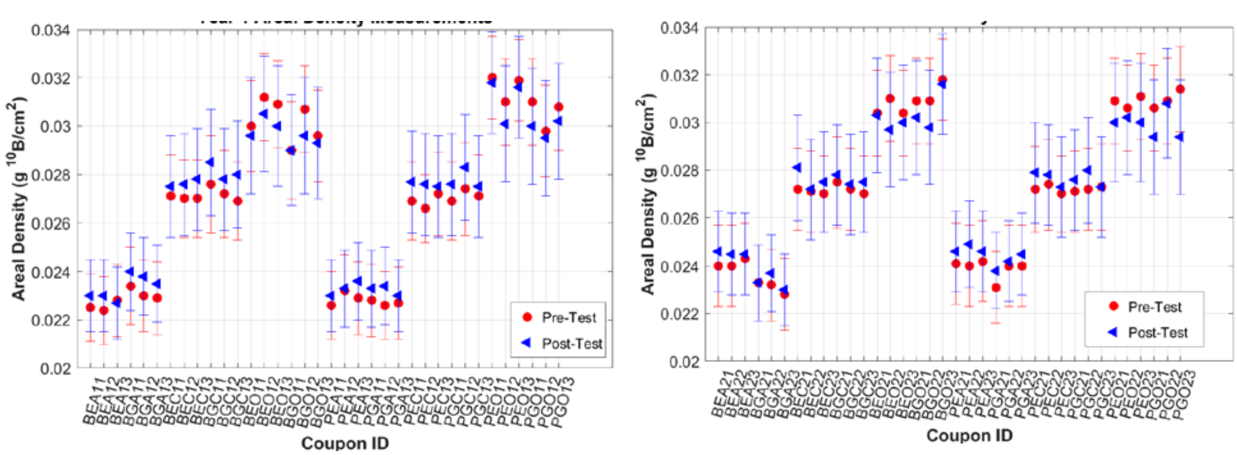

Figure 4. Areal density values ordered according to coupon label for Year 1 (left) Year 2 (right) coupons.

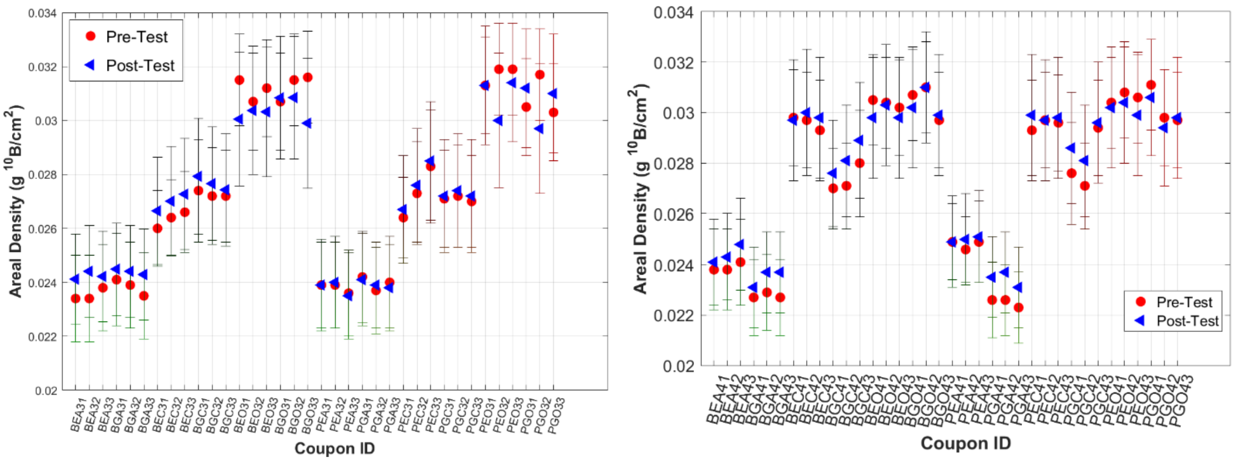

Figure 5. Areal density values ordered according to coupon label for Year 3 (left) Year 4 (right) coupons.

As can be seen from Figures 4-6, there is no statistically significant change in the areal density values for any of the coupons following immersion in test baths at elevated temperatures for Year 1-5. The changes in areal density values are within 3σ values, compared to pre-characterized values. The results are encouraging for demonstrating long-term performance of BORAL®, as areal density is the most important parameter for any neutron absorber in order to perform its intended function and maintain criticality safety margins.

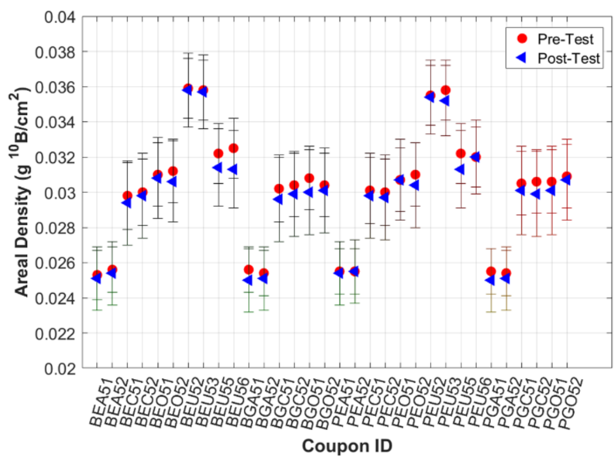

Figure 6. Areal density values ordered according to coupon label for Year 5 coupons.

Areal Density Values for Al Clad-Removed Coupons

For some of the coupons, the Al cladding surrounding the BORAL® was removed mechanically before coupons were placed into the test baths. These coupons represent the worst-case scenario, as they do not have the protective Al clad. Since there were limited number of clad-removed coupons, after the analysis that was performed at the end of year two, these clad-removed coupons were re-inserted to the test baths and reanalyzed at the end of Year 4 and 5. The clad-removed coupon prior to placement in the test bath (left), after immersion in the test bath for five years (middle) is shown in Figure 7.

The areal density values for clad-removed coupons, prior to placement in the test bath and after residing in the test bath for two, four, and five years are shown in Figure 7 (right). As evident from the figure, none of the clad-removed coupons show any statistically significant change in areal density values, even after year five. These are very substantial results, as they demonstrate that even for the worst-case scenario (when Al clad is removed), there is still no loss of BORAL®.

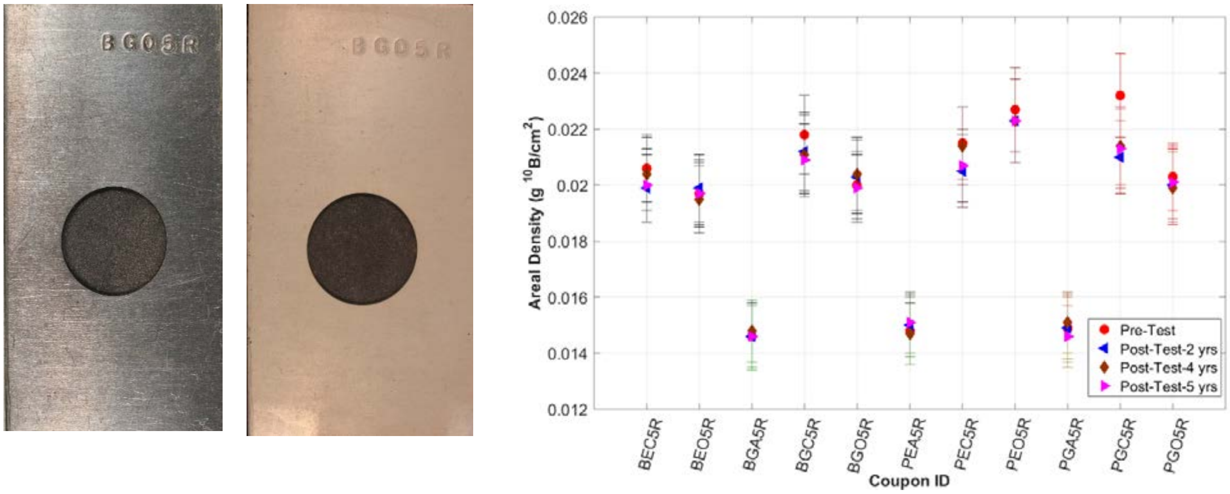

Figure 7. Clad-removed coupon prior to the placement in a test bath (left) and the same coupon after immersion in a test bath for five years (middle). Areal density values for clad-removed coupons after immersion in PWR and BWR test baths after two, four, and five years (right).

SUMMARY AND CONCLUSIONS

In this paper, EPRI's accelerated corrosion tests, aimed toward improved understanding of the long-term performance of BORAL®, are described. The areal density values, which is the most important parameter for maintaining criticality safety margins, from Year 1 to 5 did not show any statistically significant change for any of the years. This is especially important for clad removed coupons as there is no protective layer. It is also important to emphasize that despite the fact that Year 1 sulfate levels were significantly higher than recommended values for PWR coupons, as sulfate is a known corrosion accelerator, there is no significant change in areal density values. The results from accelerated corrosion test indicates that BORAL® will maintain its efficacy for long period of time for maintaining criticality safety margins in SFPs.

REFERENCES

1. Handbook of Neutron Absorber Materials for Spent Nuclear Fuel Transportation and Storage Applications: 2009 Edition. EPRI, Palo Alto, CA: 2009. 1019110.
2. Overview of BORAL® Performance Based Upon Surveillance Coupon Measurements. EPRI, Palo Alto, CA: 2010. 1021052.
3. H. Akkurt, A. Quigley, M. Harris, "Accelerated Corrosion Tests to Evaluate Long-Term Performance of BORAL® in Spent Fuel Pools," Trans. Am. Nuc. Soc., 115, 306-309, (2016).

4. H. Akkurt, A. Quigley, M. Harris, "Update on Accelerated Corrosion Tests for the Evaluation of Long-Term Performance of BORAL® in Spent Fuel Pools," Trans. Am. Nuc. Soc., 117, 319-322, (2017).
5. Akkurt, H., A. Quigley, and M. Harris, "Accelerated Corrosion Tests for the Evaluation of Long-Term Performance of Boral in Spent Fuel Pools," Radwaste Solutions, V 25, No 1, 41-43, Spring 2018.