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MAXUS® Corrosion Performance in Spent Fuel Pool Environments After 3 Years of 5-year Accelerated Corrosion Testing

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Abstract

Many commercial nuclear reactor spent fuel pool storage racks and storage and transportation packages incorporate neutron absorber material to ensure sub-criticality margin. Boron is widely credited in criticality safety analyses as a neutron absorber as it is cost effective with properties that are well documented and accepted by regulatory bodies. Neutron absorbers are usually formed in sheets, and placed within a support structure between fuel assemblies.

One key performance concern regarding metal-based neutron absorbers used in spent fuel pools is uniform and localized corrosion that may have an adverse impact on neutron absorbing isotope areal density.

MAXUS®, a three-layer aluminum-boron carbide neutron absorber metal matrix composite material, is currently qualified for use in spent fuel pool storage to maintain criticality safety vis-à-vis 10CFR50, 10CFR50.68, and 10CFR70.24. The authors identified PWR and BWR spent fuel storage pool corrosion factors facing aluminum-based, boron-10 (^{10}B) neutron absorber material performance. These factors include water temperature, pH and dissimilar materials. Further, the authors identified MAXUS® production methods used to address these factors, such as the use of Al-Mg alloy for the material's clad to not only prevent loss of ^{10}B from the aluminum boron carbide core but also to prevent blistering and peeling through metallurgical bonding of the clad and core by diffusion of Mg into the core during production. Finally, MAXUS® is being tested in simulated PWR and BWR spent fuel pool environments to confirm its corrosion resistance.

Testing of MAXUS® involves a 5-year spent fuel pool accelerated corrosion environment. The elevated temperature of the test baths at the end of 3 years simulates over 50 years of in-service performance at 27°C (80°F). Post-immersion measurements of MAXUS® include: microscopic visual examinations, physical dimension comparison to pre-characterized test samples and neutron attenuation measurements of a variety of MAXUS® ^{10}B areal densities and spent fuel rack structure bi-metallic couplings.

The 1st and 2nd year measurements of ^{10}B areal density were found to unchanged within the measurement uncertainties. This paper shall show that the most recent 3rd year measurements of MAXUS® demonstrate life of plant (including extended decommissioning storage) efficacy as a spent fuel storage rack neutron absorber.

Introduction

One of the MAXUS® application environments is commercial light water reactor fuel storage pools. The test program focused on Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) fuel storage pool operational conditions. Since the late twentieth century, US commercial light water reactors found the need to increase the storage density of fuel in the fuel storage pools. To ensure that the fuel remained subcritical, the high density fuel storage racks required a neutron absorber between each of the adjacent fuel assemblies. Early and subsequent confirmatory tests have demonstrated that radiation has little to no effect on the performance of metal-based neutron absorbers such as MAXUS®. It has been shown through material qualification and in-service testing that corrosion is the key performance concern for aluminum-based neutron absorbers.

MAXUS® Description

MAXUS® is a Metal Matrix Composite (MMC) neutron absorber that is wholly manufactured by Nikkeikin Aluminum Core Technology Co., Ltd. The manufacturing process begins with a 5000-series aluminum ingot which is rolled and pressed into a case shape. Next, atomized A1070 is mixed with a precise measure of boron carbide powder. The aluminum case is then filled with a uniform matrix of aluminum and boron carbide. Afterward, the case is welded to an aluminum frame on four sides. The filled and framed case is heated and rolled into the specified thickness. The sheet is then annealed and levelled. The MAXUS® sheet is trimmed to specified dimensions by water jet cutting. During the water jet cutting, the aluminum frame is cut from the MAXUS® sheet.

MAXUS® consists of a sandwich structure with a highly corrosion-resistant aluminum cladding, and boron carbide powder uniformly distributed within a high-purity aluminum matrix. The cladding is composed of AA 5052. The core is composed of A1070 and boron carbide (B_4C). The boron carbide in the core ranges from 20-40 weight percent depending on the design and operational needs of the neutron absorber application. See figure 1 for an illustration of MAXUS®. The MAXUS® fabrication process assures a uniform distribution of boron carbide in the aluminum core. The process also creates a tightly bound and seamless transition between clad and core (Figure 2).

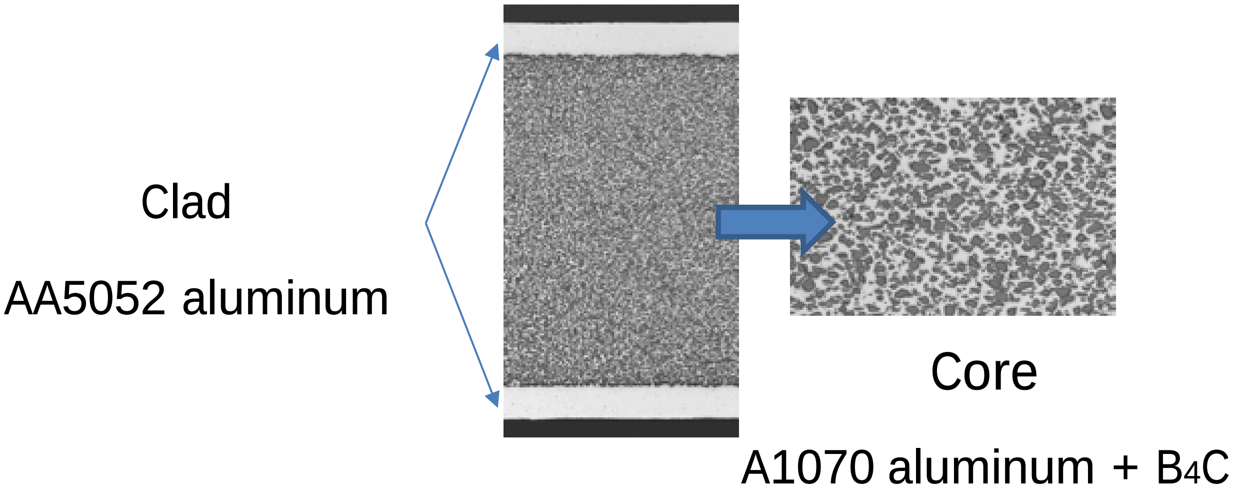

Figure 1 MAXUS® Structure

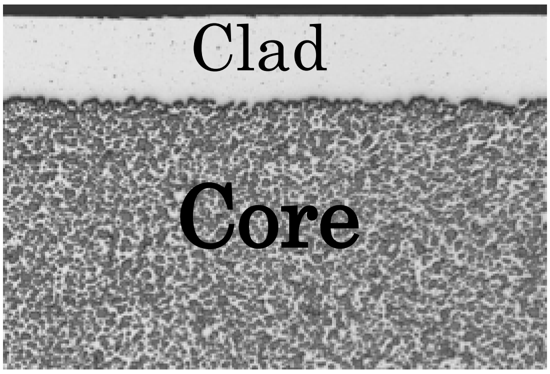

Figure 2 MAXUS® Clad/Core Detail

MAXUS® is formed into sheets that can range from 2 mm to 10 mm in thickness. The MAXUS® sheets can be bent to shape and have demonstrated excellent formability. MAXUS® has been used as a neutron absorber in both wet storage and dry storage/transport systems.

MAXUS® Qualification and Performance Testing

The Curtiss-Wright Nuclear – NETCO MAXUS® qualification report is available as a NRC record (Reference 1). The report documents the results of two-year accelerated corrosion testing and notes satisfactory performance in both BWR and PWR fuel storage pool environments.

Current extended accelerated corrosion program results

The results presented in this paper represent the third year of a five-year program of accelerated corrosion performance testing of MAXUS® in BWR and PWR fuel storage pool environments. Forty-eight (48) MAXUS® coupons were initially placed in test baths that simulate the conditions found in a BWR and PWR fuel storage pool. Two MAXUS® boron carbide concentrations were the subject of the accelerated corrosion test program: 21% and 40%. These boron carbide concentrations represent the upper and lower bounds expected for use in wet storage and dry storage and transport applications of nuclear fuel. Prior to placement in the test baths, the test coupons were pre-characterized so that upon removal after the designated test interval, the as-removed condition could be compared to the pre-characterized state. The pre-characterization included: visual inspection, high resolution photography, coupon dimension, dry weight, density and boron-10 areal density. Once pre-characterized, the two MAXUS® boron carbide concentration types were further divided into general and encapsulated coupons. General coupons are fully exposed to the test water environment. Encapsulated coupons are held in a 304L stainless steel capsule which simulates a fuel storage rack wrapper plate. The coupon used in this test program have dimensions of 5.08 cm (2 inches) by 10.16 cm (4 inches). The 21% boron carbide coupons are 2.03 mm (0.08 inches) thick, while the 40% boron carbide coupons have a thickness of 2.54 mm (0.10 inches). Table 1 represents the distribution of MAXUS® coupons initially placed in the test baths. At the end of each test interval (1/2 year, 1 year, 2 years, 3 years, 4 years, 5 years), one of each of the coupon types noted in Table 1 are removed for each of the test baths.

Table 1 MAXUS® Test Coupons

Coupon Type	Number in BWR Test Bath	Number in PWR Test Bath
21% General	6	6
21% Encapsulated	6	6
40% General	6	6
40% Encapsulated	6	6

Coupon identification

As part of the test protocol, it was necessary to develop a means of identification for the test coupons. The following convention was used to identify the coupons with a four-character code. The first character was either “2” or “4”. This character indicated MAXUS® with either 21% (“2”) or 40% (“4”) boron carbide. The second character was either “B” or “P” to identify the bath within which the coupon was placed. “B” indicated the BWR bath and “P” indicated the PWR bath. The third character was either “G” or “E”. “G” indicated a General coupon and “E” indicated an Encapsulated coupon. The fourth character was a number indicating the year of removal. For the test data reported in this paper, the year 3 coupons all have “3” as their fourth character. For example, “2BG3” was 21% boron carbide MAXUS® placed in the BWR test bath as a General coupon and removed on year 3.

Test environment(s)

The coupon test baths were designed to best represent the conditions within a nuclear power plant fuel storage pool. The test bath monitoring parameters and associated operational limits were established to simulate water storage operating requirements set forth by fuel fabricators for wet storage. These requirements drove the chemistry testing scope of pH, conductivity, fluorides, chlorides, sulfates and boron (PWR only). Both the BWR and PWR baths were filled with demineralized water with the exception that the PWR bath contains 2500ppm +/- 100ppm boron, as boric acid. All pH and conductivity readings were taken at ~20°C. The baths were operated at a nominal 91°C (195°F) to accelerate the corrosion rate.

Year three performance results – Visual exam

All coupons were subjected to a visual inspection upon removal from the test baths. High resolution photographs were taken of all coupons upon removal. None of the coupons exhibited signs of significant general corrosion, but did have evidence of localized corrosion or pitting. The degree of pitting observed was dependent on the coupon test configuration and bath. Encapsulated coupons that were placed in the PWR test bath tended to exhibit greater pitting than the other coupons. Figure 3 illustrates the surface condition of the BWR General coupons. Note that there are stains associated with the coupon holder rack on the bottom corners. Other than that, there is very little change from the pre-characterized state.

Figure 3 MAXUS® 3-Year BWR Bath General Coupons

The BWR Encapsulated coupons have two features that are different from the pre-characterized state. There was iron oxide discoloration at the location of the capsule vents. Also, there was some surface pitting near the capsule vent locations. Figure 4 illustrates the condition of the BWR Encapsulated coupons.

Figure 4 MAXUS® 3-Year BWR Bath Encapsulated Coupons

The PWR General coupons are very similar visually to that of the BWR General coupons. There are stains associated with the coupon holder rack on the bottom corners and light staining visible on the surface of 4PG3. Figure 5 illustrates the condition of the PWR General Coupons.

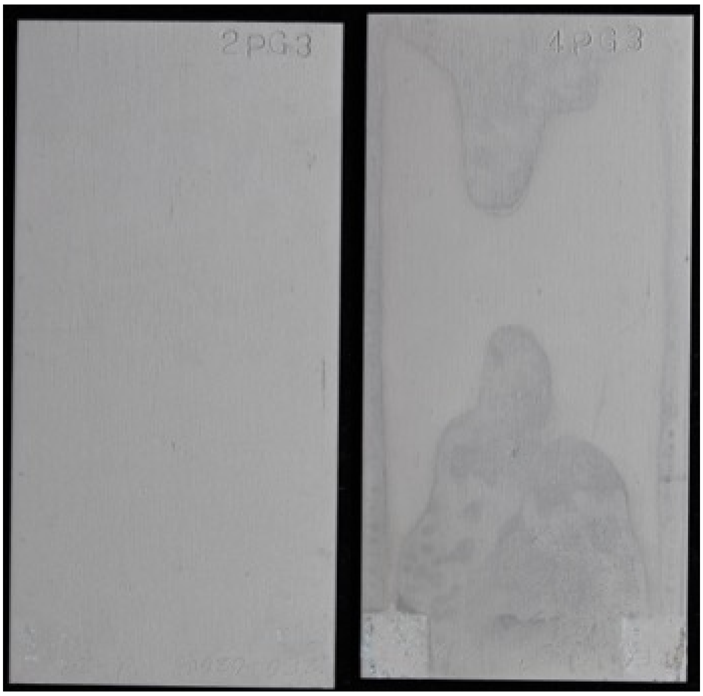

Figure 5 MAXUS® 3-Year PWR Bath General Coupons

The PWR Encapsulated coupons have similar features to that of the BWR Encapsulated coupons. There is rust staining of the coupon near the capsule vents and there are indications of pitting. The pitting of the Encapsulated PWR coupons appears to be more developed than that of the BWR coupons. Figure 6 illustrates the condition of the PWR Encapsulated coupons.

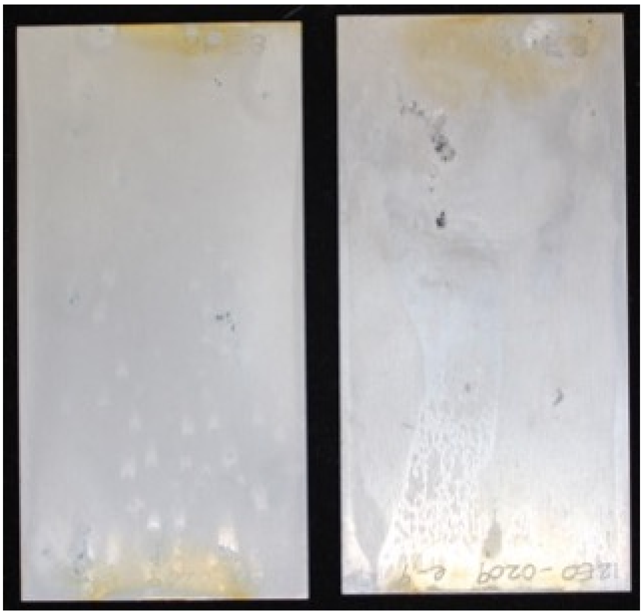

Figure 6 MAXUS® 3-Year PWR Bath Encapsulated Coupons

Year three performance results – Physical dimensions

The length, width, thickness, density and dry weight of the 3-year test coupons were measured and compared to the pre-characterization values. No discernable changes were noted.

Year three performance results – General corrosion

Considering commercial nuclear power plant operations, the nominal bulk fuel storage pool coolant temperature was assumed to be 27^{o}C (80^{o}F). During refueling outages, the temperature can increase up to 49^{o}C (120^{o}F). The test baths operated at 91^{o}C (195^{o}F) to accelerate the corrosion rate to simulate a longer in-service exposure. A correction was made to create an equivalent corrosion rate at the lower temperatures. The Arrhenius function was used to create an in-service equivalency. Exposure to the test bath temperature of 91^{o}C (195^{o}F) for three years was thus determined to be equivalent to approximately eighteen (18) years at 49^{o}C (120^{o}F) and fifty-four (54) years at 27^{o}C (80^{o}F). None of the year three coupons experienced a weight, density or other dimension change. Therefore, the general corrosion rate of the year three coupons was assessed to be very close to zero. This determination is consistent with findings from examination of year one and year two coupons.

Year three performance results – Blistering/Delamination

No blistering or delamination of the coupons was observed in any of the test coupons to date. This is expected due to the near full density of the MAXUS® material and the absence of any porosity.

Year three performance results – Localized corrosion (Pitting)

Localized corrosion was observed on all test coupons. The pitting has occurred in small pockets where the local chemistry becomes ideal. In higher areas of water flow such as exposure to the open circulation within the test bath that the General coupons experience, the local surface conditions are not amenable to pitting. However, in localized stagnation points or areas of low water flow, pitting was observed to be more prevalent. These pits appear to be the result of crevice geometry and thus more present in the Encapsulated coupons as compared to the General coupons. This effect is accelerated in the lower pH environment of the PWR test bath.

Year three performance results – Areal density

As stated earlier, the purpose of using MAXUS® or any other neutron absorber in a fuel storage pool or cask is to ensure sub-criticality. The only material degradation mechanism that is evident in the accelerated test program to date is localized corrosion. Therefore, it follows that impact of localized corrosion should be measured by the most important metric of boron-based neutron absorbers, namely the boron-10 areal density. The parameter was measured at the Penn State Breazeale Nuclear Reactor in State College, PA USA. Table 2 shows the results of pre-characterize and post-immersion test of the MAXUS® coupons. Note that the calculated difference in areal density is bounded by the 3-sigma uncertainty of the neutron transmission measurement. Therefore, there is no impact of general or localized corrosion in the key parameter of the MAXUS® neutron absorber performance.

Table 2 MAXUS® Coupon Areal Density (g·cm^{-2})

Coupon ID	Areal Density Pre-Characterized	Uncertainty (3σ)	Areal Density Post-Test	Uncertainty (3σ)	Difference
2BG3	0.0137	0.00062	0.0140	0.00065	0.0003
2BE3	0.0139	0.00063	0.0140	0.00064	0.0001
4BG3	0.0307	0.00103	0.0302	0.00183	-0.0005
4BE3	0.0312	0.00106	0.0309	0.00197	-0.0003
2PG3	0.0136	0.00062	0.0139	0.00064	0.0003
2PE3	0.0138	0.00063	0.0141	0.00065	0.0003
4PG3	0.0315	0.00108	0.0309	0.00195	-0.0006
4PE3	0.0317	0.00109	0.0308	0.00194	-0.0009

Conclusions

No significant general corrosion was measured in any of the MAXUS® test coupons. No blistering or delamination was noted in any of the MAXUS® test coupons. Local, limited corrosion in the form of pits in the MAXUS® cladding surface was observed. However, the accelerated corrosion program demonstrates that the key neutron absorber performance parameter – areal density, is unaffected by BWR and PWR spent fuel pool environments up to 54 years of operation at a bulk pool temperature of 27 °C (80 °F). The conclusion of the 5-year test program is expected to demonstrate adequate neutron absorber performance through plant end of life including license renewal and decommissioning.

Acknowledgments

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