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5-Year Accelerated Corrosion Testing of MAXUS® for Spent Fuel Pool and Dry Cask Performance

Matthew L. Eyre
Eyre Consultancy, Inc.
Ulster Park, NY USA

Daisuke Nagasawa
Nippon Light Metal Company, Ltd., Shizuoka, Japan

Toshiaki Yamazaki
Nikkeikin Aluminium Core Technology Company, Ltd., Tokyo, Japan

Aaron C. Herfurth
Nikkeikin Aluminium Core Technology Company, Ltd., Tokyo, Japan

Abstract

Many pool fuel storage racks and fuel storage/transportation packages incorporate neutron absorbers to improve the space efficiency of nuclear fuel held therein.

The dominant performance concern regarding metal-based neutron absorbers is oxidation, whether from long-term residence in a spent fuel pool rack or short-term pool exposure experienced by spent fuel canisters/casks. A number of dry cask designers/fabricators have leveraged high-temperature, immersion-based corrosion tests to bound absorber performance of dry cask pool exposure and response to residual moisture.

MAXUS®, an aluminum-boron carbide neutron absorber metal matrix composite material, is qualified for use in spent fuel pools and dry casks. The authors identified Light Water Reactor (LWR) fuel pool environmental factors that affect aluminum-based, boron-10 (^{10}B) neutron absorber performance. These include water temperature, pH and dissimilar materials. Further identified are production methods that address these factors. To confirm adequate in-service performance, corrosion resistance testing was done in simulated LWR pool environments.

The material testing involved up to 5-year exposure to simulated Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) pool accelerated corrosion environments. Test material configurations include flat and bent coupons. The flat coupons are used to determine overall material corrosion performance and allows for established means of ^{10}B areal density measurement. Bent coupons confirm the performance of absorber configurations requiring mechanical cold work to achieve final shape of the absorber. These bent coupons simulate rack inserts that have been used extensively in US spent fuel pools and dry cask absorber panel configurations requested by system designers.

Post-immersion tests included: visual examinations, dimension measurements, neutron attenuation measurements of ^{10}B areal densities and evaluation of the effect of forming work on non-flat absorber configurations.

Test coupons were periodically removed, measured and compared to pre-characterized values. The physical configuration and ^{10}B areal density for all coupons were found to be essentially unchanged, with no blisters or delamination noted. This paper shows that the results of the completed 5-year test program demonstrate MAXUS® has life of plant efficacy as a spent fuel storage rack neutron absorber. These results also address dry cask operation absorber material exposure to spent fuel pool water during cask loading, drying and residual moisture after closure.

Introduction

MAXUS® is a commercially available clad neutron absorber composed of boron carbide (B_4C) within an aluminum matrix. The cladding facilitates manufacturing and protects the aluminum-boron-carbide core.

MAXUS® is widely used as a LWR fuel neutron absorber material in fuel pools and dry storage and transportation casks to ensure criticality safety.

The original material qualification testing sponsored by Nikkeikin Aluminium Core Technology Company, Ltd. (Reference 1) has been supplemented by a 5-year accelerated corrosion test to confirm and expand the duty qualification expectations of the MAXUS® neutron absorber material.

MAXUS® Detailed Description

MAXUS® is a Metal Matrix Composite (MMC) neutron absorber that is wholly manufactured by Nikkeikin Aluminium 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 (B_4C) powder. The aluminum case is then filled with a uniform matrix of aluminum and B_4C. 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 sheet is trimmed to specified dimensions by water jet cutting. During the water jet cutting, the aluminum frame is cut from the sheet. The fabrication process assures a uniform distribution of B_4C in the aluminum core.

Thus, MAXUS® becomes a highly corrosion-resistant clad structure with B_4C powder uniformly distributed within a high-purity aluminum matrix. The clad is composed of AA5052 and the core is composed of A1070 and B_4C. The core B_4C is ranges from 20-40 weight percent depending on the design and operational needs of the neutron absorber application. See figure 1 for a through-thickness cutaway illustration of the MAXUS® structure. The materials and the fabrication process create a tightly bound and seamless transition between clad and core (Figure 2).

MAXUS® is formed into sheets that can range from 2 mm to 10 mm in thickness. The sheets have demonstrated excellent formability by meeting varying customer requirements for material configuration. MAXUS® has been widely used as a neutron absorber in both pool storage and dry cask storage and transport systems.

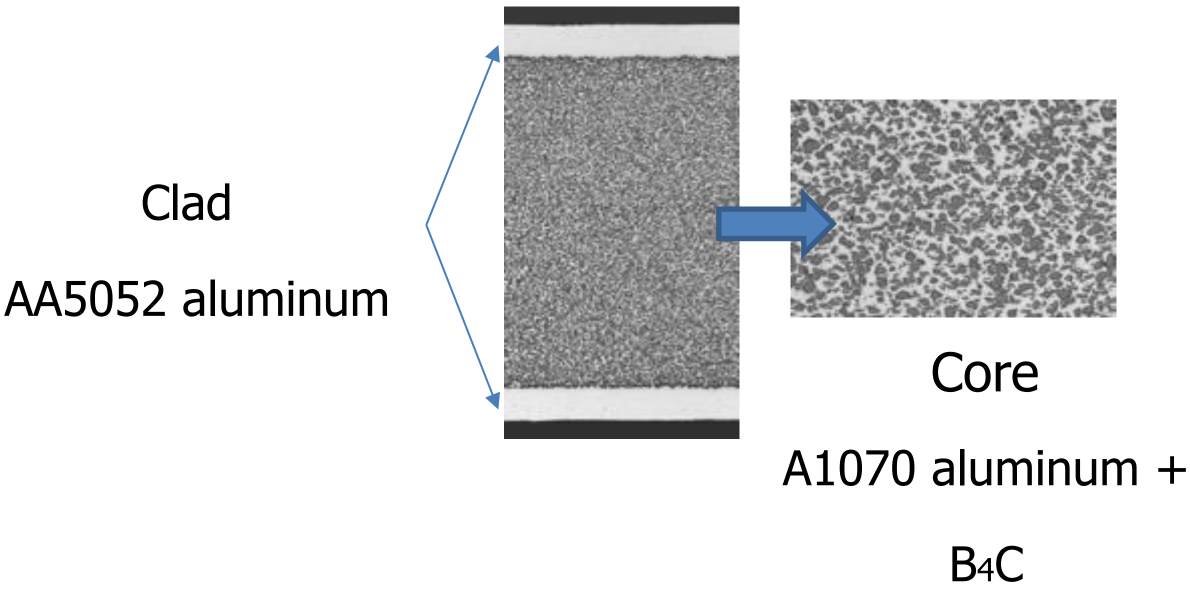


Figure 1 MAXUS® Structure

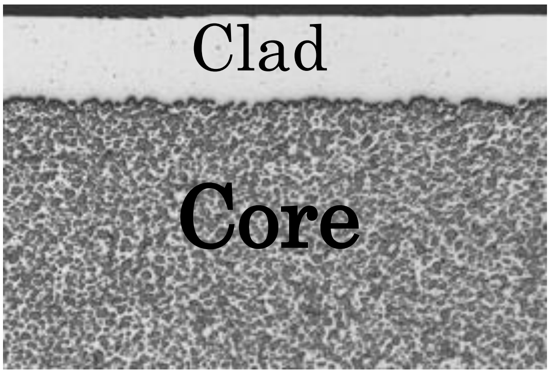


Figure 2 MAXUS® Clad/Core Detail

Qualification and Performance Testing

The MAXUS® qualification report is available as a US Nuclear Regulatory Commission record (Reference 1). The report documents the results of a two-year accelerated corrosion test and concludes that satisfactory performance is achieved in both BWR and PWR fuel storage pool environments.

5-year extended accelerated corrosion program

The results presented in this paper represent the culmination of a five-year program of accelerated corrosion performance testing of MAXUS® in BWR and PWR fuel storage pool environments. Forty-eight (48) flat coupons were initially placed in test baths that simulate the conditions found in BWR and PWR fuel storage pool. Two boron carbide (B_4C) concentrations were the subject of the accelerated corrosion test program: 21wt% and 40wt%. These B_4C 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, these 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® B_4C 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 or dry cask retention plate. The flat coupons used in this test program have dimensions of 5.08 cm (2 inches) by 10.16 cm (4 inches). The 21wt% B_4C coupons are 2.03 mm (0.08 inches) thick, while the 40wt% B_4C coupons have a thickness of 2.54 mm (0.10 inches). Table 1 represents the distribution of flat 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 were removed from each of the test baths.

Table 1 MAXUS® Flat Test Coupons

Coupon Type	BWR Test Bath	PWR Test Bath
21wt% B_4C General	6	6
21wt% B_4C Encapsulated	6	6
40wt% B_4C General	6	6
40wt% B_4C Encapsulated	6	6

During the last year of the corrosion study, twelve (12) bend coupons were placed in the test baths. This was to assess the effect of cold work on the corrosion performance of MAXUS®. All bend coupons were 2.3 mm (0.09 inches) thick and cold bent to an angle of 90 degrees with a bend radius of 9 mm (0.35 inches). Table 2 represents the distribution of MAXUS® bend coupons in the test baths.

Table 2 MAXUS® Bend Test Coupons

Coupon Type	BWR Test Bath	PWR Test Bath
10wt% B_4C Bend	3	3
30wt% B_4C Bend	3	3

Bend coupons were removed from the test baths per the schedule noted in Table 3. Note that all bend coupons may be considered “general” in that the bend coupons were not encapsulated but fully exposed to the test bath environment.

Table 3 Bend Coupon Removal Schedule

Coupon Type/Bath	Bath Removal @ 6 months	Bath Removal @ 12 months
10wt% B_4C Bend/BWR	**1**	**2**
30wt% B_4C Bend/BWR	**1**	**2**
10wt% B_4C Bend/PWR	**1**	**2**
30wt% B_4C Bend/PWR	**1**	**2**

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 flat coupons with a four-character code. The first character was either "2" or "4". This character indicated MAXUS® with either 21wt% ("2") or 40wt% ("4") B_4C. 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 5 coupons all have "5" as their fourth character. For example, "2BG5" was 21wt% B_4C MAXUS® placed in the BWR test bath as a general coupon and removed at the end of year 5.

Due to administrative requirements, the bend coupons were identified in a different manner. Table 4 illustrates the identification of the bend coupons used in the corrosion performance study.

Table 4 Bend Coupon Identification

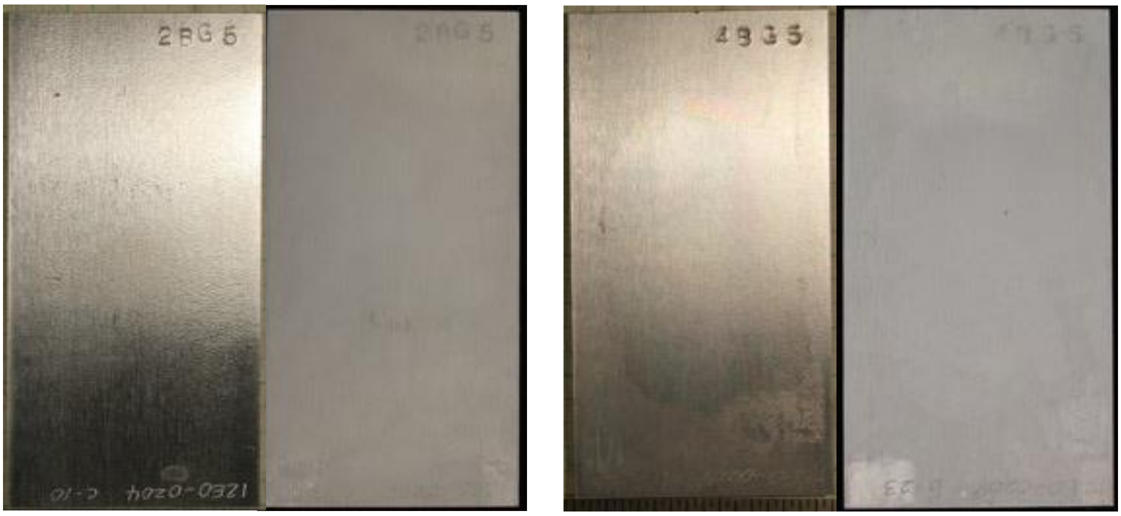
Coupon ID	B_4C Concentration	Bath Type	Months in Bath
14E0-1616-14	10wt%	BWR	6
14E0-1620-10	30wt%	BWR	6
14E0-1616-11	10wt%	PWR	6
14E0-1620-5	30wt%	PWR	6
14E0-1616-7	10wt%	BWR	12
14E0-1616-12	10wt%	BWR	12
14E0-1620-3	30wt%	BWR	12
14E0-1620-6	30wt%	BWR	12
14E0-1616-13	10wt%	PWR	12
14E0-1616-15	10wt%	PWR	12
14E0-1620-7	30wt%	PWR	12
14E0-1620-14	30wt%	PWR	12

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, sulphates and boron (PWR only). Both the BWR and PWR baths were filled with demineralized water with the addition 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. A correction was made to create an equivalent corrosion rate at the lower spent fuel pool temperatures. The Arrhenius function was used to create an in-service equivalency. Exposure to the test bath temperature of 91°C (195°F) for five years was thus determined to be equivalent to approximately thirty (30) years at 49°C (120°F) and ninety (90) years at 27°C (80°F).

<u>Year five flat coupon performance results – visual exam</u>

All coupons were subjected to measurement and visual inspection upon removal from the test baths. High resolution photographs were taken of all coupons upon removal. The length, width, thickness, density and dry weight of the flat 5-year test coupons were compared to the pre-characterization values. No discernable changes were noted. No blistering or delamination of the flat coupons was observed in any of the test coupons. This was expected due to the near full density of the MAXUS® material and the absence of any porosity. None of the coupons exhibited signs of significant general corrosion, but some exhibited 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 had greater pitting than the other coupons. Figure 3 compares the surface condition of the BWR general coupons to their pre-characterized state.



21wt% B_4C BWR General 40wt% B_4C BWR General

Figure 3 MAXUS® 5-Year BWR Bath General Coupons

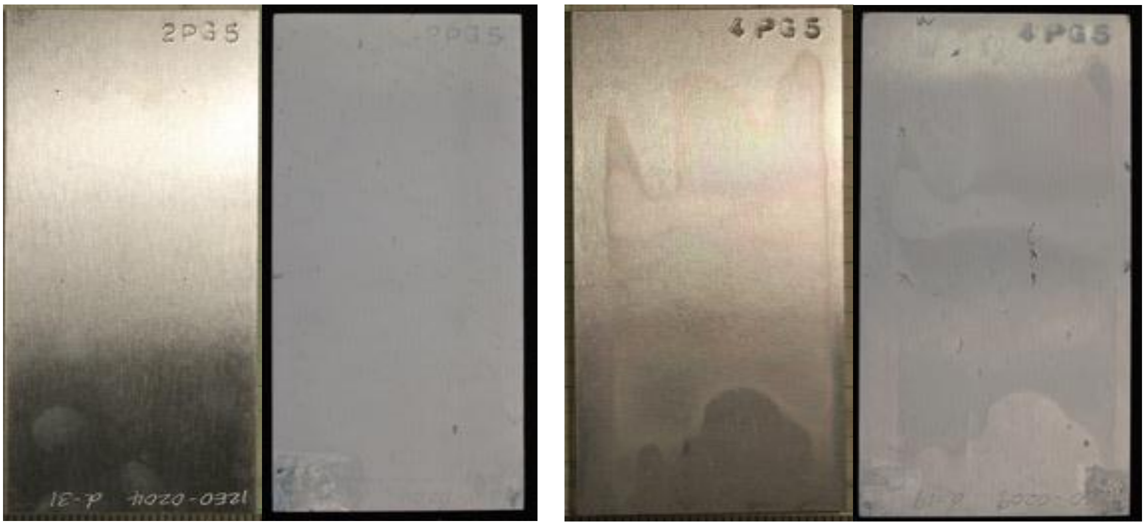
The pre-characterized coupon photos are to the left of the as-tested coupons. Note that there are stains associated with the coupon holder rack on the bottom corners. Other than that, there is very little change from the pre-characterized state.

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 of the 40wt% B_4C coupon. Also, there was some surface pitting near the capsule vent locations of both coupons. Figure 4 illustrates the condition of the BWR encapsulated coupons. As for Figure 3, the pre-characterized coupon photos are to the left of the as-tested coupon photos.

21wt% B_4C BWR Encapsulated 40wt% B_4C BWR Encapsulated

Figure 4 MAXUS® 5-Year BWR Bath Encapsulated Coupons

The as-tested state of the PWR general coupons are very similar visually to that of the BWR general coupons. The as-tested coupons have stains associated with the coupon holder rack on the bottom corners and light staining visible on the surface. Figure 5 illustrates the condition of the PWR general Coupons. Similar to previous coupon figures, the pre-characterized coupon photos are to the left of the as-tested coupon photos.



21wt% B_4C PWR General Coupons 40wt% B_4C PWR General Coupons

Figure 5 MAXUS® 5-Year PWR Bath General Coupons

The as-tested condition of the PWR encapsulated coupons have similar features to that of the as-tested 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. As previously, the pre-characterized coupon photos are to the left of the as-tested photos.

21wt% B_4C PWR Encapsulated Coupons 40wt% B_4C PWR Encapsulated Coupons

Figure 6 MAXUS® 5-Year PWR Bath Encapsulated Coupons

<u>Year five flat coupon performance results – general corrosion</u>

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. None of the test coupons (years 0.5 through 5) experienced a weight, density or other dimension change. Therefore, the general corrosion rate of the test coupons was assessed to be very close to zero. Table 5 illustrates the calculated corrosion rate at pool operational temperatures. It should be noted that higher pool operation temperatures occur during refueling outages. Typical dry cask loading operations occur during non-outage periods at lower pool operating temperatures.

Table 5 Equivalent Corrosion Rate for 27°C (80°F) and 49°C (120°)
[microns/yr / mils/yr]

Coupon Type		Corrosion Rate @ 27°C	Corrosion Rate @ 49°C
0.5 year	General	0.000	-0.025 / -0.001
	Encapsulated	0.000	0.000
	BWR	0.000	0.000
	PWR	0.000	-0.025 / -0.001
1 year	General	0.000	0.000
	Encapsulated	0.000	0.000
	BWR	0.000	0.000
	PWR	0.000	0.000
2 year	General	0.000	0.000
	Encapsulated	0.000	0.000
	BWR	0.000	0.000
	PWR	0.000	0.000
3 year	General	0.000	0.000
	Encapsulated	0.000	0.000
	BWR	0.000	0.000
	PWR	0.000	0.000
4 year	General	0.000	0.000
	Encapsulated	0.000	0.000
	BWR	0.000	0.000
	PWR	0.000	0.000
5 year	General	0.000	0.000
	Encapsulated	0.000	0.000
	BWR	0.000	0.000
	PWR	0.000	0.000

Year five flat coupon performance results – localized corrosion (pitting)

Localized corrosion was observed on many of the flat test coupons. The pitting 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 further enhanced in the lower pH environment of the PWR test bath.

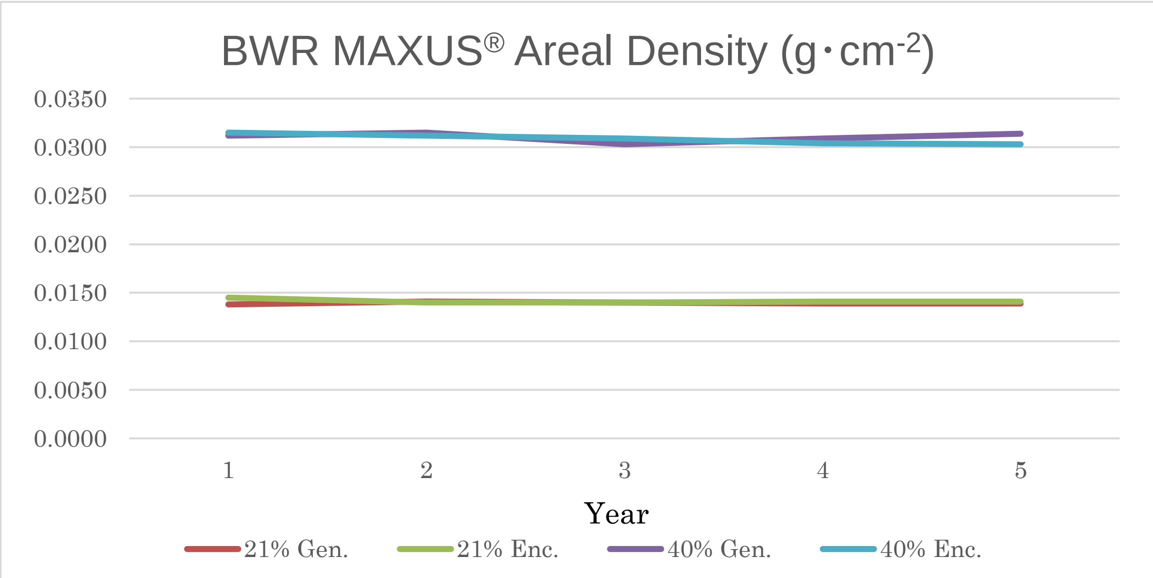
Year five flat coupon performance results – areal density

As stated earlier, the purpose of using any neutron absorber in a fuel storage pool or dry cask is to ensure sub-criticality. The only material degradation mechanism that is evident at the conclusion of the 5-year accelerated test program 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 ^{10}B areal density. That parameter was measured at the Penn State Breazeale Nuclear Reactor in State College, PA USA. Table 6 shows the results of pre-characterize and post-immersion test of the flat, 5-year test 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 neutron absorber performance.

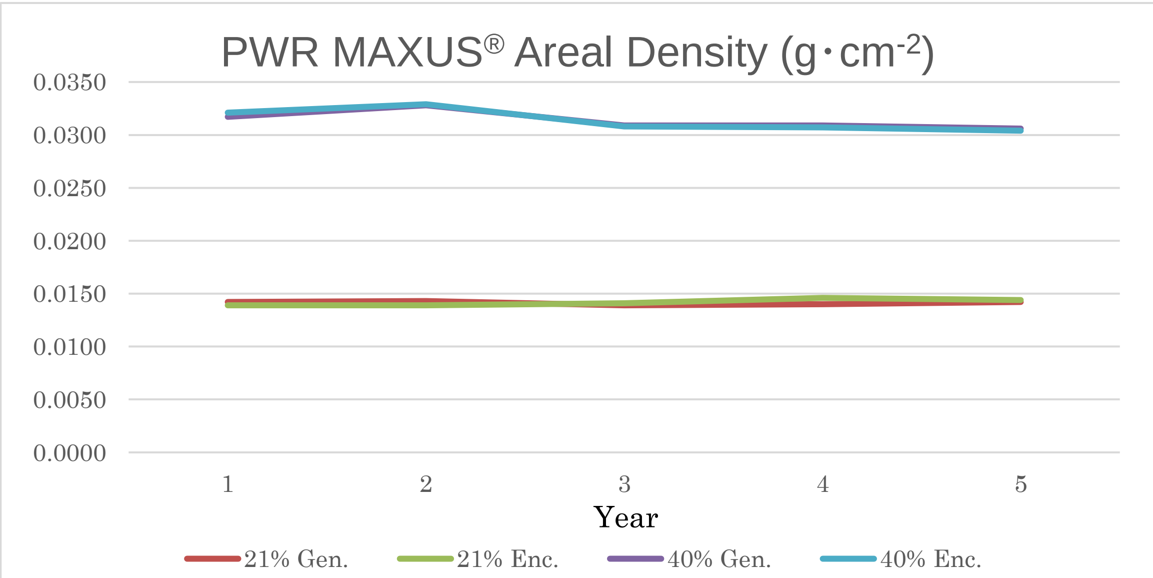
Table 6 Year 5 MAXUS® Flat Coupon Areal Density (g･cm^{-2})

Coupon ID	Areal Density Pre-Characterized	Uncertainty (3σ)	Areal Density Post-Test	Uncertainty (3σ)	Difference
2BG5	0.01390	0.00064	0.01390	0.00064	0.00000
2BE5	0.01381	0.00063	0.01408	0.00065	0.00027
4BG5	0.03211	0.00111	0.03142	0.00207	-0.00069
4BE5	0.03121	0.00106	0.03033	0.00186	-0.00088
2PG5	0.01400	0.00064	0.01421	0.00066	0.00021
2PE5	0.01431	0.00066	0.01440	0.00067	0.00009
4PG5	0.03098	0.00105	0.03059	0.00191	-0.00039
4PE5	0.03109	0.00105	0.03042	0.00187	-0.00067

The year 5 areal density data are consistent with the areal densities previously measured in earlier year test coupons. See Graphs 1 and 2 for BWR and PWR areal density measurement trends respectively for the five-year program. In the graphs, “21%” and “40%” refer to the concentration of B_4C in the test coupon cores.



Graph 1 BWR Areal Density Trend Over 5-Year Test Program



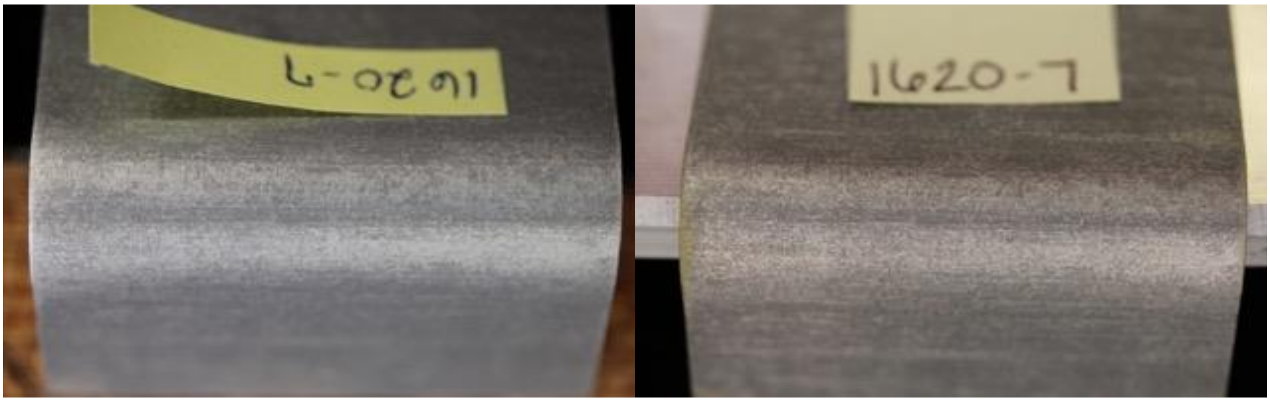
Graph 2 PWR Areal Density Trend Over 5-Year Test Program

Bend coupon performance results – visual exam

The bend coupons were subjected to visual inspection and photography upon removal from the test baths. No significant change from the surface conditions as recorded in the pre-characterization photos of the bend coupons were noted. No blistering or delamination of the bend coupons was observed. Representative bend coupons were selected from each bath to illustrate the change or lack thereof in the surface conditions. Figure 7 compares the pre-characterized bend coupon 14E0-1620-7 (30wt% B_4C) to the coupon after 12-month immersion in the PWR bath. The pre-characterization photo is on the left of Figure 7 with the post-immersion photo on the right. A slight iron oxide stain can be observed on the edges of the coupon. Otherwise, no significant change features can be noted. Figure 8 compares the pre-characterized bend coupon 14E0-1620-6 (30wt% B_4C) to the coupon after 12-month immersion in the BWR bath. Aside from the slightly different photo lighting, there is no discernible difference between the pre-characterized and post-immersion coupon surface conditions as noted in the photos. As with the PWR bend coupon comparison, the pre-characterized coupon is on the left.

Bend coupon performance results – general and localized corrosion

No significant indication of general corrosion was noted in the bend coupons either through the visual examination or by comparison of pre-characterized and post-immersion coupon weight. Examples of bend coupon visual examinations are provided in Figures 7 and 8. Table 7 illustrates the measured changes in bend coupon weight and effective corrosion rate per year consistent with that reported for flat coupons. The maximum weight gain was 0.03% and the maximum weight loss was 0.13%. There is no indication of corrosion impact to the cold worked bend coupons.



PWR Bath, 12 month, 30wt% B_4C

Figure 7 MAXUS® 12-month, PWR Bath Bend Coupon

BWR Bath, 12 month, 30wt% B_4C

Figure 8 MAXUS® 12-month, BWR Bath Bend Coupon

Table 7 MAXUS® Bend Coupon Weight Comparison

Bath	Bath Time (months)	Coupon ID	Pre-characterized weight (g)	Post-Immersion weight (g)	Weight Change	Change %	Corrosion Rate @ 27°C micron/yr
BWR	6	14E0-1616-14	32.48	32.48	0.00	0	0
BWR	6	14E0-1620-10	31.79	31.80	0.01	0.03	0.25
PWR	6	14E0-1616-11	32.40	32.40	0.00	0	0
PWR	6	14E0-1620-5	32.00	32.01	0.01	0.03	0.25
BWR	12	14E0-1616-7	32.18	32.19	0.01	0.03	0.25
BWR	12	14E0-1616-12	32.43	32.44	0.01	0.03	0.25
BWR	12	14E0-1620-3	32.19	32.20	0.01	0.03	0.25
BWR	12	14E0-1620-6	32.32	32.33	0.01	0.03	0.25
PWR	12	14E0-1616-13	32.41	32.41	0.00	0	0
PWR	12	14E0-1616-15	32.26	32.26	0.00	0	0
PWR	12	14E0-1620-7	32.05	32.05	0.00	0	0
PWR	12	14E0-1620-14	31.84	31.80	-0.04	-0.13	1.5

Bend coupon performance results – areal density

The MAXUS® bend coupons were tested at the Penn State Breazeale Nuclear Reactor in State College, PA USA in a manner similar to the flat coupons. The areal density of the bend coupons experienced no significant changes as a result of absorber material cold work and immersion in the test baths. Table 8 provides test result details regarding the bend coupons.

Table 8 MAXUS® Bend Coupon Areal Density (g-^{10}B/cm^2) Comparison

Coupon ID	Pre-characterized		Post-immersion		Areal Density Change	Change %
	Areal Density	3σ	Areal Density	3σ		
14E0-1616-14	0.0075	0.0004	0.0075	0.0004	0.0000	0
14E0-1620-10	0.0220	0.0010	0.0220	0.0010	0.0000	0
14E0-1616-11	0.0074	0.0004	0.0075	0.0004	0.0001	1.35
14E0-1620-5	0.0223	0.0010	0.0222	0.0010	-0.0001	-0.45
14E0-1616-7	0.0076	0.0004	0.0075	0.0004	-0.0001	-1.32
14E0-1616-12	0.0076	0.0004	0.0076	0.0004	0.0000	0
14E0-1620-3	0.0224	0.0010	0.0222	0.0010	-0.0002	-0.89
14E0-1620-6	0.0223	0.0010	0.0220	0.0010	-0.0003	-1.35
14E0-1616-13	0.0076	0.0004	0.0076	0.0004	0.0000	0
14E0-1616-15	0.0075	0.0004	0.0075	0.0004	0.0000	0
14E0-1620-7	0.0224	0.0010	0.0222	0.0010	-0.0002	-0.89
14E0-1620-14	0.0220	0.0010	0.0219	0.0010	-0.0001	-0.45

Conclusions

No significant general corrosion and no blistering or delamination was observed in any of the MAXUS® test coupons. Limited localized corrosion in the form of pits in the MAXUS® cladding surface was observed in a number of the flat coupons. The 5-year 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 90 years of operation at a bulk pool temperature of 27 ºC (80 ºF). The results of the 5-year accelerated corrosion test program demonstrate adequate neutron absorber performance through plant end of life including license renewal and decommissioning. The bend coupon corrosion testing shows that cold work has no discernable effect on the corrosion performance of MAXUS® in PWR or BWR spent fuel pool environments.

The temperature and duration of flat and bend coupon testing demonstrate that a clad neutron absorber material such as MAXUS® is unaffected by spent fuel dry storage cask loading and closure operations even should cask loading or drying be delayed and the dry cask resides in the wetted condition for an extended period of time. The corrosion test results bound the expected and unanticipated aqueous exposure for dry cask neutron absorbers and demonstrate unaffected neutron absorber efficacy.

Acknowledgments

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