An aging management program for neutron absorber materials in SFPs

EPRI's multiyear research provides nuclear plants with an efficient aging management program that ensures criticality safety margins are maintained for spent fuel pools.

By Hatice Akkurt

Spent fuel pools (SFP) were originally designed with low-density storage racks that maintained sub-criticality based on geometric separation (distance between fuel cells). With the increasing need for fuel storage, the nuclear industry now relies on the use of fixed neutron absorber materials (NAM) in SFP racks to maintain sub-critical safety margins while increasing pool storage capacity. Some types of NAMs in use include Boraflex, BORAL, Carborundum, Metamic, and Borated stainless steel[1]. Some of the NAMs, most significantly Boraflex, have shown substantial degradation over time, and these materials either had to be replaced or be reevaluated with removal of credit for the absorber, which means reliance on distance for criticality safety and loss of storage space. Operating experience, however, has shown the majority of other NAMs are continuing to perform their intended function. This operating experience is documented in two Electric Power Research Institute (EPRI) reports[1,2] and includes a database of coupon monitoring results from many SFPs spanning more than 20 years[2]. (In this context, "coupon" refers to the samples, cut from the same material representing the absorber panels and placed in the SFP when neutron absorber panels were installed, and taken out for inspection at pre-defined intervals.)

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SFP lifetimes are increasing, and operating experience has documented that there are many pools without a coupon monitoring program or with a limited number of coupon samples remaining. Therefore, EPRI is developing a global industrywide learning aging management program (i-LAMP). The first phase of this program is focused on BORAL, the most widely used material in many countries, but EPRI plans to expand this program to other metallic NAMs.

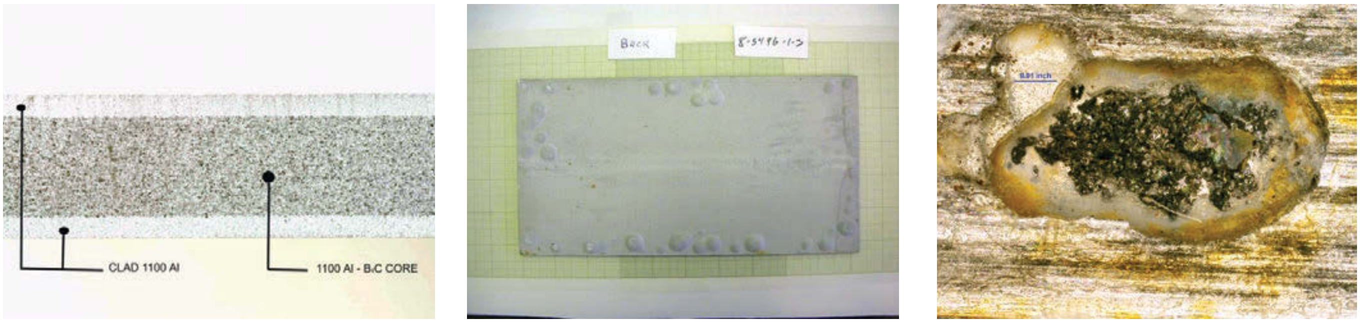
EPRI's multiyear research on these materials is providing nuclear plants with an efficient management approach for SFPs while ensuring that criticality safety margins are upheld. This article will provide an overview of ongoing EPRI projects on NAMs, including performance evaluation using laboratory and actual data, and monitoring approaches for wet storage applications.

Background

In SFPs, fixed NAMs are used to increase storage capacity while maintaining criticality safety margins. The specific questions surrounding fixed NAMs include the following:

- What are the conditions of the neutron absorber panels in SFPs? Is there any gross degradation that could cause potential concern for criticality safety of the pools?
- Is the coupon monitoring approach currently in use today adequate for assessing the condition of the panels as part of an aging management program?
- For plants that do not have coupons, do current *in situ* measurement approaches provide accurate results? Could such *in situ* approaches be used as an alternative monitoring approach? If not, can alternative monitoring approaches be developed?

The metal matrix composite (MMC) NAMs include BORAL, Metamic, Boralcan, Bortec[1], and MAXUS[2]. Some of these MMCs include aluminum (Al) cladding on both sides of the core containing boron carbide (B_4C) and Al mixture. Examples include BORAL[1], MAXUS[2], and Bortec[1]. Although cladding serves as a protective layer, it also makes the material susceptible to the formation of blisters, which are raised delaminations between the B_4C core and protective cladding and which can displace the moderator (water).



Photos: EPRI

Fig. 1. BORAL coupon with (from left) Al cladding on both sides, multiple blisters developed over time, and pitting that breached the cladding.

MMC NAMs are more susceptible to blistering at high temperatures, depending on the material's vintage and porosity. The other MMCs, such as Metamic and Boralcan, do not have cladding; consequently, they are not susceptible to blistering. All of the MMCs are susceptible to pitting corrosion (hereafter, pitting) over time.

As an example, Fig. 1 shows a BORAL coupon with Al cladding on both sides (left), on a coupon that developed multiple blisters over time (center), and pitting with 100x magnification, breaching the cladding (right).

Given the observed blistering and pitting to date, the key research questions include the following:

- Are the observed blistering and pitting to date at a level that could cause potential concern for criticality safety of the SFPs?
- At what sizes and panel locations can blisters and/or pits start to show an impact on SFP criticality?

To shed light on these technical questions using actual plant data, supplemented by laboratory or modeling and simulation data, EPRI initiated several projects focused on NAM performance and monitoring. An overview of each of these projects follows.

Accelerated corrosion testing

EPRI initiated its five-year accelerated corrosion testing project in January 2013[3-5]. The objectives of this project included the following:

- Demonstrate 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.

Since its first manufacturing, the BORAL manufacturing process went through several changes. To evaluate the impact of the various vintages, samples from different vintages of BORAL were collected and characterized. The characterized coupons were then placed in test baths that maintain typical pressurized water reactor and boiling water reactor water chemistry. At the end of each year, a number of coupons were removed and analyzed to determine the corrosion

Photo: EPRI

Fig. 2. BORAL coupons set in a test bath.

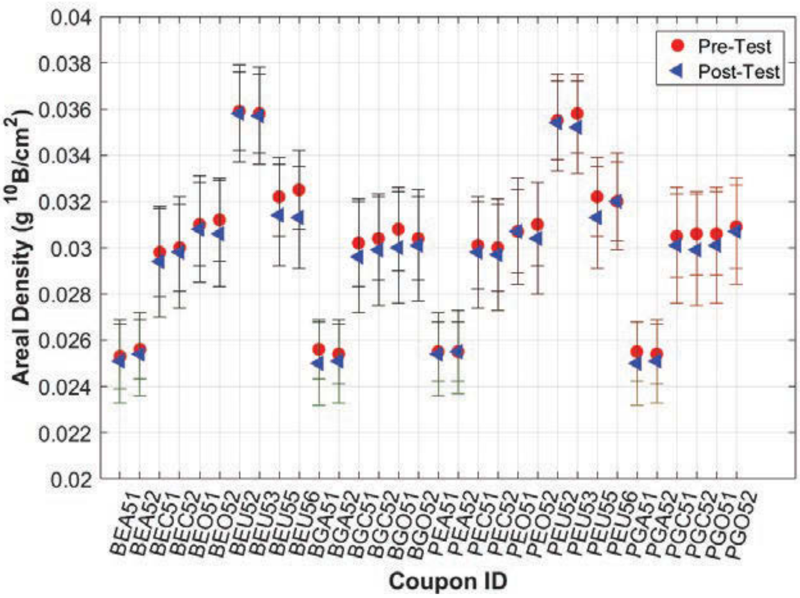


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Fig. 3. Areal density values of coupons prior to placement in the test baths after immersion for five years.

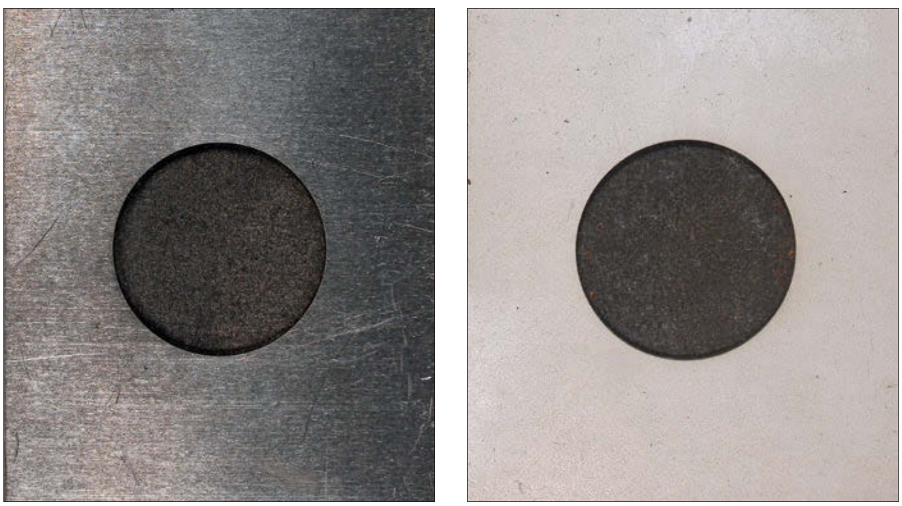

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Fig. 4. Clad-removed coupon prior to insertion into the test bath (left) and after five years (right).

rate. The coupons, bare in the front and with stainless steel (SS) encapsulation in the back, are shown in Fig. 2, in one of the test baths.

Typically, SFP water temperature varies from 27°C to 38°C (80°F to 100°F). The corrosion rate was accelerated by conducting the tests at elevated temperatures, with test baths maintained at 91°C (196°F) to simulate corrosion effects representing more than 60 years of operation during the five-year duration of the study.

Prior to placement in the test baths, the coupons were characterized for length, width, thickness, material density, and neutron absorber areal density so the results could be compared to post-bath results. At the end of each year, a number of coupons were pulled out and analyzed. The coupon analyses included the following:

- High-resolution photography.
- Dimension measurements.
- Density measurements.
- Neutron absorber areal density measurements.
- Pit characterization using microscopy, when applicable, after residing in test baths.
- Blister characterization, when applicable, after residing in test baths.

To date, all coupons from years one to five have been removed and analyzed. Figure 3 shows the areal density values as characterized prior to placement in the test baths and after immersion in test baths for the year-five coupons. 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.
- The last number indicates the sample number for that year as multiple samples, from the same vintage, were placed in test baths to evaluate variations within the same vintages.

These results did not show any statistically significant change in areal density even after five years in the high-temperature test environment (representing over 60 years of in-plant environment). It should be noted that, although not included in this article, the previous years' results did not show any statistically significant change in areal density. The previous results from years one to four from the accelerated corrosion coupon tests are presented in references 3-5.

For a subset of the coupons, the Al cladding was removed on one side of the coupon to test for the worst-case scenario and evaluate the robustness of the BORAL cermet core when the protective cladding layer is not present. Figure 4 shows one of the clad-removed coupons prior to insertion into the test bath (left) and after five years in the test bath (right). These clad-removed coupons were removed after two years and re-inserted for continued testing. The areal density values after two, four, and five years of insertion are presented in Fig. 5. As evident from the values shown in the figure, the changes in areal density values are within 3σ values, compared to pre-characterized values. Therefore, none of the clad-removed coupons shows any statistically significant change in areal density values, even after year five in the test environment.

These results demonstrate that even for the worst-case scenario (when Al clad is removed), there is still no loss of BORAL after five years of testing, which approximately corresponds to more than 60 years of operation.

The results to date from the accelerated corrosion test are encouraging for demonstrating long-term performance of BORAL, as areal density is the most important parameter for any neutron absorber to maintain criticality safety margins. An EPRI report that summarizes the results from years one to five of the project will be published in late 2019.

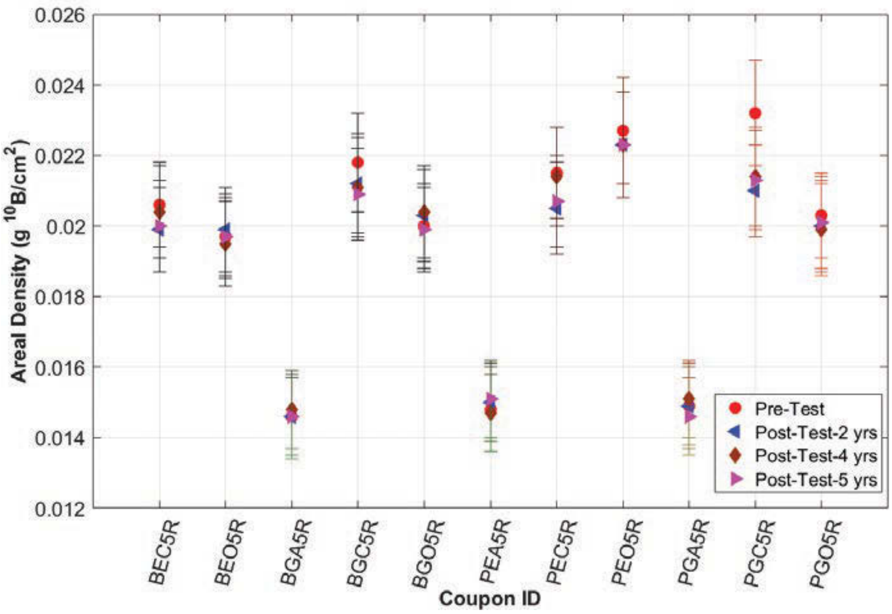

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Fig. 5. Areal density values of coupons after two, four, and five years of insertion in the test bath.

Zion project

EPRI initiated a comparative analysis project at the shutdown Zion nuclear power plant in Illinois to improve understanding of the long-term performance of BORAL in SFPs and to evaluate the performance of coupon and *in situ* monitoring approaches. The results of this project allowed comparison of coupons and *in situ* measurement data against actual measurement data obtained from the neutron absorber panels harvested from the Zion SFP to gain insights into the accuracy of the current monitoring approaches.

The Zion coupon analysis results are presented in an EPRI report[6] and a paper[7]. The results showed that coupons were, in general, in very good condition even after residing in the Zion SFP for more than 22 years, showing a small amount of pitting. There was no statistically significant change in areal density in any of the coupons.

Then, *in situ* measurements were performed on a selected number of panels to determine the accuracy of the *in situ* measurements against laboratory measurements. For this purpose, the neutron absorber panels from the Zion SFP, for which *in situ* measurements were performed previously, were removed for laboratory analysis and compared against the coupon and *in situ* measurement results. All panels were inspected following removal and cutting. The panels were generally in very good condition. Two of the panels were damaged outside of the pool due to plasma torch cutting and developed blisters. Out of the remaining 12 panels, only one section for one of the panels showed a small blister. The panels showed general and localized corrosion and flow patterns, but nothing that raised concerns regarding their ability to maintain criticality safety margins. Figure 6 shows the coupon tree removal (left) and rack module removal (right) from the Zion SFP.

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Photo: EPRI

Photo: EPRI

Fig. 6. Coupon tree removal (left) and rack module removal (right) from the Zion SFP.

The areal density measurements, which were performed at the Penn State University Breazeale Nuclear Reactor, showed that all of the areal density values are above the manufacturer's specified minimum certified areal density values. The minimum certified areal density value was the value used in the criticality safety analysis for the license amendment request by Zion in 1992 prior to installation of the racks. Furthermore, the majority of the areal density values are above the nominal reported values, even after residing in the Zion pool for more than 20 years.

The blistering and pitting observed in plants to date have negligible impact on the results and conclusions of SFP criticality safety analyses.

The Zion panel results and comparison to coupons are presented in an EPRI report[8] and other papers[9,10]. In general, neutron absorber panels removed from the Zion SFP were in very good condition. Although some of the panels showed minor pitting, there was no statistically significant change in measured areal density values for any of the panels. Compared to the coupons, the panels showed substantially fewer pits.

Prior to the removal and analysis of the panels from the Zion SFP, *in situ* measurements using the currently available inspection tool were performed. The objective of the *in situ* measurements was to enable a true blind comparison of laboratory versus *in situ* measurement results on the same panels to evaluate the accuracy of the *in situ* measurement tool. First, *in situ* measurements were performed, and the results indicated potentially significant degradation of the absorber material and corresponding absorber material loss. However, when the same panels were removed from the Zion SFP and analyzed at the Penn State research reactor laboratory, these same panels showed no sign of degradation, except for some flow patterns and minor pitting. More importantly, they showed no signs of absorber loss based on the areal density measurements. The comparison of the panel results to the *in situ* results is still ongoing and the results will be published in an EPRI report in early 2020.

Blistering & pitting impact

EPRI initiated a project to evaluate the impact of blisters and pits on SFP reactivity. Since BORAL has the longest history among SFP NAMs, the operating experience to date for BORAL has been evaluated to determine the area of applicability in terms of pit and blister sizes and locations. Hypothetical extreme cases were evaluated to determine the bounds for future operation. For broader applicability, simulations were performed for a generic NAM, which has no protective cladding, so that the results can be applicable not only for BORAL, but also for other metal matrix composite NAMs used in SFPs. Analysis was performed for two fuel types used in PWRs to determine the impact of different fuel types as well as absorber materials with different thickness and areal densities. Simulations were performed at unborated conditions so that the results would also be applicable for NAMs used in BWR SFPs or other SFPs that do not contain soluble boron. The results of this study are published in an EPRI report[11]. For this study, blister and pit simulations were performed to cover conditions ranging from essentially pristine neutron absorber panels to panels with defects that go far beyond actual current operating experience. Based on the computational results, the main conclusions are as follows:

- The blistering and pitting observed in plants to date have negligible impact on the results and conclusions of SFP criticality safety analyses.
- Significantly larger pit and blister sizes (several orders of magnitude), compared to current operating experience, are needed to observe any statistically significant impact on reactivity.

The results and conclusions presented in this study are applicable to wet storage environments using metal matrix material containing B_4C and Al for both PWR and BWR SFPs.

i-LAMP

There are a number of nuclear plant SFPs that use BORAL as a NAM and do not have a coupon monitoring program or have a limited number of coupon samples remaining. Given the fact that many of the SFPs have similar properties and exposure, EPRI proposed to initiate an industrywide Learning Aging Management Program (i-LAMP) as an alternative monitoring approach for NAMs in SFPs[12,13]. This would allow SFPs with similar materials, age, and operating environments to work collaboratively using a "sister pools" concept for coupon monitoring programs.

The potential benefits of a program like i-LAMP include, but are not limited to:

- Coordinated monitoring, which allows identification of potential issues sooner since issues that happen in one location may occur at a future time at other plants with similar materials and operating en-

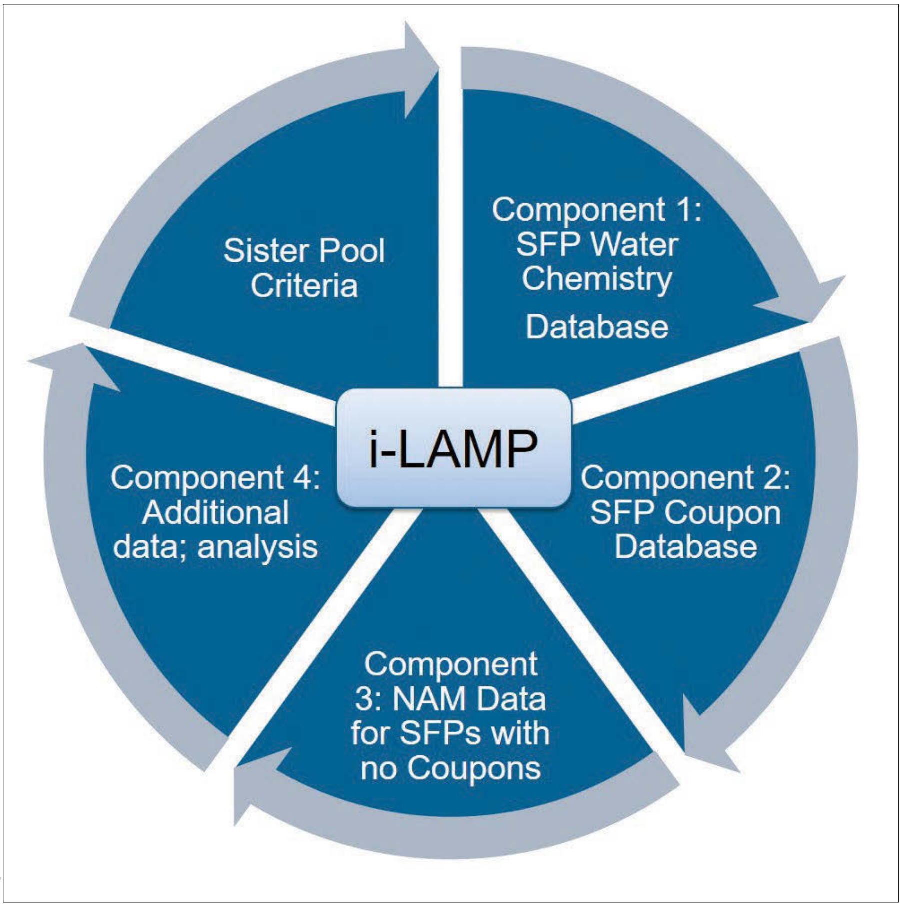

Fig. 7. Overview of the i-LAMP framework.

vironments. At Neutron Absorber User Group (NAUG) meetings, a portion of the meeting is devoted to operating experience sharing, which allows for identification and resolution of issues. The i-LAMP builds on the efforts of the NAUG and allows for coordinated efforts and the creation and maintenance of databases to allow for simplified analysis.

■ This approach would allow trending, identification of outliers, and development of an improved technical basis for guidelines and future monitoring.

The general overview of the proposed i-LAMP is illustrated in Fig. 7 at left. The i-LAMP has four components:

Component 1: SFP Water Chemistry Database. For this component, EPRI has been collecting historical SFP water chemistry data from a majority of the utilities across the globe. Once historical data collection is complete, the database will continue to populate the data at regular intervals.

Component 2: SFP Coupon Database. EPRI has been collecting the historical coupon data from utilities, with the objective of populating a database to evaluate trends and outliers and to gain perspective on correlations, if any, against chemistry data. The coupon database is currently focused on BORAL, but will be extended to other materials in the future.

EPRI's proposed i-LAMP program provides a global aging management framework to ensure the safe and efficient operation of SFPs both now and in the future.

Component 3: NAM characteristics data for SFPs with no coupons. EPRI is collecting data on the properties of absorber materials for a database (thickness, areal density, installation and manufacturing year) to determine and develop sister pool criteria.

Component 4: Additional data and analysis needs. After the collection and analysis of all the data, EPRI will evaluate if there is any need for collection of additional data, analysis, etc.

All four components will inform the final development of sister pool criteria. Figure 7 shows how each component communicates with the others within the i-LAMP framework and will be revisited at regular intervals.

NAM handbook update

EPRI's NAM handbook includes information on characteristics of different types of NAMs that have been used for storage and transportation of used fuel. It contains information on all past and current NAMs used for wet and dry storage and provides data on each absorber (including physical, mechanical, and neutronic properties). Furthermore, the handbook provides information on where these materials have been used and the problems that were experienced, if applicable. The most recent version of the neutron absorber handbook was published by EPRI in 2009[1].

The handbook has been serving as a single source of information for the majority of NAM types used by the global nuclear industry. EPRI is currently working on updating the handbook since the last release, as there have been new material developments, many additional tests conducted, and operating experience gained. The revised version is anticipated to be published in 2020.

NAUG

EPRI formed the Boraflex User Group in the 1980s when issues with Boraflex were initially identified. The initial goal of the group was to find solutions geared toward mitigating the potential impacts of Boraflex degradation on the industry. Over the years, the mission of the group evolved and became more comprehensive to include all the absorber materials used in the industry. Subsequently, the name changed to the NAUG, which is now a forum where utility members share experiences, observe practices across the industry, and identify and prioritize near- and long-term needs and research projects.

The NAUG meetings are held annually for EPRI's utility members. However, when a need or interest is identified, regulators and vendors are also invited to attend the open portion of the meeting for information exchange and discussions.

Safe SFP management

NAMs in SFP racks are a critical component to maintaining sub-critical safety margins while increasing pool storage capacity. Thus, it is important to identify and monitor degradation in NAMs to understand if this degradation could have an impact on their intended safety function. To better understand NAM degradation, EPRI initiated a number of projects over the past several years. These projects relied on laboratory tests (accelerated corrosion test), data and material from actual pools (Zion comparative analysis project), and computational results (evaluation of impact of blistering and pitting on reactivity). The results of these projects demonstrated that the degradation of NAMs is very slow and the degradation observed to date has no statistically significant impact on SFP reactivity.

Going forward, it is important that an aging management program for SFPs be established to ensure that criticality safety margins are maintained. EPRI's proposed i-LAMP program provides a global aging management framework that utilizes a coordinated monitoring program, trending, and experience sharing to ensure the safe and efficient operation of SFPs both now and in the future.

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