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Roadmap for the Industrywide Learning Aging Management Program (i-LAMP)

For Neutron Absorber Materials in Spent Fuel Pools

3002013122

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ABSTRACT

Neutron absorber materials are used in spent fuel pools (SFPs) to maintain criticality safety margins while increasing fuel storage space. Given the fact that SFP lifetimes are increasing and there are a number of pools without a coupon monitoring program or with a limited number of coupon samples remaining, an industrywide learning aging management program (i-LAMP) is being proposed. The program will initially start with BORAL®, the most widely used material in the U.S., and later be extended to other metallic neutron absorber materials. In this report, the proposed industrywide learning aging management program, its components, roadmap and schedule for the development and implementation of i-LAMP are presented.

Keywords
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PRIMARY AUDIENCE: Neutron absorber material users for spent fuel pools

SECONDARY AUDIENCE: Neutron absorber material users in general, including regulators and vendors, for wet storage applications

KEY RESEARCH QUESTION

Neutron absorber materials (NAMs) are used in spent fuel pools (SFPs) to maintain criticality safety margins while increasing fuel storage space. With the increasing plant life, there is a need to maintain neutron absorber material monitoring in the SFP. The primary question posed in this study is: Can an industrywide aging management program be implemented 1) to bound the pools that do not have coupon monitoring programs, 2) to allow earlier identification of trends and any potential issues to facilitate the control and mitigation of aging effects?

RESEARCH OVERVIEW

To demonstrate the viability of an industrywide monitoring program, key components of such a program have been identified. The preliminary data collection and analysis for these key components have been performed. The roadmap and timelines for the full implementation of an industrywide monitoring program have been developed.

KEY FINDINGS

- Based on the data collected to date, SFP water chemistry guidelines are, in general, followed closely except for occasional unintentional sulfate excursions.
- Based on the data from operating experience, the blisters and pits on the BORAL® material observed to date do not have any statistically significant impact on reactivity and significant margin exists before there is any significant impact on reactivity. The reactivity impact of blisters and pits observed to date are presented in a companion EPRI report, 3002013119 and readers are referred to that report for more information.
- Data collection and analysis will lead to the development of sister pool criteria. The sister pool criteria will be re-visited at regular intervals as part of the learning aging management program.

WHY THIS MATTERS

For long term effective management of neutron absorber material aging, it is necessary to develop a coordinated industry-wide learning aging management program. In this report, the components, roadmap, and timeline are presented. Once developed and adapted by utilities, this i-LAMP can be useful for identification of any NAM aging issues in a timelier manner vs. individual plant NAM monitoring.

HOW TO APPLY RESULTS

Once the program development is complete, several guidelines will be published by EPRI to guide the utilities on implementation of the industrywide program. For the development of the program, it is recommended that utilities continue to participate by sending the SFP water chemistry, coupon, and any other data that is deemed relevant to EPRI.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- This report is the first report in a series of anticipated reports. During the development and implementation of the industrywide monitoring program, several reports will be published to provide progress updates. Additionally, several guidelines are anticipated to be published as part of the program implementation.
- EPRI's Neutron Absorber Users Group (NAUG) is an annual meeting hosted by EPRI, and attendance is generally limited to utility members. NAUG is a platform for exchanging operational experience and determining research needs. It is intended that this i-LAMP effort will be a primary topic that the NAUG members will follow and provide feedback to EPRI through its formation, implementation, and maintenance.

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ACRONYMS

BWR	Boiling Water Reactor
EPRI	Electric Power Research Institute
i-LAMP	Industrywide Learning Aging Management Program for neutron absorber materials in spent fuel pools
NAM	Neutron Absorber Material
NAUG	Neutron Absorber User Group
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
OE	Operating Experience
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
SFP	Spent Fuel Pool
SPC	Sister Pool Criteria

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1 INTRODUCTION

Spent fuel pools (SFPs) 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 in SFP racks to maintain sub-critical safety margins while increasing pool storage capacity. Some types of neutron absorber materials in use include Boraflex, BORAL®, Carborundum, Metamic, and Borated stainless steel [1]. Some of the neutron absorber materials, most significantly Boraflex, have shown significant degradation over time, and these materials either had to be replaced or be reevaluated with removal of credit for the absorber. Operating experience (OE), however, has shown that the majority of the other neutron absorber materials are continuing to perform their intended function. This operating experience is documented in two EPRI reports [1, 2] and includes a database of the coupon monitoring results from many spent fuel pools spanning over 20 years [2].

The SFP lifetimes are increasing and operating experience has documented that there are a number of pools without a coupon monitoring program or with a limited number of coupon samples remaining. Therefore, EPRI is developing an industrywide learning aging management program (i-LAMP). This program will initially start with BORAL®, the most widely used material in the U.S., and later be extended to other metallic neutron absorber materials. In this report, the proposed industrywide learning aging management program, its components, roadmap and schedule for development and implementation of the i-LAMP are presented.

The organization of this report is as follows: Section 2 describes the background of neutron absorber materials, monitoring approaches, and ongoing EPRI research activities that are designed to improve long term performance of neutron absorber materials. The problem statement and proposed solution for an industrywide monitoring program are described in Section 3. The first component of the program is SFP water chemistry and discussed in Section 4. The second component of the program is the SFP coupon database and presented in Section 5. Sections 6 describes the additional data needs for SFPs without coupons while Section 7 describes potential needs for additional data and analysis. The initial criteria for the definition of sister pools are described in Section 8. The i-LAMP program and its path forward are described in Sections 9 and 10, respectively.

2
BACKGROUND ON NEUTRON ABSORBER MATERIALS

In this section, both the background on neutron absorber materials and a brief overview of ongoing EPRI research activities are presented.

2.1 Neutron Absorber Materials

A brief description of selected neutron absorber materials (NAMs) is presented in this section. More extensive details on each of the neutron absorber types can be found in Reference 1.

Boraflex consists of B_4C particles bound in a silicone rubber matrix. When exposed to radiation, especially gamma, Boraflex degrades significantly [1, 3]. Degradation results in the dissolution of silica into the SFP water and loss of B_4C from the silicone rubber matrix. The degradation was initially identified with the rise of silica levels in the SFP water. Pool water chemistry is characterized at regular intervals to ensure normal operating ranges for specific molecular species as determined by EPRI water chemistry guidelines [4, 5].

Carborundum is composed of B_4C particles in a phenol formaldehyde resin and can be implemented as plate- or sheet-type absorber material. The primary degradation mechanisms include loss of weight and off-gassing from SFP water exposure [1, 6].

BORAL® is a metal matrix composite containing a boron carbide (B_4C) and Al-1100 mixture [1]. The most common material in this category is BORAL®. The core (center of sheet) contains a uniform mixture of boron carbide and Al-1100 alloy. The cladding (Al-1100), which is on both sides of the core, serves as a barrier. Aluminum cladding is susceptible to uniform corrosion in the SFP environment and can lead to blisters between the core material and the cladding over time.

Operating experience with BORAL® has shown that over time blisters and pits (visible primarily via close visual examinations and microscopy) are observed. The EPRI database contains coupon data from utilities spanning more than 20 years and has demonstrated that no loss of the design function of BORAL® has been observed to date [2].

The category of aluminum-based metal-matrix composite NAMs without cladding includes materials like **Metamic** and **Boralcan**. Compared to BORAL®, they are fully dense (no porosity) and there is no aluminum cladding (i.e., the materials are homogenous). Consequently, there are no issues with blistering as is seen in BORAL®. Prior to placement in pools, extensive tests for Metamic were performed, including radiation testing at the Ford Nuclear reactor at the University of Michigan. These tests did not reveal any significant degradation issues [1, 7]. In fact, there was no change in the ^{10}B areal density after the testing when compared to pre-characterized values. Accelerated corrosion tests for Metamic were also performed at 91°C (196°F) for more than 8000 h. At the conclusion of the tests, general corrosion and pitting was observed; however, no significant loss or change in areal density was observed [1, 7].

2.2 Overview of Ongoing EPRI Research Activities on Neutron Absorber Materials

In this section, a brief overview of ongoing EPRI research activities on neutron absorber materials is presented.

2.2.1 Accelerated Corrosion Testing for BORAL®

EPRI initiated the five-year accelerated corrosion testing project in January 2013 [8-10]. The objectives of this project include 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 PWR and BWR water chemistry. At the end of each year, a number of coupons are removed and analyzed to determine the corrosion rate.

Typically, SFP water temperature varies from 27°C to 38°C (80°F to 100°F). The corrosion rate is 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.

At the end of each year, a number of coupons are pulled out and analyzed. The coupon analyses include the following:

- High resolution photography
- Dimension measurements
- Density measurements
- Areal density measurements
- Pit characterization using microscopy, when applicable
- Blister characterization, when applicable.

It should be noted that 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 can be compared to post-bath results. 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.

To date, coupons from years 1 to 4 have been removed and analyzed. The results did not show any statistically-significant change in areal density, even for the clad-removed coupons. The accelerated corrosion coupon results to date are presented in References [8-10].

2.2.2 Zion Comparative Analysis Project

EPRI initiated the Zion comparative analysis project to improve understanding of the long-term performance of BORAL® in SFPs and to evaluate the performance of different monitoring approaches. The results of this project allow comparison of coupon and *in situ* measurement data

against measurement data obtained from the neutron absorber panels harvested from the Zion SFP to gain insights into current monitoring approaches.

The Zion coupon analysis results are presented in an EPRI report [11] and multiple papers [12-13]. The Zion coupon results showed that coupons were, in general, in very good condition even after residing in the Zion SFP for over 22 years, showing a small amount of pitting. There was no statistically-significant change in areal density in any of the coupons.

Then, the neutron absorber panels from the Zion SFP were removed and compared against coupon and *in situ* measurement results. The Zion panel results and comparison to coupons are presented in an EPRI report [14] and papers [15-16]. 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 areal density values for any of the panels. Compared to coupons, panels showed substantially fewer pits.

Although the preliminary analysis showed that *in situ* results underestimated the areal density, the comparison of panels to *in situ* results are still ongoing and the results will be published in an EPRI report in late 2018 or early 2019.

2.2.3 Evaluation of Impact of Blisters and Pits on SFP Reactivity

EPRI initiated the evaluation of the impact of blisters and pits on spent fuel pool reactivity to determine long-term aging effects on reactivity. The results of this study are published in an EPRI report [17]. The computational results demonstrated the blisters and pits observed to date, based on operating experience, have no statistically-significant impact on reactivity. Furthermore, the computational results also established that to observe any significant impact on reactivity, the blister and pit sizes need to be substantially larger (by several orders of magnitude) than what has been observed to date. The computational results demonstrate the presence of significant margin between observations to date and the level of blistering or pitting required to produce a statistically-significant impact on reactivity.

2.2.4 Neutron Absorber Material Handbook

EPRI's neutron absorber material handbook includes information on characteristics of different types of neutron absorber materials that have been used for storage and transportation of used fuel. It contains information on all past and current neutron absorber materials used for wet and dry storage and provides data on each absorber (including physical, mechanical, and neutronic properties). Furthermore, it 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 serves as a single source of information for the majority of neutron absorber material types used in the nuclear industry. Since the last release, there have been new material developments, many additional tests conducted, and operating experience gained. Consequently, EPRI is currently working toward updating the handbook. It is anticipated that the revised version will be published by the end of 2019 or early 2020.

2.3 EPRI's Neutron Absorber User Group (NAUG)

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

The NAUG meetings are held annually and attendance is by invitation only, limited to 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.

3
PROBLEM STATEMENT AND PROPOSED SOLUTION

There are a number of SFPs that use BORAL® as a neutron absorber material and do not have a coupon monitoring program or with 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 neutron absorber materials in SFPs.

3.1 i-LAMP Overview

The general overview of the proposed i-LAMP is illustrated in Figure 3-1. As shown in the figure, i-LAMP has four components:

- **Component 1:** SFP Water Chemistry Database
- **Component 2:** SFP Coupon Database
- **Component 3:** NAM data for SFPs with no coupons
- **Component 4:** Additional data and analysis needs

Using these four components, **sister pool criteria (SPC)** will be developed. As shown in Figure 3-1, as part of the learning aging management, each component communicates with each other and will be re-visited at regular intervals. The details for each of the components are described in the following sections.

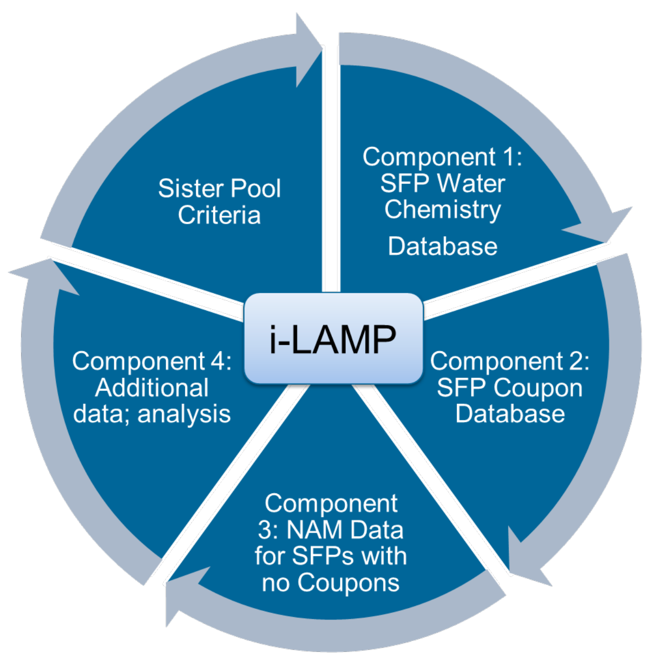

Figure 3-1
Overview of i-LAMP with all the components leading to a learning aging management program to monitor neutron absorber materials in SFPs

3.2 i-LAMP Benefits

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

- Coordinated monitoring, which allows identification of any potential issue sooner. At the NAUG, a portion of the meeting is devoted to OE 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.

4

COMPONENT 1: SFP WATER CHEMISTRY DATABASE

The SFP water chemistry is monitored at regular intervals at all the SFPs in the U.S. and in many of the countries around the world. SFP water chemistry measurements serve two purposes:

- Ensuring compliance with water chemistry guidelines for corrosion. The EPRI BWR and PWR water chemistry guidelines [4-5] recommend Chloride (Cl), Fluoride (F), and Sulfate (SO_4) levels below 150 ppb to reduce the corrosion potential. The guidelines were developed primarily to reduce corrosion of the fuel.
- It is a monitoring tool, when there are anomalies, the chemistry levels will be an early indicator. For example, boraflex degradation was first identified when SFP silica levels were elevated.

In other programs, water chemistry is used as part of an industrywide monitoring program for the same purpose.

The overall objectives for the development of the SFP water chemistry database, as envisioned as part of a learning aging management program, is depicted in Figure 4-1.

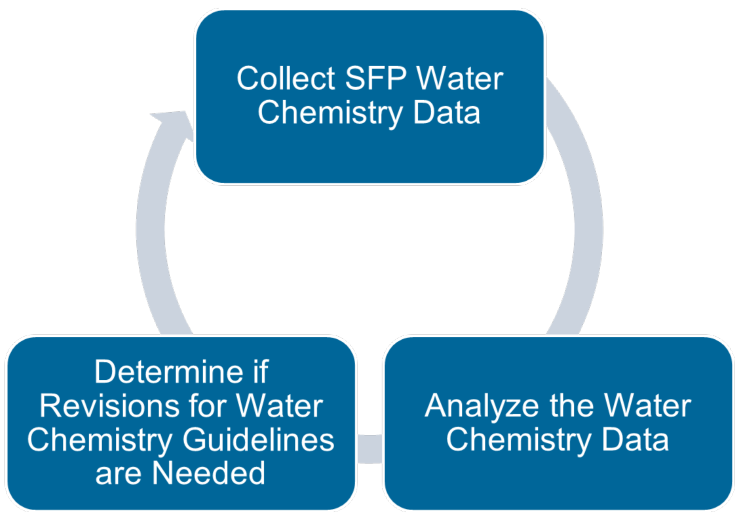

Figure 4-1
Illustration of the overall objectives of the SFP water chemistry database

4.1 Data Collection for the SFP Water Chemistry Database

The SFP water chemistry data collection for this Component started in late October, 2017. To date, SFP water chemistry data from over 30 pools have been collected, corresponding to over 70,000 data points, and are currently being populated to the database. The collected data include all the measured parameters for each pool. The parameters that are measured and recorded at every SFP thus far include:

- pH
- Conductivity
- Chloride (Cl) concentration
- Fluoride (F) concentration
- Sulfate (SO_4) concentration

Additionally, for PWRs

- Boron (B) concentration
- Sodium (Na) concentration

For pools that still have Boraflex, silica levels are also measured.

Very few pools also measure Aluminum (Al) but the majority of utilities discontinued this practice since Al levels were usually below detectable limits.

At this point, no additional measurements are required. The historic SFP water chemistry data from all US utilities (~100 SFPs) and other participating countries (for example, Mexico, Taiwan, Korea) will be collected and populated into the database by mid-2019.

Once the collection of historic data is complete, it is anticipated the database will be updated with the new data approximately every six months.

4.2 Examples of SFP Water Chemistry Data

For illustration purposes, several examples from the SFP water chemistry data that have been collected to date are presented in the following figures. For some of the SFPs, the time interval of measurements span over two decades. For the initial analysis, the measured SFP water chemistry data from all of the SFPs (including PWRs and BWRs) are merged.

In the figures, the recommended levels are shown with a dark red solid line.

The Cl levels for over 30 pools are presented in Figure 4-2. The figure includes over 10,000 measurement points. As evident from the figure, all the measured Cl levels are within the recommended levels without any exception. The maximum measured Cl level is 150 ppb.

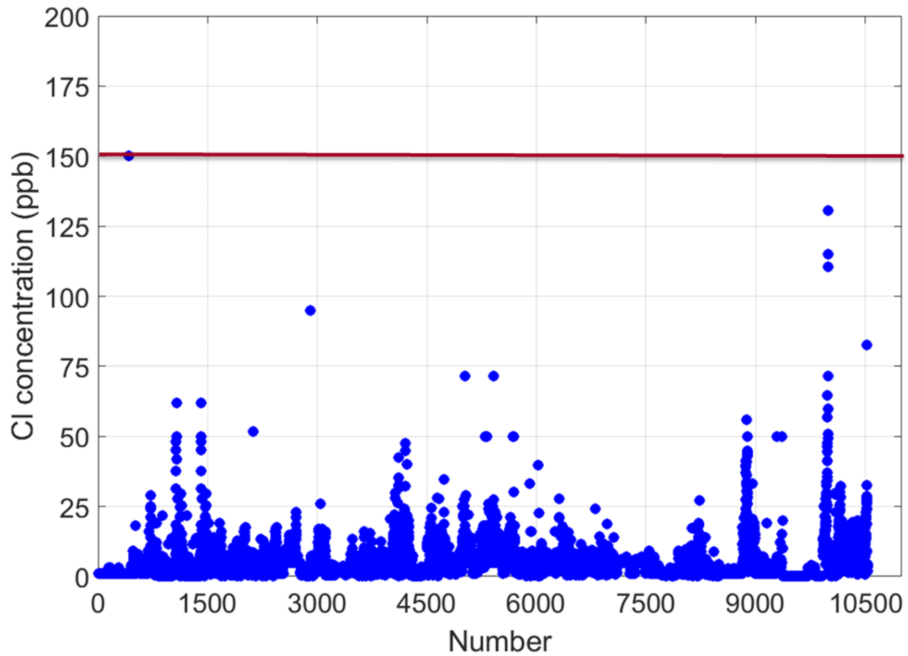

Figure 4-2
The measured Cl levels for over 30 SFPs

The measured F levels for the same SFPs are presented in Figure 4-3. As evident from the data representing over 10,000 data points shown in Figure 4-3, the F levels are well below the recommended 150 ppb for all the measured points. The maximum measured F level is 64 ppb, well below the recommended value.

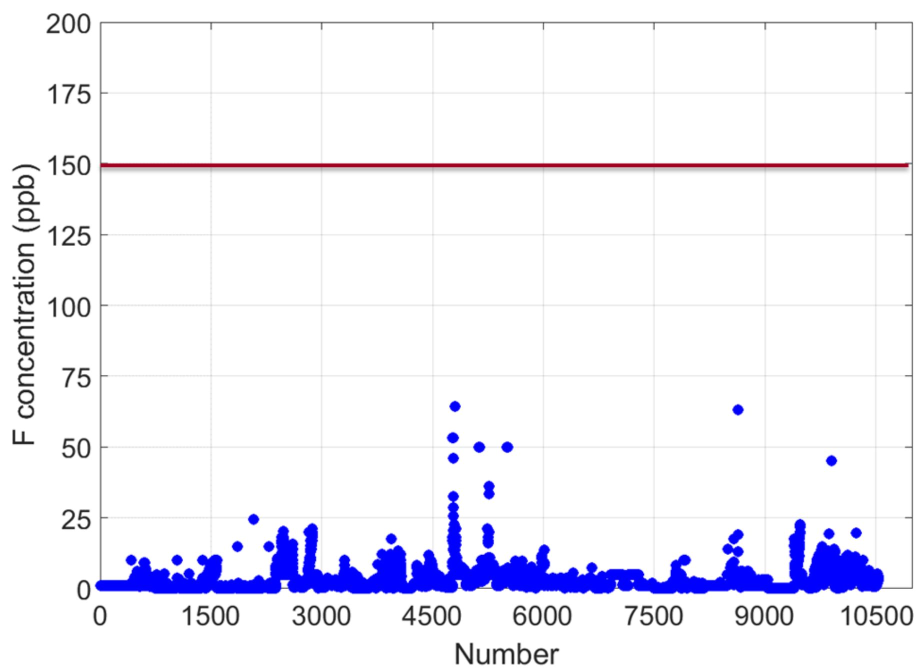

Figure 4-3
The measured F levels for over 30 SFPs

The measured sulfate levels, for the same SFPs, are presented in Figure 4-4. As shown in the figure, several measurements are above the recommended level of 150 ppb. A closer inspection and preliminary analysis of the data showed that

- The maximum measured sulfate level in the data collected **to date** for these SFPs is 446 ppb (~3x higher than the recommended value).
- Out of 10,500 measurement points, 126 data points are above the recommended level of 150 ppb. It should be noted that all the points that are above the recommended value do not belong to the same SFP. Furthermore, when excursions occur, plants monitor the sulfate levels more frequently.
- For any single SFP, the maximum number of consecutive days where the sulfate levels were above 150 ppb, was 12.

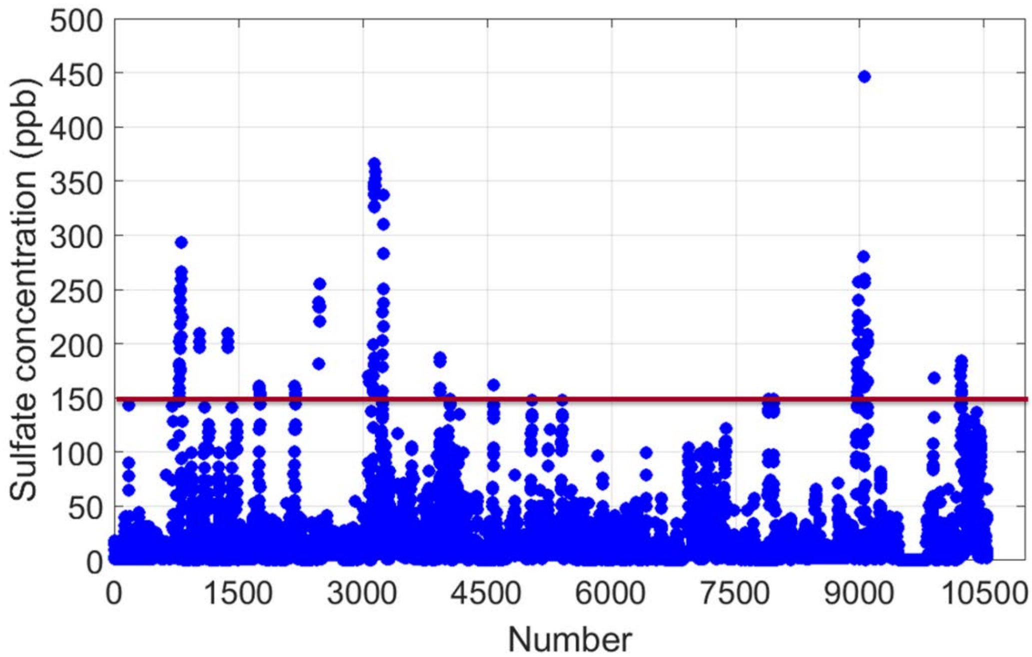

Figure 4-4
The measured sulfate levels for over 30 SFPs

To understand the impact of elevated sulfate levels, additional information is needed. This will be addressed as part of Component 4, need for additional data and analysis.

4.3 SFP Water Chemistry as Part of i-LAMP

Once all the data are collected and analysis performed, the need for any revision on water chemistry guidelines may be evaluated depending on the results. Additionally, an analysis will be performed to determine if there is any need for additional data collection (for example, starting the collection of Al data for all SFPs).

As part of the learning aging management, the SFP chemistry data collection sufficiency analysis will be re-visited every 2-3 years, with the possibility of increased intervals in the future.

5

COMPONENT 2: SFP COUPON DATABASE

The SFP coupon database is being developed to collect the data, analyze the data to determine bounding conditions (changes in areal density, maximum observed blisters/pit sizes to date), trends (as a function of time in service), and any potential relation between potential degradation and any relation to SFP water chemistry and other parameters.

The overall cycle for the SFP coupon database is illustrated in Figure 5-1.

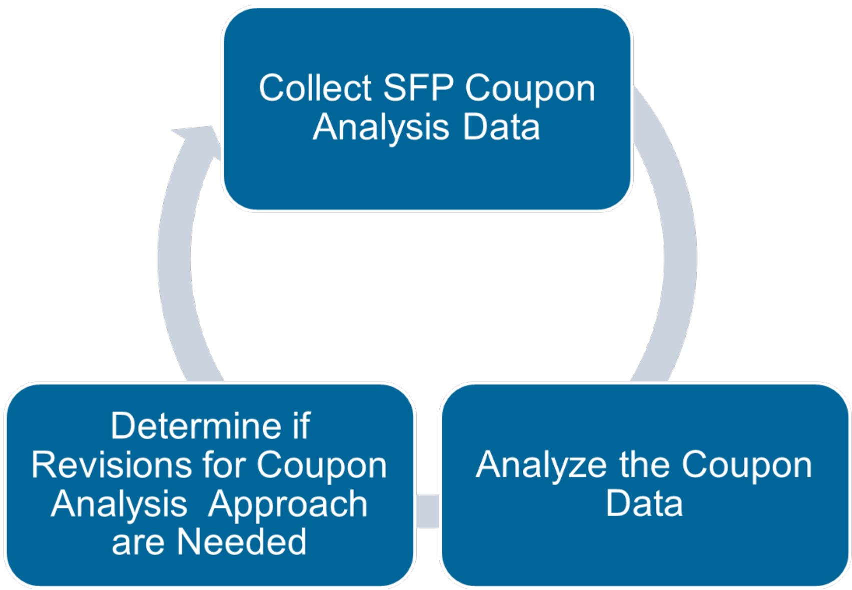

Figure 5-1
SFP coupon database flowchart illustrating overall objectives and cycle as part of i-LAMP

5.1 SFP Coupon Data Collection

Unlike SFP water chemistry, development of the coupon database poses more challenges. First, there are multiple vendors performing coupon analysis. Second, some of the utilities are performing their own in-house analysis. Subsequently, there are variations in the analyses performed and in the documentation of the results. Furthermore, some of the historic coupon analysis reports are not available electronically. Hence, these reports are being scanned and converted to electronic form.

The data that are being extracted from coupon reports currently include:

- Pool name
- Rack installation year
- Rack type (egg crate versus flux trap)
- Stainless steel encapsulation or not
- Coupon unique ID number

- Coupon analysis year(s), if the same coupon is analyzed multiple times
- Dimension data (pre-characterization and post-irradiation)
    - Height, width, thickness
- Weight
- Areal density values (pre-characterization and post-irradiation)
- Pit & blister data
- Pictures

The current plan is to link the coupon data in the database (including pictures) to the original coupon report from which the data was extracted. This would also allow easier cross checking with the original reports/documentation.

5.2 Examples of SFP Coupon Data

In this section, some of the features from the SFP coupon data to date are presented.

5.2.1 SFP Coupon Pit Data

The measured pit depth and area as a function of frequency are presented in Figure 5-2 and Figure 5-3, respectively. These figures include over 100 coupon data points representing over 20 SFPs, including both PWR and BWR, with service time varying from 1 to 18 years. Based on the actual coupon data from these SFPs:

- Maximum observed pit depth is ~0.1016 cm (0.04 in)
- Maximum observed pit area is ~ 0.3 cm^2 (0.046 in^2)

It should be noted that the maximum pit depth and area includes Al cladding, which is usually 0.025 cm (~10-12 mil) thick [1]. The analysis performed to determine the impacts of pitting on SFP reactivity showed that this size of pitting has a negligible impact on reactivity even when extrapolated to the entire panel surrounding the storage cell [17].

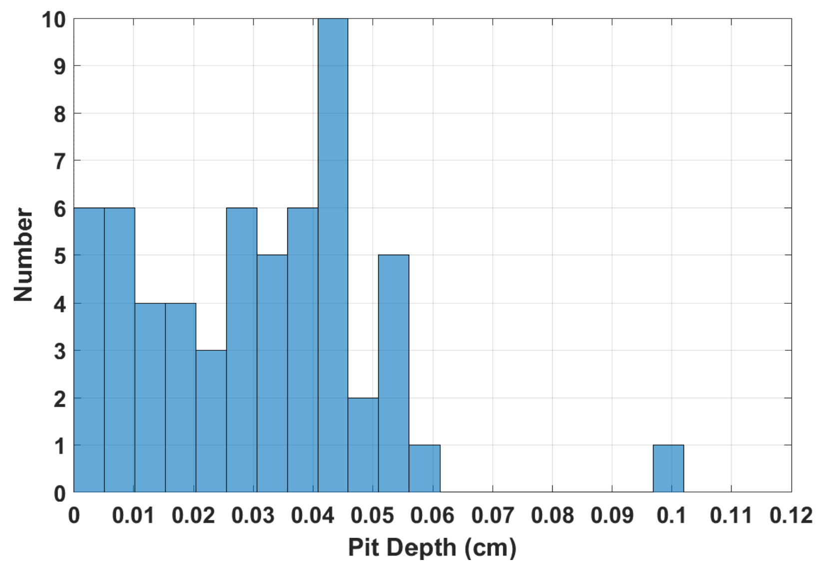

Figure 5-2
Pit depth as a function of frequency for SFP coupons

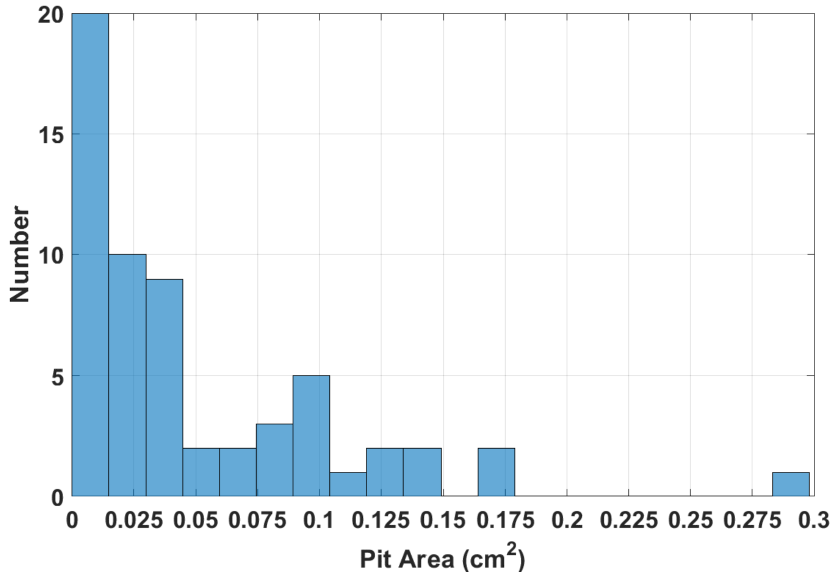

Figure 5-3
Pit area as a function of frequency for SFP coupons

5.2.2 SFP Coupon Blister Data

The measured blister height and area as a function of frequency are presented in Figure 5-4 and Figure 5-5, respectively. These figures include over 100 coupon data points representing 20 SFPs with service time varying from 1 to 18 years. It should be noted that the majority of the coupons (80%) did not show any blisters. For the remaining coupons, the majority showed only a few blisters while several of the coupons showed a larger number of blisters. Based on the actual coupon data from SFPs:

- Maximum blister height is ~0.4 cm (~0.16 in)
- Maximum blister area is ~21.4 cm^2 (~3.32 in^2)

The analysis performed to determine the impact of blisters on SFP reactivity showed that blisters of these sizes have negligible impact on reactivity [17].

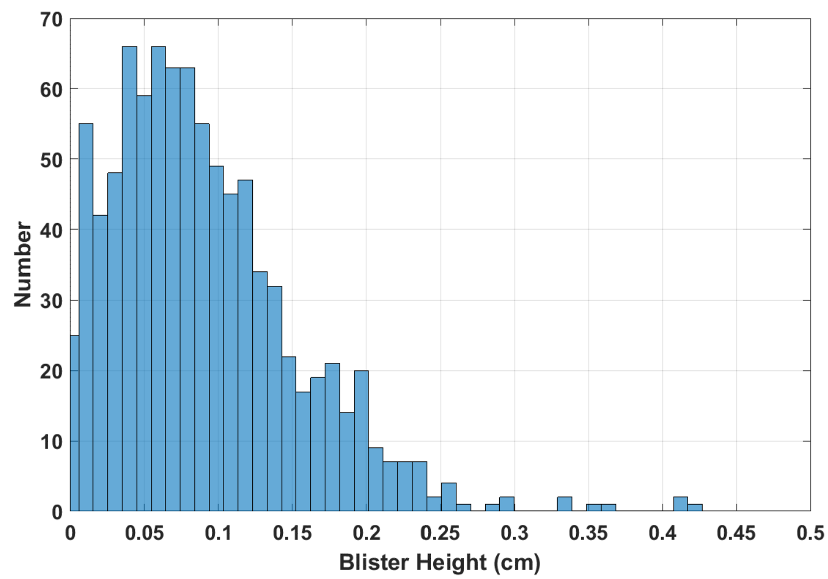

Figure 5-4
Blister height as a function of frequency for SFP coupons

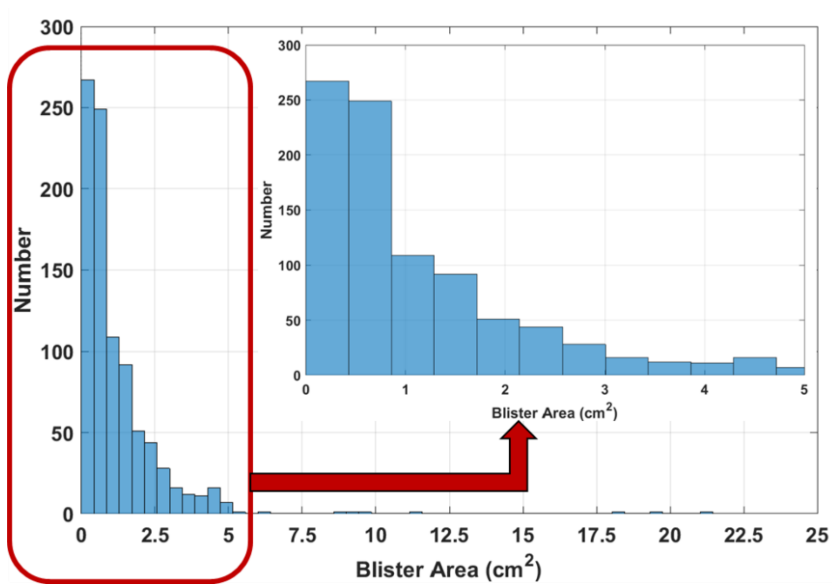

Figure 5-5
Blister area as a function of frequency for SFP coupons

5.2.3 Trending Blister Growth Over Time

Currently, there are a few pools that perform visual inspection at regular intervals and re-insert the coupon into the SFP. For these pools, the analysis includes visual inspection and dimension measurements. These inspections also include the measurement of the blister height, which allows trending over time.

As an example, the blister growth data for a coupon over a long period of time is presented in this section. The coupon was placed in the SFP in 1983 and belongs to one of the currently operating SFPs. This SFP has an egg crate rack geometry (Region 1) with neutron absorber

panels that are encapsulated in stainless steel. The coupon itself was also initially encapsulated; however, in 1991, the SS encapsulation was removed and since then, the coupon resides in the SFP without any encapsulation. The coupon size is 15.24x15.24 cm (6x6 in).

The pictures of the coupon showing blisters on the front and back side of the coupon are available from 2010 and 2017. The pictures for the front and back of the coupon from 2010 (left) and 2017 (right) are shown in Figure 5-6 and Figure 5-7, respectively. As shown in the figure, the front side of the coupon has four blisters with varying sizes. The back side of the coupon, has two blisters with varying sizes. As is evident from the pictures, there is no significant change in blister size between 2010 and 2017.

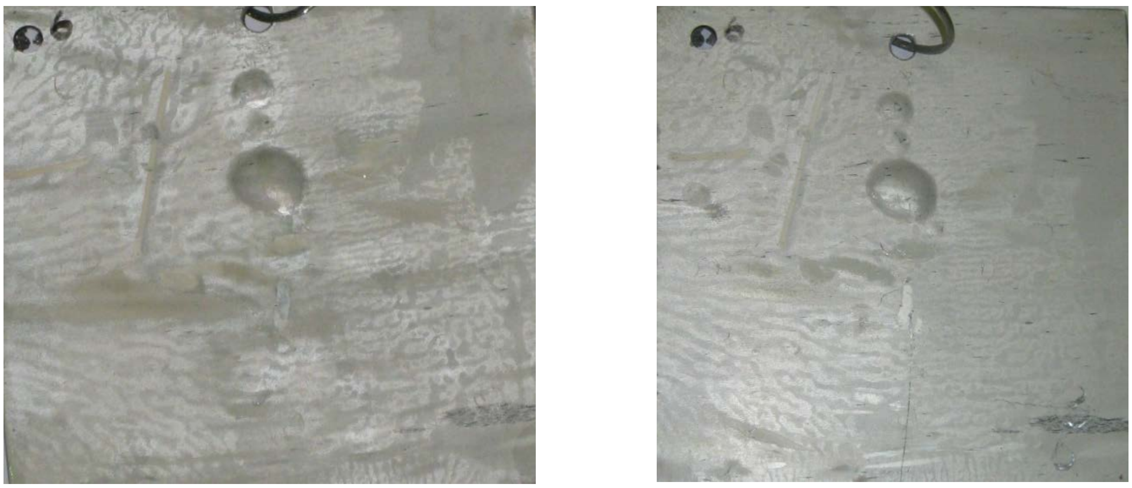

Figure 5-6
Front side of the coupon from 2010 (left) and 2017 (right)

Figure 5-7
Back side of the coupon from 2010 (left) and 2017 (right)

Between 1991 and 2017, the blister height measurements were taken at certain intervals. For this coupon, the blister height and area as a function of measurement year are presented in Figure 5-8 and Figure 5-9, respectively. In these figures, F-1 to F-4 represent the blisters on the front side of the coupon and B-1 to B-2 represent the blisters on the back of the coupon. As is evident from the figure, between 1991 and 2017, there is no large variations in blister growth. The variation in sizes is mainly due to the measurement uncertainty which includes changes in measurement equipment, human performance, selection of measurement points, and potential other factors that are not fully confirmed. These figures demonstrate that even for older vintages of BORAL®, which are most susceptible to blister growth, after initial formation of the blisters, blisters stabilize and do not continue to grow. Although only one coupon with the largest blister sizes is included in this report as an example, similar behavior was observed in other coupons in the same pool.

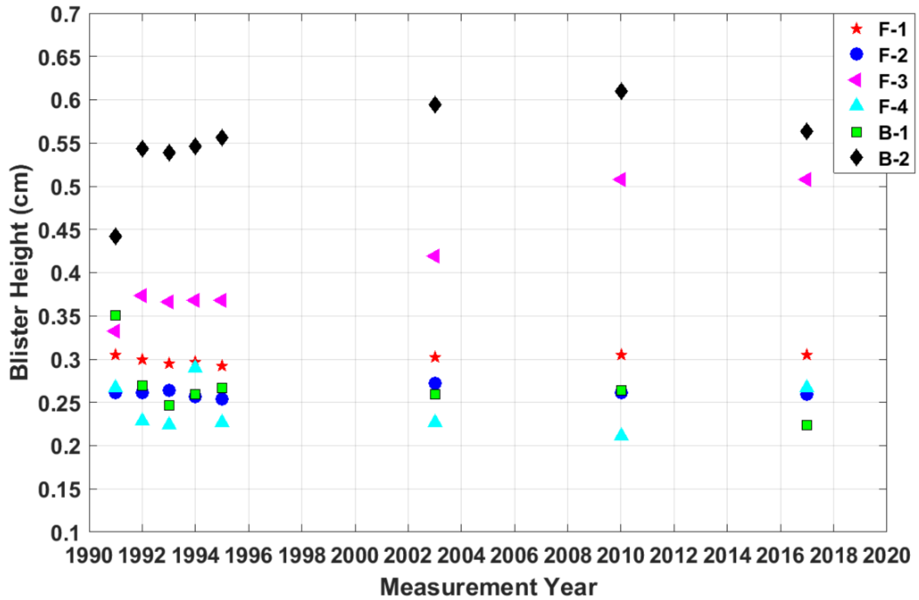

Figure 5-8
Blister height as a function of measurement year

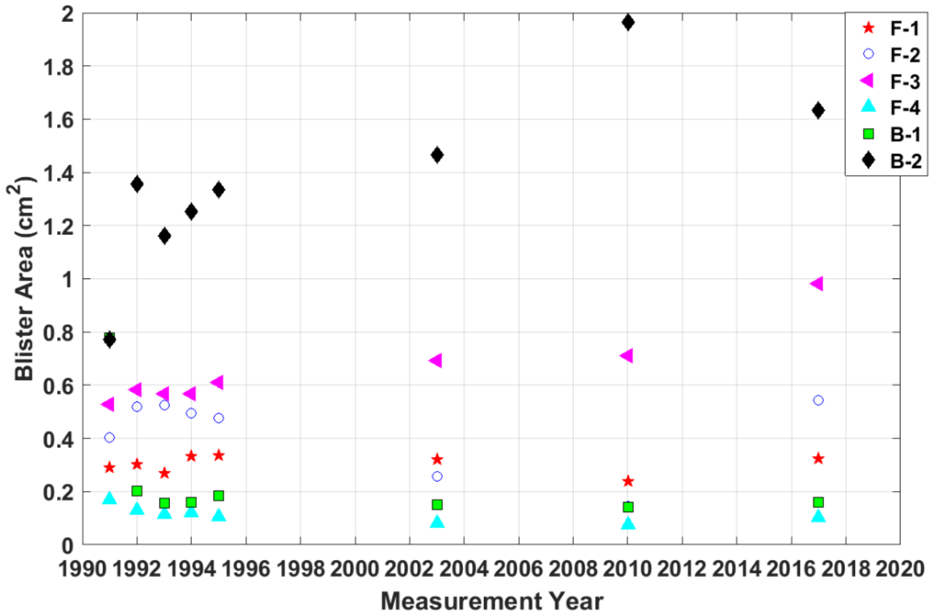

Figure 5-9
Blister area as a function of measurement year

6
COMPONENT 3: BASIC INFORMATION NEEDED FOR SFPS WITH NO COUPONS

To develop an industrywide monitoring program and develop sister pool criteria for the entire fleet of SFPs, basic information on neutron absorber materials from all the participating SFPs will need to be gathered. This data collection and analysis will allow for the development of sister pool criteria.

Therefore, for SFPs without a coupon program, some of the basic information related to neutron absorber materials also needs to be collected and analyzed. The basic information needed for SFPs without coupons includes, but is not limited to:

- Neutron absorber material areal density values
- Neutron absorber material thickness
- Manufacturing and installation year
- Manufacturer and vendor information may also be needed

The coupon database (Component 2) will already include information on the rack geometries. This is important since there are many different variations in rack geometry. If it is determined that there is a correlation between coupons and racks, then the information on rack geometries for SFPs without a coupon program will also be collected.

Additionally, if it is determined that the NAM properties in this Component are not bounded by the NAM properties in Component 2, additional analysis will be needed. The scope of the additional analysis will be determined after the completion of the data collection and analysis of the range of variations.

7
COMPONENT 4: EVALUATION OF POTENTIAL NEEDS FOR ADDITIONAL DATA AND ANALYSIS

For a given neutron absorber material, aging effects in SFPs are a function of:

- Time in the SFP
- Cumulative neutron dose
- Cumulative gamma dose
- Temperature
- Water chemistry
- Type and vintage of the material

Table 7-1 summarizes the ongoing EPRI research on NAMs and the corresponding parameters it addresses. For SFP coupon database, dose information is not collected; however, given the variations in time for coupons residing in SFPs, the coupon analysis results will indirectly provide the impact of the radiation on NAM performance. A brief overview of these research projects was presented in Section 2 and more description is available in References [8-17]. As shown in the table, the ongoing research projects provide additional information on long-term performance of NAMs and the impact of certain parameters. For example, for the accelerated corrosion project, the coupons were placed in test baths representing PWR and BWR water chemistry at elevated temperatures. During the first year, sulfate levels were unintentionally significantly higher (1500 ppb) than the EPRI recommended levels (150 ppb. None of the coupons in the PWR test bath showed significantly more degradation, which can demonstrate that even at higher sulfate levels, the material is still robust.

However, when the historical SFP water chemistry and coupon data collection is completed, any variations will be evaluated to determine if additional research projects are required to close the information gaps and improve the understanding of the long-term impacts on the material's intended function.

Table 7-1
Summary of ongoing EPRI research on neutron absorber materials

Key Parameters ⇨ EPRI Studies ⇩	Temperature	Radiation	Chemistry (Cl, F, SO_4)	Blisters / Pits	In Situ Testing Coupons / Panels
Accelerated Corrosion **(Elevated Temperature)**	✓		✓	✓	
Zion Comparative Analysis	✓	✓	✓	✓	✓
Impact of Blisters and Pits on Reactivity				✓	
SFP Water Chemistry & Coupon Databases	✓	✓	✓	✓	

8
SISTER POOL CRITERIA

In order to be able to make meaningful comparative conclusions from the data collected as part of the databases, it will be important to determine which parameters make SFPs similar. To do this, an evaluation of the data will need to be done to determine the sister pool criteria.

8.1 Background

The use of plant specific data for sister plant surveillance is used in several other areas. Some examples include

- Reactor Pressure Vessel (RPV) program [18].
- Boiling Water Reactor Vessel Internal program (BWRVIP) [19, 20]
- In dry storage, a similar program is used for monitoring of dry storage casks [21].

Each of these programs established the program based on the specific application and intended function of the monitored component.

8.2 Development of Sister Pool Criteria for SFPs

The development of the sister pool criteria (SPC) is highly dependent on the quality of data collected in the databases (Components 1-3) and additional analysis, if it is deemed necessary. Figure 8-1 illustrates the dependence of components with each other and in determining the sister pool criteria.

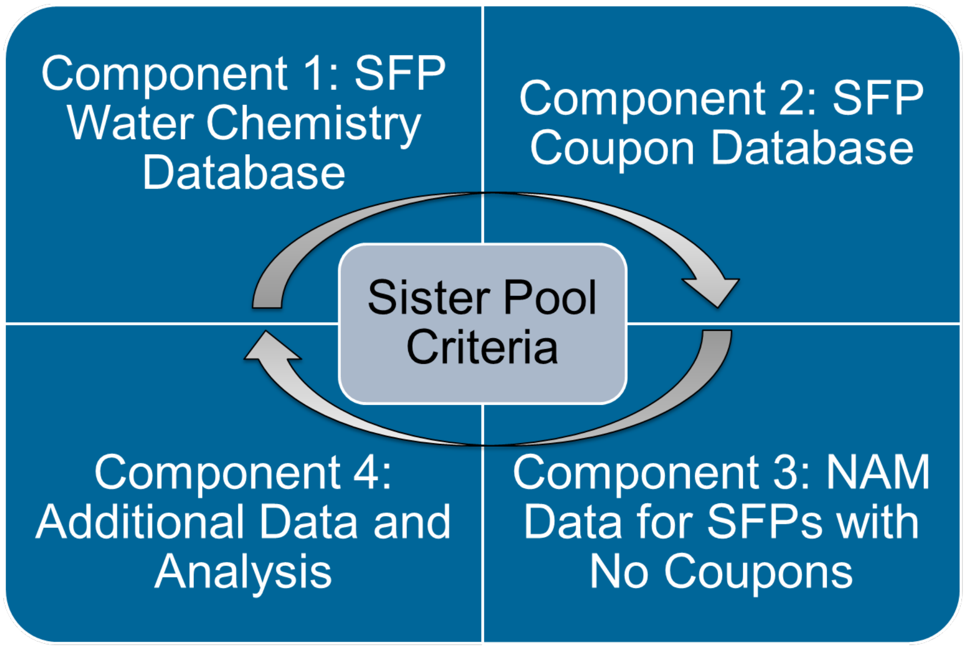

Figure 8-1
Illustration of dependence of sister pool criteria and Components 1 to 4

The data collected will need to address the potential variables that will need to be considered in the development of the sister pool criteria and this is further explored in Section 8.2.1. During the collection of the relevant data, each of these Components will be analyzed and synergized to determine if there are any correlations or trends. This process is outlined in Section 8.2.2.

8.2.1 Potential Variables for Consideration in Sister Pool Criteria Development

Data collection will ultimately feed into the sister pool criteria analysis, so it is important to keep in mind some of the potential variables that would need to be considered in the sister pool analysis. A list of the potential variables that may be needed for the sister pool criteria analysis and development are tabulated below. The list of potential variables also includes the Component for which the variable would be collected.

Potential variables that are considered for sister pool criteria development:

- **Water Chemistry –** Component 1 (Section 4 of this report)
- **Reactor type** (PWR or BWR) - Component 1 (Section 4)
- **Vintage Type –** Component 2 for SFPs with Coupons, Component 3 for SFPs with no coupons (Sections 5 and 6 of this report, respectively)
- **Areal density –** Component 2 for SFPs with Coupons, Component 3 for SFPs with no coupons (Sections 5 and 6)
- **Thickness –** Component 2 for SFPs with Coupons, Component 3 for SFPs with no coupons (Sections 5 and 6)
- **Manufacturing and installation years –** Component 2 for SFPs with Coupons, Component 3 for SFPs with no coupons (Sections 5 and 6)
- **Rack geometries –** Component 2 for SFPs with Coupons, Component 3 for SFPs with no coupons (Sections 5 and 6)
- **Dose and Temperature limits –** Component 4 (Section 7)
- Other variables, as determined **–** Component 4 (Section 7)

8.2.2 Sister Pool Criteria Development Process

The following are the generalized steps of the sister pool criteria process:

1. **Collection of the data:** For the initial determination of the SPC, it is very important to have completed the collection of the historical data for Components 1-3. After the initial collection, having updated data will help to inform if the criteria would need to be revised.
2. **Analysis of the data:** Each of the Components will be analyzed and, when appropriate, synergized. During the analyses, it is important to remain cognizant and focus on the intended function of the neutron absorbing material in the SFP: maintain subcriticality in the SFP.
    a. Component 1, SFP water chemistry analysis (see Section 4)
    b. Component 2, coupon data analysis (see Section 5)
    c. Synergy of Components 1 and 2: There may be portions of Components 1 and 2 that may have synergistic effects. After the Component 1 and 2 analyses are completed, these results can be analyzed against each other to determine if there is a synergistic effect. The cross analysis of SFP water chemistry and coupon data for the evaluation of the possible

synergistic effects and determination of an overlap region where increased impact of aging and other potential degradation is observed is illustrated in Figure 8-2.

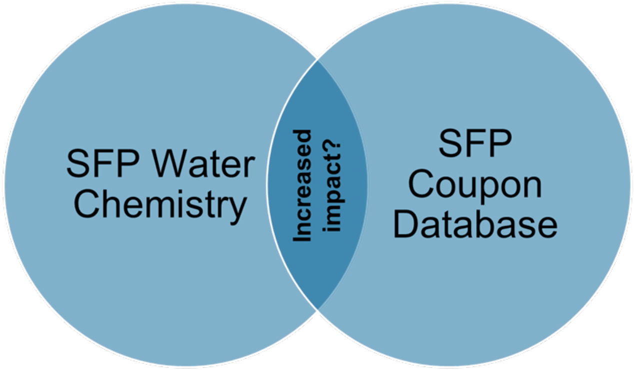

Figure 8-2
Illustration of cross analysis of SFP water chemistry and coupon database to determine if an overlap region exists where increased aging or potential degradation is possible

d. Synergistic Component 2 and Component 3 analysis: After the collection of coupon data as part of Component 2 for SFPs with coupons and NAM data for SFPs without coupons (Component 3), they will be analyzed together to determine if SFPs without coupons are a subset of the SFPs with coupons, as illustrated in Figure 8-3. If not, additional analyses will be required for SFPs without coupons not covered by the Component 2 SFPs with coupons.

Figure 8-3
Illustration of ideal case for Component 3, which will be a subset of Component 2

e. Synergistic Component 1, 2 and 3 analyses: There may be portions of Components 1, 2, and 3 that may have synergistic effects. After the Component 1, 2, and 3 analyses are completed, these results can be analyzed to determine if there is a synergistic effect and if

there is need for additional data and evaluations based on the synergistic analysis. Additional analysis will be part of Component 4, as illustrated in Figure 8-4.

Figure 8-4
Illustration of potential synergistic effects and need for additional analysis, part of Component 4

3. **Development of the sister pool criteria:** Once all the Components have been analyzed and the synergistic effects determined, the sister pool criteria can be developed. As a starting point, for simplicity, initially only two bins are proposed. The first bin contains all SFPs with coupons. The second bin will contain the SFPs that currently do not have coupons.

    a. **Initial Bin 1: SFPs with coupons –** The SFPs in this bin have a coupon monitoring program, and this bin will identify the bounding conditions that will inform the sister pool criteria. It is important to consider the potential variables when determining the sister pool criteria.

    b. **Initial Bin 2: SFPs with no coupons –** The SFPs in this bin do not have coupons and therefore, would ideally be bounded by the sister pool criteria developed from Bin 1. Figure 8-3 shows the ideal case where the SFPs with no coupons are bounded by the SPC determined by the SFPs with coupons (Bin 1). If it cannot be determined that all the SFPs in this bin are bounded by the SPC from Bin 1, then further analysis, as shown in Figure 8-4, will be needed.

4. **Re-evaluation of Components 1-4 for updates:** Analysis of the data will continue to determine if refinement of the SPC is needed. Sub bins may be created and analyzed as needed.

8.3 Considerations for early shutdown pools

Once the i-LAMP has been established, it will be important to maintain the sample size in order to maintain its effectiveness. For this reason, EPRI's recommendation is for SFPs that are participating in the program and are planning to be decommissioned to communicate with their sister pools and move the coupon tree to a sister pool. This will be further defined upon completion of the analysis of the initial data set.

9
I-LAMP: INDUSTRYWIDE LEARNING AGING MANAGEMENT PROGRAM

After the sister pool criteria have been defined (Section 8), the i-LAMP guidelines will be developed, with input from the industry. These guidelines will be published by EPRI as recommendations and will be reviewed at each NAUG meeting for any changes that may be necessary. EPRI will perform an initial detailed evaluation of these guidelines 3 years after publication and then followed by every 5 years. This proposed interval will be adjusted as needed.

9.1 Initial Setup of the i-LAMP Guidelines

Each of the Components (1-4) will be developed as described in Sections 4-7. Figure 9-1 outlines the current vision of the components, corresponding ownership, and access to each of the Components. As shown in the figure, EPRI will host the SFP water chemistry and coupon databases and access will be limited to the EPRI members.

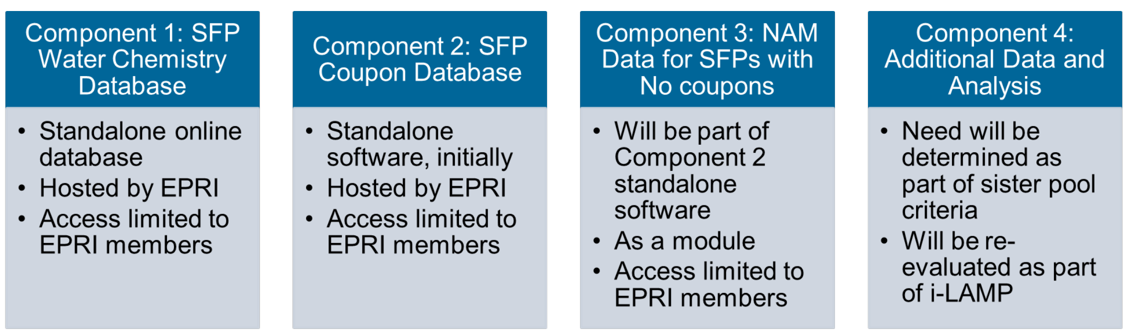

Figure 9-1
Outline of the Components in i-LAMP

Once these Components are initially populated and the sister pool criteria developed, the initial version of the i-LAMP guidelines will be developed following these proposed steps:

1. EPRI publishes SPC guidelines
2. Industry uses SPC guidelines to establish the sister pools (NAUG can be a forum for the development of SPC)
3. Technical basis for each of the sister pool categories is developed based on the EPRI tools and guidelines and industry feedback
4. EPRI publishes the i-LAMP guidelines
5. i-LAMP established; repeat above steps as needed

9.2 Future Potential Expansion of the i-LAMP

During the initial set up of the i-LAMP guidelines, it will start with SFPs that contain BORAL®. In the future, the i-LAMP guidelines will be expanded to include other neutron absorber materials. To do this, the data for Components 1-4 would need to be inputted into the databases and sister pool criteria developed before the i-LAMP guidelines for additional materials can be created.

The i-LAMP guidelines could also be expanded to include guidance for sSFPs to perform coordinated coupon measurements. This could initially be applied to SFPs that contain BORAL®, and once other materials have been inputted into the system, could be expanded to other material coupon testing as well. The guidance on these coordinated measurements and analysis will also need to be determined. The ability to perform coordinated measurements is of high interest since some of the potential benefits include:

1. Reduces the burden on sister pools to perform frequent inspections.
2. Reduces overall risk and dose incurred on workers.
3. Reduces overall cost.
4. Provides ability to select coupons that are of most interest among the samples in a rotating manner to improve understanding of the behavior, as needed.
5. Preserves the coupon population.

9.3 Recommendations for Industry Practices

For the best results of using the i-LAMP guidelines, the preliminary EPRI recommendations for guidance development and updates include:

- Guidance for coordination of shutdown plant/pool coupon tree removal and subsequent re-insertion into an identified host sister pool
- Guidance to standardize data collection for ease of sister pool criteria analysis
- Guidance for standardizing coupon removal and measurements taken
- Guidance for re-inserting the coupons
- Determine if updates are needed for the EPRI Water Chemistry Guidelines

It is also recommended that those with SFP NAM participate in the NAUG. This meeting will be beneficial to those members attending due to these agenda items:

- Review of the sister pools and sister pool criteria.
- Sharing of operating experience. While some of the operating experience will be captured in the coupon database, it is important to keep up to date with the industry operating experience of all materials. This can be done through reviewing the INPO database, participation in NAUG, keeping up to date on NRC generic communications, and other relevant information sources.

10 SUMMARY AND PATH FORWARD

In this report, the components of the proposed industrywide learning aging management program are presented. At this preliminary stage, it is proposed to have two bins for sister pool criteria: One of the bins will include SFPs with a coupon monitoring program while the other bin will include SFPs without a coupon monitoring program. Once the data collection and analysis are complete, sister pool criteria will be revised as needed.

The proposed schedule is illustrated in Figure 10-1 and will be updated as the work progresses. Based on the initial proposed schedule, it is anticipated by the end of 2019, data collection and analysis will be completed and will be determined if finer binning is needed. Once the data collection and analysis are complete, guidelines for sister pool criteria development will be developed and discussed at NAUG meetings. Depending on the analysis results, it will be determined if guideline development for water chemistry and coupon analysis is needed. If it is deemed necessary, EPRI will develop the guidelines and communicate to the industry and regulator.

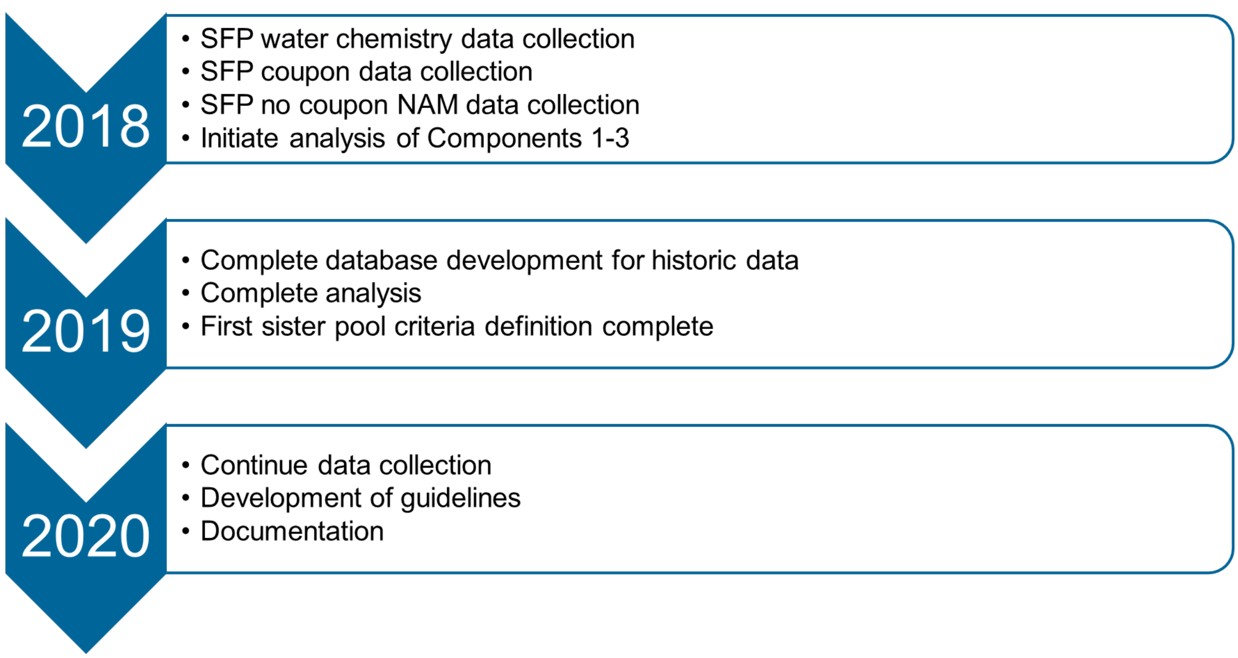

Figure 10-1
Graphical illustration of the near-term plans for development and implementation of i-LAMP

11
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. T. C. Haley, "*Boraflex, Racklife, and BADGER,*" NRC ML 12216A307, September 2012.

   http://pbadupws.nrc.gov/docs/ML1221/ML12216A307.pdf

4. *BWRVIP-190 Revision 1: BWR Vessel and Internals Project, Volume 1: BWR Water Chemistry Guidelines – Mandatory, Needed, and Good Practice Guidance*. EPRI, Palo Alto, CA: 2014. 3002002623.

5. *Pressurized Water Reactor Primary Water Chemistry Guidelines: Volume 1, Revision 7.* EPRI, Palo Alto, CA: 2014. 3002000505.

6. M. Hiser, A. Pulvirenti, M. Al-Sheikhly, "*Monitoring Degradation of Phenolic Resin-Based Neutron Absorbers in Spent Nuclear Fuel Pools,*" NRC ML13141A182, June 2013.

   http://pbadupws.nrc.gov/docs/ML1314/ML13141A182.pdf

7. *Qualification of METAMIC for Spent-Fuel Storage Application*, EPRI, Palo Alto, CA: 2001. 1003137.

8. 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).

9. 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).

10. Akkurt, H., A. Quigley, and M. Harris, "Accelerated Corrosion Tests for the Evaluation of Long-Term Performance of Boral in Spent Fuel Pools," R*adwaste Solutions*, V 25, No 1, 41-43, Spring 2018.

11. *Evaluation of BORAL® Coupons from Zion Spent Fuel Pool*. EPRI, Palo Alto, CA: 2016. 3002008195.

12. H. Akkurt, S. Feuerstein, M. Harris, and S. Baker, "Overview of Zion Comparative Analysis Project for Assessment of BORAL® Neutron Absorber Material Performance and Monitoring in Spent Fuel Pools," Proceedings of the ANS Conference: 2015 International Conference on Nuclear Criticality Safety. Charlotte, NC (September 13–17, 2015).

13. H. Akkurt, S. Feuerstein, M. Harris, and A. Quigley, "Analysis of BORAL® Coupons from Zion Spent Fuel Pool," *Trans. Am. Nuc. Soc.*, **113**, 372–375 (2015).

14. *Evaluation of BORAL® Panels from Zion Spent Fuel Pool and Comparison to Zion Coupons*. EPRI, Palo Alto, CA: 2016. 3002008196.

15. H. Akkurt, M. Harris, A. Quigley, "Evaluation of Neutron Absorber Panels from Zion Spent Fuel Pool," *Trans. Am. Nuc. Soc.*, ***115**, 645–647 (2016).*

16. H. Akkurt, "*Comparison of Neutron Absorber Panels and Monitoring Coupons from Zion Spent Fuel Pool*," Proc. of International High-Level Radioactive Waste Management (IHLRWM 2017), April 2017, Charlotte, NC.
17. *Evaluation of the Impact of Neutron Absorber Material Blistering and Pitting on Spent Fuel Pool Reactivity*, EPRI, Palo Alto, CA: 2018. 3002013119.
18. *MRP-278, Materials Reliability Program: Reactor Vessel Integrity Primer (MRP-278): A Primer on Theory and Applications*. EPRI, Palo Alto, CA: 2010. 1020854.
19. *BWRVIP-233, Revision 1: BWR Vessel and Internals Project, Evaluation of Stress Corrosion Crack Growth in Low Alloy Steel Vessel Materials in the BWR Environment: Technical Basis for Revisions to BWRVIP-60-A*. EPRI, Palo Alto, CA: 2011. 1022841
20. *NEI 03-08 Rev. 2: Guideline for the Management of Materials Issues.* January 2010.
21. Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel – Final Report (NUREG-1927, Revision 1), 2016.

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