PNNL-27120 Rev. 1

Criteria and Planning Guidance for Ex-Plant Harvesting to Support Subsequent License Renewal

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Prepared for the U.S. Nuclear Regulatory Commission
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CONTRACT DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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Summary

This document supersedes and replaces the previous harvesting criteria and planning guidance (PNNL-27120), which was inadvertently released while still under development. Revision 1 contains an updated set of criteria and simplified guidance for harvesting.

The decommissioning of some nuclear power plants (NPPs) in the United States after extended operation may provide an opportunity to increase knowledge about materials aging and degradation, through the harvesting of, and subsequent research on, service-aged materials. Insights into degradation mechanisms in materials from studies on harvested materials can provide confirmation of the effectiveness of aging management approaches used by the nuclear industry. In addition, evaluation of material properties of systems, structures, and components (SSCs) from operating or decommissioned NPPs may provide insights into the actual safety margins, and increase confidence that long-lived passive components will be capable of meeting their functional requirements during extended operations.

A strategic and systematic approach to sampling materials from SSCs in both operating and decommissioned plants will help reduce costs and improve the efficiency and value of materials harvesting. The ability to harvest materials in a cost-effective manner is expected to lead to additional opportunities for benchmarking laboratory-scale studies on materials aging, and provide insights into prioritizing materials/components replacement needs in operating plants.

This document describes a potential approach for prioritizing sampling (harvesting) materials using a number of criteria that incorporate knowledge about the specific technical issues that could benefit most significantly from harvesting. Beyond the implications to safe operation of NPPs, the basic criteria to assess specific harvesting opportunities should include:

- Unique field aspects, if any, that drive the importance of harvesting the material (e.g., legacy material formulations and fabrication methods)
- Ease of laboratory replication of material and environment combination
- Applicability of harvested material for improving our knowledge base with respect to materials degradation
- Availability of reliable in-service inspection techniques for the material
- Availability of materials for harvesting, and the estimated cost of both harvesting activities and subsequent activities.

Additional related criteria for prioritizing harvesting of components/materials relevant to the specific needs of the organization developing a harvesting plan will vary and could include:

- State of knowledge of the material, environment, and age-related degradation of interest
- Operating experience related to the material, environment, and age-related degradation of interest
- Availability of aging management programs (AMPs) to manage age-related degradation of interest
- Available options for mitigation of the age-related degradation, including the performance of the mitigation option
- The ease of replacement for components

- Applicability of information obtained from potential harvesting opportunities (e.g., boiling water reactors only, pressurized water reactors only, or fleet-wide)
- Knowledge areas that will be improved by harvesting, including how it will inform AMPs.

These criteria help define the specific problems that will be addressed and the knowledge gained through the use of the harvested materials. These criteria along with lessons learned from previous campaigns can be used to develop a harvesting plan that can be customized for the specific needs of the organization sponsoring the harvesting and the opportunities at hand.

Acknowledgments

The work described in this report was sponsored by the Office of Research (RES) at the U.S. Nuclear Regulatory Commission (NRC). The authors gratefully acknowledge the guidance provided by Mr. Patrick Purtscher, Mr. Matthew Hiser, and Dr. Amy Hull from NRC-RES during the course of this study. Also, we gratefully acknowledge Ms. Kay Hass and Ms. Janice Haigh for their invaluable assistance in the technical editing and formatting of this report. Finally, the authors would like to acknowledge the technical peer reviewers for their feedback and assistance with this report.

Acronyms and Abbreviations

ADAMS	Agency-wide Documents Access and Management System
ALARA	as low as reasonably achievable
AMP	aging management program
BWR	boiling water reactor
CASS	cast austenitic stainless steel
CM	condition monitoring
Code	American Society of Mechanical Engineers Boiler and Pressure Vessel Code
CSPE	chlorosulphonated polyethylene
DMW	dissimilar metal weld
dpa	displacements per atom
EAB	elongation-at-break
ECCS	emergency core cooling system
EMDA	Expanded Materials Degradation Assessment
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
EQ	environmental qualification
FDR	frequency domain reflectometry
GALL	Generic Aging Lessons Learned
IASCC	irradiation-assisted stress corrosion cracking
ISI	in-service inspection
LWR	light water reactor
NDE	nondestructive examination
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OE	operating experience
PMDA	Proactive Materials Degradation Assessment
PWR	pressurized water reactor
RPV	reactor pressure vessel
RRIM	Reactor Reliability and Integrity Management
SCC	stress corrosion cracking
SLR	subsequent license renewal
SME	subject matter expert
SSC	systems, structures, and components
TDR	time domain reflectometry

Contents

Figures

Tables

1.0 Introduction

As of January 1, 2019, the nuclear power fleet in the United States consists of 98 operating reactors, of which 89 have received licenses to operate beyond the original license period of 40 years (NRC No Date, Appendix A). The license renewal for these plants extends their operating life to 60 years and the U.S. nuclear power industry is now looking at a further extension of this operating license period, with the first applications for extending the operating license to 80 years submitted to the U.S. Nuclear Regulatory Commission (NRC) in 2018 (Dominion Energy Virginia 2018; Exelon Generation Company 2018; Florida Power & Light 2018).

The NRC regulations in 10 CFR 54.31(d) allow nuclear power plants (NPPs) to renew their licenses for successive 20-year periods. As summarized in SECY-14-0016 (SECY-14-0016 2014; Vietti-Cook 2014), the most significant technical issues challenging power reactor operation beyond 60 years are degradation in four classes of systems, structures, and components (SSCs) (INL 2016):

- Reactor pressure vessel (RPV) neutron embrittlement at high fluence
- Irradiation-assisted stress corrosion cracking (SCC) of reactor internals
- Concrete structure and containment degradation
- Electrical cables qualification and condition assessment.

Understanding of the causes and possible mitigation of the effects of aging degradation forms the basis for developing aging management programs (AMPs) to ensure the continued functionality of and maintenance of safety margins for NPP SSCs. The AMPs, along with the appropriate technical basis, are used to demonstrate reasonable assurance of safe operation of the SSCs during the subsequent license renewal (SLR) period. The NRC, in its Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report (NRC 2017a, b, c, d) documents, has identified acceptable aging management approaches to address the major technical issues for subsequent license renewal for plant operation from 60 to 80 years.

While many plants are continuing to operate and some have begun applying for continued operation through the SLR period, other plants in recent years have shut down or decided to cease operations in the near future. As these plants enter decommissioning, there are expected to be several opportunities for accessing and harvesting service-aged materials for use in materials degradation research activities. In addition, it is likely that opportunities to sample materials from operating plants will also arise as plants consider replacing specific components that may have shown degradation. Given the significant opportunities for materials harvesting from decommissioning and operating NPPs, it is beneficial to have a strategic and systematic approach to materials harvesting.

A key challenge to understanding materials aging and degradation in the NPP environment is the ability to perform tests on materials that are aged in a representative environment. Often such tests are performed (and materials performance data obtained) through accelerated aging experiments, where the material being tested is subjected to higher stressors (e.g., temperature, stress, neutron flux) than those seen in operation. Such tests enable the experiments to be completed in a reasonable timeframe and can be benchmarked with performance data from materials that have seen more representative service aging.

Where available, such benchmarking can be performed using surveillance specimens exposed to field conditions during the course of operation of the reactor. However, surveillance specimens are often limited to critical components such as the RPV, and do not exist for components in other locations in a plant. In such cases, benchmarking of laboratory tests may be achieved by harvesting materials from reactors. The resulting insights into material aging mechanisms can add to confirmatory evidence of the effectiveness of aging management approaches used by the nuclear industry, as well as insights into the operating margins while maintaining confidence that long-lived passive components will be capable of continuing to meet their functional requirements during extended operations. The results from testing of harvested materials could also help in assessing the reliability of specific methods for condition assessment or nondestructive evaluation (NDE) that may be applied to assess aging of these components in the field.

While harvesting may be quite valuable to increase technical knowledge of materials aging, it may not always be practical. In some cases where harvesting may be desired, the components are in areas with high radiation doses, which makes harvesting significantly more expensive and logistically challenging. In other cases, the benefits of harvesting may not be enough to overcome the costs associated with procurement, evaluation, and subsequent disposal of the materials.

Given the limited opportunities and associated challenges for materials harvesting, it is beneficial to have a strategic and systematic approach to materials harvesting. This approach will help ensure that the processes to identify, assess, and prioritize harvesting opportunities apply the limited resources in the most effective manner to harvesting opportunities with the greatest value. This document describes the considerations for prioritizing materials harvesting using several criteria that were defined using lessons learned from previous harvesting campaigns. These criteria also help define the specific research questions that will be addressed and the knowledge gained through the harvesting process.

The focus of this document is on criteria and guidance for prioritizing harvesting needs and a process to assess the value of specific harvesting projects to allow for fully informed harvesting decision-making.

2.0 Harvesting Prioritization

This section describes the sources of information used in the assessment and proposes several criteria for use in the prioritization of harvesting decisions. Examples are included that show the application of these criteria to provide a qualitative assessment of harvesting priority.

2.1 Literature Sources

A wide variety of literature exists with information on materials degradation that may be relevant to aging of NPP components. Early materials aging insights for light water reactor (LWR) components were summarized in a number of documents (Blahnik et al. 1992; Shah and MacDonald 1993; Livingston et al. 1995; Morgan and Livingston 1995; NRC 1998). More recently, the literature in this area includes the NRC GALL reports, and the GALL-SLR (NRC 2010b, 2017d, a), with NRC staff's evaluation of the acceptable aging management for the period of extended operation from 40 to 60 years and from 60 to 80 years (SLR), respectively; *Expert Panel Report on Proactive Materials Degradation Assessment (PMDA)* (Andresen et al. 2007); and *Expanded Materials Degradation Assessment (EMDA)*, NUREG-7153 (Andresen et al. 2014; Bernstein et al. 2014; Busby 2014; Graves et al. 2014; Nanstad et al. 2014).

The Electric Power Research Institute (EPRI) has also documented materials aging issues in the form of Materials Degradation Matrix and Issue Management Tables (EPRI 2013b, c, a). The matrix is used to document potential degradation mechanisms for primary system components, while the Issue Management Tables provide a tool to assist industry with identifying and prioritizing research needed to resolve LWR degradation issues. Further, a number of reviews by other organizations have been used to inform research in the understanding of degradation growth in specific materials (for instance, IAEA 2000a, b; Zinkle and Busby 2009; Gillen and Bernstein 2010; IAEA 2012; McCloy et al. 2013; William et al. 2013; Cattant 2014; Leonard et al. 2015; Pape and Rosseel 2015; Simmons et al. 2015; Feron and Staehle 2016; Fifield 2016; INL 2016; Lubinski 2016; Rosseel et al. 2016b). The literature covers a broad range of materials, mechanisms, and environments, for both pressurized water reactor (PWR) and boiling water reactor (BWR) plants.

Early materials degradation analyses as well as inspection methods have tended to focus on metals and pressure boundary components, such as the phenomenon identification and ranking table analysis conducted under the proactive materials degradation assessment (PMDA) effort (Andresen et al. 2007). In addition, concrete structures and electrical cables are long-lived components that would require a significant investment if replacement is necessary. As a result, recent assessments such as the expanded materials degradation assessment (EMDA) have included knowledge gaps related to these long-lived non-metallic components (Bernstein et al. 2014; Graves et al. 2014). At the same time, there is increased attention being focused on developing condition monitoring (CM) and NDE methods for concrete and electrical cables, with the objective of defining methods and acceptance criteria that would allow degradation to be detected before it reaches a state where it begins to impact the intended function of the component. Collectively, these studies point to the value to better understand specific materials degradation mechanisms, including the conditions leading to degradation initiation and growth, and potentially methods for detecting and mitigating such degradation in a timely fashion, to confirm aging management approaches provided in GALL-SLR.

From the perspective of long-term plant operations, a number of these studies identified technical questions associated with understanding the contributing factors for materials degradation development and growth. These studies, typically conducted as expert elicitations, have resulted in phenomena identification and ranking tables listing the susceptibility of materials to specific degradation mechanisms and the level of knowledge available. The tables also include general information on the environment that these materials operate in, as the specific degradation mechanisms are intimately tied to the environmental conditions in which the material operates. These studies have been used, along with operating experience (OE) and existing guidance on materials aging management, to develop the GALL-SLR (NRC 2017d, a, e, b) documents that contain over 5000 component combinations including information on their material, environment, aging mechanisms, and a recommendation for a program to address each aging mechanism. The technical basis for changes to the AMPs in GALL-SLR are found in NRC (2017f).

It is important to note that the information in the literature sources, while similar in form, can differ in specificity. Studies such as the EMDA and PMDA have focused on specific materials (alloys, specific compositions, etc.) while other studies may refer to generic materials and recognize that differences in material composition and grade may exist. As an example, different grades of stainless steel are used in the current nuclear power fleet and while there may be similarities in how they behave under different environmental conditions, differences that are related to specific compositional variations may drive their behavior over the long term under specific operating conditions. Another example is the steels used in reactor vessels, where compositional variations are a factor in the extent of loss of fracture toughness (Sokolov and Nanstad 2016).

The implication of the preceding discussion is that certain mechanisms and materials may be considered as a high priority for obtaining additional insights into degradation initiation, growth, and detection; however, a systematic approach is needed to objectively identify these materials and mechanisms. This systematic approach could also identify one or more criteria that can be used in the prioritization process. From the perspective of materials harvesting, accounting for the connection between materials degradation and CM/NDE may be desirable. Once priorities are established, the materials identified may become the target of activities related to ex-plant harvesting.

There have been similar studies in the past, where the objective has been to develop a systematic methodology for prioritizing harvesting opportunities (Johnson Jr. et al. 2001). This study builds on these previous efforts, focuses on harvesting needs for increasing confidence in aging management, and incorporates lessons learned from harvesting efforts in the years since these previous studies.

The next subsection describes potential criteria and provides examples of the analysis that may be conducted using these criteria for identifying high-priority components/materials for ex-plant harvesting.

2.2 Criteria for Prioritizing Harvesting

Criteria for prioritizing harvesting of components/materials should be relevant to the organization's specific needs. For example, if the degradation mechanisms for a given material within a specific environment are understood sufficiently well, the harvesting priority for the material exposed to this environment is likely lower. Likewise, if there are sufficient options for monitoring, mitigation, and repair, and these have been validated in representative materials/conditions, harvesting priority may be low. Uncertainty in any of these factors may increase the priority for harvesting in an effort to reduce the uncertainty. Limited harvesting may be useful for benchmarking purposes if simulating "realistic" degradation for laboratory studies is required.

Beyond the implications to safe operation of NPPs, the basic criteria to assess and prioritize specific harvesting opportunities may be broken into five major categories:

- Unique field aspects, if any, that drive the importance of harvesting the material. This focuses on materials that are not easily available presently, such as legacy material formulations and fabrication methods that may be outdated. Also within this category would be OE associated with a specific class of materials in a relevant environment.
- Ease of laboratory replication of material and environment combination. This criterion focuses on conditions that are not easily reproducible in a laboratory environment. Of the environments of interest, radiation environments are likely to be the most challenging to duplicate. This consideration is more important for low-dose, long-term irradiation and is of interest if dose rate effects are expected to influence the mechanism initiation and growth.
- Applicability of harvested material for laboratory research into materials degradation. The focus of this criterion is on the ease with which the harvested material may be used in laboratory studies on aging and degradation, to confirm aging management approaches in GALL-SLR. Ideally, research plans for use of harvested materials would be in place prior to the actual harvesting. A related question would be whether, in addition to laboratory studies using characterization tools, the material can be used in degradation initiation and growth studies. In this context, re-aging of harvested materials under accelerated conditions may provide additional insights. In cable aging, such studies have been proposed (wear-out aging) (Gillen and Celina 2000).
- Availability of reliable CM/NDE techniques for the material and degradation mechanism. Such techniques may compensate for any uncertainties in knowledge about the formation and growth of degradation, and enable sufficient defense in depth. Note that, even with reliable CM/NDE methods being available, harvesting may be warranted in some instances if the degradation mechanism is likely to be a generic fleet-wide issue. In these cases, the harvested material may provide insights for repair/mitigation decision-making and improving the economics of plant operation. Further, it is possible that the harvested material may be useful for developing or improving CM/NDE techniques.

- Availability of material for harvesting and cost of harvesting. Knowledge of materials used in different operating and shutdown plants as well an understanding of which materials may be available for harvesting over different time horizons (short, medium, long) and the associated cost of harvesting is necessary.

These high-level criteria focus on the ability of harvested materials to address technical issues in materials performance for extended plant operation. In addition, a variety of other information should be considered, using one or more of the sources identified earlier, such as expert elicitation studies, regulatory guidance, OE, and recent research results and data.

It is important to determine whether the expected benefits from the harvested materials are likely to reduce uncertainty associated with the materials' performance through 80 years of operation of the plant. If so, this potentially provides benefits from the regulatory perspective, by allowing reductions in the conservatism of current proposed aging management approaches.

Additional related criteria for prioritizing harvesting of components/materials relevant to the specific needs of the organization developing a harvesting plan will vary and could include:

- State of knowledge of the material, environment, and age-related degradation of interest
- OE related to the material, environment, and age-related degradation of interest
- Availability of AMPs to manage age-related degradation of interest
- Available options for mitigation of the age-related degradation, including the performance of the mitigation option
- The ease of replacement for components
- Applicability of information obtained from potential harvesting opportunities (e.g., BWRs only, PWRs only or fleet-wide)
- Knowledge areas that will be improved by harvesting, including how it will inform AMPs.

2.3 Examples of Harvesting Assessment

In the interest of developing the process for prioritizing harvesting further, several examples are considered in this subsection. These examples are not intended to be comprehensive, but were selected to highlight specific aspects of harvested materials that may be considered in the harvesting decision process. In each case, the criteria described above are assessed, with the additional information listed. The result is an assessment of the priority for harvesting should the material become available due to plant retirements or planned repairs.

The first example is of a non-metallic material (electrical cable), illustrating the complexity of the problem and the possibilities for improved understanding of aging mechanisms and performance. This is followed by an example of cast austenitic stainless steel (CASS), which highlights possibilities for improved understanding of the synergism between aging mechanisms and the potential limitations of accelerated laboratory aging-based tests. This provides an example of a potential medium- to high-priority harvesting need. The next example (SCC in dissimilar metal welds [DMWs]) is evaluated for two specific scenarios and is considered a low priority for harvesting. The final example of vessel internals highlights unique aspects of field-aged materials (radiation damage) that makes harvesting a valuable but perhaps expensive proposition.

It is important to note that the priority levels (high, medium, or low) listed in the following tables are the authors' assessment of the need to harvest based solely on the specific criteria listed in each row of the table. For example, if the EMDA ranked the susceptibility to degradation high, then the qualitative assessment of the need to harvest would be high. Conversely, if the EMDA ranked the knowledge of the specific degradation high, then the qualitative assessment of the need to harvest would be low. The assessments would be expected to change depending on the goals and role of the organization planning the harvesting.

2.3.1 Electrical Cables

The issues associated with aging of electrical cables are generally complicated by the diversity in materials and formulations that were used in cables. The cable EMDA, for instance, includes 6 different environments and 14 different materials of relevance to cable aging.

Given the qualification methods in accordance with environmental qualification (EQ) requirements used when they were put into service, utilities were able to perform EQ time-limited aging analyses to show with a reasonable assurance that electrical cables would be able to perform their necessary function under a design-basis event through a first round of license extension. EQ requirements themselves were based on an assumed maximum irradiation dose, and exposure to environmental conditions similar to those during a loss-of-coolant accident. Ongoing research is addressing many of these unknowns (Gillen and Bernstein 2010; Villaran and Lofaro 2010; Fifield 2016; Fifield and Shin 2017; IAEA 2017), using new and field-aged cable specimens.

Generally, utilities have adopted a CM approach to cable aging management, where specific CM methods are used to assess the degradation condition of cable insulation. CM programs are applied to detect damage before it reaches a critical stage. The damaged cables or cable sections may then be repaired or replaced.

Harvested field-aged cables may provide additional insights into their long-term performance. Both operating and decommissioned plants may be sources of material, particularly if there is some indication of dose and/or elevated temperature exposure. However, harvesting cables has both benefits and drawbacks. On one hand, it is possible to accelerate aging in a laboratory environment; this is likely to be informative for tracking and correlating information over a full degradation lifecycle. On the other hand, such a study is not possible with a snapshot in time of a cable from a plant where the actual temperature and dose level is not known.

There is some concern that the aging seen in accelerated tests may not always correlate well with field aging. In particular, dose rates and total dose effects, synergistic effects of thermal and radiation aging, and diffusion-limited oxidation are all concerns for the applicability of accelerated aging. Further, there are many instances where the formulations of cable insulation material (polymers) in plants (material) are different from what is available today. In these cases, harvested cables can be used for studies to provide representative material for testing.

Harvested cables, when subjected to laboratory aging studies (wear-out aging) may be used with destructive (e.g., elongation at break [EAB], gel-swell, etc.) and NDE tests (e.g., line resonance analysis, micro-indenter, indenter, etc.) for increasing confidence in the ability to detect aging of concern and provide assurance that the insulation/jacketing material has not reached its end of life (defined as 50% EAB). While some of this research has been completed (Bernstein et al. 2014), there are potential benefits from additional work in this area.

From a CM perspective, the most interesting harvested cable samples will have failed some in-plant test (such as walkdown, indenter, dissipation factor and withstand tests, and time and frequency domain reflectometry [TDR and FDR]) as there are fewer examples of such cables. These cables can then be subjected to alternative tests (such as capacitance and higher-frequency FDR) and autopsy with laboratory tests such as diffusion-limited oxidation and EAB. The data from these tests can increase confidence in acceptance criteria that have been published in various industry standards (IEEE No Date).

Difficulties in laboratory replication of long-term aging studies include potential dose rate effects, possible synergistic effects with radiation and temperature, and the ability to obtain vintage formulations of the cable insulation. Given the potential for using harvested materials for further laboratory testing (including additional accelerated aging effects), the harvesting of aged electrical cables with the appropriate materials and environmental conditions may be considered generally a medium-high priority. However, the specific prioritization will depend on the actual insulation materials and the environmental conditions.

For low-temperature, low-dose environments, susceptibility to embrittlement due to radiation and thermal aging was rated by EMDA as low (0–2). This is a well understood issue with high knowledge consistent with a ranking of 3 in the EMDA assessment (on a scale of 0–3). As the environmental exposure exceeds 45°C and up to 0.1 Gy/hr., susceptibility increases for some, but not all, materials and the knowledge decreases somewhat. Thus, harvesting the more susceptible materials, such as Neoprene, silicone rubber, and chlorosulphonated polyethylene (CSPE), exposed to temperatures in excess of around 45°C and low-doses is likely to be of greater value.

Table 1 provides a summary for one type of cable in a specific environment as an example. This specific case is focused on an insulation material that is in widespread use. Data from harvested materials may be used to study effects of lower temperature aging and synergistic effects, developing methods for quantifying aging, and increasing confidence in the acceptance criteria that are currently in use for managing the effects of aging. As a result, the prioritization for this material is rated as HIGH by the authors, though other organizations may apply different weighting on the criteria resulting in a different prioritization.

Table 1. Summary of Harvesting Criteria for a Specific Electrical Cable Insulation

Material: Ethylene propylene rubber (EPR) and CSPE insulation and jacket materials Environment: 45°C–55°C, dose between 0.1–0.01 Gy/hr. (1–10 rad/hr.)		
Criteria	**Qualitative Assessment of Value to Harvest**	**Comments**
Unique field aspects, if any	high	10–12 manufacturers of vintage cable in U.S. fleet and can vary within a single plant
Ease of laboratory replication	low to medium	Long-term aging studies necessary
Applicability of harvested material for addressing technical issues	high	Wear-out aging a possibility. Requires knowledge on plant conditions for CM.
CM/ISI for detection and sizing	low to medium	Unclear how well-proposed techniques would perform for low dose rate, low-temperature aging of insulation. Access limited; long-range methods are not fully understood.
Availability of material for harvesting	high	Needs input from utilities
EMDA susceptibility score	medium to high	
EMDA knowledge score	medium	Some data exist on long-term aging. Inverse temperature and synergistic effects are a concern. Inverse temperature effects apply and CSPE is formulation-specific.
GALL-SLR	low	XI.E1, XI.E2, XI.E3A, XI.E3B, XI.E3C
OE	high	Documented in industry publications
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	medium	Synergistic effects not well understood
Options for mitigation / Ease of replacement	low-medium	Possible but can get expensive depending on specific locations
Amount of use (in a plant and fleet-wide)	high	Low-voltage and medium-voltage cables extensively used in plants
Knowledge areas to improve by harvesting	high	Contribution to database for dominant effects, synergistic effects, dose rate effects for understanding accelerated aging vs. field aging, develop and qualify CM techniques
HARVESTING PRIORITY	HIGH	Multiple variables make harvesting priority high

2.3.2 Cast Austenitic Stainless Steel

CASS is used extensively in pressure boundary components in LWR coolant systems (Chopra and Rao 2016b). Applications include piping, valves, vessel internals, pumps, support structures, brackets, and flow restrictors. CASS materials can suffer loss of fracture toughness due to thermal aging, neutron embrittlement, or a combination of the two (NRC 2010b). The impact of loss of fracture toughness on component integrity is indirectly managed by using visual or volumetric examination techniques to monitor cracking in the components.

At temperatures associated with reactor operation and in applications where the component has no significant neutron exposure, the austenite (the major constituent of the microstructure) is largely unaffected. The main microstructural mechanisms of thermal aging are associated with the precipitation of additional phases in the ferrite: (a) formation of a Cr-rich α′-regions through spinodal decomposition, (b) precipitation of a γ-phase (Ni, Si-rich) and $M_{23}C_6$ carbide, and (c) additional precipitation and/or growth of existing carbides and nitrides at the ferrite/austenite phase boundaries (Ruiz et al. 2013).

For those components that do see significant neutron exposure, both the austenite and ferrite are degraded progressively by irradiation. An accurate prediction of when synergistic effects of the two different damage mechanisms (radiation damage and thermal aging) could become important is not available. While there is some information on the combined effects of thermal aging and neutron irradiation on fracture toughness and cracking in CASS (Chopra 2015), additional research could be beneficial.

Under extended service life, the main concern is loss of fracture toughness due to aging (thermal and neutron embrittlement). SCC and fatigue are not considered generic concerns for CASS. With extended operation of CASS components and decreasing fracture toughness, failure from fabrication flaws can be a concern.

At present, accelerated aging of CASS in the laboratory and computer simulations of microstructural changes are the main tools used to understand the aging of CASS in service. It would be useful to harvest reactor materials to validate the current accelerated aging programs, computer models, and existing regulatory positions, which are based on conservative evaluations of the thermal aging behavior. Microscopy and mechanical testing of harvested materials will confirm our understanding of aging behavior. In addition, accelerated aging of harvested materials will provide information on new degradation mechanisms that could crop up under extended life. While radiation damage has not been a concern in CASS, harvesting of both unirradiated material (piping, pumps, etc.) and irradiated material (reactor internals) would allow reliable evaluation of radiation effects on degradation.

The information on CASS may be mapped into the different criteria identified in Section 2.3 as follows:

1. The combination of material (CASS), degradation mechanism, and environment is rated high in the EMDA mainly for fracture of PWR piping in reactor water (no irradiation) and BWR vessel internals in primary water (radiation dose up to 1.5 displacements per atom [dpa]).
2. Both the knowledge and confidence scores are fairly high (~2, on a scale of 0–3) for CASS for all degradation mechanisms, indicating that CASS degradation mechanisms are fairly well understood. In addition, there have been clear evidence of the loss of fracture toughness associated with thermal aging; but there is limited instances of inservice flaws detected in affected components and no examples of leakage or component failure associated with the material degradation mechanisms in components fabricated from CASS.
3. The material, mechanism, and environment for thermal aging and loss of fracture toughness can be simulated in the laboratory. However, the harvesting of in-service components can confirm the relationship obtained from laboratory data; specifically, the relationship between accelerated testing time and service time. In addition, synergistic effects are difficult to reproduce in the laboratory. There are data in the literature that suggests significant loss of fracture toughness for neutron exposures between 0.5 and 5 dpa due to the interaction of neutron and thermal embrittlement effects (Chopra 2015).

4. Reduction in fracture toughness as a result of thermal embrittlement can result in significantly less ability to tolerate large cracks (Chopra and Rao 2016a). The delta ferrite content in CASS is one of the factors that controls crack (specifically SCC) initiation susceptibility, with higher delta ferrite generally resulting in lower SCC susceptibility but higher thermal embrittlement susceptibility. However, other factors (such as fabrication irregularities or cold work) may contribute to increasing the susceptibility to SCC (Byun and Busby 2012). There is also active research to address potential gaps related to thermal embrittlement during SLR (for instance, Byun et al. 2016).
5. ISI methods have been developed for the detection of surface-breaking cracks in CASS and are progressing for sizing cracks in CASS components as well. While there is not a clear need at this point for such technologies, it can be noted that no in-service inspection (ISI) technologies are ready for field use to measure the degree of thermal embrittlement of CASS.

Harvested CASS materials from components that are not exposed to significant neutron irradiation are usually not necessary for condition assessment technology development; appropriate material conditions can be achieved and investigated by accelerated aging of laboratory specimens. However, harvesting would allow calibration of accelerated aging in the laboratory against long-term service in a reactor environment.

Harvested materials from components that are exposed to significant neutron irradiation would be useful to understand the interaction of radiation and thermal aging; appropriate material conditions may not be achieved and investigated by exposing laboratory specimens to accelerated aging.

The limited OE with CASS, the high reproducibility of thermal aging conditions in the laboratory, and the potential availability of CM/ISI methods reduce the urgency for harvesting these materials when exposed to other conditions and, in our opinion, limit the priority to a low-medium rating, as summarized in Table 2. Conversely, the limited availability and high cost of laboratory-generated reactor coolant and neutron flux environment-exposed CASS elevates interest and importance in these kinds of harvested material as summarized in Table 3.

Table 2. Summary of Harvesting Criteria for CASS, for Thermal Aging Embrittlement, in Reactor Coolant, No Irradiation

Criteria	Qualitative Assessment of Value to Harvest	Comments
Unique field aspects, if any	low	Vintage material
Ease of laboratory replication	medium	Extensive modeling of accelerated aging data, but limited confirmation from service degradation
Applicability of harvested material for addressing technical issues	low	Calibrate and validate accelerated aging procedures; degradation initiation and growth studies; new/improved ISI procedures
CM/ISI for detection and sizing	medium	No NDE for loss of fracture toughness. Harvested materials useful to study condition assessment methods and develop workarounds.
Availability of material	medium	Needs input from utilities
EMDA susceptibility score	low-medium	CF-8M most susceptible
EMDA knowledge, confidence score	medium-high	
GALL-SLR	low	AMP X1.M1, M12
OE	low	Loss of fracture toughness is well documented, but most applications have no active cracking mechanisms
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	medium	Extensive modeling of accelerated test data
Options for mitigation / Ease of replacement	low	Some components like pumps can be replaced
Amount of use (in a plant and fleet-wide)	medium	Diversity in material composition and microstructure across plants. CF8M used in about 1/3 of PWRs that use CASS for Class 1 piping.
Knowledge areas to improve by harvesting	high	Relation between accelerated tests and real-world service time, in-service material composition and microstructure
HARVESTING PRIORITY	LOW-MEDIUM	Generally well-understood mechanisms, lower susceptibility drive the priority.

Table 3. Summary of Harvesting Criteria for CASS in Reactor Coolant and Neutron Flux Environment

Criteria	Qualitative Assessment of Value to Harvest	Comments
Unique field aspects, if any	high	Vintage material, synergistic effects
Ease of laboratory replication	high	Relating accelerated aging studies to real-world service time
Applicability of harvested material for addressing technical issues	high	Calibrate and validate accelerated aging procedures; assessment of the combined effects of thermal aging, coolant effects, and neutron irradiation; degradation initiation and growth studies; new/improved ISI procedures
CM/ISI for detection and sizing	medium	No nondestructive approaches for loss of fracture toughness assessment. Coarse-grained materials challenge ultrasonic testing. Challenge for meeting crack detection and sizing accuracy in thick-walled specimens.
Availability of material	high	Needs input from utilities
EMDA susceptibility score	medium	BWRs up to ~1.2 dpa, some PWR internals in primary water (up to 0.5 dpa)
EMDA knowledge, confidence score	medium	All mechanisms
GALL-SLR	low	AMP XI.M9, M16A
OE	low	Loss of fracture toughness well documented, but no service-induced flaws found in limited inspections
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	medium	Synergistic effects not well understood.
Options for mitigation / Ease of replacement	low-medium	Limited due to neutron flux environment
Amount of use (in a plant and fleet-wide)	high	Diversity in material composition and microstructure across plants. CF-8M has highest uncertainty.
Knowledge areas to improve by harvesting	medium	Synergistic effects of radiation and thermal embrittlement on fracture toughness, relation between accelerated tests and real-world service time, in-service material composition and microstructure
HARVESTING PRIORITY	MEDIUM	Known susceptibility, potential for vintage materials with field irradiation to study synergistic effects, but limited OE drive the priority.

2.3.3 Dissimilar Metal Welds

DMW joints are extensively used in NPP primary systems, and encompass a host of materials and locations. DMW are generally used to join ferritic and austenitic piping components, and employ either austenitic stainless steel or nickel-alloy materials as the weld material. The ferritic end is buttered with several layers of a material close in properties to the main (austenitic) weld material, with a post-weld heat treatment usually applied to reduce residual stresses (Taylor et al. 2006). OE has shown the possibility of SCC in such welds in PWRs for certain alloys employed.

The list below briefly describes how information on DMWs may be mapped into the different criteria identified above. The focus is on Alloy 82/182 welds in these examples, given their wide use and OE.

1. For the combination of DMW and primary reactor water at temperatures between 100°F–150°F, the susceptibility to SCC is low (1–2 on a scale of 0–3). With higher pressures (i.e., higher stress) and temperatures, the susceptibility increases.
2. Both knowledge and confidence scores are fairly high because OE and laboratory studies have shown numerous cases of SCC in materials at high temperatures and pressures. In contrast, there is limited OE for cracking at lower temperatures and pressures.
3. There is general consensus on the combination of factors that leads to crack initiation in these materials. These conditions can be simulated in the laboratory in accelerated aging tests. Limited data on crack growth rates in DMW materials have been generated in accelerated aging tests, but it is not clear how well the data matches field experience.
4. Crack initiation in these materials is a function of several factors including the residual stresses and welding temperature variations. There is limited data on crack initiation in DMWs in general and additional studies are in progress (Toloczko et al. 2019).
5. Harvested materials may be used to address technical issues related to crack initiation susceptibility and crack growth rates. However, it is likely that only a limited set of harvested materials may be needed (if any), given the ease with which the environmental conditions in operating plants may be replicated in a laboratory.
6. Several studies have demonstrated the viability of using one or more NDE techniques for detecting, characterizing, and monitoring SCC growth in these materials. While quantifying the reliability of these methods is a topic of active interest, data to date appear to indicate the possibility of detecting and sizing with reasonable accuracy (Cumblidge et al. 2010; Meyer and Heasler 2017; Meyer et al. 2017).

Tables 4 and 5 show a similar analysis summary for SCC in 82/182 welds in different environments. In this case, given the level of knowledge available about the susceptibility of the material to cracking when exposed to the environment and the options for detecting such cracking, these materials are considered in our opinion to be at a low-priority level in spite of the different environmental conditions listed in the examples.

Table 4. Summary of Harvesting Criteria for Example of SCC in DMW in PWR Primary Environments

Temperature: < 60ºC
Example Components: Emergency Core Cooling System Accumulator Piping to Cold Leg

Criteria	Qualitative Assessment of Value to Harvest	Comments
Unique field aspects, if any	high	Vintage material
Ease of laboratory replication	low	
Applicability of harvested material for addressing technical questions	low	Temperatures are considered to be too low for SCC to be a concern
CM/ISI for detection and sizing	low	Detection and sizing capability TBD but generally capable of meeting acceptance criteria set in the Code
Availability of material	low	Needs input from utilities
EMDA susceptibility score	low	Temperatures considered too low for SCC to be concern
EMDA knowledge, confidence score	low	High confidence in understanding of material and degradation behavior in selected environment
GALL-SLR	low	Nothing listed for environment for this example
OE	low	No OE in Licensee Event Report searches
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	low	Given lower susceptibility at cold leg temperatures, this is considered a low priority issue
Options for mitigation / Ease of replacement	low	Given low susceptibility, this is not considered to be an issue
Amount of use (in a plant and fleet-wide)	medium	Extensive
Knowledge areas to improve by harvesting	low	Crack initiation probability considered low for the environment listed
HARVESTING PRIORITY	LOW	No OE on the welds drives the low priority.

Table 5. Summary of Harvesting Criteria for Second Example of SCC in DMW in PWR Primary Environments

Temperature: >250ºC
Example Components: Piping, Piping Components, Pressurizer Components and Penetrations

Criteria	Qualitative Assessment of Value to Harvest	Comments
Unique field aspects, if any	high	Vintage material; Reactor coolant environment exposure
Ease of laboratory replication	low/medium	
Applicability of harvested material for addressing technical issues	medium	Calibrate and validate accelerated aging procedures, degradation initiation and growth studies, new/improved ISI procedures
CM/ISI for detection and sizing	low	Available techniques appear sufficient for detection. Access issues dictate probability of detection and sizing performance. Detection and sizing generally capable of meeting acceptance criteria set in the Code.
Availability of material	medium	Needs input from utilities
EMDA susceptibility score	high	Degradation well documented
EMDA knowledge score	low	Confidence in understanding of material and degradation behavior in selected environment
GALL-SLR	low	AMP XI. M1, M2, M19, M32 (depending on structure/component)
OE	high	Numerous examples of cracking at elevated temperatures
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	medium-high	Confirmation of laboratory testing results at high temperatures would be of interest
Options for mitigation / Ease of replacement	low	overlays, MSIP, etc.
Amount of use (in a plant and fleet-wide)	high	Extensive
Knowledge areas to improve by harvesting	medium	Crack growth rates, crack initiation time, mitigation proposals (overlay) also being studied
HARVESTING PRIORITY	LOW	Multiple ongoing studies, significant advances in degradation understanding, availability of NDE drives priority assessment

2.3.4 Vessel Internals

Vessel internals comprise a wide range of structures and components, with one defining characteristic: they are all exposed to the highest fluences within a NPP. Vessel internals are generally made of austenitic stainless steels (typically 304 or 316L) and the materials may be subjected to several processing steps, including cold work and welding, to form the component. Given the potentially high fluences experienced by these materials, several degradation mechanisms may occur over time, including irradiation-assisted SCC (IASCC), as well as other irradiation-assisted processes.

In the case of austenitic stainless steel exposed to irradiation and the primary systems water environments in LWRs, the following generic assessments may be made:

1. Susceptibility and confidence scores for SCC and other degradation mechanisms are generally high.
2. Knowledge scores are generally low-medium, but this is a function of the specific degradation mechanism and specific environmental information.
3. OE has shown cracking in a variety of internals components in both PWRs and BWRs.
4. Some open questions exist as far as the specifics of irradiation-assisted degradation mechanisms and the factors contributing to initiation and growth. A number of microstructural changes are possible in the presence of radiation, including void swelling, segregation, and precipitation. Additional understanding of the factors that contribute to these mechanisms can reduce uncertainties in assessing their impact on the material functional performance.
5. ISI methods exist that can detect the presence of cracking and dimensional changes in components. The reliability of these methods is a function of several factors of physical access for inspection, and a number of factors associated with the inspection deployment technology. In addition, the effectiveness of ISI can become limited if the critical flaw size (i.e., flaw length and through-thickness depth beyond which the integrity of the component may be affected with continued operation) is less than the detection limits.
6. Internal components embody certain unique aspects that are hard to duplicate in the laboratory (Johnson Jr. et al. 2001). Unlike DMWs, and to some extent CASS, the environmental conditions (especially higher fluences) are hard to achieve in the laboratory. Even with access to specialized facilities, there is concern that degradation mechanisms may be flux rate- and spectrum-dependent, indicating that accelerated aging conditions typically encountered in test facilities may not be representative of the field-aged component.
7. Some internal components may be amenable to replacement.

Collectively, these criteria drive the need for harvesting internal components if available and result in a prioritization of medium in our opinion to high shown in Table 6.

Table 6. Summary of Harvesting Criteria for Reactor Vessel Internals Manufactured from Austenitic Stainless Steel

Criteria	**Qualitative Assessment of Value to Harvest**	Comments
Unique field aspects, if any	high	High-fluence irradiation; vintage material
Ease of laboratory replication	high	Accelerated aging tests vs. field aging service time
Applicability of harvested material for addressing technical issues	high	Conditions in LWRs are critical for degradation like void swelling
CM/ISI	medium	Available techniques may be sufficient. Access issues may dictate probability of detection and sizing performance. Challenging environment for continuous monitoring.
Availability of material	high	Some internals in operating reactors may be replaced
EMDA susceptibility score	high	Internals are susceptible to multiple aging mechanisms
EMDA knowledge score	medium	Basic knowledge of known mechanisms
GALL-SLR	low	XI.M9, M16A
OE	high	Baffle bolt cracking, cracking in other internal components (generally fasteners, bolts), including core shroud and core barrel
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	medium	synergistic effects need to be studies more
Options for mitigation / Ease of replacement	medium	Limited options
Amount of use (in a plant and fleet-wide)	high	Internals of all NPP
Knowledge areas to improve by harvesting	high	Degradation mechanisms (IASCC, swelling, segregation, etc.), flux rate and irradiation spectrum effects, microstructural property changes, and links to mechanical properties
HARVESTING PRIORITY	MEDIUM–HIGH	Unique field aspects and degradation mechanisms drive this prioritization

3.0 Harvesting Planning

3.1 Summary of Ex-plant Harvesting Lessons Learned

Harvesting activities have been carried out at a number of plants over the years. The intent of this section is not to be a comprehensive review of all past harvesting efforts, but rather to be representative of recent activities in order to draw appropriate lessons learned.

Harvesting efforts over the years have spanned a number of material types, including reactor internal components, RPV and other Class 1 components, cables, and concrete.

Past harvesting efforts have included decommissioned plants as well as cancelled or terminated plants. Of the cancelled or terminated plants, the harvesting effort appears to have been opportunistic and focused on accessing components that were fabricated, but not commissioned. Examples of these plants include Shoreham, River Bend Unit 2, and the Washington Public Power Supply System Units 1 and 3. In these cases, the focus was primarily on harvesting metallic components with a view to obtaining as-built materials for studies on crack growth, fracture toughness, and fabrication flaw density.

In recent years, harvesting efforts have generally focused on accessing materials from plants that have ceased operations. Examples of these efforts in the U.S. include Zion (both units) and Crystal River Unit 3, and in Spain, Zorita. Zion is a decommissioned two-unit Westinghouse-designed four-loop PWR facility. The units were commissioned in 1973 and permanently shut down in 1998 (Rosseel et al. 2016a). Crystal River Unit 3 is a PWR that ceased operation in 2013. Zorita is a 160-MWe PWR designed by the Westinghouse Electric Corporation, and operated for approximately 38 years (NRC 2010a). It was permanently disconnected from the national power grid on April 30, 2006. During this period, approximately 26.4 effective full-power years of reactor operation were accumulated and the highest fluence on the reactor vessel internals was estimated to be 50 dpa (Hiser et al. 2015). A number of other plants that have ceased operations have been identified as potential sources of material for harvesting. Meanwhile, a limited amount of harvesting has been performed at several other operating plants, usually in conjunction with a repair or replacement activity.

In many recent instances where materials were identified as being available for harvesting, a significant amount of effort appears to have been put into planning the harvesting. For instance, as part of the effort on material harvesting from the Zion Unit 1 RPV, detailed planning activities were undertaken to develop a segmentation plan for the RPV to gather material from the beltline region (Rosseel et al. 2016a). Both base-metal regions and beltline weld regions are included in the harvested sections and are planned for use in laboratory studies. Comparisons with fracture toughness of surveillance specimens are expected to provide insights into the changes in fracture toughness over time.

This level of prior planning, often including research plans for the harvested material, has been typical of several other harvesting efforts, for instance, baffle bolts and reactor internals (Hiser et al. 2015; EPRI 2017; NRC 2017f; Smith and Burke 2017), and electrical cables (Fifield 2016), and in many cases, were based on harvesting priorities driven by the specific needs of the research. For example, harvesting of beltline weld region from cancelled or terminated plants was used in studies on fabrication flaw density in the beltline weld region. Knowledge gained on fabrication flaw size and distribution in RPVs as a result of the studies of Simonen et al. (2002) played a role in the development of 10 CFR 50.61a. For these studies, harvested material included sufficient material on either side of the weld to enable studies on the weld and adjacent material.

Recent experiences (such as at Zion, Crystal River Unit 3, and Zorita) showed the process of harvesting can be expensive and challenging. Challenges and increased costs occur because of high levels of radiation resulting in a need to manage exposure to workers (as low as reasonably achievable; ALARA), transportation of specimens in appropriate casks, the need for testing in hot cells, and eventual disposal of irradiated specimens. A related challenge was the complexity of securing engineering and labor support for a harvesting task when the primary contractor in charge of the operation is focused on dismantling the plant.

While harvesting materials with known degradation issues is generally useful, in the case of harvesting post-plant closure it may also be a challenge. Identifying materials with known degradation conditions may be difficult without the ability to perform some form of nondestructive or destructive examination of the material if appropriate documentation about the components is not readily accessible. Given the challenges associated with securing engineering and labor support for harvesting post-plant closure, obtaining the necessary support for this type of examination activity or documentation search is also likely to be challenging and costly.

Part of the issue is that, in most cases, information on the exact environment in which the material was operating may not be available. Often, all that is available (especially after a plant has closed and is in the decommissioning phase) is the total number of years the material was used while the plant was in operation and a general idea of the environment based on its location. While the environmental conditions for some components (such as RPV or internals) can be calculated relatively precisely based on plant operational data, the lack of such information can be problematic for components exposed to localized extreme environments. For instance, in the case of cables, the possibility of localized hot spots (from uninsulated piping close by) may be a contributor to significant local thermal aging. This type of information is more readily available when the cable is harvested from an operating plant and additional measurements of environmental conditions may be taken during operation (for instance, through infrared thermography measurements) prior to harvesting.

3.2 General Guidelines for Harvesting Plans

With the experience to date harvesting materials from plants and the associated lessons learned, several best practices may be identified for future strategic harvesting exercises. Note that similar best practice documents have been developed by others for specific classes of materials[a] and that many of the insights from such documents are broadly applicable.

Based on lessons learned from past harvesting experiences as well as other harvesting guidance documents, the following will need to be addressed prior to developing a harvesting plan:

- Clearly identifying the benefits of harvesting the material by understanding the unique knowledge to be gained relative to past research and OE.
- Describing how the harvested material will be used. This will require development of a research plan (even if at a high level initially) that will be executed with the harvested material and how the studies are expected to improve knowledge of the technical issue. Several excellent examples exist for research plans (for instance, Leonard et al. 2015; Fifield 2016).
- Determine the necessary resources for harvesting. Use the justification and prioritization for harvesting to secure the necessary engineering/labor support prior to beginning the procedure. In discussions with technical staff who have been involved in harvesting activities, this was the number one item raised, especially when the harvesting activity is an adjunct to decommissioning the plant. In this case, the decontamination and decommissioning activities take precedence and the harvesting activity will need to accommodate any changes in schedules necessary to ensure that the primary activity is completed on schedule.
- Timeline for harvesting. A fall out of the resource planning issue above is the need for developing the harvesting plan, and, in consultation with plant personnel, a notional schedule for the harvesting.
- Post-harvesting receipt of material. The plan should also include information on where the material will be sent and in what form (complete component, segmented into smaller pieces, etc.), and the condition of the material after harvesting (contaminated, if cleaned to what extent, etc.).

(a) EPRI. 2014. *Plant Engineering: Field Guide for Harvesting Service-Aged Cable (Cable Harvesting Guide) Version 2014*. EPRI Report 3002002994, Electric Power Research Institute (EPRI), Palo Alto, California. EPRI members may access this software at http://cableharvest.epri.com.

  - A requirements document that covers receiving and working with the material is necessary. In particular, if the material is to be handled as radioactive material, additional precautions will need to be taken for shipping, storage, and use in research. Activated and/or contaminated material may require hot-cells for storage and use.
  - Note: Depending on the material and its condition (contaminated, activated), regulations for shipping (U.S. Department of Transportation regulations) will vary and need to be accounted for in scope, schedule, and budget for the harvesting activity.
  - Depending on its eventual end-use location, necessary approvals should be in place prior to executing the harvesting plan.
- Waste handling. Depending on the material and research plan for its use, provisions will need to be made to handle any waste streams generated during the process. This includes not only the waste generated during harvesting but subsequently during research. Specimens created from harvested material may need to be stored for longer terms, and provisions are necessary for long-term storage of the material if necessary.

Note the prioritization criteria described earlier in this document provides a potential pathway to identifying the benefits of harvesting in context with existing knowledge and OE to help define the priority for harvesting the specific material. The associated research plan should include a description of the specific research and expected outcomes that improve knowledge of the technical issues. This may happen, for instance, through propagating the technical findings into the relevant technical literature and codes and standards.

A number of elements should to be kept in mind as the harvesting plan is developed. These include:

- Clearly identifying the component/material to be removed. Labels, tags, etc. are possible ways in which the component (or location on a component, if only a portion is being harvested) can be identified. Given the need to potentially coordinate the harvesting activity with other activities at the site, such identification can reduce the potential for mistaken harvesting of material.
- Documenting the environment in the vicinity of the component prior to removal. This includes not only the temperature, radiation, etc., but also the presence of other components in close proximity and how they interact with the component being harvested. For instance, vibration from a nearby pump may play a role in accelerating degradation in the component being harvested.
  - Radiation surveys of materials may be needed before and after harvesting to determine if the material is contaminated or can be free-released. This also provides information on necessary decontamination activities that may be needed.
  - The level of contamination and activation of the material will dictate the actual harvesting approach to meet ALARA requirements.
- Information about the condition (degradation and aging) should be documented if available. If possible, additional measurements should be taken before or after harvesting to confirm the condition of the material prior to its use in any aging-related studies.
- As large a section of material as possible should be removed. Note that this may be constrained by budget or dose to personnel. Any special features (such as terminations, splices, and cable accessories for the case of cable harvesting; welds, heat-affected zone, and base metal for similar and dissimilar welds) should be identified in the harvesting plan, and if necessary, retained.

Parameters that should be documented (if available), or source documentation to be identified and collected during this process include:

- Physical description
  - Category (examples: nozzle weld, instrumentation and control cable, medium-voltage cable, baffle bolt)
  - Construction information (configuration, special processes used)
  - Manufacturer/date
  - All available information on the materials comprising the component to be harvested or composition (e.g., certified material test reports)
  - Dimensions and special features
- Service parameters
  - System
  - Component design function
  - Usage parameters (how often was it used if intermittently used)
  - Safety/maintenance rule significance
  - Age in service
- Installation data
  - Installation location (containment, auxiliary building, other building, outside, buried)
  - Connected components
  - Supporting structures or conveyances
- Stressors
  - Installation
  - In-service mechanical and structural
  - Environmental degradation: temperature, pressure, fluence, humidity
  - Other damage potential
- Plant/fleet experience
  - Testing interval and history
  - In-service failure or degradation
  - Available data on ISIs, surveillance, or other condition assessments for degradation

Generating all of the necessary harvesting plan information is time consuming, but is crucial, especially for topics that have significant complexity. Where possible, the plan should be assembled before any opportunities arise for harvesting. Critical details that will require knowledge about the harvesting plant/location are who will perform the harvesting, when will harvesting be performed, where is the material, what is its condition, and how much should be harvested? Having the rest of the information pre-assembled will provide a significant advantage towards expediting the procedure. For this purpose, having the necessary information available, perhaps in a searchable database, will facilitate the process.

4.0 Information Tools for Harvesting Planning

The previous sections dealt primarily with approaches for prioritizing the needs for harvesting of materials from plants for addressing one or more issues. Identification of technical issues and development of a harvesting plan to address some of these issues will require other information. Such information can include the state of knowledge about materials performance, availability of materials for harvesting, and OE.

One way to efficiently use this information is an integrated tool set that will enable rapid assessment of technical gaps and well-informed decisions on harvesting. This section briefly describes desirable characteristics of tool suites for this purpose.

4.1 Reactor Reliability and Integrity Management Library Overview

As described earlier, harvesting has several phases, including determining the priority, developing a plan to complete the harvesting, conducting the actual harvesting of materials, and eventual use of the material (including the dissemination of results from research conducted on the material). The Reactor Reliability and Integrity Management (RRIM) Library is envisioned as a suite of integrated tools (Figure 1) that focus on providing decision makers with necessary information to deliver informed recommendations based on the available data. The following tools have been identified as critical to development of the RRIM Library:

- Generic plant framework
- Knowledge repository
- Harvesting management.

The generic plant framework is built into the aging management review tables in the GALL and GALL-SLR reports, which are categorized by plant type (PWR or BWR), structure and/or component, material, environment, and aging effect/mechanism. This generic information, which also forms the starting point for the plant-specific AMP, feeds into the knowledge repository block in Figure 1 along with other sources on materials degradation [PMDA 2007 and EMDA 2014 reports (Andresen et al. 2007; Andresen et al. 2014; Bernstein et al. 2014; Busby 2014; Graves et al. 2014; Nanstad et al. 2014), which represented the state of knowledge from a panel of SMEs when they were published, along with current operational experience and research results].

The harvesting management can then be developed by combining the knowledge repository along with the priorities of the organization sponsoring the work (SME input). Once these factors are developed, the harvesting plan can be created, taking into account the multiple factors discussed above in Section 3.0 (inventory of previously harvested materials, opportunities from plants that are shutting down or replacing components, procedures needed to actually harvest the materials, and the costs associated with the procedures). Given the plan, the actual harvesting completes the harvesting management, and allows for the research to be done and the results fed into the plant AMPs and GALL / GALL-SLR AMPs.

It is important to note that these are only envisioned tools at this time. If the harvesting needs change, the tool sets described here may need to be augmented or modified to account for these changes.

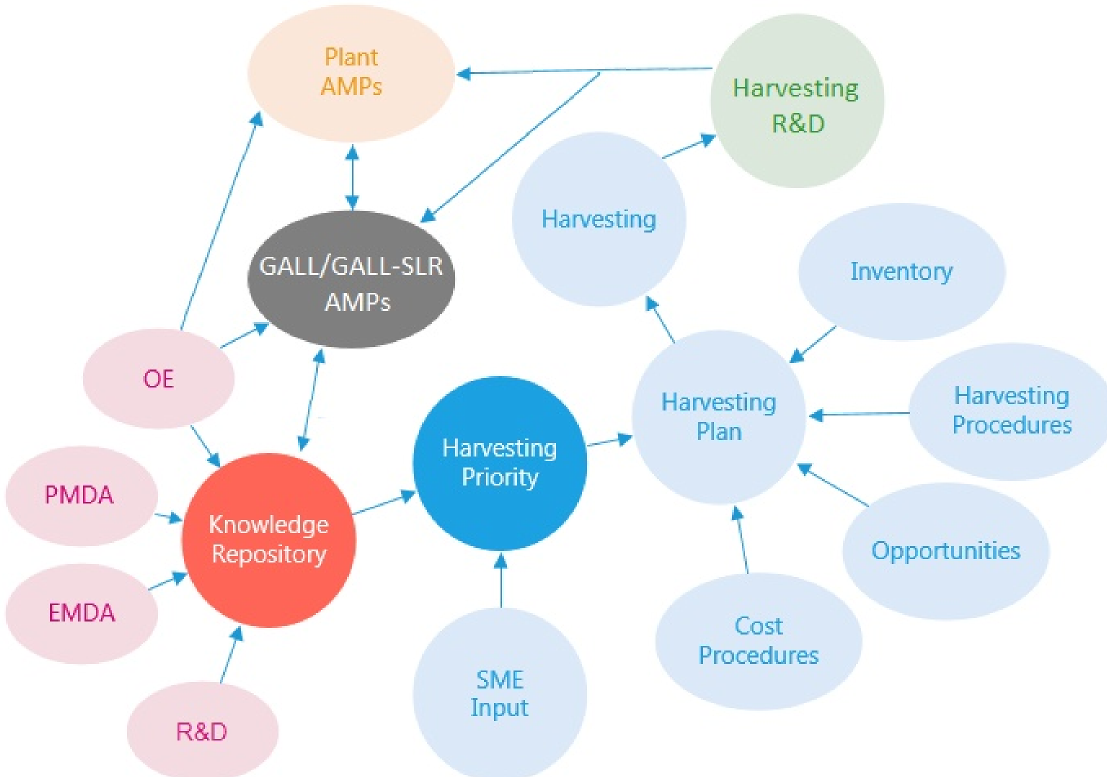

Figure 1. Reactor Reliability and Integrity Management Library Concept

4.2 Work to Date

A demonstration website was set up to model what the knowledge repository may look like (Figure 2). The demonstration site only contains OE entries as a sample data set; SME expertise would be needed to incorporate documents such as the proactive management of materials degradation tool, EMDA, and GALL-SLR into discrete knowledge elements. The visualization below provides an example of publicly available information about plant OE, along with the ability to search and sort the information (from more than one source, including public websites and a subset of EMDA information) by SSC type, material, environment, and degradation mechanism. The demonstration site for the knowledge repository would be one starting point for a detailed analysis of the required capabilities for the RRIM tool suite described earlier.

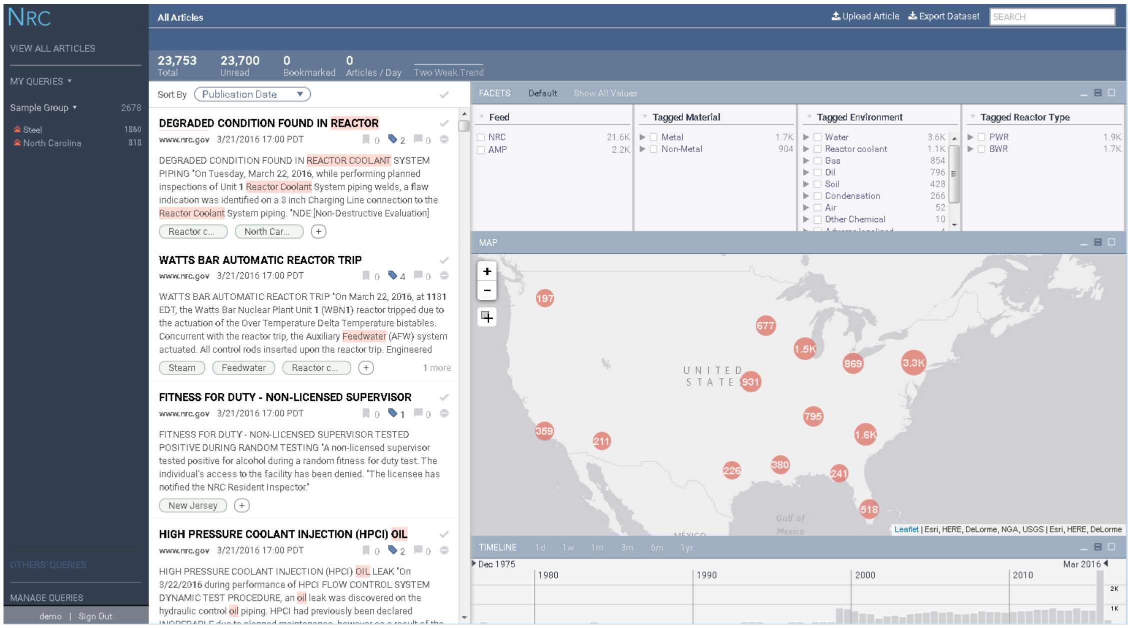

Figure 2. Example Visualization of Knowledge Repository to Support Harvesting Decision-Making

5.0 Summary and Path Forward

Previous materials degradation studies on harvested materials have provided valuable technical insights to ensure and confirm the effectiveness of aging management approaches used by the nuclear industry. The results from additional harvesting activities will add to confirmatory evidence of the effectiveness of aging management approaches used by the nuclear industry through better understanding of actual material property changes with plant age and improved understanding of the initiation and growth of degradation mechanisms of relevance to extended plant operation. Evaluation of material properties in SSCs from actual decommissioned NPPs will also provide a basis for comparison with results of laboratory tests and calculations.

Given the costs associated with any harvesting effort, potential approaches will need to prioritize materials using a number of criteria beyond the implications to safe operation of NPPs. These criteria for initial consideration include:

- Unique field aspects that drive the importance of harvesting the material
- Ease of laboratory replication of material and environment combination
- Applicability of harvested material for addressing technical issues (dose rate issues, etc.)
- Availability of reliable ISI techniques for the material
- Availability of an inventory for harvesting.

Additional related criteria for prioritizing harvesting of components/materials relevant to the specific needs of the organization developing a harvesting plan will vary and could include:

- State of knowledge of the material, environment, and age-related degradation of interest
- OE related to the material, environment, and age-related degradation of interest

- Availability of AMPs to manage age-related degradation of interest
- Available options for mitigation of the age-related degradation, including the performance of the mitigation option
- The ease of replacement for components
- Applicability of information obtained from potential harvesting opportunities (e.g., BWRs only, PWRs only, or fleet-wide)
- Knowledge areas that will be improved by harvesting, including how it will inform AMPs.

These criteria help define the specific problems that will be addressed and the knowledge gained through the use of the harvested materials. These criteria, along with lessons learned from previous campaigns, can be used to develop a harvesting plan that can be customized for the specific needs and opportunities at hand.

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Prepared for the U.S. Nuclear Regulatory Commission
under a Related Services Agreement with the U.S. Department of Energy
CONTRACT DE-AC05-76RL01830

U.S. DEPARTMENT OF ENERGY