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

December 2017

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U.S. DEPARTMENT OF
ENERGY

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Abstract

As U.S. nuclear power plants look to subsequent license renewal (SLR) to operate for a 20-year period beyond 60 years, the U.S. Nuclear Regulatory Commission and the industry will be addressing technical issues around the capability of long-lived passive components to meet their functionality objectives. A key challenge will be to better understand likely materials degradation mechanisms in these components and their impacts on component functionality and safety margins. Research addressing many of the remaining technical gaps in these areas for SLR may greatly benefit from materials sampled from plants (decommissioned or operating). Because of the cost and inefficiency of piecemeal sampling, there is a need for a strategic and systematic approach to sampling materials from structures, systems, and components (SSC) in both operating and decommissioned plants. This document describes a potential approach for sampling (harvesting) materials that focuses on prioritizing materials for sampling using a number of criteria. These criteria are based on an evaluation of technical gaps identified in the literature, research needs to address these technical gaps, and lessons learned from previous harvesting campaigns. The document also describes a process for planning future harvesting campaigns; such a plan would include an understanding of the harvesting priorities, available materials, and the planned use of the materials to address the technical gaps.

Summary

The decommissioning of some nuclear power plants (NPPs) in the United States after extended operation provides an opportunity to address a number of materials degradation questions that add to confidence in the aging management systems used by the nuclear industry. Addressing these questions is expected to provide reasonable assurance that systems, structures, and components (SSCs) are able to meet their safety functions. Many of the remaining questions regarding degradation of materials will likely require a combination of laboratory studies as well as other research conducted on materials sampled from plants (decommissioned or operating).

Evaluation of material properties of SSCs from operating or decommissioned NPPs can provide a basis for comparison with results of laboratory studies and calculations to increase confidence that long-lived passive components will be capable of meeting their functional requirements during operation beyond 60 years. A strategic and systematic approach to sampling materials from SSCs in both operating and decommissioned plants will help reduce costs and improve efficiency of materials harvesting. In turn, the ability to efficiently harvest materials is expected to lead to opportunities for benchmarking laboratory-scale studies on materials aging, identifying constraints on materials/components replacement in operating plants, and determining condition assessment methods that may be applied to these components in the field.

This document describes a potential approach for prioritizing sampling (harvesting) materials using a number of criteria that incorporate knowledge about the specific technical gaps closed through the sampling process. At the highest level, the major criteria are:

- Unique field aspects, if any, that drive the importance of harvesting the material
- Ease of laboratory replication of material and environment combination
- Applicability of harvested material for addressing critical gaps (dose rate issues, etc.)
- Availability of reliable in-service inspection techniques for the material
- Availability of materials for harvesting.

A number of information sources on materials degradation in NPPs were reviewed to assess key technical gaps that may be relevant for SLR. Information from these sources were cross-referenced (where possible) and collated to assess harvesting priority. In this document, several examples of this process are described, along with experiences from harvesting materials at several operating and closed plants. Using these lessons learned from previous harvesting campaigns, a harvesting process is defined that includes many of the criteria that should be taken into account during any harvesting campaign.

The use of information tools can assist with this harvesting process, and one concept for such a tool is described in this document. This tool is expected to provide a mechanism for easily sorting and searching through information from multiple sources, integrate subject matter expert input into the technical gaps assessment and prioritization process, and generate the appropriate prioritized harvesting plan. In theory, such a tool could be extended to include a mechanism for collating the findings from any research conducted using the harvested material and enable a seamless way for accessing the necessary information for any subsequent decisions.

Acknowledgments

Acronyms and Abbreviations

ALARA	as low as reasonably achievable
AMP	aging management program
ASME	American Society of Mechanical Engineers
BWR	boiling water reactor
CASS	cast austenitic stainless steel
CM	condition monitoring
Code	ASME Boiler and Pressure Vessel Code
DBE	design basis event
DMW	dissimilar metal weld
dpa	displacements per atom
EAB	elongation-at-break
EMDA	enhanced materials degradation assessment
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
GALL	Generic Aging Lessons Learned
IASCC	irradiation-assisted stress corrosion cracking
ISI	in-service inspection
LWR	light water reactor
NDE	nondestructive evaluation
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OE	operating experience
OMB	outside the missile barrier
PMDA	proactive materials degradation assessment
PWR	pressurized water reactor
RPV	reactor pressure vessel
RRIM	Reactor Reliability and Integrity Management
SCC	stress corrosion crack
SLR	subsequent license renewal
SME	subject matter expert
SSC	structures, systems and components
XLPE	crosslinked polyethylene
XLPO	crosslinked polyolefin

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1.0   Introduction

The nuclear power fleet in the United States currently consists of approximately 98 operating reactors, of which 87, as of October 2017, have received licenses to operate beyond the original license period of 40 years (NRC N.D., 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.

The U.S. Nuclear Regulatory Commission (NRC) regulations in 10 CFR 54.31(d) allow nuclear power plants (NPPs) to renew their licenses for successive 20-year periods. The biggest challenges for the NRC and the industry will be addressing the major technical issues for this second ("subsequent") license renewal (SLR) beyond 60 years. As summarized in SECY-14-0016 (SECY-14-0016 2014; Vietti-Cook 2014), the most significant technical issue challenging power reactor operation beyond 60 years is assuring long-lived passive components are capable of meeting their safety functions. In particular, the accumulation of degradation in four classes of systems, structures, and components (SSCs) is of concern (INL 2016):

- Reactor pressure vessel (RPV)

- Reactor internals and primary system components

- Concrete and containment degradation

- Electrical cables.

Understanding the causes and control of degradation mechanisms 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 SLR period.

Addressing many of the remaining technical gaps for SLR may require a combination of laboratory studies and other research conducted on materials sampled from plants (decommissioned or operating). Evaluation of materials properties of SSCs from decommissioned NPPs will provide a basis for comparison with results of laboratory studies and calculations to determine if long-lived passive components will be capable of meeting their safety functions during operation beyond 60 years. Because of the cost and inefficiency of piecemeal sampling (i.e., harvesting materials on an ad-hoc basis), there is a need for a strategic and systematic approach to sampling materials from SSCs in both operating and decommissioned plants.

This document describes a potential approach for sampling (harvesting) that focuses on prioritizing materials using a number of criteria. These criteria also help define the specific problems that will be addressed and the knowledge gained/technical gaps closed through the sampling process. Using a number of lessons learned from previous harvesting campaigns, a harvesting process is defined that includes many of the criteria that should be taken into account during any harvesting campaign.

2.0   Nuclear Plant Materials Harvesting

A key challenge to addressing the gaps in materials aging and degradation through 80 years of operation is the ability to perform tests that mimic the aging process in operating plants. Often, such tests are performed (and materials performance data obtained) through accelerated aging experiments, where the

material under test is subjected to higher stresses (mechanical, thermal, and/or radiation) than those seen in operation. Such tests enable the experiments to be completed in a reasonable timeframe but need to be benchmarked with performance data from materials that have seen more representative service aging.

Where available, benchmarking can be performed using surveillance specimens. In most cases, however, benchmarking of laboratory tests will require harvesting materials from reactors.

Over the past several years, a number NPPs (both within the United States and elsewhere) have either permanently ceased operation or have indicated that they will shut down in the next few years. These shutdown plants provide an opportunity to extract materials that have real-world aging and provide an avenue for benchmarking laboratory-scale studies on materials aging. The resulting insights into material aging mechanisms and precise margins to failure will be essential to provide reasonable assurance that the materials/components will continue to perform their safety function throughout the plant licensing period. The extracted materials could also help in determining specific methods for condition assessment or non-destructive evaluation (NDE) that may be applied to these components in the field to assess component aging.

Note that while shutdown nuclear plants provide an unparalleled opportunity for ex-plant harvesting, similar harvesting opportunities may exist in operating plants. Scheduled repairs or replacements may provide opportunity to extract materials to address specific knowledge gaps associated with materials performance during SLR. In other instances, specific but unusual operational experience may dictate the need to harvest materials to better understand the observed phenomena.

Harvesting is not the sole answer to addressing knowledge gaps. In some cases where harvesting is most needed, such as the RPV, internals, and concrete in the shield walls, the components exist in areas with high radiation doses. Because of the need to minimize personnel radiation doses to levels as low as reasonably achievable (ALARA), worker access to these areas is stringently controlled. The benefits of harvesting may not be enough to overcome the costs of procurement, evaluation, and subsequent disposal of the materials.

Given the advantages and disadvantages associated with harvesting, there is a need for processes to identify, assess, and prioritize harvesting opportunities. The next section discusses criteria for harvesting and provides examples of applying these criteria.

3.0   Materials and 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. Several examples are included that show the application of these criteria to provide a qualitative assessment of harvesting priority.

3.1   Literature Sources

There are two general classes of degradation mechanisms that are of interest (Cattant 2014). The first class is mechanisms that lead to failure (such as corrosion, fatigue, or wear) while the second class concerns materials aging (such as irradiation embrittlement and thermal aging). In general, the second class of degradation mechanisms results in a change in material properties (reduction in toughness, increase in hardness, etc.) that can facilitate failure through one of the failure mechanisms. In this document, this distinction is not strictly followed and the terms "degradation mechanism" and "aging" are used somewhat generically to refer to either of the two classes.

A wide variety of literature exists with information on materials degradation that may be relevant to life extension of NPPs. Early materials aging insights for light water reactor 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 Generic Aging Lessons Learned (GALL) reports (NRC 2010a, 2017b, a); *Expert Panel Report on Proactive Materials Degradation Assessment (PMDA)* (Andresen et al. 2007); *Proactive Management of Materials Degradation - A Review of Principles and Programs* (Bond et al. 2008); and *Expanded Materials Degradation Assessment (EMDA)*, NUREG-7153:

- Volume 1 (Busby 2014)

- Volume 2 (Andresen et al. 2014)

- Volume 3 (Nanstad et al. 2014)

- Volume 4 (Graves et al. 2014)

- Volume 5 (Bernstein et al. 2014)

The GALL report is the NRC staff's generic evaluation of the acceptable aging management for the period of extended operation based on the technical basis developed in the EMDA and PMDA. Based primarily on the operating experience from the fleet of operating plants in addition to EMDA and PMDA, GALL assesses the acceptable aging management approach for passive SSCs, based on material type and operating environment. The Electric Power Research Institute (EPRI) has also documented materials aging issues in the form of Materials Degradation Matrix and Issue Management Tables (EPRI 2013a, b, c). The matrix is used to document potential degradation mechanisms for primary system components, while the tables provide the basis for determining the consequence of component failures along with possible mitigation options. Further, a number of technical gaps have been identified in the understanding of degradation growth in specific materials; these are the current focus of active research by a number of organizations (IAEA 2012; McCloy et al. 2013; INL 2016).

Two factors play an important role in the ability to detect and mitigate materials degradation. First is an understanding of the materials degradation processes that contribute to the progression of degradation and, if not detected and mitigated, an eventual loss of structural integrity. The second factor is the availability of NDE methods and associated condition monitoring (CM) techniques that are capable of detecting the degradation in a timely fashion (before it grows to the point where loss of structural integrity occurs).

It is important to note that these two factors are connected and advances in one may help address any perceived deficiencies in the other. For instance, lack of a comprehensive understanding of the mechanism (how it develops and grows) may be mitigated somewhat if adequate methods for detecting the degradation are available. Likewise, lack of adequate methods for detection may be mitigated if improved understanding of the mechanisms exists.

Note that the sources of information for these two factors are not always connected. A number of studies have examined the ability to detect degradation in a timely manner. These studies have generally focused on assessing the reliability of NDE methods and the factors impacting reliability. Current techniques such as ultrasonic testing and eddy current testing that are applied for NPP in-service inspection (ISI) tend to focus on detecting signatures from mechanisms (such as cracking) that lead to failure. These studies are usually based on a comprehensive round-robin assessment of the technique, instrumentation, or personnel (Crawford et al. 2015; Meyer and Heasler 2017; Meyer et al. 2017; Ramuhalli et al. 2017). These types of studies have led to changes in the American Society of Mechanical Engineers (ASME) Boiler and

Pressure Vessel Code (hereafter the Code) around the implementation of techniques to assure reliable detection of cracking in the field (Doctor et al. 2013).

It is important to note that current NDE techniques have not seen real-time or in situ application for the detection and characterization of general materials aging. However, there is a rich set of literature that is examining the applicability of these same techniques as well as new techniques for this purpose, although the work has stayed largely in the basic research phase (Bond et al. 2009, 2011; Meyer et al. 2012; IAEA 2013; Ramuhalli et al. 2014; Fifield and Ramuhalli 2015).

3.2   Literature Assessment

The literature identified above, especially for materials degradation mechanisms, cover a broad range of materials, mechanisms, and environments, for both pressurized water reactor (PWR) and boiling water reactor (BWR) plants.

From the perspective of SLR, a number of studies, such as the EMDA and PMDA, have identified technical gaps 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.

It is important to note that the information in the literature sources identified in Section 3.1, while similar in form, differs 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 while recognizing 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.

A specific example of this is the structural steels used in RPVs, where compositional variations may be a driving force in the loss of fracture toughness (Sokolov and Nanstad 2016). Concern now focuses on the possibility of late-blooming phases (Malerba 2013) that may cause changes in fracture toughness over longer operating periods. However, the development of such phases appears to be a function of the specific composition and the operational environment.

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 PMDA effort (Andresen et al. 2007). As plants consider SLR out to 80 years of operation, concerns about non-metallic passive components are increasing. These long-lived components, broadly divided into concrete and electrical cables, are generally difficult (if not impossible) to replace and would require a significant investment if across-the-board replacement is considered. As a result, recent assessments such as the EMDA have included a significant emphasis on identifying 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 CM and NDE methods for concrete and electrical cables, with the objective of defining methods and acceptance criteria that would provide reasonable assurance that degradation would be detected before it reaches a state where it begins to affect the safe operation of the plant.

Collectively, these studies point to several potential knowledge gaps regarding specific materials and degradation mechanisms. These knowledge gaps are related to an understanding of the conditions leading to degradation initiation and growth, and to methods for detecting and mitigating such degradation in a timely fashion. Note that this is not a blanket statement about all materials and all mechanisms; in many instances, sufficient knowledge exists about the mechanism and methods for detection such that appropriate AMPs may be used successfully to manage these mechanisms of aging and degradation out to 80 years of operation.

The implication of the foregoing discussion is that certain mechanisms and materials, within the context of SLR, may be considered as a high priority when it comes to addressing technical gaps in 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, priorities may also need to account for the connection between materials degradation and CM/NDE, and include an assessment of available NDE or other CM techniques. Assuming such a prioritization can be made, the materials identified would then 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 for SLR, and incorporates lessons learned from harvesting efforts in the years since these previous studies.

The next several subsections describe potential criteria and provide several examples of the analysis that can be conducted using these criteria for identifying high-priority components/materials for ex-plant harvesting.

3.3   Criteria for Prioritizing Harvesting

3.3.1   Criteria

Criteria for prioritizing harvesting of components/materials need to be relevant to the organization's specific needs. For example, one of the questions that will need to be addressed is whether for a given material within a specific environment, the failure mechanisms are understood sufficiently. If so, 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 drive up the priority for harvesting in an effort to reduce the uncertainty. For CM/NDE, the needs are generally about the mechanism and geometry but not how the degradation was created (accelerated vs. real time). A need also exists in simulating "realistic" degradation, and this is where limited harvesting may be useful for benchmarking purposes.

Given this background, criteria for prioritizing harvesting may be broken into five major categories, with several other lower level criteria for fine-tuning the information. At the highest level, the major criteria are:

- 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 operating experience (OE) associated with a specific class of materials in a relevant environment. If OE is available, especially

for materials considered to be low in susceptibility to a specific degradation mechanism, for instance stress corrosion cracking (SCC), it may be worth harvesting the material if possible.

- 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 is more so for low-dose, long-term irradiation and is a concern if dose rate effects exist that may influence the mechanism initiation and growth.

- Applicability of harvested material for addressing critical gaps. The focus of this criterion is on the ease with which the harvested material may be used in laboratory studies to address gaps in knowledge. 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).

- 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. 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) is necessary.

Note that the focus of this document is on identifying harvesting needs; other parallel activities are underway (and are expected to continue into the future) to identify material availability.

These high-level criteria focus on the ability of harvested materials to address gaps in materials performance knowledge for SLR. In tabulating the answers to these criteria, a variety of information will need to be gathered, possibly using one or more of the sources identified earlier. These include expert elicitation studies (EMDA, Materials Degradation Matrix, etc.) on the susceptibility of various materials in relevant environments to a number of degradation mechanisms. In addition to the susceptibility information from these expert panels, knowledge and confidence may be gained in the specific combination of material, degradation mechanism, and environment. In parallel, information in the GALL documents associate similar combinations with relevant AMPs, while other available documents provide insights into specific knowledge gaps.

Specific information from these studies that would be needed include:

1. Whether the material, degradation mechanism, and environment combination rated "high susceptibility" in expert elicitation reviews such as EMDA.

2. Whether the material, degradation mechanism, and environment combination rated "low knowledge" in the expert elicitation reviews such as EMDA.

3. AMPs that may be applicable to address the combination of the material, degradation mechanism, and environment.

4. Presence of OE associated with the material, degradation mechanism, and environment combination.

5. The level of understanding of the mechanism (ranges of environmental factors, initiation times and growth rates, other factors such as compositional variations, etc.). In effect, this is related to identifying the critical gaps in knowledge and also the ease with which the material, degradation mechanism, and environment combination may be simulated in the laboratory.

6. Options for mitigation, if any. Effective mitigation techniques (including a relatively easy and inexpensive path to replacement of the component) point to a relatively high level of understanding of the degradation mechanism. As a result, the added benefits from harvesting may be limited in these instances.

7. Amount of material use (plant-wide and fleet-wide). In addition to addressing the criterion on material availability, this information also plays into an assessment of the harvesting benefit. Widespread use of a specific material under similar environmental conditions could point to a large (potentially fleet-wide) benefit from harvesting.

It is important to determine whether the expected benefits from the harvested materials will clearly reduce any uncertainty associated with the materials' performance through 80 years of operation of the plant. If so, this potentially provides benefits from the regulatory perspective, while reducing any uncertainty around safety margins in these components.

3.4 Examples

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 cover the potential range of priorities as well as 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 insulation), illustrating the complexity of the problem and the unknowns in aging mechanisms and performance. This is followed by an example of cast austenitic stainless steel (CASS), which highlights several unknowns in 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.

3.4.1 Electrical Cables

The issues associated with aging of electrical cables are generally complicated by the diversity in materials and formulations that were used in vintage cables. Given the qualification methods used when they were put into service, utilities were able to perform 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. However, as utilities approach a decision on SLR, there is a general consensus that available data on long-term performance of cables is sparse and in some instances contradictory.

Generally, utilities have adopted a CM approach to aging cable management. Given the uncertainties and knowledge gaps, they do not necessarily expect the cable to last for 80 years. Rather through their CM

program, they are assured that they can detect damage before it becomes critical. The damaged cables or cable sections may then be repaired or replaced.

Harvesting cables has 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 inspection techniques 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.

However, there is 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 (vintage material) are different from what is available today. In these cases, harvested vintage cables can be used for studies to provide the necessary data and plug the knowledge gaps.

From a CM perspective, the most interesting harvested cable samples will have failed some in-plant test (such as walkdown, indenter, withstand test, and time and frequency domain reflectometry [TDR and FDR]). These cables can then be subjected to alternative tests (like capacitance and higher-frequency FDR) and autopsy with laboratory tests like diffusion-limited oxidation and elongation at break (EAB).

Both operating and decommissioned plants may be sources of material, particularly if there is some indication of dose and/or elevated temperature exposure. A key advantage of material from these plants is the ability to compare laboratory and NDE tests of artificially aged cable to the naturally aged cable for verification of equivalency.

Harvested cables, when subjected to laboratory aging studies (wear-out aging) may be used with destructive and NDE tests (EAB, line resonance analysis, gel-swell, micro-indenter, atomic force microscopy, 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 has been done (Bernstein et al. 2014), there are still knowledge gaps that could benefit from this work.

The Cable EMDA includes the following classifications of material:

1. Cables at 35°C–50°C (95°F–122°F) and zero dose

2. Cables at 35°C–50°C (95°F–122°F) and up to 0.01 Gy/hr. (1 rad/hr.)

3. Cables at 45°C–55°C (113°F–131°F) and up to 0.1 Gy/hr. (10 rad/hr.)

4. Cables at 45°C–55°C (113°F–131°F) and up to 1 Gy/hr. (100 rad/hr.)

5. Cables at 60°C–90°C (140°F–194°F) and zero dose

6. Medium voltage cables in long-term wet conditions

For the above categories, material considerations were:

1. Crosslinked polyethylene (XLPE) (wet cables)

2. Crosslinked polyolefin (XLPO) (not for wet conditions)

3. Modern tree retardant XLPE

4. Flame-retardant ethylene propylene rubber (EPR)

5. EPR/neoprene

6. EPR/chlorosulphonated polyethylene (CSPE)

7. Black EPR

8. Pink EPR

9. Brown EPR

10. Butyl rubber

11. Neoprene

12. CSPE

13. Chlorinated polyethylene

14. Silicone rubber (not suitable for wet conditions)

For low-temperature, low-dose cases, susceptibility to embrittlement due to radiation and thermal aging was 0 to 2 (low susceptibility), and this is a well understood issue with knowledge consistently ranking at 3 (on a scale of 0–3). As the environmental exposure exceeds 45°C and up to 0.1 Gy/hr., susceptibility increases particularly with Neoprene, silicone rubber, and CSPE and the knowledge falls to 2–3. Thus, harvesting materials (especially Neoprene, silicone rubber, and CSPE) exposed to temperatures in excess of around 45°C and low-doses is likely to be of value. Table 1 provides a summarization for one type of cable in a specific environment, as a single example of non-metallic materials. Given the critical gaps and widespread nature of their use, these are considered a high priority.

Table 1. Assessment of Electrical Cable Insulation Harvesting Priority. Insulation and jacket materials considered are EPR and CSPE, at temperatures between 45°C–55°C and dose between 0.1–0.01 Gy/hr. (1–10 rad/hr.)

Criteria	Qualitative Assessment	Comments
Unique field aspects, if any	Vintage formulations, depending on manufacturer, real-world conditions.	10–12 manufacturers of vintage cable in U.S. fleet. Within a single plant, cable types and manufacturers can vary.
Ease of laboratory replication	Low-medium (long-term aging studies necessary)	
Applicability of harvested material for addressing critical gaps	High – Wear-out aging a possibility. Evaluation of CM for field degradation.	Requires knowledge on plant conditions
Condition monitoring/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	TBD	Needs input from utilities
EMDA susceptibility score	Generally High (2–3)	
EMDA knowledge score	Medium (mostly 2)	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	Documented as a potential issue	AMP updates ongoing
OE	Yes	Documented in industry publications
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	Medium	See knowledge gaps below
Options for mitigation	Low	
Ease of replacement	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
Critical gaps in knowledge	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

3.4.2   Cast Austenitic Stainless Steel

CASS is used extensively in pressure boundary components in light water reactor (LWRs) coolant systems (Chopra and Rao 2016). Applications include piping, valves, vessel internals, pumps, support structures, brackets, and flow restrictors.

OE for material degradation has not been broadly encountered under 40 years of life. Under extended service life, the main concern is loss of fracture toughness due to aging (thermal and neutron embrittlement). Stress corrosion cracking and fatigue are not considered generic concerns for CASS. Under prolonged thermal aging, elements segregate and undesirable Cr-rich regions form within the ferritic phase, leading to degradation of mechanical properties. It is not known how radiation damage will interact with thermal aging.

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 program, computer models, and existing regulatory positions. Microscopy and mechanical testing of harvested materials will improve 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, it would be prudent to harvest both unirradiated material (piping, pumps, etc.) and irradiated material (reactor internals) so that radiation effects on degradation under life extension can be reliably evaluated.

Below describes how the information on CASS may be mapped into the different criteria identified above.

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 up to 1.5 dpa).

2. Both the knowledge and confidence scores are fairly high (~2, on a scale of 0–3) for CASS for all degradation mechanisms, because there have been limited instances of degradation in the OE and those were generally attributed to poor material quality or incorrect material processing.

3. The material, mechanism, and environment for thermal aging and loss of fracture toughness can be simulated in the laboratory. However, the relation between accelerated testing time and real-world service time is not clearly validated. Synergistic effects are difficult to reproduce in the laboratory. It would be valuable to look at the heat-affected zone in welded CASS material.

4. Knowledge gaps: There is 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). This interaction needs to be understood for life extension.

5. Harvested materials can be used to address critical knowledge gaps in two areas: (1) calibration and validation of current accelerated testing procedures; and (2) assessment of the combined effects of thermal aging, coolant effects, and neutron irradiation. Degradation initiation and growth studies can be conducted with harvested materials. New/improved ISI procedures may be developed to detect degradation.

6. Reduction in fracture toughness as a result of thermal embrittlement can result in significantly increased crack propagation rates. While 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, it is possible that other factors (such as fabrication irregularities or cold work) play a role in increasing the susceptibility to

SCC (Byun and Busby 2012). There is also active research to address potential gaps related to SCC initiation and thermal embrittlement during SLR.

The main microstructural mechanisms of thermal aging at less than 500°C 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). The formation of Cr-rich α'-regions by spinodal decomposition of δ-ferrite phase is the primary mechanism for the thermal embrittlement (Byun et al. 2016). The significant material signatures in the context of condition assessment for thermal aging appears to be the amount of Cr-rich α'-regions produced by spinodal decomposition of δ-ferrite and material hardness induced by thermal aging.

7. ISI methods are being evaluated to assess their ability to detect cracking in CASS. Currently, no technologies are deployed in the field for monitoring the thermally aged condition of CASS, nor does there appear to be an obvious immediate need for such technologies.

In the event of a pressing need for such technology, the feasibility of monitoring the thermally aged condition of steels is suggested by the sensitivity of certain magnetic and ultrasonic NDE measurements to the precipitation and growth of second phases. It is reported that magnetic hysteresis loop analysis and magnetic Barkhausen noise emission can be used to estimate the amount of a non-ferromagnetic second phase material in a ferromagnetic material (Raj et al. 2003). Dobmann (2006) has investigated magnetic loop measurements for characterizing thermal embrittlement of WB36 low alloy steel. An estimate of the amount of copper phase precipitation is obtained from magnetic coercivity and results are presented that indicate a correlation between the coercivity measurements and Vickers hardness measurements. Similar studies are underway to assess precipitation of Cr-rich phases using magnetic measurements.

Harvested components are usually not necessary for condition assessment technology development as appropriate material conditions can be achieved and investigated by accelerated aging of laboratory specimens. Harvested materials may be useful to understand the interaction of radiation and thermal aging, to calibrate accelerated aging in the laboratory against long-term service in a reactor environment, and to estimate/predict the life time of CASS components for life extension. While the NRC is not currently funding research in this area, harvested CASS materials may help provide additional data to further inform the NRC's regulatory decision-making.

The information above is summarized in Table 2.

Table 2. Summary of Harvesting Criteria for CASS, for All Mechanisms, in Reactor Water in Primary Loop Components

Criteria	Qualitative Assessment	Comments
Unique field aspects, if any	Vintage material, synergistic effects (especially radiation)	
Ease of laboratory replication	Low-medium	Gap relating accelerated aging studies to real-world service time
Applicability of harvested material for addressing critical gaps	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.	Potential need to validate methods for simulating SCC
Condition monitoring/ISI for detection and sizing	Limited (medium difficulty). Coarse-grained materials challenge ultrasonic testing. Challenge for meeting detection and sizing accuracy in thick-walled specimens.	Condition assessment methods for SLR may be unconventional. Access issues dictate probability of detection and sizing performance. Harvested materials useful to study issue and develop workarounds. Cases in the Code. Appendix to Section XI.
Availability of material	TBD	Needs input from utilities
EMDA susceptibility score	Generally high	BWR piping in reactor water (no irradiation), 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	Variety of structures and similar components identified	No specifics on material composition
OE	Limited	Mostly due to poor material quality or incorrect processing
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	Medium	See knowledge gaps
Options for mitigation	Low	
Ease of replacement	Low	
Amount of use (in a plant and fleet-wide)	High (use of highest susceptibility CASS – CF8M – is lower)	Diversity in material composition and microstructure across plants. CF8M used in about 1/3 of PWRs that use CASS for Class 1 piping.
Critical gaps in knowledge	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	Multiple studies available using accelerated tests
HARVESTING PRIORITY	MEDIUM-HIGH	

3.4.3   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 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).

A challenge with DMW is the presence of different materials within the weld, resulting in different material properties. These differences can result in reduced material toughness near some of the interfaces. Localized high temperatures and residual stresses may increase susceptibility to SCC in certain environments. Operating experience has also shown the possibility of cracking in such welds.

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

1. For the combination of DMW and primary reactor water at temperatures between 100°–150°F, the susceptibility to SCC is low (1–2 on a scale of 0–3). With higher pressures and temperatures, the susceptibility increases.

2. Both knowledge and confidence scores are fairly high because OE and laboratory studies have shown numerous evidence 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 may require additional studies.

5. Harvested materials may be used to address technical gaps 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 the reliability of these methods is still a topic of active interest, preliminary data appear to indicate the possibility of detecting and sizing to ASME Code requirements.

Tables 3 and 4 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 to be at a lower priority level.

Table 3. Example Assessment for SCC in DMW: 82/182 Welds, for SCC, in PWR Primary Environments (Borated Demineralized Water (normally stagnant), 100°F–150°F, 640 psia). Components: ECCS Accumulator Piping to Cold Leg.

Criteria	Qualitative Assessment	Comments
Unique field aspects, if any	Vintage material	
Ease of laboratory replication	Medium/high	
Applicability of harvested material for addressing critical gaps	Calibrate and validate accelerated aging procedures; degradation initiation and growth studies	
Condition monitoring/ISI for detection and sizing	Available techniques may be sufficient for reasonable assurance of detection	Detection and sizing capability TBD but generally capable of meeting acceptance criteria set in the Code
Availability of material	TBD	Needs input from utilities
EMDA susceptibility score	Low-medium	Temperatures considered too low for SCC to be concern. However, cracking is a generic concern for these materials.
EMDA knowledge, confidence score	Generally high	
GALL-SLR	Nothing obvious listed for environment for this example.	AMPs are for components similar to the one listed above
OE	No.	Nothing was identified in Licensee Event Report searches to date
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	Medium-high	
Options for mitigation	Low	Given low susceptibility, this may not be an issue
Ease of replacement	Low	Given low susceptibility, this may not be an issue
Amount of use (in a plant and fleet-wide)	High	
Critical gaps in knowledge	Crack initiation time	Crack initiation probability considered low for the environment listed
HARVESTING PRIORITY	LOW	

ECCS = emergency core coolant injection system

Table 4. Example of SCC in DMW: SCC in 82/182 Welds in PWR Primary Environment (reactor water, 653°F, 2250 psia) for Components: RCS Pressurizer DMWs, RPV DMWs, RCS SG, ECCS Accumulator Piping to Cold Leg, ECCS CVCS Piping to RCS Cold Leg

Criteria	Qualitative Assessment	Comments
Unique field aspects, if any	Vintage material	
Ease of laboratory replication	Medium/high	See gap on relating accelerated aging studies to real-world service time
Applicability of harvested material for addressing critical gaps	Calibrate and validate accelerated aging procedures, degradation initiation and growth studies, new/improved ISI procedures	Multiple studies available on SCC initiation and growth in nickel alloys and DMWs, mitigation proposals (overlay) also being studied.
Condition monitoring/ISI for detection and sizing	Available techniques appear sufficient for reasonable assurance of detection in pressure boundary components (ultrasonic testing, eddy current testing) and internals (visual testing). Generally easy to apply ISI (assuming access).	Potential need to validate methods for simulating SCC. 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	TBD	Needs input from utilities
EMDA susceptibility score	Generally high	
EMDA knowledge score	Generally high	
GALL-SLR	Variety of structures and similar components identified, but no specifics on materials available	AMP XI. M7, M1, M2, M19: SG, Water Chem., ISI
OE	Yes	
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	Medium-high	See knowledge gaps
Options for mitigation	Low	
Ease of replacement	Low	
Amount of use (in a plant and fleet-wide)	High	
Critical gaps in knowledge	Crack growth rates, crack initiation time	Multiple studies available on SCC initiation and growth in nickel alloys and DMWs, mitigation proposals (overlay) also being studied.
HARVESTING PRIORITY	LOW	Multiple ongoing studies, significant advances in degradation understanding, availability of NDE drive priority assessment.

ECCS = emergency core coolant injection system
RCS = reactor coolant system

3.4.4 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 a number of cracks initiating and growing in baffle former bolts.

4. Critical gaps in knowledge include the specifics of irradiation-assisted degradation mechanisms— factors contributing to initiation and growth. A number of microstructural changes are possible in the presence of radiation, including void swelling, segregation, and precipitation. Gaps exist in understanding the factors that contribute to these mechanisms and 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, including the critical flaw size (i.e., flaw length and through-thickness depth beyond which the structural integrity of the component may be affected with continued operation), physical access for inspection, and a number of factors associated with the inspection deployment technology.

6. Internal components embody certain unique aspects that are hard to duplicate in the laboratory. Unlike DMW, and to some extent CASS, the environmental conditions (especially higher fluences) are hard to generate 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. In this respect, internal components resemble electrical cables in that there is some evidence that field aging results in different microstructural conditions than accelerated conditions; at the same time, like cables (but unlike most metallic components including DMW and CASS), at least 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 to high.

Table 5. Example of Vessel Internals for Degradation in Austenitic Stainless Steels for Vessel Internals

Criteria	Qualitative Assessment	Comments
Unique field aspects, if any	High-fluence irradiation; vintage material	
Ease of laboratory replication	Low	Accelerated aging tests vs field aging service time
Applicability of harvested material for addressing critical gaps	Mechanisms of irradiation-assisted degradation—microstructure and mechanical properties	Re-irradiation may assist with understanding materials performance at SLR fluences.
Condition assessment/ISI	Available techniques (ultrasonic, visual) may be sufficient for reasonable assurance of detection. Sizing – maybe. Ease of ISI can be low depending on access.	Access issues may dictate probability of detection and sizing performance. Challenging environment for continuous monitoring.
Availability of material	Some materials being harvested; closed plants may provide additional opportunity	
EMDA susceptibility score	Generally high	Based on OE primarily
EMDA knowledge score	Generally low	
GALL-SLR	Variety of structures and similar components identified, but no specifics on materials available	
OE	Yes	Baffle bolt cracking, cracking in other internal components
Level of understanding of mechanism (environmental factors, initiation and growth of degradation, related factors)	Low-medium	See knowledge gaps
Options for mitigation	Low	
Ease of replacement	Depends on component	Some components (for instance, baffle bolts) can be replaced relatively easily.
Amount of use (in a plant and fleet-wide)	High	
Critical gaps in knowledge	Degradation mechanisms (IASCC, swelling, segregation, etc.), flux rate and irradiation spectrum effects, microstructural property changes, and links to mechanical properties.	
HARVESTING PRIORITY	HIGH	Unique field aspects and degradation mechanisms drive this prioritization.

4.0   Harvesting Plans

4.1   Ex-plant Harvesting Experience

4.1.1   Harvesting Projects

Harvesting activities have been carried out at a number of plants in years past. These 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 been decommissioned. The bulk of the effort appears to have been on three plants—Zion (both units) and Crystal River Unit 3 (all in the U.S.), and Zorita (in Spain). Zion is a decommissioned two-unit Westinghouse-designed four-loop PWR facility. The units were commissioned in 1973, permanently shut down in 1998, and placed into SAFSTOR in 2010 (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 2010b). 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 58 dpa. A number of other plants that have ceased operations have been identified as potential sources of material for harvesting and include Kewaunee and San Onofre Generating Station (both units). At the same time, a limited amount of harvesting has been attempted at several other plants, usually in conjunction with a repair or replacement activity.

4.1.2   Cable Harvesting Experience

4.1.2.1   Background

The nuclear power cable community has long recognized the value of aged cable samples. For instance, EPRI developed a Cable Harvesting Users Guide website[1] that continues to accept recommendations from the community and provides guidelines to maximize the value of harvested cable. The guide indicates that the purpose of harvesting is to determine present condition, remaining life, and allow forensic analysis for insight into actual field-aging mechanisms and determine their influence on long-term performance. The guide is intended to benefit the utility in the following ways:

- If a utility identifies cables that are judged to be limiting by use, type, and/or operating environment, and the cables are shown to be acceptable with adequate remaining life, that utility may be able to demonstrate that work required by the regulatory authorities for other cables may be deferrable.

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(1) 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.

- Evaluation of service-aged cables is one strategy for determining the limits of remaining life for NPP cables. Equally important to understanding and managing aging of in-service cables is to gain practical insight into those cable material and construction systems that can be demonstrated to have performed well.

Key candidates for removal and harvesting are:

- Cables that have experienced unanticipated in-service failures

- Cables with observed aging degradation under specific service conditions

- Cables from systems identified by the plant as those with specific concerns (e.g., high safety significance or particular vulnerability)

- Cables from systems with plant-unique service or environmental conditions (e.g., salt water infiltration or water immersion, high operating temperature, high radiation)

- Cables that are examples from a large installed base; may include cables of particular construction and materials, from a single manufacturer, or of a single manufacturing vintage.

While it is recognized that cable harvesting may occur in conjunction with an environment where the task is secondary to either returning a plant to service or plant dismantlement, recognition of a best-practice removal protocol is helpful to maximizing the value of the harvested cable. Recommended cable removal protocol includes:

- Clearly identifying the cable to be removed

- Photographing the cable environment prior to removal

- Tagging or somehow unambiguously identifying the cable prior to or just after removal.

As long a section of cable as possible should be removed. Terminations, splices, and cable accessories should be retained as much as possible.

Identification of interesting parameters associated with the cable can include and should consider:

- Cable physical description
  - Cable category (instrumentation and control, low voltage, medium voltage)
  - Construction (configuration, number of conductors)
  - Manufacturer/date
  - Materials (jacket, insulation, conductor jacket)
  - Cable lengths and segments

- Service parameters
  - System
  - Service application
  - Current and voltage
  - Duty factor
  - Safety and maintenance rule significance
  - Age in service

- Installation data
  - Installation location (building, outside, buried)
  - Terminations
  - Supporting structures or conveyances
- Stressors
  - Installation
  - In-service mechanical and structural
  - Environmental degradation
  - Other damage potential
- Plant fleet cable experience
  - Testing interval and history
  - In-service failure or degradation
  - Other

4.1.2.2   Known Naturally Aged Harvested Cable Examples

On May 19, 2016, Zion Solutions harvested and placed into six steel drums, four sets of Zion Unit 2 cables with lengths up to 30 ft. of XLPO, low- or high-density polyethylene, EPR, silicone, Hypalon, etc., in collaboration with the NRC. Cables were harvested from:

- Accumulator discharge motor operated valve cabling, outside the missile barrier (OMB), lower level of containment
- Instrumentation cables – instrument racks, OMB, lower-level containment
- Air-operated valve cabling, OMB, lower level of containment
- Cables in electrical penetrations, OMB, containment; elevation 617 ft.

A test plan for these cables has been developed and tests such as EAB and additional aging/qualification tests have been initiated (as of the writing of this report).

Harvesting of cables was also recently performed at the Crystal River Unit 3 plant, which was shut down in 2009 for refueling and an uprate. The construction efforts caused damage to the containment structure that was ultimately determined to be too costly to repair. In 2013, it was announced that Crystal River Unit 3 would not restart and decommissioning activity was begun. Cables were harvested from the plant in 2015. Photographs were taken for many of these cables inside the plant just prior to their removal. Some of these cables have asbestos filler between the jacket and insulation; however, this is a recognized hazard that can be managed with minimal additional precautions as long as testing does not include jacket removal. A research plan has been developed for harvested high-priority cables (Fifield 2016) and is currently being executed.

Several cables were also removed from service from the Fermi nuclear station in 2015 for forensic examination. The cables were:

- 5C/#16AWG, 600V, Rockbestos XLPE/Neoprene (~ service from 1978–2010; 32 years)

- 4C/#12AWG, 600V, Okonite EPR-Neoprene/ Hypalon (~1977–2010; 31 years)

All XLPE insulations were determined to be like new based on indenter modulus and EAB. Neoprene jackets were approaching embrittlement level. The EPR-Neoprene/Hypalon jacket showed signs of aging based on both indenter modulus and EAB (Anandakumaran and Auler 2015).

In contrast to cables removed from (now closed) plants, there have been a number of examples of naturally aged cables harvested from storage. For instance, several warehouse-aged cables that had been purchased and stored for more than 20 years but not placed in service were made available to EPRI by the Palo Verde plant for evaluation. Testing at EPRI confirmed that cable insulation degradation when not exposed to severe environmental or operation stresses was limited.[1]

A third source has been cables removed from service due to failure of the cable (generally based on failing one or more tests conducted in the field). While such failures appear to be relatively rare in the field, removal of cables to prevent a future failure may occur after visual or electrical testing indicates a potential problem. In 2015, a 1000V three-phase cable with cracked Neoprene jacket and EPR insulation was removed from service at the Beaver Valley NPP after failing electrical test acceptance criteria. Forensic examination of the cable revealed tensile stresses in excess of ultimate yield strain. Chlorine and its compounds (probably hydrochloric and chloric acid) were found to contaminate the cable surface including crack walls, forming a conductive path between cable conductor and ground (Fryszczyn 2015). Several cables were also removed from the Kewaunee turbine building and sent to Analysis and Measurement Services Corp. for forensic evaluation in 2015. Cables included Boston Insulated Wire two-conductor 12 AWG CSPE jacket/CSPE insulation cable; Kerite three-conductor 12 AWG XLPO jacket/XLPO insulation cable; and Okonite four-conductor, 14 AWG Neoprene jacket/cloth wrap/EPR-Neoprene insulation. Of three naturally aged cables tested, two showed no signs of aging degradation and one showed signs of significant degradation for only the jacket (Toll 2015).

Several other harvested cables (from a number of plants) contributed to a series of reports on medium-voltage cable aging failure mechanisms mainly on butyl rubber and different types of EPR cables. It has been observed that the cables do not degrade homogeneously in water, but in discrete locations, enabling operators to isolate the degraded cable section, remove it, and splice in a new section (EPRI 2015).

4.1.3 Harvesting of Internals

4.1.3.1 Background

In recent years, OE has identified several examples of cracking in internal components, including baffle bolts, jet pump risers, core shroud, etc. A number of mechanisms are of interest, including IASCC. Given that the vessel internal components see some of the highest fluences, the acquisition of materials from these components is likely to provide a great deal of information about the behavior of these materials at high fluences. Some specific topics that are of interest include:

- Quantifying materials performance in the presence of irradiation-induced processes such as segregation, swelling, and precipitation

- Crack initiation and growth rates in the presence of irradiation-induced processes

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(1) Andrew Mantey (EPRI), Personal communication.

4.1.3.2　Known Examples

A number of harvesting efforts have been initiated in the United States and elsewhere to acquire vessel internal components. In the United States, recent efforts have included the harvesting of baffle-former bolts. The harvesting, in this case, was focused on acquiring bolts that were withdrawn from service (and replaced with improved materials) for the purposes of post-service examination (Leonard et al. 2015). These were primarily used for laboratory studies to determine the degradation mechanism and if evidence of IASCC existed with some or all of the bolts.

Similar harvesting efforts are underway at Zorita (Hiser et al. 2015), with the objective being to acquire and test materials that have experienced a range of fluences. Planned studies in this case include mechanical testing of the samples as well as testing to determine crack initiation and growth rates. In the case of Zorita, the focus is on baffle plate materials and core-barrel weld materials. These materials have been exposed to different levels of irradiation, and welds and heat-affected zone. Additional studies are planned with post-harvesting irradiation of selected specimens.

Other baffle-bolt harvesting efforts have been based on industry OE (EPRI 2017; NRC 2017c; Smith and Burke 2017).

4.1.4　Harvesting of RPV Materials

4.1.4.1　Background

RPV-related materials harvesting has a long history in the nuclear power community. The harvesting has generally been to address several questions related to the performance of the pressure vessel in the presence of irradiation and assess its likely performance under abnormal conditions. RPV materials must withstand a harsh operating environment, including neutron irradiation and time at temperature, given their function as part of the pressure boundary. Specific questions that have been raised about RPV materials include:

- Improving understanding of mechanisms driving embrittlement in RPV steels and reducing predictive uncertainties for embrittlement
- Quantifying loss of fracture toughness due to irradiation embrittlement
- Quantifying fabrication and service-induced flaws (if any) in RPV materials
- Developing techniques for mitigating embrittlement.

Clearly, the harvesting of RPV material from an operating plant is unlikely. Instead, a significant amount of studies have focused on the use of surveillance specimens that are placed inside the reactor vessel and harvested during periodic plant refueling outages. This approach also allows for supplemental capsules to be inserted into an operating reactor for a relatively short time and still get meaningful results. The exception to this is harvesting materials from terminated or cancelled plants. These are briefly summarized below.

4.1.4.2　Known Examples

A number of specimens from the beltline weld region were harvested from cancelled or terminated plants, such as the Shoreham plant. In these instances, fabricated components (especially the RPV) were accessed for the harvesting effort. These were selected specifically for studies around fabrication flaw density in the beltline weld region, and knowledge gained on fabrication flaw size and distribution in

RPVs played a role in the development of 10CFR50.61a. The harvesting priorities in these cases were driven by the specific needs of the research and included sufficient material on either side of the weld to enable studies on the weld and adjacent material.

In recent years, harvesting from the Zion Unit 1 RPV has been the focus of the U.S. Department of Energy's effort (Rosseel et al. 2016b). An appropriate segmentation plan has been developed for the RPV to gather material from the beltline weld region, between the upper and lower vertical welds. 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.

4.1.5   General Lessons Learned from Harvesting Examples

The ability to harvest field-aged materials has generally proven to be successful, but a number of lessons can be learned from these experiences.

In general, 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 prior to harvesting (for instance, through infrared thermography measurements).

Recent experiences (such as Zion and Crystal River Unit 3) showed the process of harvesting can be expensive. A related challenge was the complexity of securing engineering and labor support for a forensic harvesting task when the primary contractor in charge of the operation is primarily focused on dismantling the plant.

While harvesting materials with known degradation issues is always useful, in the case of harvesting post-plant closure, it may also be a challenge. Such information may not be readily available without performing some form of inspection. Given the challenges associated with securing engineering and labor support for harvesting, obtaining the necessary support is likely to be difficult.

4.2   Harvesting Plans General Requirements

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. Prior to developing a harvesting plan, the following will need to be addressed:

- Clearly identifying the need for harvesting the material. This will require defining the knowledge gaps that will be addressed and how these gaps are relevant to SLR.

- 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 close the knowledge gap. 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.), condition of the material after harvesting (contaminated, if cleaned to what extent, etc.).

  – Should include information on additional locations to which the material may be sent from its primary storage/use location to ensure appropriate planning can be initiated at the primary recipient facility as well as at any secondary recipient facilities.

  – A requirements document is mandatory that covers receiving and working with the material. In particular, if the material is to be handled as radioactive material, additional precautions will need to be taken for both 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 approach described earlier in this document provides a potential pathway to identifying the knowledge gaps, relevance to SLR, and defining the priority for harvesting the specific material. The associated research plan should include, in addition to a description of the specific research and expected outcomes that close the technical gaps, a pathway to using the information in a practical manner for addressing SLR needs. This may happen, for instance, through propagating the technical findings into the relevant technical literature and codes and standards.

A number of elements need 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 will need to be documented (if available) 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
  - Materials comprising the component to be harvested or composition
  - Dimensions and special features

- Service parameters
  - System
  - Service application
  - 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 inspections for degradation

Note that generating all the necessary harvesting plan information is time consuming and, where possible, 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 speeding up the procedure. For this purpose, having the necessary information available, perhaps in a searchable database, will facilitate the process.

5.0   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 gaps and development of a harvesting plan to address some of these gaps will require other information. Such information can include the state of knowledge about materials performance, availability of materials for harvesting, and operational experience.

Key to efficient use of 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 a potential tool suite for this purpose.

5.1   Reactor Reliability and Integrity Management Library

5.1.1   Overview

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

Each of these tools is described below in greater detail. It is important to note that these are only envisioned tools at this time. As harvesting needs increase, it is likely the tool sets described here will be augmented or modified to account for emerging requirements for a decision-making tool suite in this area.

5.1.1.1   Generic Plant Framework

Generic aging lessons learned plans are categorized by plant type (PWR or BWR), structure and/or component, material, environment, and aging effect/mechanism. From a RRIM tool suite perspective, this information is assigned to the Generic Aging Management Plans block in Figure 1; this block is merely intended to illustrate that the aging management plans are informed by insights from GALL as well as a

variety of other literature sources on materials degradation. This categorization provides a construct that may be used to align information from other sources to define a high-level categorization of the various elements that are of concern in a plant. This construct will be the basis for the generic plant framework in RRIM. Input from subject matter experts (SMEs) will be needed to map the knowledge elements to the framework, as each of the sources provides differing levels of granularity on the descriptions of the structure and/or components, environment, and materials. The framework will be used to further align data from other sources, which may have varying levels of detail, into a similar higher level categorization. Sources of information include the PMDA and EMDA documents.
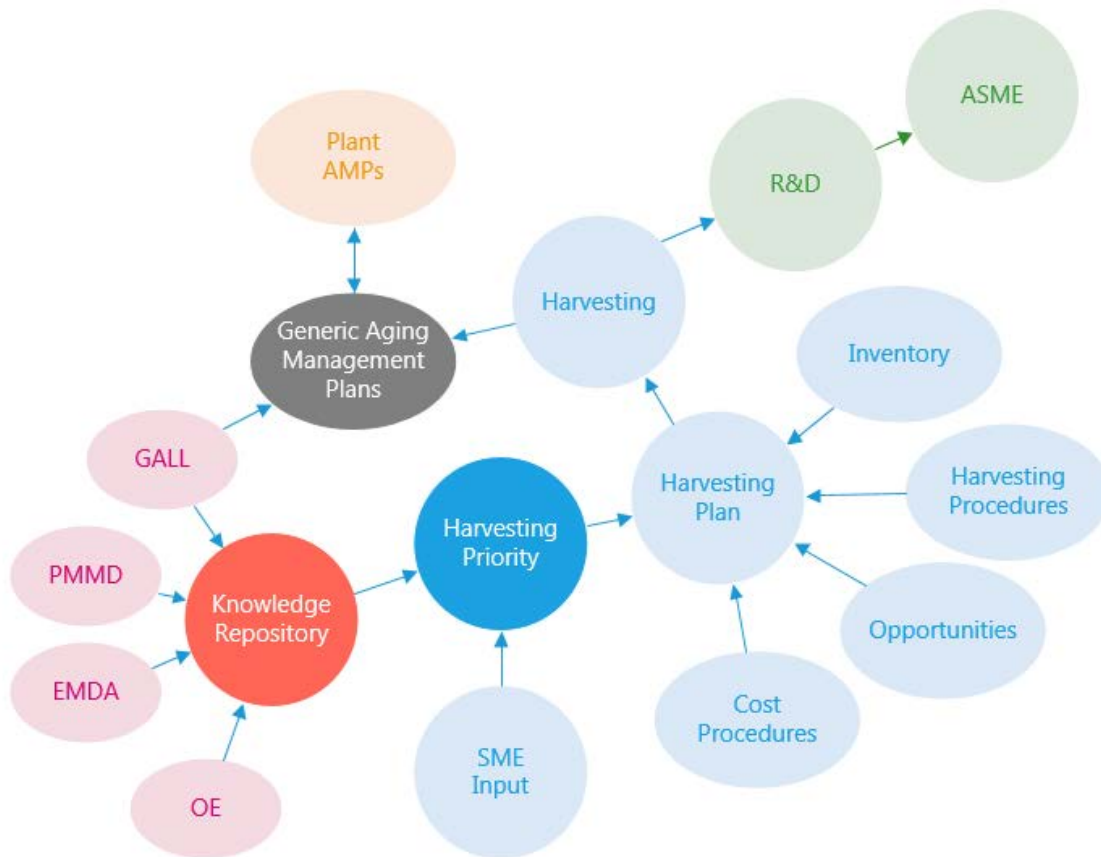

Figure 1. Reactor Reliability and Integrity Management Library Concept

5.1.1.2   Knowledge Repository

The knowledge repository will enable the correlation of a variety of information sources by mapping the data to the generic plant framework and providing searching capabilities.

The tool is envisioned to contain static content, such as information from the PMDA or EMDA. For example, the current proactive management of materials degradation tool (http://pmmd.pnl.gov) provides searching capabilities to visualize the susceptibility, confidence, and knowledge and search by the parts and degradation mechanisms as defined in the document; however, EMDA defines the parts differently.

The knowledge management tool will align the content of sources such as the EMDA and PMDA and map them into to a common structure and component list that would enable searching across both documents. The tool will also contain capabilities to automatically extract information from publicly

available relevant sites, such as the Licensee Event Report, so that new information (particularly about relevant operational experience) is automatically added. The system will provide a best attempt at mapping to the generic plant framework; however, SME input may be required to validate these mappings.

5.1.1.3   Harvesting Management

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 harvesting management tool is envisioned to support the lifecycle of the process.

This tool can be used to facilitate the harvesting prioritization as shown in the previous sections. We envision the tool as being capable of generating the unique combinations of materials, degradation mechanisms, and environments to create an entry for each unique combination within the harvesting management tool. The tool is expected to include the capability for automatically augmenting the entries with knowledge from the repository. After harvesting priorities have been determined by an SME, the tool will identify new knowledge that may impact the priorities. The tool will provide a mechanism to facilitate development of a justification, which is a key element in the preparation of harvesting plans.

The tool will also need mechanisms to capture costs, inventory, procedures, and opportunities related to harvesting. This information, augmented with priority and justification, will be the elements that provide the basis for the decision to develop a plan. The tool is also expected to facilitate capturing the results, including images and observations about the materials harvested.

5.1.2   Work to Date

A demonstration website[1] was set up to model what the knowledge repository may look like (Figure 2). The demonstration site only contains OEs 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 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.

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[1] http://hagar.pnl.gov/srs/dev/latest/v3/src/nrc/. Note: Website is only available to NRC.
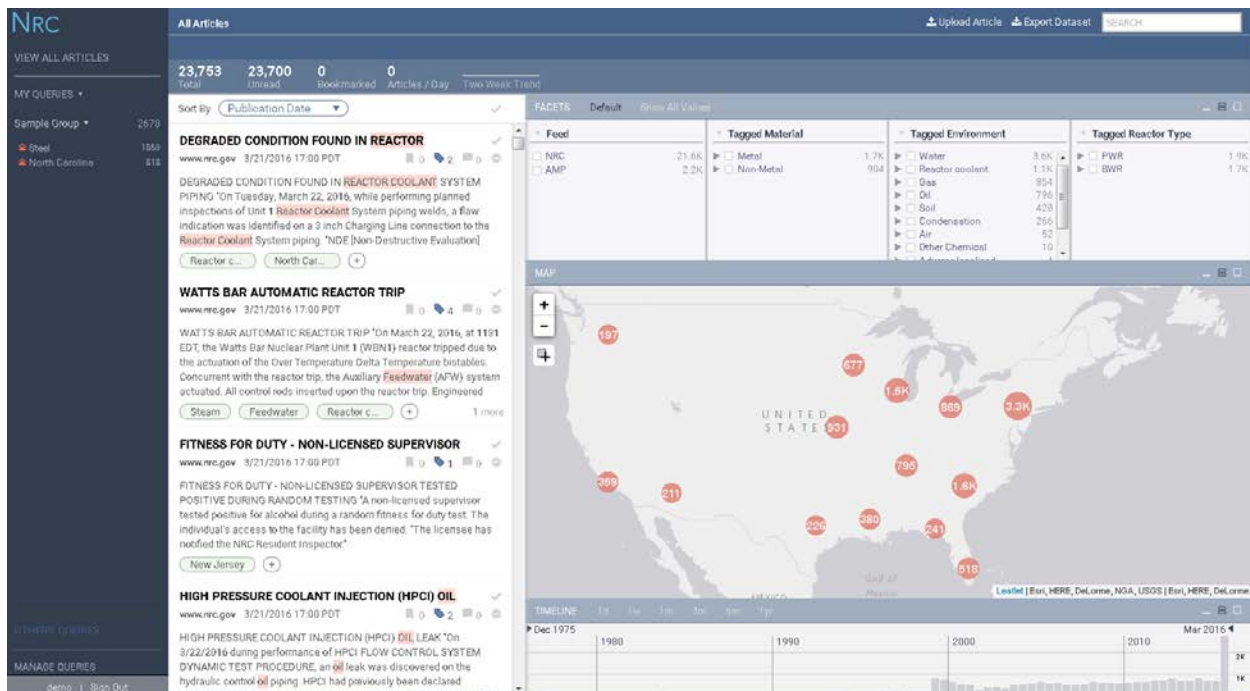
Figure 2. Example Visualization of Knowledge Repository to Support Harvesting Decision-Making

6.0   Summary and Path Forward

Addressing many of the remaining technical gaps identified in the EMDA for SLR may require accessing materials sampled from plants (decommissioned or operating). Such materials may be used to better understand actual material property changes with plant age and improve understanding of the initiation and growth of degradation mechanisms of relevance to SLR. 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, including:

- 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 critical gaps (dose rate issues, etc.)

- Availability of reliable ISI techniques for the material

- Availability of an inventory for harvesting.

These criteria help define the specific problems that will be addressed and the knowledge gained and technical gaps closed through the use of the harvested materials. A number of other factors (such as access to the material for harvesting, ability to work with the potentially contaminated material, and the plan for research using the material) play a role in defining the harvesting plan. A number of lessons may be learned from previous campaigns and these lessons can be used to develop a generic harvesting plan that can be customized for the specific needs and opportunities at hand.

A number of open questions remain in this context and will need to be addressed in follow-on research. These include:

- Requirements definition for an information tool such as RRIM. In the near term, such a tool can help as a searchable repository for identifying technical gaps. In the longer term, the tool can also assist as a repository of harvesting opportunities and with the prioritization using the criteria defined.

- Gaps assessment with respect to applying harvested materials for research and development.

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