EPRI Perspective on Harvesting

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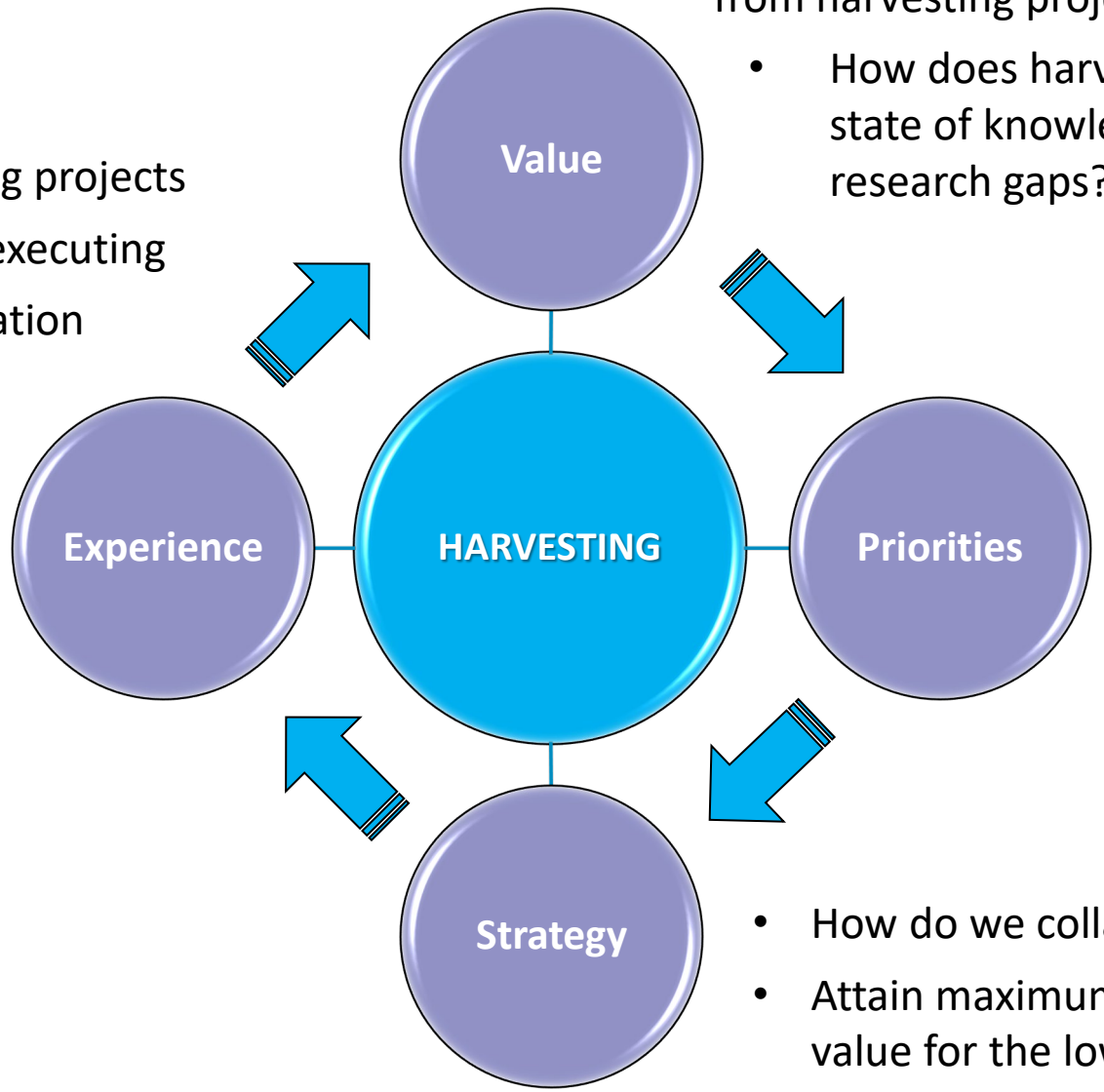
Harvesting Feedback Cycle

- Why do our Members and the public benefit from harvesting projects?
  - How does harvesting improve our state of knowledge and address EPRI's research gaps?

- Lessons learned in harvesting projects
- Challenges in planning and executing
- Testing program implementation
- Information Learned



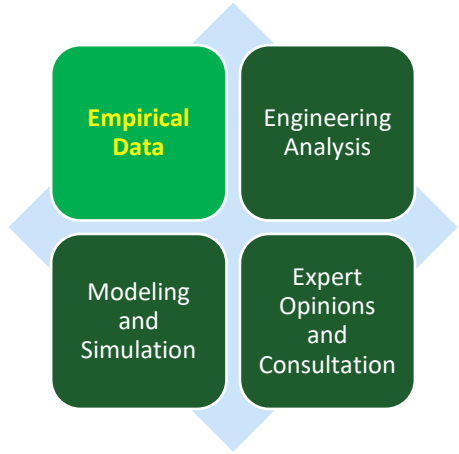
- Materials Degradation Matrix and Issue Management Tables
- Ongoing operating experience and research program findings

- How do we collaborate?
- Attain maximum research value for the lowest cost

EPRI HARVESTING PERSPECTIVE:
Primary-side and Secondary-Side Metallic Materials

Value of Harvesting

- EPRI provides materials research data to Members that meaningfully contributes to their aging management programs.
  - Identification of unexpected or accelerated material degradation
  - Supporting Codes & Standards development
  - Providing guidance for inspections and analysis



- EPRI provides a platform for plant owners to share operating experience and promptly communicate issues with EPRI's Materials Department Research Programs.

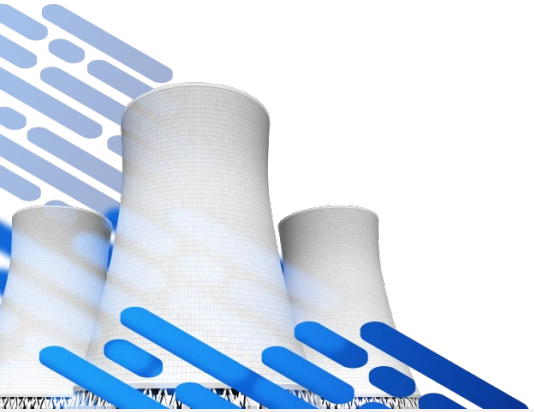
Connecticut Yankee Pressurizer Removal

Harvesting projects permit nuclear power plants to continue to contribute meaningful operating experience after shutdown.

Value of Harvesting

- Awareness of National Laboratory and Regulator-sponsored research programs on harvested materials and components.
  - In-service, non-destructive examination (NDE) effectiveness
  - Component condition evaluations for cracking, wear, local corrosion, swelling, etc.
  - Material property evaluations of aged and irradiated materials

- Opportunity to proactively research aging degradation, material properties, and novel inspection, mitigation and repair techniques.



Increasing Cost of Participation or Implementation to EPRI →

Monitoring and Reporting of Public Information ⇨ Advisor or Expert Consultation Roles ⇨ Collaboration Programs (Multiple Participants) ⇨ Independent Research Programs

Increasing Influence of EPRI →

Value of Harvesting

- Harvested nuclear reactor components provide empirical data, and specimens available from decommissioned plants after years of service exposure are **indisputably** ‘tested’ in **relevant** environmental conditions.


Indian Point Energy Center (2008 Photo)

Example for Metallic Reactor Core Internals:

- Temperature
- Water chemistry
- Operating transients
- Sustained operating stresses
- Neutron irradiation and gamma heating
- Material fabrication and installation conditions

Research Gap Priorities

- EPRI Materials Degradation Matrix, Revision 4. EPRI, Palo Alto, CA: 2018. 3002013781.
- BWRVIP-167, Revision 4: BWR Vessel and Internals Project: Boiling Water Reactor Issue Management Tables. EPRI, Palo Alto, CA: 2020. 3002018319.
- Materials Reliability Program: Pressurized Water Reactor Issue Management Tables – Revision 4 (MRP-205). EPRI, Palo Alto, CA: 2020. 3002018255.
- Materials Reliability Program: VVER Issue Management Tables (MRP-471). EPRI, Palo Alto, CA: 2021. 3002021033.

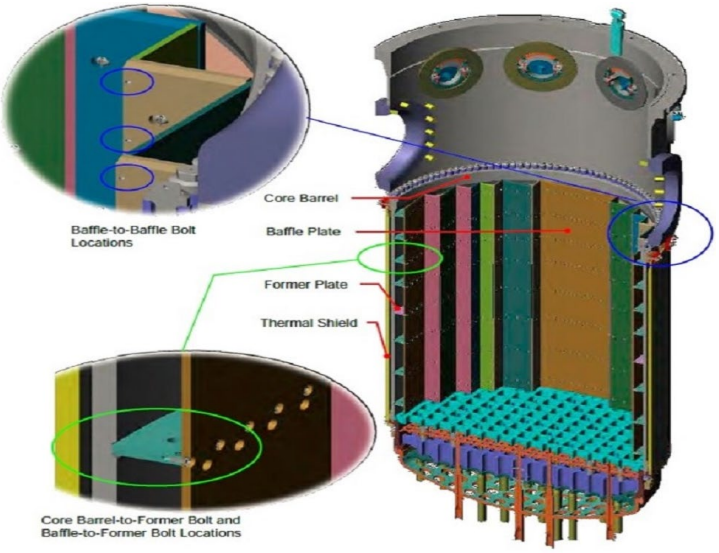
Research Gaps focus on:

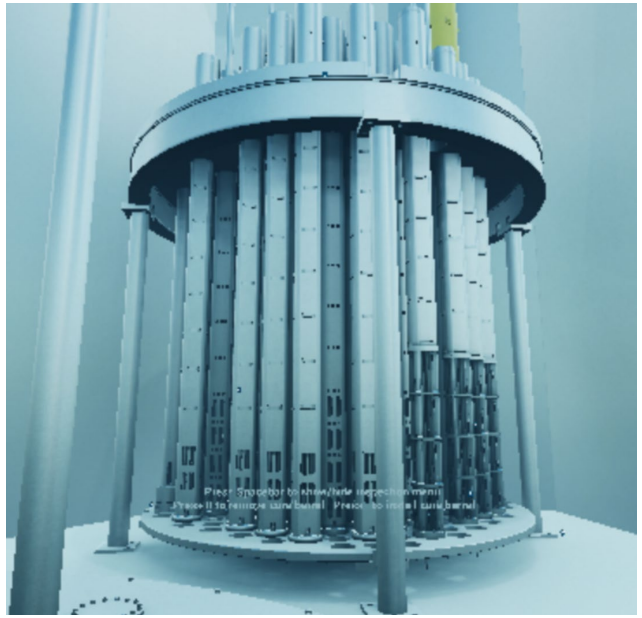
- Degradation Mechanism Understanding
- Assessment
- Mitigation
- Inspection
- Repair / Replacement

Projects are concentrated in Materials Research Focus Areas to address

Materials Research Focus Area 1: Reactor Internals Management

- Continual review of latest operating experience to evaluate significance of degradation and impact to plant operations. Updates to Inspection & Evaluation Guidance:
  - Materials Reliability Program: Pressurized Water Reactor Internals Inspection and Evaluation Guidelines (MRP-227, Revision 2). EPRI, Palo Alto, CA: 2021. 3002020105.
  - Materials Reliability Program: Inspection Standard for Pressurized Water Reactor Internals—2018 Update (MRP-228, Rev. 3). EPRI, Palo Alto, CA: 2018. 3002010399.
  - *BWRVIP-03, Revision 20: BWR Vessel and Internals Project, Reactor Pressure Vessel and Internals Examination Guidelines.* EPRI, Palo Alto, CA: 2021. 3002010675.
  - BWRVIP-41, Revision 3: BWR Vessel and Internals Project, BWR Jet Pump Assembly Inspection and Flaw Evaluation Guidelines. EPRI, Palo Alto, CA: 2010. 1021000
  - …. Many more BWR specific component / assembly Guidelines exist.





Materials Research Focus Area 2: Stainless Steel Alloys

- Microstructure and fracture toughness of highly-irradiated Type 304/316 (equivalent) austenitic stainless steel
- Characterization of helium transmutation and void swelling in high fluence (and high gamma heating) internals components of LWRs
- Grain boundary microstructure (voids, radiation-induced segregation) impacts to Environmentally-assisted cracking (EAC) susceptibility
- Crack growth rates of irradiated austenitic 300-series base metal and welds, and high-strength alloys in LWR environments
- Water chemistry effects on irradiated materials performance in stress corrosion cracking tests

- Considerable laboratory testing and historical operating experience with stress corrosion cracking (SCC), fatigue, etc.
- Currently following the EDF stainless steel SCC operating experience (industry focus group formed) and pressurizer surge-line weld cracking experience in Japan

HARVESTING TARGETS

- Irradiated weld, HAZ, and base metal Fracture Toughness and CGRs
- Void-swelling applicability in high-dose, high gamma heating regions.
- Defect population from fabrication in stainless steel welds.

Materials Research Focus Area 3: Nickel-based Alloys

- Thermal aging impacts to mechanical properties of Alloy 690 and associated weld metals (Alloy 52 and Alloy 152), including potential contributors to thermal aging in these alloys
- Crack growth rates of thermally-aged Alloy 690 and associated weld metals in LWR environments
- Strain effects from cold work or weld shrinkage on materials performance in stress corrosion cracking (SCC) tests
- Microstructure and fracture toughness of lower irradiation, high strength materials (i.e., Alloy 182, X-750, etc.)
- Water chemistry effects on materials performance in stress corrosion cracking tests

- Laboratory research programs investigating the effects of crack initiation and crack growth in base metal and weld metal of Ni-Fe-Cr alloys, with various strain conditions.
- Significant inspection experience with steam generator (SG) tubes and RVCH penetrations.

HARVESTING TARGETS

- Obtain more fracture toughness data from high-strength alloys; SCC-initiation and SCC-growth test data on harvested materials that are “aged” / weld strained.
- Evaluation of microstructure / mechanical property changes and relevance to PWSCC from thermal aging of nickel-based alloys.
- SG Tube degradation and inspection effectiveness – A600 and A690 materials.

Materials Research Focus Area 4: Low-Alloy Steel

- Adequacy of neutron fluence attenuation model (through vessel wall)
- Assessment of neutron fluence streaming in annulus (Albedo Effect) towards nozzles
- Accuracy of high neutron fluence embrittlement correlations using real vessel materials, and investigation of late blooming phases in PWR relevant fluence
- Accuracy of low fluence embrittlement correlations for extended beltline materials and nozzles using real vessel materials
- Homogeneity and representativeness of surveillance materials with reactor vessel plates, forgings, and welds – chemistry, microstructure, and mechanical properties
- Resolution of temperature and alloy chemistry (including tramp elements Cu and P) effects on potential thermal embrittlement

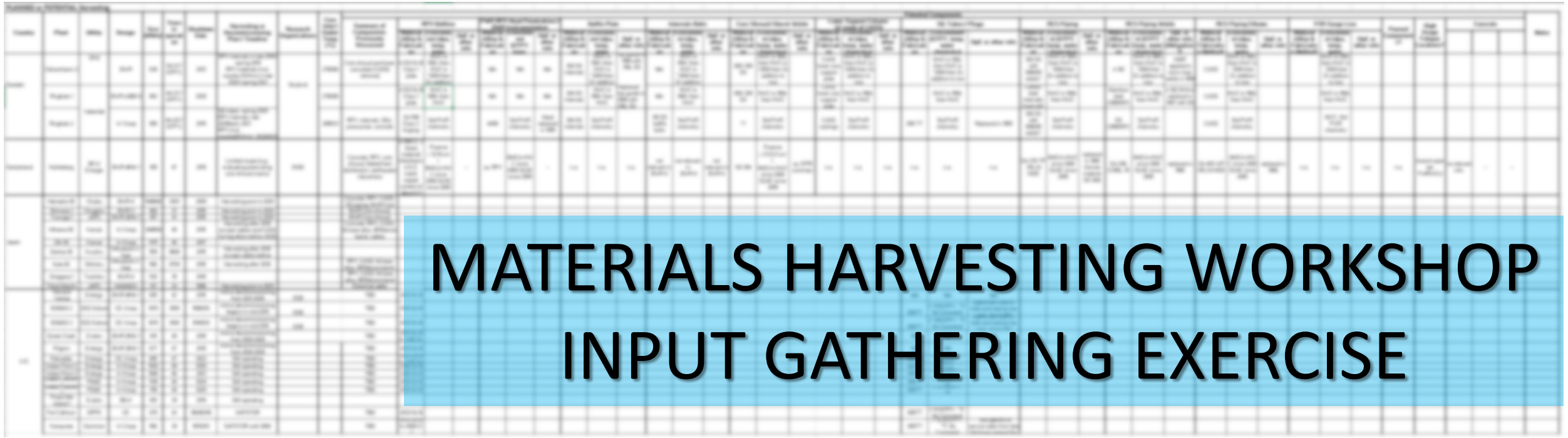
- Extensive surveillance programs with test materials and archive materials for reactor vessel belt line.

HARVESTING TARGETS

- Dosimetry and mechanical property testing of extended belt line RV materials (plates, welds, forgings)
- Evaluation of homogeneity of vessel materials and welds.
- Thermal embrittlement of base metal and welds after long-times in service at elevated temperatures.

International Materials Harvesting – Data Collection

- Data Collection
  - Listing of plants with known end-of-life dates
  - Includes key design and operating parameters, structural materials and expected neutron dose levels
  - Identify “best choice materials” to address harvesting objectives and priorities
  - Also need to consider operating experience (OE events)
  - Potentially identify opportunities for collaboration
- Ongoing Action item: Solicit input from plants in each country to populate or update spreadsheet data



Harvesting Strategies

IN-SITU INSPECTION

- Examination of components outside of outage critical path
- More detailed inspections than were prescribed by industry Codes & Standards
- Research on new non-destructive examination (NDE) techniques
- Evaluation of NDE detection limits with components that will later be harvested and examined in a laboratory

LABORATORY EXAMS

- Examination in a laboratory setting for small indications, wear, distortion, residual stress, general corrosion, etc.
- Destructive examination to assess microstructural and mechanical property changes
- Fabrication of test specimens for assessing performance in normal or aggressive environmental conditions

ADDITIONAL AGING

- Additional neutron irradiation at research reactors, or re-insertion into surveillance capsules
- Longer thermal aging to initiate microstructural response – at LWR temperatures or accelerated aging experiments.
- Sustained exposure to off-normal water chemistry for oxide evaluations

EPRI'S APPROACH FOR HARVESTING (2022)

INDEPENDENT RESEARCH

- **Alloy 690 Oxide Film Formation and Corrosion Kinetics (SG Tubes)**
- **Low Alloy Steel Thermal Embrittlement (Pressurizer Vessel and Welds)**
- **Inspection / In-Situ Examination: Thermal Shield Flexures and Support Block Bolts**

CONSULTING

- Kori Unit 1 Decommissioning and Harvesting Program
  - Harvesting work led by the Korean Atomic Energy Research Institute (KAERI).
  - EPRI has provided consultation on the harvesting program planning and R&D objectives directly with KAERI and Korea Hydro & Nuclear Power (KHNP)

COLLABORATION

- **Sherlock Program**: The Cruas Unit 4 Steam Generator is the subject of material harvesting and examination efforts.
- **Studsvik Materials Integrity Life Extension (SMILE) Project**: Ringhals and Oskarshamn harvested materials from decommissioned units or retired vessels available for harvesting and examination.

MONITORING

- U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) harvesting projects
- Nuclear Regulatory Commission (NRC) sponsored harvesting projects

Harvesting Implementation Experience

- **Planning**
  - Archive records for initial material specification, welding, installation conditions, etc. can be difficult to access **after plant shutdown**.
  - Environmental conditions/history are challenging to access, and costly to calculate if it involves neutron fluence/gamma heating assessment.
  - Scheduling for access of materials to retrieve or inspect is very complex once a turnover occurs in plant (site) ownership from Operator to Decommissioning Agent.
    - **PRIORITY** is the decommissioning schedule
    - Site support for harvesting is secondary
  - Contracting with Decommissioning Agent can be more cumbersome, and require separate contracting terms, conditions, audits, etc. to implement.

Dresden Unit 1 (November 26, 2013 Photo)
Courtesy of U.S. NRC

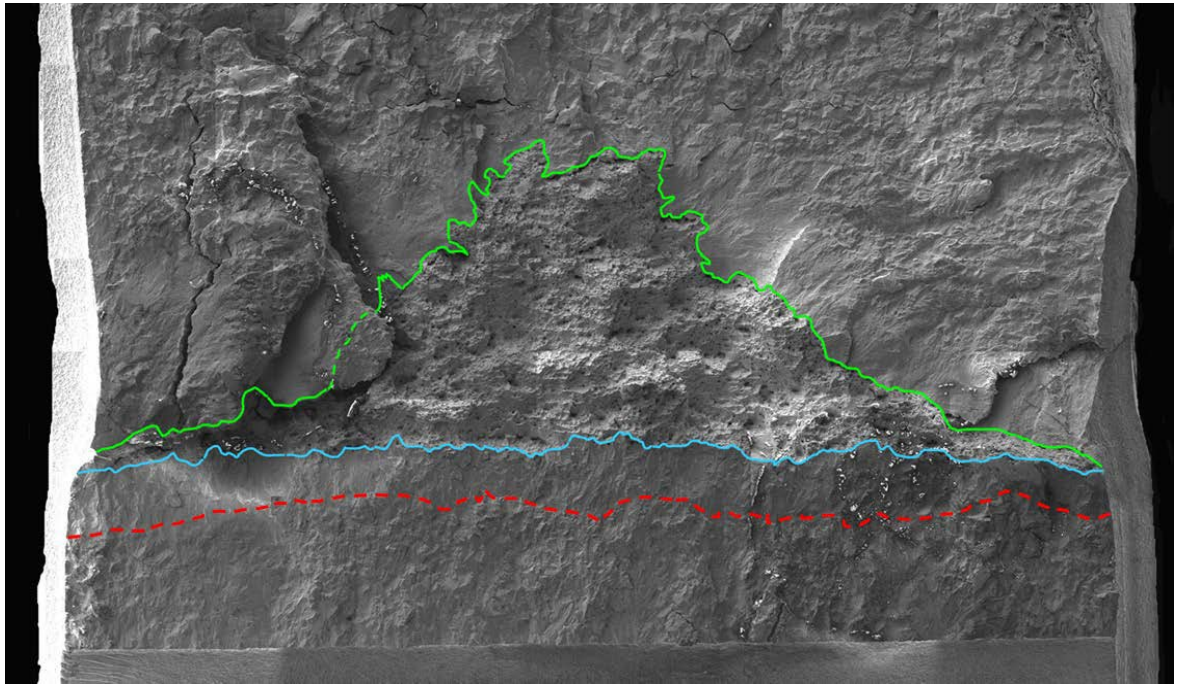
Harvesting Implementation Experience

- **Site Activities**
  - Gaining access to the refueling bridge or auxiliary bridge during reactor internals segmentation is generally not be permitted due to schedule impact:
    - Cutting tool change outs
    - Night shift flexibility
  - Reactor internals in the stand may have access issues for specific tooling in locations where cavity wall is in close proximity.
  - Health physics oversight, scaffolding, escorting, etc. labor costs must be accounted for – even if inspection or harvesting work is performed by an independent contractor.
  - Challenges with decontamination activities, or other segmentation/cutting actions by owner or its contractors can have profound impacts on schedule of harvesting.

San Onofre Nuclear Generating Station
(September 20, 2021 Photo)
Courtesy of U.S. NRC

Harvesting Implementation Experience

- **Testing Activities**
  - Coordinating availability of laboratory resources can be challenging with complex schedules related to harvesting, and packaging / shipping after harvesting.
  - Test results that challenge the expectations established with prior test data can require significant scrutiny.
    - Duplication of testing if possible confirms the experience and data
    - Outlier determinations on relevance of that plant's material to similar fleet of plants
  - Obtaining test data can take many years after planning; difficult to show "progress" to stakeholders starting from planning phase.
  - Irradiated material test specimens are costly to fabricate, getting large #'s of repeat tests for given set of test conditions and material parameters is not usually practical.



HAZ Fracture surface and tracing of crack fronts, taken from MRP-451 (Zorita Weld HAZ)

EPRI HARVESTING PERSPECTIVE:
Electrical Cables
Instrumentation & Control (I&C) Cables

Overview

EARLY AGING MANAGEMENT RESEARCH – LOW VOLTAGE CABLES

MEDIUM VOLTAGE CABLE FAILURE MECHANISM RESEARCH

DOE, EPRI, NRC RESEARCH COORDINATION COLLABORATION

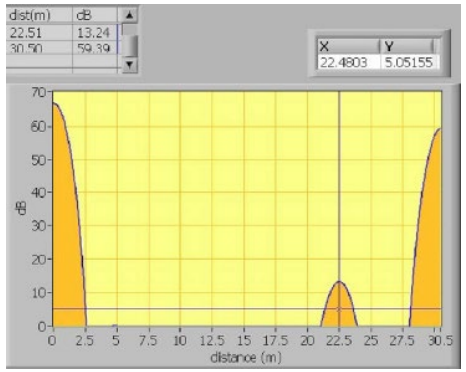
CURRENT ACTIVITIES

CABLE HARVESTING IS AN ONGOING EFFORT

Cable Aging Management Research Focus Area

- EPRI has been doing research on cable aging and condition monitoring of cable insulations since the mid-1990s
- Research required samples representative of plant cables for test specimens
- Cables were not “harvested” from the plant, but they were obtained from storeroom stock of cables leftover from plant construction
- Cables used in the frequency domain reflectometry study were loaned to support further research on this test

Oven-aged cables used for training aids for personnel doing plant walkdowns showing stages of thermal aging – EPRI Report 1001391



Oven-aged cables used for blind evaluation of frequency domain reflectometry capabilities required 30-meter length samples with various defects (thermally aged, nicks, cuts, etc.) EPRI report 1015206

Oven-aged cables used for training aids for demonstrating how to use the indenter to monitor cable hardening.

Medium Voltage Cable Failure Mechanism Research

- EPRI embarked on a multi-year research effort between 2007-2015 to understand the failure mechanism of MV Cables with a history of being wetted
- Tens of thousands of feet of cables of all relevant insulation types were harvested from numerous member sites and provided to EPRI
  - Some cables failed in-service
  - Others were removed due to poor test results
  - Cables were in-service for long periods of time (25-35 years)
- The research resulted in eight reports that
  - Improved the understanding of water-treeing failure mechanism
  - Showed the value of using very low frequency Tan delta to identify degraded insulation
- Cables not used in the EPRI study were shipped to PNNL for future research

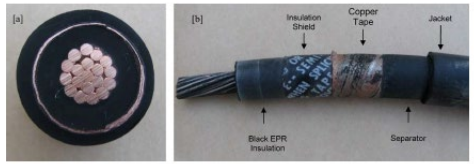
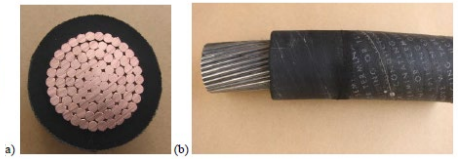


Figure 4-1
Construction of the 5 kV cable manufactured by Okonite [a] transverse view, [b] lengthwise view



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struction of the butyl rubber–insulated cable used in the study. Only the cable core is wn ([a] transverse view and [b] lengthwise view.)

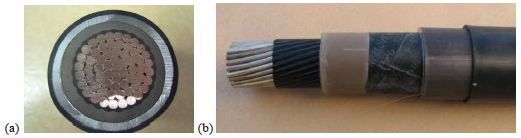


Figure 5-1
Construction of brown EPR-insulated cable ([a] transverse view and [b] lengthwise view)

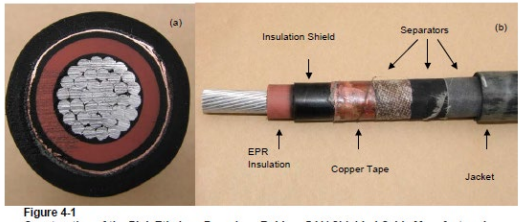


Figure 4-1
Construction of the Pink Ethylene Propylene Rubber, 5-kV Shielded Cable Manufactured by Okonite; (a) Transverse View, (b) Lengthwise View

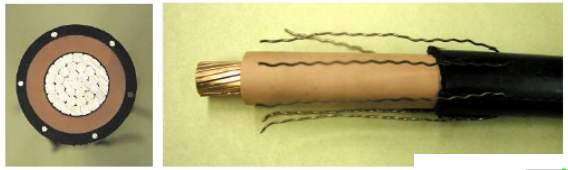
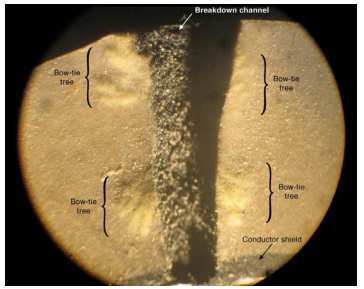
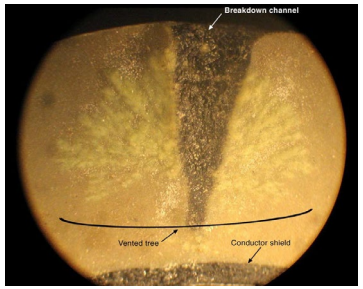


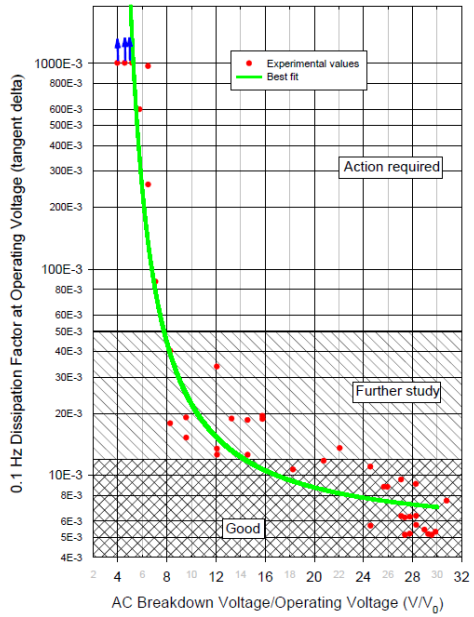
Figure 6-2
Construction of Anaconda UniShield cable

Samples of Each Insulation Type Design Were Evaluated in the Research





Localized Water-Tree Defect

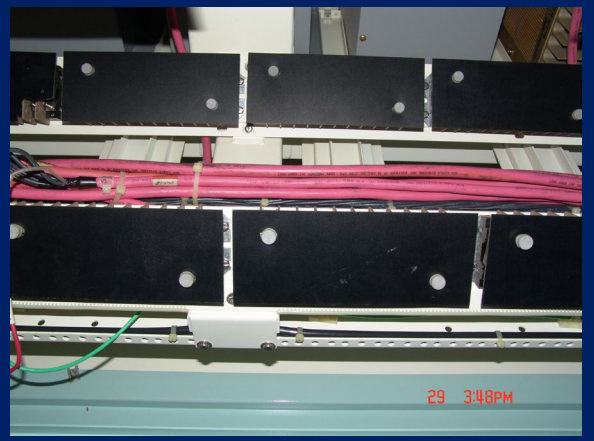


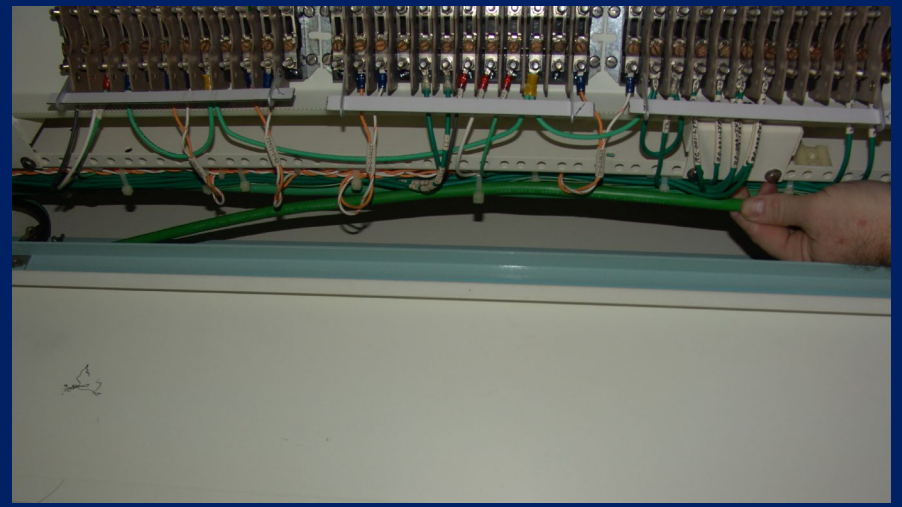
VLF Tan Delta versus AC Breakdown

Failure Mechanism Reports: 1015070, 1018777, 1021069, 1022965, 1024894, 3002000554, 3002002993, 3002005323

DOE, EPRI, NRC Research Coordination and Collaboration

- The coordination and collaboration group was formed in 2012 timeframe to address cable aging issues and identified research knowledge gaps
- Research projects needed representative cable types so harvesting opportunities were explored
- DOE and NRC coordinated to harvest cables and other materials from Zion
- EPRI coordinated 1135’ of cables harvested from Crystal River 3 in 2015-16
  - Original plant cables (Kerite, BIW and Okonite) and newer Rockbestos cables from inside and outside the bioshield wall were harvested
  - Cables supported DOE, EPRI, and NRC research projects
- Lesson learned was cost and coordination of harvesting post plant shutdown and after transfer of license to decommissioning entity is difficult/costly
- Opportunities for cable harvesting post shutdown at SONGS, Kewaunee, Oyster Creek, and TMI were explored, but did not result in any cable harvesting





Recent Cable Harvesting Opportunities

- Emergent opportunities have resulted in obtaining some LV and MV cable harvesting
  - Palo Verde sent EPRI a failed LV cable in 2019
  - Peach Bottom and Callaway sent replaced MV cable to PNNL in 2020 timeframe
  - Callaway sent EPRI three sections of degraded cable replaced in 2022 for forensic examination
- Vattenfall has penetration pigtails for LV and MV cables with US pedigree that are being pursued for 2023 harvesting

Cost Effective Opportunistic Harvesting Continues to Be Pursued

EPRI HARVESTING PERSPECTIVE:
Concrete

Concrete Research - Overview

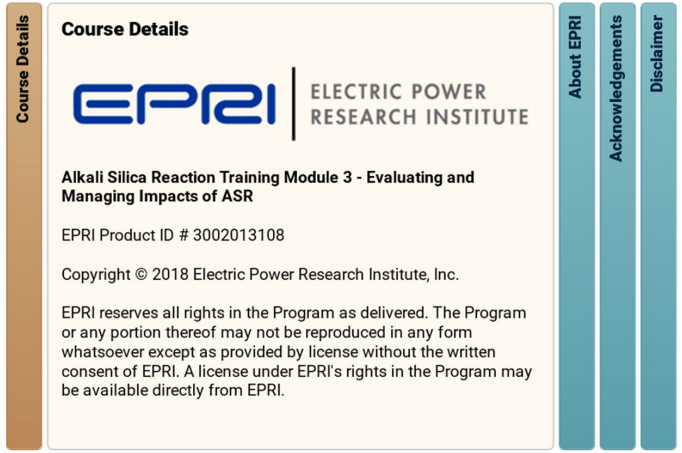
Strong collaboration with utilities, research Institutions and regulators.

Examples: Joint projects with Material Aging Institute – Candu Owners Group – ORNL – CEZ – and others

Field demonstrations – Deployment

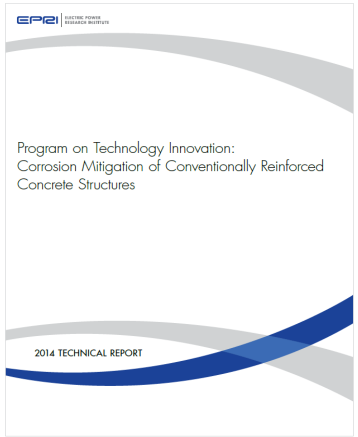
Workshops

On line courses



Field Guides

Reports



Value of Harvesting

- Concrete research is focused on ageing management, inspection, repair of structures, and developing industry guidance
- Harvesting is of great interest due to the material being exposed to operating conditions that may be different than conditions in a laboratory environment
- Opportunities to harvest concrete samples provide valuable information for developing guidelines for inspection, testing, and analysis
- The effects of irradiation in concrete is one of the points of interest that is specifically linked to the nuclear industry

Collaboration

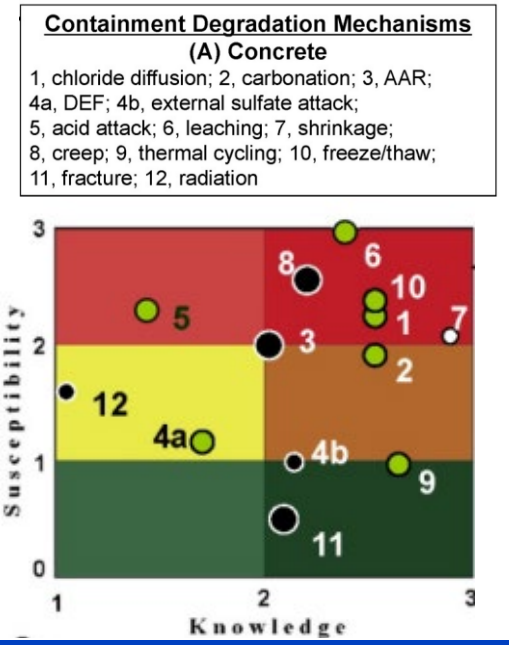
- EPRI collaborated in the effort of the EMDA.
- Effects of irradiation in concrete were identified as requiring further research.
- EPRI has been involved in several attempts to harvest irradiated materials from decommissioned plants
- Currently there are new opportunities in which EPRI is collaborating with regulators and national laboratories on this effort

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7153, Vol. 4
ORNL/TM-2013/532

Expanded Materials Degradation Assessment (EMDA)

Volume 4: Aging of Concrete and Civil Structures



Harvesting and characterizing irradiated concrete is of great interest

Opportunities and research

- There are some harvesting opportunities in the US and Europe and EPRI is currently involved in information exchange
- Not only harvesting but access to facilities is also important for development and validation of NDE methods and characterization of materials in-situ
- In addition to irradiation of concrete other areas of interest include:
  - Deterioration of liners embedded in concrete
  - Chemical transport through concrete
- EPRI continues collaboration with utility members, national laboratories, and regulators in the area of harvesting and research related to harvested material.

Summary

- EPRI continues to harvest materials to support age-related materials degradation studies for long-term operation:
  - Significant value and relevance of harvested materials
  - Need Industry support to catalog system/material database for harvesting plans
  - Inspections and Research collaborations offer cost-savings
  - Early planning required to access most value and avoid schedule issues
- Materials Issue Programs, Electrical / I&C Programs, and Concrete NDE Programs at EPRI have unique needs but we have learned considerably from Zorita and Crystal River Harvesting Projects.
- New projects with Ringhals, Indian Point, Cruas and others will deliver continued benefit to EPRI research programs in the years ahead.

Harvesting is a key EPRI strategy for obtaining empirical data