LWRS-Materials Research
Harvesting Ex-Service Materials

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Remote from Oak Ridge National Laboratory

LWRS Program Goal and Objectives

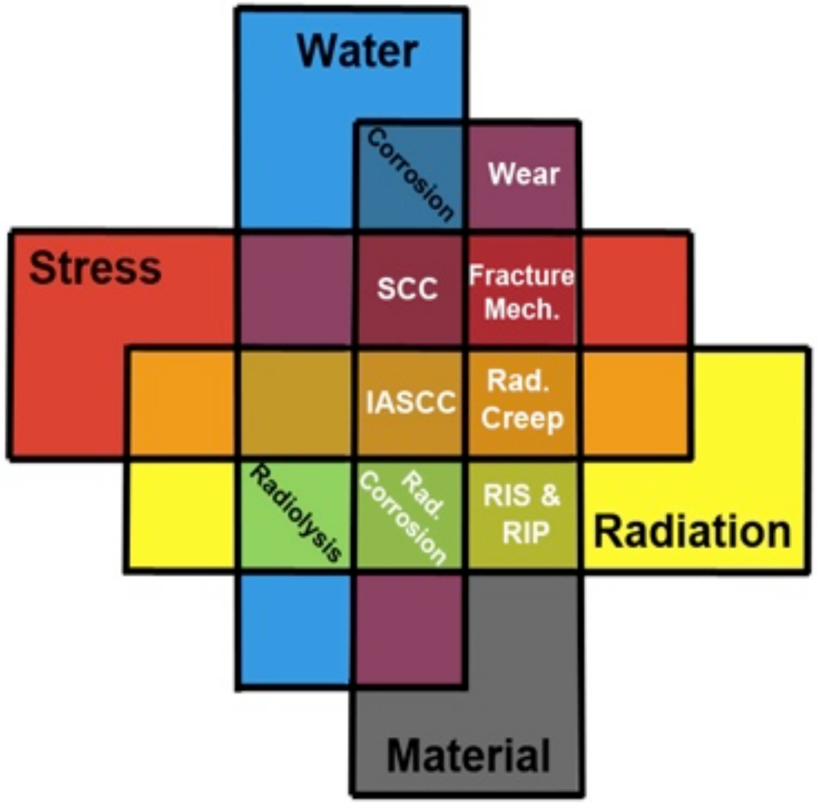
- **Goal**
  - **Enhance the safe, efficient, and economical performance of the nation's nuclear fleet and evaluate extending the operating lifetimes of this reliable and green source of electricity**.
- **Objectives**
  - **Enable long-term operation of the existing nuclear power plants**
  - **Deploy innovative approaches to improve economics and economic competitiveness** of LWRs in the near-term and in future energy markets
  - **Sustain safety, improve reliability, enhance economics**
- **Research and development focus areas**
  - Plant modernization
  - **Materials Research**
  - Flexible plant operation and generation
  - Risk-informed systems analysis
  - Physical security

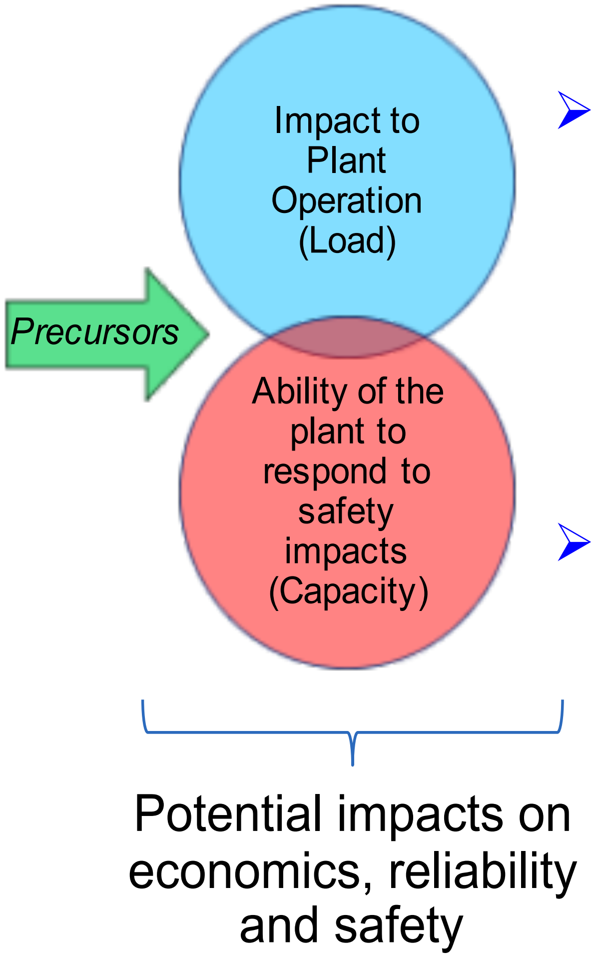
DOE's program for LWR RD&D

Nine Mile Point (Courtesy of Exelon)

Materials Research: Goals and Objectives

Materials in multiple environmental conditions at extended times



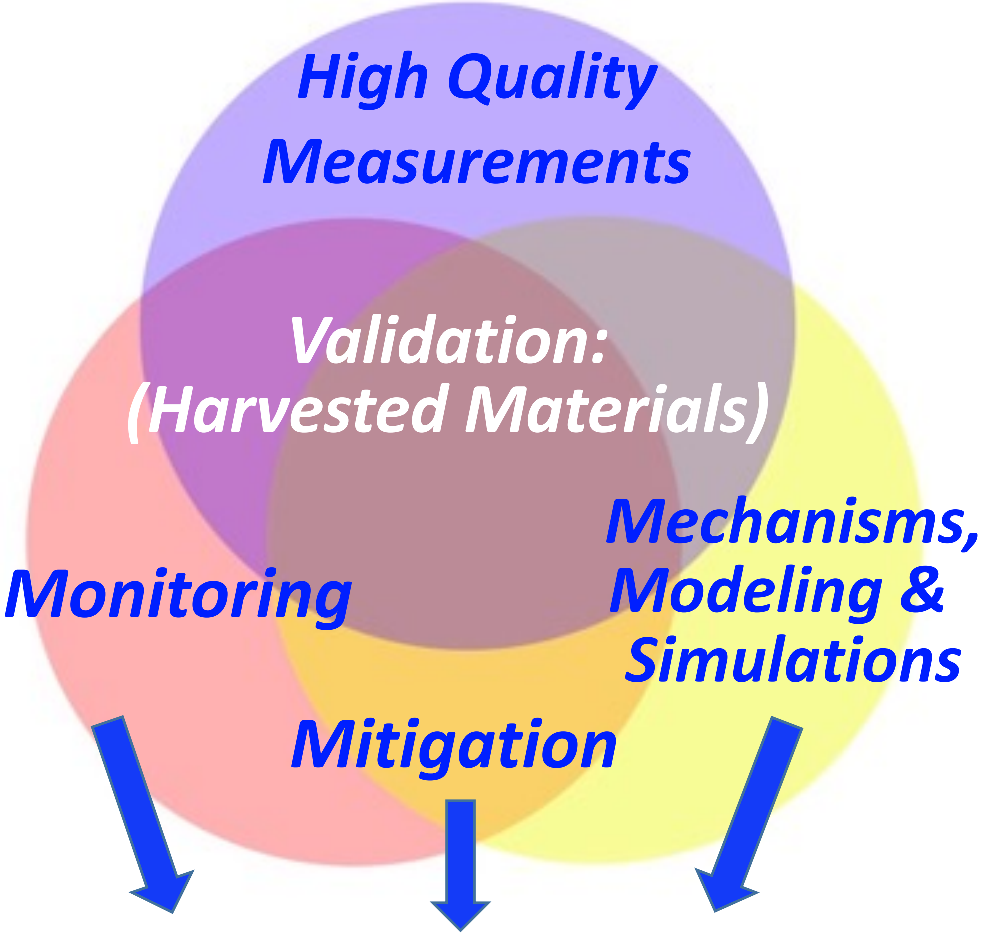


- To **develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials** in nuclear power plants
- To **provide data and methods to assess the performance** of systems, structures, and components (SCC) **essential to safe and economically sustainable nuclear power plant operations.**

Addressing aging management knowledge gaps requires a multifaceted research approach

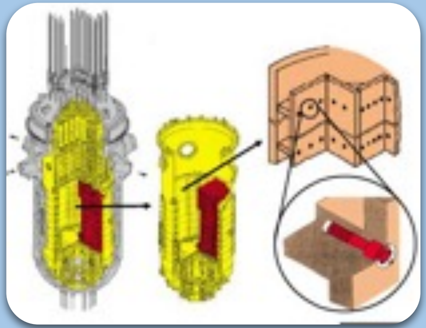
Guided by sound nuclear materials research approach:

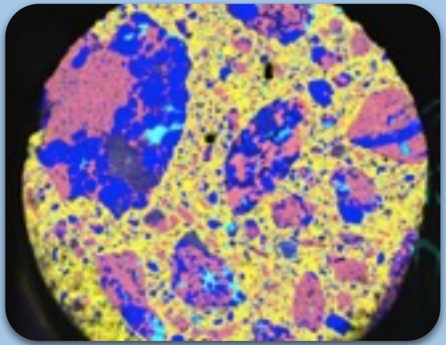
- *Measurements of degradation* (high quality data)
  - *Structure and properties of materials under stress and radiation*
- *Mechanisms of degradation* (scientific understanding)
- *Modeling and simulation* to predict degradation
- *Monitoring degradation* (non-destructive examination)
- *Mitigation strategies* (for economic productivity)
- *Materials Harvesting* (Validation of models, codes & standards)



Working with Industry & NRC to improve margins and sustainability

Materials Research Focus Areas





Reactor Pressure Vessel

Core Internals, and Pressure Boundaries

Mitigation Methods

Concrete

Cable Aging

Benefits of service-aged materials

Fills knowledge gaps when there is limited operational data or experience and informs current degradation models

The **DOE-NE, LWRS Program** activities at:

- **Zion:** Cables, Electrical components, and through-wall RPV materials
- **PWR NPPs:** Baffle former bolts change outs
- **Crystal River 3:** **EPRI led** effort to obtain cables in collaboration with **LWRS** and NRC
- **San Onofre Nuclear Generating Station** Unit 2: Unirradiated Concrete in collaboration with **NRC (Lead) with LWRS and EPRI support**

Harvesting Difficulties and Limitations

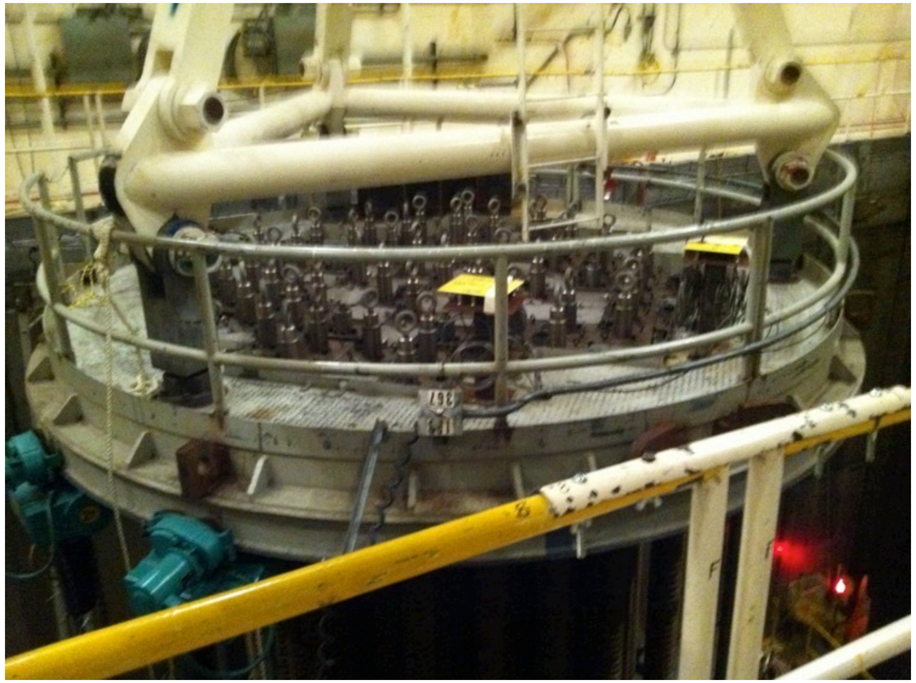
- **High cost to harvest, test, store, and dispose**
- **High costs require multiparty cooperation to spread costs which adds to complexities**
- **Scheduling difficulties (both with decommissioning companies and operating plants)**
- **Getting sufficient material pedigree (records)**
- **Potentially limited research value (cost/benefit)**
- **Limited opportunities**
- **Difficult logistics**
  - Contracting
  - Final disposition and disposal
  - Liability
  - Shipping

Zion Harvesting & Coordination 2011 - 2017

- In support of extended service (and current operations), **ORNL coordinated and contracted activities with Zion Solutions (Energy Solutions).**
- In collaboration with the US NRC, EPRI, and the nuclear industry, **a list of materials of interest for possible Zion harvesting was compiled and the feasibility of obtaining materials examined.**
- **Focus:**

Structures and components of interest:

- **Thru-wall beltline RPV sections**
- **Cables**
- ~~**Concrete bore samples**~~
- ~~**Access to stored fuel containment**~~



Zion Unit 1 Containment Cables acquired Spring 2012 for US NRC (Part 1)

- **Harvested 6 sets of cables, ~ 25' in length**, and each containing **two cable types - CRDM DC power and position indicator**. Also harvested **8 thermocouple cables** identified during 2011 containment tour

sponsored controlled

Zion Harvesting 2013: Electrical Components for the US NRC

Zion Electrical Components: During February 25, 2013, site visit, the US NRC identified an **L shaped bus bar that was harvested in 2013 for fire protection testing.**

Zion Cables Part 2 (2013-2017)

Harvested Zion **Unit 2** low and medium voltage cables in collaboration with the NRC

- **Accumulator Discharge MOV Cables**
- **Instrumentation Cables**
- **Air-Operated Valve Cables**
- **Cables in Electrical Penetrations**

I&C cables from Zion and Crystal River

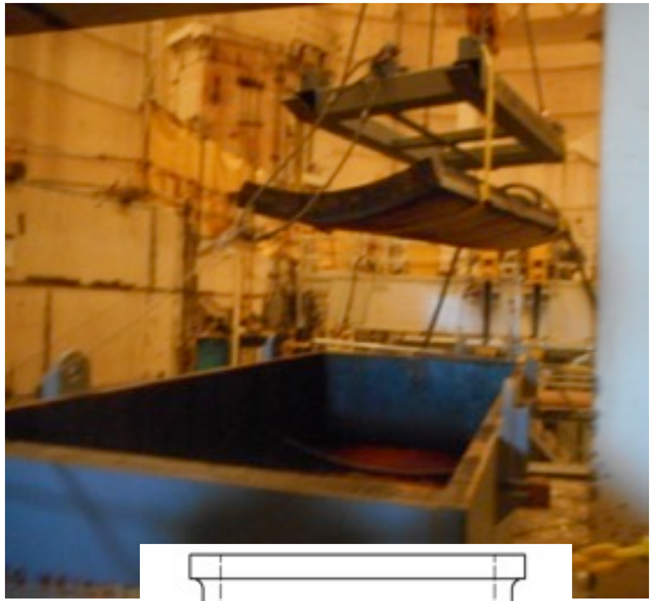
- **Harvested I&C cables play a critical role in**
  - **(1) developing models to quantify the influence of environmental degradation and**
  - **(2) developing practical NDE techniques to track the degradation in current NPPs.**

- **Many Zion Cables contained asbestos**

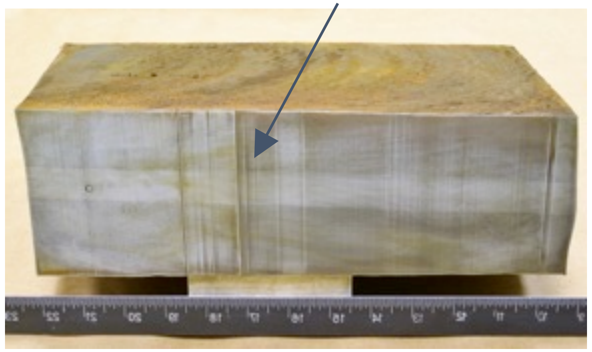
- In **collaboration with EPRI & NRC in 2016, over 5,000** feet of I&C cable ***outside of containment* from Zion and Crystal River NPPs** have been harvested and environmental degradation studies on highest priority materials have been tested

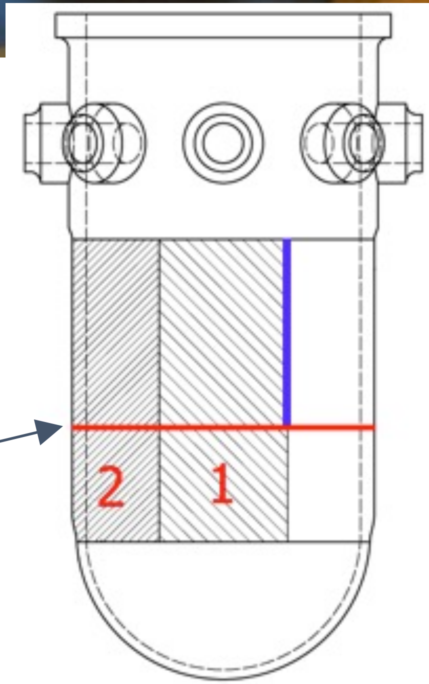
Zion Unit-1 RPV Harvesting 2014-2017

- **Two panel sections, ~14 tons each, were harvested in November 2015, package and shipped to be cut into blocks and machined into >1,000 individual test specimens**
- **Goals of research:**
  - Evaluation of radiation damage models
  - Comparison with surveillance and high-flux reactor experiments
  - Determine the attenuation and through wall variation in base and weld metal.
  - Mitigation techniques - annealing / re-irradiation studies.



WF-70, Belt-line Weld

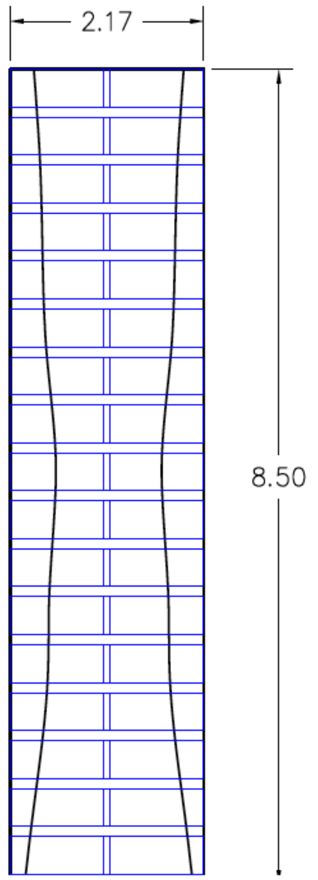




Through Wall Attenuation Study of Welds and Base Metal Research Plan 2017- 2023/24

Test CVN, SS-3 tensile, and fracture toughness specimens from the WF-70 beltline weld and base metal material to assess radiation damage models

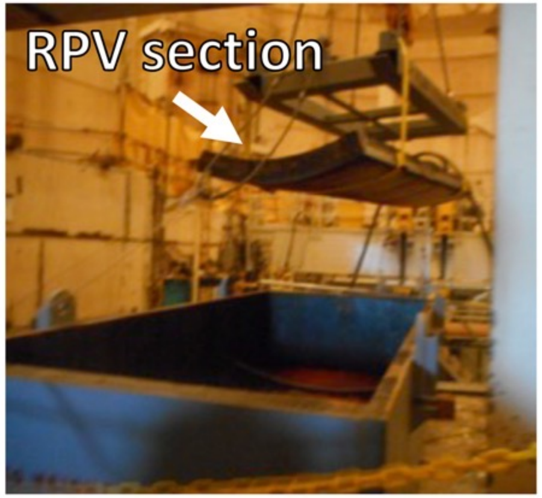
Specimens centered in weld

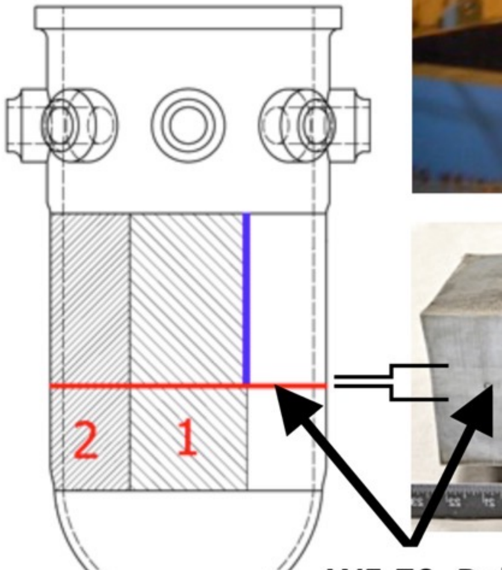


1. Determine the **through-thickness variation in chemical composition of the welds (especially Cu).** (September 2017)
2. The chemical composition, **especially the Cu content, is relatively uniform**, which **allowed us to perform CVN and tensile tests and compare with surveillance results.**
3. **Mechanical testing**: **CVN, tensile, hardness, and fracture toughness** through thickness to **evaluate attenuation effects is nearing completion**.
4. **Microstructural characterization** (**Atom probe, SANS, SEM, TEM, and microhardness**) **has been and is being performed through thickness to evaluate attenuation effects** using specimens obtained from 10 x 10 x 0.5 mm coupons.
5. Similar testing (3 and 4) **through the thickness of base metal is also being performed (mini-CT collaboration with CRIEPI – CNWG)**
6. **Thermal annealing** of these RPV materials may also be performed to **compare with the same weld metal (WF-70) previously irradiated in test reactors & annealed. Need funding to perform this research**

Zion RPV Harvesting

Evaluate radiation damage models and compare results to surveillance and test reactor experiments
Evaluate attenuation and through wall variations in properties and composition of the base metal and the belt-line weld





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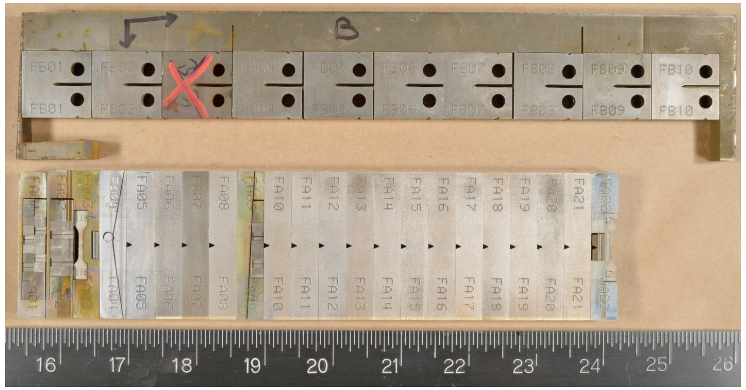
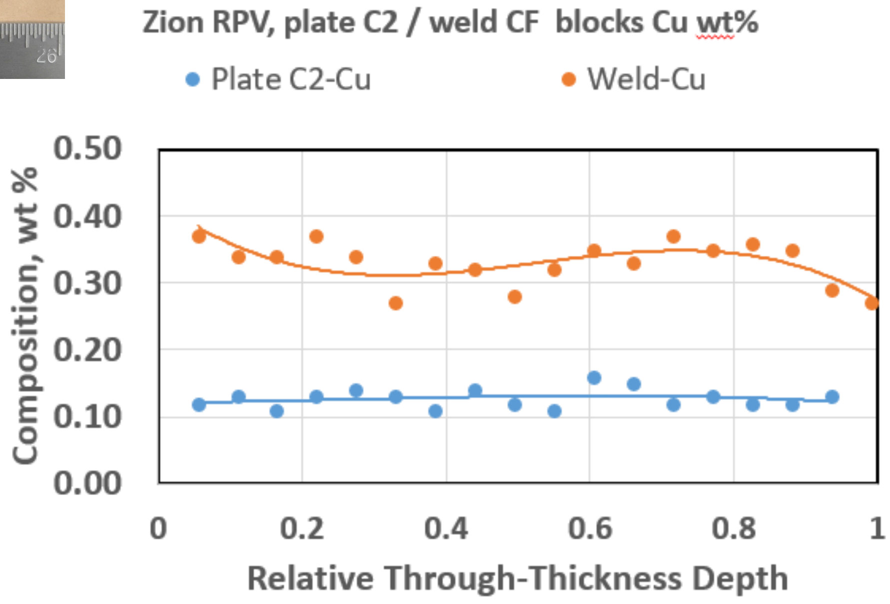




Harvesting | Machining | Testing | Publication

Zion Unit-1 RPV Harvesting Summary

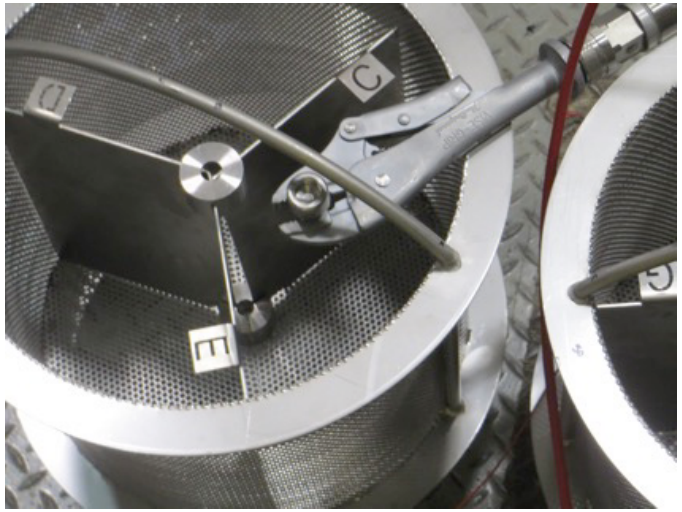
An important component of understanding Materials degradation: Harvesting and examination of service-aged materials

Access to materials from active or decommissioned nuclear power plants provides an **invaluable resource for which there is limited operational data or experience** to:

- **It will inform relicensing decisions and aging management programs**
- **Validate ASTM E-900 and current physically-informed transition-temperature shift models (e.g.: EONY / now OWAY) to further develop the scientific basis for understanding and predicting long-term environmental degradation behavior.**

Internals: Baffle Former Bolts

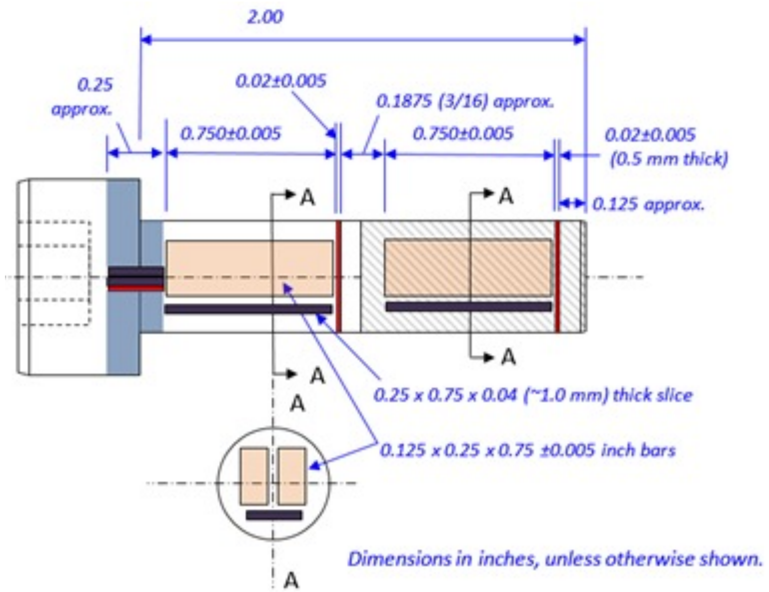
- Retrieval of bolts August 2016
- **Post-service/irradiation evaluation of high fluence bolts that were withdrawn from service in 2011 from 2-loop down flow plant.**
- **Alloy 316, irradiation profiles spanning 15 to 42 dpa** (variation of fluence along bolts with overlap between the two bolts - same fluence, different temperatures).
- **Fracture toughness / fatigue crack growth testing, and microstructural examinations**.



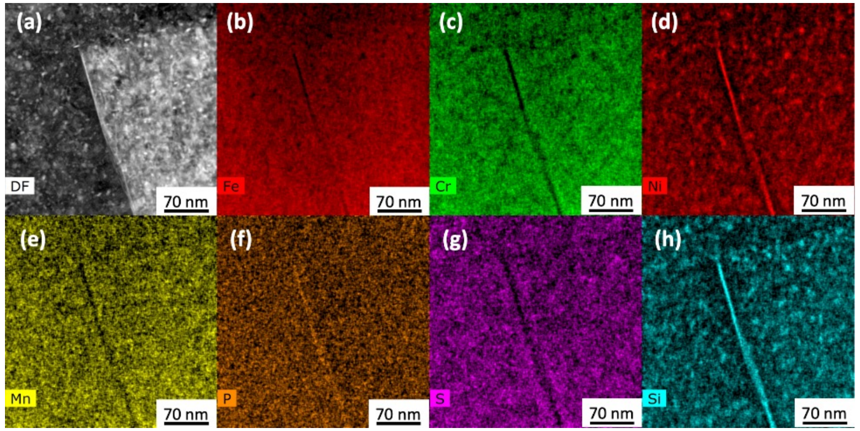
Harvesting and Evaluation of Baffle Former Bolts

Provide critical information for evaluating end of life microstructure and properties as a benchmark of international models developed for predicting radiation-induced swelling, segregation, precipitation

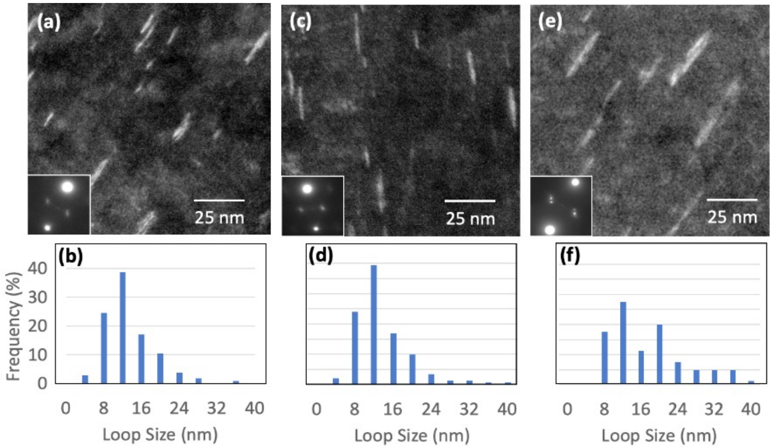
Bolt #	Fluence (10^{22} n/cm^2, E>1 MeV)/Estimated dpa		
	Head	Mid-shank	Mid-thread
4412	2.78/41	2.27/34	1.46/22
4416*	1.91/29	1.56/23	1.00/15



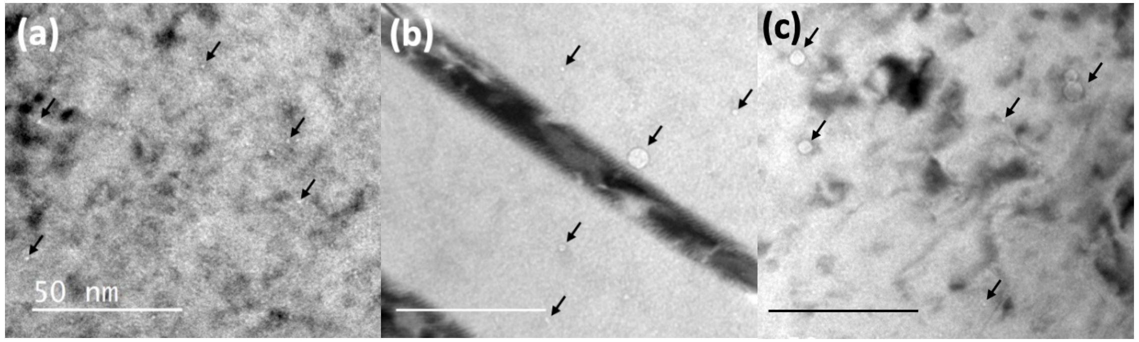
Baffle former bolt machining plan



STEM/EDS mapping showing RIS



Dislocation loop characterization



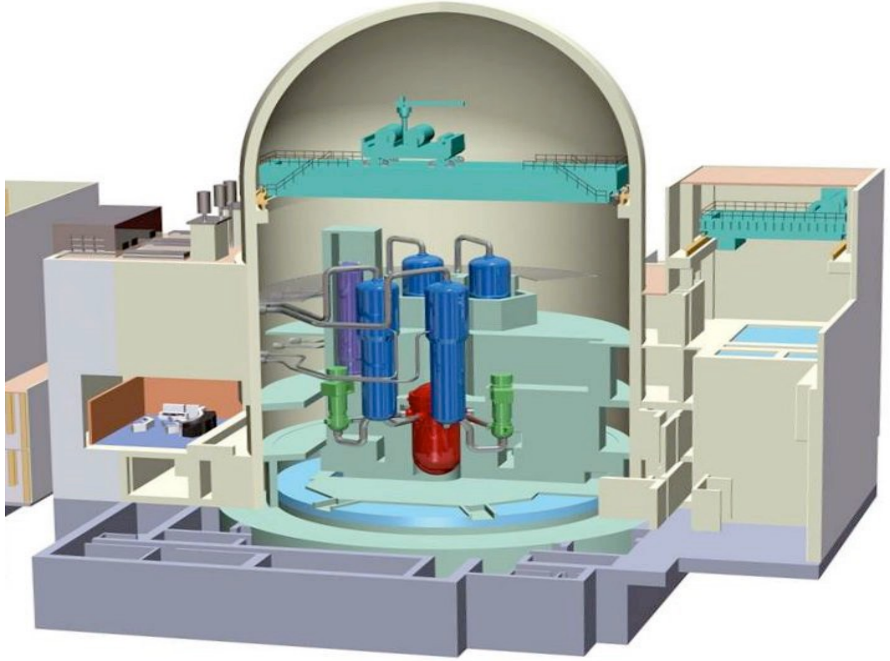
Cavity characterization

BFB Preliminary Conclusions:

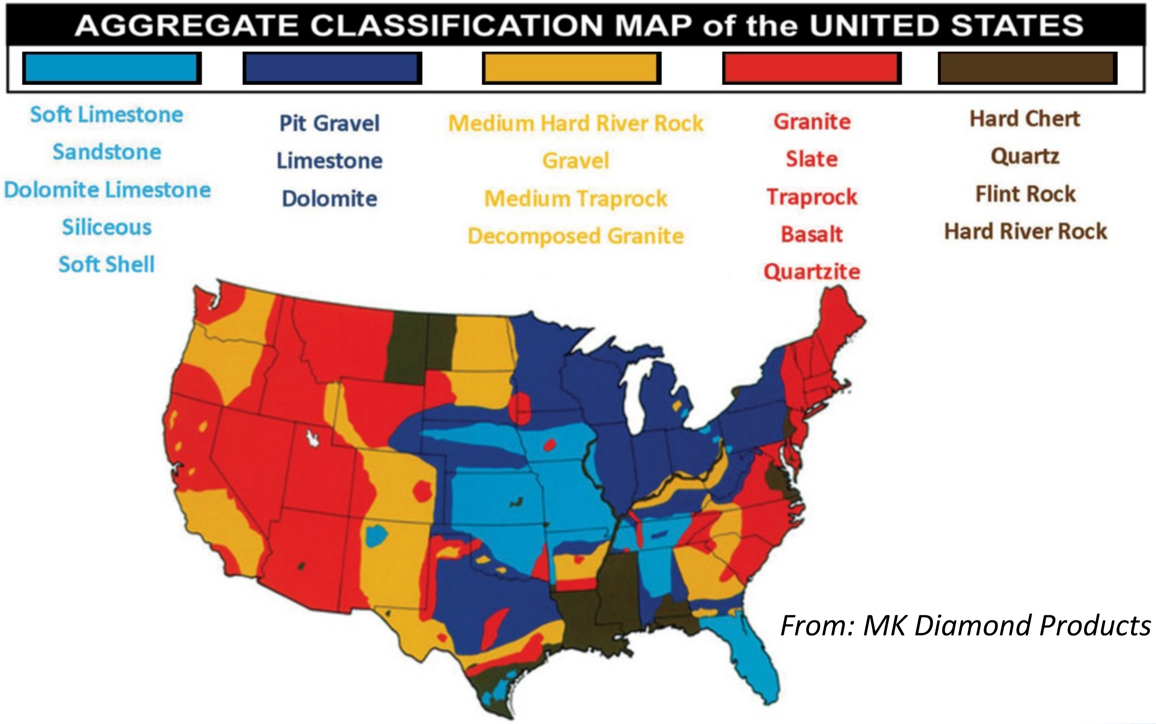
- Post-irradiation evaluation **revealed dislocation loops, cavities, and radiation induced segregation (RIS).**
- Significant **irradiation hardening was observed**
- **Bend bar specimens** exhibited **stable ductile crack growth in room temperature fracture toughness testing**
- Compared with the unirradiated condition, **in-service neutron irradiation resulted in significant degradation of BFB fracture toughness;** however, the **degradation was bounded by the NUREG/CR-7027 (2010) lower bound trend curve**
- **The additional data and analysis of results will be used to develop & validate phenomenological models of irradiation damage on stainless steel 316 under light water reactor conditions.**

Challenges of evaluating concrete structures

- **Largest structural material used in reactor**
- **A locally sourced material**
- **Concrete mixture: Silicate-bearing aggregates are more prone to RIVE than calcareous aggregate.**
- Inner concrete barrier structure in PWR's may see up to 5 x 10^{19} n/cm^2 (E>0.1 MeV) at 80 EFPY - some loss in mechanical properties expected**.**
- **FOCUS: Evaluation of safety performance and margins in accident scenarios**.



Source: U.S. Nuclear Regulatory Commission



From: MK Diamond Products

Importance of harvested concrete

- **Harvesting provides a unique opportunity for evaluating the research needs of concrete**:
  - Increase knowledge of irradiated concrete as **older literature data are not comprehensive, with irradiation conditions not well established, or significantly different than that expected in LWR's.**
  - **Multiple dependent variables acting on concrete that may be difficult to experimentally test including neutron irradiation, gamma irradiation, temperature, relative humidity, aggregate chemistry, stress / creep and cumulative effects of age.**
- Materials harvested from plants can provide a unique opportunity to **examine the influence of all the impacting variables on specific aggregate types**. Sampling from various parts of the plant to isolate out different variable effects.
- Information gained will be important for the **development of computer models to determine the changes concrete has undergone and its performance**, expected aged lifetime and capability under accident scenarios.

(Unirradiated) Concrete core harvesting to assess characterization methods

- **Three (3) cores** were harvested in October 2021 from the **San Onofre Nuclear Generating Station (SONGS), Unit 2**

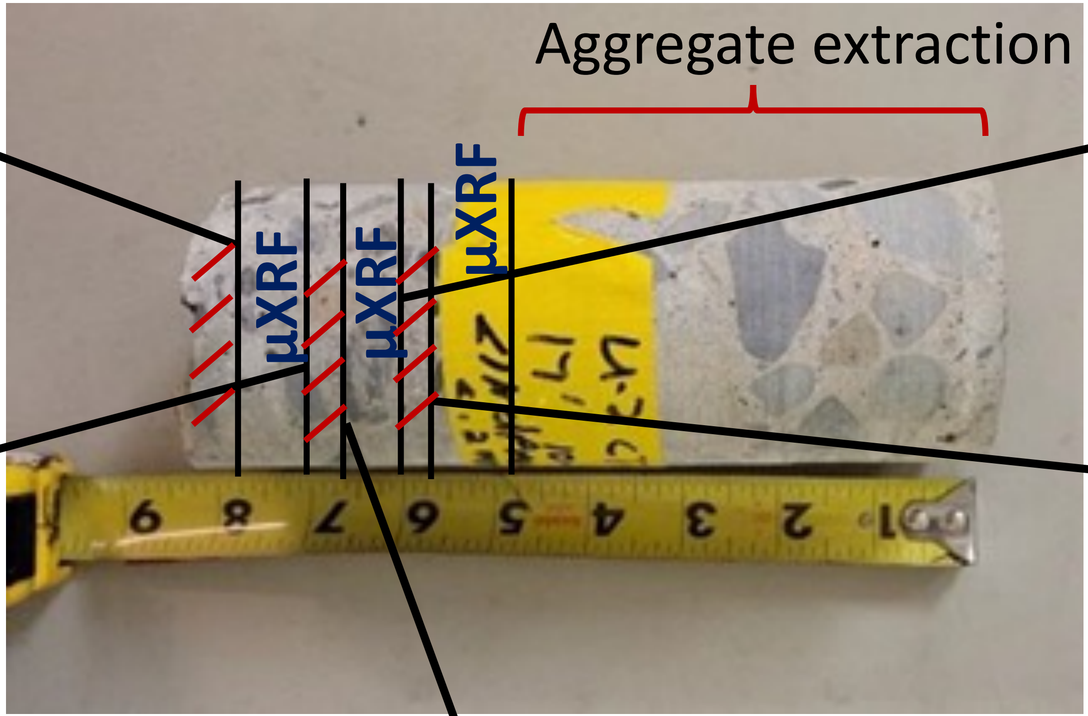
- Approx. 3" diameter cores were obtained from **outside the Steam Generator Room 2 on the North Wall of the primary shield at elevations 45', 30' and 17'**

17'

30'

45'

Specimen preparation for µ-XRF, petrography and aggregate extraction



3 slices were cut for petrography of the 5 different surfaces on the images (materials have been sent to Spectrum petrographics for thin section preparations on slides of 2 x

3 **slices were cut to map 6 different surfaces with µXRF** of which 5 will approximately match the petrography slides

Preliminary Conclusions and future work

- Confirmed **material of interest due to Silicate presence in** aggregates
- Estimated volumetric expansion of aggregates **~1% according** to phase composition by Rietveld refinement and estimated EOL neutron dose
- Perform higher resolution **µXRF** (pixel size of 15 µm), **EDS**, **petrography** and **XRD-Rietveld refinement** to obtain a more informed picture of chemical phases and grain size distributions to reconstruct mineral phase maps in 2D
- Perform **simulations** of irradiation damage taking the phase maps as input
- **Harvest irradiated cores and compare actual damage to simulations**

Lessons Learned and Issues to Consider (1)

- **Long range goals, objectives, framework, partners**
  - Workshop at Zion NPP, May 5, 2011, including DOE National Labs, Industry, NRC, and EPRI
  - Discussions with Zion/Energy Solutions, NRC, Westinghouse, EPRI, utilities)
- **Partnerships (Leverage resources, opportunities for collaboration, publish and share results)**
  - Cables (DOE led joint effort with NRC at Zion U1 and U2)
  - Cables (EPRI led effort with NRC and DOE (ORNL and PNNL)
  - Cables from operating plants (EPRI led and shared with DOE: ORNL and PNNL)
  - RPV (CNWG Collaboration with CRIEPI to test mini-C(T) specimens from Zion)
- **Limited opportunities**
  - **Previous attempts to obtain RPV material from Trojan, SONGS 1 via the US NRC HSSI Program were unsuccessful**
  - **Attempts to obtain surveillance capsules from Zion Unit 2 [capsule X (2e19)](LWRS) and Palisades [high Ni] (HSSI) were unsuccessful**
  - Future US opportunities (**to be determined**)
  - Future International opportunities (**to be determined**)

Lessons Learned and Issues to Consider (2)

- **Research value**
  - Compromise between availability and value (EFPY/ fluence)
- **Scheduling issues**
  - Working within the critical path of the decommissioning organization (private vs. government.)
  - Discussions and meetings with D&D Organization since this not their highest priority (not a reflection of lack of cooperation)
  - **Requires regular site visits and contacts**!

Lessons Learned and Issues to Consider (3)

- **Flexibility**
  - Ability to modify plans to maintain objectives, adjust to schedule changes and stay within cost constraints)
- **Quantity of material harvested**
  - Sufficient material to validate models and compare with accelerated experiments
  - Sufficient to support from collaborations and partnerships
- **Material Pedigree**
  - Records (composition and initial properties), reports (including inspection, qualification, and surveillance results)
  - Characterization after harvesting
- **Hazardous Materials**
  - Handling at site, transportation, handling at testing site, disposal, time, and costs
- **Logistics**
  - Contracts (8 for Zion materials), liability, shipping, disposal of waste
- **Costs (harvesting, handling, storage, fabrication, testing, & managing)**
  - **Yes; it is very expensive from planning to execution and testing!**

Harvesting Service-aged Materials

An *important component of understanding Materials degradation:*
Harvesting and examination of service-aged materials

Access to materials from active or decommissioned nuclear power plants provides an invaluable resource for which there is limited operational data or experience to:

- **Inform relicensing decisions and aging management programs**
- **Validate Models, Codes and Standards** to further develop the scientific basis for understanding and predicting long-term environmental degradation behavior.

Discussion / Questions

This research was supported by the U. S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability (LWRS) Program under contract DE-AC05-00OR22725 with UT-Battelle, LLC, contractor for Oak Ridge National Laboratory.

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