LWRS Overview and Select Highlights

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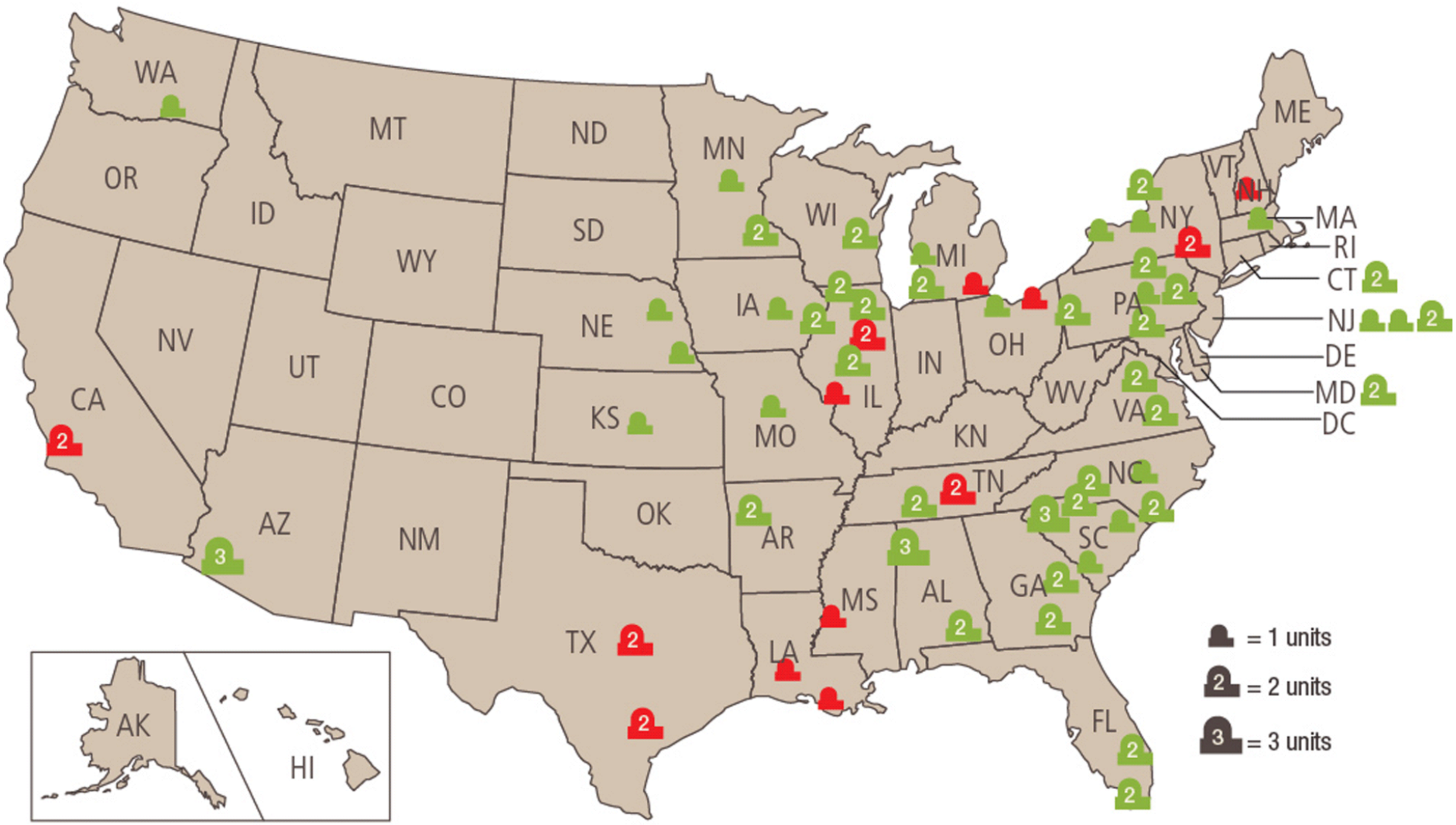
DOE-NE Cross-cut Coordination Meeting
August 16, 2016

Light Water Reactor Sustainability R&D Program

Operating U.S. Nuclear Plants and Status…..



Licensed to Operate (100)

Original License (19) License Renewal Granted (81*)

** The NRC has issued a total of 83 License Renewals, two of these units have permanently shut down.*

As of January 2016

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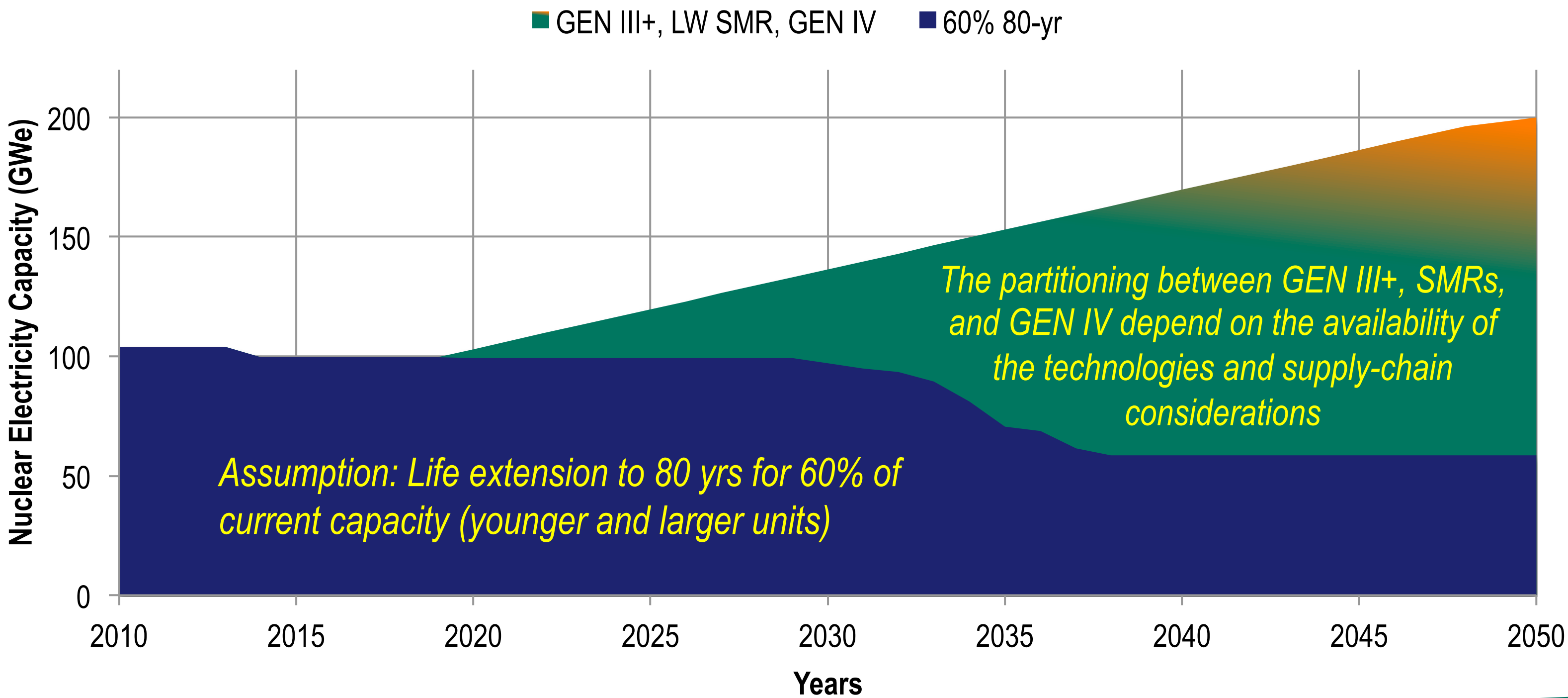
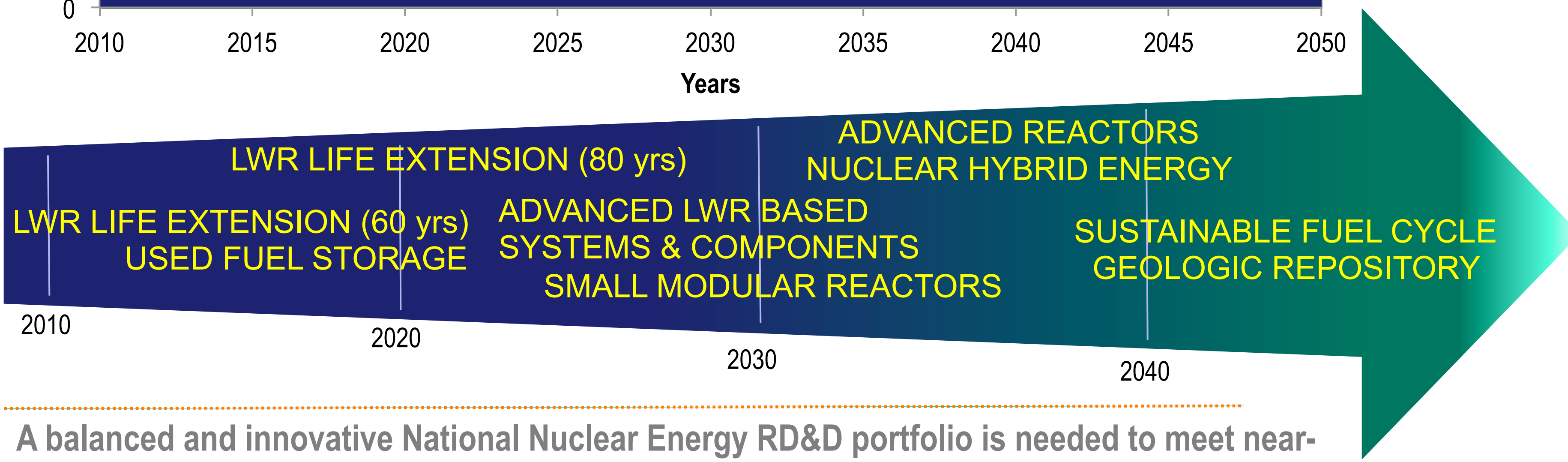
U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

National Nuclear Energy RD&D Roadmap

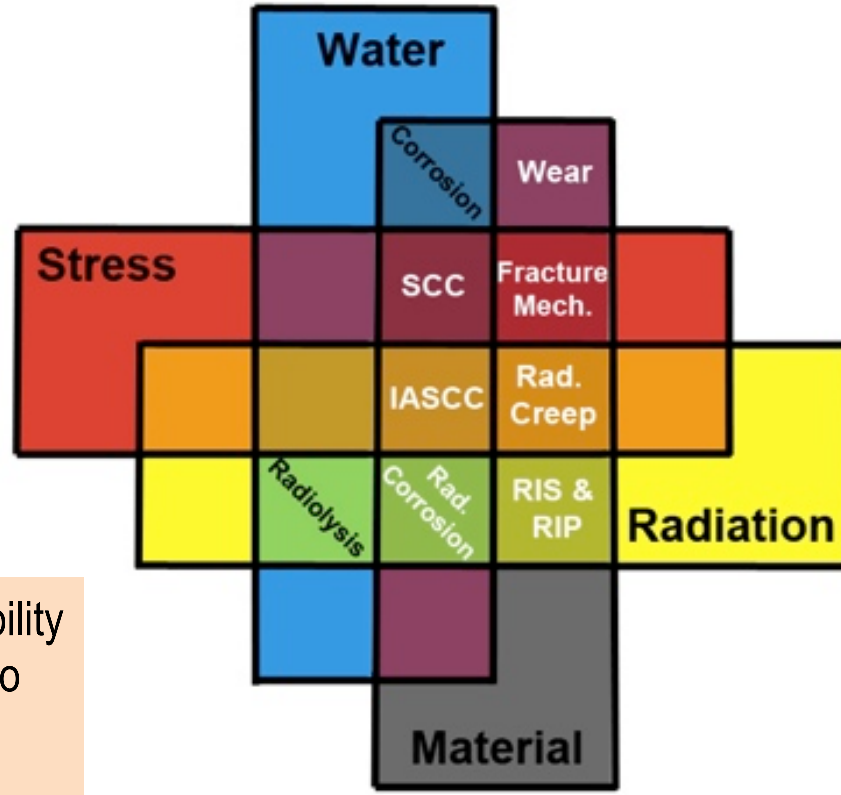




A balanced and innovative National Nuclear Energy RD&D portfolio is needed to meet near-terms priorities and long-term goals given the long development and deployment period for nuclear technologies.

credit: DOE-NE Five-Year RD&D Program Recommendations FY'18 – FY'22: Pasamehmetoglu, Icenhour, and Combs

Extension of service life may cause new challenges for materials……



Various mechanisms have impact on plant economics, reliability and safety

The vision of the DOE Light Water Reactor Sustainability (LWRS) Program is to enable existing power plants to safely provide clean and affordable electricity beyond current license periods (beyond 60 years)

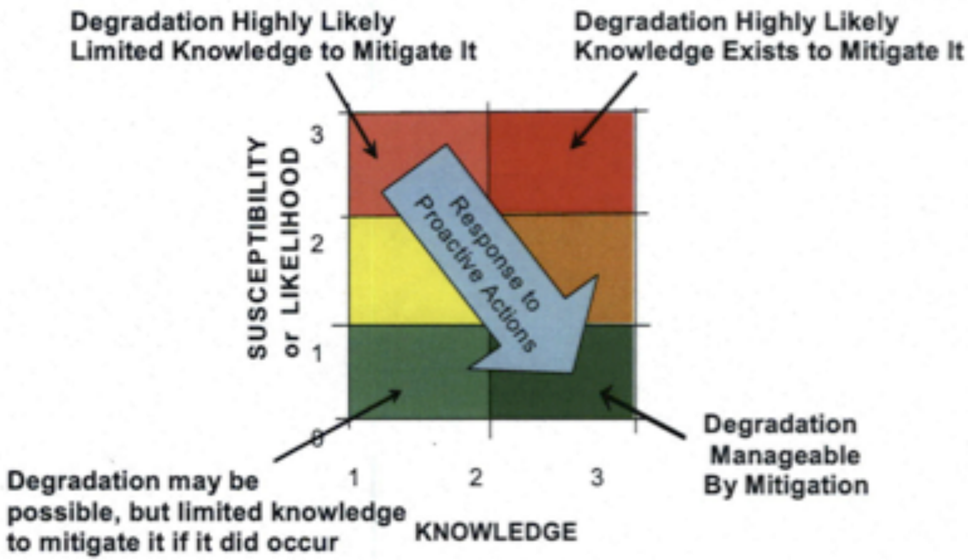
The goals of materials research in the LWRS program is to develop the fundamental scientific basis to understand, predict and measure changes in materials as they age in reactor environments.

Apply that knowledge in developing new methods for monitoring, new materials and new technologies that enhance plant performance and safety.

Research is directed at understanding known issues of degradation and how to minimize, control or monitor them. Research must also identify new phenomenon before they become life-limiting….

- To address aging-related degradation the NRC proactively identify scenarios that could affect reactor components, resulting in 2005 with NUREG/CR-6923, "Expert Panel Report on Proactive Materials Degradation Assessment," (PMDA) report.

- Follows the phenomena identification and ranking technique (PIRT) process, with degradation scenarios ranked according to:
  a. the probability of occurrence,
  b. level of knowledge concerning that process,
  c. confidence in ranking.



- To address degradation effects and scenarios possible in the 40 to 80 year timeframe, encompassing second license renewal-operating period, DOE and NRC expanded the initial PMDA activity (*NUREG 6923)* to encompass broader systems and longer lifetimes…...

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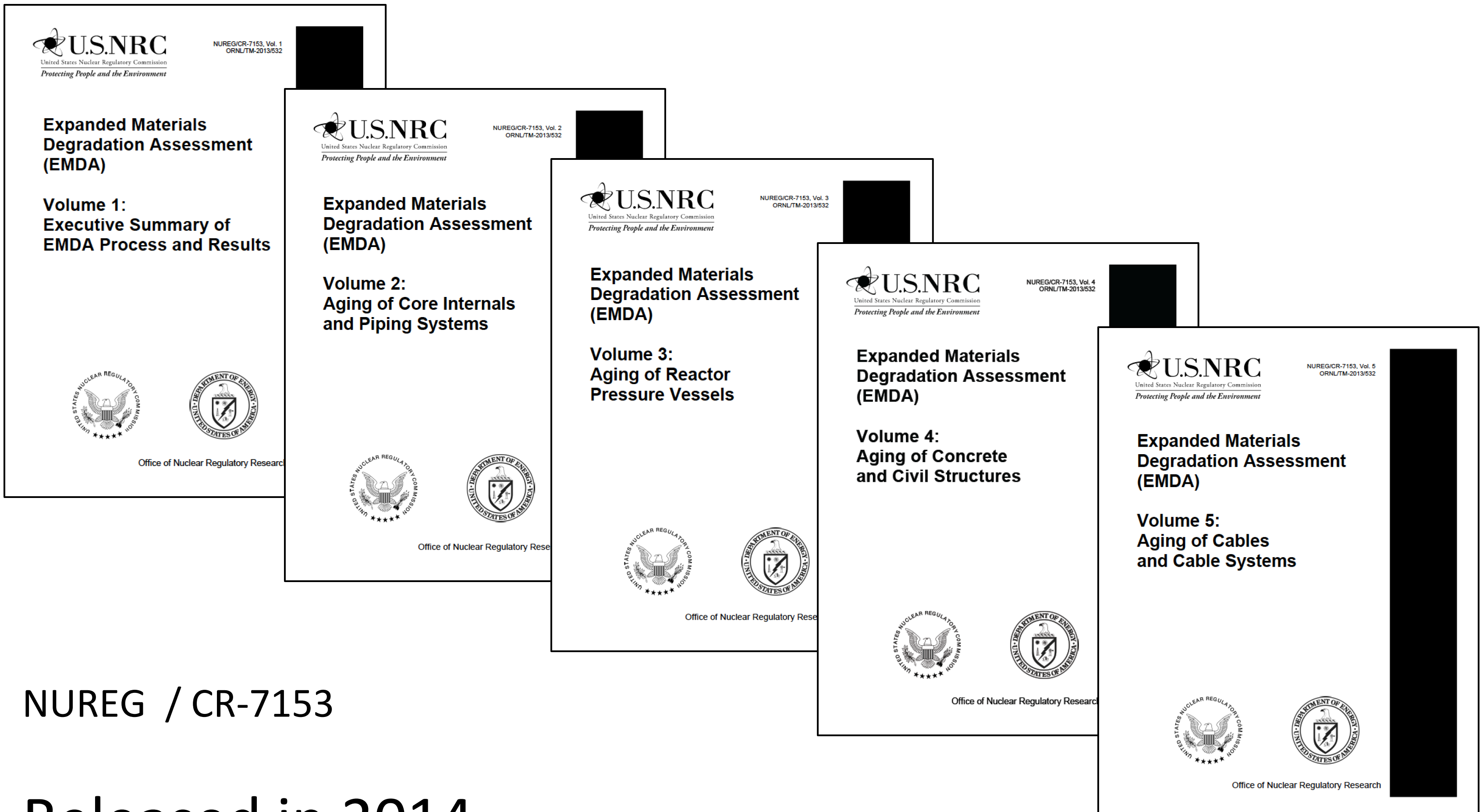
DOE and NRC have investigated issues of reactor aging beyond 60 years to identify possible knowledge gaps



NUREG / CR-7153

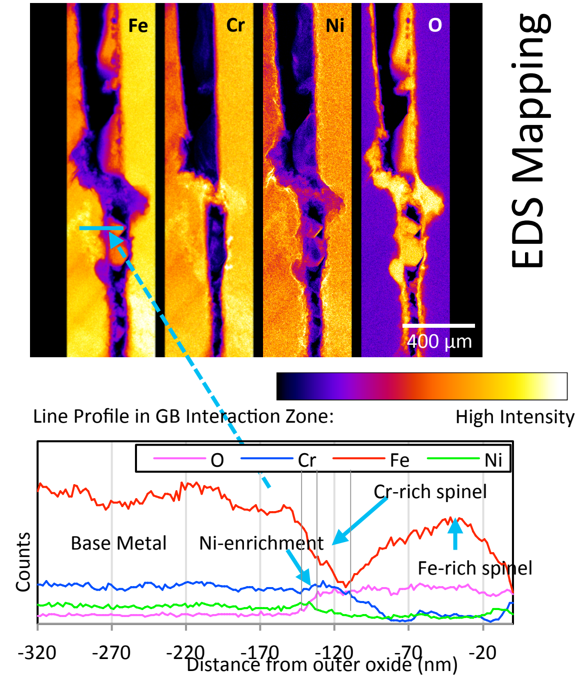
Released in 2014

LWRS U.S. DEPARTMENT OF ENERGY Nuclear Energy U.S.NRC United States Nuclear Regulatory Commission Protecting People and the Environment

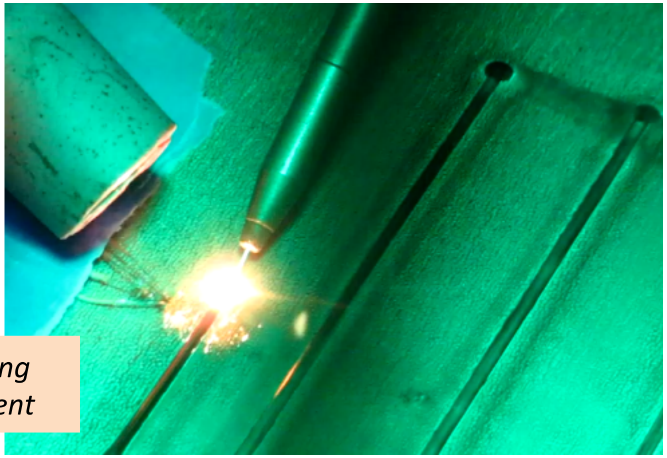
Directed Goals of the LWRS / MAaD Pathway

- Develop a mechanistic understanding of the degradation modes of RPV and core internals, and develop techniques for mitigating their effects.
- Development of advanced replacement alloys (decreased susceptibility to radiation damage and IASCC) - cooperation with EPRI and universities.
- Establish condition monitoring techniques for cables and concrete structures - cooperation with regulators and industry partners.
- Development of a fully coupled thermo-hydro-mechanical-chemical model for reliably predicting the performance of concrete structures.
- Development of procedures, techniques and computational modeling tools for laser and friction stir welding methods tailored to particular repair situations (material type, He level, etc.).

Chemical mapping of solute segregation at IASCC crack tip

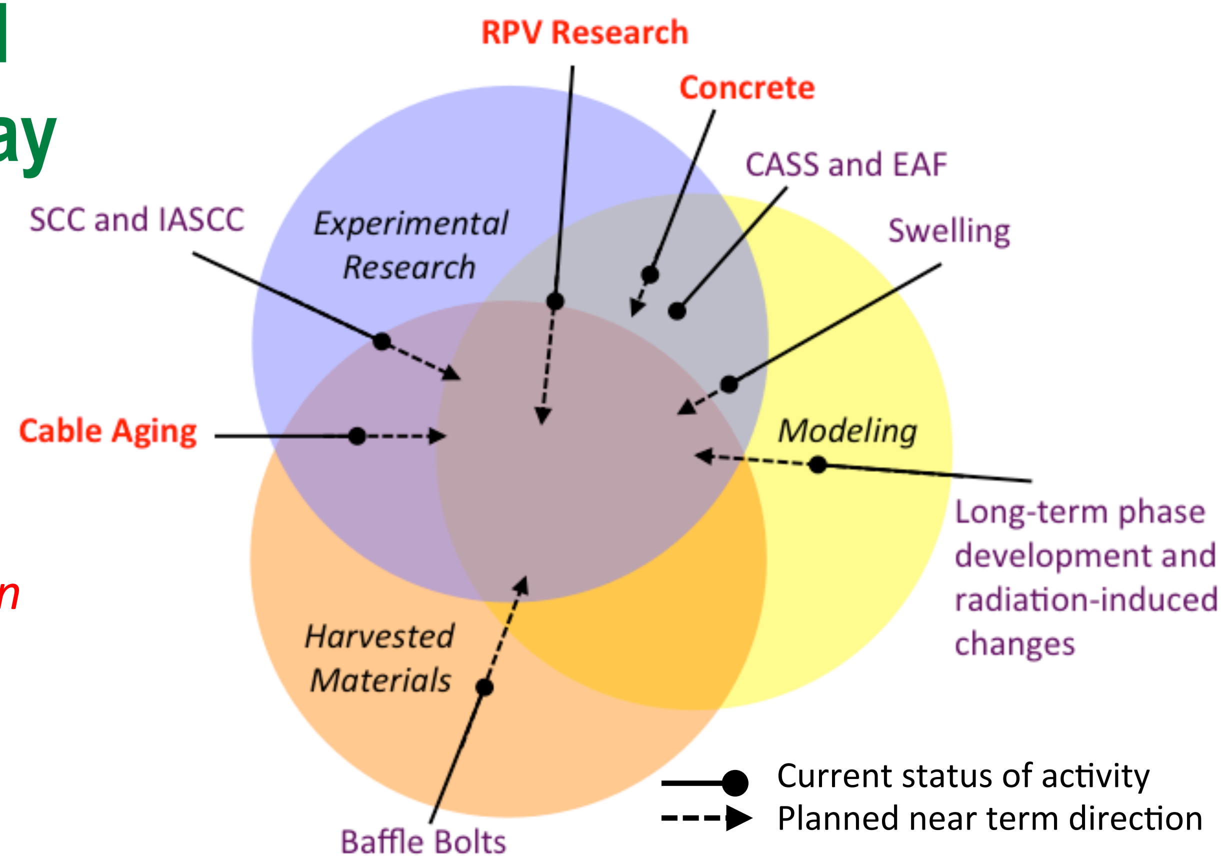


Utilizes the capabilities of the DOE National Laboratories, Universities and Institutions throughout the world….



Laser welding / cladding technology development

Materials Aging and Degradation Pathway Methodology



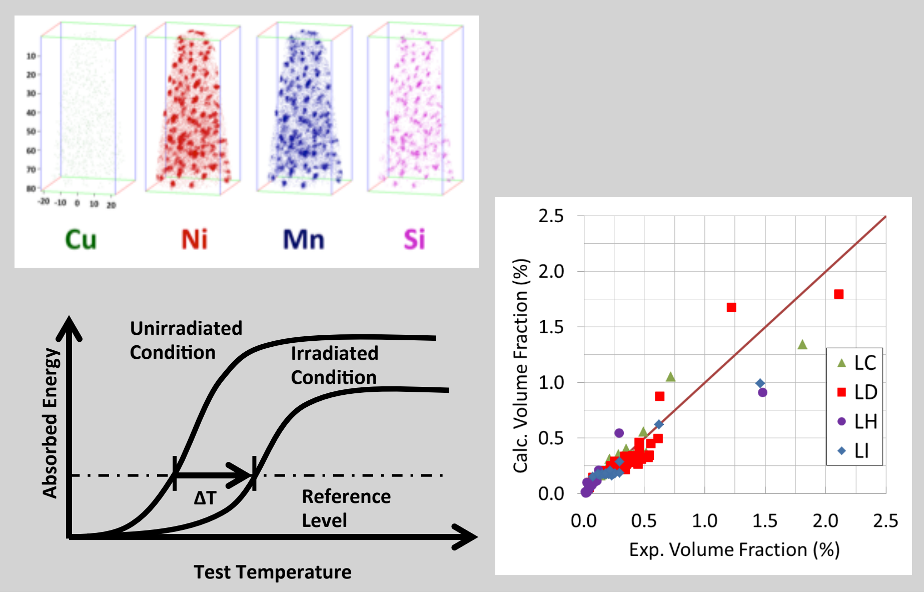
Addressing scientific gaps in knowledge of extended life predictions, requires a multidirectional approach.

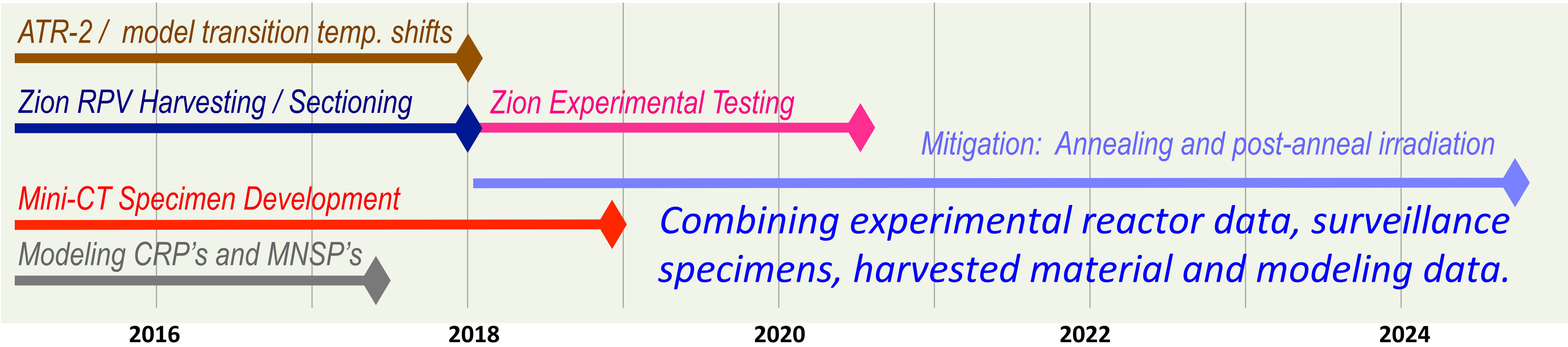
- Individual tasks within the pathway provide contributions to the overall pathway goal through high quality scientific measurement of materials performance to understand the active modes and mechanism of degradation.

Reactor Pressure Vessel (RPV)

Evaluation of risk for high fluence embrittlement after long service life and possible mitigation techniques through the mechanistic understanding effects of……

- High fluence, flux and composition
- Neutron attenuation and through thickness variability
- Aging / irradiation on weldments
- Bias in toughness values derived from pre-cracked Charpy specimens
- Examination of thermal annealing mitigation techniques - including re-irradiation





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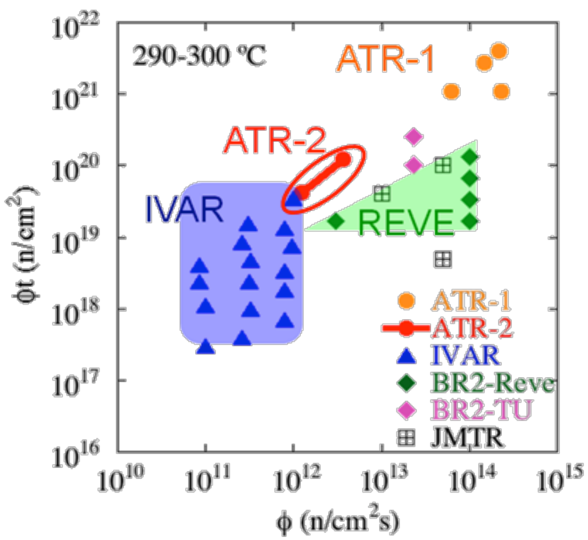
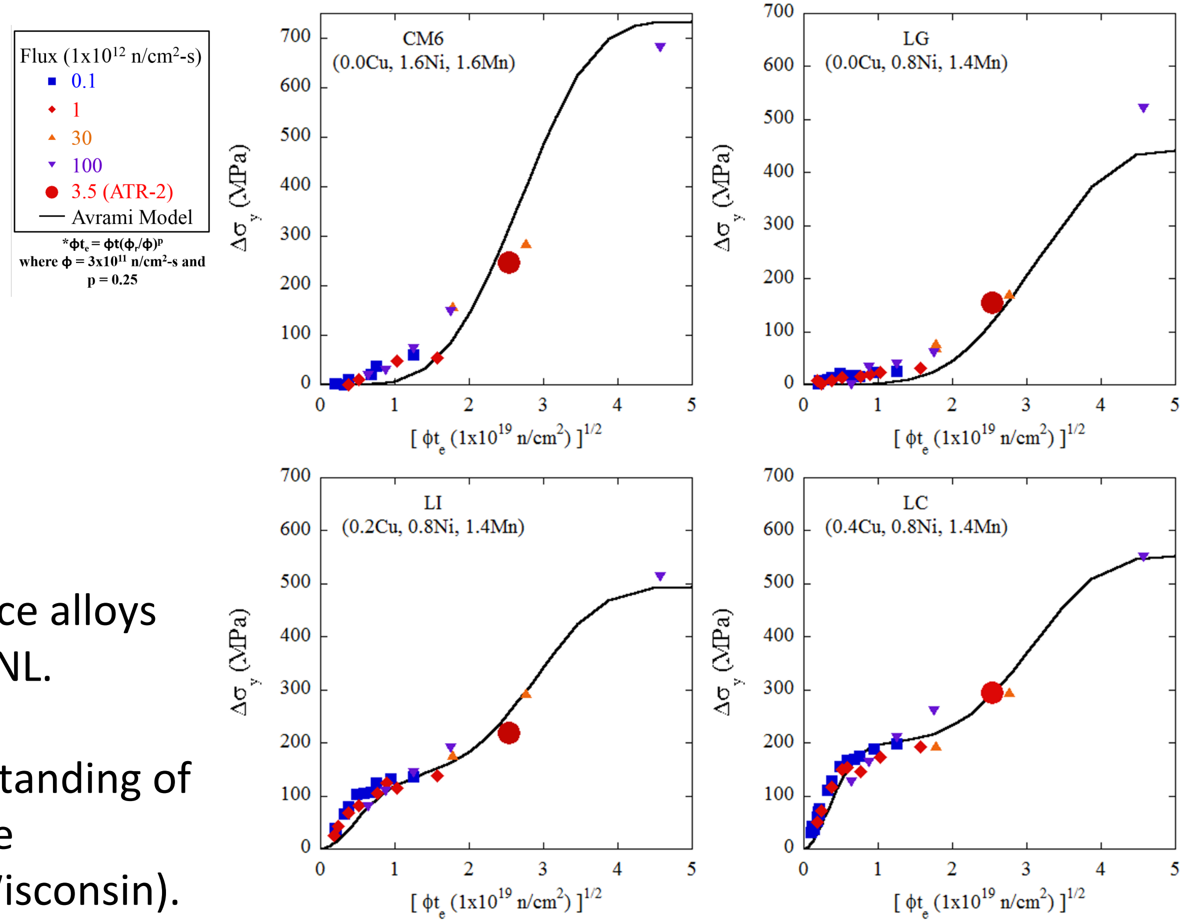
ATR-2 Experiment

Experiment designed to bridge previous test reactor and surveillance data for insight on the effects of flux and fluence in many alloys with systematic variations in composition.





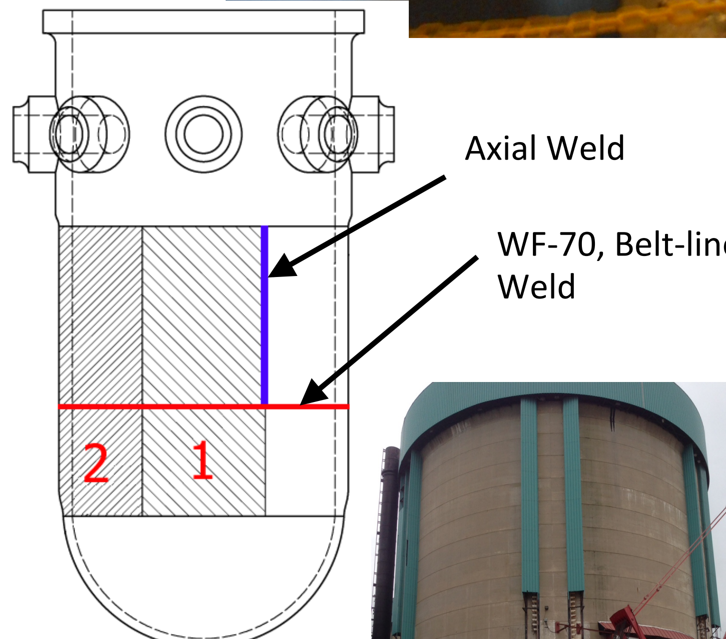
- Testing of model and surveillance alloys well underway at UCSB and ORNL.
- Range of alloy compositions.
- Model development for understanding of Cu-rich and Mn-Ni-Si precipitate formation and stability (U. of Wisconsin).

Total of ≈ 180 low alloy steels (~ 1600 specimens); peak/average fluences = $1.3/1.0\times10^{20}$ n/cm^2 ; four temperature zones: 250, 270, 290 and 310 °C.

Zion Unit-1 RPV Harvesting

In support of extended service and aging management …. procurement of materials, structures, components, and items of interest for the DOE LWRS Program, ERPI, and the U.S. NRC, from the decommissioned Zion Unit 1 & 2

- RPV panels removed in 2015, test specimens fabrication through 2017.
- Sections contain belt-line weld (Linde 80, WF-70 weld)
- Peak fluence = 0.75×10^{19} n/cm^2 (>1MeV), anticipated temperature transition shift is 145°F.
- High interest in:
  - Evaluation of radiation damage models
  - Attenuation studies, through wall variation in base and weld metal.
  - Mitigation techniques - annealing / re-irradiation studies.
- Summary of samples to be machined by type:
  - 419 Charpy specimens (239 base metal, 180 weld)
  - 272 Tensile specimens (128 base metal, 144 weld)
  - 136 Coupons (64 base metal, 72 weld)
  - 192 Fracture toughness: 112 (0.5T CT base), 80 (0.4T CT weld)

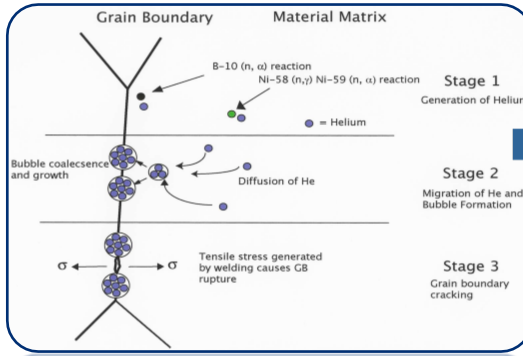


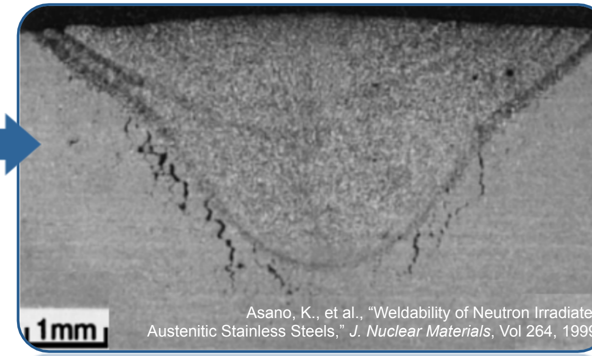
Mitigation Technology: Advanced Weld Repair

A Collaborative Effort: *DOE under LWRS and EPRI under Long Term Operation*

Objective:

- Develop advanced welding technologies for repairing highly irradiated reactor internals without helium-induced cracking
- Demonstrate these technologies on irradiated stainless steels in a new hot cell welding facility at ORNL





Asano, K., et al., "Weldability of Neutron Irradiated Austenitic Stainless Steels," *J. Nuclear Materials*, Vol 264, 1999.

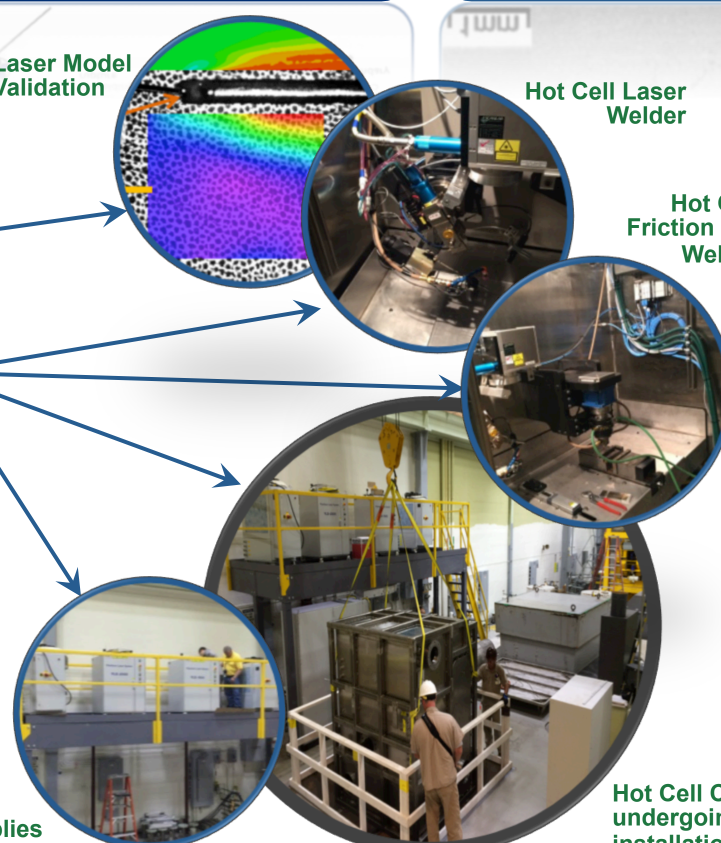
Recent Accomplishments:

- Weld process model for in-situ temperature and stress/strain refined and validated
- Friction stir weld demonstration run completed in June of cubicle installed at hot cells
- Irradiated coupon shipments initiated for PIE and welding preparation

Laser Model Validation

Hot Cell Laser Welder

Hot Cell Friction Stir Welder



Installed power supplies to laser subsystem

Hot Cell Cubicle undergoing installation

For more information, see the January 2016 LWRS Newsletter

Upcoming:

- Irradiated FSW in cubicle – FY17

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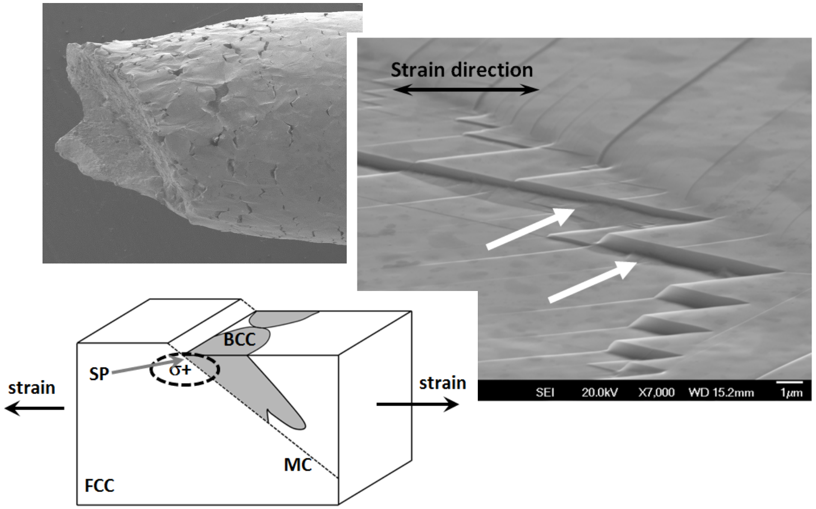
Additional LWRS-Metals Research Highlights



Irradiated 304 (4.4 dpa) tested under PWR conditions, showing martensitic regions along dislocation channels

Mechanisms of IASCC

- Analysis of key contributing variables to develop a mechanistic understanding from which mitigation or controlled management efforts can be applied for long-term operations.
- Understanding the role of grain boundary and adjacent grain orientations to applied stress on susceptibility.
- Understanding how alloy impurity composition, radiation induced segregation and defects influence susceptibility.
- Examination of water chemistry on crack growth in irradiated materials.

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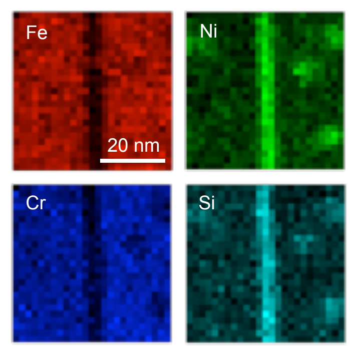
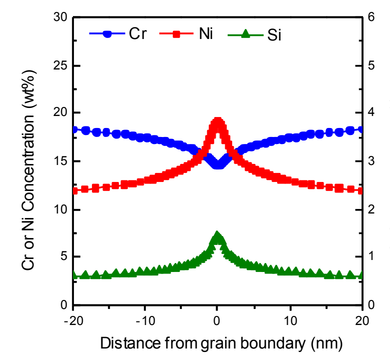
Computational Modeling of RPV and Core Internals

- Developing computational models for thermal and irradiation and effects on solute segregation and precipitate kinetics in stainless steel.
- Developed separate models for Cru-rich and Mn-Ni-Si precipitation in RPV steels - current work involves developing a combined model.
- Progress in developing a comprehensive microstructural-based model for swelling under LWR conditions - for FY2017.

Radiation induced segregation on high angle grain boundaries in 47 dpa, 320 °C irradiated 304 steel



Experimental composition map



Modeled

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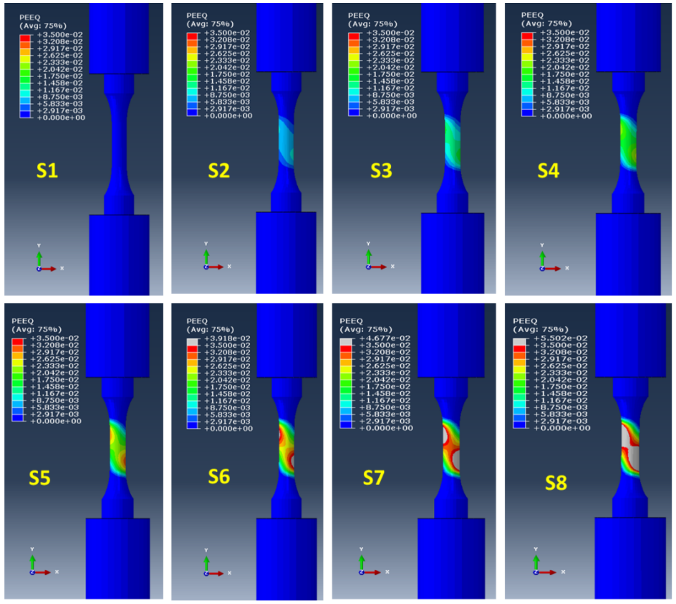
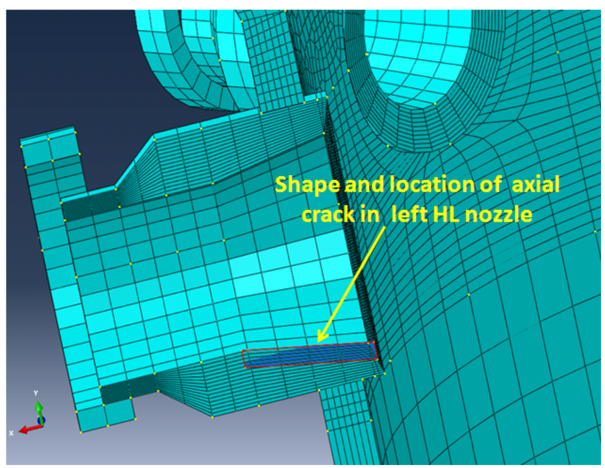
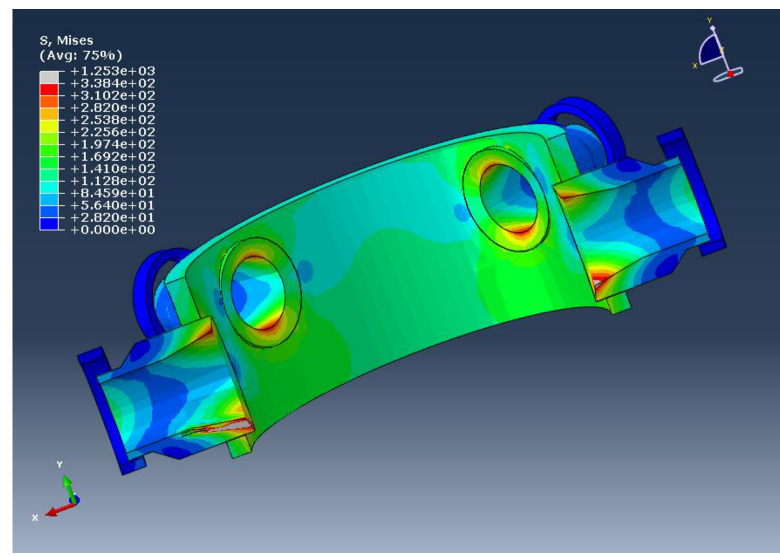
Environmentally Assisted Fatigue



FE simulated accumulated plastic strain profile at the end of different simulation steps

- Model EAF mechanisms through mechanistic based approach supported by experimental studies to identify key variables.
- Develop finite element based fatigue model to provide a capability of extrapolating the severity of degradation under realistic reactor environment loading cycles and under multi-axial stress states of components.
- Recent work: Thermal mechanical stress analysis of RPV nozzle sections with pre-existing crack analyzed under simulated load following conditions - crack did not grow, but created a large stress distribution that could influence primary water SCC resistance.



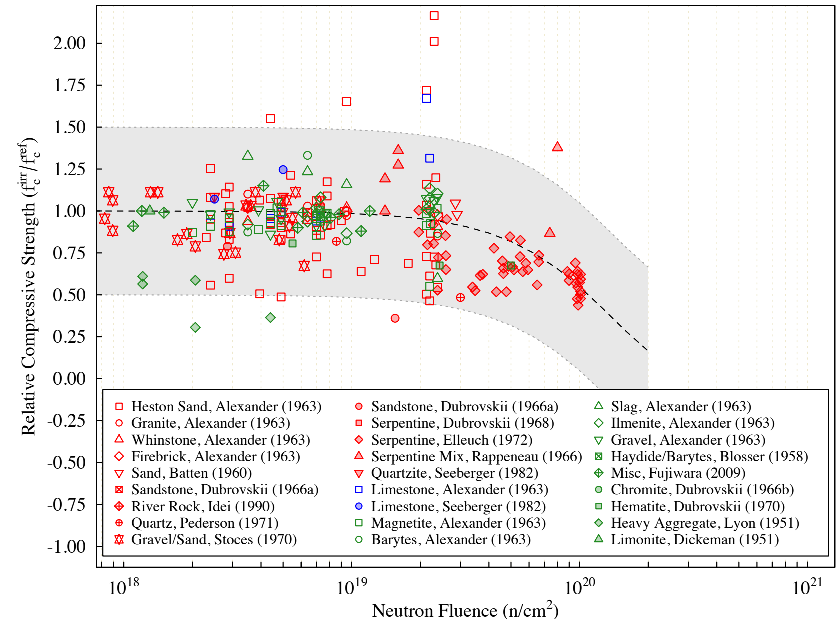


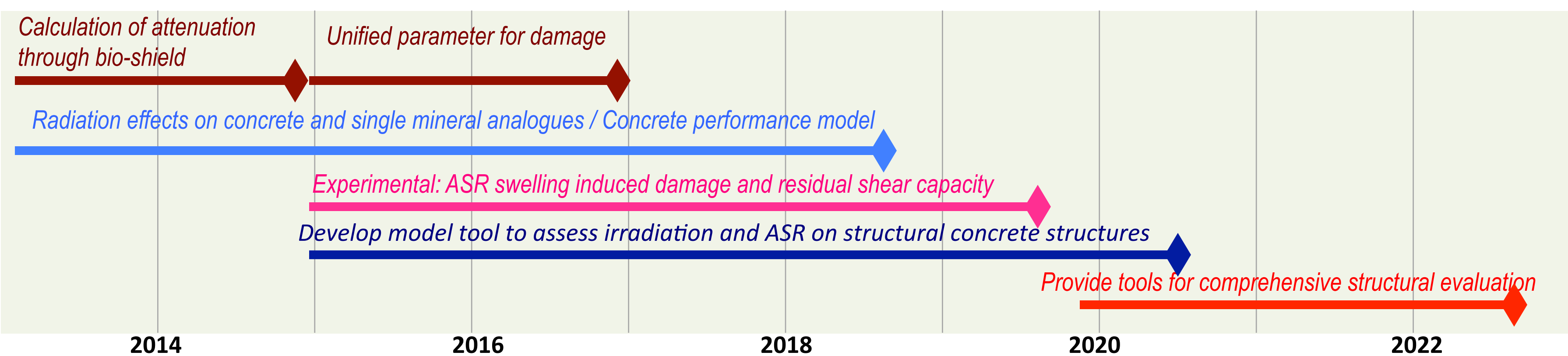
Shape and location of axial crack in left HL nozzle of RPV, with a Von-Mises stress contour at a typical full-power condition.

Concrete Performance in Nuclear Structures

Provide scientific evaluation of the degradation modes of nuclear concrete structures and assess the safety and serviceability

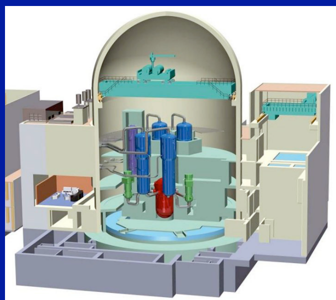
- Influence of irradiation (spectrum, flux, fluence, and temperature).
- Effects of different concrete mixes
- Alkali-silica reaction (ASR) influence on structure load bearing stability
- Explore advanced signal processing techniques to improve NDE detection and identification of degradation mode and condition

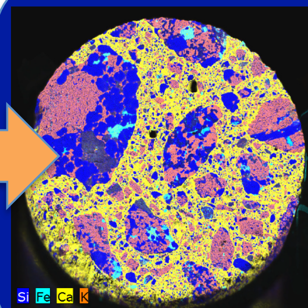




Concrete Modeling Strategy

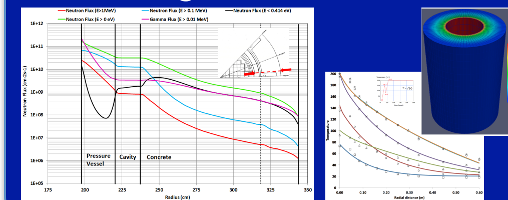
Harvested Materials



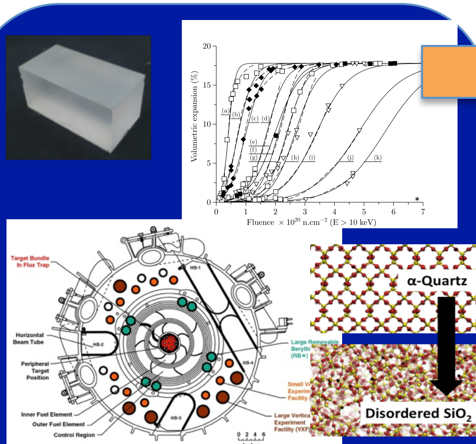


Evaluation of plant specific concrete aggregates: phase, composition, size

Modeling of attenuation, temperature and moisture through concrete shield

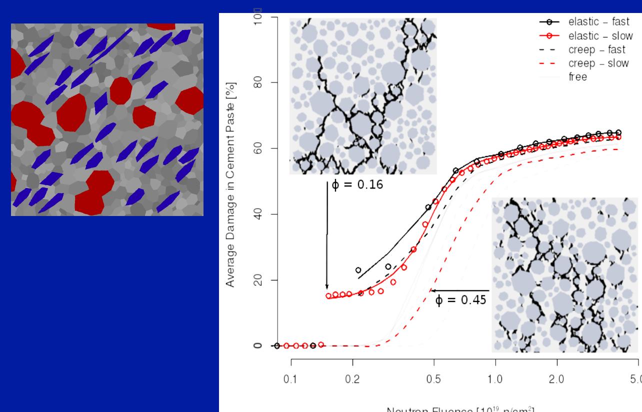


IMAC Database (irradiated minerals/aggregate/concrete)

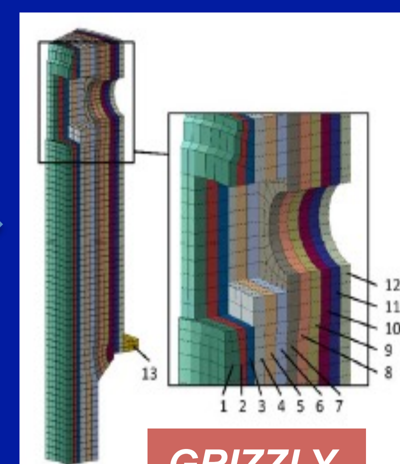


Experimental studies on RIVE and ASR

Irradiation and ASR affected concrete performance modeling



Structural simulation of long-term plant performance

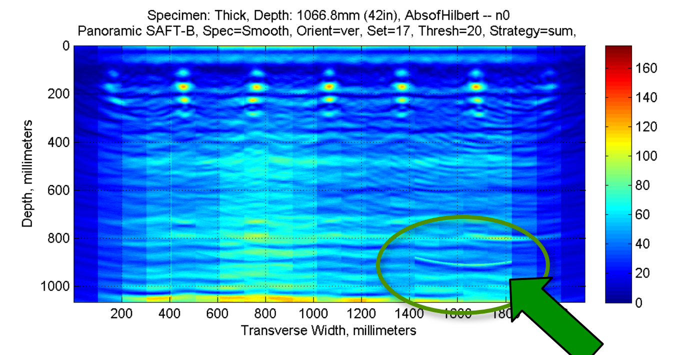


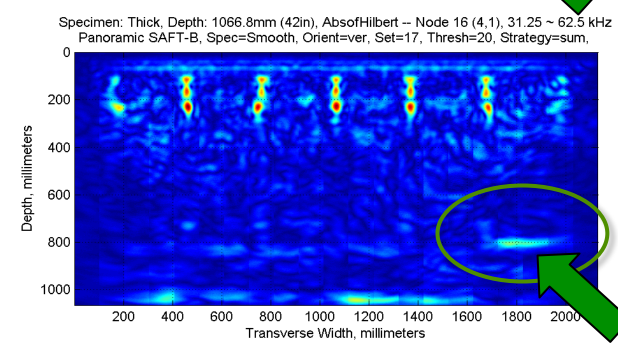
Nondestructive Evaluation (NDE) of Concrete Structures in Nuclear Power Plants

Purpose: Develop NDE techniques to permit monitoring of concrete and civil structures. Could be revolutionary and allow for an assessment of performance that is not currently available via core drilling in operating plants. Would reduce uncertainty in safety margins and is valuable to both industry and regulators.

Accomplishments

- Verified improvements in the detection of delamination and foreign organic materials – on ”thin” (DOT) and “thick” (nuclear structure) specimens.
- Improved existing techniques by using advanced signal processing (Synthetic Aperture Focusing Technique with frequency banding)
- Verification using fabricated defects





Future Plans

- Develop/refine technique for the detection of alkali-silica reaction (ASR)
- Develop technique for the detection of damage due to irradiation
- Explore the benefits of model based image reconstruction (MBIR)

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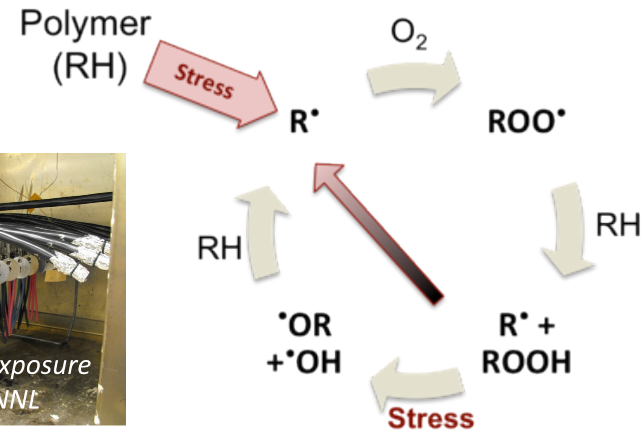
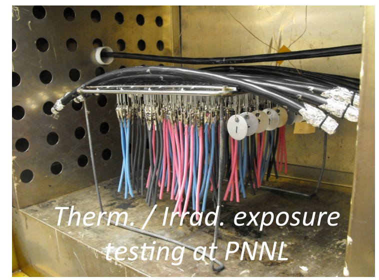
Cable Aging and Condition Monitoring

Develop cable aging models and NDE techniques to support long-term operation of nuclear power plant cable systems through…..

- Accelerated aging of cable insulation and jacket materials representative of material currently in use
- Electrical, chemical, and mechanical characterization to establish aging trends and key factors for cable condition monitoring
- Evaluate and develop promising commercial NDE methods and technologies through collaboration with vendors and industry, with goal of tracking key cable health indicators



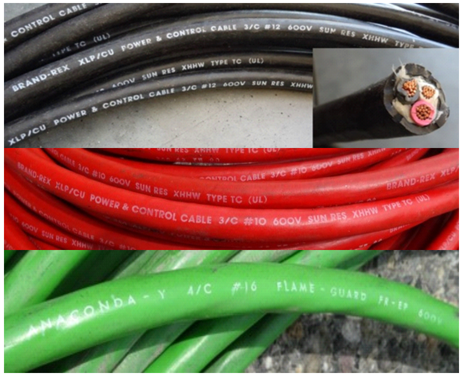


Key Research Directions

- Synergistic thermal and irradiation effects on degradation
- Inverse temperature effects
- Determining activation energies for degradation
- Dose rate effects
- Diffusion limited oxidation in LOCA tests
- Development of NDE techniques to evaluate cable useful life

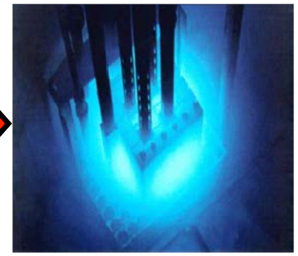
Work combines experimental testing on representative materials used in plants and harvested ex-service cables.

Technical Approach to Cable Aging Program



Harvest representative cables from NPPs, EPRI, NRC

Exposure to Environmental Stressors



Radiation

Thermal

Moisture

Mechanical, physical, and electrical property changes due to chemical changes

Visual Inspections & NDE Technologies

Remaining Useful Life Predictions

Targeted Outcomes

Detailed Understanding	Effective Treatments	Key Indicators of Cable Aging	Transformational NDE	Models/Methods of Predicting Useful Life

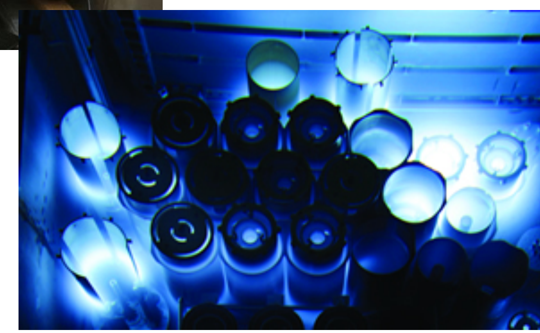
Understanding Degradation Modes and Remaining Useful Life Through Testing

Recently completed tasks

- Combined thermal / irradiated series of XLPE
- Accelerated thermal aging of harvested CSPE cables completing
- Correlated swell / gel results with EAB for thermally aged EPR

Combined thermal and irradiation exposure testing at PNNL

Gamma exposure testing at HFIR



Data collected from variations in dose rate, thermal aging, accumulated dose; all provide fundamental information for model development

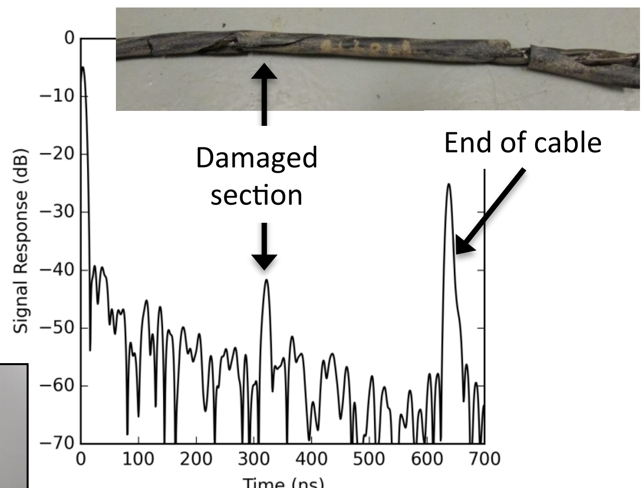
Addition of harvested material

- Zion Unit 1 CRDM cables (power and position indicator)
- Zion Unit 2 low and medium voltage instrumentation cables in collaboration with the NRC: LDPE, HDPE, EPR, SiR, CSPE, etc.
- Crystal River Unit 3 (PWR, 1976 - 2013), collaboration with EPRI and NRC: EPR and XLPE insulated cables.

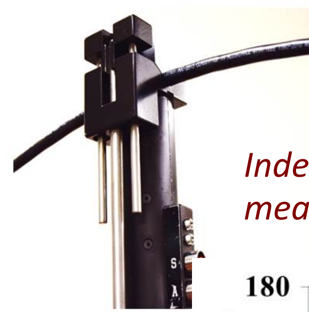
Develop and validate NDE technologies for condition monitoring of cables, with the ultimate goal to transfer techniques / knowledge to industry…

- Evaluate for susceptibility – focus on rooms / areas with highest temp and highest radiation. Special attention to the most safety critical components.
- Visual walk-down looking for visible indications on jackets.
- FDR, Tan-Delta and other bulk tests looking for worst case areas of degradation on sample of cables.
- Local specific NDE (indenter, capacitance) at local area identified with bulk tests.
- Consider repair / replace where indicated.

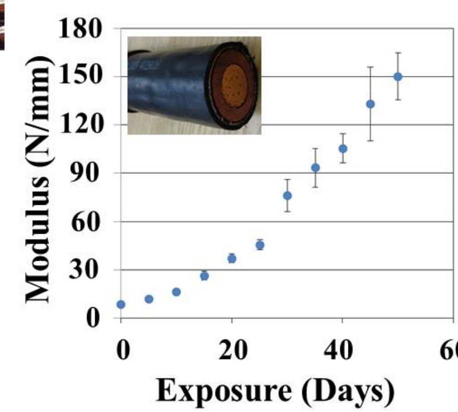
Condition Monitoring



Frequency Domain Reflectometry (FDR) spectrum showing 18-inch thermally aged section identified along 200 ft of cable.



Indenter modulus, local measurement.



NDE techniques currently require correlation with destructive examination techniques

Key Planned Accomplishments

Industry	By 2017	*By 2018 - First SLR License Application Submitted*	*By 2020 - First SLR license Approved by NRC*	*By 2024 - First License Renewal Expires*
LWRS Program	Model for Cu-rich and Mn-Ni-Si precipitate development in RPV steels.	Model for transition temperature shifts in RPV steels.	Concrete performance model	RPV mitigation techniques and evaluation: annealing and post-anneal irradiation studies
	Combined thermal and radiation induced segregation / precipitation models	Mini-CT Specimen Development and Validation	Predictive degradation model for cables	Methods for Cable Rejuvenation
	Fatigue crack initiation and propagation modeling in reactor coolant system pipe base and weld material.	Transfer of weld repair techniques on irradiated materials to industry	Predictive model capability for IASCC susceptibility.	Development and testing of new advanced alloys with superior degradation resistance.

Discussion?

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Light Water Reactor Sustainability