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EPRI - NSUF Collaboration to Develop Integrated Solutions for Nuclear Power Industry

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EPRI

Nuclear Science User Facility Annual Review Meeting

March 1-2, 2016

Safe and Economical Operation of LWR Fleet

- 99 commercial nuclear power reactors provide approximately 20% of the nation's total electricity in US
  - *65 pressurized water reactors (PWR)*
  - *34 boiling water reactors (BWR)*
- US light water reactor (LWR) fleet will play a major role in the transformation of the future energy-supply system
  - A part of pathways to decarbonization
- Industry needs integrated solutions to ensure safe and long-term operation of LWR fleet, including:
  - Safety and reliability
  - Economics
  - Technology innovations to improve efficiency

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Manage Plant Aging Effectively

- Physical ageing associated to the degration in the functionality of components, structures, systems, etc.
  - Irradiation embrittlement due to increase in end-of-life fluence
  - Environmentally assisted cracking due to accumulative transients (mechanical or chemical) and microstructure evolutions
  - Embrittlement due to thermal aging
  - Degradations due to synergetic effects of materials, irradiation, environments, thermal process
- Non-physical ageing
  - *Technological (knowledge) obsolescence*
  - *Lack of an effective system or certain safety design features*
  - *Obsolescence in products or procedures*

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The Ultimate Goal is Zero Fuel Defects

- Increases in both burnup and cycle length allow plants to operate more efficiently and produce more electricity. However, fuel failures threatens nuclear's cost competitiveness:
  - *Lost generation of electricity*
  - *Increased inspection and repair costs*
  - *Premature discharge of fuel assemblies*
  - *Increased plant background radiation*
  - *influence public acceptance of nuclear power*
- Despite the challenging environment, the industry continues to expect and strive for zero defects:
  - *More-effectively pursue mitigation techniques*
  - *Identify root causes for the industry's toughest fuel problems*

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NSUF Capabilities are Important to Industry

- Shortage in R&D capabilities for LWR materials and fuel researches and developments:
  - *Neutron irradiation facilities*
  - *Capabilities for post-irradiation examination or testing*
- Scientific excellence and Innovation
  - *Experience based (emperical) approach vs. proactive (mechanistic) approach*
  - *New hypotheses, new techniques, new methodologies …*
- Collaborative R&D
  - *Expanding scientific network – DOE programs & labs, universities, utilities, NSSS vendors, EPRI, non-US interests and capabilities…*
- Development of new generation of talents

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Maximize Impact

- Maximize impact -- How can NSUF program be effective leading a thoughtful coordination and (more importantly) integration?
  - *With all NSUF capabilities*
  - *With other relevant DOE programs*
  - *With industry R&D programs and international R&D programs*
- Maximize impact -- What is the balance in understanding industry needs and continuing scientific excellence?
  - *Define and emphsize relevancy*
- How to coordinate capacity and availability?
  - *ATR, hot FIB, transportation, etc…*
- How to manage expectations?
  - *From collaborators and customers*
  - *From partners*

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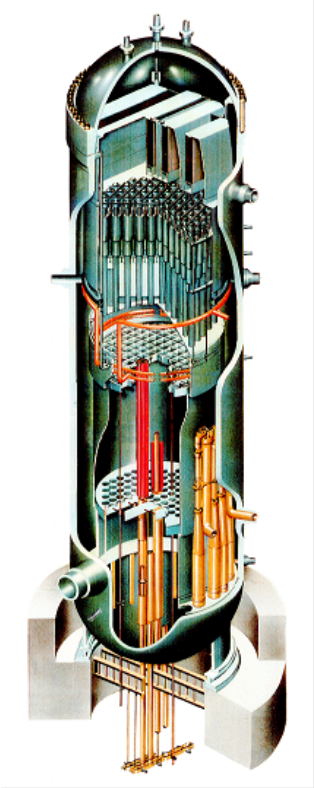
LWR Industry -- Integrated Materials Aging Management for Primary System Components



Inspection

- *how to inspect*
- *what equipment and techniques are available*
- *What are the associated uncertainty*

Assessment

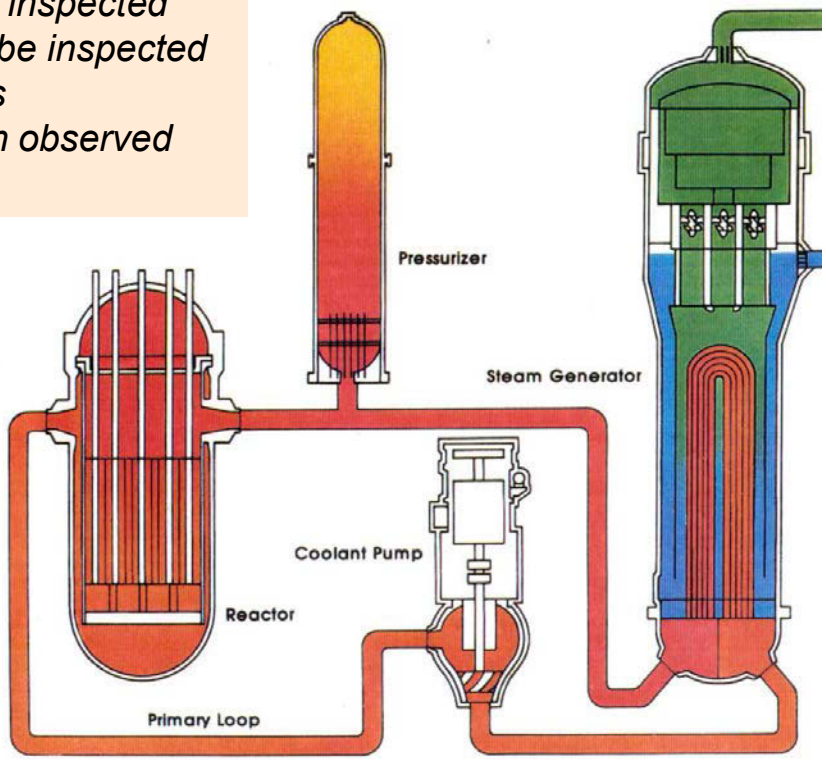
- *What needs to be inspected*
- *When it needs to be inspected*
- *Inspection options*
- *How to disposition observed degradation*

Mitigation

- *How can degradation be prevented or reduced*

Repair/Replacement

- *What techniques are available*
- *What are associated requirements that must be met*



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Opportunities in NSUF-EPRI Collaboration

- Advanced Fuel R&D
  - The NFIR experiment in ATR
  - Accident tolerant fuels irradiation experiment in ATR
  - Reactivity initiated accidents (RIA) like transient testing in TREAT
  - Mechanistic Understanding of Hydrogen Pickup by Zr-based Alloys
- Materials Degradation R&D
  - Late occurring damage & flux effects on RPV embrittlement trends
  - Better understanding of fundamental IASCC processes
  - Abilities to predict void swelling rates and significance
- Long term operation and flexbile operation
  - Irradiation aging of electrical cables
  - Irradiation aging of concrete and containment structures
  - Welding of highly irradiated materials
- Advanced Nuclear Technology
  - Small modular reactors (SMRs) and GEN-IV

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NSUF-EPRI Opportunities in Materials R&D

- LWR neutron irradiation and PIE
  - Effects of synergetic aging in CASS and stainless steel welds
  - Void swelling studies in LWR condition
  - Development of radiation resistant alloys (ARRM project)
  - Development of HIP materials
  - Welding of highly irradiated materials
  - Further irradiation for specific objectives
  - In-core or hot-lab IASCC experiments
- Ion irradiation and post irradiation characterization
  - Irradiation microstructure studies and modeling
  - Understand the effects of high fluence (through simulation)
  - Void swelling studies and modeling (Rapid simulation project)
  - IASCC initiation mechanistic studies
- Advanced characterization capabilities
  - TEM / APT for many LWR irradiated samples
  - Explore new analytical techniques (small-volume techniques)

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NSUF Plays Important Roles in EPRI R&D

- Active participation
  - X-750 project (on going)
  - Zr-alloy Irradiation Growth Project (on going)
  - Irradiation Effects on PM-HIP Alloys (on going)
  - Study Effects of Synergetic Aging for CASS (proposal)
  - Understanding of H Pickup by Zr-based Alloys (proposal)
  - Contribute to NSUF sample library
- Long engagements with researchers and facilities
  - Not under NSUF framework
  - Past and on going projects at MIBL, IVEM, UC Berkeley …
- Annual NSUF Industry Advisory Committee (ANIAC) meeting – NSUF sounding board
  - Last meeting was held in July 2015 at EPRI-Charlotte
  - Need to plan for next meeting

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In Conclusion

- NSUF program and capabilities are important to enhance EPRI R&D for nuclear power industry in materials and fuel areas
- Thoughtful collaboration, coordination, integration are keys to maximize NSUF impact in helping US industry develop integrated solutions
- We look forward to continuing and strengthening NSUF – EPRI collaborations

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Together…Shaping the Future of Electricity

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Backup Slides

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LWR Materials Aging Management Objectives

- Maximize the operating life and reliability of Light Water Reactor passive long-lived components to support current and extended operations.
- Predict component degradation mechanisms and their rate of occurrence to estimate the end of component useful life.
- Anticipate impacts on plant operations related to implementing materials management activities
- Perform fundamental research to understand the physical bases of degradation mechanisms and develop physically based models

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Priority Based Materials R&D Planning

- **Materials Degradation Matrix, MDM**
  - A comprehensive listing of likely degradation mechanisms
  - Knowledge on degradation mechanisms and mitigation measures
- **Issue Management Table, IMT**
  - Assessing the consequences of failure
  - Identifying gaps in inspection, mitigation, repair/replacement
  - Prioritizing IMT gaps to establish R&D project plans
- **Roadmaps**
  - 5-10 year time frame to solve a particular materials aging issue
  - Tieing associated gaps together
  - Coordinating activities
- **Developing Project Plan**
  - Detailed description of the tasks
  - Resources required
  - Identifying contractors and collaborators

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Systematic Approach to Managing Materials Issues

Industry Materials Degradation Matrix

MDM

- Develop a fundamental understanding of the degradation phenomena/mechanisms

Issue Management Table

IMTs

- Perform operability and safety assessments
- Develop Inspection and evaluation guideline
- Evaluate available mitigation options
- Develop repair & replace options
- Monitor and assess plant operation experience
- Obtain regulatory acceptance

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EPRI Materials Degradation Matrix (MDM)

(EPRI Report: 3002000628. Available through www.epri.com)

Table 3-2 PWR Reactor Vessel Internals

MATERIAL	DEGRADATION MODE													
	SCC		Corrosion				Wear	Fatigue		Reduction in Fract Properties		Irradiation Effects		
	IG/TG	IA	Wstg.	Pitting	FAC	Foul	Wear	HC	LC-Env.	Th.	Env.	Emb.	VS	IC / SR
SS: 300 Series Base Metal	Y LTO p2-1a	Y LTO p2-2a	N	N	N	N	Y IMP p2-7a	Y LTO p2-8a	Y LTO p2-9a	N	Y LTO p2-11a	Y LTO p2-12a	Y LTO p2-13a	Y LTO p2-14a
SS: 300 Series Welds & Clad	Y LTO p2-1b	Y LTO p2-2b	N	N	N	N	N	Y LTO p2-8b	Y LTO p2-9b	Y LTO p2-10b	Y LTO p2-11b	Y LTO p2-12b	Y LTO p2-13b	Y LTO p2-14b
CASS	Y LTO p2-1c	? LTO p2-2c	N	N	N	N	N	Y p2-8c	Y LTO p2-9c	Y IMP p2-10c	Y LTO p2-11c	Y LTO p2-12c	N .	N .
Ni-Alloy: Base Metal (A600)	Y IMP p2-1d	N	N	N	N	N	Y IMP p2-7d	Y p2-8d	Y LTO p2-9d	N	Y p2-11d	N .	N .	N .
Ni-Alloy: X-750	Y LTO p2-1f	? LTO p2-2f	N	N	N	N	Y p2-7f	Y LTO p2-8f	Y LTO p2-9f	N	Y LTO p2-11f	? LTO p2-12f	N .	N .
SS: Precip. Hardened (A-286)	Y LTO p2-1g	Y LTO p2-2g	N	N	N	N	Y LTO p2-7g	Y LTO p2-8g	Y LTO p2-9g	Y LTO p2-10g	? LTO p2-11g	Y LTO p2-12g	N	Y LTO p2-14g
SS: Martensitic	Y LTO p2-1h	N	N	N	N	N	Y p2-7h	Y p2-8h	Y LTO p2-9h	Y LTO p2-10h	? p2-11h	N	N	N

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MDM Summary for BWR

Embrittlement correlation uncertainties, application of lower fluence PWR surveillance data	Low-alloy steel reactor vessel shells & welds
IGSCC initiation in nickel-base alloy vessel ID attachment welds and crack extension into irradiated reactor vessel shells	Jet pump riser brace welds Low-alloy steel reactor vessel shells
Fundamental knowledge regarding the key factors influencing IASCC initiation and growth in welded stainless steel structures exposed to BWR coolant	Welded structures subject to high fluence (i.e, core shroud, top guide)
High fluence CGR data	Welded structures subject to high fluence (i.e, core shroud, top guide)
Effect of 80-year EOL fluence on performance of high-strength core periphery components (fracture toughness, tensile strength, SCC growth rates)	X-750 jet pump beams, core shroud tie rod repairs, XM-19 tie rod repairs, jet pump, and fuel support castings

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MDM Summary for PWR

Late occurring damage & effects on embrittlement trends	LAS reactor vessel shells & welds
Capabilities to predict PWSCC initiation in thick-wall primary system DM welds and welded Ni-alloy components	Unmitigated Alloy 600/82/182 butt weld locations, BMN penetrations, RPV head penetrations (Tcold heads)
Fundamental understanding of factors causing SCC of stainless steels in PWR primary system service	CEDM canopy seal welds, PZR penetrations, stagnant piping
Capabilities to predict IASCC initiation in high-dpa fasteners	Baffle bolting
Modeling / prediction of void swelling rates and significance	Baffle / Former Assemblies, Welded Core Shrouds
Effect of 80-year EOL fluence on performance of high-strength core periphery components and characterizing the effect of microstructure / as fabricated component condition on vulnerability to SCC	X-750 CRGT support pins, A286 fasteners, CASS support flanges
Alloy 690/52/152 long-term performance / SCC resistance	Replacement components, repairs
Prediction of ODSCC, PWSCC initiation trends, development of effective mitigation technologies	Alloy 600TT tube bundles
Evaluation of ODSCC vulnerabilities (e.g., PbSCC)	Alloy 690TT tube bundles

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EPRI Materials Issue Management Tables (IMT)

- PWR IMT Rev-3 (2013): EPRI Report 3002000634
- BWR IMT Rev-3 (2013): EPRI Report 3002000690

(Available through www.epri.com)

Table A-11 ASME Class 1 Piping, Fittings, and Valves - Babcock & Wilcox

Component & ID No.	Material	Degradation Mechanism	Conseq. of Failure	Mitigation	Repair / Replace	I & E Guidance	Gaps
11.1 Hot Let & Branch Lines							
11.1-1 Primary Loop Piping Components & Branch Connections (includes CS branch connections for surge line, decay heat removal line)	CS-SS Clad *(A106; SA-516)*	Fat: LC-Env RiFP: Env Ext: SCC, Wstg Pitting	B, E, G	**Water Chemistry - Primary** EPRI 1014986	**ASME Sect. XI** IWA-4000	**Inservice Inspection** IWB-2500-1 **Risk Informed ISI:** CC-N-716 Reg. Guide 1.200 NUREG - 1855 EPRI 1018427 **Boric Acid Corrosion Cont.** WCAP-15988-NP *BAC Prog.* NRC GL 88-05 **LC-Env Fatigue** MRP-148 *Fatigue Management* MRP-149 *Lic. Basis Mon.* MRP-47 *Fatigue Env. Effects* NUREG-1801, X.M1 *Fat. Mon.* NUREG/CR-6260 NUREG/CR-6909	P-DM-09 P-AS-01 P-AS-02 P-AS-36 P-I&E-22

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BWR IMT -- High Priority Gaps

ID	Gap Description
B-AS-07	Environmental Effects on Fatigue Resistance: Pressure Boundary Components
B-AS-09	Assess the Impact of High Fluence on Fracture Toughness
B-AS-10	Assess the Impact of High Fluence and HWC Mitigation Technologies on SCC Crack Growth Rates
B-AS-18	Jet Pump Degradation Management
B-AS-26	High Strength Alloys
B-AS-29	Steam Dryer Evaluation Methodology
B-AS-32	Assessment of Core Plate Rim Hold Down Bolts
B-MT-02	ECP Measurement, Estimation, and Validation
B-MT-04	On-Line NMCA Deposition Effectiveness and Implementation
B-MT-05	Water Chemistry Optimization for Power Operation, Startup and Shutdown
B-I&E-03	Inspection of Shroud & Shroud Support Weld Locations
B-RR-02	Welding Processes for Repair of Irradiated Material
B-RG-05	Evaluation of Remote EVT-1
B-RG-09	Management of License Renewal Issues

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BWR IMT -- Medium Priority Gaps

ID	Gap Description
B-DM-06	Environmental Effects on Fracture Resistance
B-DM-07	Chloride Transient Effects on Low Alloy Steel Crack Growth Rates
B-AS-05	Assess Neutron Dose Rate Effects on Embrittlement of C&LAS
B-AS-11	Assess Non BWR Reactor Irradiated Materials Data Applicability to the BWR Environment
B-AS-15	FIV and High Cycle Fatigue Assessment: Reactor Internals
B-AS-22	High-Cycle Thermal Fatigue: Piping Locations
B-AS-27	Alloy 182 / Creviced Alloy 600 SCC Susceptibility & Irradiation Effects
B-AS-28	Impact of BWR Nozzle Penetrations on Pressure-Temperature Limit Curves
B-AS-30	Material Surveillance Program Implementation for 80-Year Service Lives
B-AS-33	Equivalent Margins Analysis for BWR Nozzles ƒn
B-MT-01	Alternative Mitigation Technologies
B-I&E-01	Inspection of Core Plate Rim Hold Down Bolts
B-I&E-02	Inspection of Hidden Weld Locations (Thermal Sleeves & Piping)
B-RR-05	Alternate High-Strength Materials
B-RR-08	Availability of Laser Welding for Repairs to Highly Irradiated Components
B-RG-08	Reactor Pressure Vessel Material Surveillance Program Implementation for 80-Year Service Lives
B-RG-10	R.G. 1.161 and ASME Section XI Appendix K Stress Intensity Factor Equation Non-conservatisms

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PWR IMT -- High Priority Gaps

ID	Gap Description
P-AS-02	Environmental Effects on Fatigue Life: Pressure Boundary Components
P-AS-09	SCC of Stainless Steels Exposed to Primary Water
P-AS-11	PWSCC Crack Growth Rates for Alloys 600, 82, and 182
P-AS-12	PWSCC Factors of Improvement for Alloys 690, 52, and 152
P-AS-13a	Thermal & Irradiation Embrittlement Synergistic Effects on CASS
P-AS-13b	Thermal & Irradiation Embrittlement Synergistic Effects on SS Welds
P-AS-14a	IASCC Characterization: Generic Data Needs
P-AS-14b	IASCC Characterization: Baffle Bolting
P-AS-17	Flow-Induced Vibration and Wear of Reactor Internals
P-AS-19	PWSCC Management for Ni-Alloy Reactor Internals
P-AS-27	Alternative ASME Section XI Appendix G Methodology
P-AS-28	Neutron Embrittlement of Nozzle Forgings and Upper Shell Course
P-AS-38	Fluence Impact on Stainless Steel Mechanical Properties (Toughness, Tensile Strength)
P-AS-46	CASS Piping Component Thermal Aging Embrittlement & Long-Term Integrity Assess.
P-I&E-03	NDE Technology for J-Groove Weld Locations
P-I&E-12	NDE Technology for Examination of CASS
P-I&E-21	Reactor Internals Generic Acceptance Criteria
P-RG-06	NDE Qualification for Reactor Internals Inspection (VT Evaluation)
P-RG-09	Pipe Rupture Probability Re-Assessment (xLPR)

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PWR IMT -- Medium Priority Gaps

ID	Gap Description
P-AS-04	Neutron Embrittlement of Reactor Pressure Vessel Steels
P-AS-05	Fluence Spectra Effects on Low-Alloy Steel RPV Materials
P-AS-15	Void Swelling of Stainless Steels
P-AS-16	Fatigue Environmental Effects in Reactor Internals
P-AS-36	Outstanding Issues Associated with Thermal Fatigue of ASME Class 1 Piping
P-AS-37	80-Year Reactor Vessel Material Surveillance Program Management
P-AS-45	Equivalent Margin Analysis
P-DM-09	Environmental Effects on Fracture Resistance
P-I&E-08	NDE Technology for Detection and Characterization of Baffle & Former Assembly IASCC
P-I&E-11	NDE Accessibility Evaluation for Reactor Internals
P-I&E-25	NDE of Bottom Mounted Nozzle Penetrations
P-MT-02	PWSCC Mitigation via Surface Treatment Stress Improvement (Peening)
P-MT-09	PWSCC Mitigation via Chemical Surface Treatments
P-RG-05	ASME Section XI, Appendix VIII Flaw Sizing Criteria
P-RG-11	Replacement Component Fitness for Service Acceptance and Acceptance by UT
P-RR-03	Welding Processes for Repair of Irradiated Material
P-RR-04	Improved Weldability of Ni Base Alloy Weld Metal
P-RR-06	Repair Guidelines for Reactor Internals
P-RR-08	Alternate Materials for Reactor Internals Repair / Replacement (Esp. Bolting)
P-MT-01	PWSCC Mitigation via Water Chemistry Controls (Zn/H2)
P-RG-10	Management of License Renewal Issues

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