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# EPRI Primary Systems Corrosion Research Program

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EPRI

**NRC – Industry Meeting**
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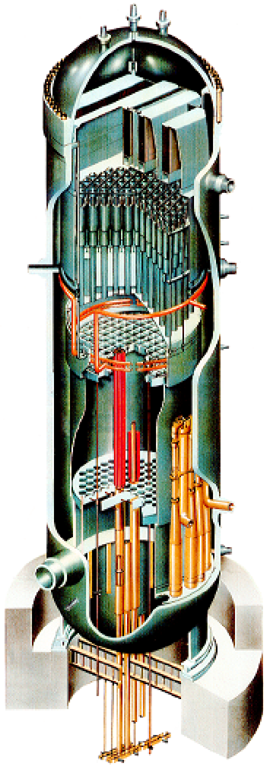
# Integrated Materials Aging Management for Primary System Components

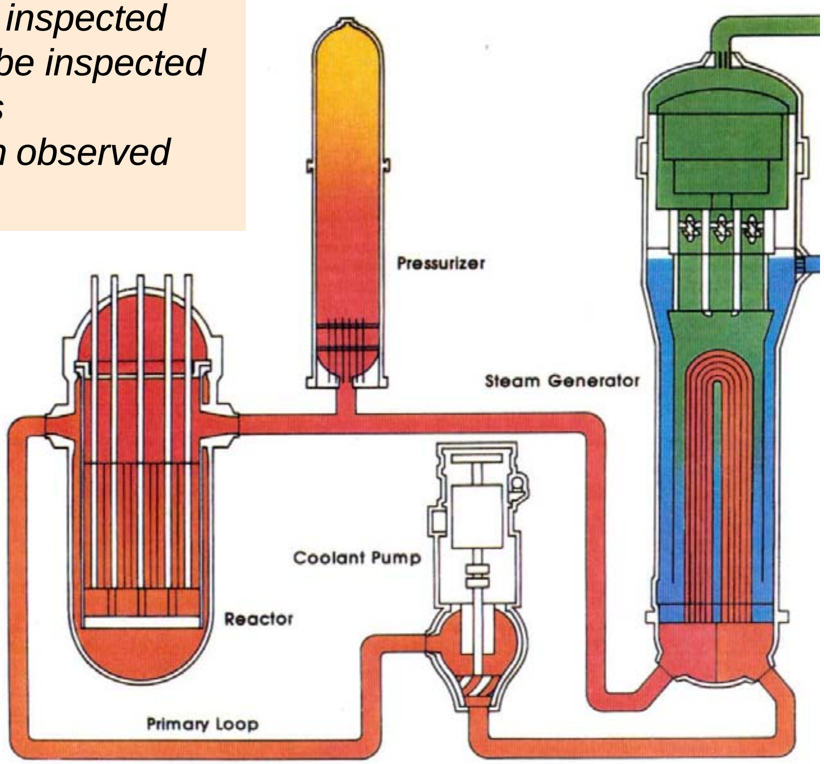


**Inspection**
- *how to inspect*
- *what equipment and techniques are available*
- *What are the associated uncertainty*

**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*



# PSCR Research with Industry Focus

**R&D gaps in materials degradation:**
- Cracking mechanisms
- Causes of embrittlement
- Effects of environments
- Understanding in radiation damages

**BWRVIP**

**MRP / SGMP**

**WRTC**

**LTO**

## PSCR Research:
- First of a kind approach / Exploratory
- Mechanistic studies / fundamental sciences
- Coordinated data generation / models
- Collaborative R&D

**Knowledge gaps in plant component reliability and integrity :**
- Effects of environment on fatigue life
- SCC of SS & Ni-alloys components in LWR
- Thermal & irradiation aging of CASS / SS welds
- Fluence effects on mechanical properties & IASCC
- Neutron embrittlement of RPV steels
- Void swelling and irradiation creep in reactor internals
- ODSCC of Alloy 600TT SG tubes

***Scientific Clarification & Technical Bases to:***
- *Develop engineering solutions*
- *Inform regulatory & code issues*





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# 2014 - PSCR Alignment with Industry Needs

- 2014 PSCR scope aligns with the needs across issue programs (including LTO, ANT), with focuses on fundamental mechanisms; examples include:
  - EAF: MRP and BWRVIP will evaluate how operating environments impact fatigue behavior; PSCR will focus on understanding **why** operating environments alter fatigue behavior.
  - Zorita project: MRP will focus on obtaining the mechanical properties and corrosion resistance of the materials under given fluence; PSCR will study the microstructures of these materials to enhance **fundamental understanding** and ability to interpolate / extrapolate / predict
  - SCC Initiation: PSCR will generate SCC initiation data on Alloy 600 / 600TT and 304SS to develop a **predictive capability** for assessing the vulnerability of Alloy 600 components, Alloy 600 TT steam generators tubes, and 304SS BWR vessel internals.
- Objective is to provide the technical basis to support issue program's aging management strategies:
  - Current Challenges: Shroud cracking; PRV RPV steel embrittlement mechanisms; PWR bottom head/PWSCC-Ni; IASCC-SS; Pb-ODSCC of SG tube; …
  - Potential Threats: Void swell-SS; BWR LAS SCC; …



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# Generic Materials Degradation Strategic Issues

*MDM Revision-3*

1. SCC initiation prediction, modeling, and mechanistic Understanding
   – *All austenitic primary system components*
2. Understanding fundamental IASCC processes and characterization of parameters influencing IASCC Susceptibility
   – *Near core reactor internals*
3. Understanding the true effect of coolant exposure on the fatigue resistance of plant components and evaluation of this effect with respect to conservatisms included in original design calculations
   – *Austenitic pressure boundary components with significant fatigue usage (e.g. PWR surge line components)*
4. Understanding the influence of environment (H, etc) on fracture properties for materials with higher yield strengths and varied microstructures (as well as understanding how these effects could manifest in material subject to significant neutron fluence
   – *X-750, CASS, RPV steels*

# PSCR 2014 Projects – TI

| Task | | Title | |
|---|---|---|---|
| A | | **SCC Crack Initiation and Propagation Studies and Prediction Models** | |
| | A1 | Application of synchroton x-rays to investigate SCC mechanisms in LWRs *(POLIM program)* | Tohoku |
| | A2 | Small-volume mechanical characterization of irradiated materials | UCB |
| | A3 | Mechanistic model for environmental fatigue crack propagation | MCS |
| B | | **Innovative Applications of High Resolution Microscopy to Study Environmentally Assisted Cracking** | |
| | B1 | Role of hydrogen in PWSCC crack initiation | AREVA |
| | B2 | Ex-situ APT/Nano-SIMS studies on Irradiated SS *(DOE co-fund)* | U Mich |
| | B3 | Relationship of grain boundary deformation and IASCC *(DOE co-fund)* | U Mich |
| | B4 | Advanced characterization studies of LWR materials | Oxford |
| | B5 | State of art review of oxide films and SCC initiation | P. Scott |

New tasks

# PSCR 2014 Projects – Base Scope

| Task | | Title | |
|---|---|---|---|
| **1** | | **Advanced Radiation Resistant Materials Program** | |
| | 1a | Development of Radiation Resistant Material *(DOE co-fund)*<br>*Phase-1: 2013-17*<br>*Phase-2: 2018-22* | Misc |
| **2** | | **Irradiated Materials Research** | |
| | 2a | Identification of key factors in IASCC of austenitic alloys in core internals *(DOE co-fund)* | U Mich |
| | 2b | CT size and orientation effects on IASCC-Zorita material | Studsvik |
| | 2c | IASCC CGR Model -- Data Compilation; Analysis; Expert Panel | MCS |
| | 2d | IASCC initiation model for stainless steels | SIMRAND |
| | 2e | Modeling of effects of microstructure on mechanical properties & fracture toughness | CRIEPI |
| | 2f | Modeling of effects of microstructure on localized deformation | TBD |

New tasks





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# PSCR 2014 Projects – Base Scope *(cont'd)*

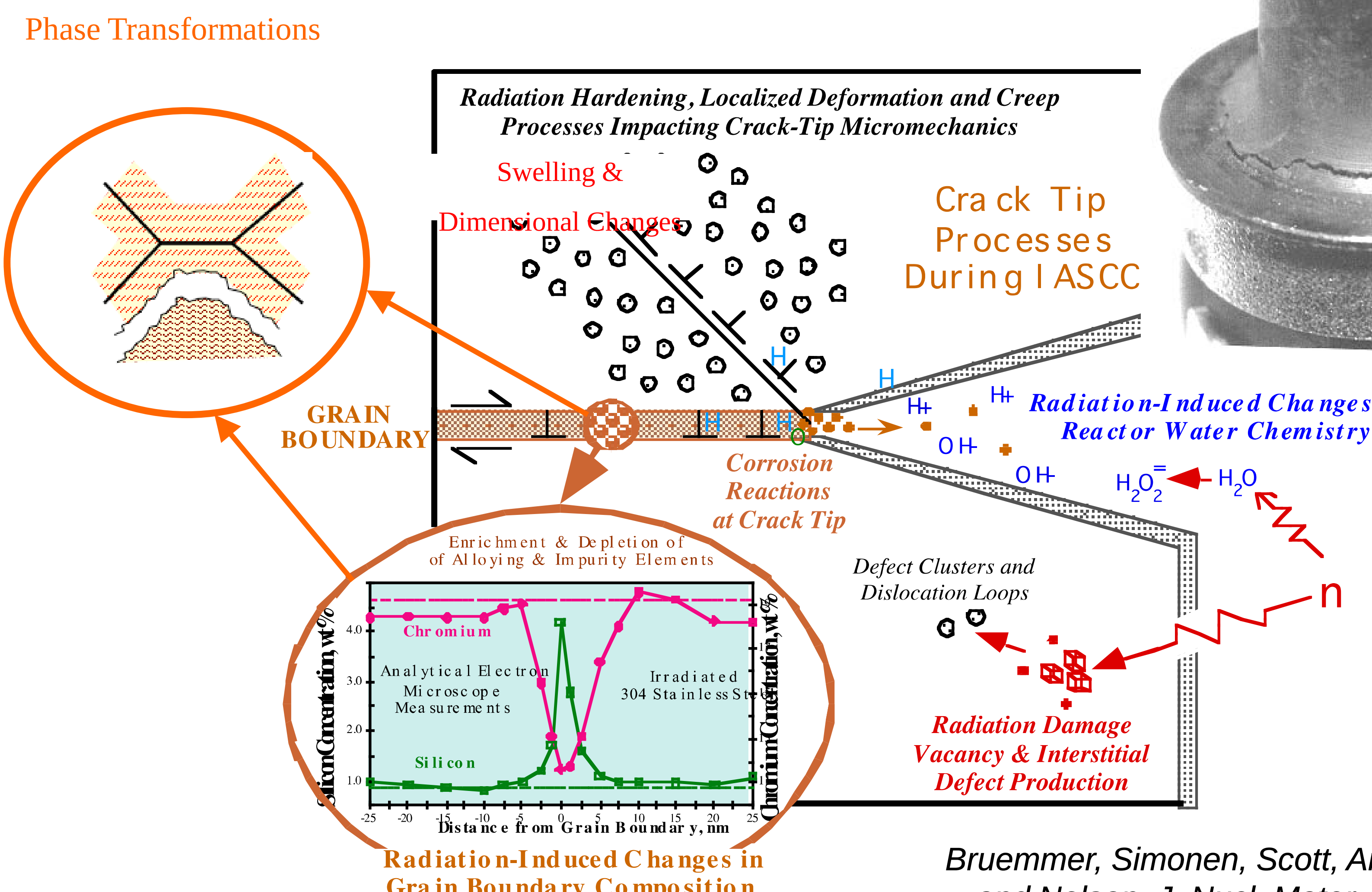
| Task | | Title | |
|---|---|---|---|
| **3** | | **Revision of MDM, Materials Handbook and Materials Information Portal** | |
| | 3a | Materials Degradation Matrix for VVER | Misc |
| | 3b | Revision of Materials Handbook | DEI |
| **5** | | **Mechanistic understanding and modeling of EAF enhancement and retardation in BWR and PWR environments** | |
| | 5a | Mechanistic understanding of loading effects on environmental fatigue crack growth | AMEC |
| **6** | | **Synergetic Effects of Thermal and Irradiation Aging** | |
| | 6a | In-situ TEM study of phase evolution under ion irradiation on thermally aged CASS/SS weld | ANL |
| | *6b* | *Investigate neutron irradiation induced embrittlement on thermally aged SS weld / CASS – (Did not receive approval on ATR NSUF proposal)* | *INL MIT Florida* |
| **7** | | **SCC Initiation Test Methodologies** | |
| **8** | | **Exploratory Study of Effect of Irradiation on EAF** | |

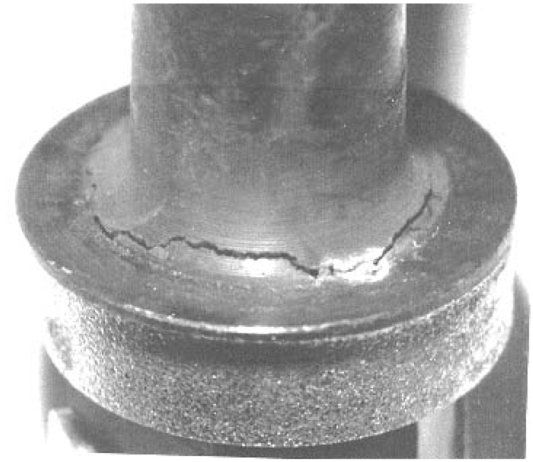
New tasks

# 2014 Projects on IASCC Mechanisms

- EPRI and DOE co-fund work on Bor-60 irradiated stainless steels with specific alloy designs
- Investigation on the cause-and-effect relationship of localized deformation and IASCC initiation.
  - Understand the effects of post irradiation anneal on localized deformation, and on IASCC susceptibility
- Mechanistic understanding of IASCC in support of development of radiation resistant alloys
- Model developments to link irradiated microstructures to IASCC, and mechanical properties / fracture toughness

# Many Irradiation Processes Influence Material Performance & Susceptibility to Cracking

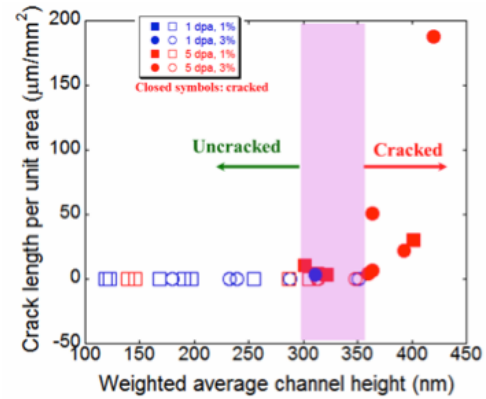


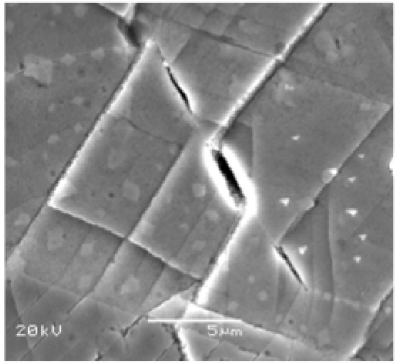
*Bruemmer, Simonen, Scott, Andresen, Was, and Nelson, J. Nucl. Mater., 274 (1999)*

# Localized Deformation Based IASCC Mechanism

Localized deformation correlates with IASCC




Cracking occurs at dislocation channel – GB intersections




Cracking is due to either:

- **Strain in grain boundary that ruptures the oxide film**
- **High localized stress that ruptures the oxide film**

- **Determine the origin of cracking – is it stress or strain based?**
- **Develop prediction of cracking location.**
- **Roles of cold- work, composition, GB Si, Ni or Ni+Cr , …**
- **Role of radiation-induced precipitates on cracking**
- **Effects of ECP**





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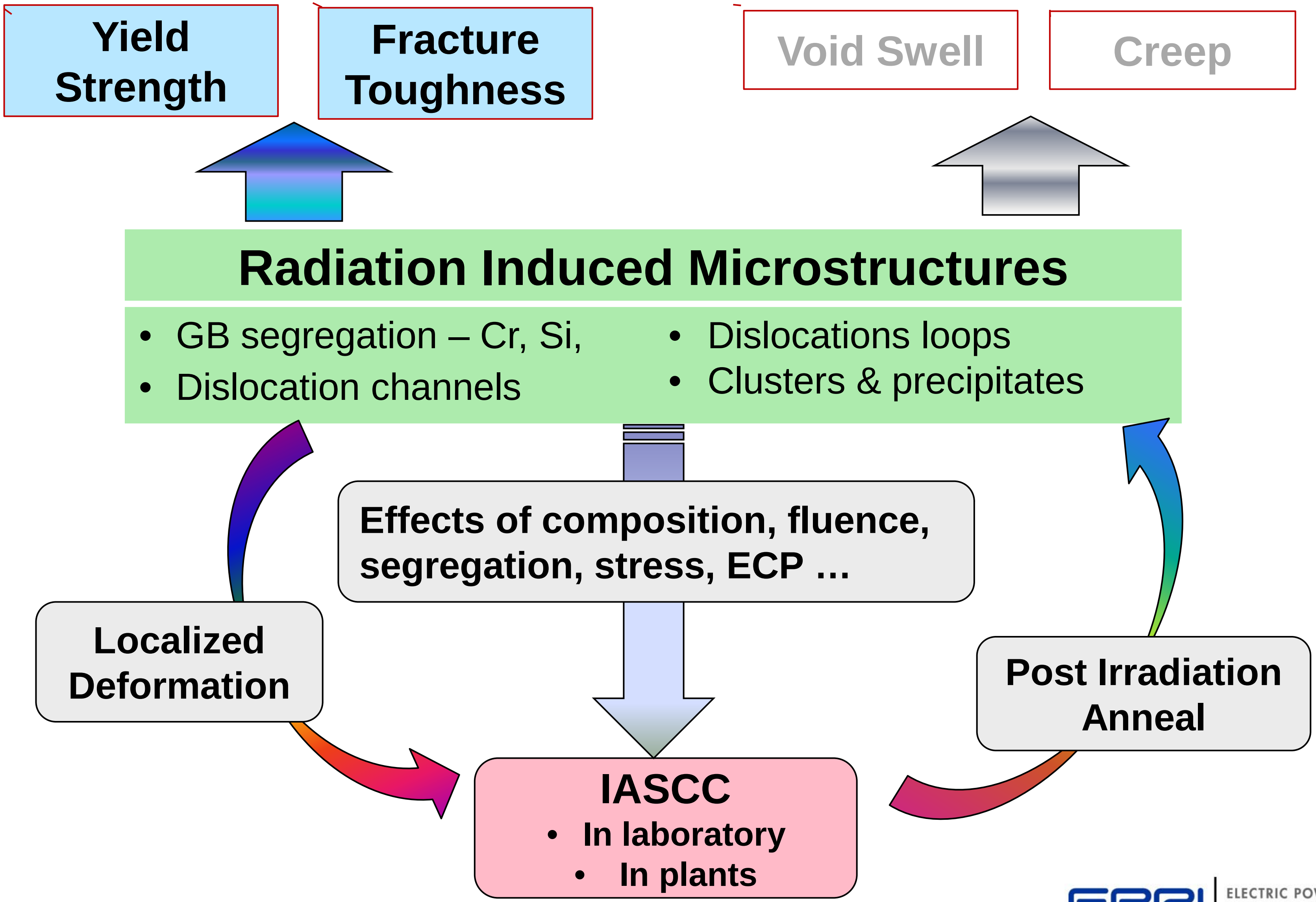
# Modeling Irradiated Material Properties & IASCC



# 2014 Projects on SCC Initiation

Focus on development of SCC initiation experiment methodology and initiation model

- Mechanistically-based understanding of factors influencing SCC initiation
- Near-term focus on developing semi-empirical SCC initiation correlation on Alloy 600/600TT, Alloy 82/182, and stainless steels
- High quality data of time-to-initiation, with statistical significance
- Broad range of water chemistry to cover PWR primary, PWR secondary, and BWR
- Understand GB oxidation and its link to SCC mechanisms
- Long-term goal is to obtain more mechanistically-based understanding on SCC initiation to guide effective mitigation and inspection, and develop more robust prediction model



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# 2014 Projects on EAF

1. Understand the factors and accompanying interactions that influence crack propagation of stainless steel due to EAF when exposed to cyclical stresses in high temperature water
   - Factors that influence the crack propagation or retardation
     - Microstructural and oxide film characterization of the crack tip region
   - Effects of loading (stress) type – hold time effects
   - Effects of chemical composition of material (sulfur content)

2. Understand effects of EAF on irradiated (reactor internal) materials
   - Assemble the readily-available fatigue crack propagation data on irradiated specimens
   - Analyze how the fatigue crack growth rates in irradiated stainless steels compare with non-irradiated crack growth rates, under similar loading and environments
   - Identify necessary additional research, if any, and document the available data and findings

# Proposed 2015-16 New Tasks (preliminary)

- Rapid Radiation (ion & high-flux neutron) to Study the Effects of High Fluence Radiation on Materials Properties and Performance
- Development of Improved LWR Void Swelling Model
- Assessment of Localized Deformation in Field-Irradiated Materials, and Investigation of Low-dpa SCC Cracking in BWR Internals
- Investigate Effects of Fluence on Grain Boundary Oxidation & Weakening of Highly Irradiated Stainless Steels in PWR Internals
- Microstructure Assessment of Intergranular Oxidation and Surface Oxide Film Associated to Intergranular SCC (both in BWR & PWR)
- Local Stress Measurements in Support of Mechanistic Understanding of Environmentally-Assisted Cracking

# Rapid Radiation to Study the Effects of High Fluence on Materials Properties and Performance

Objectives:

Cost effective way to address the high priority knowledge gaps on the lack of understanding the effects of high fluence radiation to properties and performance of stainless steels in reactor internals

- *Achieving fluence for extended operation (from 60 to 80 years)*
- *Taking into account of cost and schedule*

Approaches:

1. Utilize high flux neutron and ion beam radiations to achieve high fluence
   - *In-depth understanding of physics: microstructures, defects, precipitates*
   - *Radiation damage: Mechanical properties and fracture toughness*
   - *Effects on IASCC*
2. Develop model to bound the effects of fluence
3. Bench mark with LWR radiation data from harvested plant materials (Zorita, Hatch, DC Cook, Ginna, etc…)





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# Develop Improved LWR Void Swelling Equations

- Current void swelling equations adopted by PWRs:
  - Based on fast-reactor data at temperatures higher than LWRs
    - Extrapolated to cover the full range of PWR dpa rates
    - No data for temperatures below about 370°C
    - Different He / H generation in PWRs

- Verify the applicability of the current void swelling equations for LWR components at high fluence
  - Microstructure-based characterization to assess the contributions of void formation vs. radiation induced precipitation
    - Examine LWR irradiated materials (e.g.: flux thimble tubes, etc)
    - Void number density, size, and total volume
    - Compositional variations associated with void formation
    - H, He, and H/He ratio associated with void formation

# PSCR Contact Information

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