Overview of Primary Systems Corrosion Research (PSCR)

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Outlines

• 2014 R&D Results
• 2015 R&D
2014 Deliverables – Available through PSCR Cockpit

- 3002003103 IASCC Crack Growth prediction Model
- 3002003105 Identifying Mechanisms and Mitigation Strategies for Irradiation Assisted Stress Corrosion Cracking of Austenitic Steels in LWR Core components
- 3002003041 Role of hydrogen in PWSCC crack initiation of Ni-based alloys
- 3002003100 Summary Report on SCC Initiation Experiment of Alloy 690 in Supercritical Water
- 3002003047 Nano-Scale Characterization of PWSCC Initiation in Ni-based Alloys
- 3002003051 Study of Cause-and-Effect between localized deformation and IASCC initiation
- 3002003106 In-situ TEM study of combined effects of thermal and irradiation aging on CASS microstructure
- 3002003049 Annual POLIM Program Report on International Cooperative Research in Mechanistic Understanding of Stress Corrosion Cracking
- 3002003042 Role of Creep and Creep Crack Growth in SCC in Austenitic Materials

- 3002003104 Effects of Environments on Fracture Resistance of Alloy 182 -- Delayed to 2015
Key R&D Projects Completed in 2014

- Development of IASCC Crack Growth Models For BWR and PWR Internals
- (EPRI-DOE /LWRS co-fund) Identifying mechanisms and mitigation strategies for irradiation assisted stress corrosion cracking of austenitic steels in LWR core components
- Investigating the effect of irradiation on the microstructure of thermally aged cast austenitic stainless steel (CASS)
- Investigating the feasibility of using supercritical water testing for SCC initiation evaluation in Alloy 690
- Development of stress severity-based IASCC initiation model
- POLIM – an international cooperative research on SCC of Ni-alloys and stainless steels in LWR environments
Highlight -- Development of IASCC Crack Growth Models For BWR and PWR Internals

- The models account for effects of irradiated yield stress (dose), stress intensity K, ECP, temperature, type of loading (constant load vs. PPU)
  - Model for high ECP environment – BWR NWC
  - Model for low ECP environment – BWR HWC & PWR

- There was no significant difference in the CGRs between BOR 60 fast reactor and LWR irradiated materials after accounting for the above factors

- Analysis showed that a common model can be used for BWR-HWC and PWR environments with a temperature term to account for higher PWR temperatures

- After accounting for above parameters there is still a large heat-to-heat (and specimen-to-specimen) variability. This variability is reflected in heat coefficients in the models
Knowledge Transfer with the New IASCC Models

- EPRI report has been published: 3002003103 -- “Models of Irradiation-Assisted Stress Corrosion Cracking of Austenitic Stainless Steels in Light Water Reactor Environments”; and is available to PSCR, MRP and BWRVIP members

- The report will provide the technical basis for crack growth disposition curves for irradiated BWR and PWR stainless steel internals

- A paper based on the report will be presented at the July 2015 ASME PVP Conference in Boston

- The paper will provide the basis for the proposed disposition curves and will be used to develop an ASME code case
Outlines

• 2014 R&D Results

• 2015 R&D
# List of 2015 Project

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Continuing Focus on Irradiation Damage Mechanisms

Yield Strength
Fracture Toughness
Void Swell
Creep / Relaxation

Irradiation Induced Microstructures
- GB segregation – Cr, Si,
- Dislocation channels
- Dislocations loops
- Clusters & precipitates

Effects of composition, fluence, segregation, stress, ECP …

Localized Deformation
IASCC
- In laboratory
- In plants

Post Irradiation Anneal
Irradiated Materials Research is Aimed to Improve Mechanistic Understanding Based on Irradiated Microstructures

- TI-Breakthrough Project -- Rapid simulation of the effects of high fluence on irradiation embrittlement and void swelling
- TI Project, *co-fund with LWRS*: Studying the effects of high fluence neutron irradiation on localized deformation, and developing engineering solutions to counter IASCC
  - *Co-fund with LWRS*: Development of Radiation Resistant Material (ARRM)
  - MALL project, *with CRIEPI*: Modeling of irradiated mechanical properties & Fracture Toughness
- Preparation for code development of IASCC crack growth model
  - Study the effects of heat variability on effectiveness of HWC for IASCC mitigation in BWR
New Project: Rapid Simulation of Irradiation Damage in LWR Internals at High Fluence

- **Objective:** Develop and validate an approach based on heavy ion irradiation (Fe$^{2+}$ or Ni$^{2+}$) with He/H implantation and fast neutron irradiation for cost effective and rapid simulation of irradiation damage in PWR internals at high fluence.

  **Background:** PWR Internals are expected to experience high fluence exceeding 100 dpa at certain locations during first and second license renewal (60-80 years). There is a need for data and validated models to predict the degree of irradiation damage expected in austenitic stainless steel internals at high fluence.

- **Benefit:**
  - A validated approach could be used to evaluate the effect of high fluence more rapidly and more cost effectively than using extracted irradiated materials to be re-irradiation in LWRs.
  - The project will provide a technical basis for fitness assessment of PWR reactor internal component materials with increased fluence, to ensure the safe and reliable operation of nuclear power plants for extended operation life.
Overall Project Plan

Receive LWR plant materials → Select locations with LWR fluence at 0, 50, 75, 100 dpa

Benchmark ion irradiation → At equivalent fluence, LWR (neutron) vs. simulated (ion+neutron)

Rapid Simulation → Ion irradiation to achieve high fluence (≥ 160 dpa, ion+neutron)

Prediction models for high fluence (≥ 160 dpa) stainless steel:
- Irradiated microstructure and microchemistry
- Mechanical properties
- Void swelling behavior
Develop Simulation Model:
Benchmarking LWR irradiation against (ion+LWR) irradiation

Define simulation parameters:
- Temperature
- Dose rate
- He/H ratio

As-received LWR irradiated SS. (0-100 dpa)

Simulated Irradiation of SS (Ion + neutron irradiation) (up to 100 dpa)

Characterization-1
- Microstructure TEM, APT
- Mechanical Properties Tensile and hardness (Micro and nano)

Characterization-2
- Microstructure TEM, APT
- Mechanical Properties Tensile and hardness (Micro and nano)

Material-Condition 1

Ion Irradiation

EXPERIMENT 1

Neutron Irr.
- 0 dpa
- 50 dpa
- 75 dpa

Neutron + Ion Irr.
- 50,75 & 100 dpa
- 75 & 100 dpa
- 100 dpa

EXPERIMENT 2

Characterization-3
- Microstructure TEM, APT
- Mechanical Properties Tensile and hardness (Micro and nano)

Material-Condition 3

Simulated Irradiation of SS (Ion + neutron irradiation) (≥ 160 dpa)

Material-Condition 2

Final Prediction Models
For high fluence (≥160dpa) SS:
- Irradiated microstructure
- Mechanical properties
- Void swelling

Final Ion Irradiation
Rapid Simulation of High Fluence by Ion Radiation to FTT**

** FTT – flux thimble tube

FTT with LWR neutron irradiation

FTT with Ion + Neutron irradiation

Final Ion irradiation to achieve hi - dpa

≥ 160 dpa

0 dpa

50 dpa

75 dpa

100 dpa

Ion irradiation

Dose (dpa)

Distance from tip of bullet nose (mm)
Schedule and Milestones

- Procurement and characterization of LWR irradiated material with APT/TEM
- Correlation of microstructure vs tensile, microhardness and nano-hardness properties
- Ion beam irradiation & characterization of zero dpa and pre-irradiated LWR material
- Compare microstructures and nano-hardness from neutron & ion beam irradiations to validate approach and develop improved damage models
- Ion irradiations to simulate damage at high fluence of ≥ 160 dpa and to model properties

New project, Starts in 2015
SCC Mechanistic Studies: Grain Boundary Oxidation and Cohesive Strength of Grainboundary in LWR Environments

Work closely with EDF-MAI in developing mechanistically based SCC initiation models. Initial efforts focused on nickel alloys.

- **Initiation Data**
  - Field Data
  - Previous lab data
  - On-going EPRI studies
    - PSCR initiation study on microstructural effects
    - MRP-NRC initiation data

- **GB Oxidation Characterization**
  - MAI + EPRI effort in GB oxidation characterization
    - GB oxidation (@PNNL)
    - GB strength
    - GB residual stress
  - LWRS-PNNL on IGA (intergranular attack)

- **Initiation Models**
  - To improve EDF SCC initiation models based on microstructures, oxidation, deformation and fracture behaviors

\[ t_i = \frac{1}{i_m \times i_\sigma \times i_T} \]
2015 PSCR Deliverables -- Committed

| 3002005475 | Mechanistic Understanding of Effects of Post Irradiation Annealing on IASCC |
| 3002005476 | Crack-tip Strain Rate Model for Environmental Assisted Fatigue |
| 3002005474 | Irradiation Assisted Stress Corrosion Cracking (IASCC) Initiation Model for Stainless Steels |
| 3002005478 | Summary Report on Recent Oxidation Studies – Literature Review |
| 3002005623 | Guidelines for Material Procurement for Use in LWR Environments |
| 3002005470 | Materials Handbook for Nuclear Plant Pressure Boundary Applications |
| 3002005473 | Integrated Materials Information DVD |
PSCR R&D Through Broader Collaboration

- Increase collaborations with DOE-LWRS
  - Current co-funding: IASCC mechanisms, ARRM
  - In discussion: high fluence effects/void swelling, SCC mechanisms

- Better coordination with MAI
  - In discussion: Microstructural investigations on GB for SCC & IASCC
  - Approved: APT round robin (2015-16)

- Collaboration with CRIEPI in MALL program
  - Modeling of mechanical properties for irradiated stainless steels

- Increase participation in DOE NSUF program
  - To utilize ATR and partner user facilities
  - To engage with US universities through NSUF projects
New Approach in Strategic Planning for PSCR R&D

**Objective**: Effectively integrate PSCR R&D activities into resolution of key materials degradation issues identified in MDM and IMTs

- Expected result will be more focused prioritization, coordination and support across materials programs to optimally utilize the resources and target research at the most appropriate gaps
  - Use IMTs as initial starting point
  - Consider key needs and existing tools
    - Mechanistic understanding -- degradation mechanisms and correlations/models to support model development and mitigation solutions
    - Engineering solutions – develop data, test methods and fundamental models to support IP efforts to close gaps and create engineering solutions in areas such as assessment methodologies, guidelines, codes/regulations, etc.
New Approach

1. Down Selection -- Review entire set of IMTs gaps, identify and down-select the gaps to which fundamental research can help to resolve
   - DM and MT gaps usually fall in this category
   - RG and I&E gaps usually do not fall in this category
   - AS and RR gaps are mixed

2. Gap Analysis -- For each selected IMTs gap, understand the issue and identify the near-term and long-term strategies to resolve the issue.
   - Describe the key elements of the IMT gap selected
   - Understand the projects associated to the IMT gap
   - Evaluate the adequacy for issue resolution
     - Identify remaining or additional fundamental R&D items needed for issue resolution

3. Compile all fundamental R&D items, and prioritize
   - Cross-check list with the MDM (including LWR, PHWR/CANDU, VVER …)
   - Consider needs to support subsequent license renewal (SLR) or long-term operation

4. Develop PSCR portfolio
   - Consider projects with substantial impact
   - Coordinate with issue programs
   - Collaborate with DOE & international R&D groups
PSCR 2015 Annual Technical Meeting

- Will be held on October 7 - 8, 2015, at EPRI office in Charlotte, NC
- Provides an opportunity for in-depth technical presentations & discussions, and for interaction between members and technical experts

- First annual technical meeting was held on November 3 - 4, 2014, Charlotte, NC
  - New meeting format to add a meeting with more technical focuses
  - Well attended with more than 40 attendees:
    - Good representation of US and international members
    - Strong participation of US and international researchers
    - Participation by NSSS vendors
    - DOE-LWRS and ATR NSUF staffs
    - EPRI technical staffs
Together…Shaping the Future of Electricity