# Overview of Primary Systems Corrosion Research (PSCR)

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**NRC – Industry Meeting**

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# Outlines

- **2014 R&D Results**
- 2015 R&D

# 2014 Deliverables – Available through PSCR Cockpit

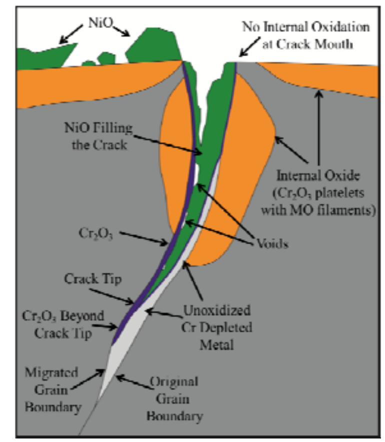
- ✓ 3002003103 **IASCC Crack Growth prediction Model**
- ✓ 3002003105 **Identifying Mechanisms and Mitigation Strategies for Irradiation Assisted Stress Corrosion Cracking of Austenitic Steels in LWR Core components**
- ✓ 3002003041 **Role of hydrogen in PWSCC crack initiation of Ni-based alloys**
- ✓ 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**

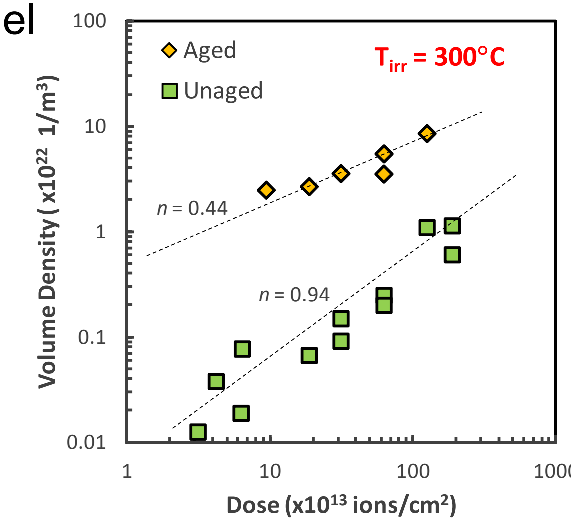
- o *3002003104* ***Effects of Environments on Fracture Resistance of Alloy 182 -- Delayed to 2015***

# 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

Crack Morphology of Alloy 690 strained in SCW environment




Defect Evolution in Ferrite phase of CF8 CASS after ion irradiation

# *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**

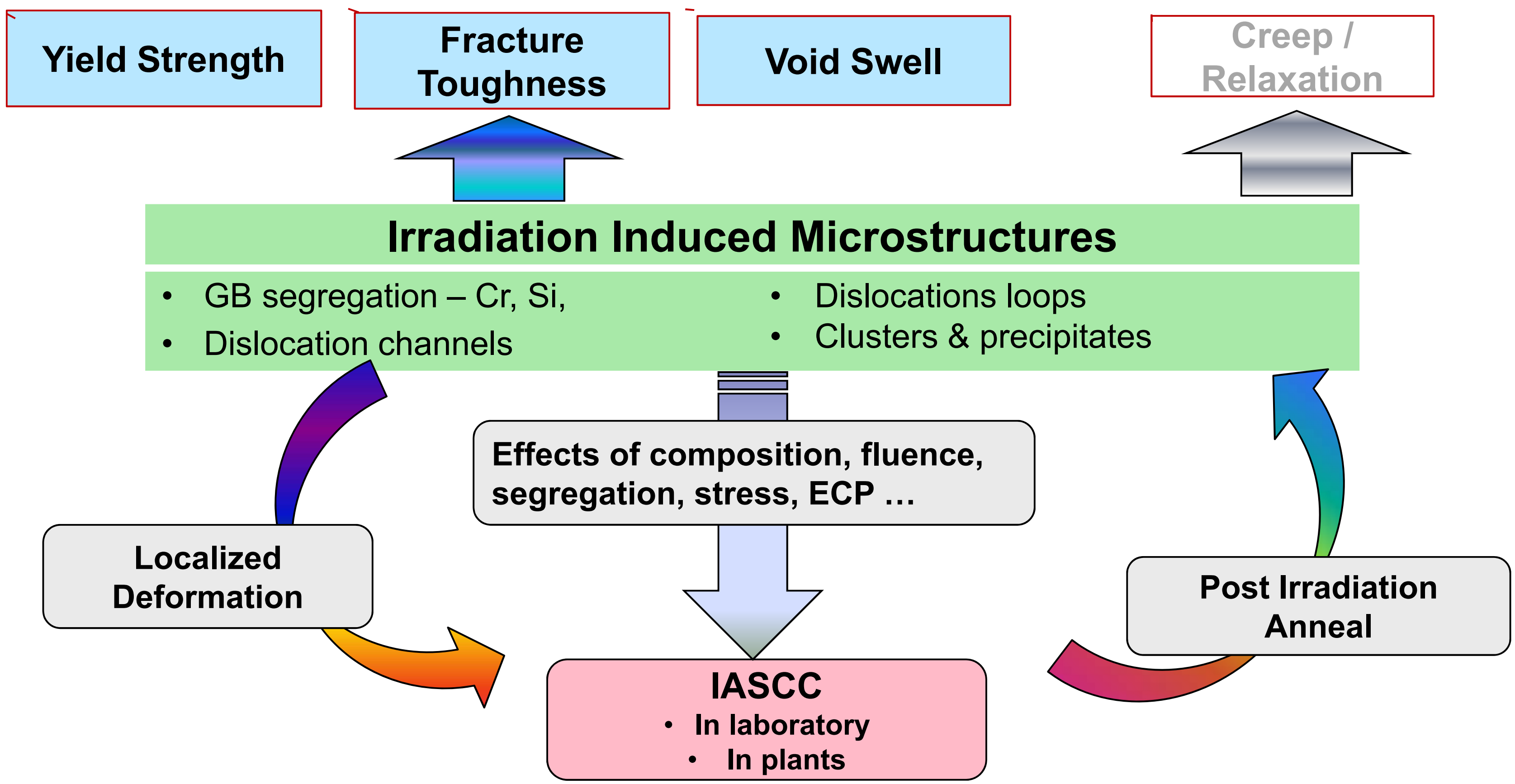
# Outlines

- 2014 R&D Results
- **2015 R&D**

# List of 2015 Project

| | | |
|---|---|---|
| Irradiated materials | Development of Radiation Resistant Material (ARRM) | Base |
| | CT size and orientation effects on IASCC (Zorita) | Base |
| | IASCC CGR Models Codification | Base |
| | Modeling of irradiated mechanical properties & Fracture Toughness | Base |
| | Small-volume mechanical property evaluation for irradiated materials | TI |
| | Effects of high fluence neutron irradiation on localized deformation and IASCC | TI |
| | Develop engineering solutions to counter IASCC | TI |
| | Rapid Simulation of High Fluence -- Ion radiation of LWR irradiated FTT | TI |
| | Round Robin – APT Data Acquisition and Analysis for Irradiated SS | MAI |
| SCC | Determine distinct SCC dependence (e.g. effects of microstructures) | Base |
| | Investigate GB oxidation of Alloy 600/600TT in PWR *(in discussion with PNNL)* | Base |
| EAF | Mechanistic understanding of loading effects on EAF CGR | Base |
| | Investigation the effects of irradiation on EAF CGR | Base |
| | Mechanistic model for environmental fatigue CGR | Base |
| MDM | Development of MDM-VVER & CANDU - IMT | Base |
| | Revision of Materials Handbook | Base |
| | Materials Information Portal (MIP) update | Base |

# Continuing Focus on Irradiation Damage Mechanisms



# 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

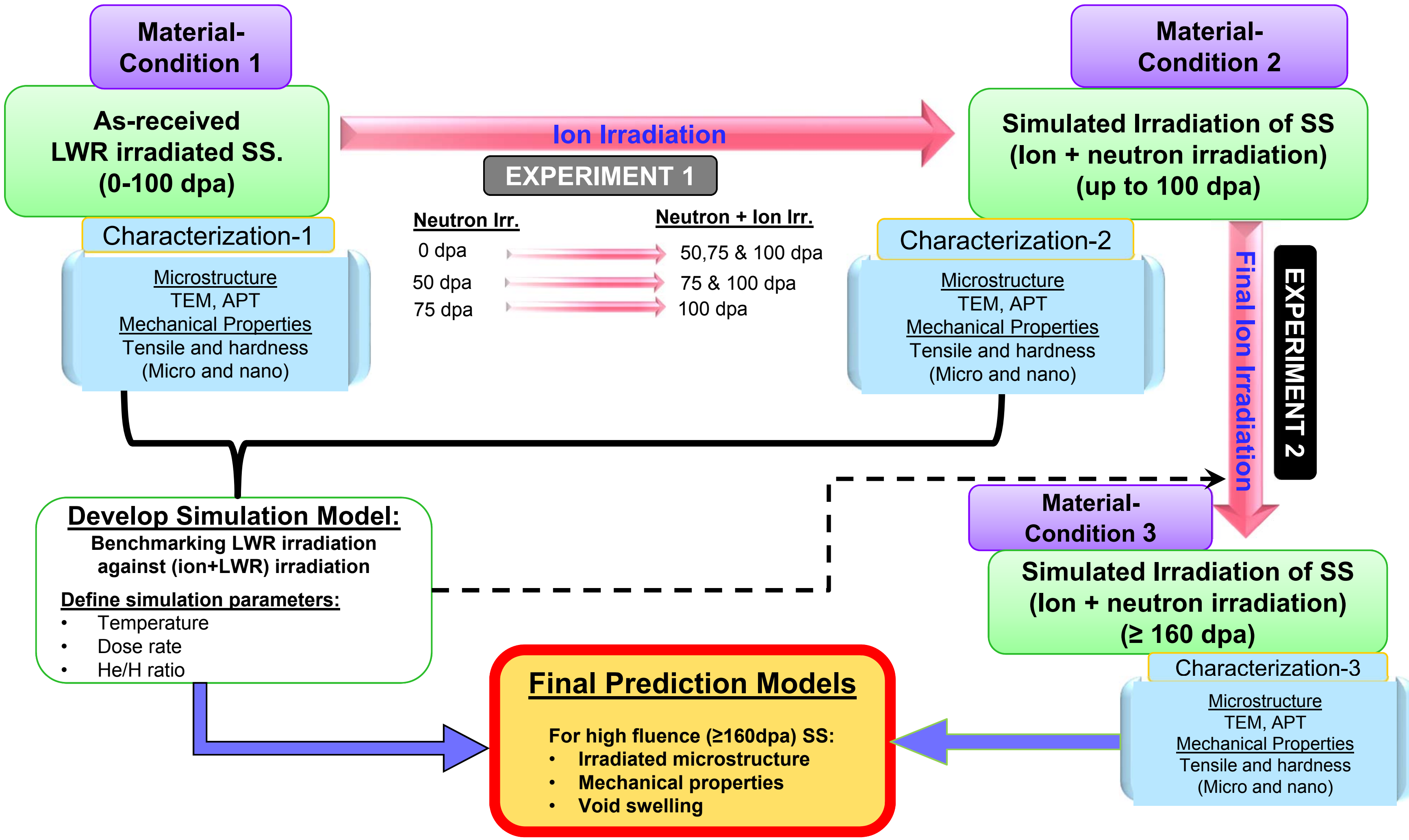
Receive LWR plant materials → Select locations with LWR fluence at 0, 50, 75, 100 dpa

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:**

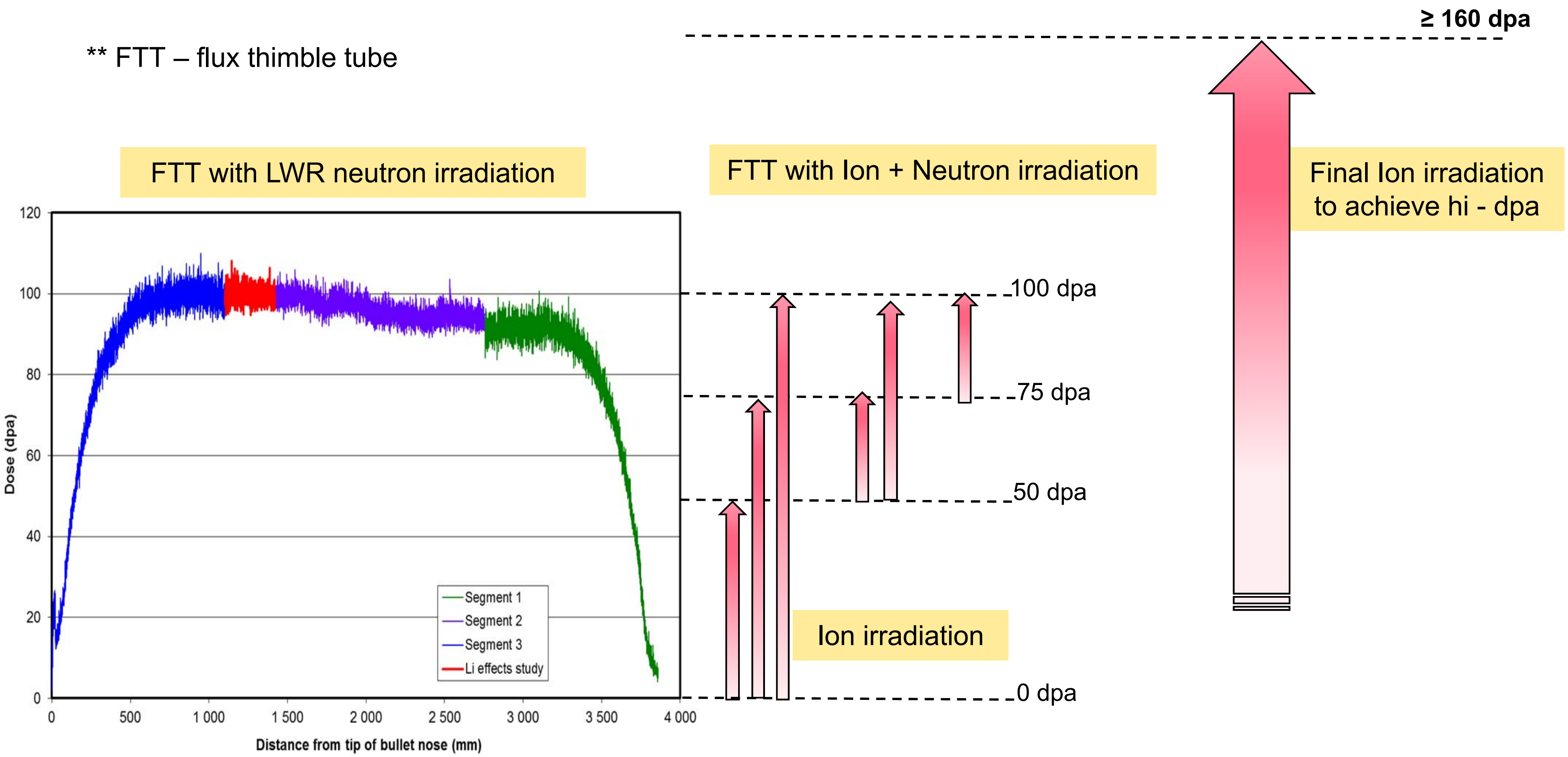
- **Irradiated microstructure and microchemistry**
- **Mechanical properties**
- **Void swelling behavior**



Material-Condition 1
As-received LWR irradiated SS. (0-100 dpa)
Characterization-1
Microstructure
TEM, APT
Mechanical Properties
Tensile and hardness
(Micro and nano)
Ion Irradiation
EXPERIMENT 1
Neutron Irr.
Neutron + Ion Irr.
0 dpa
50,75 & 100 dpa
50 dpa
75 & 100 dpa
75 dpa
100 dpa
Material-Condition 2
Simulated Irradiation of SS (Ion + neutron irradiation) (up to 100 dpa)
Characterization-2
Microstructure
TEM, APT
Mechanical Properties
Tensile and hardness
(Micro and nano)
Final Ion Irradiation
EXPERIMENT 2
Develop Simulation Model:
Benchmarking LWR irradiation against (ion+LWR) irradiation
Define simulation parameters:
• Temperature
• Dose rate
• He/H ratio
Material-Condition 3
Simulated Irradiation of SS (Ion + neutron irradiation) (≥ 160 dpa)
Characterization-3
Microstructure
TEM, APT
Mechanical Properties
Tensile and hardness
(Micro and nano)
Final Prediction Models
For high fluence (≥160dpa) SS:
• Irradiated microstructure
• Mechanical properties
• Void swelling

# Rapid Simulation of High Fluence by Ion Radiation to FTT**

** FTT – flux thimble tube





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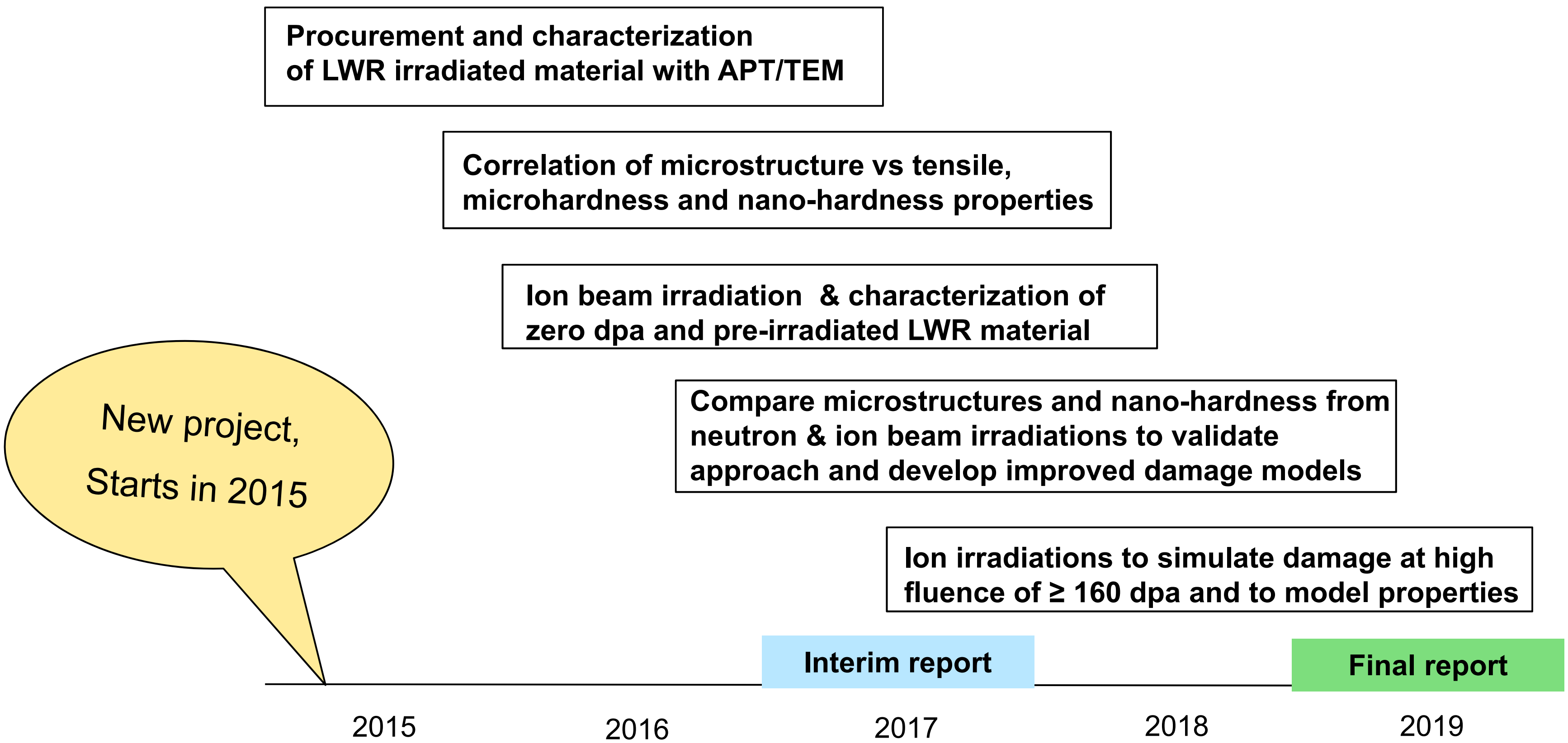
# Schedule and Milestones



# 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 microstructral 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: Microsturctral 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

***Collaboration, Coordination, & Integration***

# 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 venders*
    - *DOE-LWRS and ATR NSUF staffs*
    - *EPRI technical staffs*

# Together…Shaping the Future of Electricity