Overview of NRC-EPRI PWSCC Initiation Testing

- Status Update

Materials Reliability Program

Industry-NRC Materials R&D Meeting

June 2-4, 2015

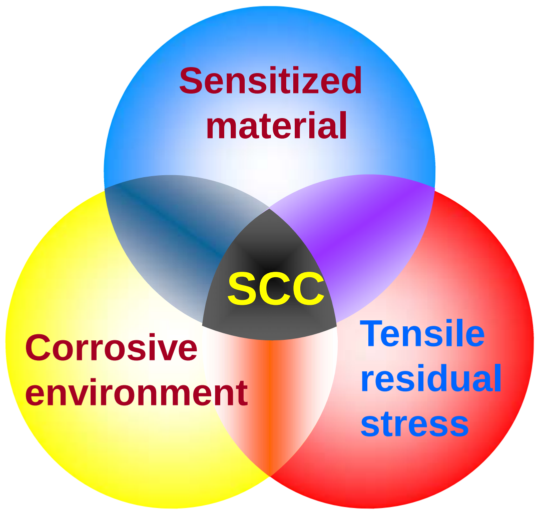
Rockville, MD

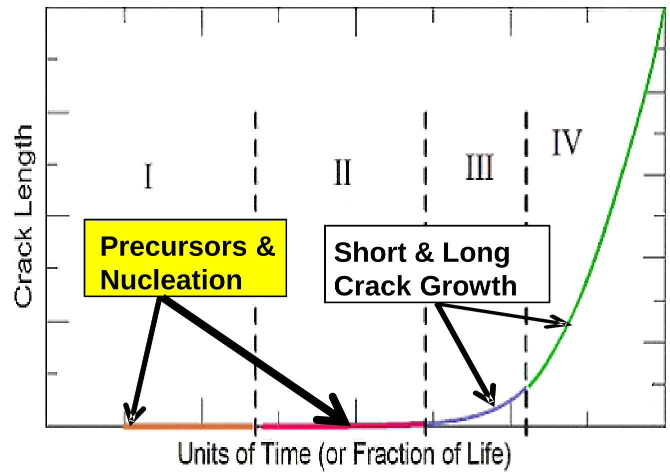
Presentation Outline

- Background on PWSCC Initiation
- Goals and Needs from PWSCC Initiation Research
- Summary

Primary Water Stress Corrosion Cracking (PWSCC)

- PWSCC is a corrosion mechanism that has been observed in Pressurized Water Reactor (PWR) plants and is enabled by materials, environment, and stress
- PWSCC in PWRs occurs in locations with Alloy 600 and 82/182 weld materials + tensile stresses + primary coolant water
- Process is defined by ***crack initiation*** followed by crack growth
- Rate of process is driven by crack promoters, tensile stresses in and near welds, material properties, and temperature
- Significant uncertainties in
  - As-fabricated bulk and surface conditions
  - Stress levels
  - Variation of material properties within a material heat
  - Extrapolating correlations for many decades of operation

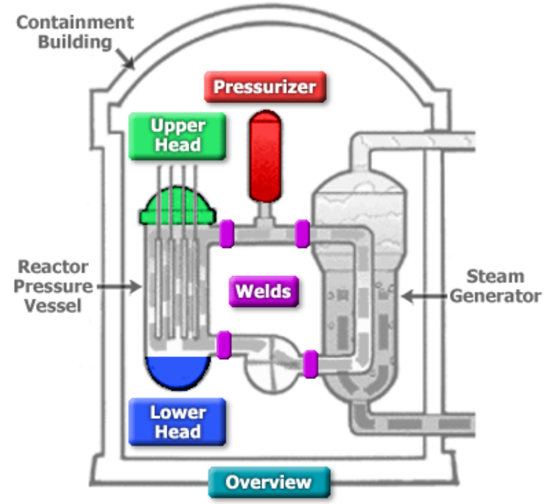


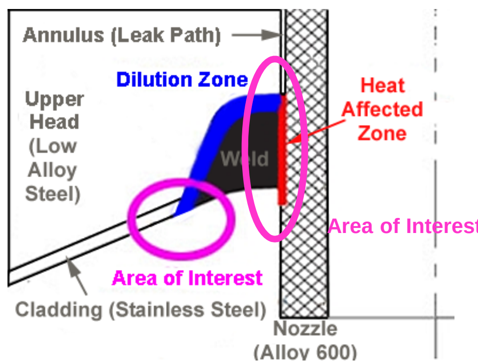


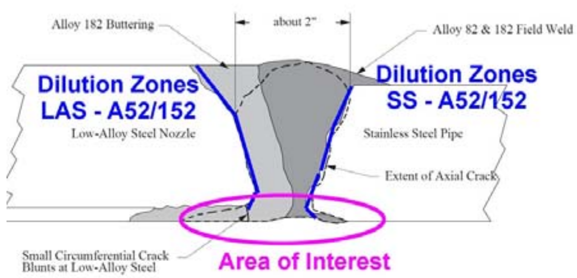
US NRC Reactor Regulations (NRR)

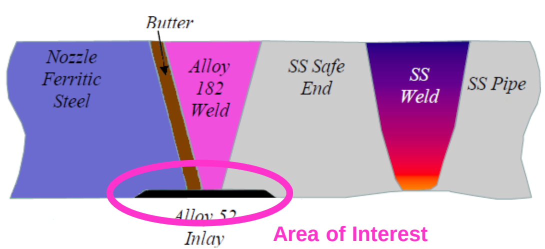
Inspection Requirements

Area	ASME	Regulation
Upper Head	ASME CC N-729-1	10 CFR 50.55a(g)(6)(ii)(D)
Pressurizer	ASME CC N-722-1	10 CFR 50.55a(g)(6)(ii)(E)
Lower Head	ASME CC N-722-1	10 CFR 50.55a(g)(6)(ii)(E)
Piping DM Welds	ASME CC N-770-1	10 CFR 50.55a(g)(6)(ii)(F)





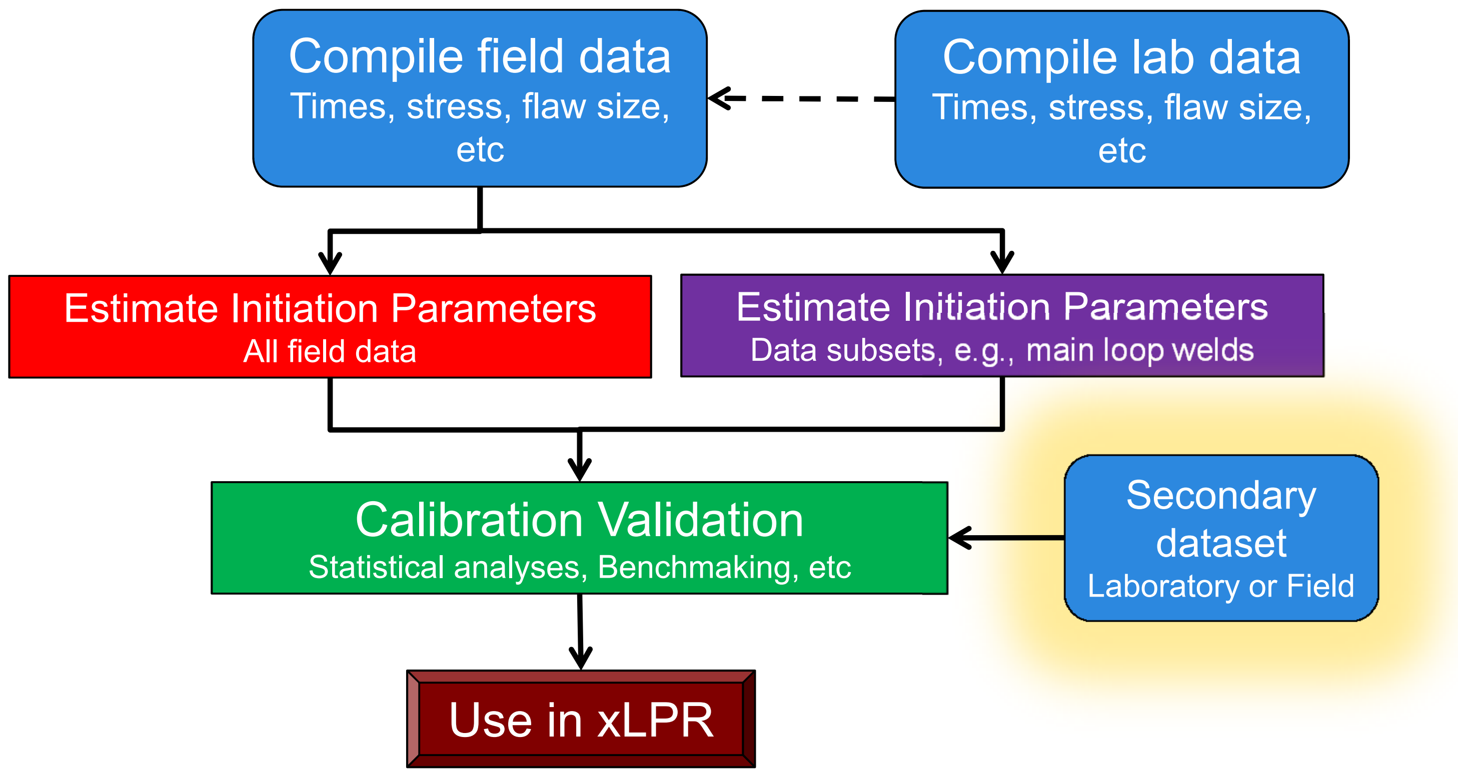




US NRC NRR
Testing Goals

- **Alloy 600/690 and 182/152 Weld Materials**
  - Vendor supplier materials
  - Sufficient number of heats of materials
  - Sufficient number and variety of welds
  - Consider binning results due to HAZ and Dilution Effects
- Alloy 690
  - *Heat Affected Zone (TBD)*
- Alloy 152/52
  - *Dilution layer testing (TBD)*
    - *Stainless steel (safe-end, cladding)*
    - *Low alloy steel (buttering, temper bead welding and narrow groove effects)*
  - *Consider effects of hot cracking and ductility dip cracking (TBD)*
  - *Testing on 52M, 52MSS, 152i/52i, and new combinations*

xLPR PWSCC Initiation Model Calibration



PWSCC Initiation Testing

US NRC RES Data Needs

- Laboratory data to support both the calibration and validation of the PWSCC initiation models
  - Distribution of time to initiation as a function of
    - Stress, temperature, materials
- Materials susceptible to PWSCC in LBB systems – Alloy 600, 690 and welds
- Develop insights to improving PWSCC initiation models

Programmatic Needs of Industry

- Inspection intervals for some components with Alloys 690/52/152 are currently limited by ASME Code and NRC requirements developed with conservative treatment of resistance to PWSCC initiation
- The absence of detected PWSCC initiation in these alloys in plants to date, and the great difficulty in initiating PWSCC in these materials in laboratory tests, indicates that longer inspection intervals may be technically justifiable, e.g., on a risk-informed basis

Component	Inspection Interval
Alloy 690 reactor vessel head nozzles	10 years per Code Case N-729-1 for volumetric exam
Alloy 82/182 dissimilar metal piping welds mitigated by Alloy 52/152 inlay/onlay	10 CFR 50.55a(g)(6)(ii)(F)(5) requires all such welds to be volumetric + surface inspected each interval, ~ each 10 years
Alloy 52/152 dissimilar metal piping welds, e.g. at steam generator nozzles	Section XI requires these welds to be inspected volumetric (and in some cases surface) each interval, ~ each 10 years – except plants may reduce frequency per RI-ISI
Alloy 690 base material with circ. weld and HAZ (new plants)	Same as above
Alloy 690 small-bore heater sleeves and instrumentation nozzles with Alloy 52/152 J-groove welds	System leak check each RFO

Overview of Data Needs

- A key challenge to implementation of models reflecting the detailed condition of PWR components is that component-specific data are often not available for making life predictions:
  - Detailed surface condition including local surface cold work and surface damage (e.g., effects of grinding, abusive machining, weld repairs) (magnitude and depth of surface cold worked layer)
  - Normal variability in carbide microstructure
  - Cold work level from material processing
  - Uncertainty in mechanical properties after installation steps
  - Presence, type, and extent of manufacturing defects
  - In some cases large uncertainty in near-surface residual stress levels (e.g., dependent on presence of weld repairs on ID surface)

Overview of Data Needs (cont'd)

- Thus, empirical models based on plant statistical data for most relevant categories of materials and fabrication are often applied in practice
- In the empirical approach, laboratory data are applied:
  – To develop adjustments for the effect of:
    - Temperature
    - Stress or stress ratio (if known)
    - Microstructure (if known)
  – In validation studies
- Similarly, plant data can be applied to validate models fit to laboratory data
- Specifically, laboratory data are needed:
  – To support validation/calibration efforts for the xLPR Program
  – To support factor of improvement (FOI) modeling to determine appropriate inspection requirements for Alloy 690/52/152 components (mitigation, repair, replacement, and new)

Data Needs for xLPR (Alloys 82/182)

- Laboratory initiation data for Alloys 82/182 may be used:
  - In validation activities for the xLPR model fit to plant data
  - To validate or improve current lab-based models already included in xLPR
  - To support or develop other initiation models for future inclusion in xLPR
- The xLPR Initiation Subgroup has started a validation/calibration effort to apply published laboratory data and the latest plant experience
  - The effort has provided preliminary recommendations for testing priorities
- Several key laboratory studies for Alloys 82/182 performed over the period 1991-2011 were previously identified:
  - Large amounts of initiation data for Alloy 82 have been developed by DOE (Bettis/KAPL) research
  - Large amounts of initiation data for Alloy 182 have been developed by French research
  - There are significant amounts of additional initiation data for Alloys 82 and 182, e.g., regarding relative times to SCC for 82 vs. 182

Application of Initiation Test Results to Plant Predictions

xLPR Initiation Modeling Framework

Parameters Directly Applied to Statistical Models

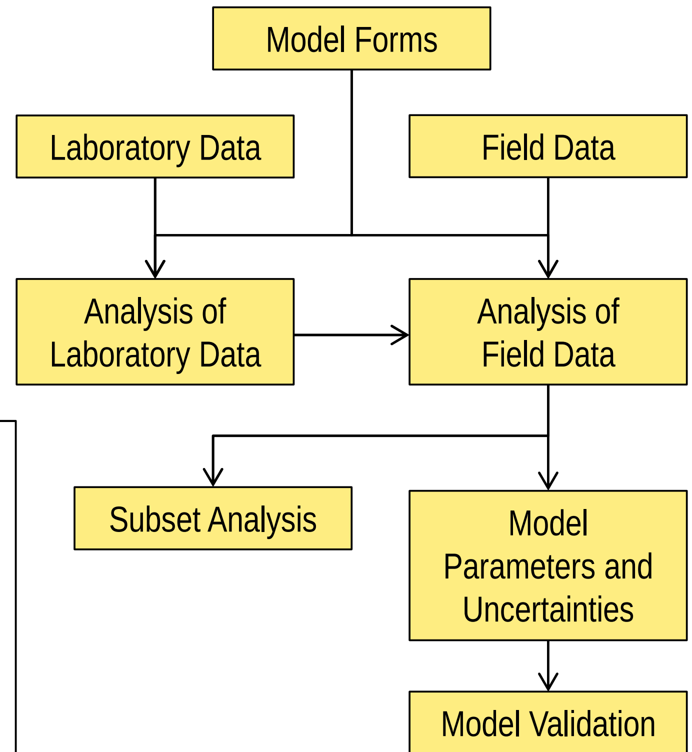
t_{INI}, δ_{INI}, σ, T, YS, UTS, E

$$t_{INI} = \Lambda \cdot f\,(T, \sigma, \ldots;, Q, n, \ldots)$$

t_{INI} – initiation time
δ_{INI} – initiation depth
σ – surface stress
T – temperature
YS, UTS, E – yield strength, ultimate tensile strength, elastic modulus (some models)

Additional Information to Assess Qualitative Trends or to be Explicitly Modeled in Future Evaluations

Surface roughness, surface cold work (magnitude and depth), material microstructure, hardness, EBSD results, surface defects, weld interface zones



Laboratory data

- Well quantified time and size of first initiation
- Often used to fit effect model parameters, e.g. activation energy
- Challenging to apply initiation time for normalized operating conditions based on lab data because of general lack of detailed knowledge of surface condition and other factors for modeled plant components

Field Data

- Imprecise knowledge of surface condition and material properties, but reflects actual plant conditions
- Variable size of first detection, probability of non-detection, false calls
- Are normalized to reflect equivalent condition (relative to modeled effects)
- Used in regression of initiation time for normalized operating conditions: Λ

Data Needs to Support Alloy 690/52/152 Factors of Improvement (FOI)

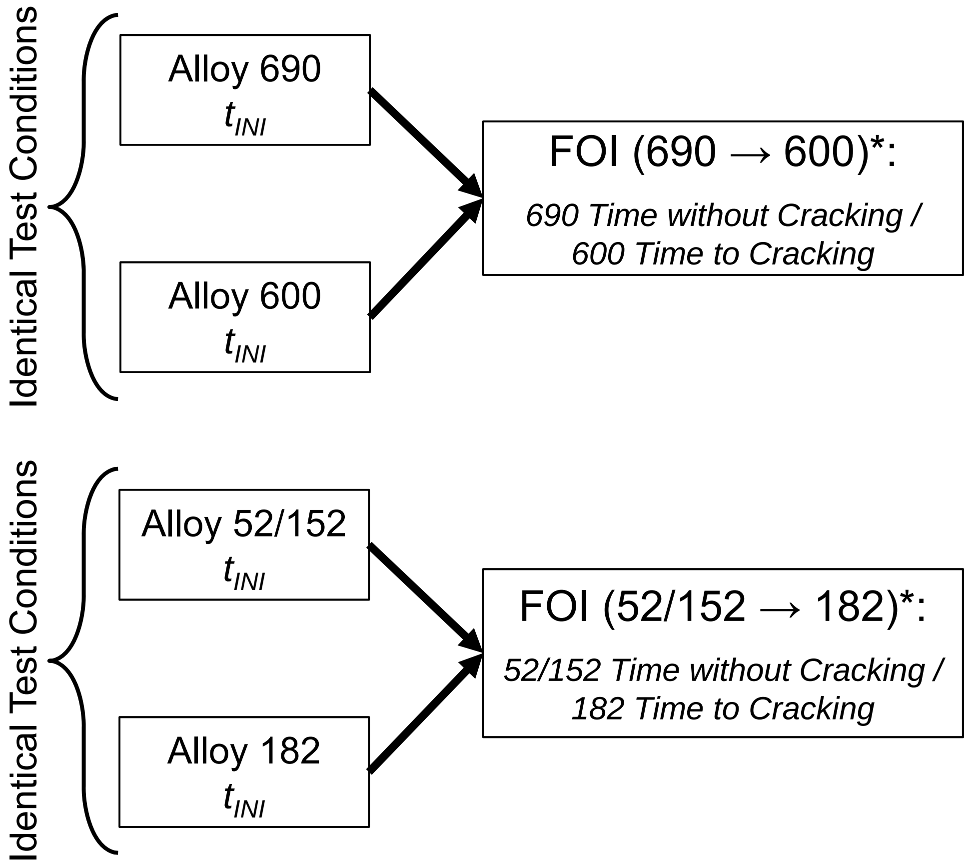
- The lack of PWSCC detected in the field and in essentially all lab tests without fatigue cracks or high applied strain is encouraging
- Detailed understanding of all factors affecting the potential for initiation is not necessary in order to take appropriate credit for the improved initiation performance of Alloys 690/52/152 in comparison to Alloys 600/182
- FOI approach facilitates rational inspection requirements that better reflect true PWSCC risk
  - More realistic bounds on the risk for Alloys 690/52/152
- Previous initiation testing demonstrated a minimum FOI of about 26 (Alloy 690 vs. mill-annealed Alloy 600) (MRP-111, EPRI ID #1009801)
- Data are needed to investigate larger FOIs and provide confidence for all material conditions of practical concern
  - Demonstration of FOI of ~60 is desirable to show that PWSCC initiation of a flaw of engineering scale (e.g., 1 to 3 mm depth) is unlikely over 60 years of operation

Data Needs to Support Alloy 690/52/152 Factors of Improvement (FOI) (cont'd)

- Material conditions relevant to plant applications:
  - Cold worked Alloy 690 base metal material
  - HAZ of Alloy 690 base metal and other conditions at weld fusion lines
  - Areas with high residual plastic strains and stresses, especially in and adjacent to welds and repair welds
  - Surface layers abused by grinding or abusive machining (magnitude and depth of surface cold worked layer)
  - Dilution zones of Alloy 52/152 weld metal at interfaces with lower Cr metals such as Alloys 600/82/182, SS, CS, and LAS
  - Weld flaws (e.g., hot cracks and lack of fusion defects)
- It is appropriate to prioritize initiation FOI testing on the material conditions known from Alloy 690/52/152 crack growth rate testing to have the potential for elevated PWSCC susceptibility
- Initiation test data for Alloy 600 and Alloy 182 are also needed:
  - Under same conditions as Alloy 690 and Alloys 52/152 as FOI baseline
  - Comparative tests of the baseline materials to typical materials from plants

Application of Initiation Test Results to Plant Predictions

Factor of Improvement (FOI) Calculation for PWSCC Resistant Materials (Alloys 690/52/152)



* If cracking occurs in Alloys 690/52/152, the factor of improvement may be calculated as the ratio of Weibull characteristic times for each alloy:

$$\text{FOI} = \frac{\theta_{690}}{\theta_{600}} \text{ or } \frac{\theta_{52/152}}{\theta_{182}}$$

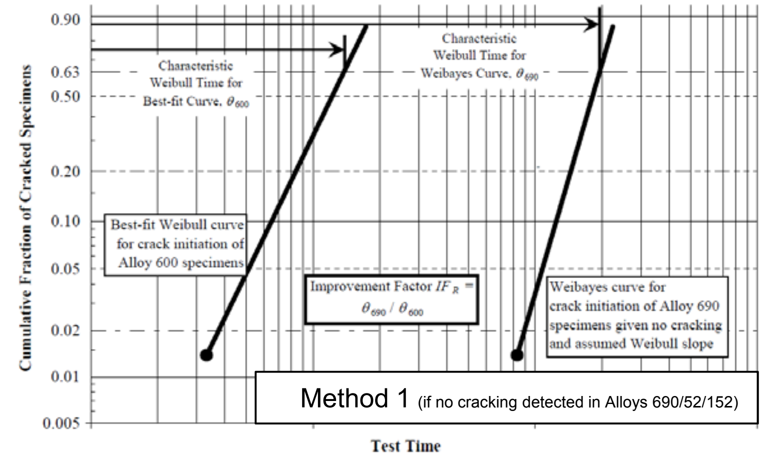


Figure 10-1
Weibull Plot Illustrating First Method for Determining Material Improvement Factor

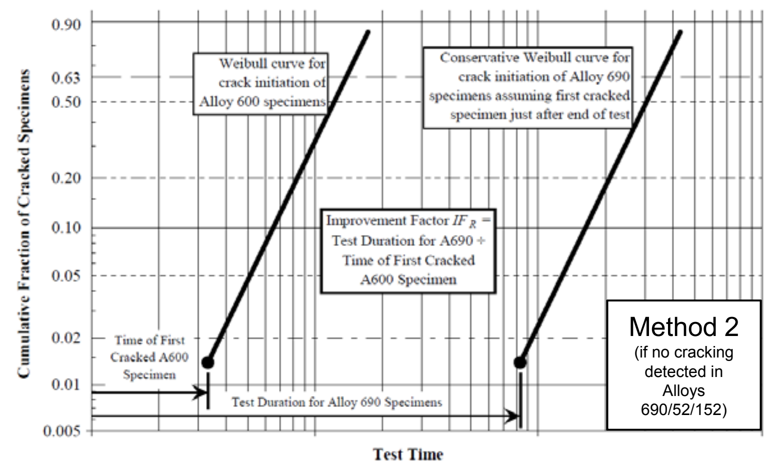
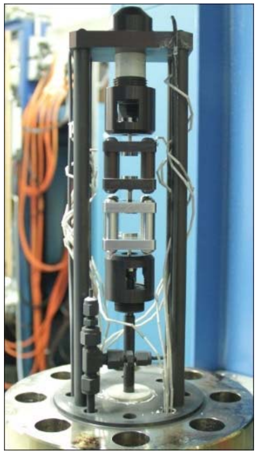


Figure 10-2
Weibull Plot Illustrating Second Method for Determining Material Improvement Factor

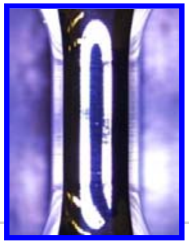
Figures from: *Materials Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110NP): Evaluations Supporting the MRP Inspection Plan*, EPRI, Palo Alto, CA: 2004. 1009807-NP. NRC ADAMS Accession No. ML041680506

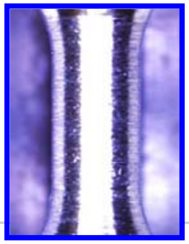
EPRI-NRC Cooperative Initiation Program

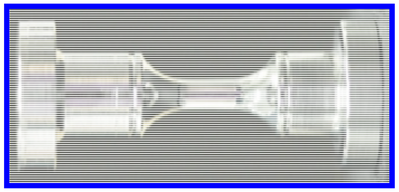
Summary of Current Tasks



Task	Deliverables	Completion Date
Test plan development	- Detailed plan including initial test matrix - Acquire materials for testing	08/2015 06/2015
Prepare testing and evaluation infrastructure	Two 36-specimen test rigs Report detailing the planned testing approach, technical basis, and verification and validation methods	08/2015 *(test start date)*
Alloy 600/82/182 crack initiation testing	Raw data, technical reports, and other information as it is developed	2018
Alloy 690/52/152 crack initiation testing	Raw data, technical reports, and other information as it is developed	2018
Expert Panel Project Review	Panel summary report	Annually







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