Status of U.S. NRC Research Activities for Primary Water Stress Corrosion Cracking Testing

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The views expressed in this presentation are those of the authors, not necessarily those of the U.S. NRC.

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Motivation for NRC–Testing Program

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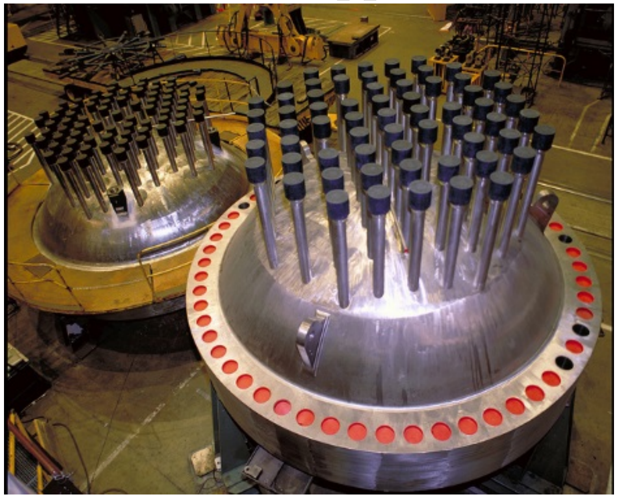
- Establish independent and confirmatory technical basis for structural integrity analyses of nickel-based alloy components and welds

- Support an efficient and effective process for making regulatory decisions on issues such as in-service inspection relief requests and ASME Code actions

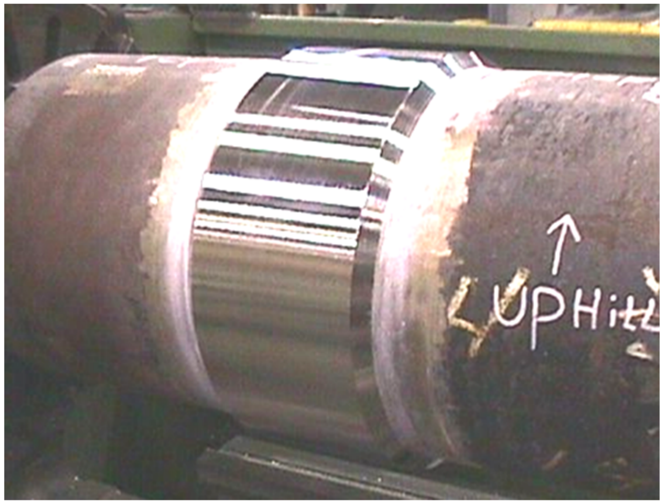
- Leverage resources to benefit complementary research programs, such as peening and subsequent license renewal

Regulatory Issues

CC N729 – upper heads

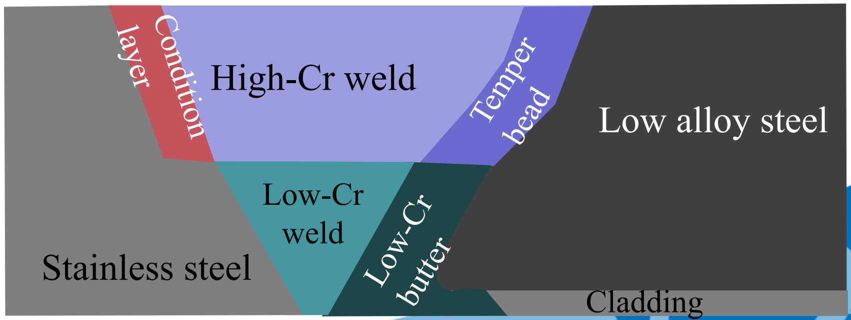


CC N770 – piping welds



Half-nozzle repairs

CC N847 – excavation and weld repair



NRC Research Strategy

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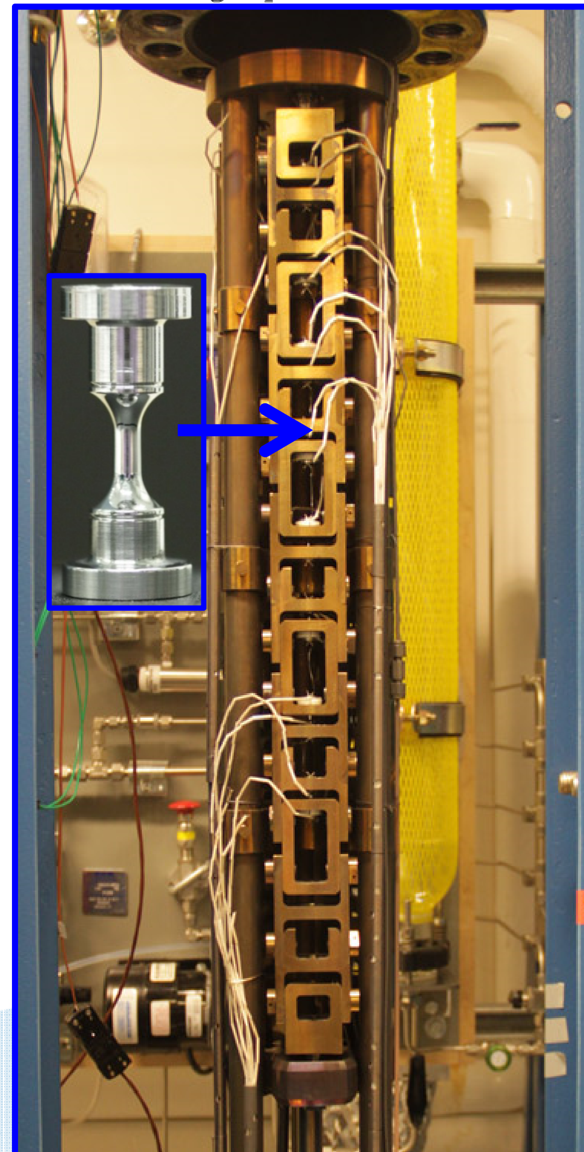
- Begin systematic acquisition of crack initiation data to determine if they could be used in models for component integrity analyses
- Continue acquisition of crack growth rate data for Alloys 690, 52, and 152 with focus on remaining high-priority knowledge gaps
- Follow progress of EPRI PWSCC Expert Panel for insights on unresolved technical issues and to identify need for additional testing

Crack Initiation Testing

- Framework:
  - Co-funded program by NRC and EPRI under Addendum to Memorandum of Understanding
  - NRC and EPRI independently analyze jointly acquired data
- Conceptual principles:
  - Use previously demonstrated testing approach
  - Test relatively high number of specimens
  - Minimize "accelerants" such as high temperatures and dopants
  - Experimental duration of <5 years
- Test materials: Alloys 600, 690, 182, 52, and 152 – multiple heats of each, some CW
- Rationale:
  - Acquire confirmatory data for xLPR
  - Compare relative initiation times of low-Cr and high-Cr materials

Crack Initiation Testing

- Testing parameters:
  - Tensile bar specimens
  - 36 specimens (3 x 12-specimen chains) in each of two autoclaves
  - PWR water chemistry at 360^{o}C
  - Specimens instrumented to detect crack initiation by direct current potential drop
  - Load approximately at material yield stress
- Testing organization:
  - One test machine for Alloys 600 and 182 specimens – two to three loadings anticipated of about one year duration for each
  - One test machine for Alloys 690/52/152 – single loading anticipated for five year duration
- Progress:
  - Alloys 690/52/152 loading began Jan. 2016
  - First Alloy 600 or 182 loading expected to begin by Apr. 2016



Crack Growth Rate Testing of Alloy 690

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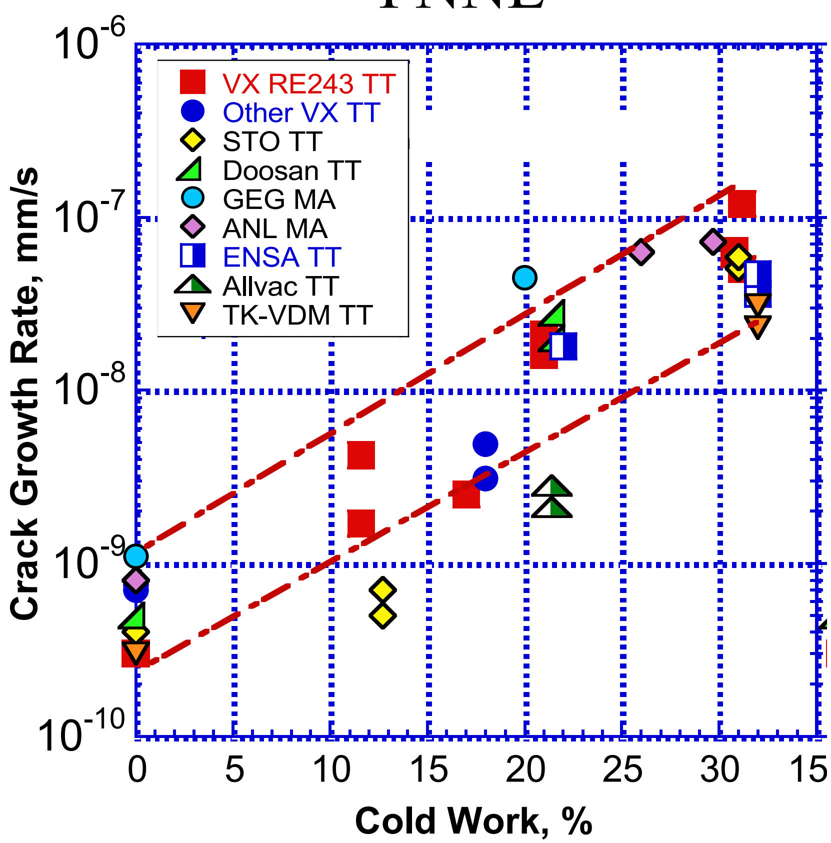
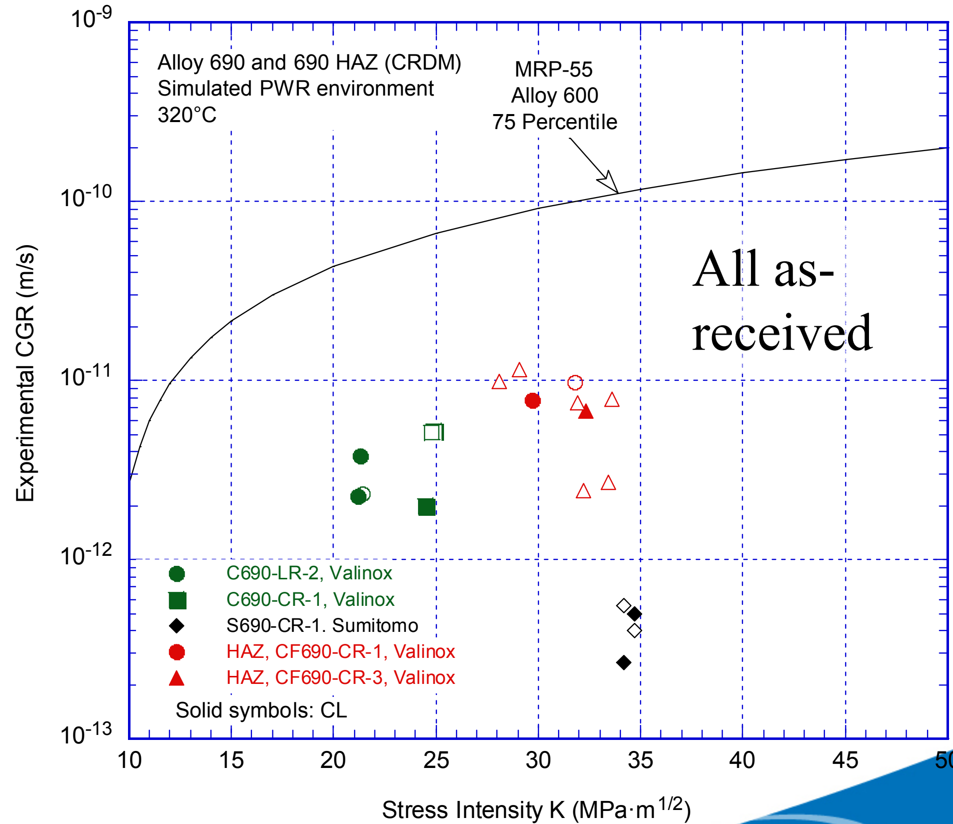
- Current status:
  - Completed tests on 40+ specimens from 10+ heats
  - No additional tests planned at this time.
- Key findings:
  - Very low crack growth rates ($\sim 10^{-9}$ mm/s) in as-received condition
  - Crack growth rate increases with increasing cold work
  - HAZ does not appear to have notably higher susceptibility
- Path forward: Further analysis of data by PWSCC Expert Panel. Key issues may include:
  - Cold work levels in actual plant components
  - Test specimen orientation relation to crack growth directions in plant components
  - Comparing laboratory-tested heats to plant component heats

Alloy 690 Crack Growth Rate Data

PNNL



ANL



Crack Growth Rate Testing of Alloys 52/152

- Current status:
  - Completed tests on 20+ specimens from 10+ welds
  - About 10 weld specimens currently in test
- Key findings:
  - Most "typical" weld metal shows low crack growth rate (<10^{-8} mm/s), even in some cases with high intergranular engagement
  - Limited data near Alloy 152-low alloy steel and Alloy 52M-Alloy 182 interfaces give notably higher crack growth rates, above 10^{-7} mm/s
- Path forward:
  - Testing for high-priority knowledge gaps: weld dilution, weld repairs, weld defects, weld parameter variations, overlays/inlays/onlays
  - Further analysis by PWSCC Expert Panel, e.g., weld dilution in plant components, test specimen orientations, laboratory-tested welds versus plant component welds

Alloys 52/152 Crack Growth Rate Data

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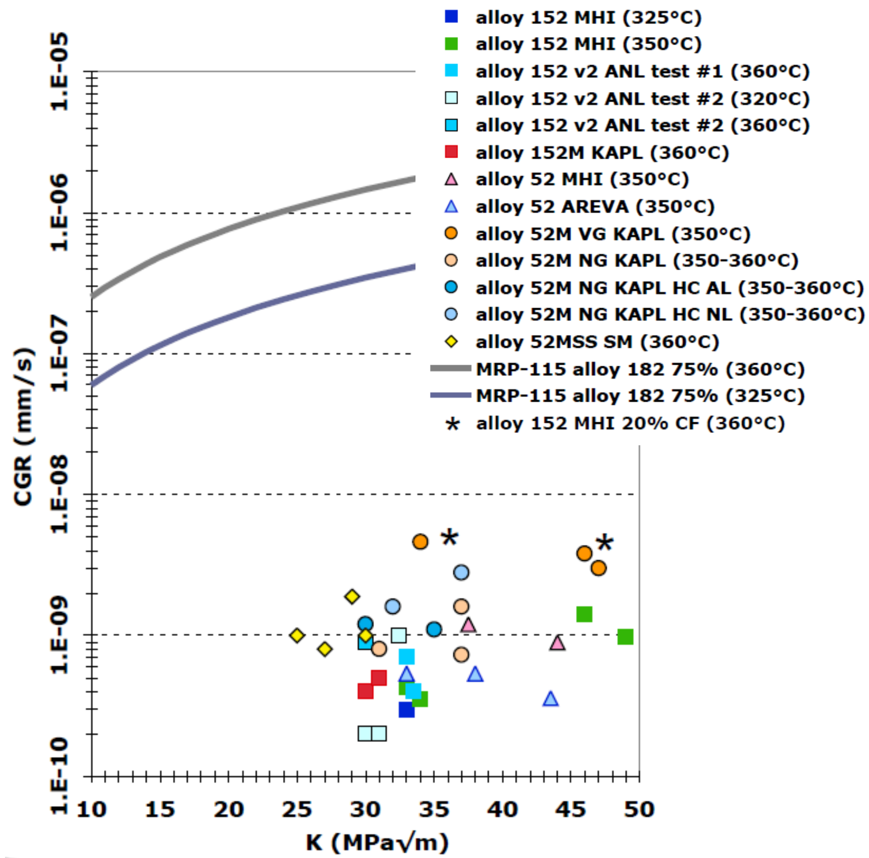
PNNL



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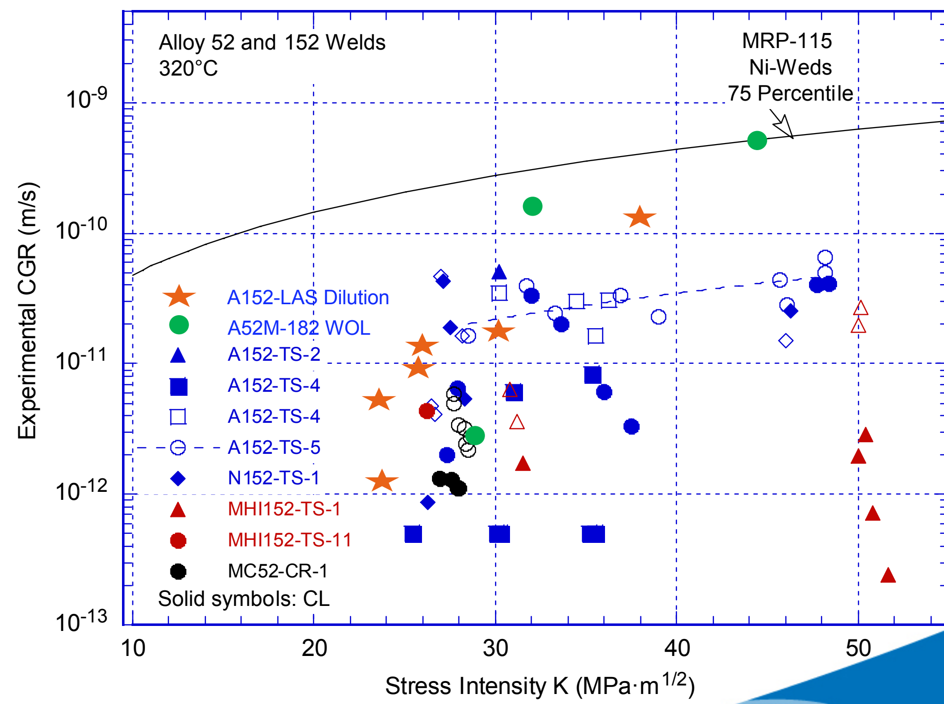
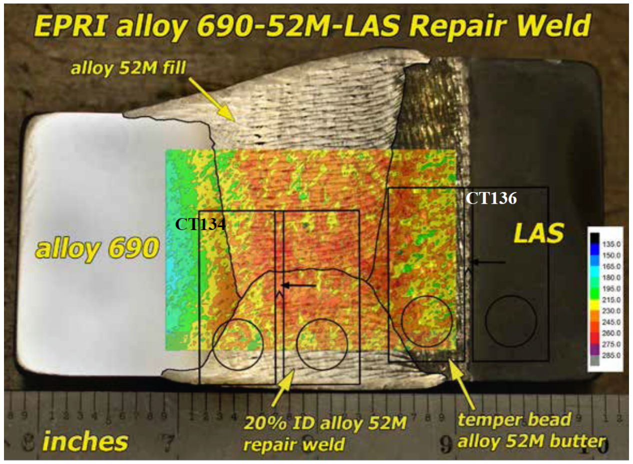
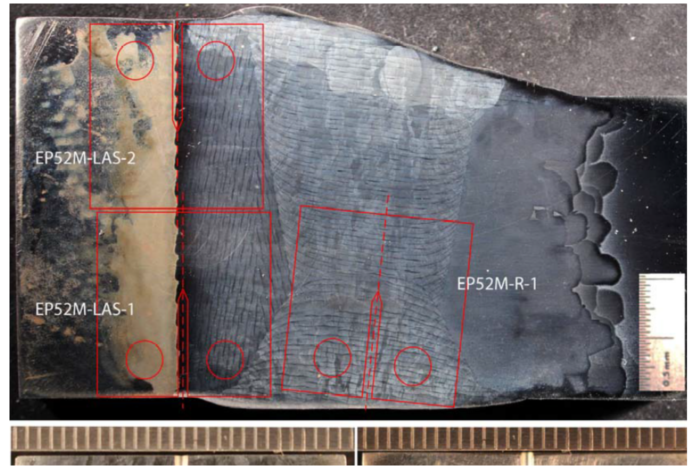
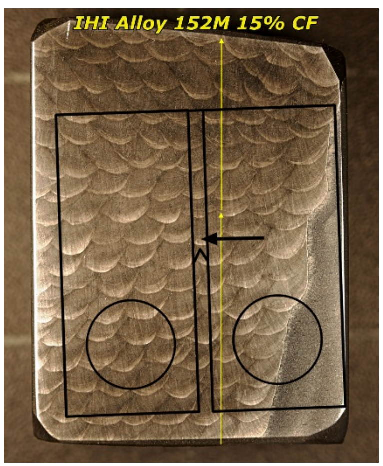


Ongoing or Recent Completed Tests

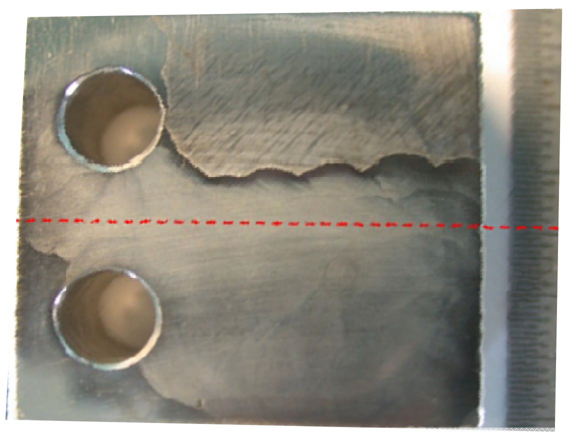




Weld repair mockup specimens, PNNL (left) and ANL (right)



PNNL cold forged weld

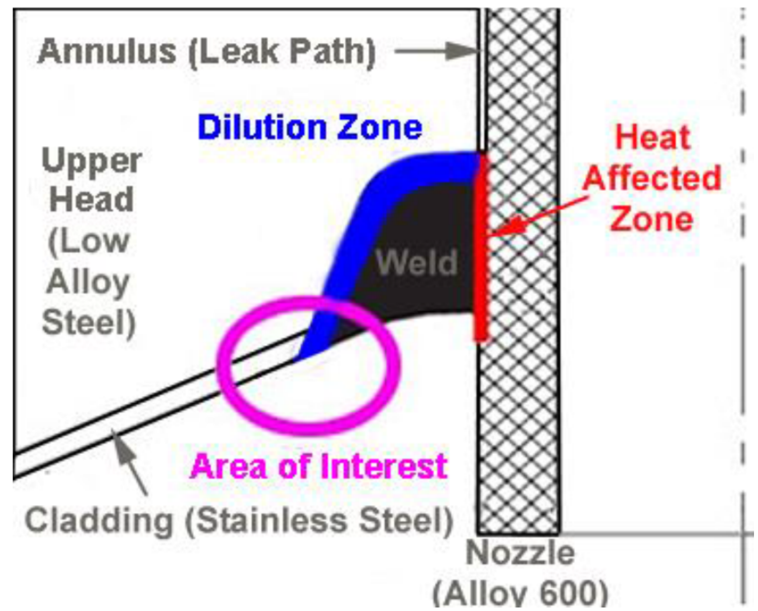


ANL Alloy 152/LAS 2nd layer weld beads

PNNL Alloy 152/LAS 1st layer dilution weld

Potential Upcoming Tests

- Alloy 52M and 52i overlays on Alloy 182
- Alloy 52M narrow groove welds with ductility dip cracks
- Alloy 52/152 – stainless steel – low alloy steel triple interface
- CIEMAT/ENSA Alloy 690/52/152 CRDM mockup

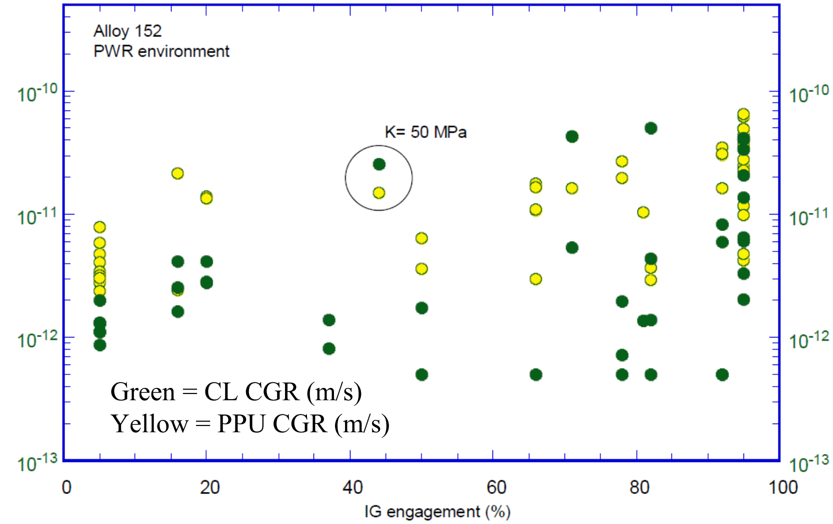


Crack Growth Rate Expert Panel

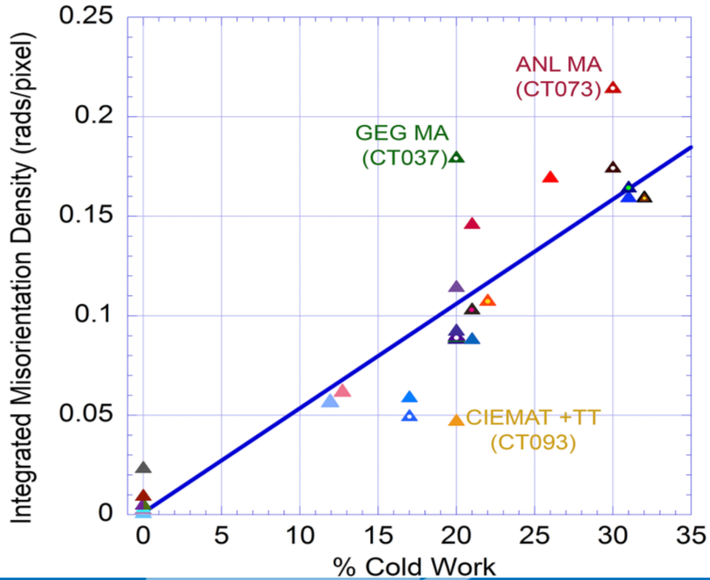
- NRC supports Alloy 690 Expert Panel via Memorandum of Understanding with EPRI
- Primary participation is through NRC contractors at ANL and PNNL who are members of Data Evaluation Group
- NRC may observe but not vote with the Data Applications Group
- Recommendations or conclusions of Expert Panel are subject to NRC review prior to endorsement

Perspectives on Some Expert Panel Issues

- Periodic partial unload (PPU) test data
  - Clear basis needed if PPU data for Alloys 690/52/152 are treated differently than for Alloys 600/82/182
  - Consider inclusion of PPU data on case-by-case basis

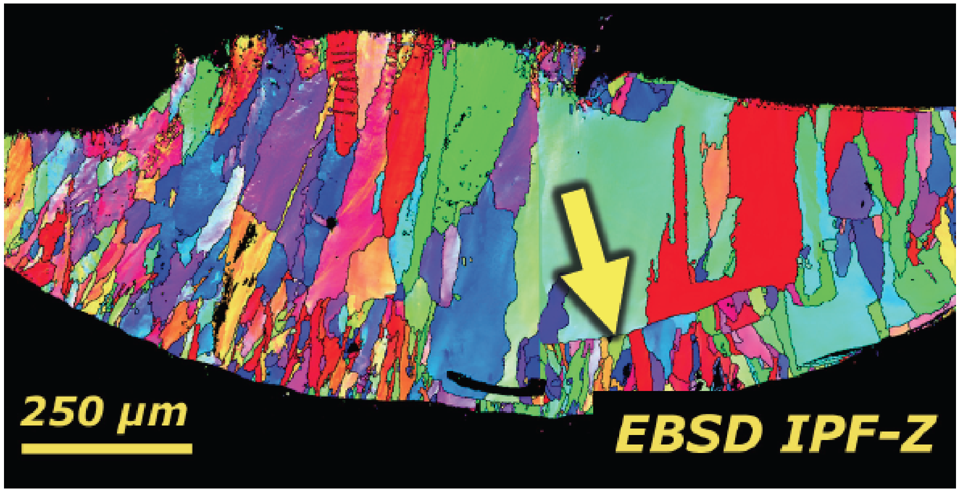


- Cold work
  - Cold work levels in plant components best justified by data from mockups and ex-plant materials (e.g., hardness measurements, internal strain mapping)
  - Consider fabrication-related work (rolling, forging, shaping) and "finishing" work (grinding, pipe fit up)

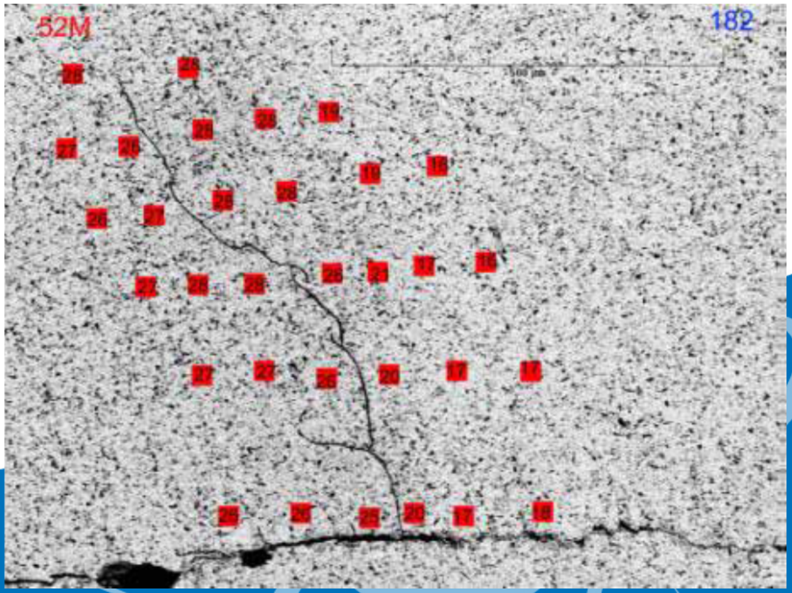


Perspectives on Some Expert Panel Issues

- Weld dilution
  - Cr content may not be only factor affecting crack growth rate
  - Consider whether through-wall weld dilution zone cracking is plausible considering potential influence of microstructural features and necessary residual stress state



- Crack growth directions
  - Crack growth direction in plant components may be influenced by product form (plate, tube, weld) and work form (rolling, forging)
  - Clear basis needed if certain specimen orientations (e.g., plate S-L) are corrected or normalized for orientation bias



Summary

- PWSCC testing program supports technical bases for safety evaluations including for in-service inspection requirements of upper head nozzles and piping welds.
- PWSCC initiation testing program is just underway to acquire data for both high-Cr and low-Cr alloys
- PWSCC growth rate testing program is primarily focused on Alloy 52 and 152 weld metals, including effects of dilution, repairs, and weld defects.
- NRC is participating in the PWSCC Crack Growth Rate Expert Panel and anticipates further work on a number of technical issues.

Acronyms

- ANL – Argonne National Laboratory
- CC – ASME Code Case
- CIEMAT – Centro de Investigaciones Energéticas, Medioambientales y Technológicas
- CRDM – Control rod drive mechanism
- CW – Cold work
- ENSA – Equipos Nucleares S.A.
- EPRI – Electric Power Research Institute
- LAS – Low alloy steel
- PNNL – Pacific Northwest National Laboratory
- PPU – Periodic partial unloading
- PWR – Pressurized water reactor
- PWSCC – Primary water stress corrosion cracking
- xLPR – Extremely Low Probability of Rupture code