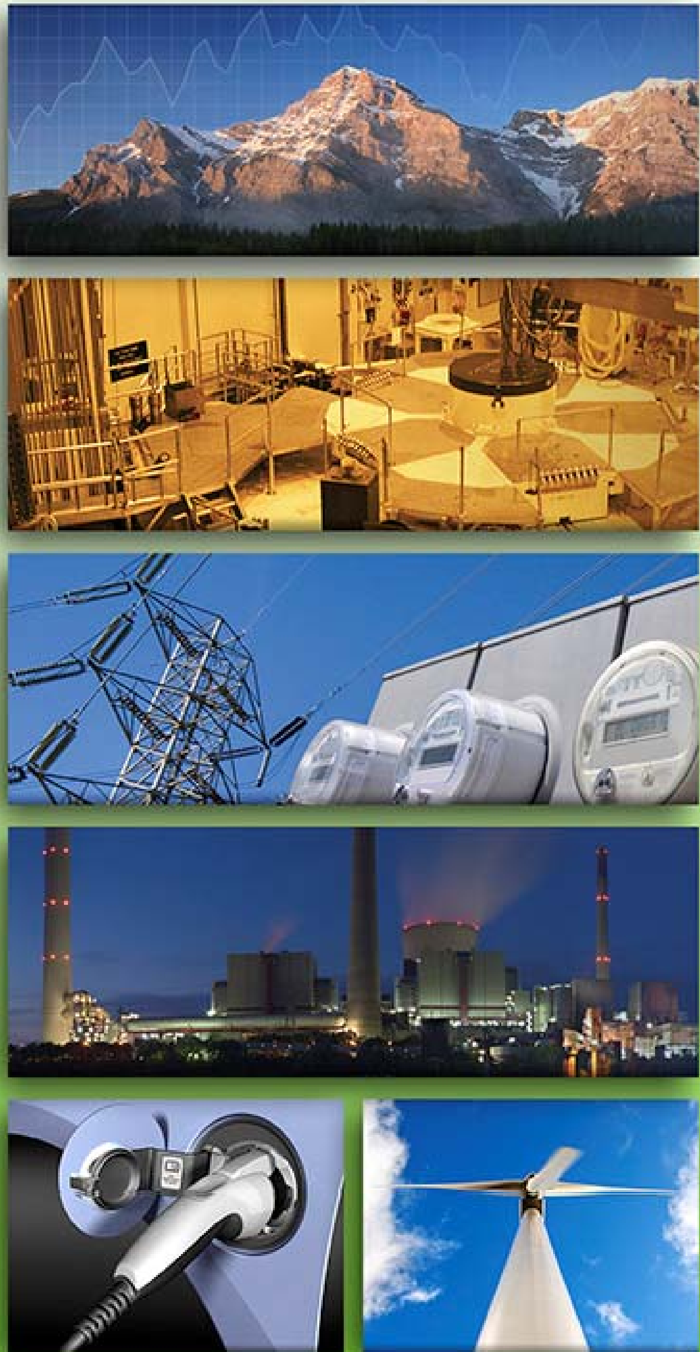

PWR Materials Reliability and Weld Repair Research Meetings

January 24-26, 2012, Charlotte, NC

Paul Crooker, Greg Frederick
EPRI

Howard J. Rathbun
U.S. Nuclear Regulatory Commission

ELECTRIC POWER RESEARCH INSTITUTE

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Introduction

- Welcome
- Introduction by meeting attendees
  - Names and affiliations
  - Please fill out Sign-In sheet
- Agenda
  - Revised since Public Meeting Announcement
  - Hardcopy available
- Public Meeting Feedback (NRC Form 659) forms available

Agenda

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

	Tuesday, January 24, 2012	
Time	**Topic**	**Presenters**
1 - 3 pm	**Welding Topics**	
1:00 – 1:10 pm	Introductions	All
1:10 - 3:00 pm	- WRTC Overview - Magnetic Stir Welding - Laser Welding - Alloy 52 (Filler metal welding parameter study) - Excavated Weld Repair	WRTC Utility EPRI
3:15 – 4:15 pm	EPRI NDE Center Lab Tour	EPRI
4:15 pm	**Adjourn**	
	Wednesday, January 25, 2012	
8:00-10:15 am	**Weld Residual Stress FEA Model Validation Results**	
8:00 – 8:10 pm	Introductions	All
8:10 – 9:10 am	- WRS Handbook - WRS Validation Final Report	DEI
9:10 – 10:15 am	- Technical Letter Report - Revision to Tech Letter Report - NUREG - ACRS Briefing in 2012	**NRC**
10:15 – 10:30 am	**Break**	
10:30 - 12 pm	**WRS FEA Model Validation Follow-on R&D**	
10:30–11:15 am	- RS Measurements - Phase 2b mini-robin - Stress Intensity Factors from WRS Profiles	**NRC**
11:15–12:00 pm	- WRS and xLPR - CRDM WRS Assessment - Hardening Laws	EPRI
12 - 1 pm	**Lunch**	
1 – 5 pm	**Residual Stress R&D Topics and Public Comment**	
1:00 – 2:00 pm	xLPR - Pilot, Phase 2, WRS Validation, PWSCC Mitigation	**NRC/EPRI**
2:00 – 2:30 pm	WRS FEA Modeling	SIA
2:30 – 3:00 pm	NRC Materials Reliability and Residual Stress Research	**NRC**
3:00 – 3:15 pm	**Break**	
3:15 – 3:45 pm	DOE Welding Residual Stress Research	ORNL
3:45 – 4:15 pm	Academic and International Residual Stress Research	UC Davis
4:15 – 5:00 pm	Open Discussion/Vendor and Public Comment	All
5:00 pm	**Adjourn**	
	Thursday, January 26, 2012	
8 - 11 am	**Primary Water Stress Corrosion Cracking Mitigation**	
8:00 – 8:45 am	Technical Basis - Chemical Mitigation (MRP-263 & 307)	EPRI
8:45 – 9:30 am	Technical Basis - Peening (MRP-267)	EPRI
9:30 – 10:15 am	Topical Report (TR) Outline and Submission Plan	MRP Utility
10:15 – 10:30 am	**Break**	
10:30 – 11:15	MRP-267 & TR Outline Comments / TR Review Process	**NRC**
11:15 - 12 pm	Memorandum of Understanding Addendum	NRC/EPRI
12:00 pm	**Adjourn**	

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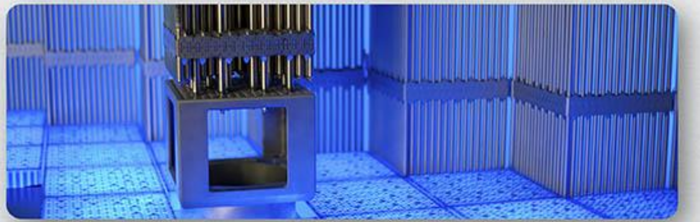
This is a Category 2 Public Meeting

- Category 1
  – Discussion of one particular facility or site
- Category 2
  – Issues that could affect multiple licensees
- Category 3
  – Held with representatives of non-government organizations, private citizens or interested parties, or various businesses or industries (other than those covered under Category 2) to fully engage them in a discussion on regulatory issues





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EPRI: Welding and Repair Technology Center - Overview

Welding and Repair Technology Center Staff

Program Chair – Dan Patten
Program Manager – Greg Frederick

January 24, 2012

Agenda

Schedule	Topic	Presenter
1PM	Welding Repair and Replacement (WRTC) – Introduction	Dan Patten – FENOC
	WRTC Code Issues	Dan Patten - FENOC
	WRTC Strategic Plan and Roadmaps	Greg Frederick, EPRI
	Alloy 52 Dilution Studies	Jon Tatman, EPRI
	Excavated Weld Repair	Francis Ku, SI
	Laser Welding	ORNL, Wei Zhang
	UW Laser Welding	WEC, Bruce Newton
	Magnetic Stir Welding	Greg Frederick, EPRI
	WRTC Capabilities	Greg Frederick, EPRI
3PM	EPRI Tour	

Agenda

EPRI – FACILITY TOUR

CHARLOTTE, NORTH CAROLINA

EPRI CHARLOTTE FACILITY TOUR

TUESDAY, JANUARY 24TH, 2012

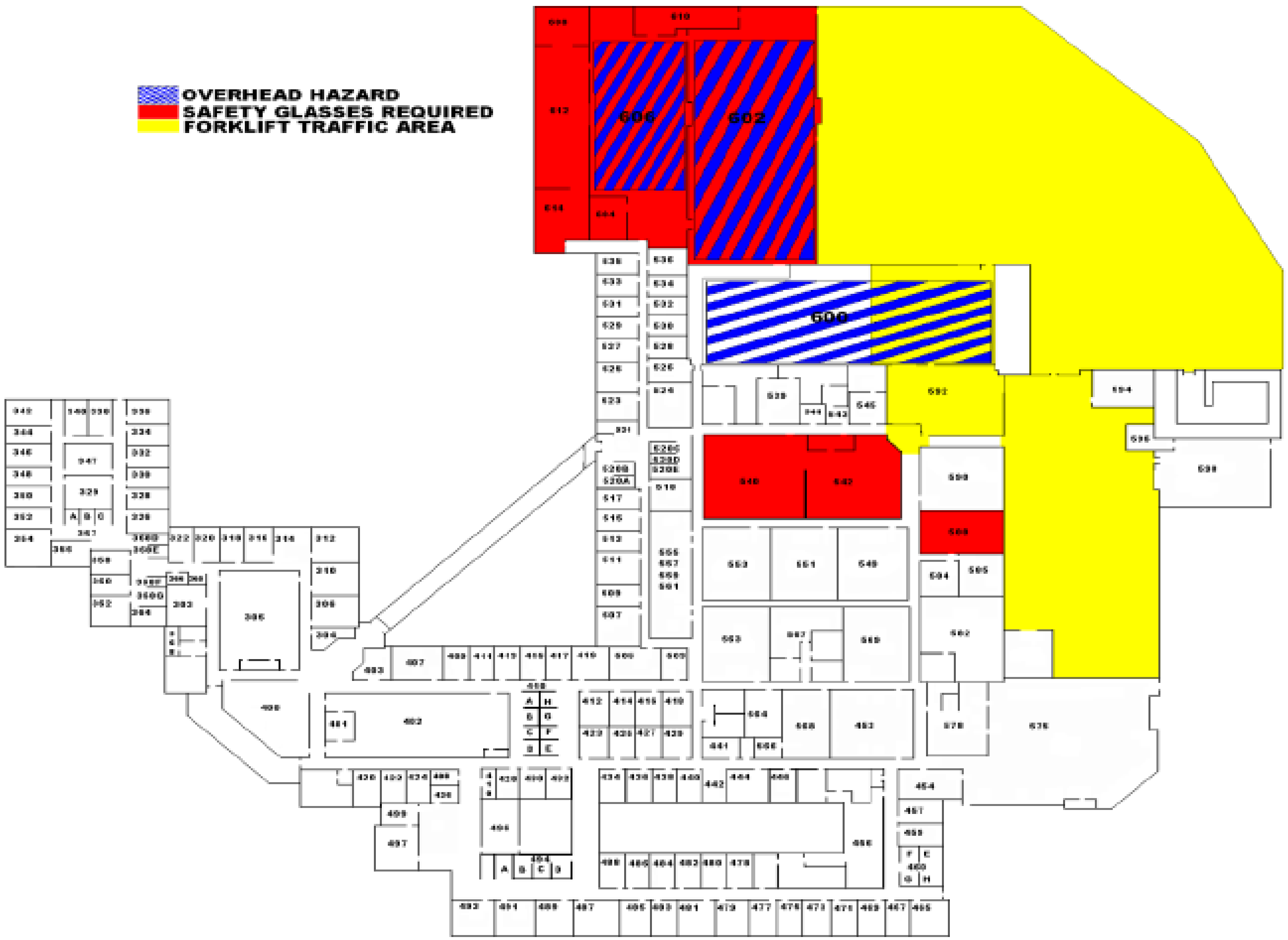
Tour Lead: Greg Frederick, Program Manager, Materials

- **Safety Brief** (15:00)
- **IGSCC Lab (PD)** (15:05 – 15:20)

  Presenter(s): Ronnie Swain, Program Manager, PD
- **Steam Generator Management Program (SGMP)** – (15:25 – 15:40)
- Presenter(s): Rich Guill, Sr. Project Manager, SGMP
- **Welding & Repair Technology Center (WRTC)** (15:45 – 16:00)

  Presenter(s): Artie Peterson, Project Manager

Agenda



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WELDING & REPAIR TECHNOLOGY CENTER

Agenda

Safety Notes:

In order to take part in the EPRI Charlotte facility tour, each participant MUST wear safety glasses in designated areas when asked and have on footwear with slip-resistant soles and substantial uppers made of leather or the equivalent that covers the entire foot and has no openings.

Pre-Tour Safety Brief:

1. Stay with your group at all times.
2. In the event of an evacuation, follow your host to the outside assembly locations.
3. If you experience a personal illness or emergency, please notify your host.
4. For emergency medical services dial 911, then notify the receptionist by dialing "0".
5. Be aware that these are active labs with the potential for unexpected hazards. Please comply with all posted warnings.

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EPRI: Welding and Repair Technology Center – Introduction

January 24, 2012

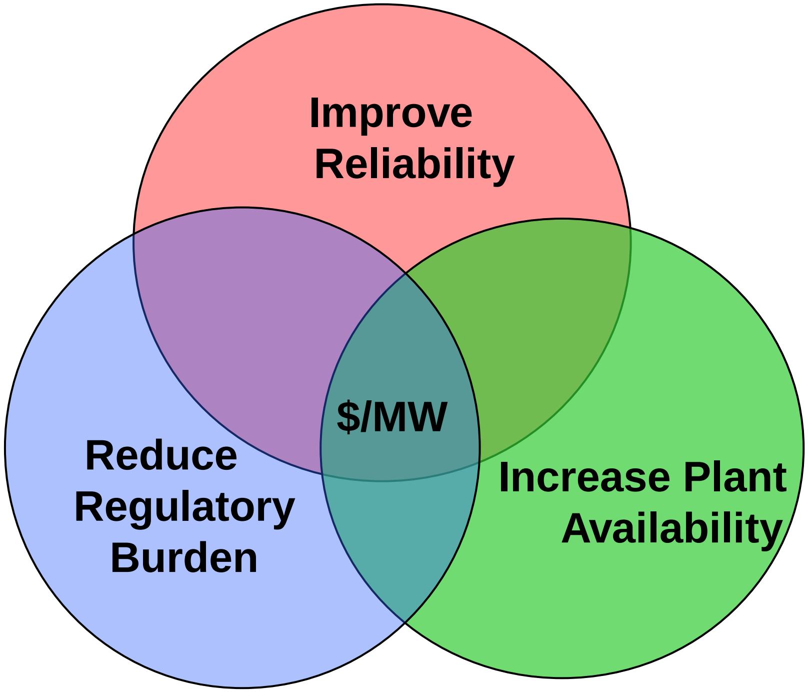
Dan Patten, FENOC
WRTC Chair

Outline - Summary

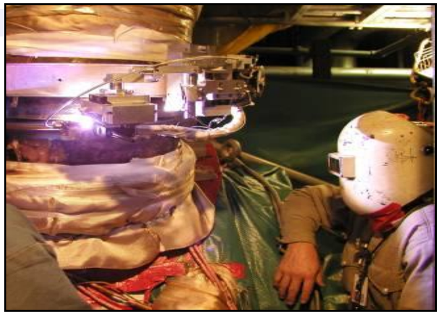
- Welding & Repair Technology Center (WRTC)
  - WRTC Mission/Strategic Plan
  - Advisory Structure
  - Meetings/Workshops

WRTC Mission

- WRTC provides tactical support and performs near term research for utilities under its current mission.
- Primary objectives
  - Develop joining and repair technologies contributing to reduced operation and maintenance costs and improved plant availability
  - Supports technical interactions with code and regulatory entities to reduce the time and cost associated with implementing new technologies and repair rules



Nuclear Sector: Welding & Repair Technology Center Program - Strategic Plan



- WRTC focus on tactical support and short-term, utility-requested R&D.
  - *address emergent repair needs*
  - *supports technical interactions with code and regulatory entities to reduce the time and cost associated with implementing new technologies and repair rules*
  - *repair and welding process optimization*
  - *information exchange (peer review)*
  - *Material testing and evaluations*

- WRTC balances fundamental research (long-term) with tactical projects (short-term)
  - *Align current WRTC resources and program objectives to proactively address resolutions of major industry issues*
  - *Collaborations with other EPRI Issues Groups and industry experts - consortiums*

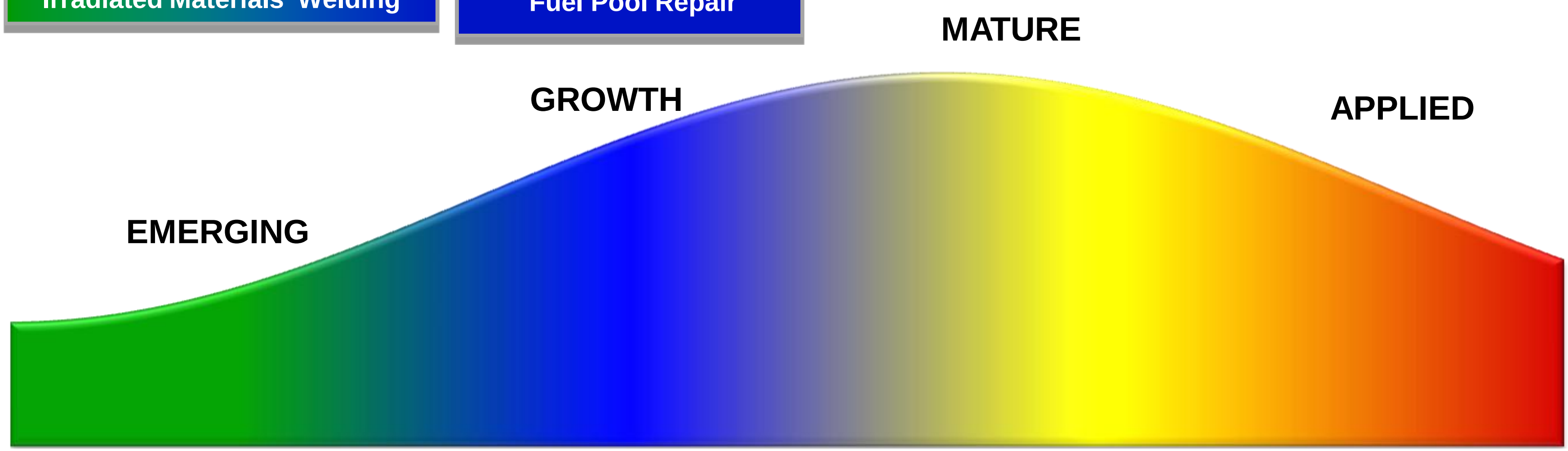
Welding & Repair Technology Center – Program Life Cycle

- New Plant Fabrication
- Long-Term Operation
- High Productivity Welding Development for R&R
- Virtual Qualifications
- Advanced Welding Materials
- Irradiated Materials Welding

- Training/Workshops
- SCC Mitigation
- Root Cause/Failure Analysis
- Information Services
- Underwater Welding
- Fuel Pool Repair

- Online Repair Tools
- Welding PQR Database
- Code Case Development
- Welding & Repair Program Development

- Repair & Replacement Guidelines
- Equipment/Process Commercialization
- ASME/AWS/NBIC Code Rules



Products regularly updated to reflect industry operating experience.

WRTC Advisory Structure

- 26 of 26 US Utility Organizations participate in WRTC (operating BWR and PWRs)
- 6 International participants
  - EDF – France – Working closely with RM technology gaps
  - KNHP – Korea
  - COG - Canada
  - CEZ NPP
  - Japan (IHI)
  - British Energy Generation Ltd.
  - *Non-Utility Membership/Participation (NSSS Vendors)*

WRTC Advisory Structure

- Nuclear Power Council
- Materials Action Plan Committee (MAPC)
  - Executive Committee
  - Technical Committee

- Welding and Repair Technology Center (WRTC)
  - Focus Committee (New)
- Welding and Repair Technology Center (WRTC)
  - Advisory Group (1 per utility)

Project /Technology area leads and contact information for WRTC

- **Greg Frederick**, (704) 595-2571, gfrederi@epri.com
  - Program Manager, Advanced Welding Applications
- **Steve McCracken**, (704) 595-2627, smccracken@epri.com
  - Welding/Repair & Replacement Activities, ASME Code
- **Dana Couch**, (704) 595-2504, rcouch@epri.com
  - Welding/Repair & Replacement Activities, Welding Program
- **Eric Willis**, (650) 855-2023, ewillis@epri.com
  - Materials/Repair & Replacement Activities, Advanced Welding
- **Artie Peterson**, (704) 595-2605, arpeters@epri.com
  - Stress Measurement/Mechanical Technologies/Testing
- **Jon Tatman**, (704) 595- 2762, jtatman@epri.com
  - Welding/Repair & Replacement Activities
- **Stacey Wells**, (704) 595-2673, sburnett@epri.com
  - Conference Activities, Website, Technical Assistant

WRTC Advisory Meetings

Two advisory meeting per year

- June and December WRTC Advisory and Technical Programs
  - Code/OE Issues Meeting
  - Project Overviews
  - Process Demonstrations
  - Introduction of new projects
  - Training Courses/Demonstrations

Welding Technology Conferences

- EPRI - WRTC supports an established conference series for Welding and Repair Technology
  - Welding and Fabrication Technology for New Power Plants and Components
    June 21-24, 2011, Omni ChampionsGate, Orlando, FL
    - Sponsored by WRTC and Fossil Materials Repair (Program 87), Boiler Life and Availability (Program 63), HRSG Dependability (Program 88)
    - 23 vendors
    - 180 attendees
    - 11 countries represented

Workshops Conducted at the 2011 Conference

ASME B31.1 Materials, Fabrication, & Examination - Doing It Right

- Discuss the bases for the B31.1 Power Piping Code rules for materials, fabrication, and inspection/examination. Special emphasis will be placed on rules that are different from other ASME Codes
- Course conductor: *Philip D. Flenner, PE*

Basics of Conducting a Failure Investigation

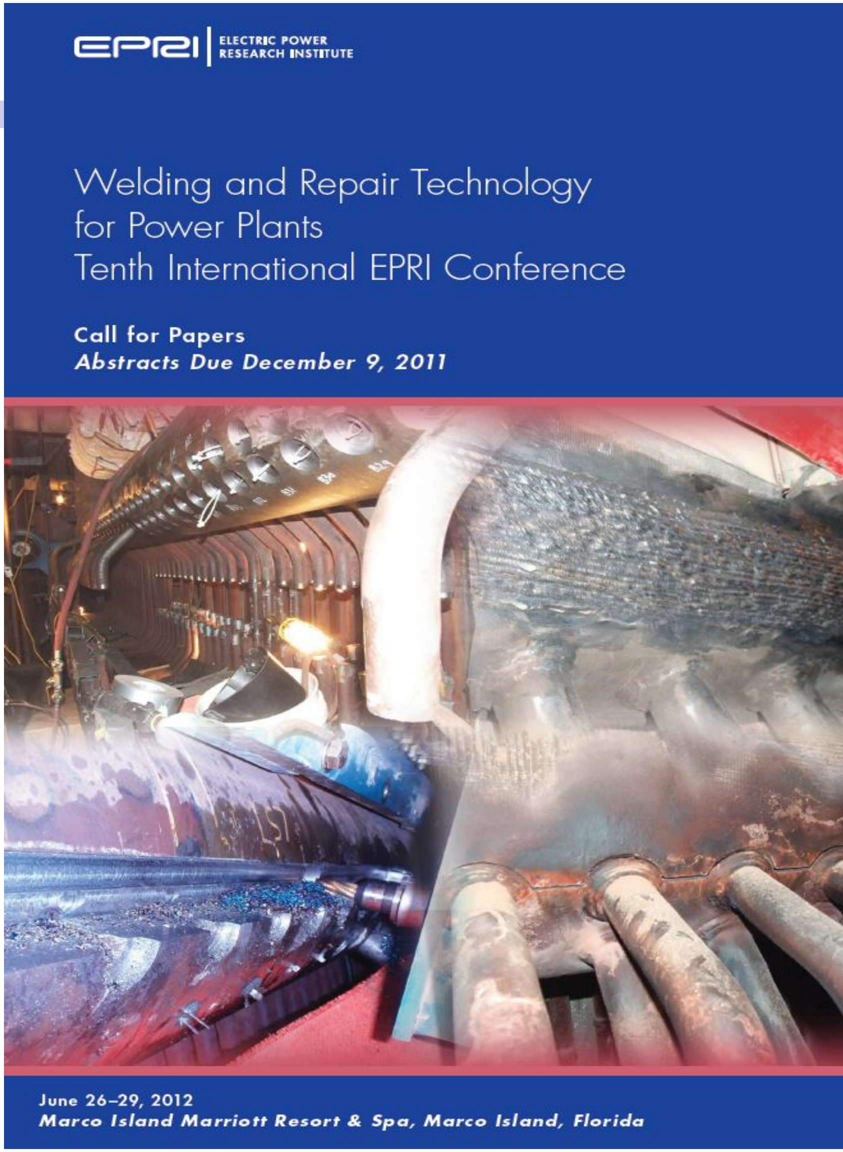
- Intended to educate the power plant engineer on the proper steps to take when conducting a failure analysis
- Course conductor: *Dr. Jude Foulds, P.E., Principal, Clarus Consulting, LLC*

Heat Treating Practices for Energy Construction: Quality and Consequences

- Discuss the basics of heat treatment and its growing significance in power construction. Emphasis on material quality and illustration of potential failures in base and weld material
- Course conductor: *Gary Lewis and Joe Borror, Superheat FGH*

2012 Welding & Repair Technology Conference

- 10th International Conference – *June 26-29, 2012 Marco Island, FL*
  - Nuclear & Fossil Topics
  - Vendor Fair and Display
  - University Studies and Student Poster Session
  - Training Workshops (June 26th)
    - Section IX and Temperbead Welding Guidelines (Temperbead Rules and Qualification)
    - Weld Modeling and simulation Tutorial (FEA)
    - Heat Treating Practices for Energy Construction



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WRTC Key Activities – Guidelines and Benchmarking

Key Issue – Nuclear Welding Program Review

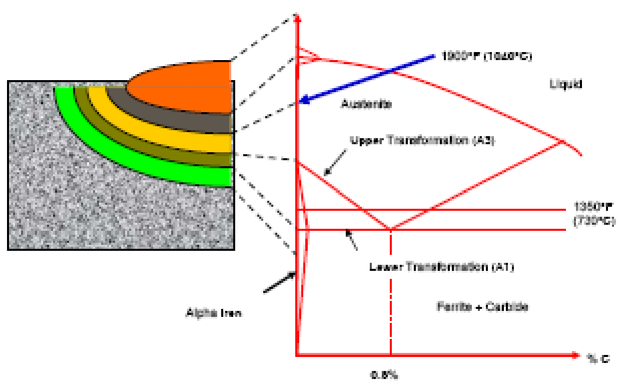
- **Final Report Issued (EPRI 1021172), Welding Program Review**
  - Captures the in-depth site visit surveys which examined and documented the implementation of Nuclear Welding Program requirements.
  - The survey was performed at the following 10 utilities:
  - OPG, Duke Energy, PPL (Partial)
  - TVA, PSEG, SNC, WCN, and CGS
  - Exelon (Limerick and LaSalle) and Bruce Power
- **2011 Efforts have concentrated on the updating of the INPO Engineering Program Guide for Welding (INPO Loaned Employee - Kristin Whiteside) and participating in self assessments.**
  - A recommended revision to INPO-EPG-17 has been returned to INPO for consideration and processing.
  - WRTC personnel have assisted TVA and Duke with self assessments of site welding programs this year.
  - Currently participating with Exelon on a common cause analysis.

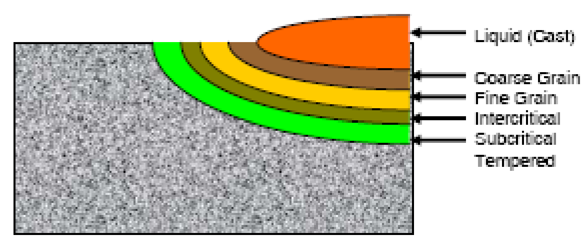
Repair Issues - Handbooks

- **Repair Welding Handbook issued last year [1021074]**:
  - Identifies basic damage mechanisms
  - Facilitates the repair decision processes
  - Provides guidance on related ASME Code and regulatory requirements
- Intended as a basic guideline to assist the user in responding to:
  - indications of degradation or unacceptable flaws
  - active leakage
- Written with consideration for the inexperienced plant engineer, but not a comprehensive “cookbook” (references original EPRI reports and other industry documents and guidelines for further guidance
- **Will be further developed in 2011 to specifically address:**
  - **Containment liner repairs**
  - **Control of magnetism during welding**
  - **Patch repairs for non-safety related piping**
  - **FME issues during post cleaning**
  - **Heat sink welding**

Repair Issues - Handbooks

- **Temperbead Guidelines [1022879] issued this year**
  - Intended to assist plant engineering to develop and implement the temperbead welding techniques.
  - The guide provides detailed information on temperbead welding, how it works, the technical objectives, use of power ratio, the consistent layer approach, importance of process controls, etc.
  - The guide addresses appropriate Codes, regulatory issues, qualification requirements based on applications, development of welding procedures, craft training, testing, NDE, selection and use of filler metals, and other key details.
  - The intent is to provide a single source document that assists the engineer in implementation of temperbead welding.





Welding Issues - Handbooks, Guidelines, and Workshops

- **Welding and Fabrication Critical Factors Workshop - Charlotte, NC, May 2011**
  – EPRI 1019209 is a tool to assist utilities develop, review and implement welding and fabrication requirements that minimize susceptibility to known BWR and PWR materials degradation
    - Tool to assess primary systems component degradation risk associated with welding and fabrication activities
    - Tool to improve decision making regarding asset management of welded components

  – Workshop objective was to familiarize users with use of this new EPRI tool
- **Training for Repair and Replacement Engineers**
  – This project provides a structured approach (curriculum) of subjects to be covered with engineers that are new to repair and replacement programs
    - **WRTC Report [1022789] issued this year**
    - Classroom Training was offered in conjunction with the WRTC December 2011 Advisory meeting.

Welding Issues - Handbooks, Guidelines, and Workshops

- **Failure Analyses Guideline and Training**
  - This project provides a structured approach for failure analyses
    - Failure Sequence of Events and Root Cause Development
    - Laboratory Examinations, Testing, & Interpretation
    - Case Histories
    - Classroom Training and Guidelines

- **Alloy 52 Weldability Workshop - Tampa, FL, November 2011**
  - Workshop will be held one day prior to the MRP Alloy 690 Experts Panel Meeting
  - Opportunity for Materials and Corrosion international experts to learn about and discuss the weldability issues with Alloy 52
  - Recognized welding experts from around the work are invited to speak on their experience with Alloy 52 weldability

Together…Shaping the Future of Electricity

WRTC Overview – Code Activities

Dan Patten

EPRI – Welding and Repair Technology Center

January 24, 2012

New WRTC Code Issues Roadmap *(draft - 2012)*

Roadmap No. RDXX – Rev. 7/9/2011

TRANSFER AND PROMOTE FABRICATION, REPAIR AND JOINING TECHNOLOGIES INTO CODES, STANDARDS, AND REGULATIONS

ISSUE STATEMENT

Advanced fabrication, repair, and joining technologies are often times adequately researched and developed, only to be shelved and not used in the nuclear industry due to difficulties associated with implementation of these new technologies into codes and standards. Moreover, considerable additional effort can be required to obtain regulatory endorsement. New joining technologies such as friction stir welding, laser welding, and advanced gas metal welding, or hybrid welding are used extensively in other industries. However, these technologies are not adequately addressed or implemented into the applicable codes, standards or regulations used in the nuclear power industry. A systematic and consistent approach toward promotion and transfer of new technologies into nuclear codes, standards, and regulations is needed to support high productivity processes in new nuclear plant construction and to allow for more efficient and cost effective solutions for repair/replacement activities in operating plants.

DRIVERS

Significant Gaps in Available Technologies – New technologies and innovative approaches for joining and repair are currently available and proven in non-nuclear industries. Additionally, new and thoroughly researched and proven technologies are available but not endorsed by the regulatory bodies. A listing of some of the current gaps is listed below.

- Adoption of fitness-for-service acceptance standards for new nuclear plant critical welds to minimize detrimental construction repairs
- Consistent temperbead weld requirements for repair/replacement activities and new construction
- Ability to reduce defects to an acceptable size by modifications
- Use of ultrasonic examination in lieu of radiography
- Full or partial rolled sleeve repair of leaking or degraded service water piping
- Applicability of hardness measurements for temperbead welding applications
- Performance of progressive surface NDE in lieu of volumetric examination
- Revision and clarification of drop weight and charpy V-notch testing for temperbead welding procedure qualification
- Implementation of inspection technologies for socket welds in small bore piping subject to fatigue failure
- Resolution of welding and repair rule inconsistencies between the various codes (e.g., Section XI, Section III, AWS, B31.1)
- Consistency in using thermal fluence as an indicator of weldability of irradiated materials
- Code consideration and Regulatory endorsement of Laser weld, friction stir welding, advance GMAW, or hybrid welding process

Construction of New Nuclear Power Plants – Current codes and standards used for construction of new nuclear power plants are not substantially different than those used in the 1970s and mid 1980s for construction of the

Nuclear Power Council Meeting 1 January 2011

Nuclear Power Council Meeting 2 January 2011

- **Significant gap in available welding & repair technologies**
  - Examples:
    - *Use of fitness-for-service /ISI acceptance criterion*
    - *Reduce defects to acceptable size by modification*
    - *UT in lieu of RT*
    - *Code consideration and NRC acceptance of laser welding, friction welding, advance GMAW, magnetic stir, etc.*
- **Purpose of roadmap is to provide long term focus and direction for code and regulatory issues**

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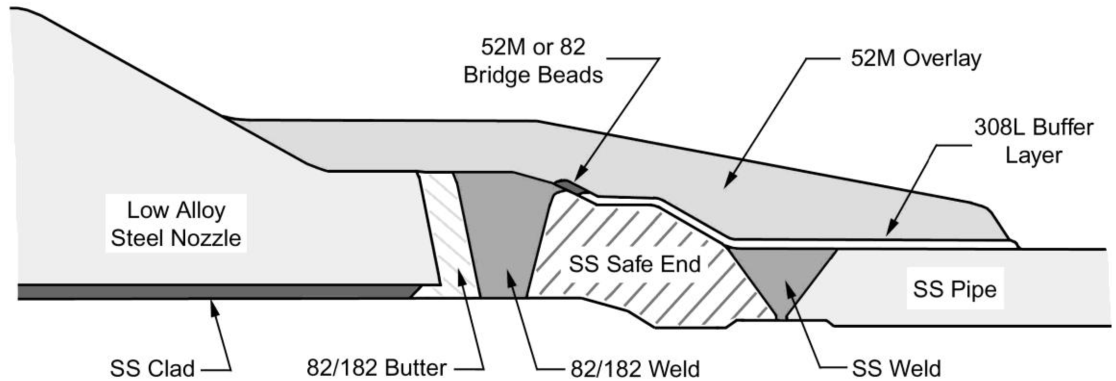
WRTC Code Activities

- **ASME Section XI**
  - Subgroup Repair & Replacement Activities
  - Working Group (WG) Welding & Special Repair Processes
    - Task Group (TG) Inlay / Onlay
    - TG Temperbead
    - TG Excavate Weld & Repair
    - New TG FFS Acceptance for XI R&R Welds
    - New TG Surface Mitigation
- **ASME Post Construction**
- **ASME Section IX (Waveform, etc.)**
- **Section III (new plant issues)**
- **B31.1 Power Piping**
- **AWS (Certifications)**

Overlay for Repair & Mitigation

In-process 52M Overlay on Pressurizer Safety Nozzle



Schematic of Typical Nozzle-to-Safe End Dissimilar Metal Weld Overlay

Code Case N-740-2 Structural WOL

Code Case N-754 Optimized WOL

Overlays Used for Repair & Mitigation in PWR Plants

Pressurizer Nozzle Structural Overlays
(dia. ~100mm, ~200mm, ~350mm)

Reactor Coolant Pump Suction Nozzle
Optimized Overlay *(dia ~850mm)*

N-740-2 Code Case for Weld Overlay

- N-740-2 provides rules for overlay repair of stainless steel welds and for dissimilar metal welds joining austenitic and ferritic base metals
- Can be used for PWSCC (primary water stress corrosion cracking) and IGSCC (intergranular stress corrosion cracking)
- Incorporates methodologies of:
  - N-638-1 & 2, Ambient temperature machine GTAW temperbead
  - N-504-2 & Appendix Q, Austenitic weld overlay repair
  - Previous relief requests approved by US Regulator
- Rules for repair of cracked dissimilar and similar metal weldments
  - Acceptance requirements for 1st layer (24% Cr for Ni alloy filler metals or 7.5FN for austenitic stainless steel filler metals)
  - Appendix I provides temper bead welding requirements
    - Area limitation increased to 500 in^2 over ferritic material
    - Weld procedure and performance qualification
    - Several methods for interpass determination

N-740-2 (Continued)

  - Design overlay sizing requirements
    - Crack growth evaluation
    - Impact on the system and other flawed weldments
  - Examination requirements
    - Surface, volumetric & Section XI laminar flaw criteria
  - PSI & ISI examination requirements
    - Examination volume & Acceptance criteria
    - Re-examination and expansion (for ISI)
- Provides rules for crack growth postulations if no prior inspection is performed or if no cracking is found by prior inspection
- Permits stainless steel ‘buffer’ layer to reduce potential for hot cracking on high P&S stainless steels
- Provides specific (somewhat relaxed) rules for design and examination of overlays installed over cast stainless steel items

N-740-3 Code Case for Weld Overlay

- **N-740-3 Structural Weld Overlay (SWOL)**
  - Revised to be consistent with N-754 (OWOL)
  - Response/resolution to US Regulator (NRC) inquiries
  - Take out PSI & ISI and reference N-770-2
  - Perform ISI prior to SWOL installation per N-770-2
  - Include recent changes in EPRI Report MRP-169
  - Increase area from 500 in^2 to 1000 in^2

N-754 Optimized Overlay for Repair & Mitigation

- **N-754 for Optimized Weld Overlay (OWOL) for SCC Mitigation & Repair**
  - For optimized (not full structural thickness) overlay for mitigation of PWSCC and IGSCC
  - Outer 25% of the original pipe wall is credited in the design sizing
  - Design, examination, and installation is similar to N-740
  - OWOL thickness is less than a full structural weld overlay provided adequate compressive stress is achieved on the ID surface
  - ISI required prior to OWOL installation per N-770-2
  - Maximum overlay area over ferritic material increased from 500 in^2 to 1000 in^2

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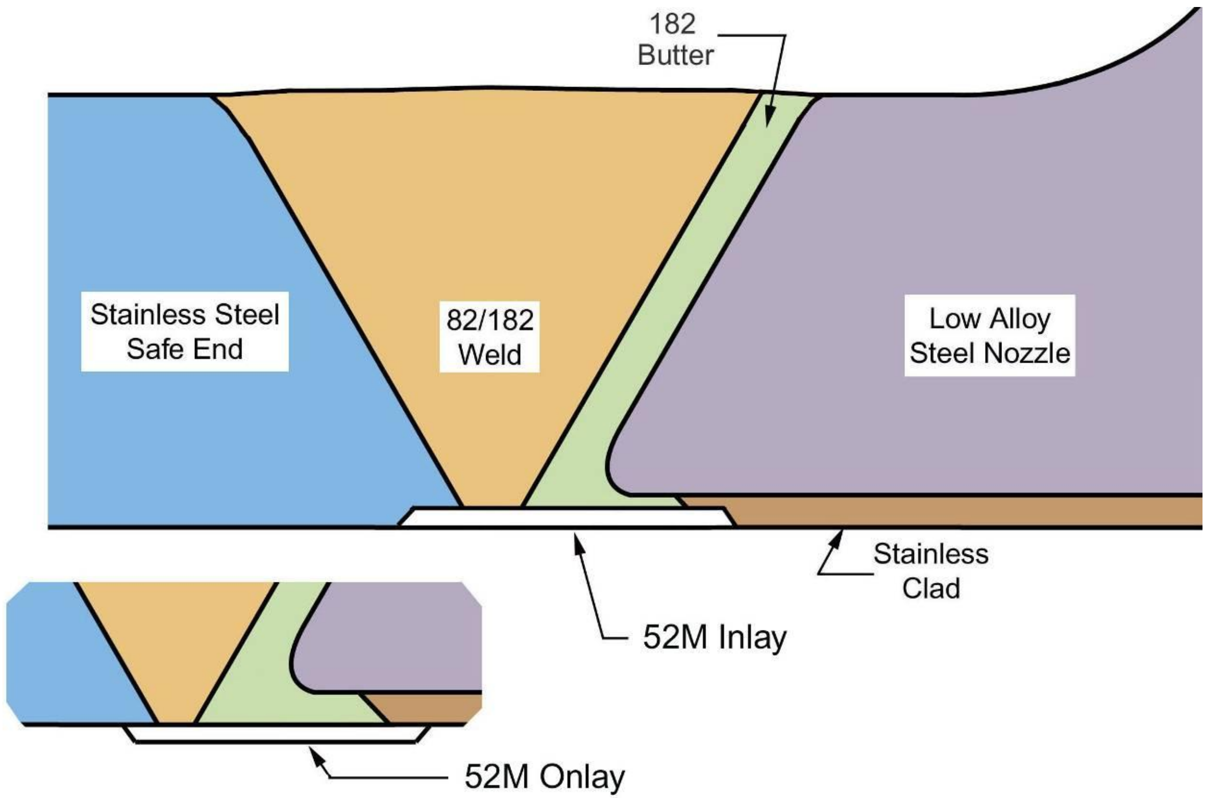
Inlay / Onlay for Repair & Mitigation



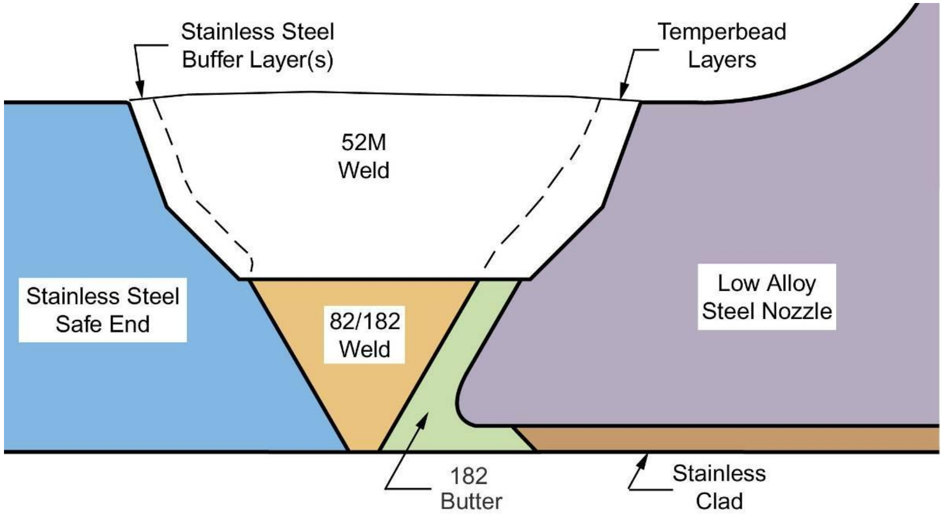
Schematic of Inlay and Onlay for PWSCC Repair & Mitigation

Inlay / Onlay for Repair & Mitigation

- **N-766 Nickel Alloy Inlay /Onlay for PWSCC Mitigation and Repair**
  - Rules for pipe ID inlay (~1/8" ID excavation) or onlay (no excavation) with 52M
  - Alternative to SWOL and OWOL
- **N-803 Ambient Temperature Underwater Laser Beam Welding for PWSCC Mitigation and Repair**
  - Rules for laser beam welding of 52M inlay/onlay without need to drain reactor vessel
  - WEC / PCI development and demonstration work at WRTC facilities is complete (moved laser to Lake Bluff)

EWR for Repair & Mitigation

- **N-XXX New case for excavate & weld repair (EWR) method to repair or mitigation PWSCC**
  - Repair or mitigation option for DM welds with limited access
  - EWR Task Group 5th meeting in Nov 2011
    - Current direction: Unlimited excavation, flaw permitted up to EWR weld deposit, will address partial arc or full 360 (limited life), will consider residual stress as mitigation factor, inspection & examination requirements will be in case



Temperbead Welding

- **N-638-6 Ambient temperature temperbead rules**
  - Provides rules for temperbead welding
  - Revise to incorporate Section IX QW-290 temperbead qualification rules
  - Remaining Regulatory Longstanding Open Items
    - Hardness testing (european codes require for temperbead)
    - Interpass temperature measurements
- **Integration of Section IX and XI Temperbead Rules**
  - N-762 permits new Section IX temperbead qualification rules
  - Action is to incorporate N-762 into Section XI IWA-4000

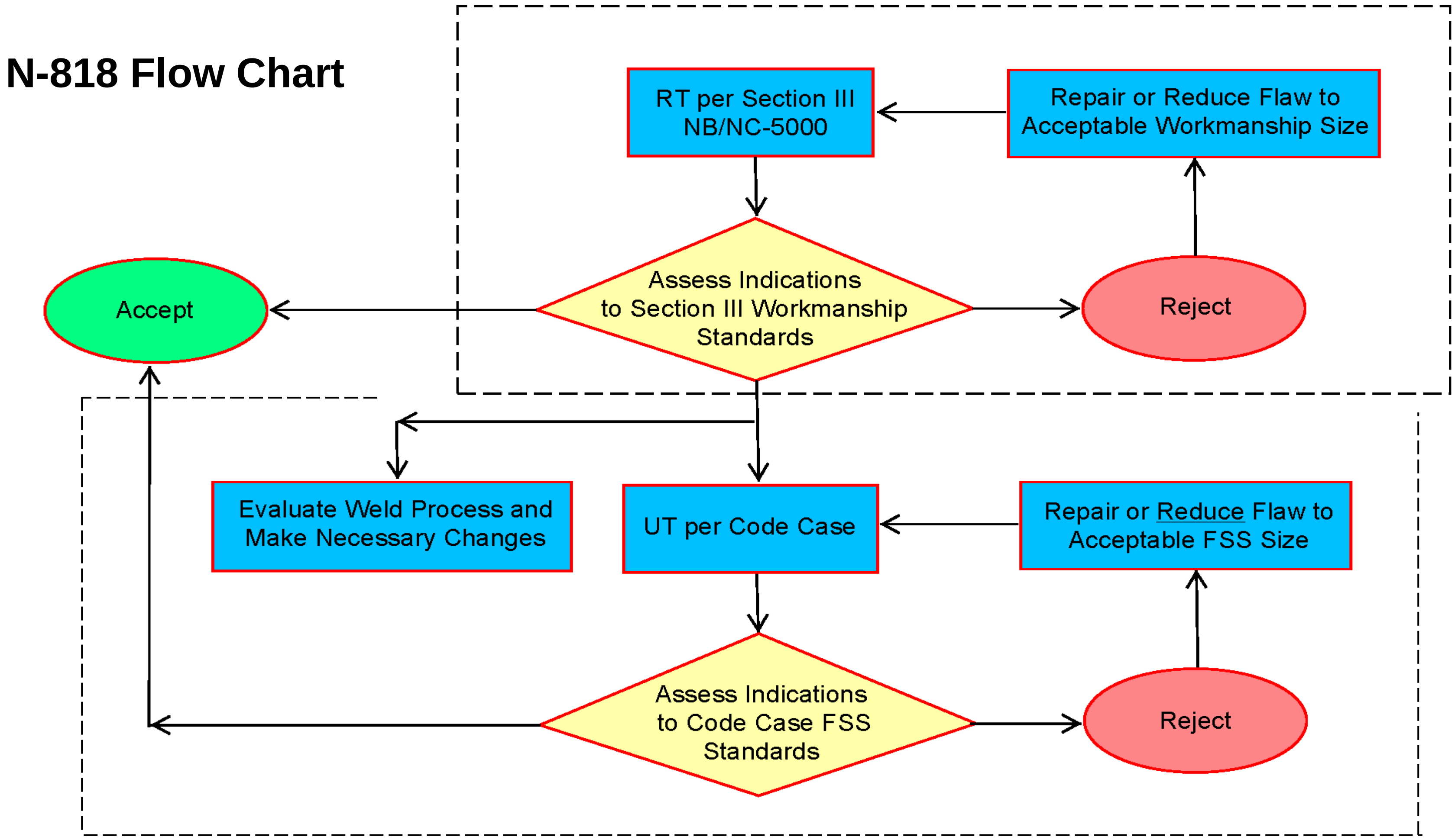
IWA-4600 SMAW Temperbead Welding

- **Eliminate 48 Hour Hold for IWA-4600 SMAW Temperbead Applications**
  - Will permit final weld NDE as soon as welding and final surface prep is complete
  - WRTC provided white paper (EPRI Doc No. 1021076) with technical basis for elimination of the 48 hr hold for SMAW

Fitness-for-Service Acceptance in Lieu of Repair

- **N-818 Fitness-for-Service Approach for Acceptance of Full Penetration Butt Welds in Lieu of Weld Repair**
  - Alternative to repair of full penetration butt welds that do not meet NB or NC-2500 RT acceptance criteria
  - Fitness-for-service criteria (similar to Section XI ISI) permitted for weld acceptance
  - PDI type ultrasonic examination with data acquisition system required
  - Surface flaws must meet NB or NC-2500
  - First step in moving towards permitting Section XI (or similar) acceptance criteria for Repair/Replacement butt welds

ASME III N-818 Case - Flow Chart & Approach

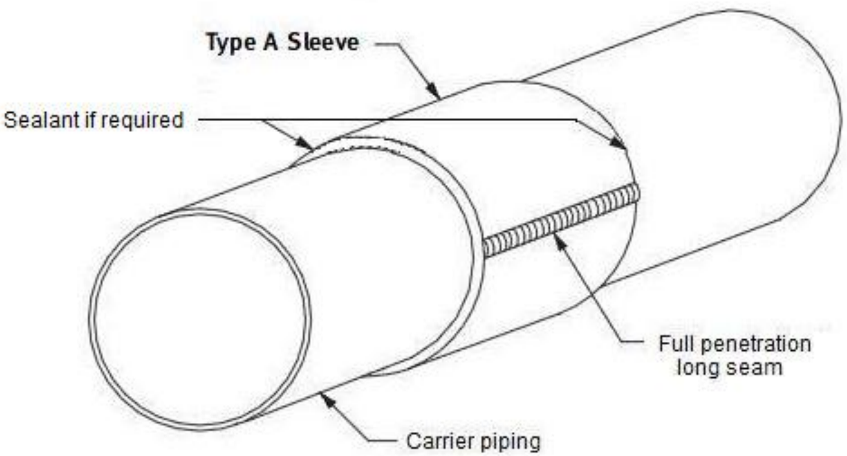


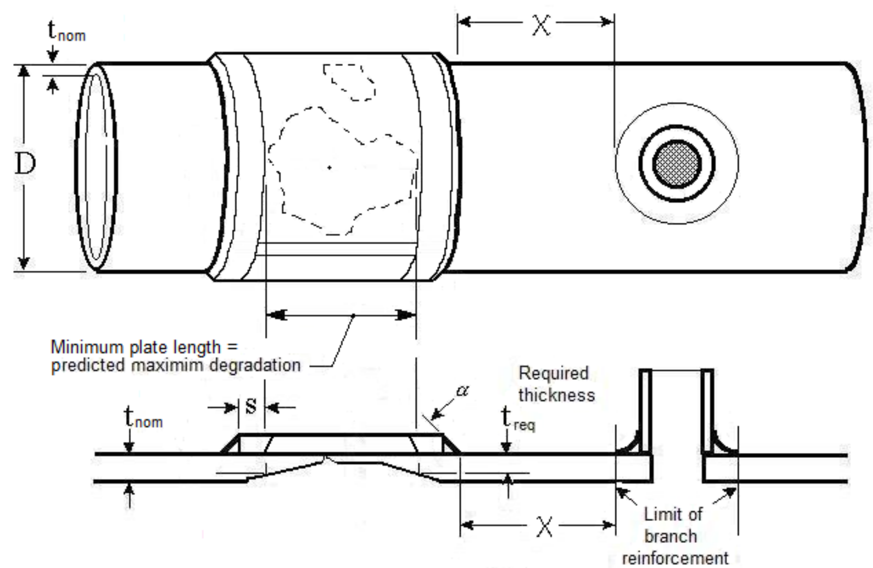
N-786 & N-789 Pad/Sleeve for Leak Mitigation

- **N-786 Sleeve Reinforcement of Class 2 & 3 Moderate Energy CS Piping**
  - Permits 360 split sleeve repair of degraded piping (wall thinning with or without leakage)
  - Permits reinforcement Type A (open ends) split sleeve or full structural Type B (sealed ends) split sleeve
- **N-789 Pad Reinforcement for Raw Water Piping**
  - Permits structural pad or pressure pad repair of degraded and/or leaking raw water piping
  - Permits 360 (sleeve) or partial (pad) repair of degraded raw water service piping (wall thinning with or without leakage)

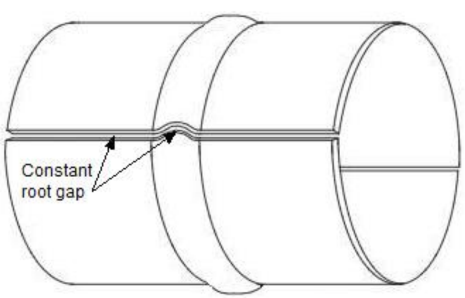
N-786 Full Sleeve

Type A Sleeve (left) or Type B Sleeve (right)





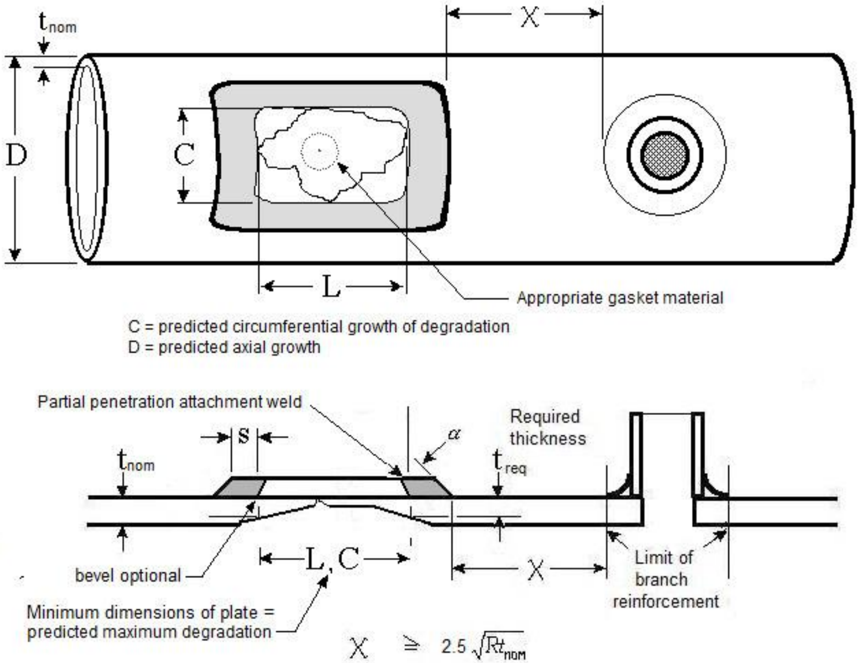
$X \geq 2.5\sqrt{Rt_{nom}}$

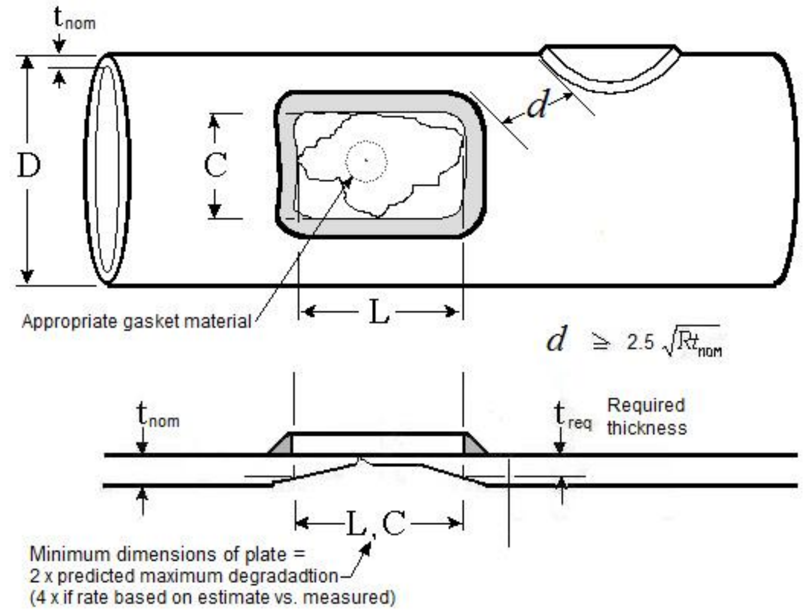


sleeve with groove weld clearance

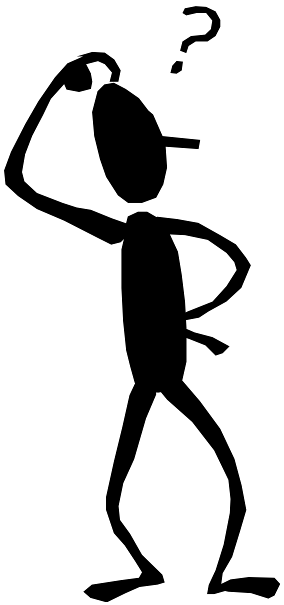
N-789 Partial Pad (plate)

Structural Pad (left) and Pressure Pad (right)





Thank You – Questions or Comments?



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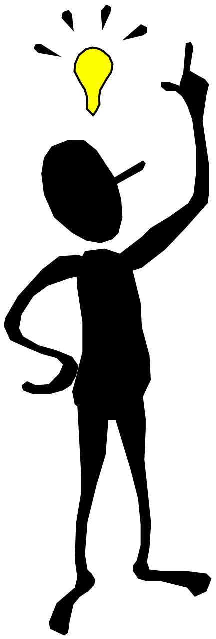
Welding and Repair Technology Center



Together…Shaping the Future of Electricity

Welding and Repair Technology Center Overview – Roadmap Development

Welding and Repair Technology Center

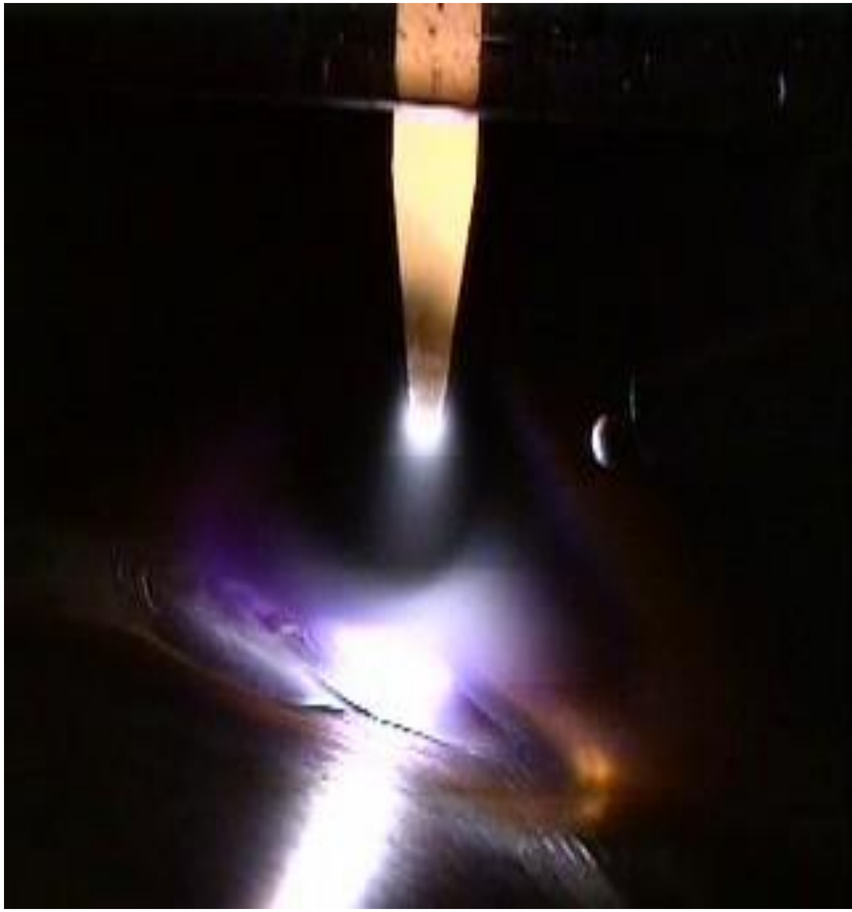
Program Manager – Greg Frederick

Program Chair – Dan Patten

January 24, 2012

WRTC Strategic Plan (Roadmaps)

- Integration of WRTC into Materials APC (Mission statement/strategic plan)
  - Identification of technology gaps in the area of welding, repair and mitigation.
  - WRTC roadmaps developed to communicate a project plan to address fundamental technology gaps (Solutions)
  - Six technology gaps or roadmaps were identified in the area of welding and repair
    - Fundamental R&D
    - Tactical or Emerging Issues



WRTC Roadmap Alignment with Strategic Plan

Roadmap development

- Three area were highlighted for further development (2011)
  - Develop new welding technology and guidance for the repair of highly irradiated material (PWR and BWR Internals)
  - Alloy 52M nickel-base filler metal weldability solution
  - Develop a new SCC resistant nickel based or alternative alloy with high weldability for dissimilar metal weld applications

WRTC Roadmap Alignment with Strategic Plan

Roadmap development

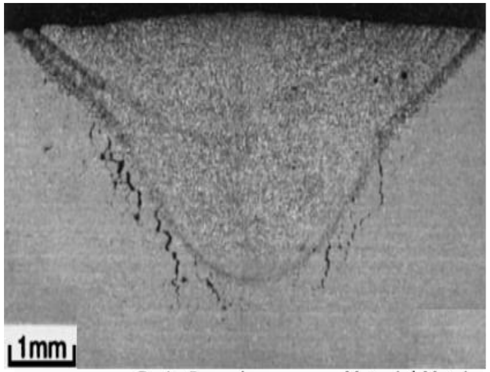
- Three additional roadmaps assigned in 2011 (2012 RM)
  - Transfer Fabrication, Repair and Joining technology into Codes
    - Promote consistency in Code requirements
  - Development of Advance Welding Processes for Nuclear Power Industry
    - Residual Stress Assessment Solutions
    - Welding Impact on Inspectability
    - Production Rates
  - Small bore piping asset management (High cycle fatigue)

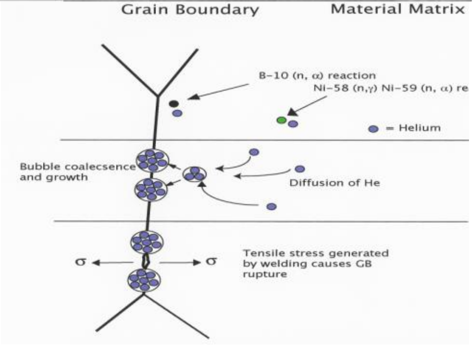
WRTC – Key Activities Roadmaps

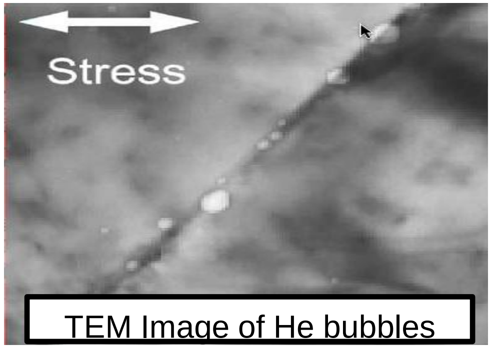
Weldability of Irradiated Materials

Develop welding technology and guidance for irradiated material (PWR and BWR Internals)

Asano et al. J. Nucl. Mat. 264 (1999)1-9





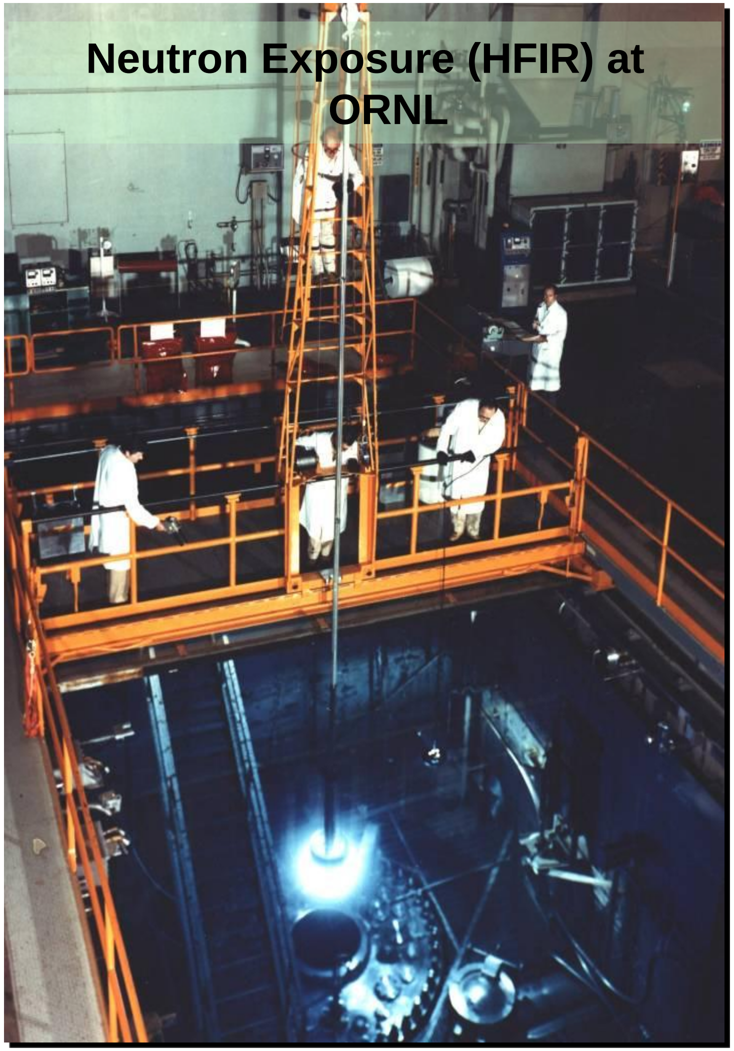


ISSUE STATEMENT

- *Continued operation of light water reactors will require repairs or replacement of reactor internal components as degradation occurs (Welding will play an important role)*
- *Weldability of the materials is altered by the formation of helium (helium-induced cracking)*

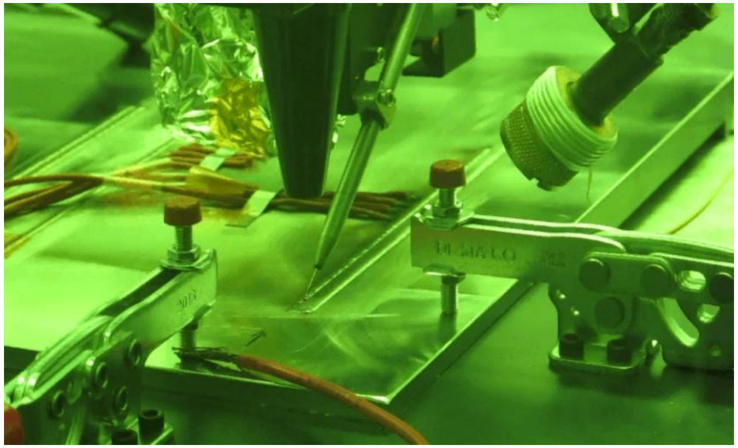
WRTC Integrated Approach to Welding Solutions for Irradiated Material

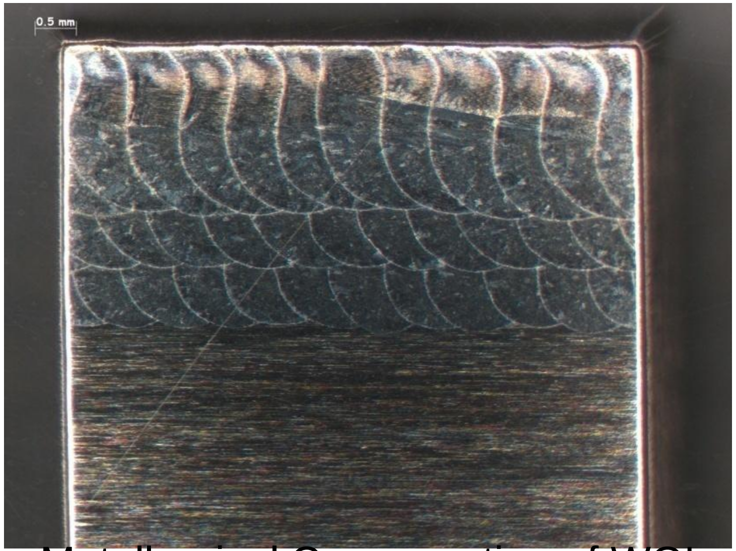
- Project Tasks
  - Develop advanced welding technology required for reactor repairs
    - Establish welding process capabilities
      - Laser welding and hybrid laser welding development
      - Assessment of Friction Stir Welding
    - Goal….Creation of a wider repair welding window for non-repairable materials
  - Work with the BWR-VIP to develop model for weldability predictions for irradiated material
  - Work with the MRP to develop thermal fluence and weldability maps for the three PWR design.
  - Work with LTO/DOE to develop hot lab weld testing evaluations and produce neutron irradiated sample set for weld tests.



Irradiated Material Weldability - Advance Welding Process

- Installation of fiber laser welding cell and manipulation system at EPRI Charlotte facility
  - Initially was working directly with WEC at Charlotte facility on UW welding.
- Welding experiments to support modeling and process improvements.
  - Temperature profile
  - Surface strain and residual stress improvement
  - Low dilution parameters
  - Evaluation of base metal interactions (hot cracking)
  - Crack sealing capabilities





Metallurgical Cross-section of WOL

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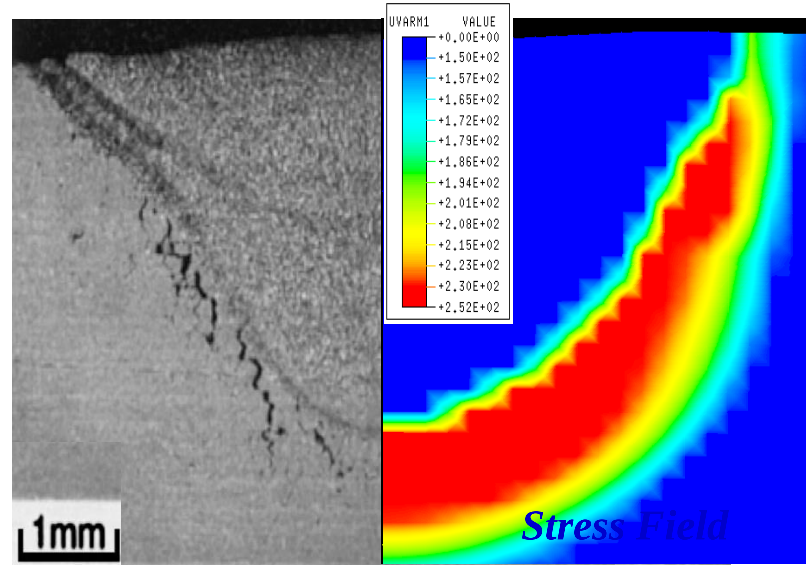
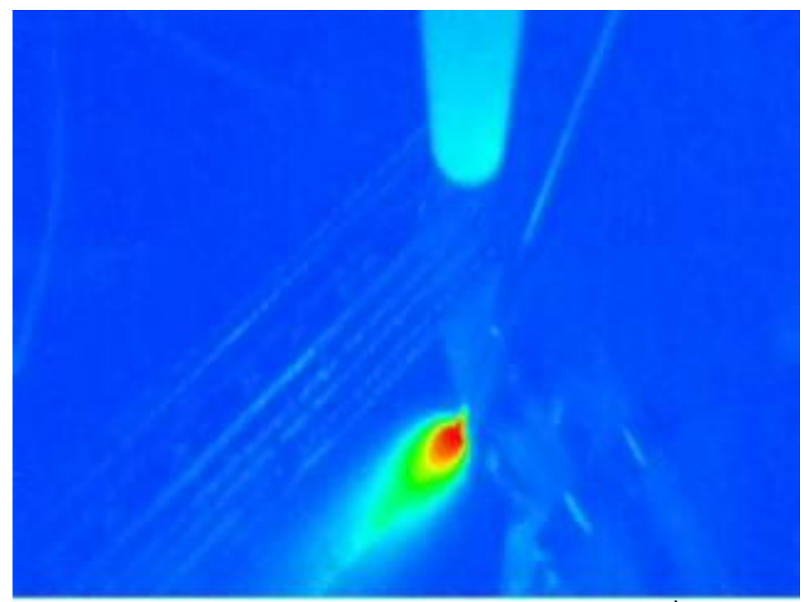
Irradiated Material Weldability - Advance Welding Process

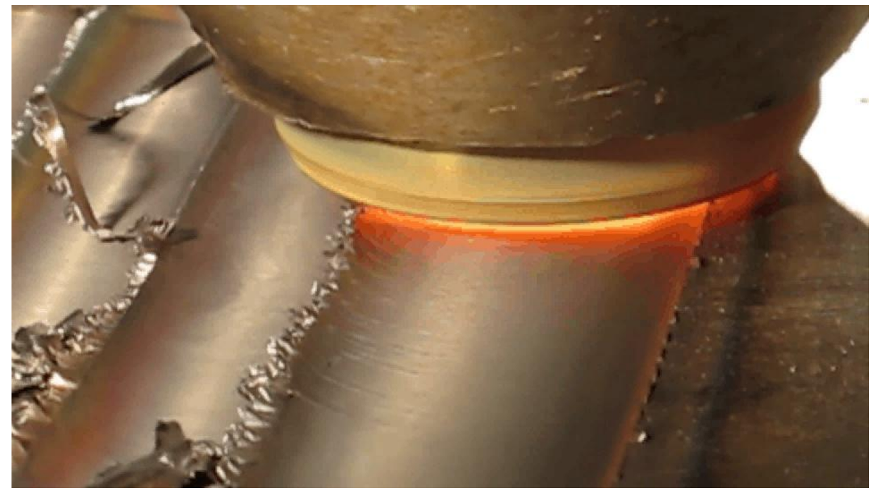
- Development Modeling Simulation to Guide Process Development and Predictive Application on Irradiated Materials
- Development of advanced computational model for hybrid welding processes
  - Develop experiment methodology for direct measurement of transient high-temperature and stress history during welding
    - Goal…..Optimize the weldability of irradiated material

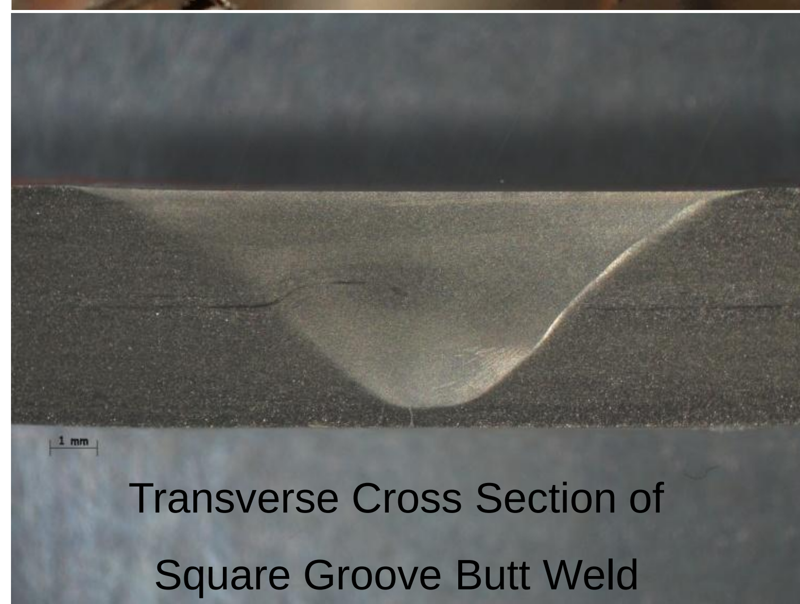




Irradiated Material Weldability - Advance Welding Process

- Friction Stir Welding (FSW) is a new, novel solid-state joining process
  - Welding methods does not produce a molten weld pool
  - Potential capability to weld on highly irradiated reactor materials
    - Significantly different stress profiles are expected
    - Preliminary simulation suggesting much slower He bubble growth in FSW
    - Welding trails have shown that FSW can be applied on the material typical of internals and vessel attachments
    - Has been successfully demonstrated for crack sealing
    - Process creates fine grain structure (improves inspectability and reduces susceptibility for hot cracking





Transverse Cross Section of

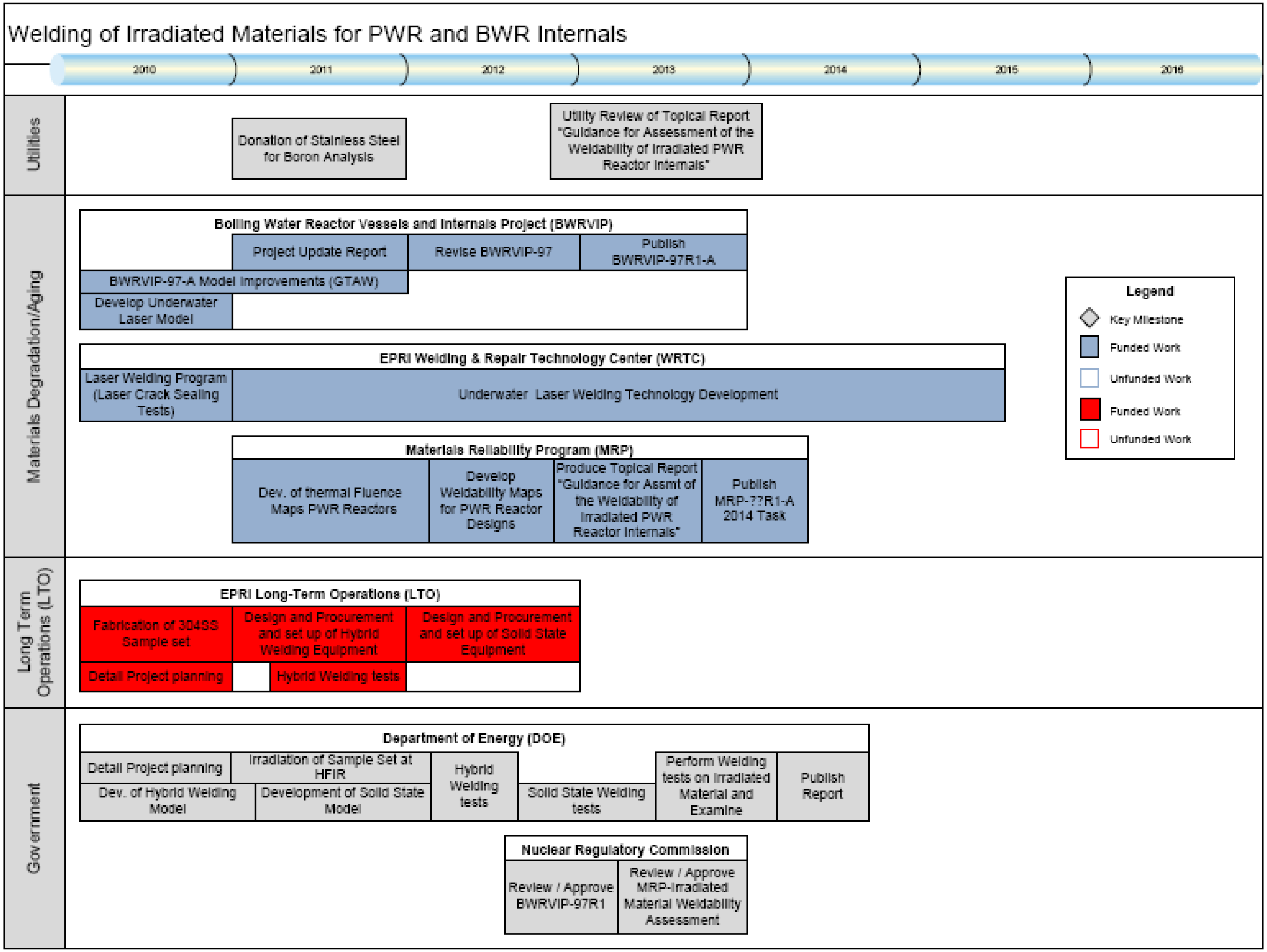
Square Groove Butt Weld

Irradiated Material Weldability - Advance Welding Process

EPRI is participating in the design and development of a new welding hot cell (ORNL)

- Welding Capabilities:
  - Conventional and hybrid laser
  - Friction stir welding
  - Powder coating
  - Cold spray
  - Inspection capabilities
  - Monitoring and material evaluations

Develop welding technology and guidance for irradiated material (PWR and BWR Internals)



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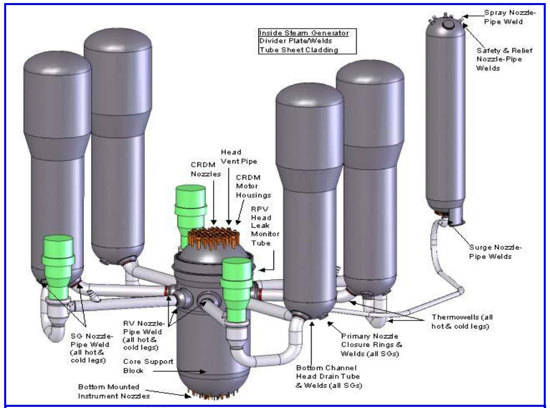
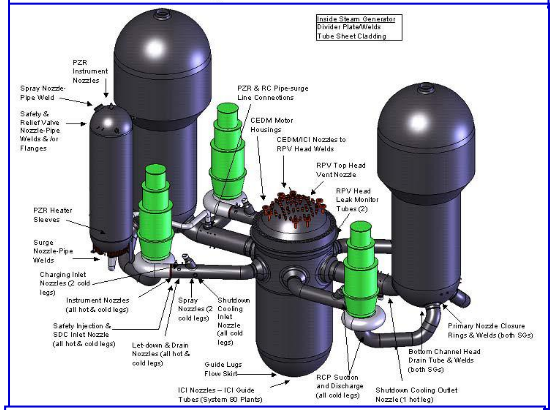
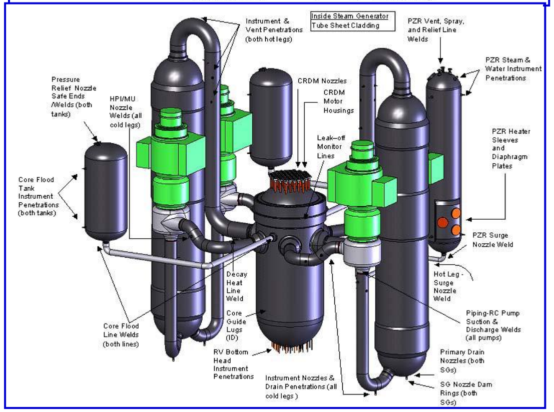
WRTC – Key Activities Roadmaps

Alloy 52M Weldability Solutions

Alloy 52M Nickel-Base Filler Metal Weldability Solutions







ISSUE

- INCONEL 182 filler metal extensively used in dissimilar metal welds for critical reactor coolant system components
  - NiCrFe-3 or Alloy 182; Ni = 59%, Cr = 17% max.
- To address primary water stress corrosion cracking (PWSCC)issues associated with Alloy182, a higher chrome alloy (Alloy 52(M) is currently required for mitigation, repair and replacement activities
  - NiCrFe-7(A) or Alloy 52(M); Ni= 59%, Cr = 30%

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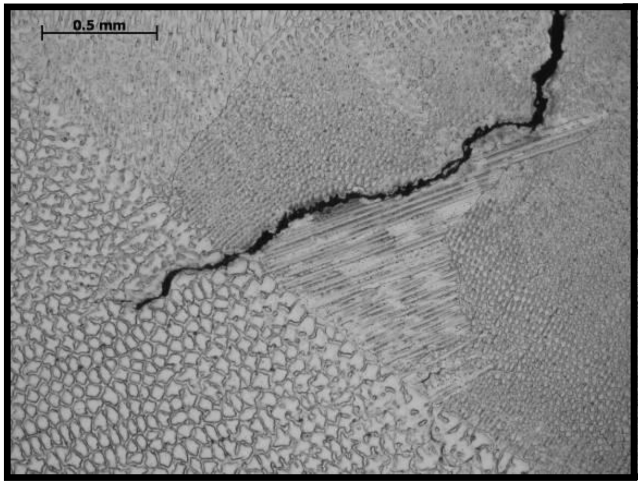
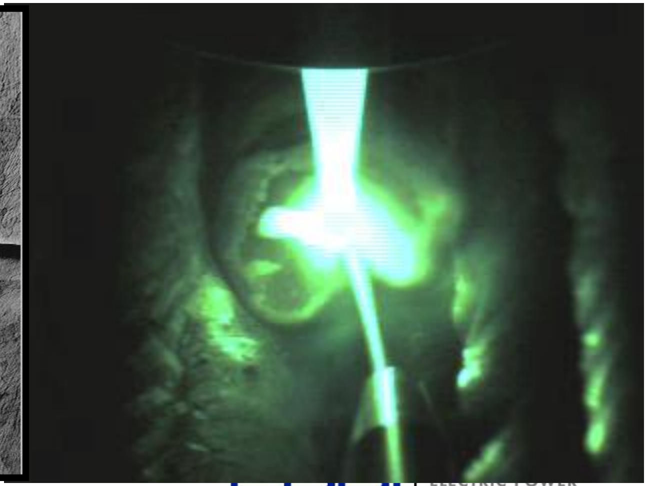
Alloy 52M Nickel-Base Filler Metal Weldability Solutions

Issue

- Weldability and crack susceptibility of 52 and 52M are complex and will continue to plaque the industry
- Adequate composition limits, narrow process controls and ranges, special requirements for isolating susceptible base materials and experience are required





Alloy 52M Nickel-Base Filler Metal Weldability Solutions

Goal

- Establish base material interactions based on chemistry and verify susceptibility to hot cracking and DDC.
- Assess welding process controls to assist with weld dilution and cracking.
- Evaluate and develop new processes to control material interactions associated with welding.
- Develop chemistry limitation equation (guidance).

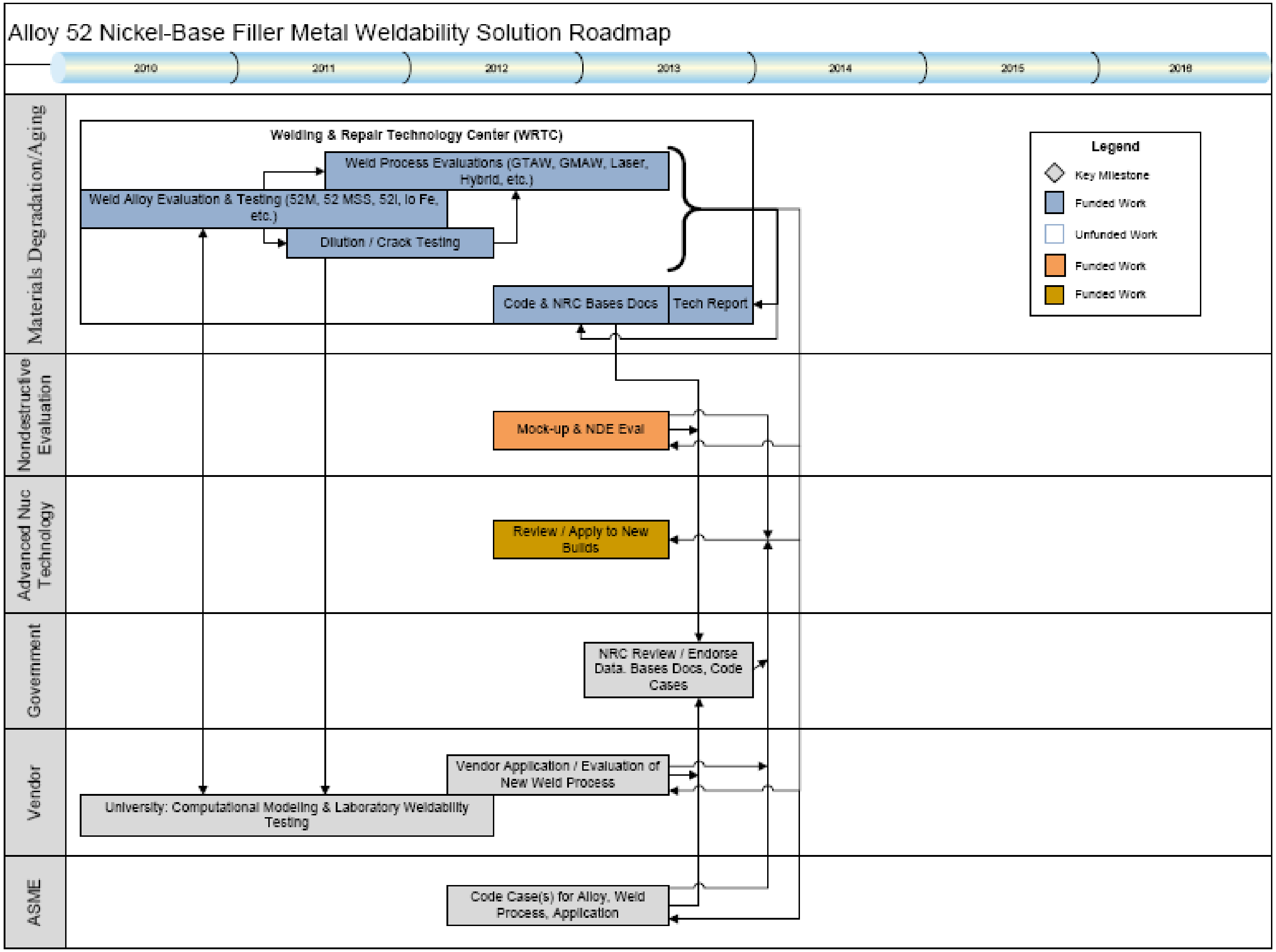
Welding Process Evaluation

- Laser welding
  - Conventional laser (wire)
  - Diode laser (powder, wire)

- GTAW process
  - Conventional GTAW
  - Magnetic Stir
  - Variable polarity welding conditions
  - Pulse Welding

- GMAW process
  - CMT (Fronious)
  - Waveform controlled processes

Alloy 52M Nickel-base filler metal weldability solution



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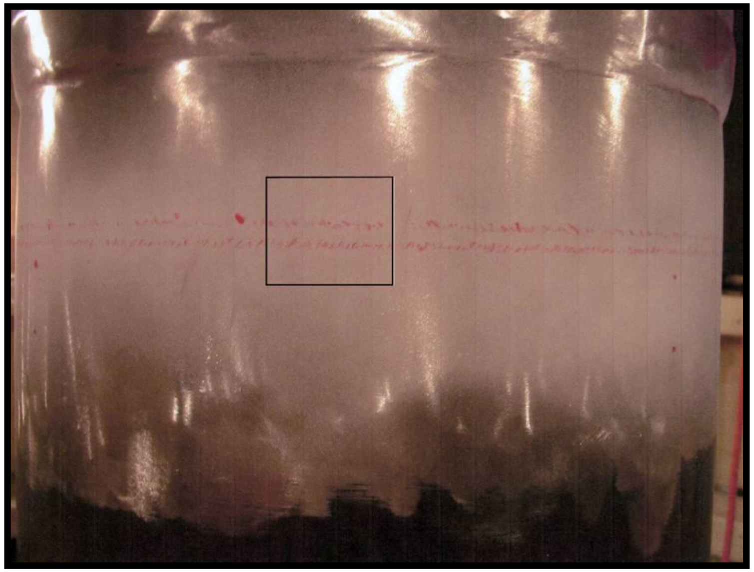
WRTC – Key Activities Roadmaps

New SCC Resistant Alloy

Motivation and Objectives

- Alloys 52 and 52M currently used for PWSCC mitigation repairs and new component fabrication
  - Developed to be similar to Alloy 690 base material to maintain similar resistance to PWSCC
  - 52 and 52M are susceptible to weld metal cracking and have less than optimum weldability



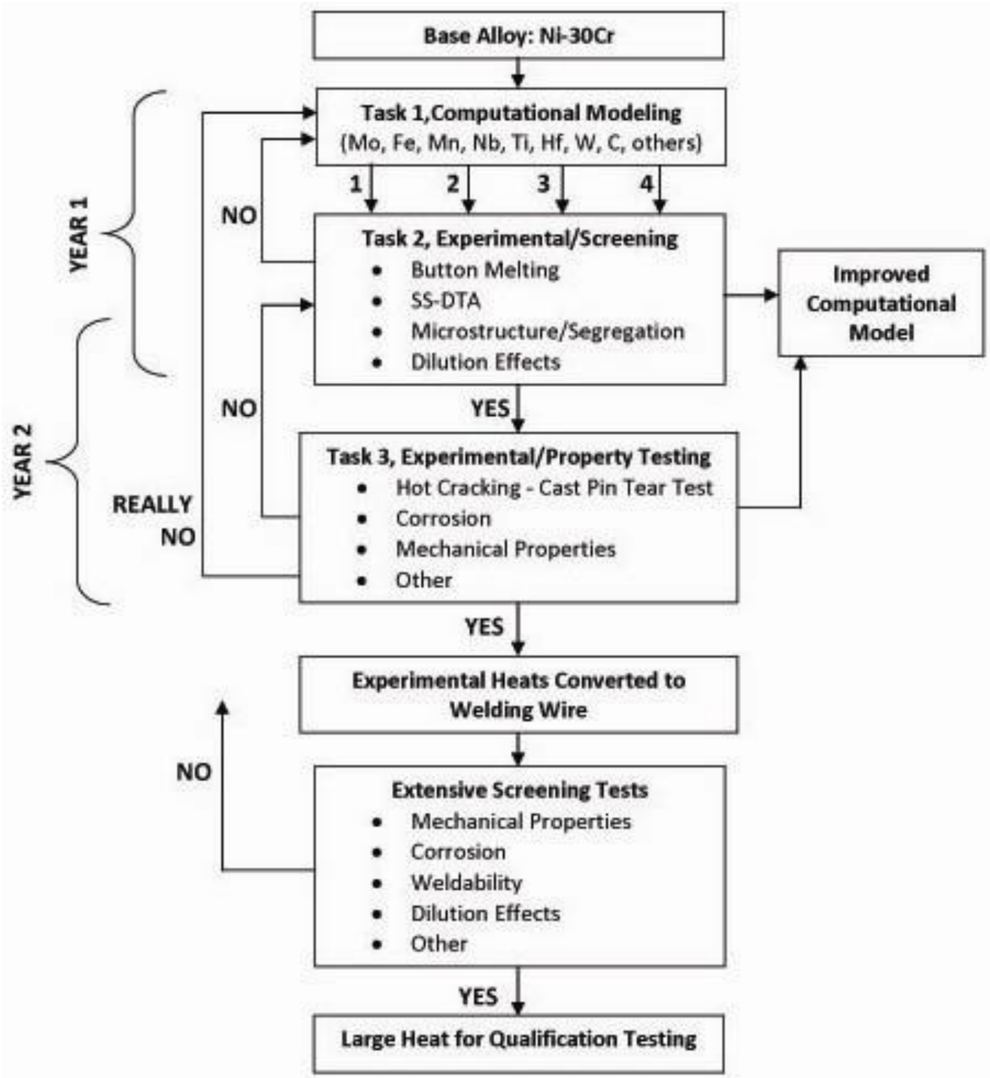
Motivation and Objectives

- New high-chromium weld alloy must have:
  - Significantly improved weldability and superior resistance to weld cracking (i.e., solidification cracking and ductility-dip cracking)
  - Maintains superior corrosion resistance (i.e., resistant to PWSCC)
  - Maintains mechanical properties similar to Alloy 690
  - Compatible with stainless steel and carbon steel

Alloy Development Scope

- Fundamental research performed to understand cracking mechanisms and weldability problems
- Development of alloy composition
  - Model welding behavior and mechanical properties of target compositions
  - Validate modeled behavior with experimental weld wire heats
  - Perform mechanical, corrosion, and crack growth rate testing
- Assess welding and nondestructive evaluation of alloy composition
  - Assess process parameters for gas tungsten arc and gas metal arc welding
  - Large scale mockups and assessment of nondestructive evaluation
  - Assess feasibility of alternative advanced welding processes (laser welding, magnetic stir, hybrid, etc.)

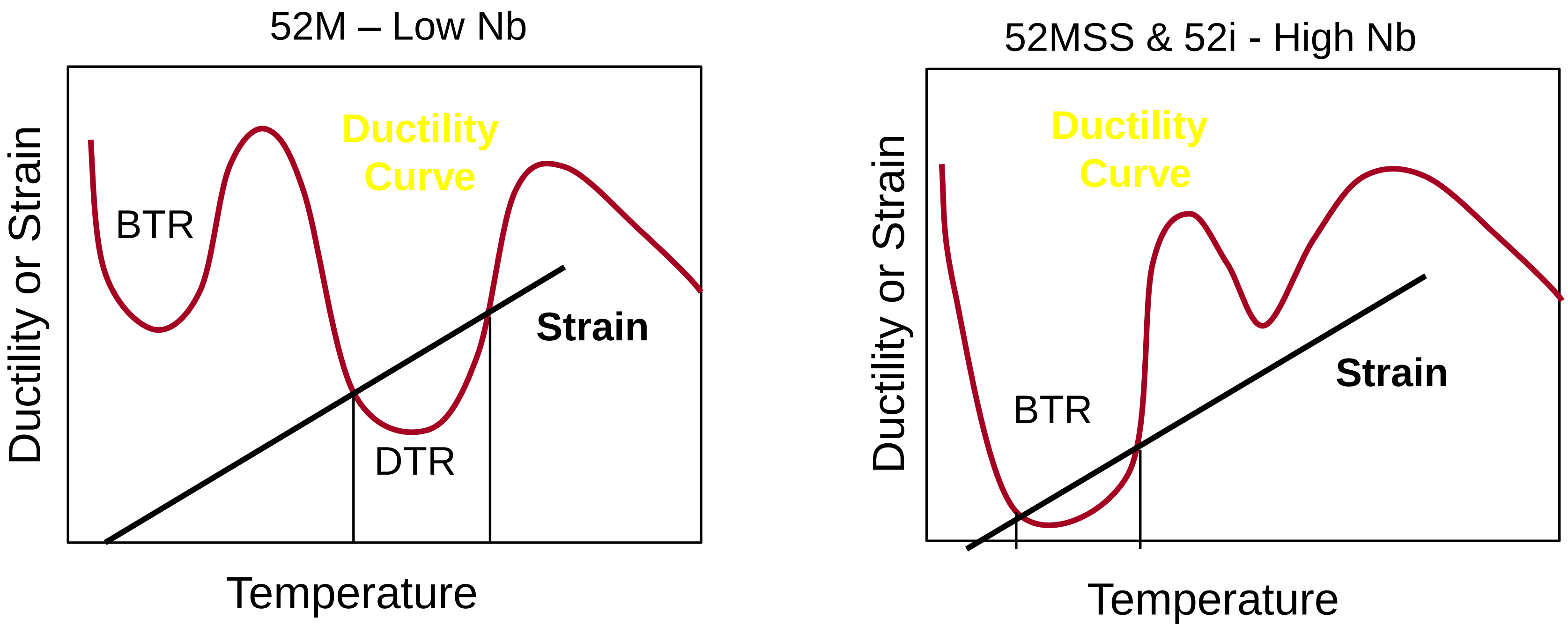
Filler Metal Development Approach



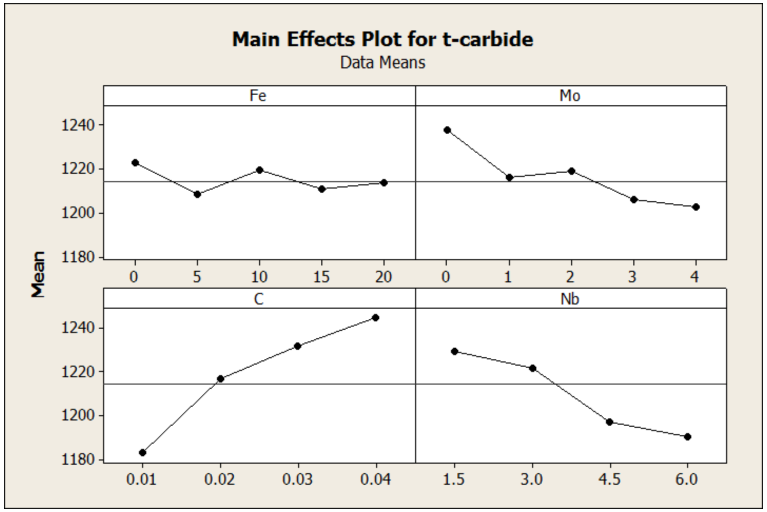
- EPRI project to develop a new filler metal was kicked off in fall of 2010
- Base composition is 30% Cr nickel-base
- Initial computational modeling at conducted to study solidification behavior and 2nd phases at the end of solidification (complete)
- Button melting experiments at OSU are in process
- New CPTT with levitation melting capability and optimized mold design developed
- ESI ProCast models to be developed to calculate strain during CPTT

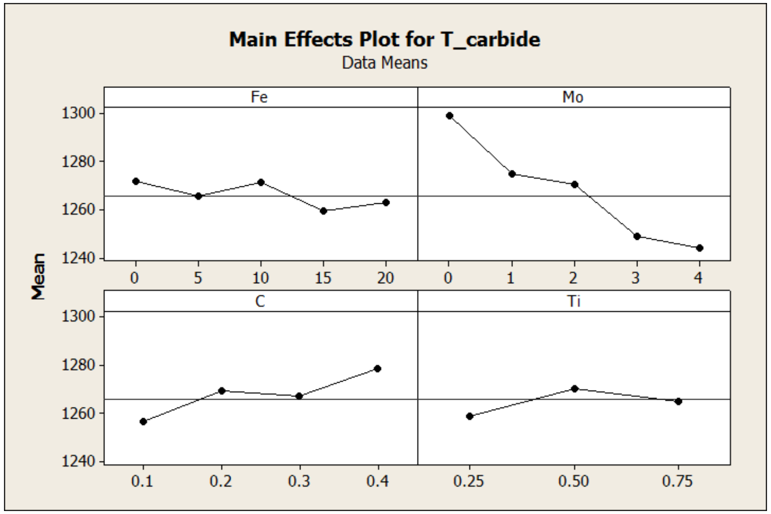
Solidification Cracking versus DDC

- Filler metals 52MSS and 52i contain 2-3 wt% Nb
  - Eliminates DDC by formation of NbC
  - Potential increase in solidification cracking susceptibility



Computer Modeling





- Computer computational modeling (ThermoCalc™) used to select four compositions for testing
- Solidification temperature range and carbide start temperatures calculated
- Design of experiments (DOE) used to evaluate four-element systems
- Main effect plots made to determine influence of variations in minor element additions

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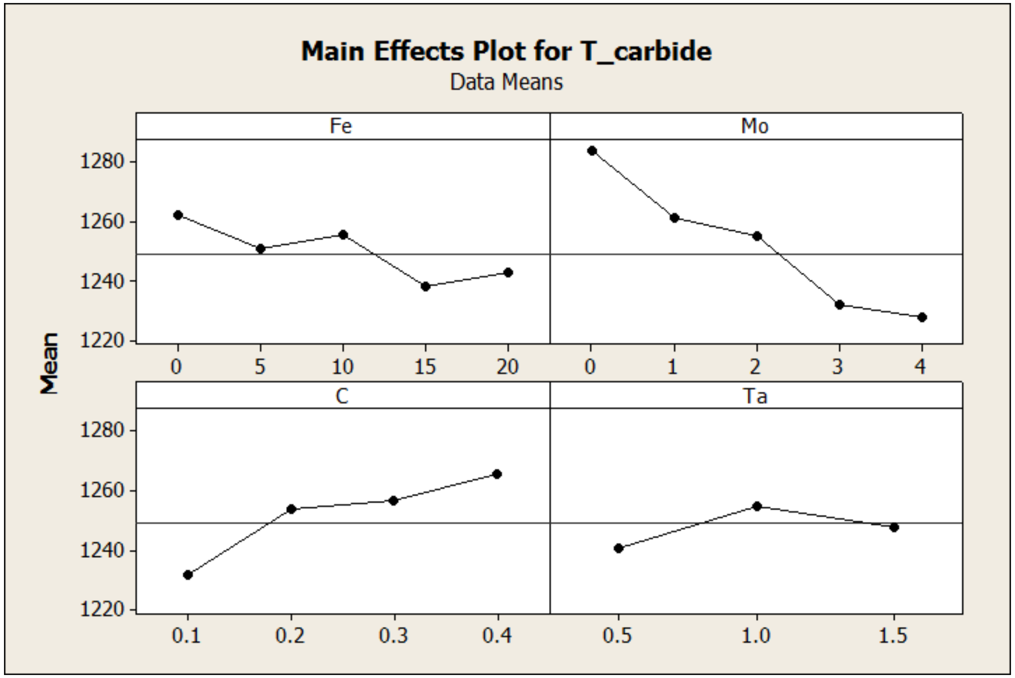
Model Based DOE

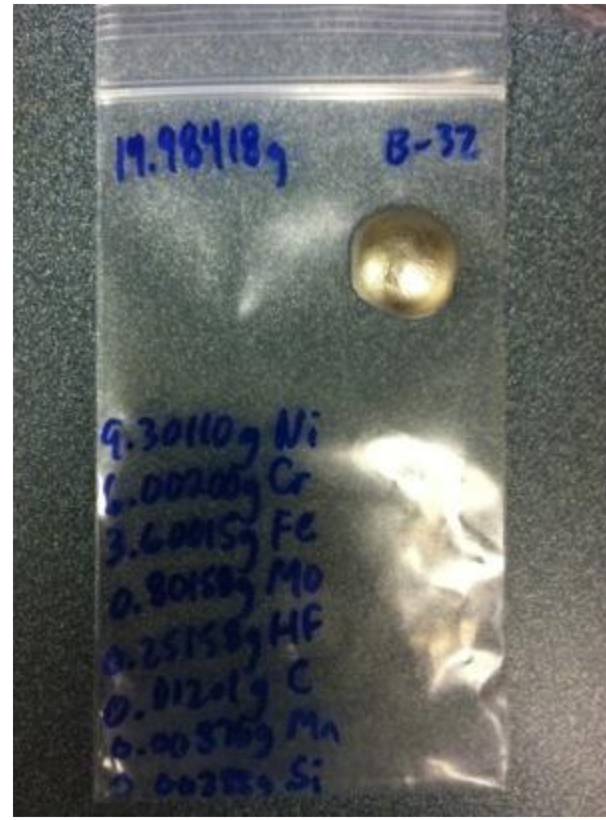
- All elements work to increase STR
- Ta, Hf have slightly lower STR's than Nb
- Mo works strongly to decrease $T_{Carbide}$
- No significant 2^{nd} order interactions
- Refine by experimental DOE



Experimental DOE

20g Buttons with Ni-30Cr and:

Element	Range(wt%)
Fe	8-18
Mo	0-4
Hf	0.5-2
C	0.02-0.06



Weighed to within 1% of target

High purity components

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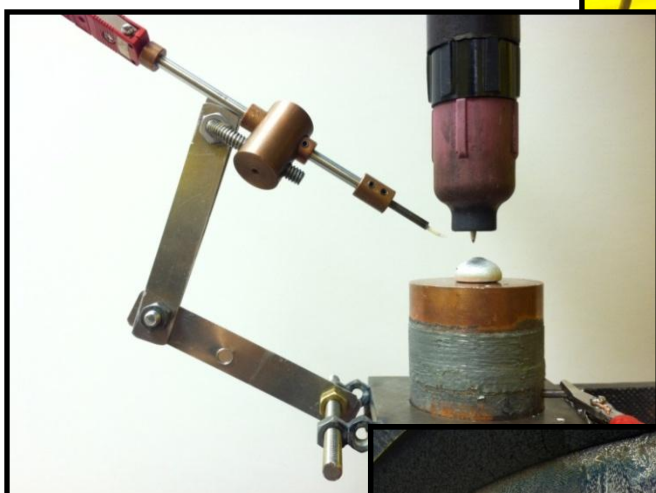
Button Melting Tests

30% Cr Filler Metal Development Project



- Buttons are partially re-melted by GTAW
- Cooling curve is measured by plunging a Type-C thermal couple into the weld metal
- Solidification temperature range and eutectic start are measured by SS DTA technique
- Solidification grain boundaries are evaluated by SEM to determine low melting point constituents that coat the solidification grain boundary and cause hot cracking

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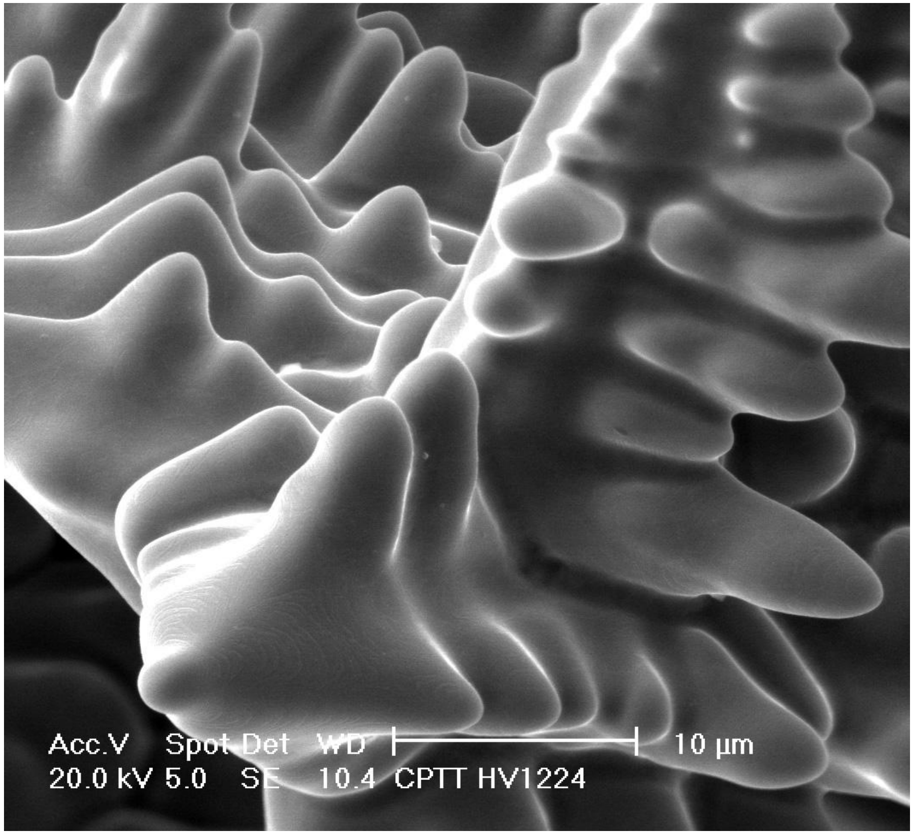
Acknowledgements



52MSS-B equiaxed dendrite
(Courtesy of Adam Hope)

OSU Professors:
John Lippold and Suresh Babu

OSU Students:
Adam Hope and Eric Fusner

Modeling DOE, Button Melting, SS-DTA , SEM/EDS

EPRI Technology Innovation

Project Funding

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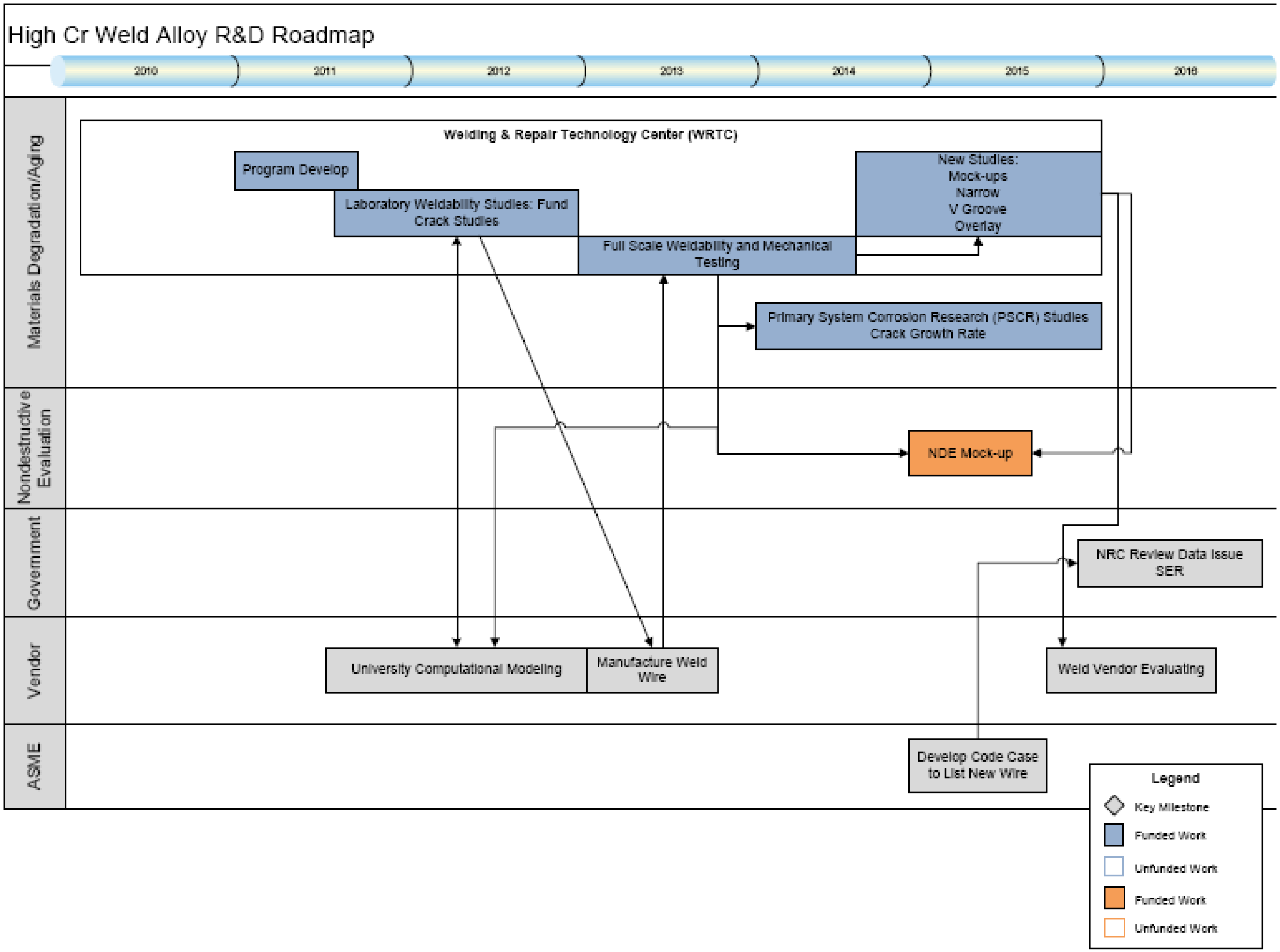
Develop a new SCC resistant nickel based or alternative alloy



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52M Solidification Cracking Study

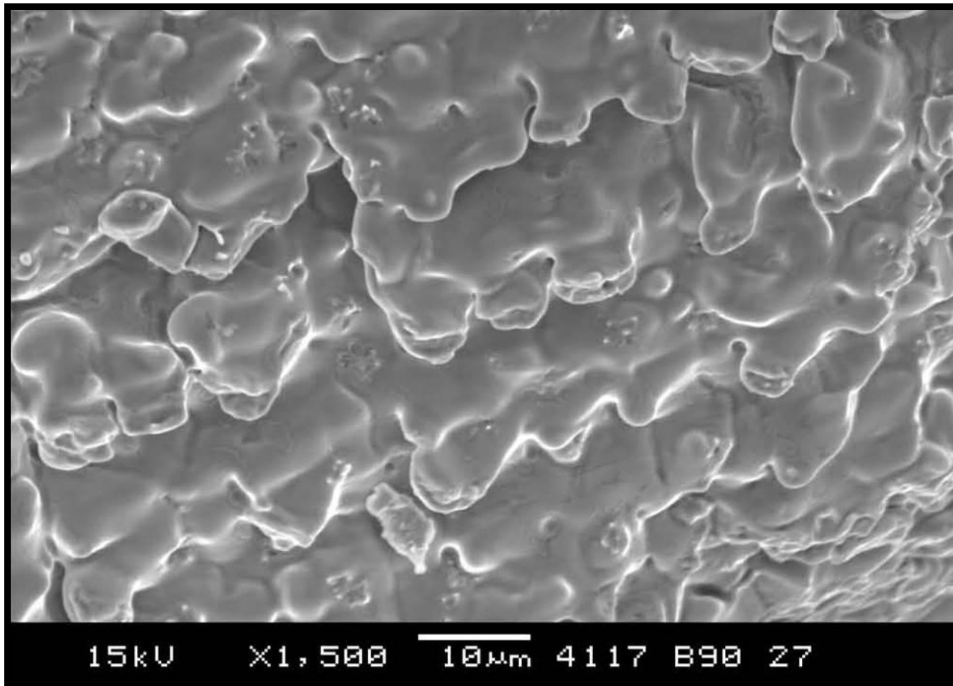
Jon Tatman & Steve McCracken
EPRI – Welding and Repair Technology Center

NRC – Industry Meeting

PWR Materials Reliability and Weld Repair Research

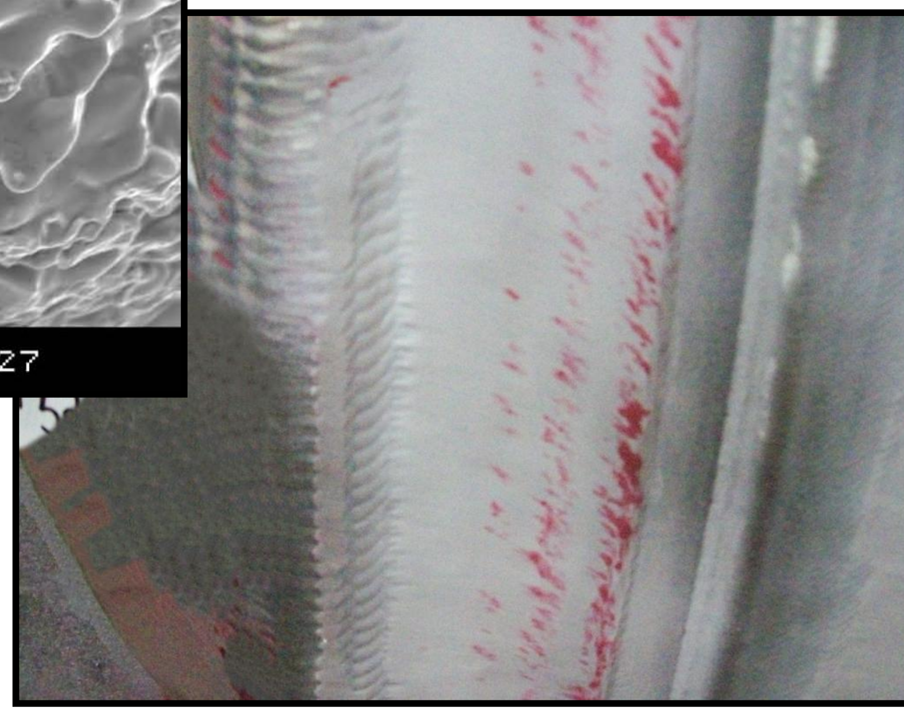
Charlotte North Carolina
January 24, 2012

Problem – 52M Solidification Cracking on CAS



Example of 52M hot cracking on CF8A pipe clad with ER308L

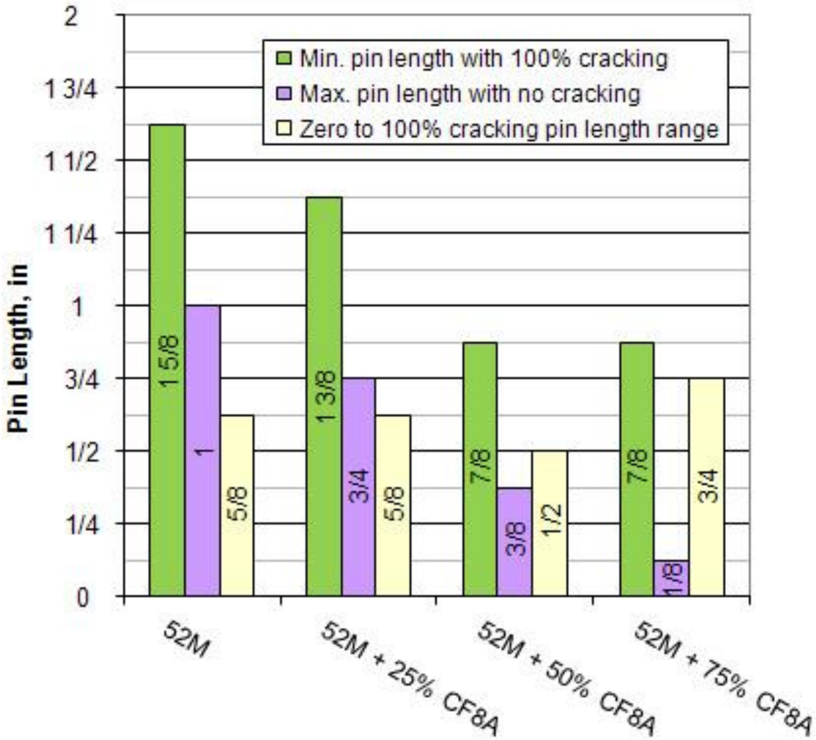
Base metal is SA-351 CF8A
0.019% S, 0.032% P, 0.72% Si

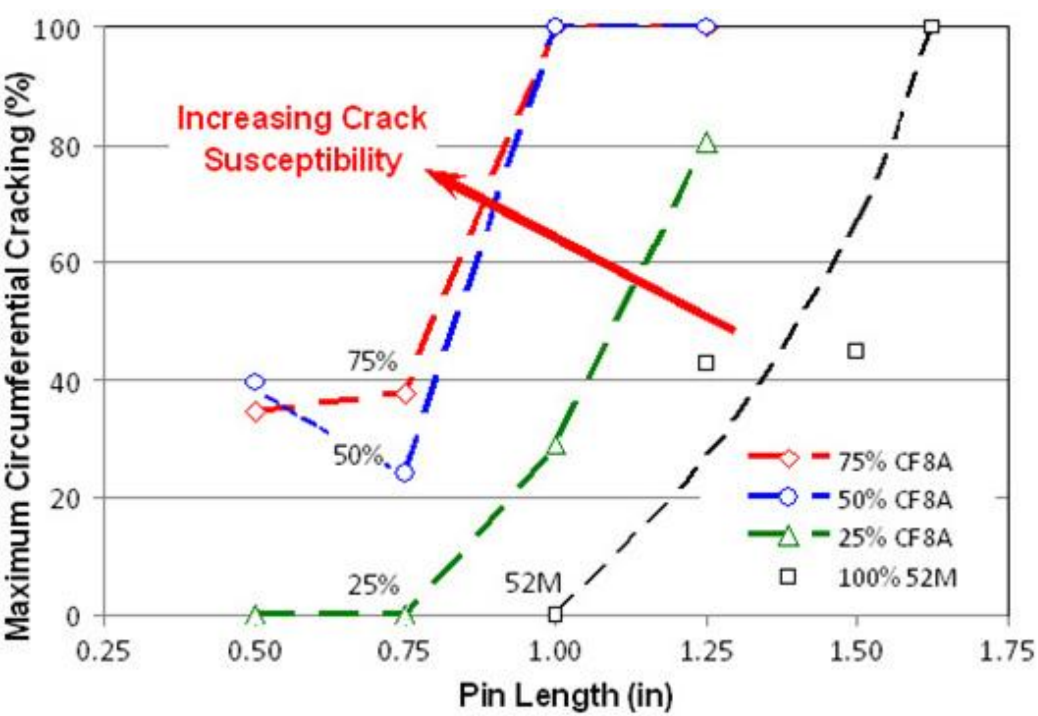


- *SEM of hot crack (above) in boat sample removed from 52M deposit*
- *52M layer (right) shows multiple liquid penetrant crack indications*

CF8A Dilution Study with CPTT

	Cr	Ni	Fe	Mn	Si	Nb	Al	Ti	Mo	C	S	P
52M	29.75	58.93	8.75	0.74	0.11	0.93	0.13	0.19	0.08	0.020	< 0.001	< 0.01
CF8A	20.9	8.4	70.6	0.59	0.92	---	---	---	0.05	0.04	0.015	0.020
25%	27.5	46.3	24.2	0.70	0.31	0.70	0.10	0.14	0.07	0.025	0.005	0.0125
50%	25.3	33.7	39.7	0.67	0.52	0.47	0.07	0.10	0.07	0.03	0.008	0.015
75%	23.1	21.0	55.1	0.63	0.72	0.23	0.03	0.05	0.06	0.035	0.012	0.0175





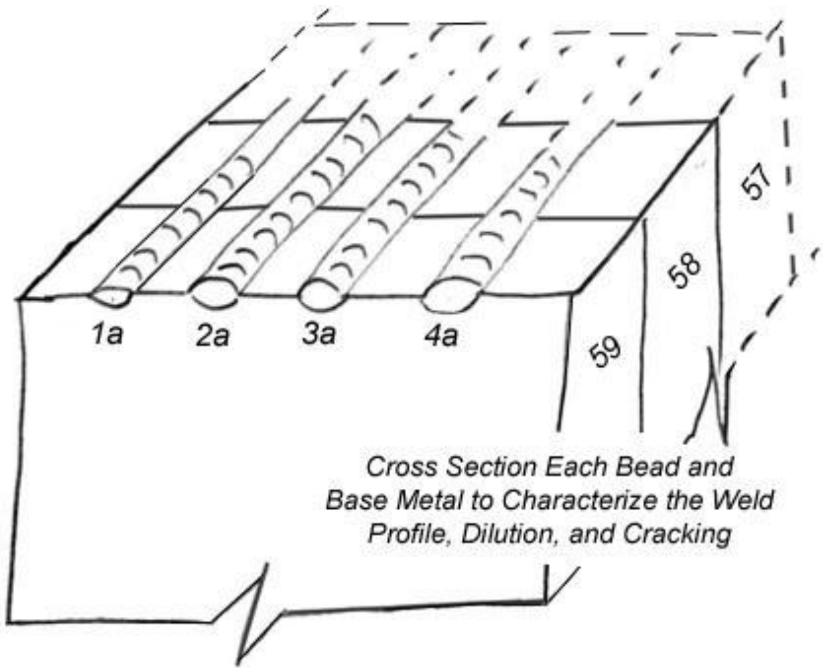
Issues and Questions to be Answered

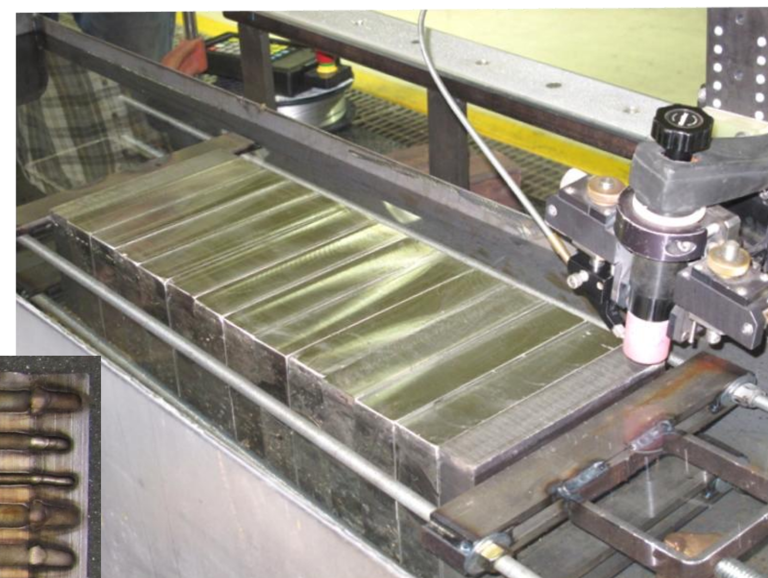
- Need to understand influence of austenitic stainless steel dilution on high chromium nickel-base filler metals used in the nuclear industry
  - What is level of dilution with stainless steel that causes solidification cracking in 52M?

    Testing to date shows 52M diluted with ~35% Fe increases susceptibility to hot cracking

  - What S & P and Si threshold(s) cause solidification cracking?
  - What is influence of Si on dilution and potential for increasing risk for solidification cracking?

Bead-on-Plate Testing at WRTC





Base Metal Samples & Filler Metals Tested

- Base metal sample matrix:
  - 6 cast austenitic stainless steel (CASS) samples
  - 4 powder metal (PM) samples
  - 2 303 plates, one with 2 layers & one with 4 layers of ER308L
  - 4 303 plates, one each with 1, 2, 3, & 4 layers of ER308L-Si

Desired matrix will bound CF8A composition range of domestic PWR reactor coolant primary water CASS piping

S & Si wt% target compositions are:

Sulfur	*Low - Med - High*
	0.001 - 0.020 - 0.040
Silicon	*Low - Med - High*
	0.05 - 0.90 - 1.80

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Table of Measured Compositions

Material Type	Sample ID	Element C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Nb	Ti	Fe
CASS CF8A	57	0.0227	0.0817	0.756	0.0246	0.0031	19.92	0.400	8.88	0.0014	0.0302	< 0.0040	0.0040	69.8
	58	0.0695	0.0752	0.797	0.0319	0.0046	19.93	0.401	8.61	< 0.0010	0.0277	< 0.0040	0.0045	70.0
	59	0.0431	0.0695	0.754	0.0288	0.0023	19.98	0.404	8.45	< 0.0010	0.028	< 0.0040	0.0036	70.2
	60	0.0405	0.945	0.744	0.0261	0.0019	20.02	0.402	8.45	0.0016	0.0273	< 0.0040	0.0044	69.3
	61	0.0483	0.953	0.734	0.0268	0.0019	20.06	0.400	8.39	0.0017	0.0278	< 0.0040	0.0041	69.3
	62	0.0581	0.959	0.720	0.0278	0.0027	20.14	0.399	8.34	0.0026	0.0271	< 0.0040	0.0041	69.3
	63	0.0446	1.95	0.741	0.0230	0.0017	19.83	0.403	8.46	0.0023	0.0275	< 0.0040	0.0047	68.5
	64	0.0581	1.98	0.734	0.0225	0.0018	19.84	0.410	8.45	0.0025	0.0268	< 0.0040	0.0044	68.4
	65	0.0470	1.95	0.756	0.0243	0.0025	19.83	0.409	8.53	0.0029	0.0276	< 0.0040	0.0046	68.4
	66	0.0531	0.0915	0.743	0.0179	0.0023	19.93	0.406	8.52	<0.0010	0.0206	< 0.0040	0.0026	70.2
	67	0.0478	1.93	0.752	0.0440	0.0030	19.82	0.403	8.46	0.0021	0.0276	< 0.0040	0.0051	68.5
	68	0.0490	0.982	1.48	0.0255	0.0040	19.77	0.408	8.55	0.0035	0.0277	< 0.0040	0.0043	68.6
PM Type 316	54B	0.0166	0.612	0.440	0.0167	0.0324	17.89	2.82	11.85	< 0.0010	0.0345	< 0.0040	0.0064	66.1
	52B	0.0219	1.70	0.597	0.0187	0.0325	17.78	2.81	12.00	0.0021	0.057	< 0.0040	0.0074	64.8
	94B1	0.0219	1.90	0.826	0.0162	0.0042	18.02	2.76	12.37	0.0062	0.0673	< 0.0040	0.0089	63.7
	12B1	0.0380	0.537	1.26	0.0277	0.0063	16.30	2.11	10.23	< 0.0010	0.255	0.0187	0.0055	68.8
Type 303	303b (303)	0.0501	0.503	1.69	0.0296	0.324	17.44	0.279	8.26	0.0036	0.0914	0.0096	0.0055	70.7
Clad ER308L	2L	0.0247	0.436	1.64	0.0193	0.0331	18.48	0.251	9.45	0.0024	0.0471	0.0047	0.0051	69.3
	4L	0.0185	0.428	1.68	0.0191	0.0047	19.13	0.249	9.90	0.0023	0.0409	0.0045	0.0053	68.3
Clad ER308L-Si	1Si	0.0499	0.724	1.76	0.0287	0.180	18.31	0.184	8.80	0.0030	0.0717	< 0.0040	0.0056	69.5
	2Si	0.0336	0.938	1.63	0.0236	0.0426	17.88	0.0824	8.93	0.0039	0.0518	< 0.0040	0.0057	70.1
	3Si	0.0321	0.968	1.64	0.0242	0.0242	18.04	0.0613	9.07	0.0039	0.0478	< 0.0040	0.0056	69.9
	4Si	0.0272	0.996	1.66	0.0242	0.0160	18.30	0.0541	9.25	0.0045	0.0469	< 0.0040	0.0058	69.4
CF8M	J92 (pipe)	0.0484	0.552	1.13	0.0214	0.0191	20.93	2.57	11.72	0.0011	0.0336	0.0044	0.0075	62.8

Power Ratio Definition

$$Power\ ratio = \frac{Power}{Cross\text{-}sectional\ area\ of\ deposited\ metal}$$

$$Power\ ratio = \frac{Amperage \times Voltage}{\left[\dfrac{Wire\text{-}feed\ speed}{Travel\ speed} \times \begin{matrix} Cross\text{-}sectional \\ area\ of\ filler \end{matrix}\right]}$$

Weld Filler Metals & Parameter Sets

Seq No.	Alloy	AWS Specification	Heat No.	Cr	Fe	Si	Mn	C	P	S	Nb	Ti	Mo	Al	Mg
a	52M	ERNiCrFe-7A	NX76W5TK	30.12	8.68	0.11	0.77	0.02	0.003	0.00005	0.85	0.17	0.04	0.11	—
b	52M	ERNiCrFe-7A	NX74W8TW	29.75	8.75	0.11	0.74	0.02	0.01	0.001	0.93	0.19	0.08	0.13	—
d	52M	ERNiCrFe-7A	NX7588TK	29.95	8.81	0.12	0.75	0.023	0.004	0.0006	0.83	0.24	0.03	0.1	—
c	52MSS	ERNiCrFe-13	NX77W3UK	29.49	8.79	0.11	0.31	0.023	0.004	0.00005	2.51	0.18	3.51	0.13	—
e	52i	ERNiCrFe-15	187775	26.98	2.55	0.05	3.04	0.04	0.002	0.001	2.58	0.37	—	0.45	0.002
f	82	ERNiCr-3	EXD63590	21.35	0.53	0.16	2.9	0.033	0.003	0.001	2.43	0.33	—	—	—

Weld Set No.	**Bead ID No.**	Filler Metal Heat	Amps	Volts	Travel Speed, ipm	WFS, ipm (0.045)	WFS, ipm (0.035)	Power Ratio (kW/in^2)	Heat Input (kJ/in)	Shielding Gas
1a	01a-52M/PM	NX76W5TK 0.045	240	9.8	4	35	58	169.0	35.3	Argon
2a	02a-52M/PM	NX76W5TK 0.045	180	9.8	4	45	74	98.6	26.5	Argon
3a	03a-52M/PM	NX76W5TK 0.045	140	9.0	4	50	83	63.4	18.9	Argon
4a	04a-52M/PM	NX76W5TK 0.045	260	9.8	4	30	50	213.6	38.2	Argon

Liburdi Dimetrics Goldtrac VI Power Supply with G-Head

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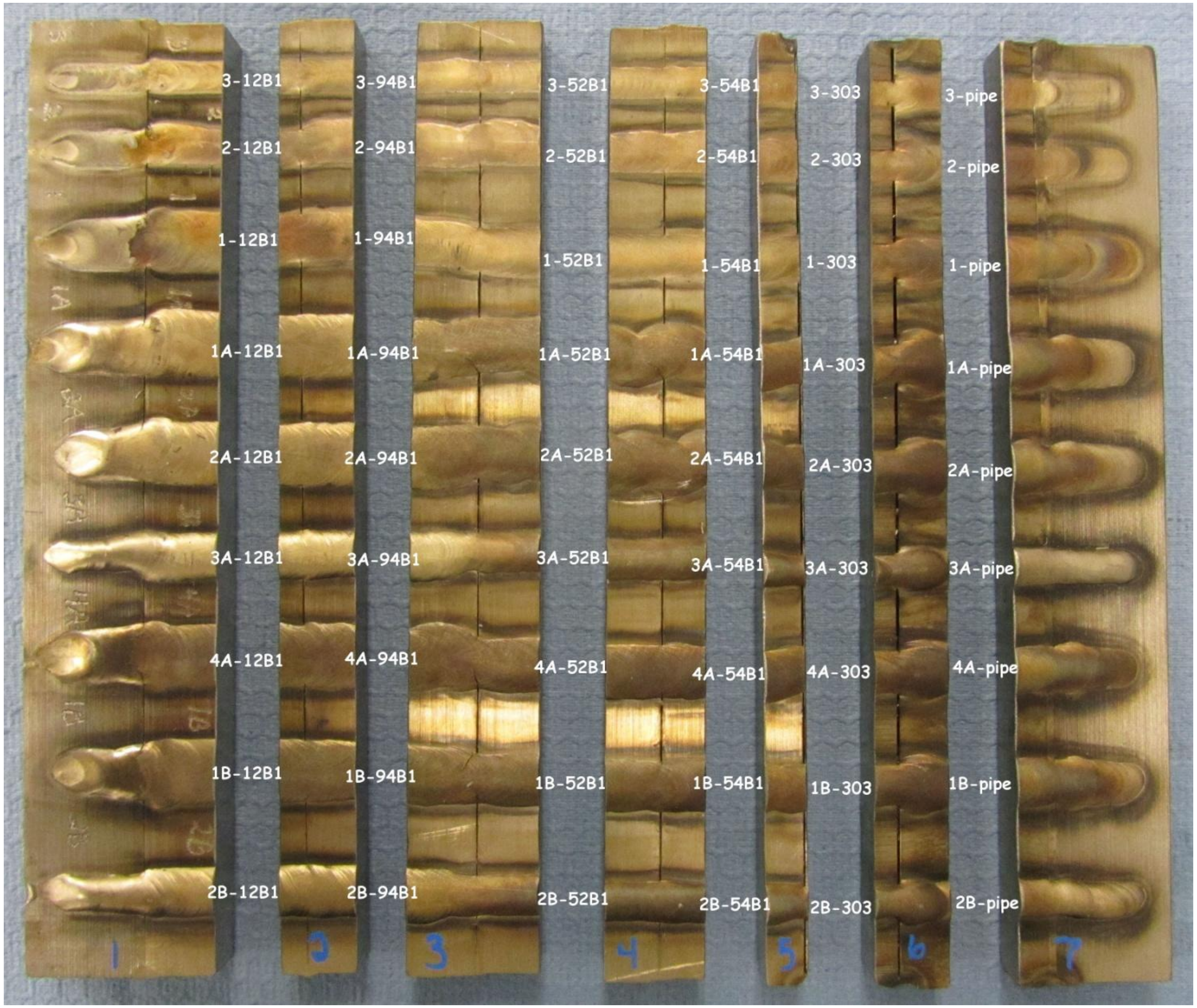
Base Metal Samples with Weld Beads



- Powder metal (PM) sample set shown
- Sample sections were cut out for mounting, polishing & crack characterization
- 303 plate and CF8M pipe included
- Note influence of adjacent base metal sample on bead shape

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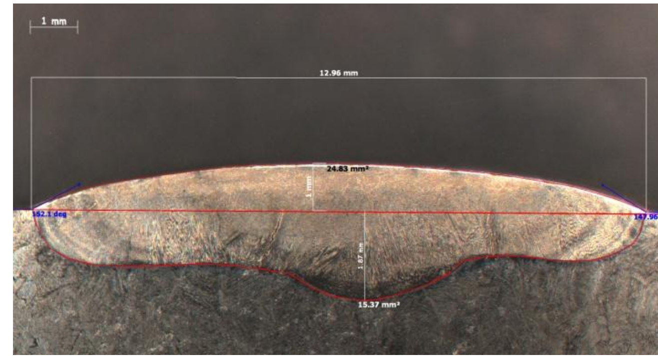
Bead Profile and Solidification Crack Analyses

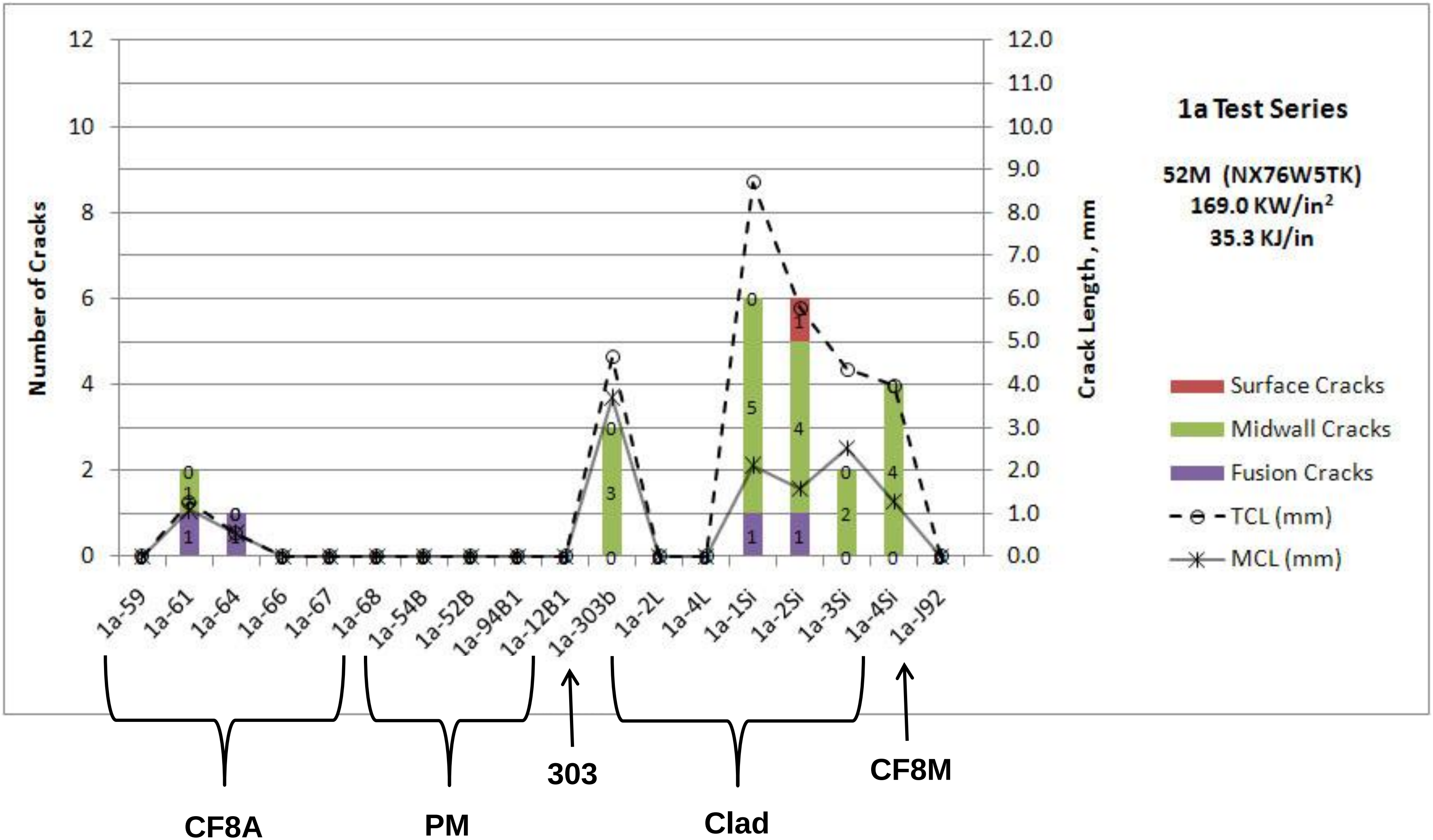
- Measured and recorded the following:
  - ✓ Composite zone areas, toe angle(s), depth, width, and penetration
- Mounts inspected for cracks at 50x
- Cracks graded as follows:
  - ✓ TNC - Total Number of Cracks > 0.2 mm
  - ✓ TCL – Total Crack Length (sum of all cracks)
  - ✓ MCL – Maximum Crack Length (single largest crack length)
  - ✓ Cracks within ≤ 0.2 mm proximity are counted and sized as one crack
  - ✓ Cracks categorization as:
    - – Surface Crack
    - – Midwall Crack
    - – Fusion Line Crack



52M Bead on CF8A Sample #63

50x Micrograph of Sample #63

Susceptibility Curve 1a – 52M (HX76W5TK)



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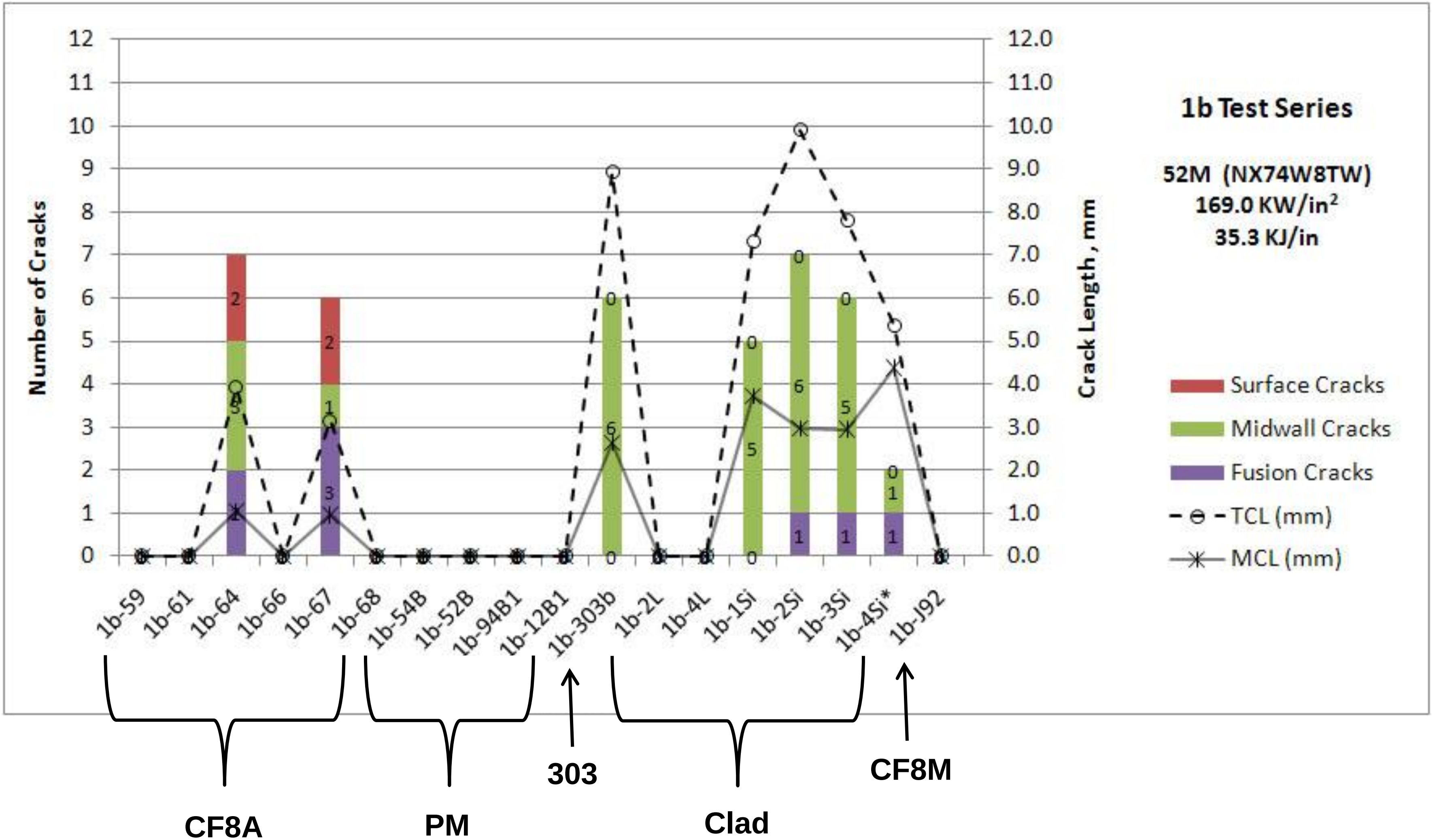
Susceptibility Curve 1b – 52M (NX74W8TW)



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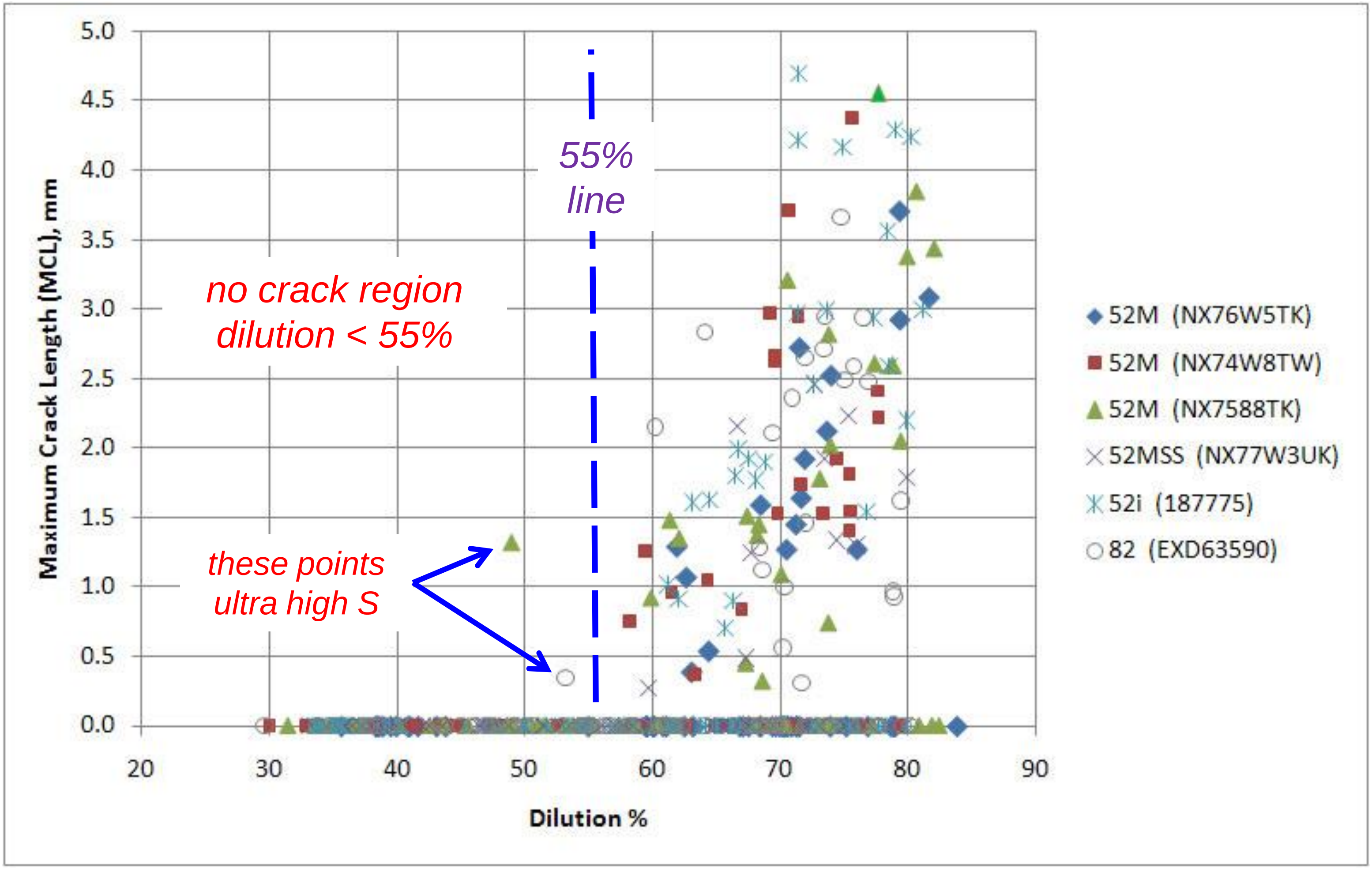
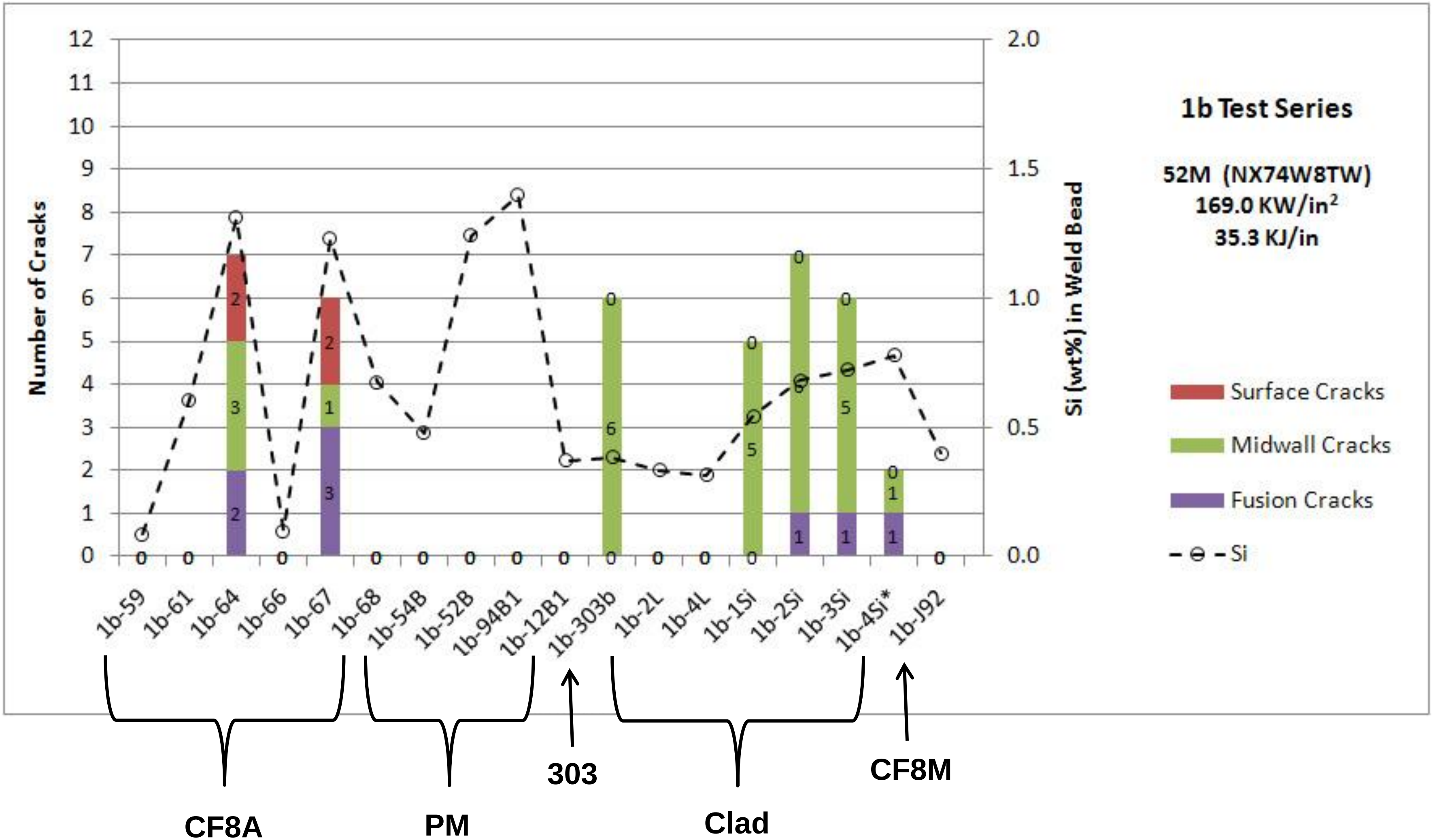
Maximum Crack Length vs Dilution



Si & Susceptibility Curve 1b – 52M (NX74W8TW)



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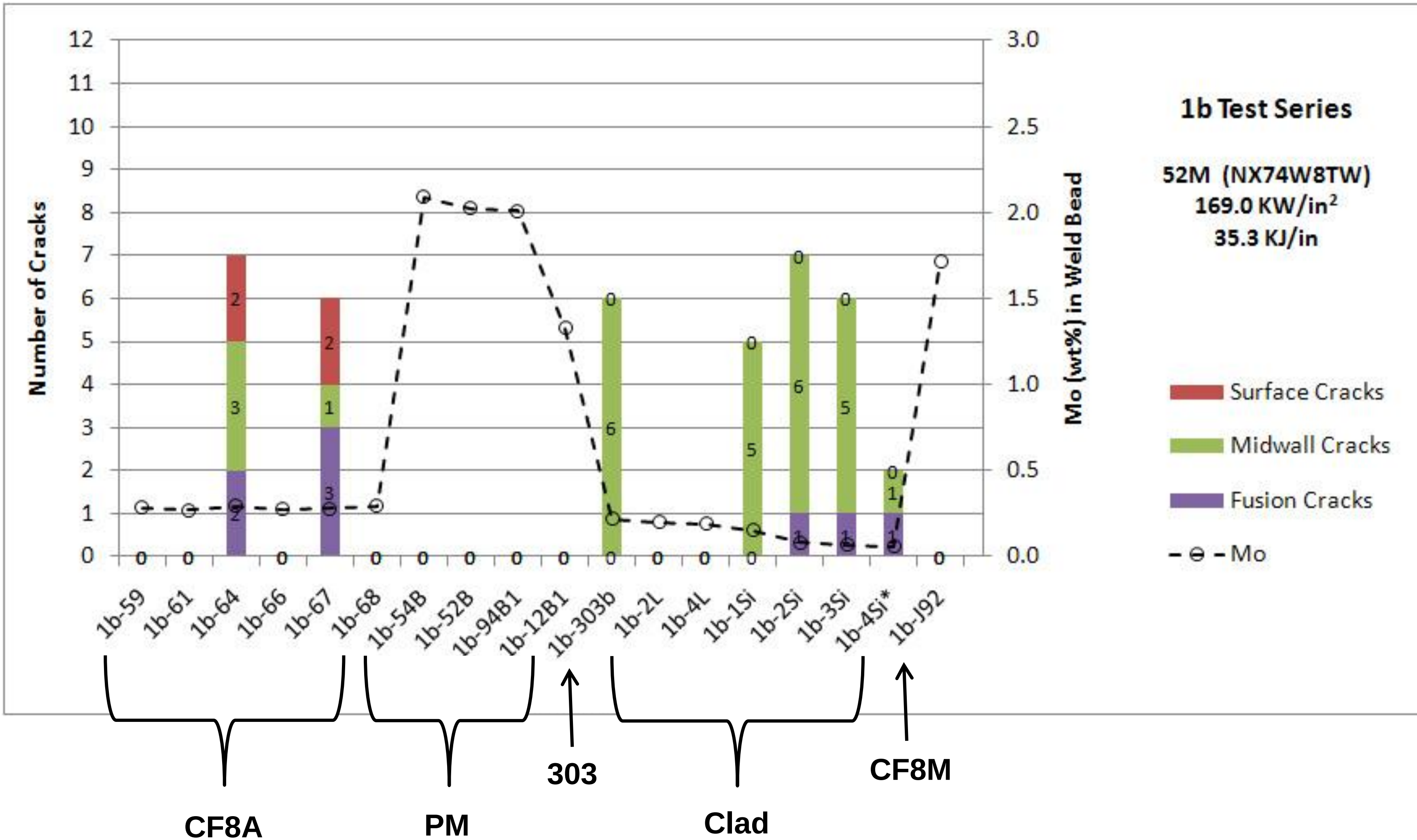
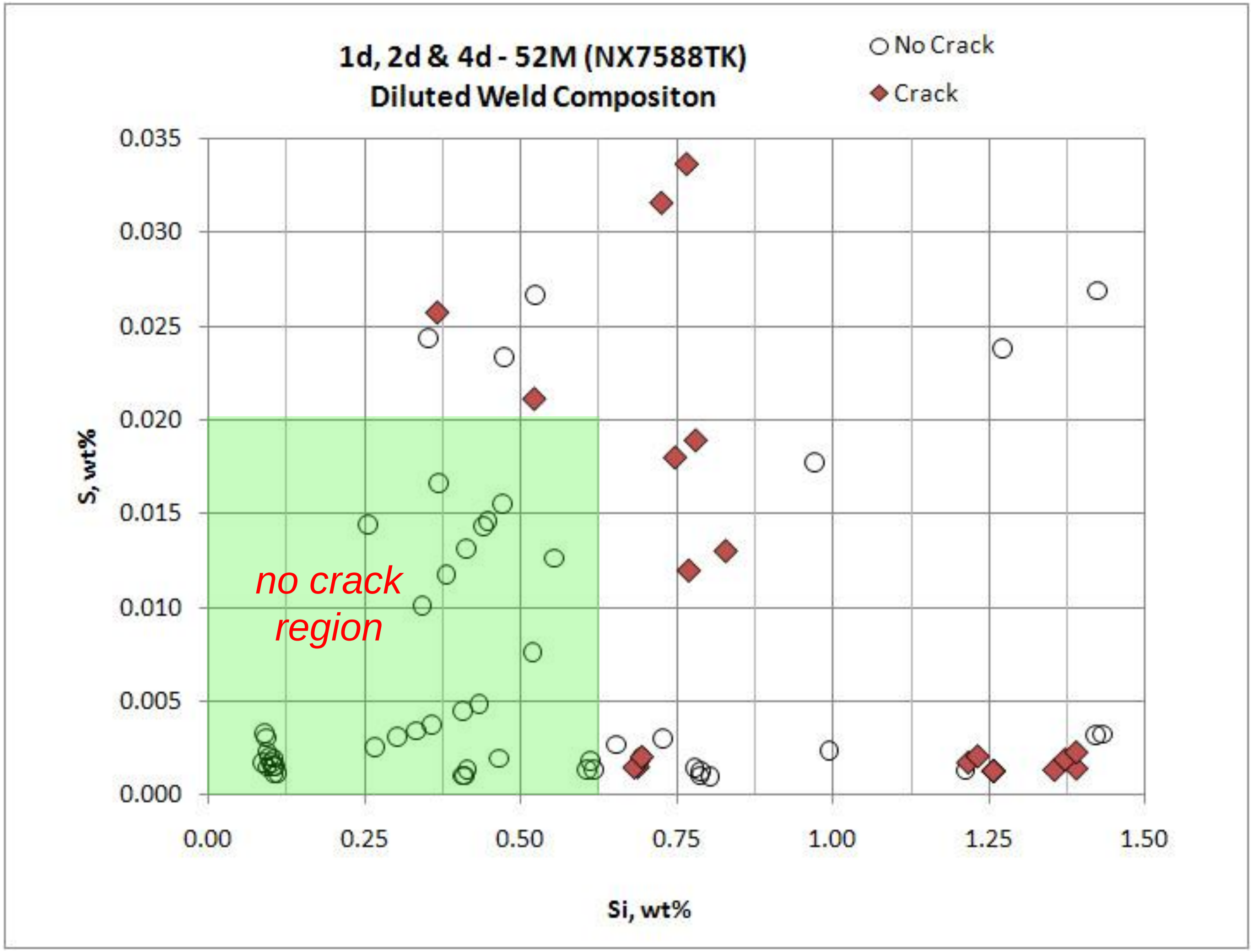
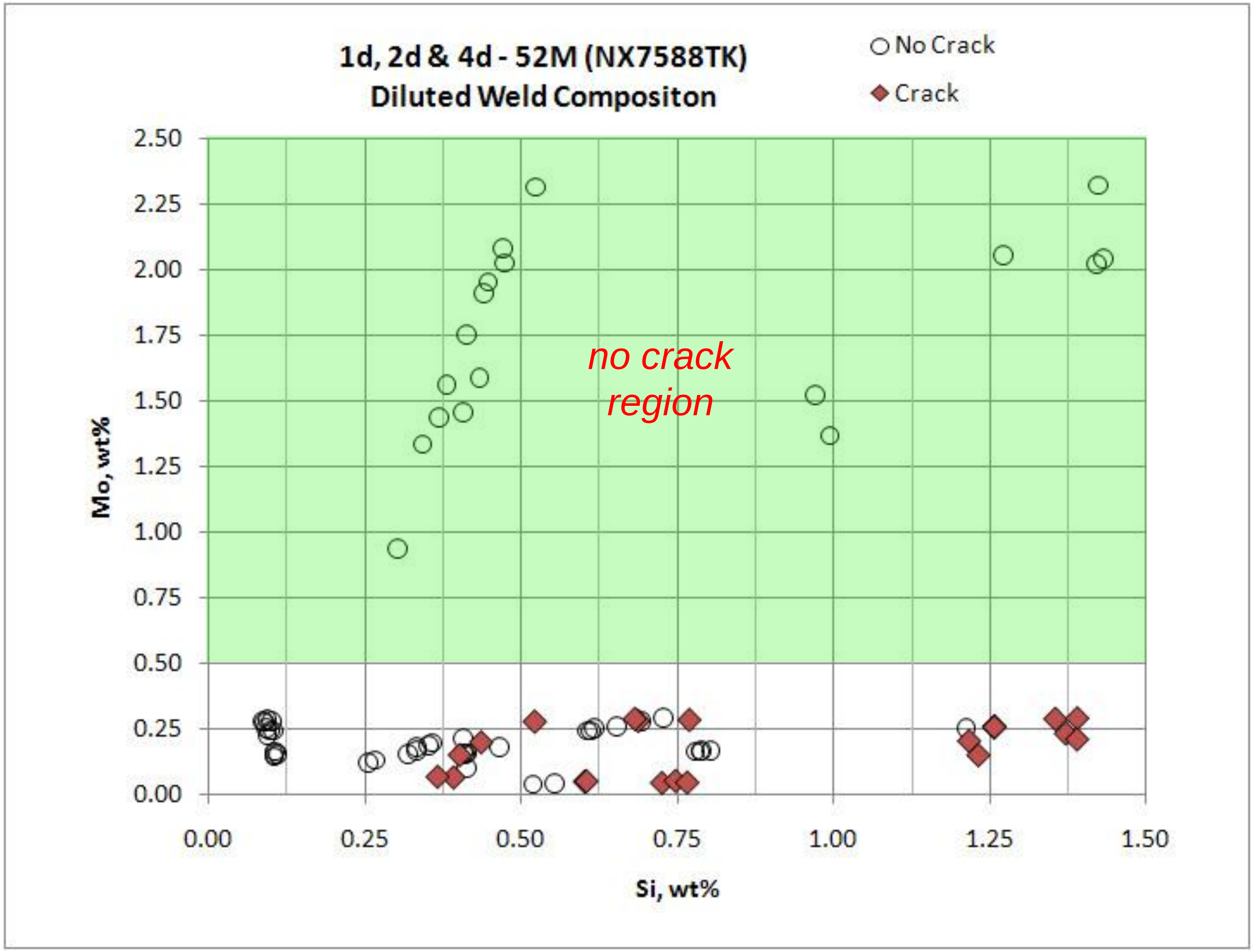
Mo & Susceptibility Curve 1b – 52M (NX74W8TW)



S-Si Crack No Crack   d – 52M (NX7588TK)



Mo-Si Crack No Crack d – 52M (NX7588TK)



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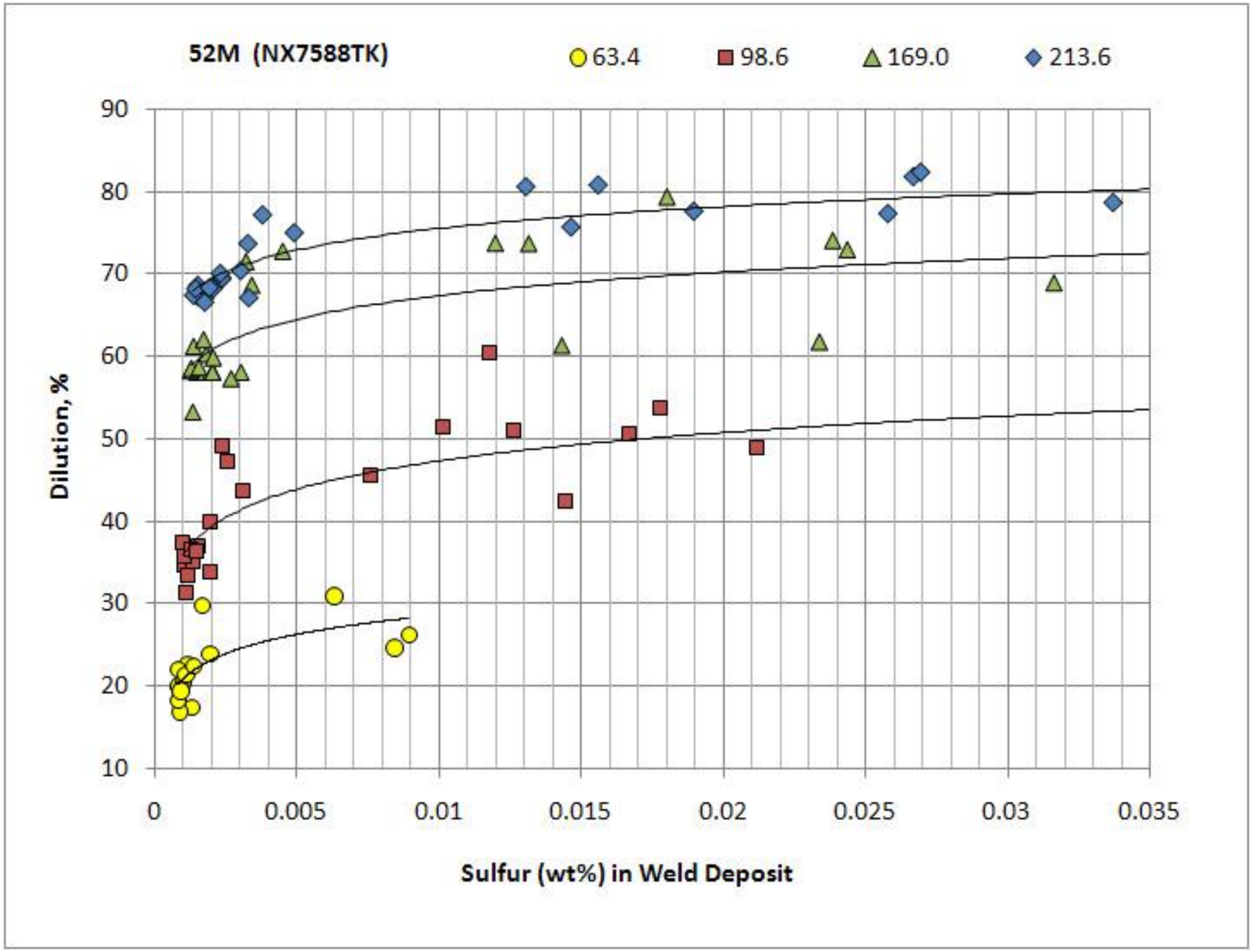
S Influence on Dilution d – 52M (NX7588TK)



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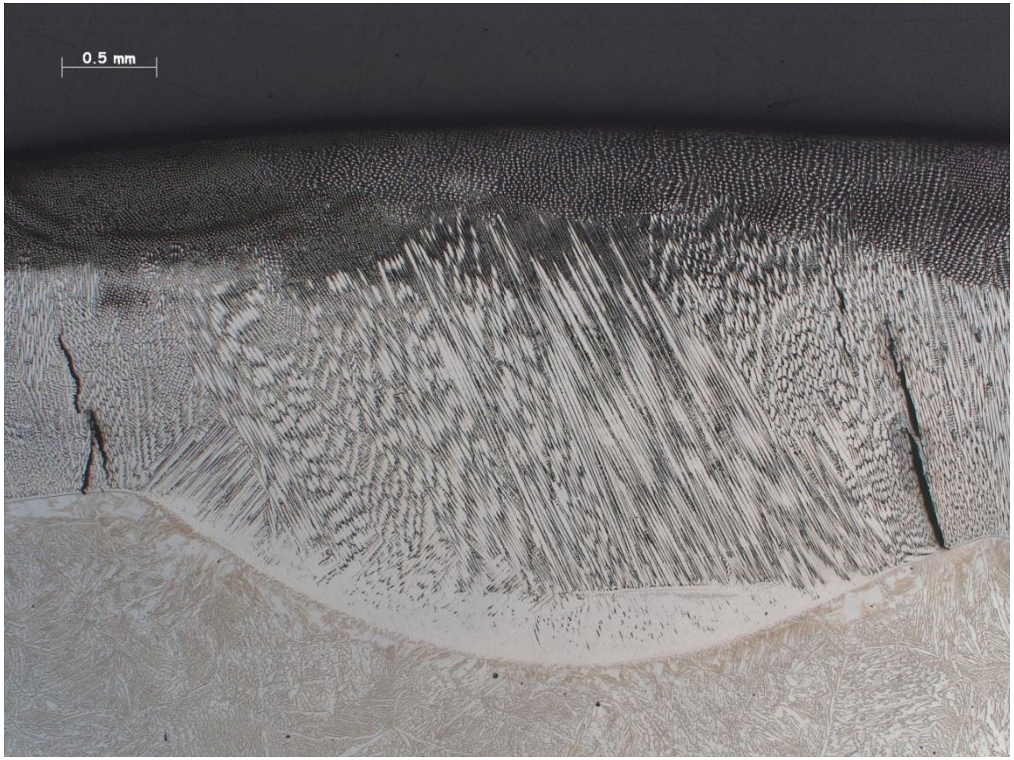
Conclusions

- Hot Cracking susceptibility can be predicted based on chemical composition of base metal
- Cracking can be controlled by limiting the weld metal dilution
- Heat to heat filler material variations need to be considered when determining hot cracking suceptibilty of weld deposits
- Power Ratio (PR) is an effective way to control weld metal dilution with cold wire <u>machine</u> Gas Tungsten Arc Welding (GTAW)

Future Work and Testing

- **Mine Data and Information from Current Bead-on-Plate Database**
  - Use bead shape to evaluate integrity of weld deposit?
  - Determine element thresholds for solidification cracking
  - Understand influence of S on dilution
  - Develop guide to optimize selection of 52M heats on specific base materials
  - Develop guide to optimize weld parameter selection & development
- **Use Design of Experiments (DOE) to define future testing**
  - Select Mo as target element for study
  - Use data to direct development of new filler metal development
- **Second set of CASS samples to be procured early 2012**
  - Will provide the desired high S samples that were not achieved in 1st sample set
- **Evaluate wider set of weld process variables on material sets**

Acknowledgements – 52M Hot Cracking Study



Solidification Cracks @ 25X
52M (NX74W8TW) Bead on
CF8A (1.95% Si – 0.0017% S – 0.0230% P)
(Courtesy of Mary Kay Havens)

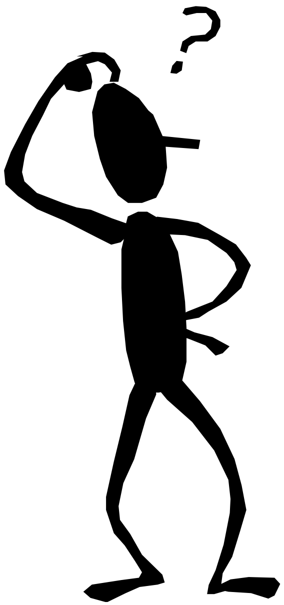
EPRI Welder & Machinist:
Mike Newman
EPRI Lab Technician:
Mary Kay Havens

Welding & Met Lab Support

EPRI
Welding & Repair Technology Center

Project Funding

Thank You – Questions or Comments?



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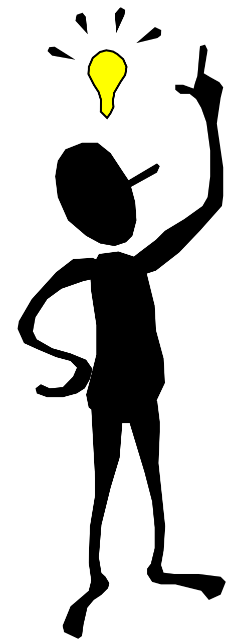
Welding and Repair Technology Center



Together…Shaping the Future of Electricity

Non-contact Infrared Thermography based Temperature Measurement during Welding

Jian Chen, Wei Zhang, and Zhili Feng, Dongxiao Qiao

Oak Ridge National Laboratory

Eric Willis, Artie Peterson, and Ken Wolfe

EPRI

Presented in Nuclear Regulatory Commission Staff and Representatives of the Nuclear Power Industry PWR Materials Reliability and Weld Repair Research Meetings, January 24-26, 2012

Motivation

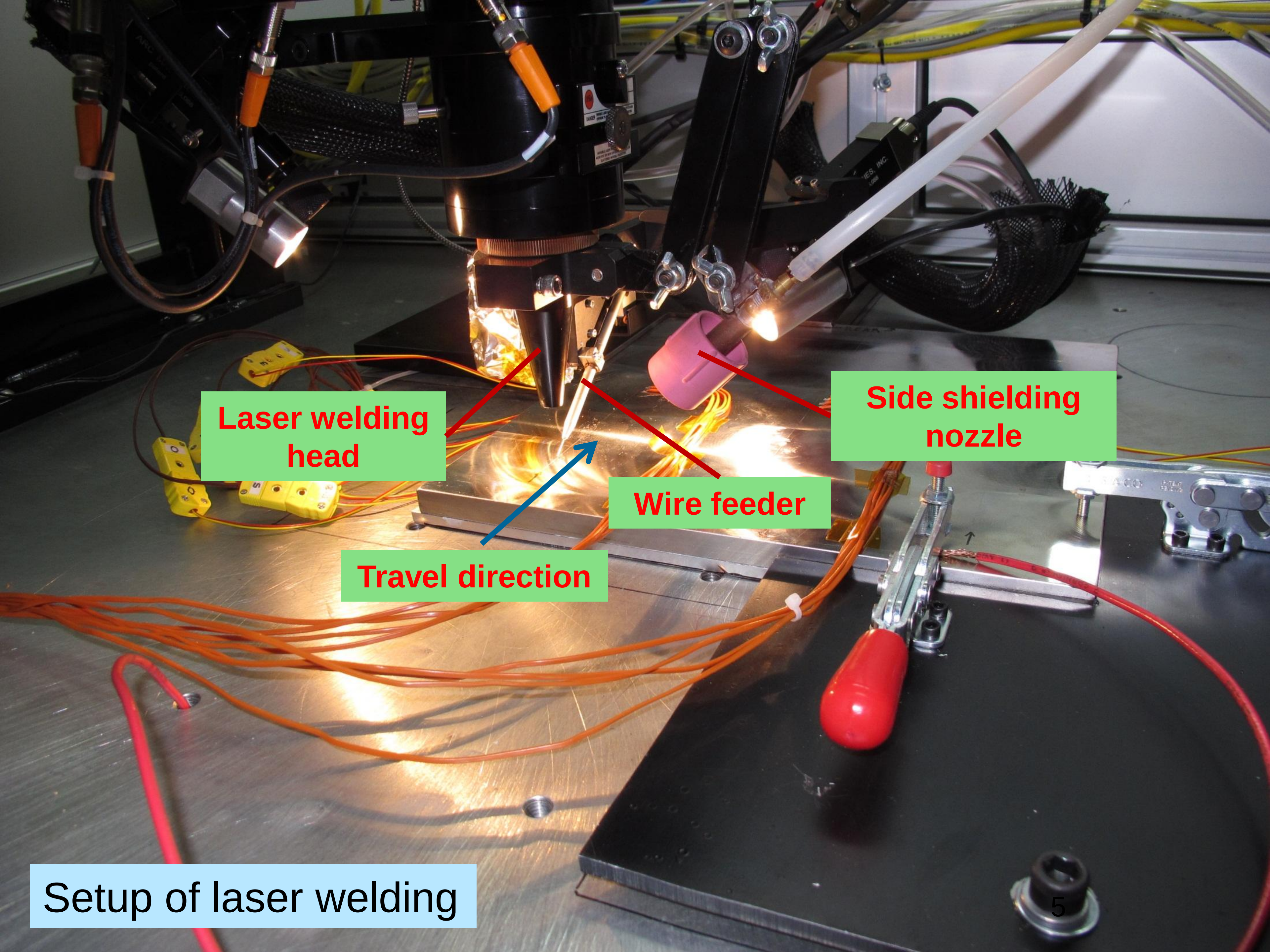
- Knowledge of temperature distribution during welding is a prerequisite to understand complex phenomena including microstructure evolution, residual stresses, etc.
- Computational models solving heat transfer equations have increasingly been utilized as a powerful tool for predicting the temperature distribution during welding.
- As many of these models simplify the interaction between heat source and workpiece material as a predefined heat input, the validation of calculated temperatures against experimental data is imperative.
- The use of contact-based thermocouples for temperature measurement during welding can be challenging especially for the low heat input welds.

Approach

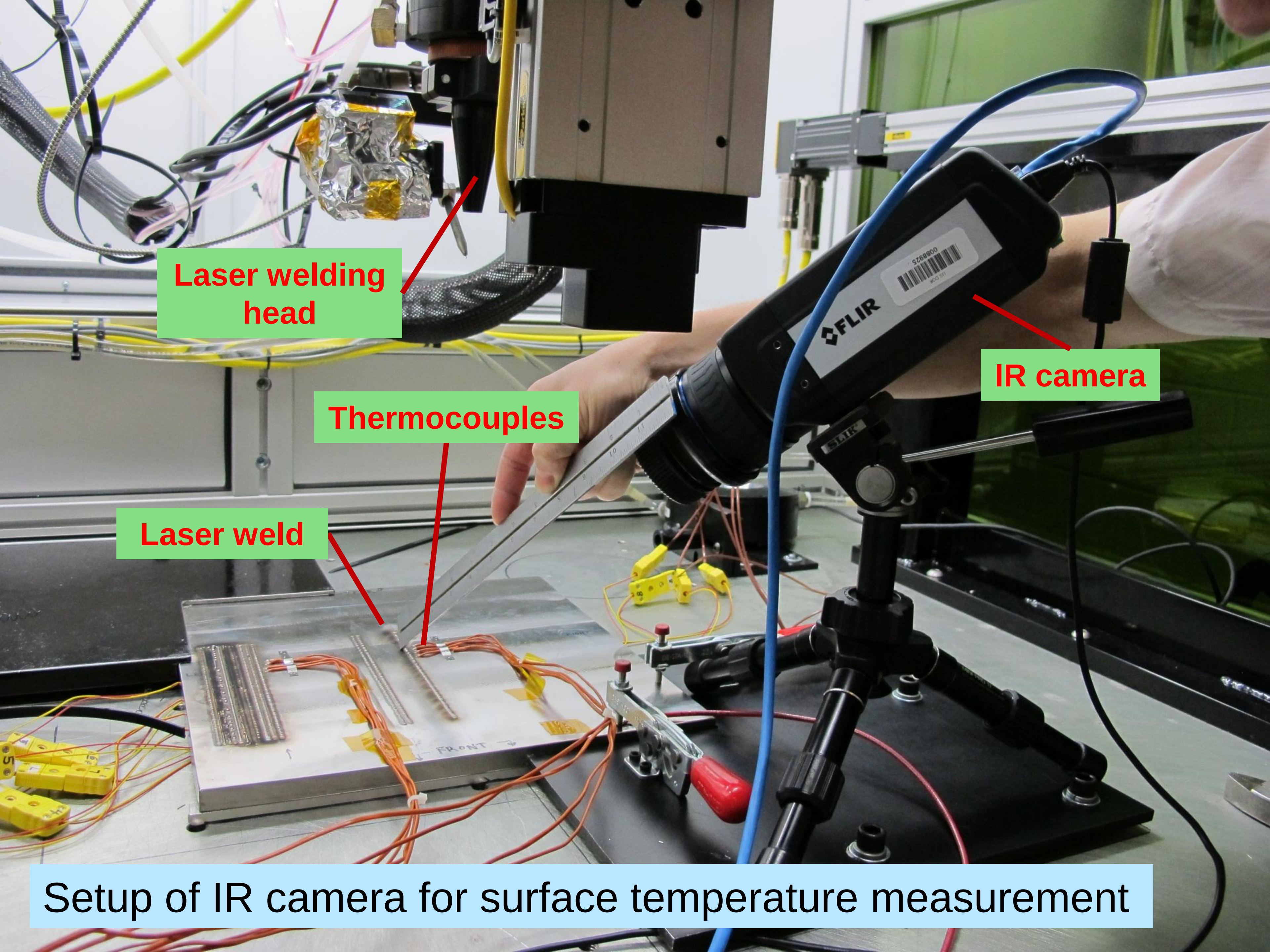
- A non-contact temperature measurement method based on infrared (IR) thermography.
- High resolutions for capturing the steep temperature gradients during laser welding.
  - Spatial resolution: 0.2 mm
  - Temporal resolution: 0.005 s
- Offline experiment for determining the infrared intensity vs. the temperature curve.

Outline

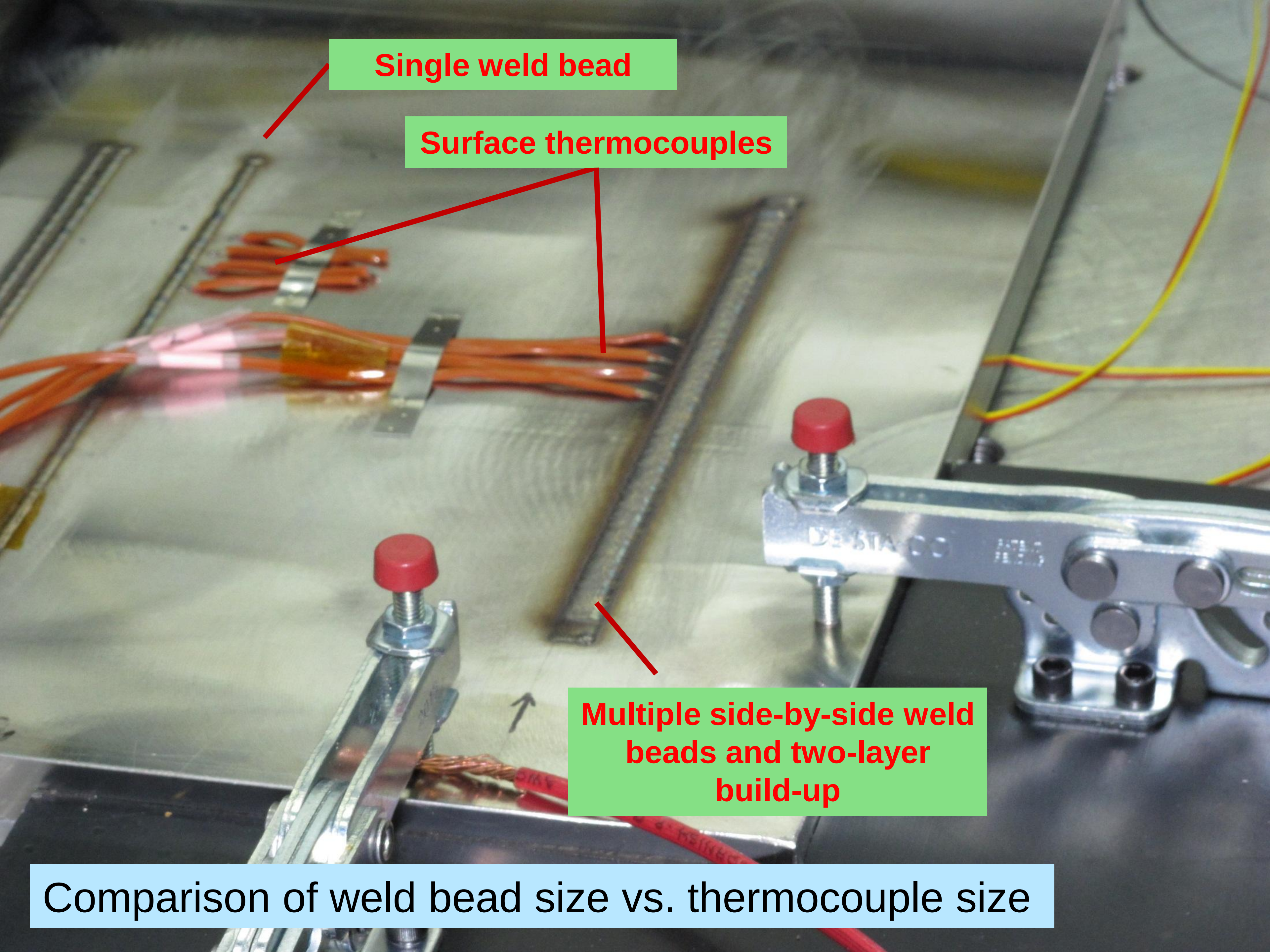
- Laser welding experiments at EPRI Charlotte
- Calibration curves for converting IR intensity into temperature
- Validation of thermal model of laser welding



Setup of laser welding

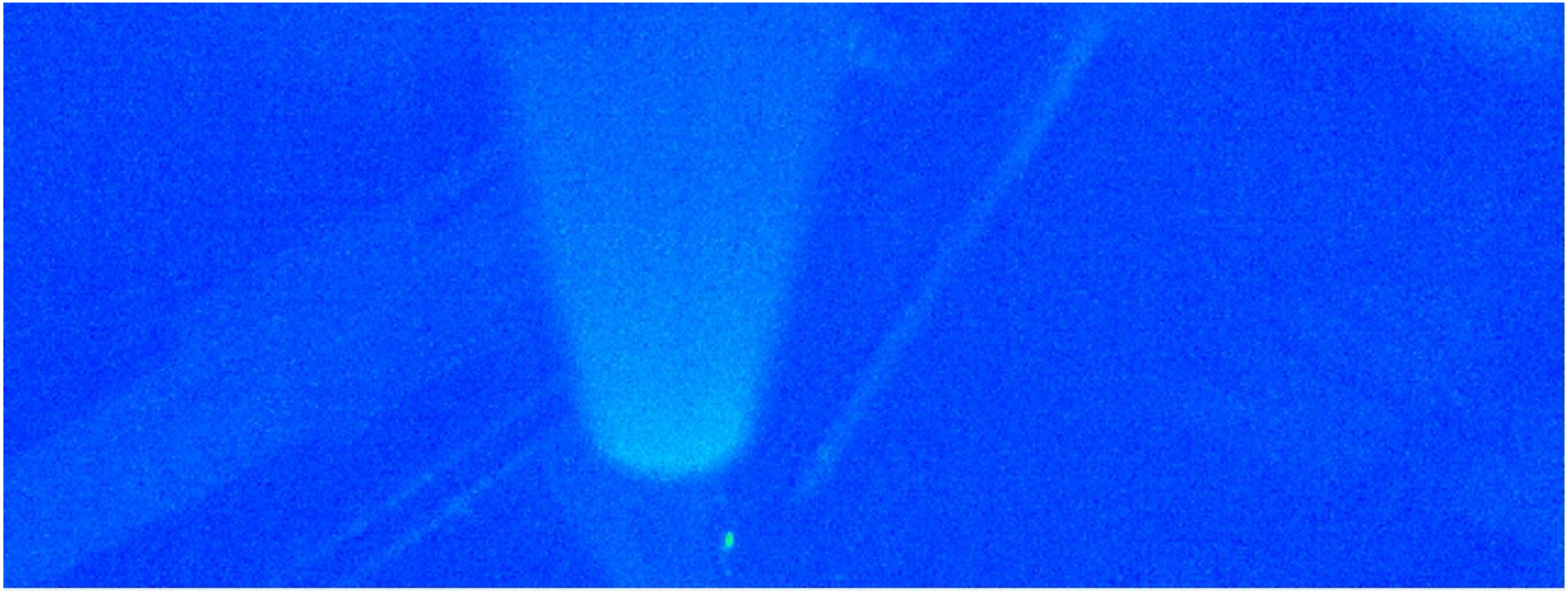


Setup of IR camera for surface temperature measurement



Comparison of weld bead size vs. thermocouple size

IR movie for a laser weld



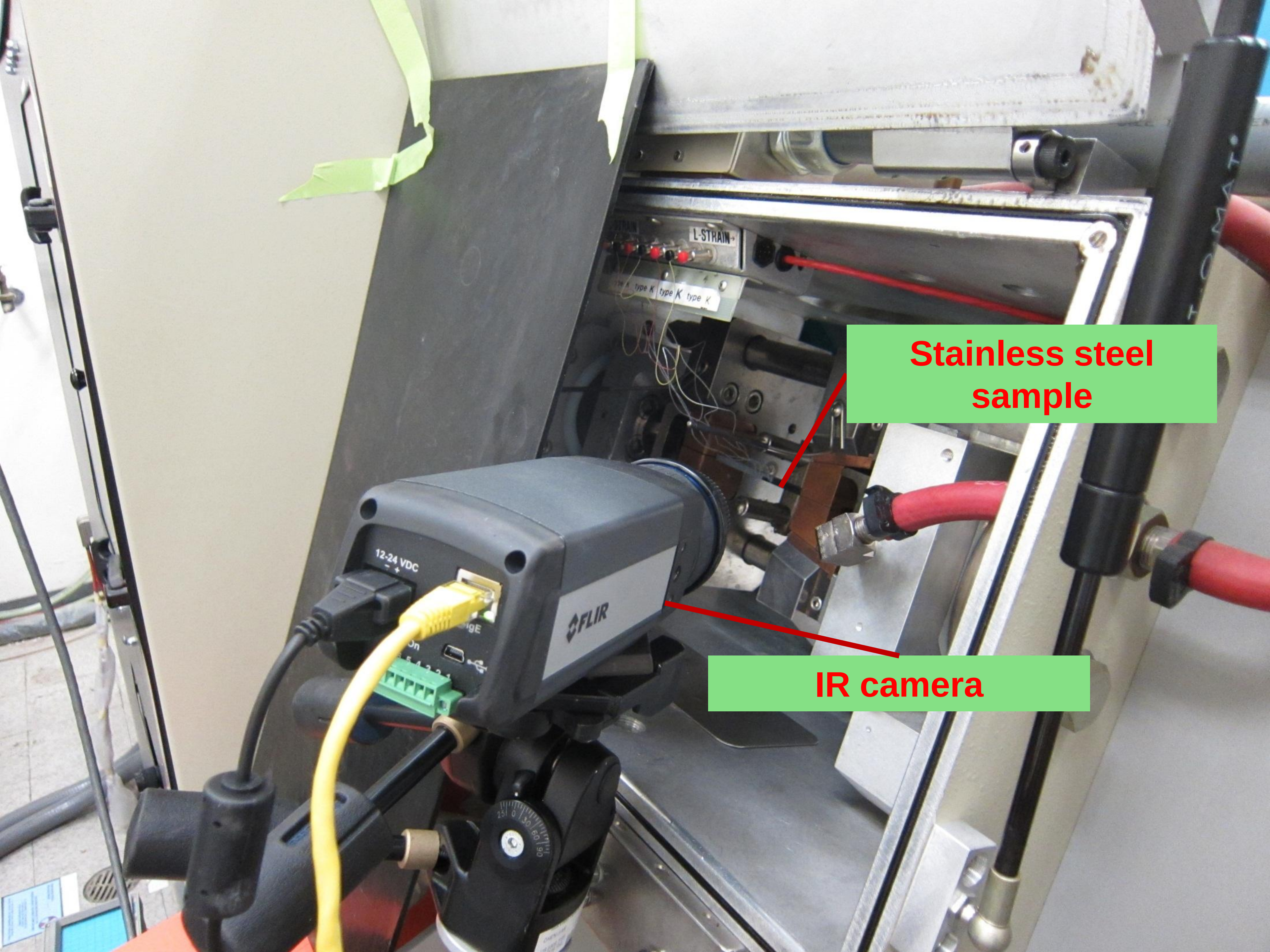
Click the image above to play the movie.

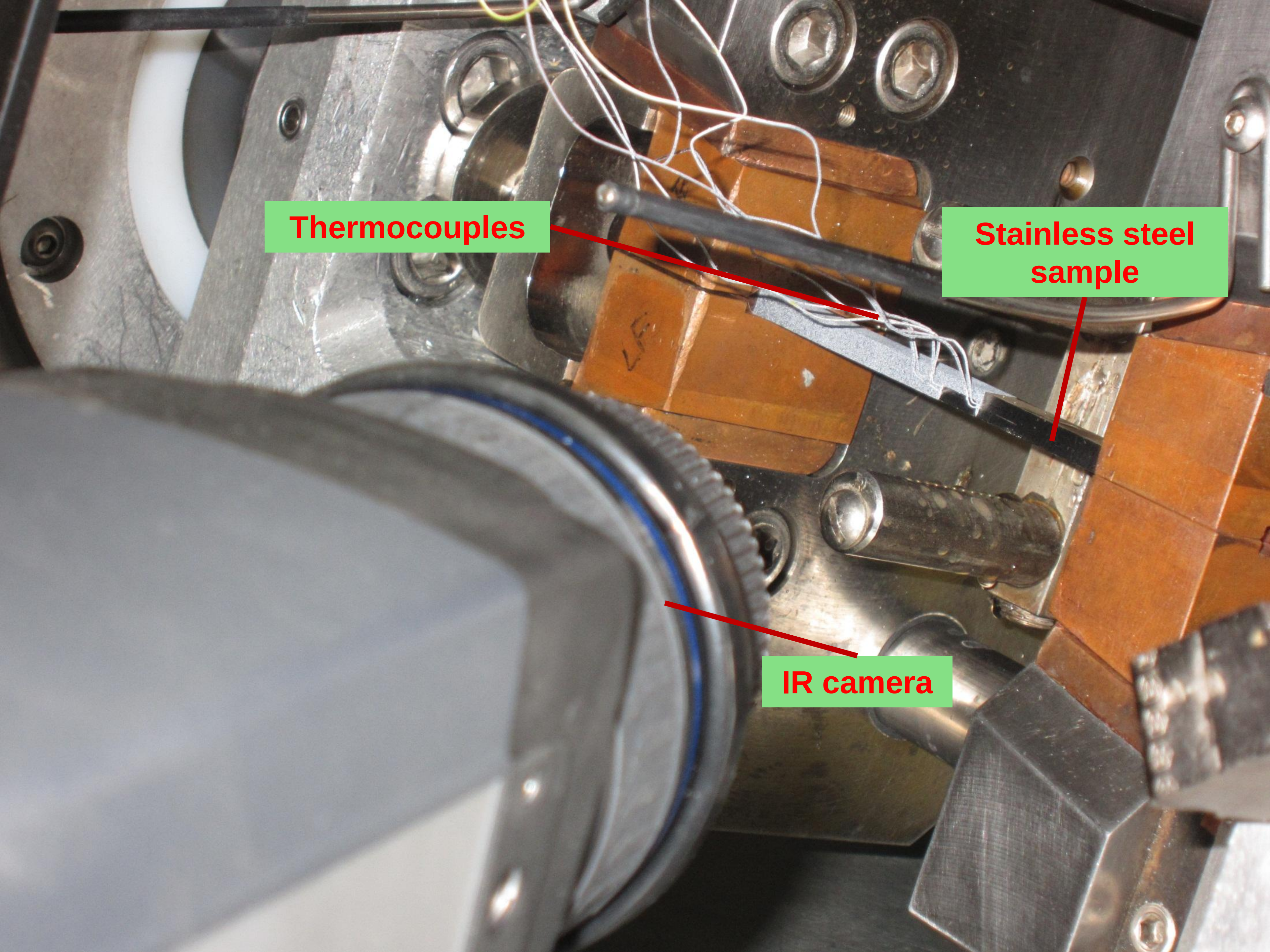
Outline

- Laser welding experiments at EPRI Charlotte
- Calibration curves for converting IR intensity into temperature
- Validation of thermal model of laser welding

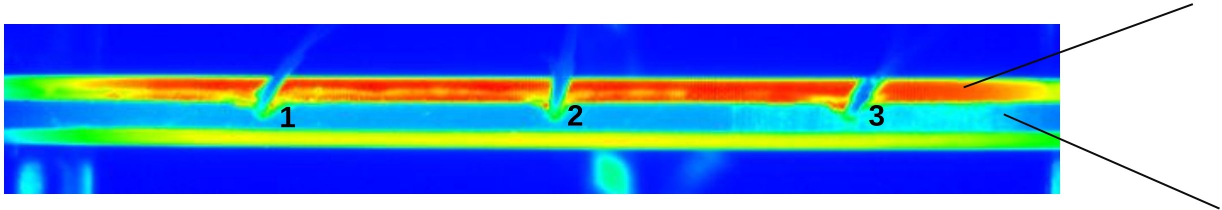
Approach for generating calibration curves

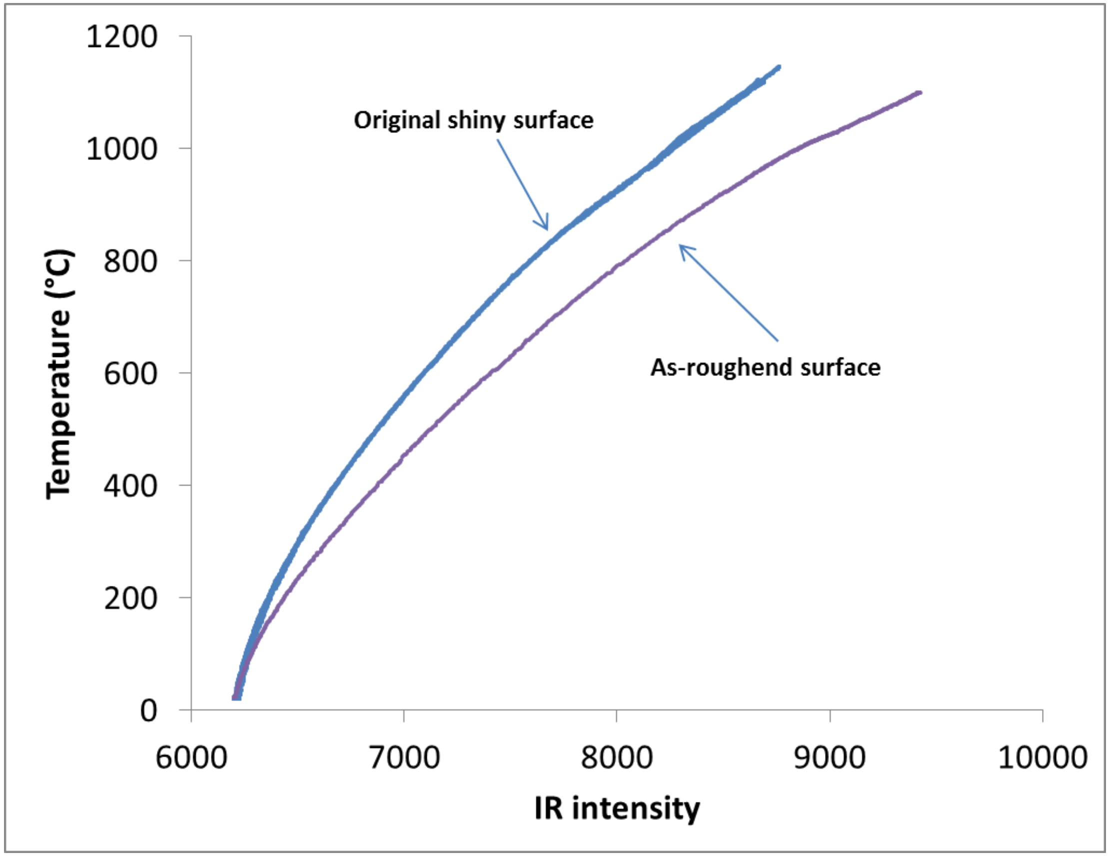
- IR camera accurately records the IR intensity emitted by sample surface, which is a function of surface temperature.
- The IR intensity vs. temperature relationship depends on many variables, among which the most critical one is the surface emissivity.
- A special approach for generating the calibrations curves for converting the IR intensity into temperature is established using the controlled heating in Gleeble.


Stainless steel sample
IR camera
L-STRAIN
type K
type K
type K
12-24 VDC
FLIR


Thermocouples
Stainless steel sample
IR camera

Calibration curves

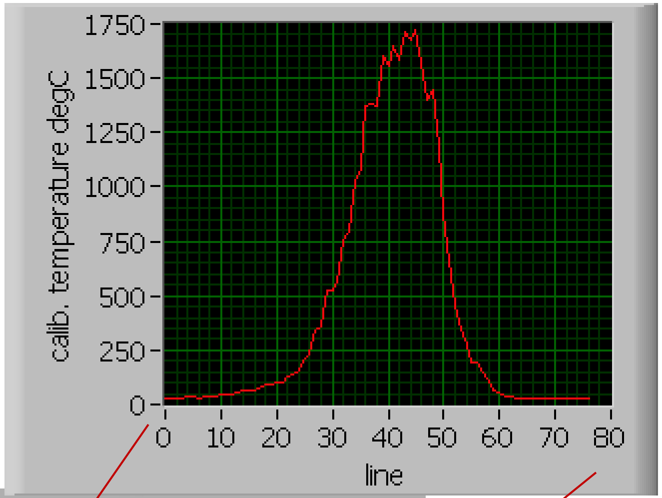


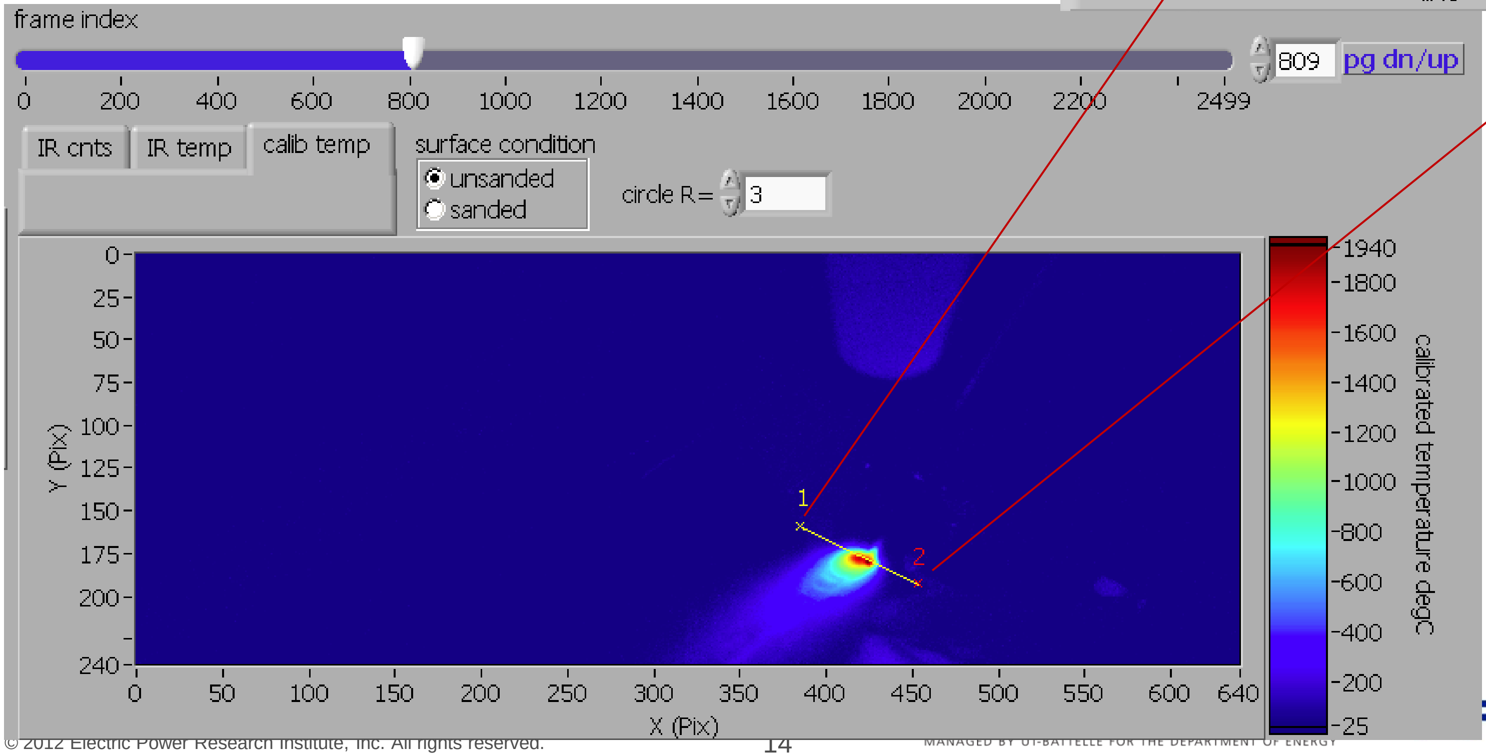


- As expected, IR intensity largely depends on the surface condition (emissivity).
- Gleeble based approach is a reliable way to generate accurate calibration curves.

Steep temperature gradient near weld

Distance from 1 to 2 about 4 mm



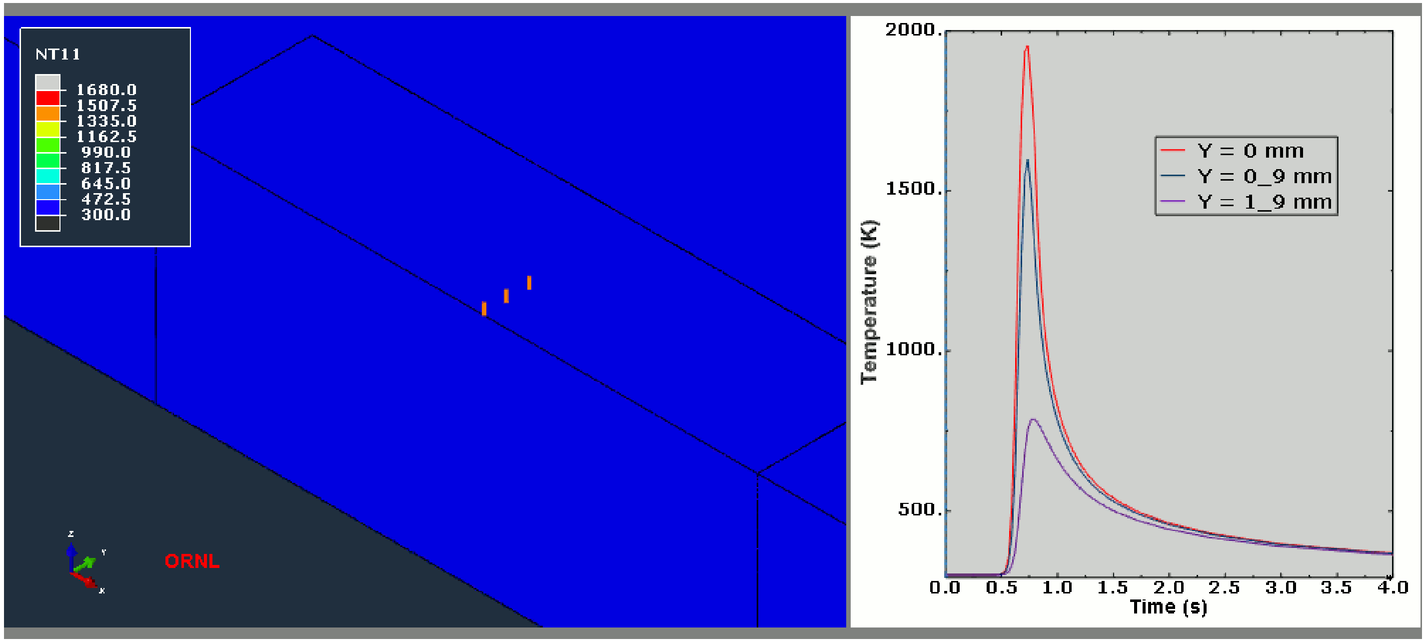


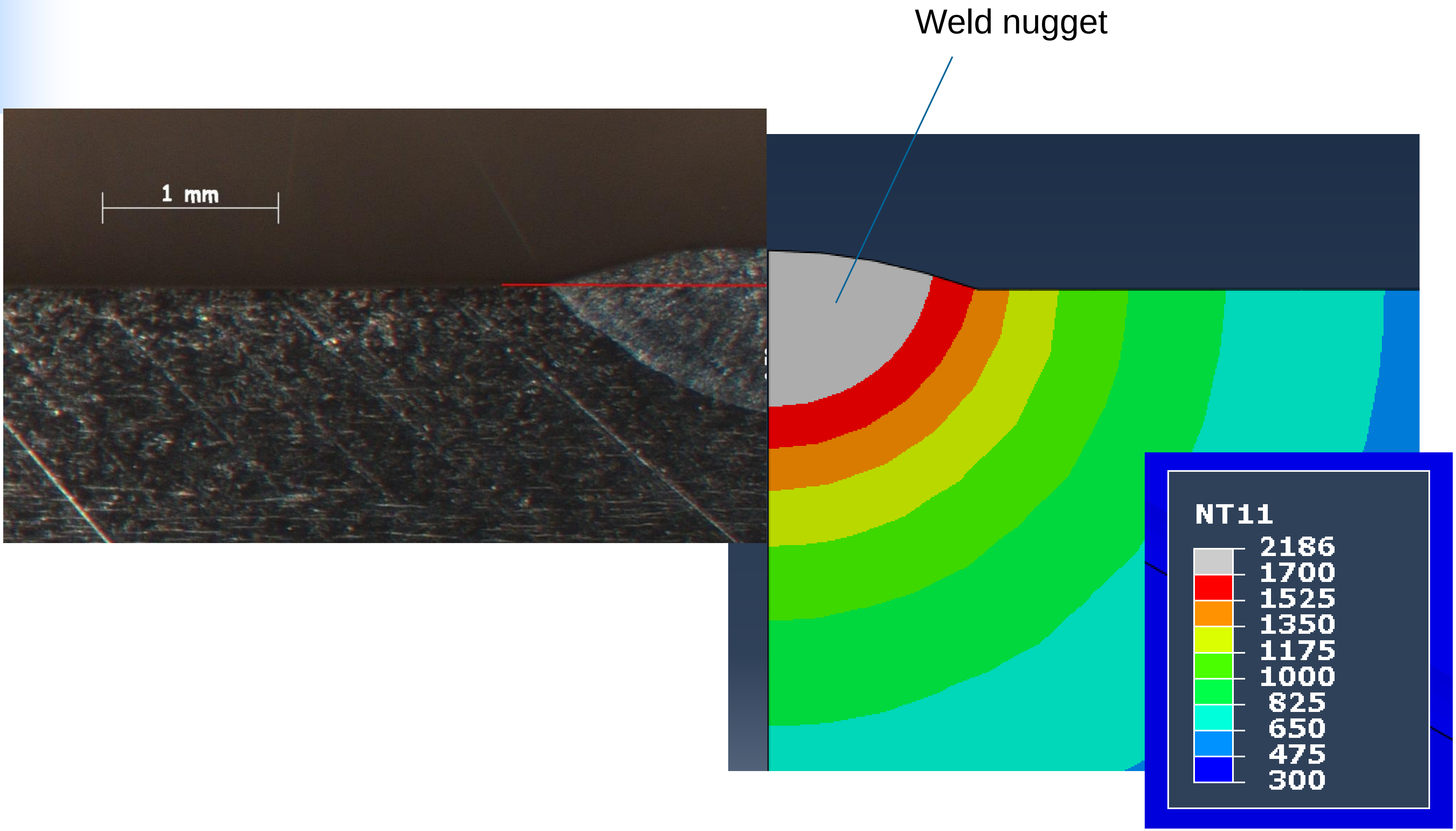
Outline

- Laser welding experiments at EPRI Charlotte
- Calibration curves for converting IR intensity into temperature
- Validation of thermal model of laser welding

Model description

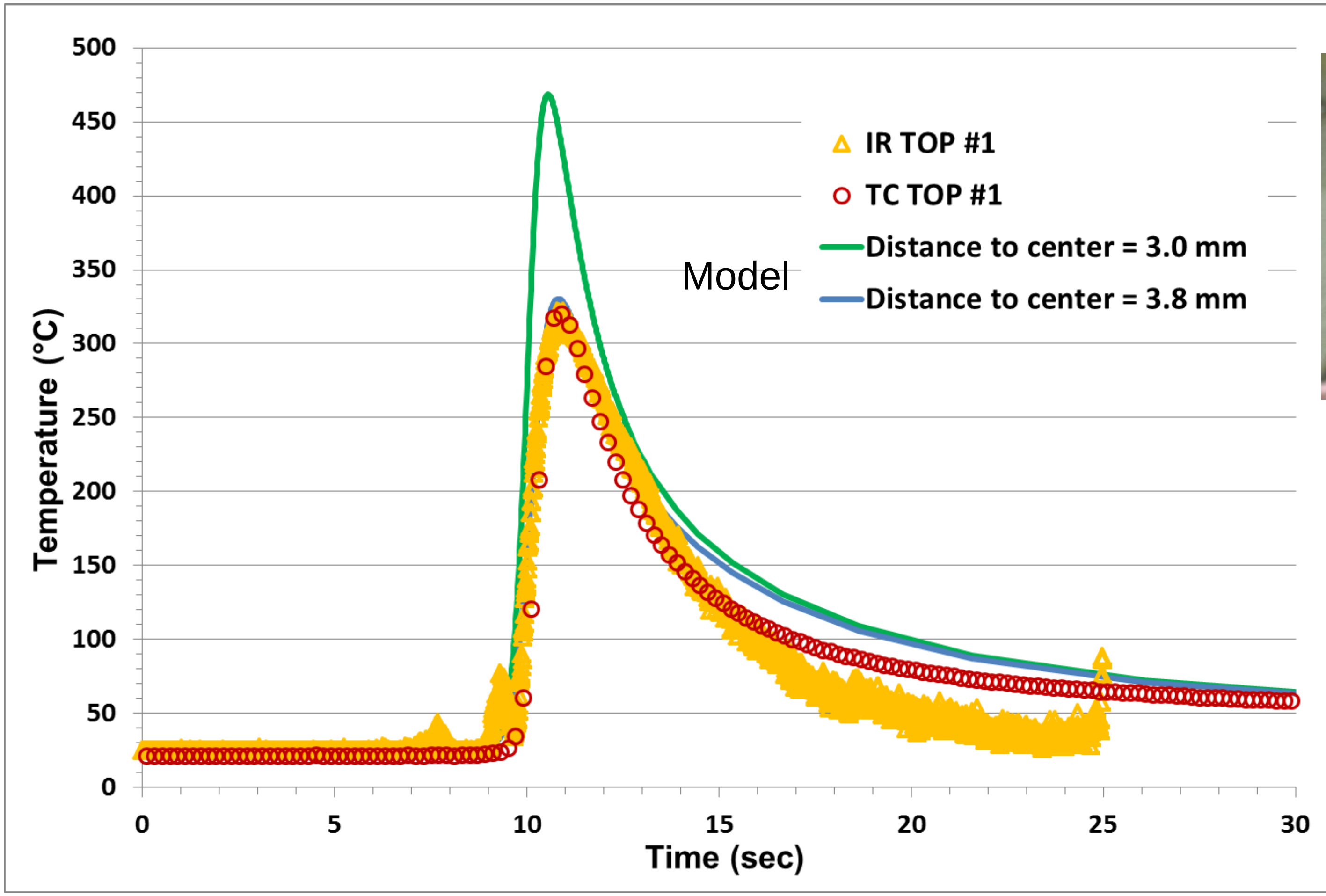
- Thermal model
  - Three-dimensional transient simulation
  - Double ellipsoid heat source for prescribing volumetric heat flux distribution
  - Heat source parameters based on nugget size

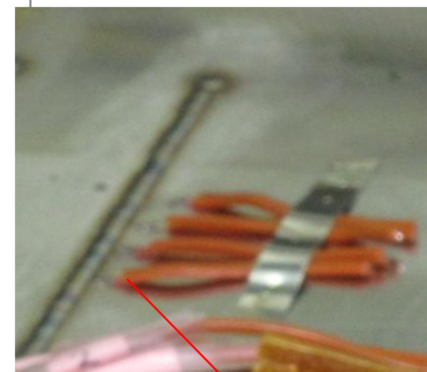




Weld nugget
1 mm
NT11
2186
1700
1525
1350
1175
1000
825
650
475
300

Comparison of temperature profile at TC #1 on the top surface

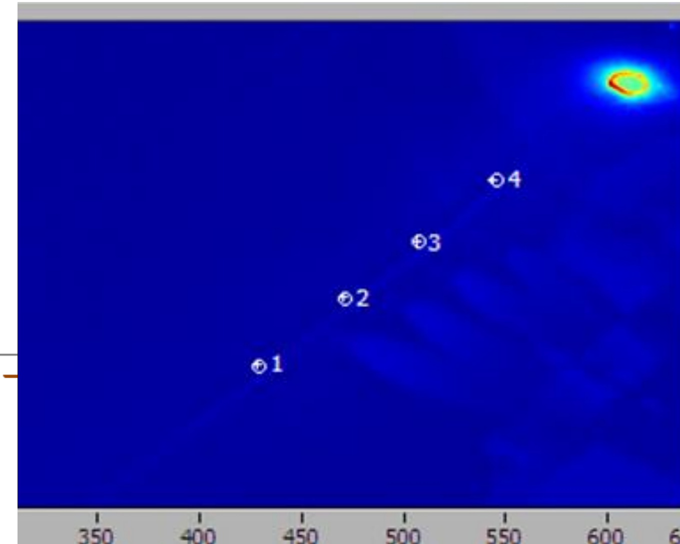


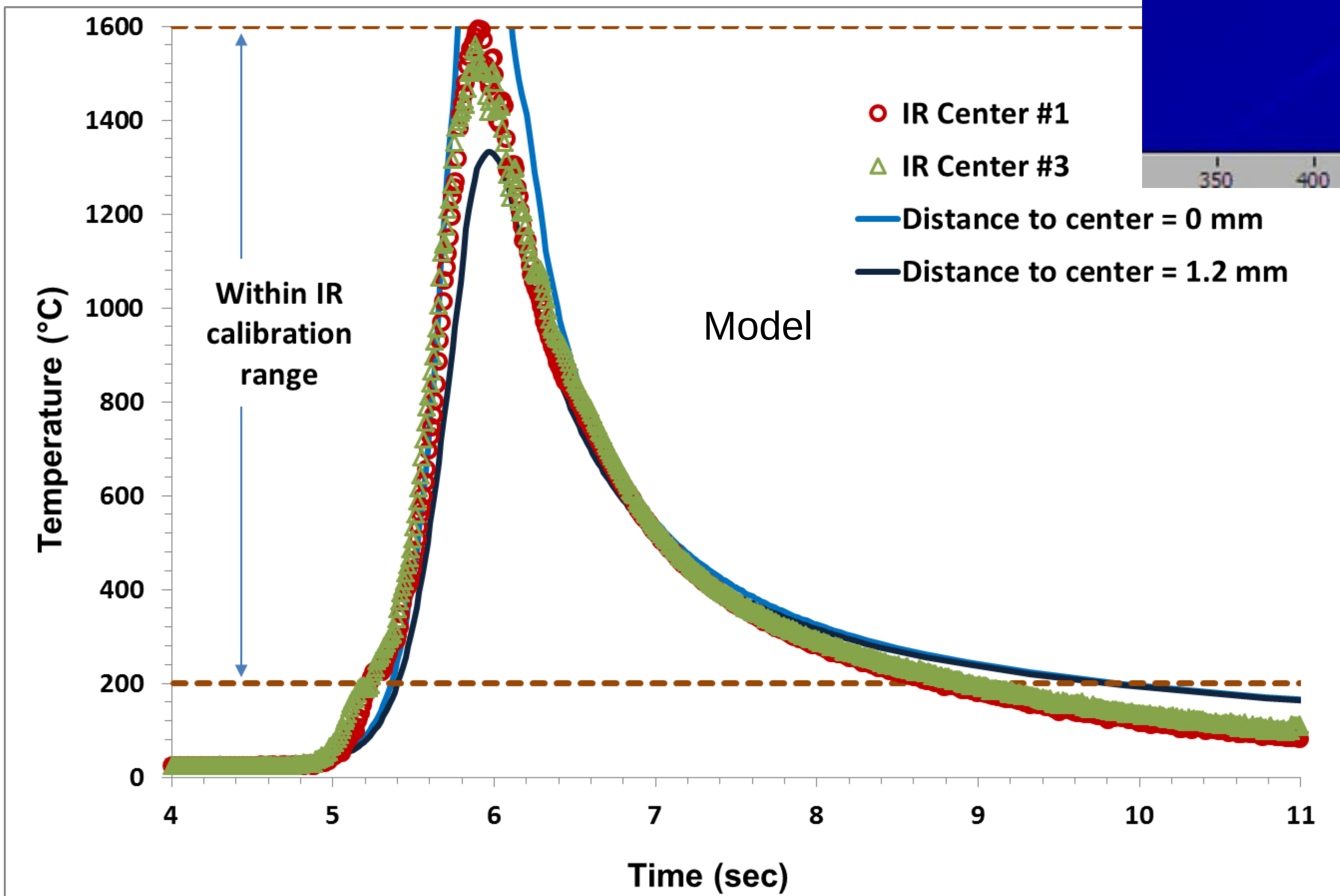


TC #1, closest to weld center line

TC #1 is located at a distance of 3.2 mm from the weld centerline

High consistency in temperature between IR measurement and model prediction on the surface.





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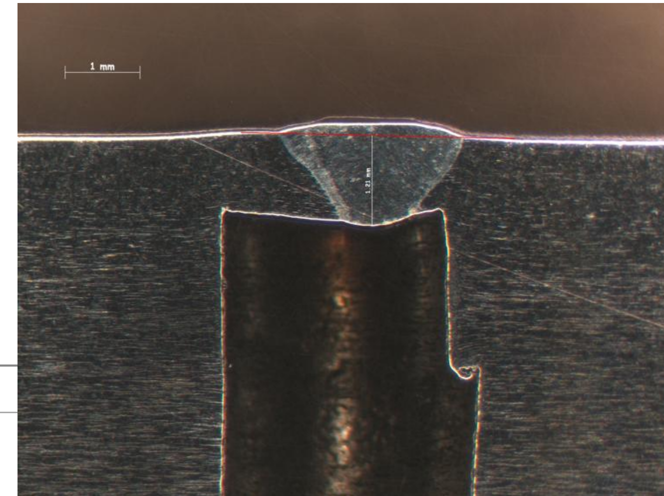
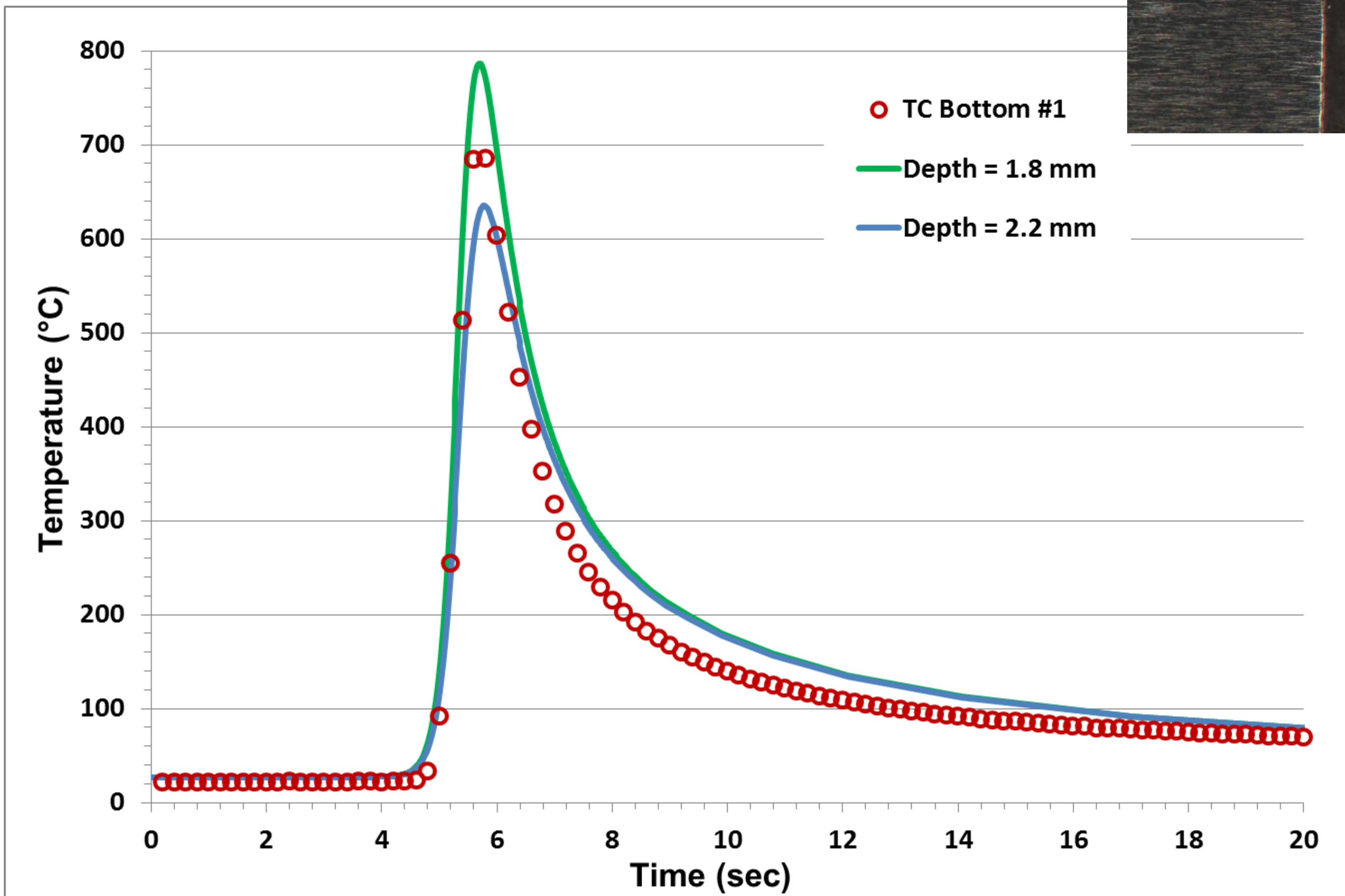
A thermocouple well, placed too close to the surface, interfering with the weld temperature field and the resulting bead shape



Bottom-mount thermocouple #1



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Summary

- Conventional thermo-couples are difficult to measure the high temperatures due to steep temperature gradients especially for low-heat input welding conditions.
- On the other hand, calibrated IR can capture high temperatures in weld HAZ.
- Good consistency is observed between the model predicted and IR measured surface temperatures.

Structural Integrity Associates, Inc.®

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EWR Residual Stress Parametric Studies

Progress and Status Update

- Eric Willis (EPRI)
- Pete C. Riccardella (SIA)
- Francis H. Ku (SIA)
- Aparna Alleshwaram (SIA)

www.STRUCTINT.com

877-4SI-POWER

Francis H. Ku

January 24-26, 2012

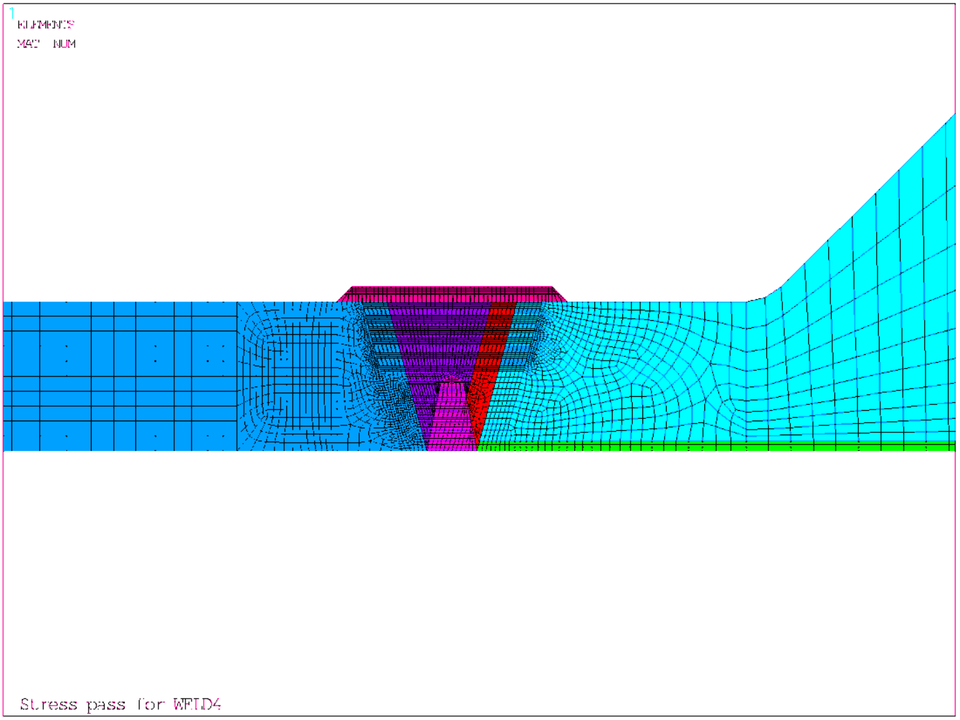
PWR Materials Reliability and Weld Repair Research Meeting, Charlotte, NC

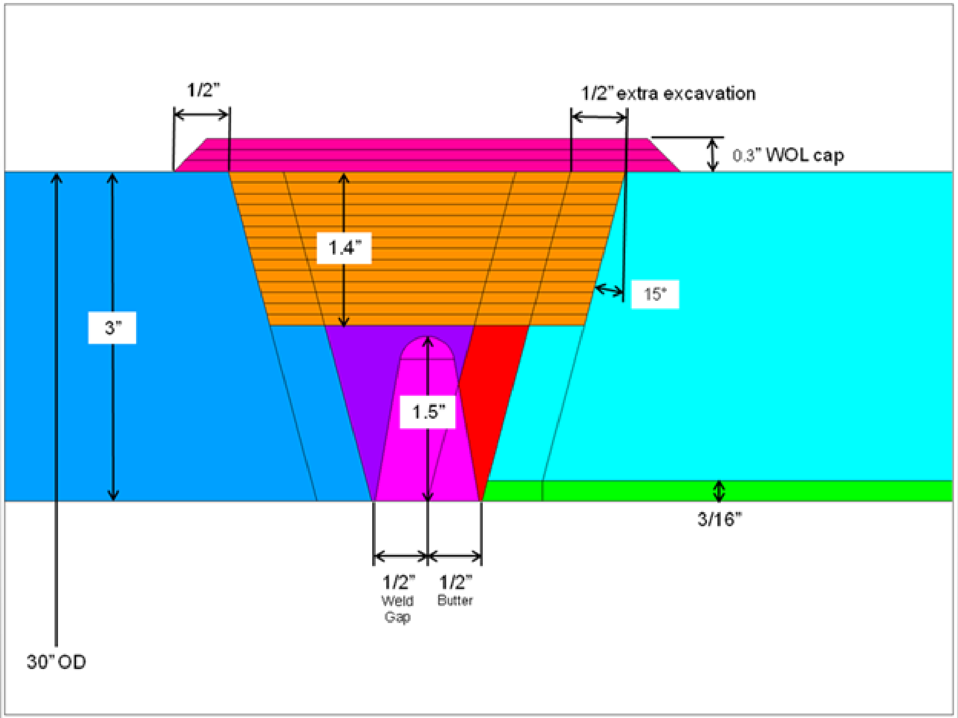
Outline

- Geometry and EWR Concepts
- Materials
- EWR Cases Considered
- 2D Finite Element Analyses
  - ✓ Residual stress results
  - ✓ Stress intensity factors
  - ✓ Conclusions
- 3D Finite Element Analyses (Planned)
  - ✓ Partial arc EWR cases

Geometry and EWR Concepts

- 30” diameter large bore nozzle
- 3” nozzle thickness
- Narrow groove DMW + 50% ID Repair
- Two excavation cavity depths and widths, optional WOL Cap





Materials

- Pipe: SA-240 Type 304 SS
- Nozzle forging: SA-508, Grade 2, Class 1
- Nozzle cladding: ER308L
- Weld butter: Alloy 82/182
- DMW: Alloy 82/182
- ID Repair: Alloy 82/182
- EWR: Alloy 52M
- WOL cap: Alloy 52M

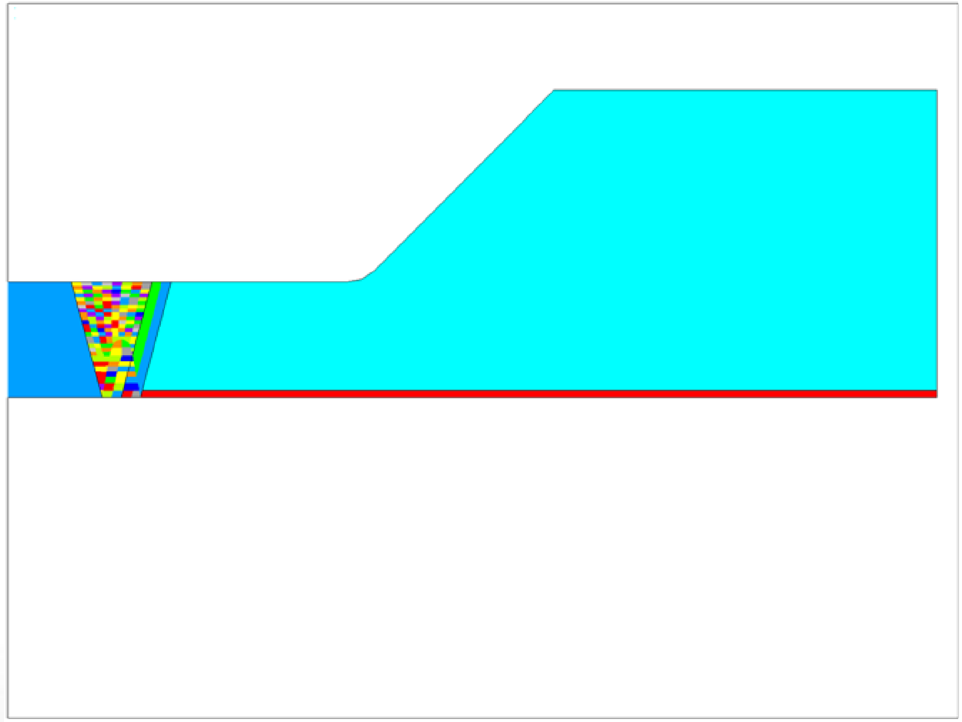
2D EWR Cases Considered

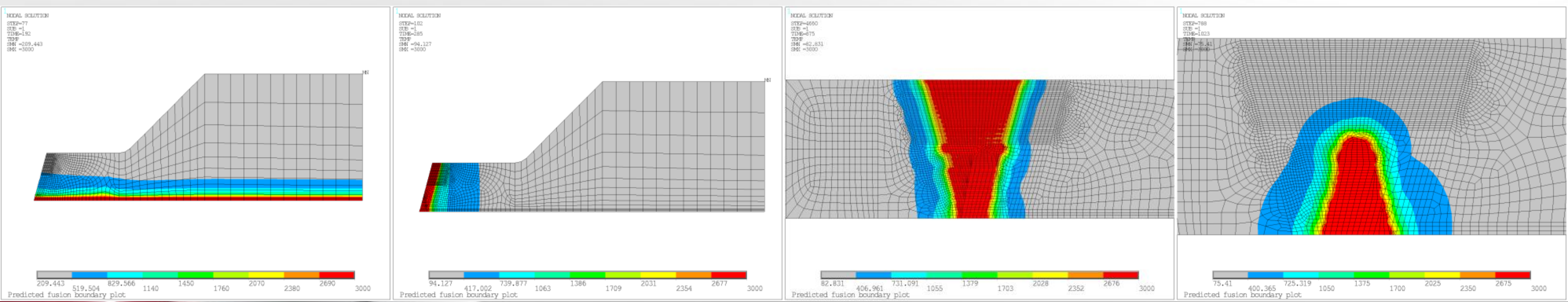
- Standard SI WRS FEA methodology
- Isotropic hardening with modified SS curves
- Axisymmetric modeling

0. Pre-EWR
1. 50% deep, narrow EWR, no WOL cap
2. 50% deep, narrow EWR, with WOL cap
3. 25% deep, narrow EWR, no WOL cap
4. 25% deep, narrow EWR, with WOL cap
5. 50% deep, wide EWR, no WOL cap
6. 50% deep, wide EWR, with WOL cap
7. 25% deep, wide EWR, no WOL cap
8. 25% deep, wide EWR, with WOL cap

Pre-EWR Condition

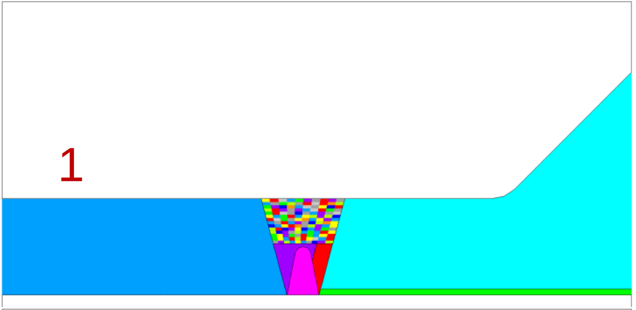
- Nozzle cladding
- Weld buttering
- Ignored PWHT
- DMW
- 50% ID Repair
- No safe end weld so conservative starting stress state





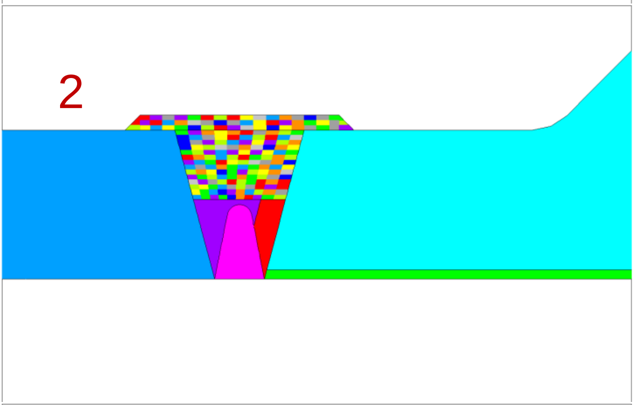
EWR Cases

1



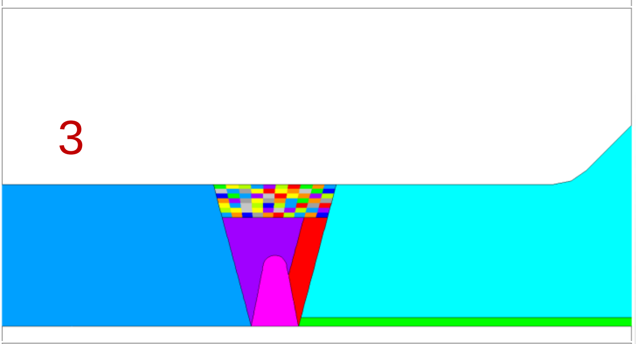
50% deep
narrow EWR

2



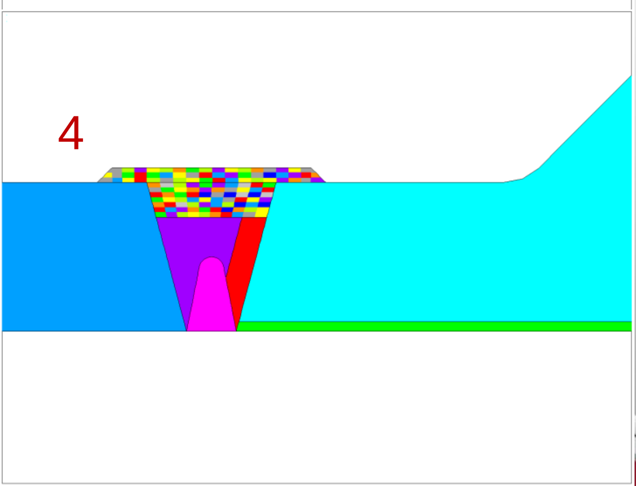
50% deep
narrow EWR
w/ WOL cap

3



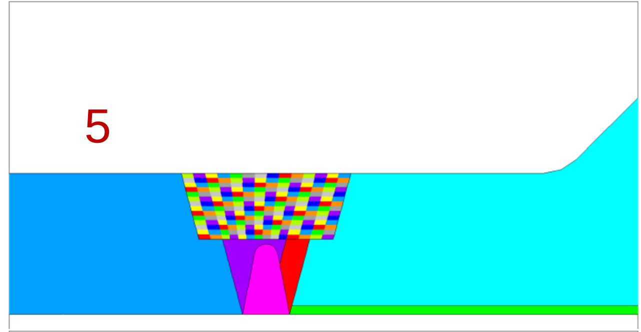
25% deep
narrow EWR

4



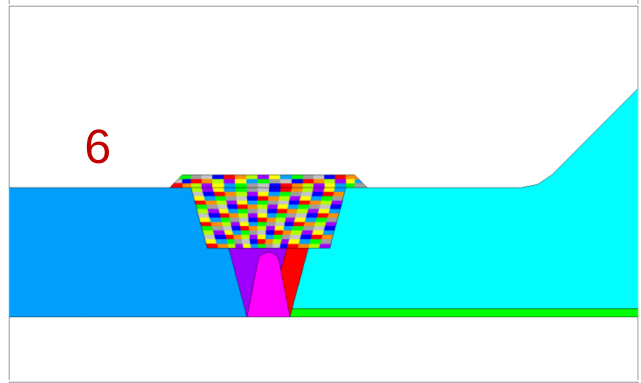
25% deep
narrow EWR
w/ WOL cap

5



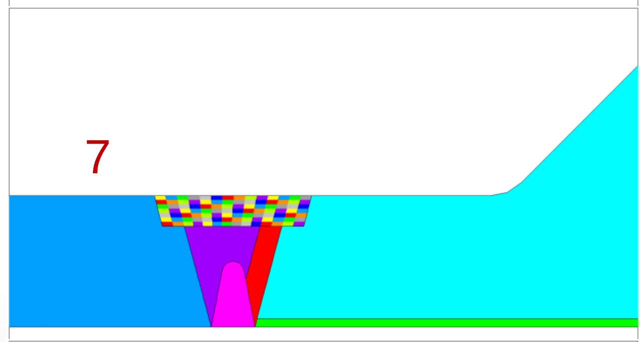
50% deep
wide EWR

6



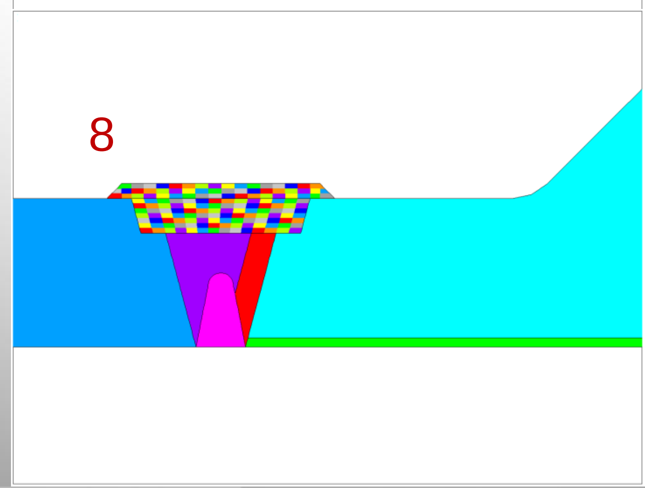
50% deep
wide EWR
w/ WOL cap

7



25% deep
wide EWR

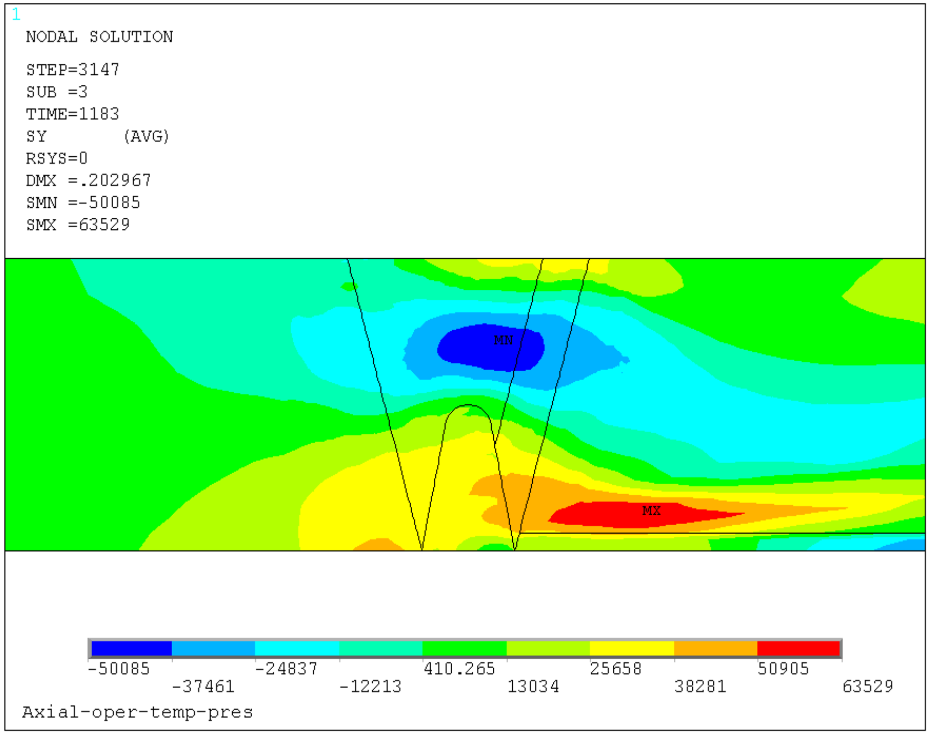
8



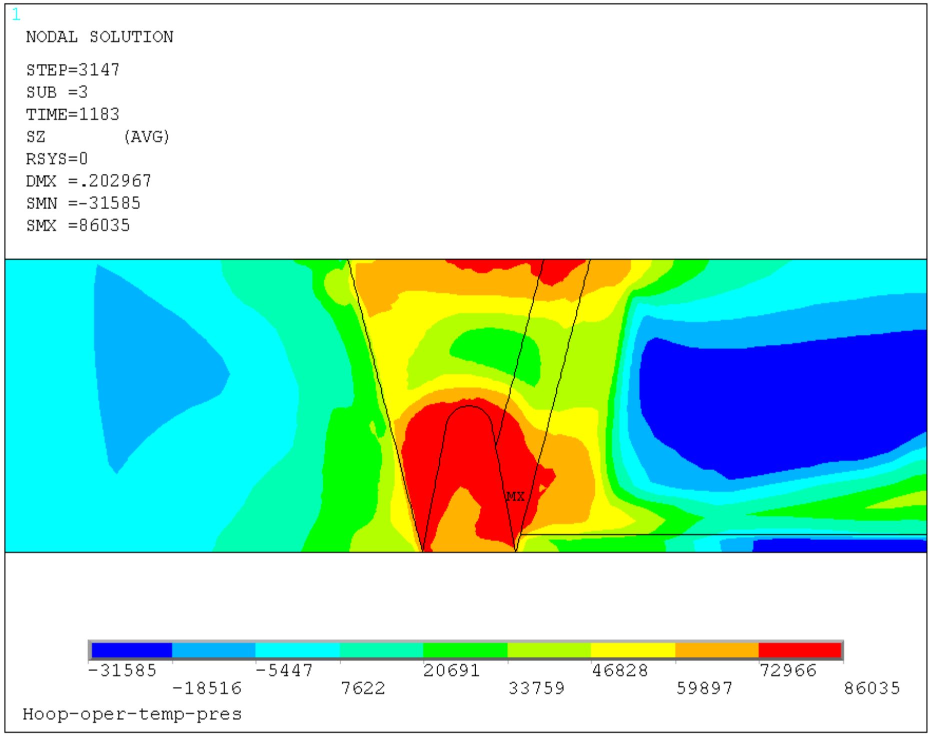
25% deep
wide EWR
w/ WOL cap

Residual Stress Results: Pre-EWR (@ operating Temperature & Pressure)

Axial Stress



Hoop Stress



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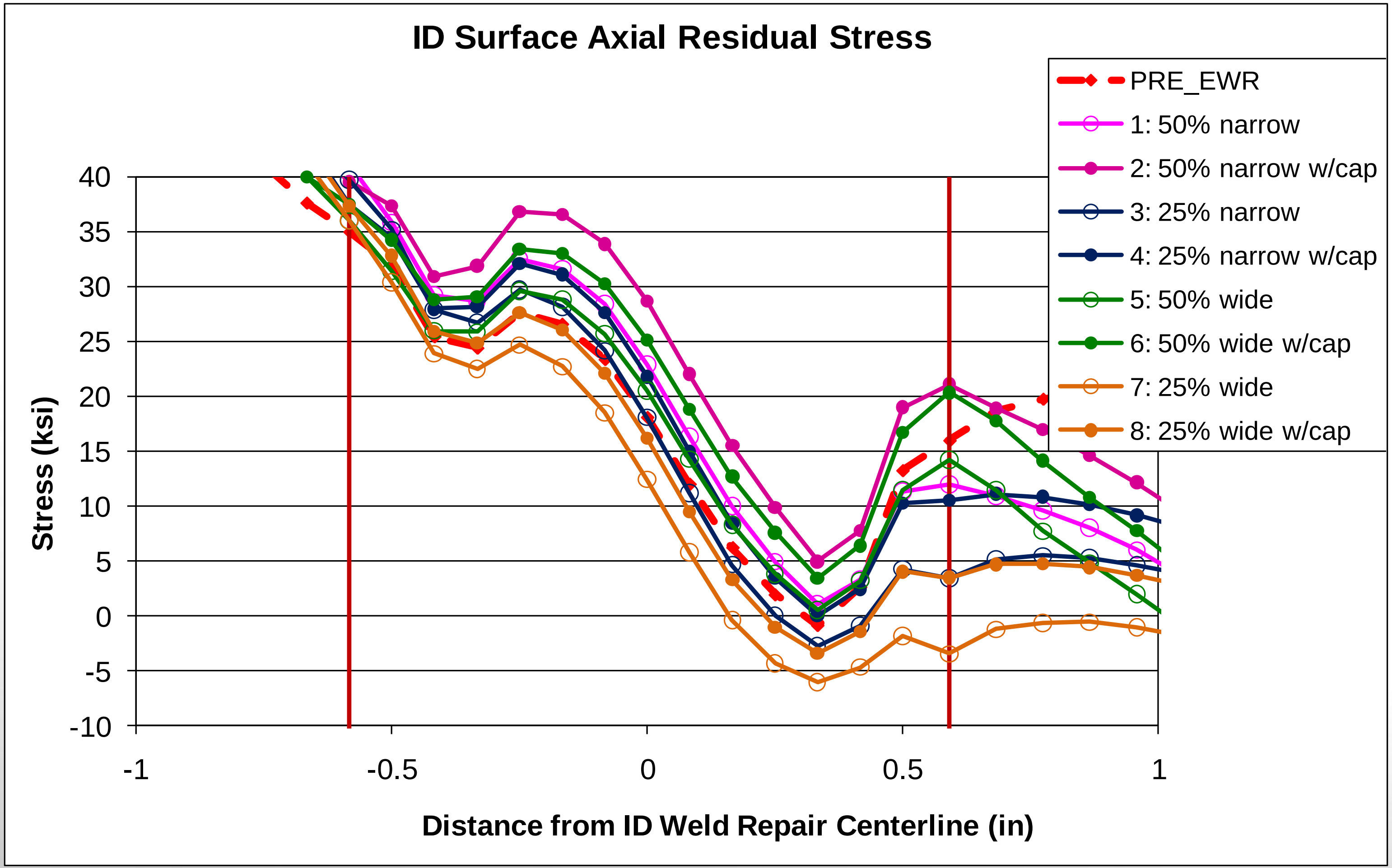
ID Surface Axial Stress Comparisons (@ operating Temperature & Pressure)



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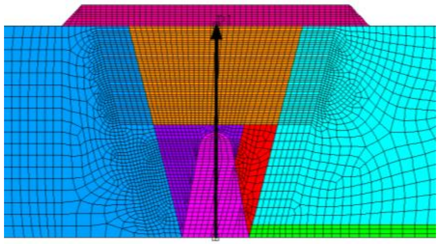
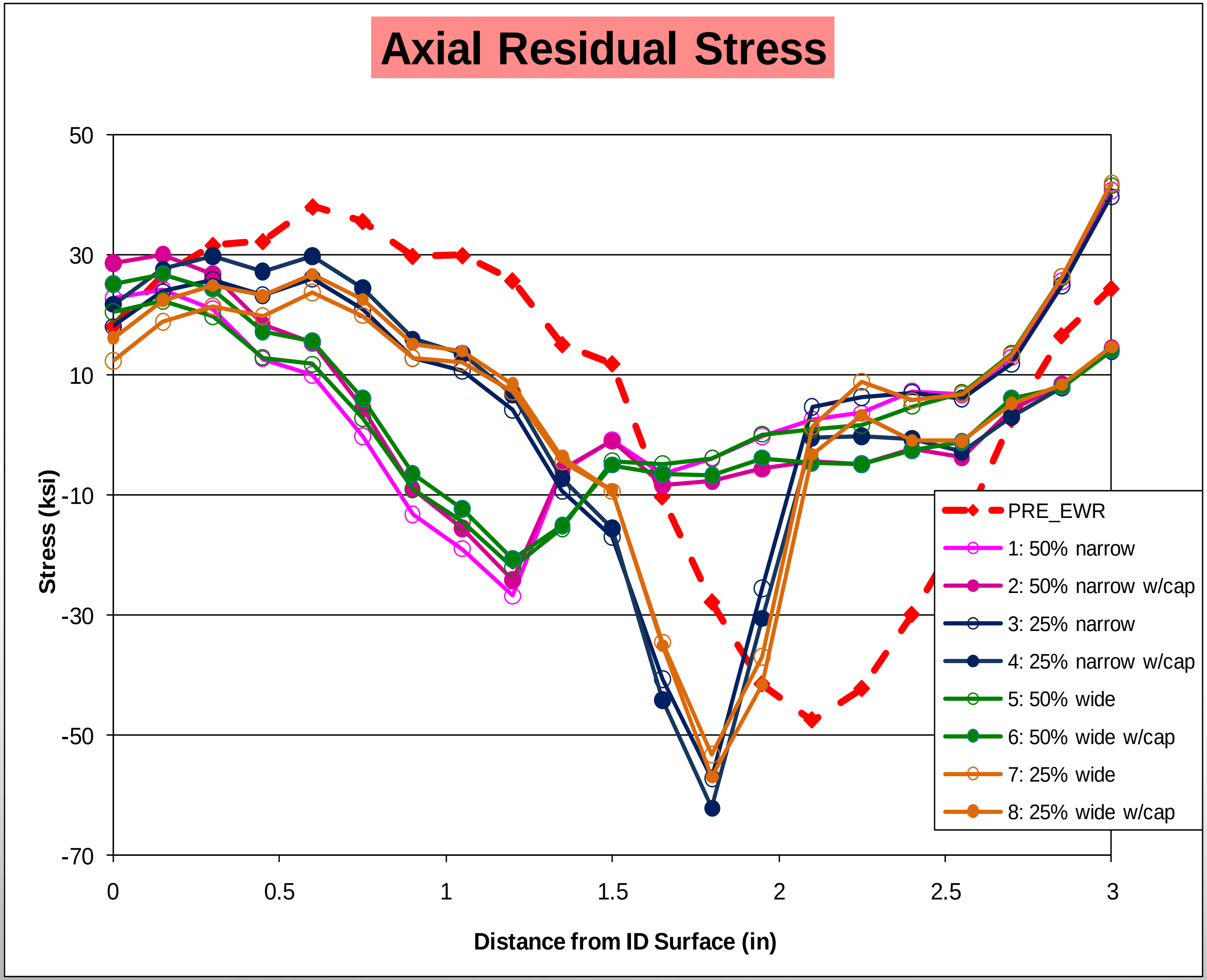
Through-Wall Axial Stress Profiles (@ operating Temperature & Pressure)

Stress Path





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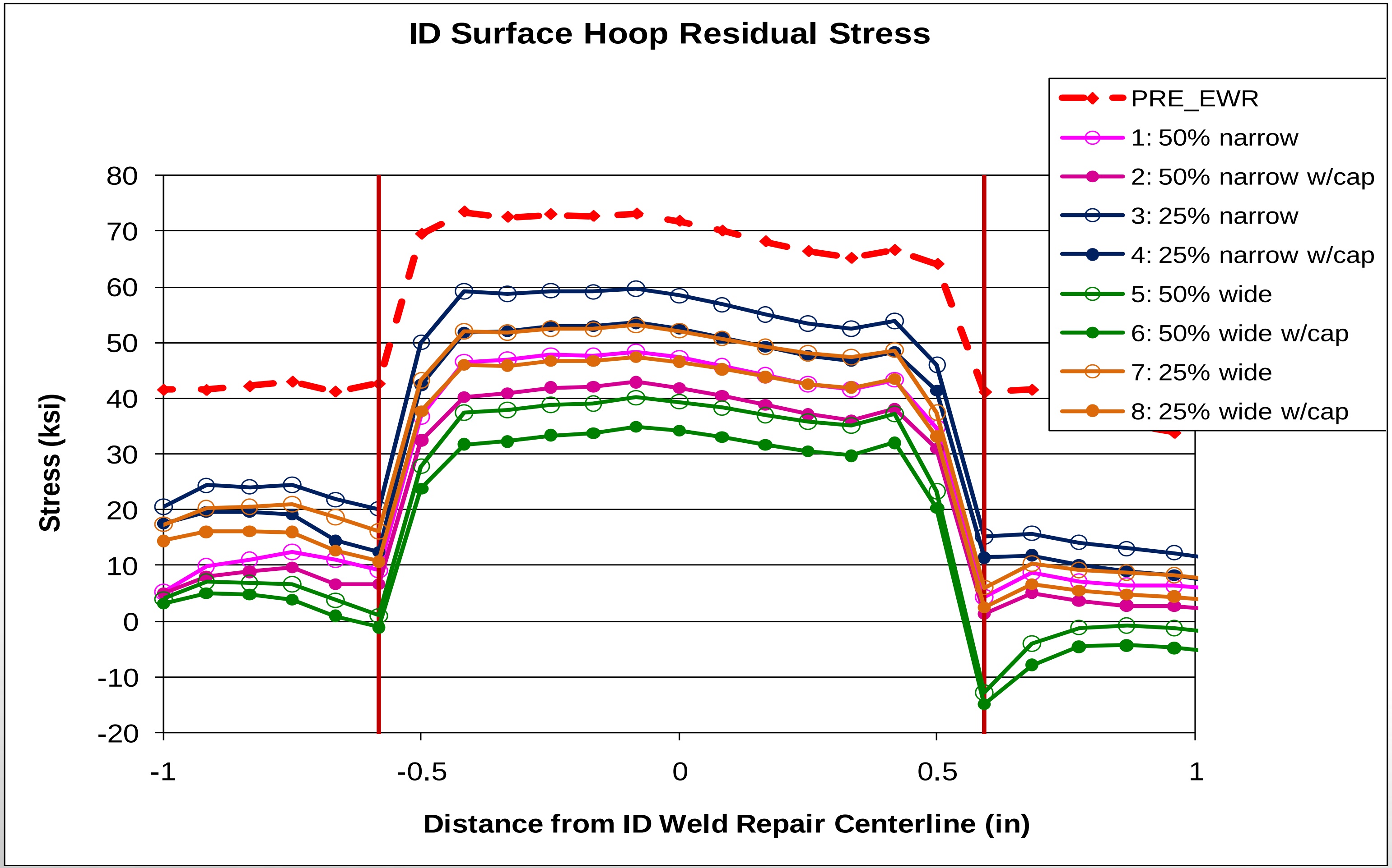
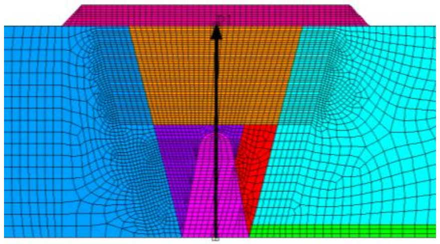
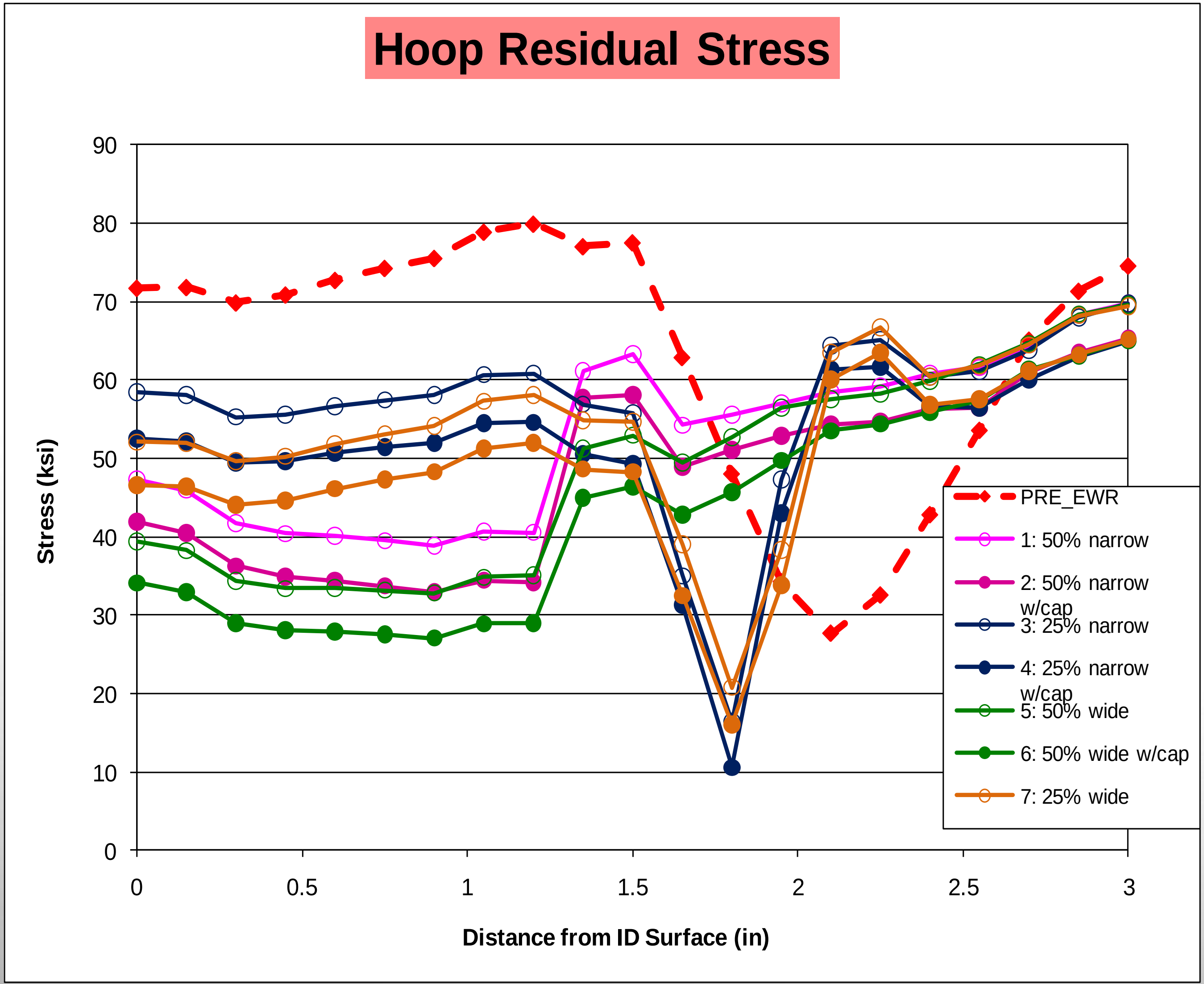
ID Surface Hoop Stress Comparisons (@ operating Temperature & Pressure)



Through-Wall Hoop Stress Profiles (@ operating Temperature & Pressure)

Stress Path





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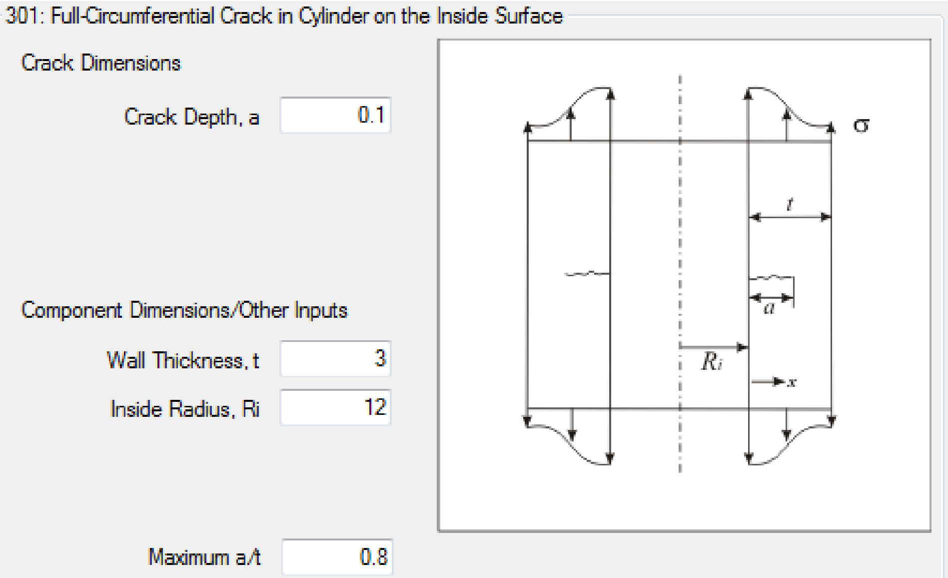
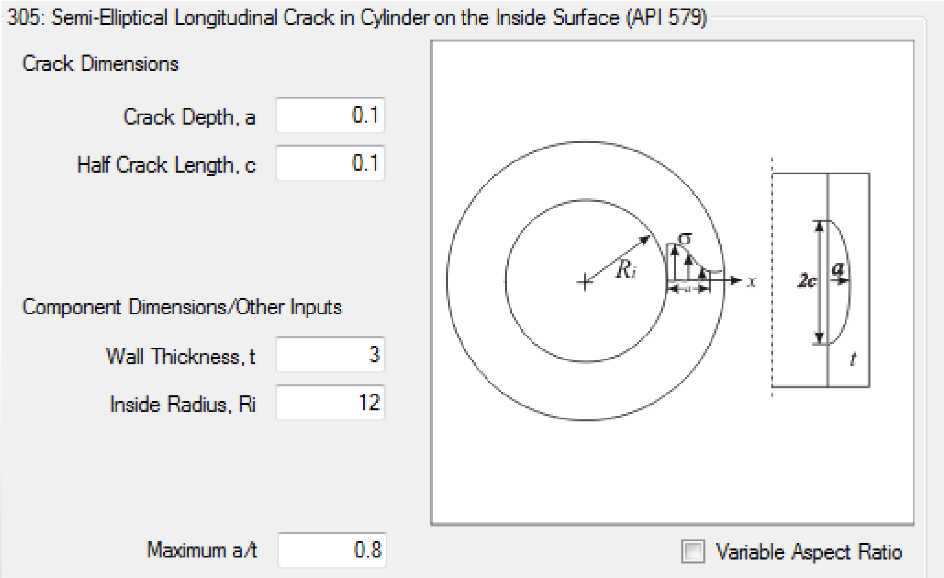
pc-Crack Fracture Mechanics Models

- Axial Stresses applied to Circumferential Crack
- Hoop Stresses applied to Axial Crack





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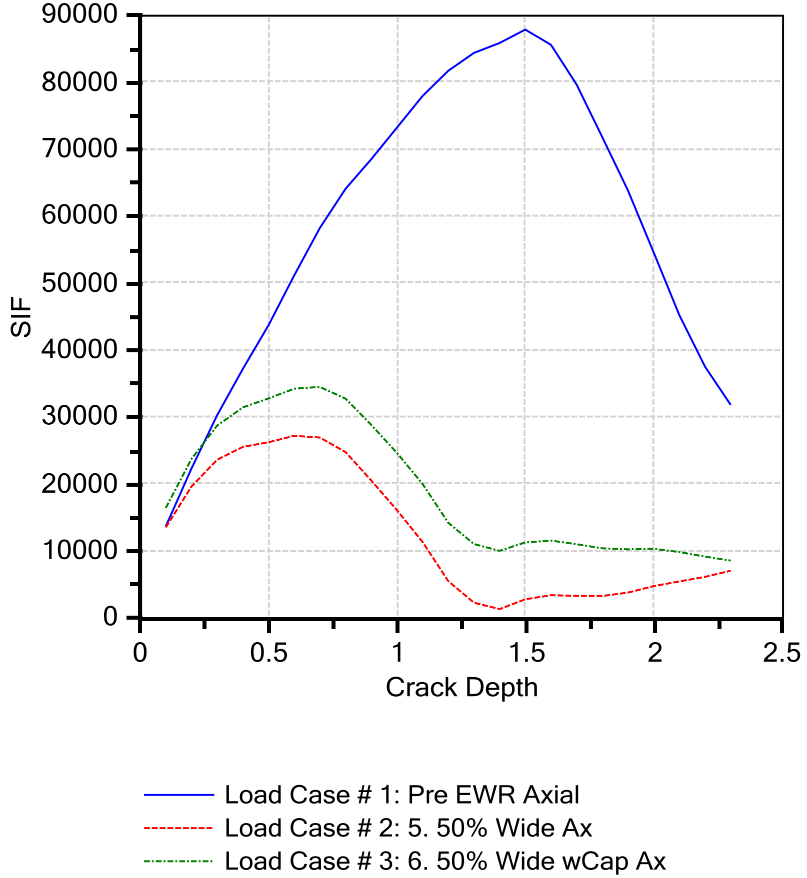
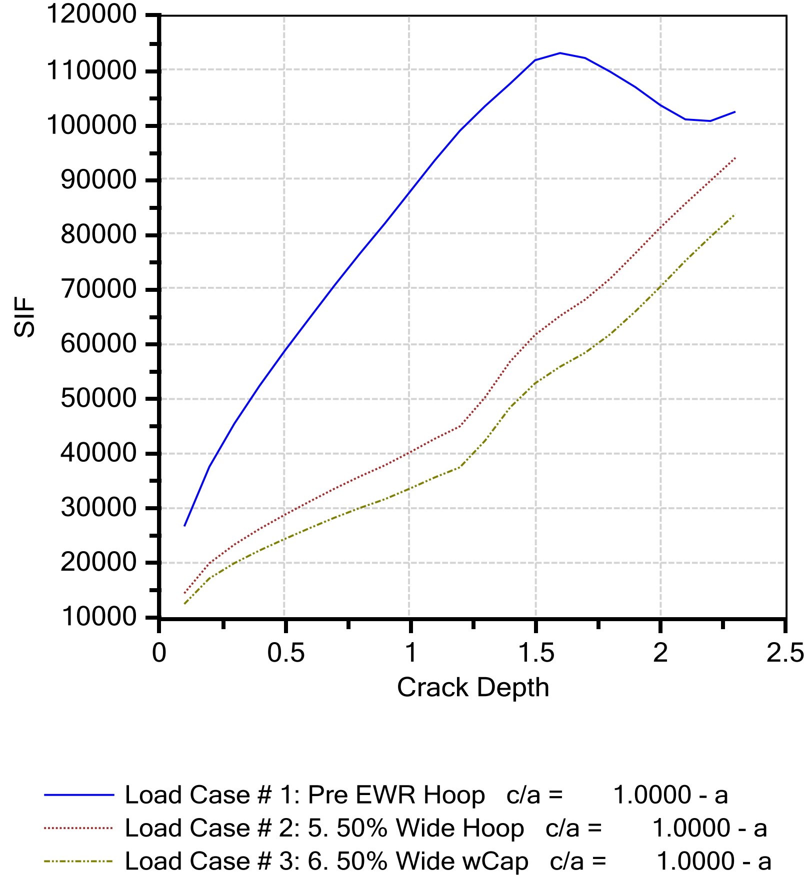
Stress Intensity Factors

- Circumferential Crack



- Axial Crack



Conclusions for 2D Evaluations

- Wide range of EWR configurations studied
  - 50% % 25% excavation cavity depth from outside surface
  - Narrow and wide cavities
  - With and without WOL Cap
- EWR produces significant residual stress improvement
  - Although not complete reversal like WOL or MSIP
  - Best configuration = 50% deep, wide EWR
  - WOL Cap adds only modest improvement
- Improvement most apparent in Circumferential Crack stress intensity factors

Planned 3D EWR FEA

- Standard SI WRS FEA methodology
- Isotropic hardening with modified SS curves
- 3D modeling with partial arc EWR

  0. Pre-EWR (include DMW and ID Repair only)
  1. --
  2. --
  3. --
  4. --
  5. 50% deep, wide EWR, no WOL cap
  6. --
  7. --
  8. --

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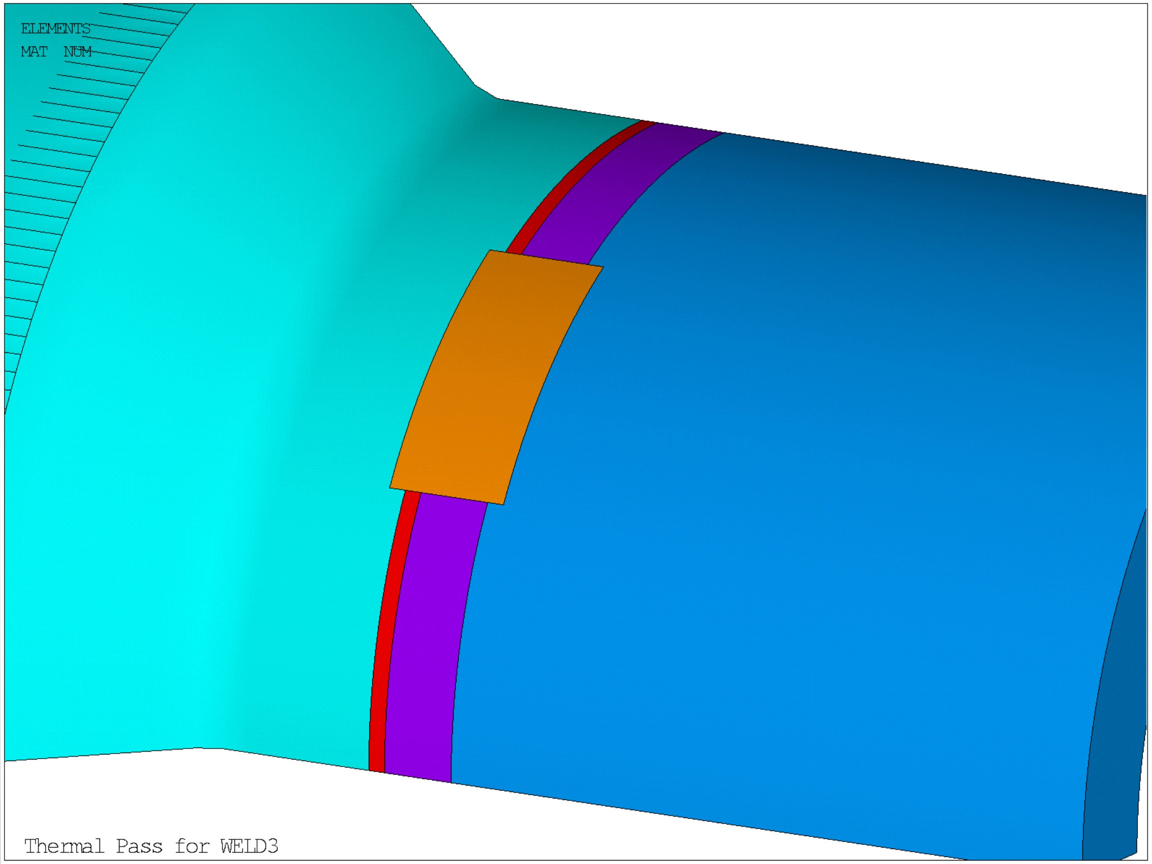
3D Partial Arc EWR Cases

- 50% deep, wide EWR, no WOL cap
- Determine effective EWR arc length:
  1. 15° partial arc
  2. 30° partial arc



Click Image to Play/Pause

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Magnetic Stir Welding

Greg Frederick & Steve McCracken

EPRI – Welding and Repair Technology Center

NRC – Industry Meeting

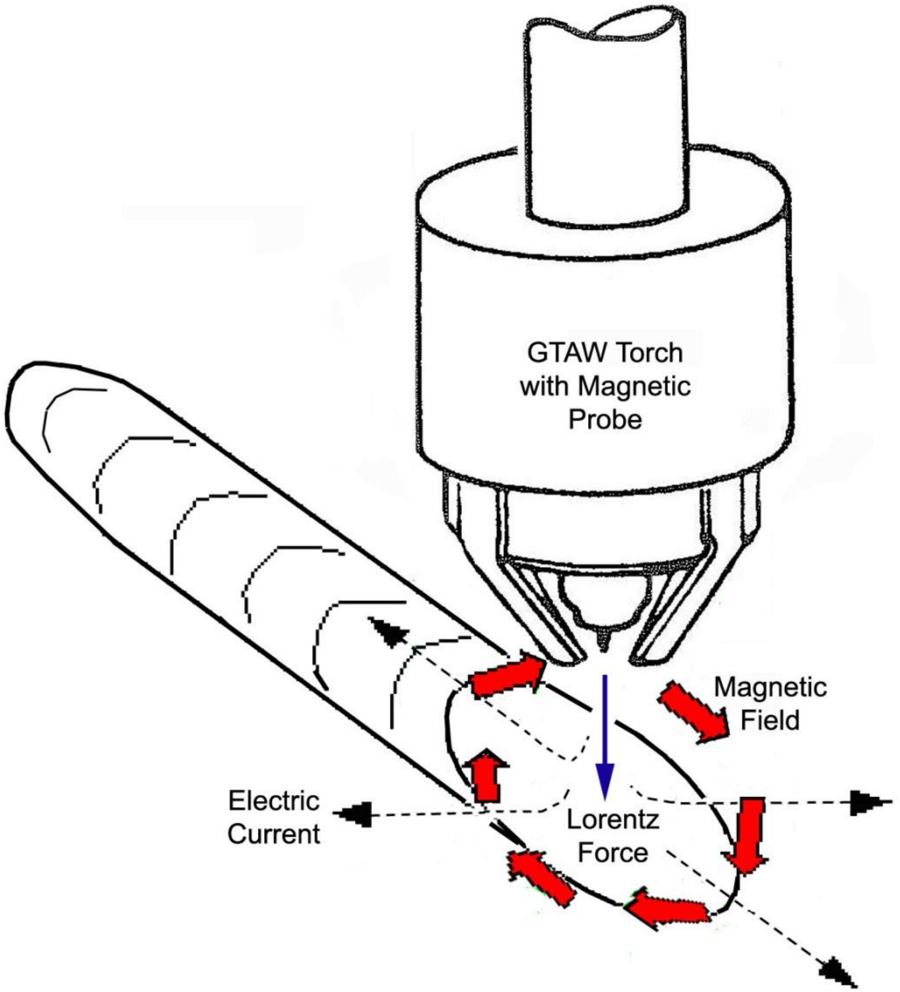
PWR Materials Reliability and Weld Repair Research

Charlotte North Carolina

January 24, 2012

Magnetic Stir Welding (GTAW)

- **Magnetic field deflects the weld arc which stirs the weld puddle**
  - Circular pattern used for this study
  - Stirring breaks up solidification pattern and produces a smaller grain size
  - Smaller weld metal grains are more conducive to UT examination (lower attenuation)
  - Smaller grains also improve resistance to solidification cracking



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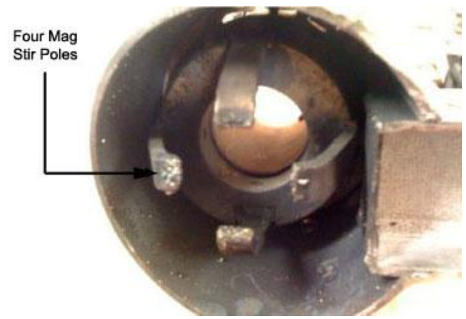
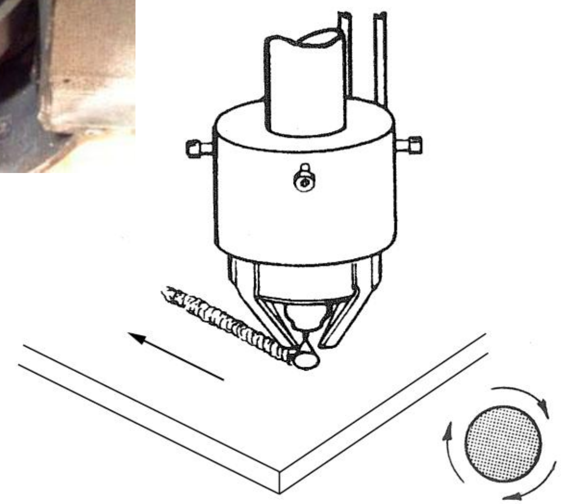
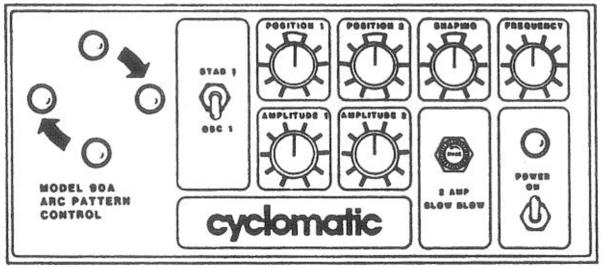
Magnetic Stirring Equipment and Settings

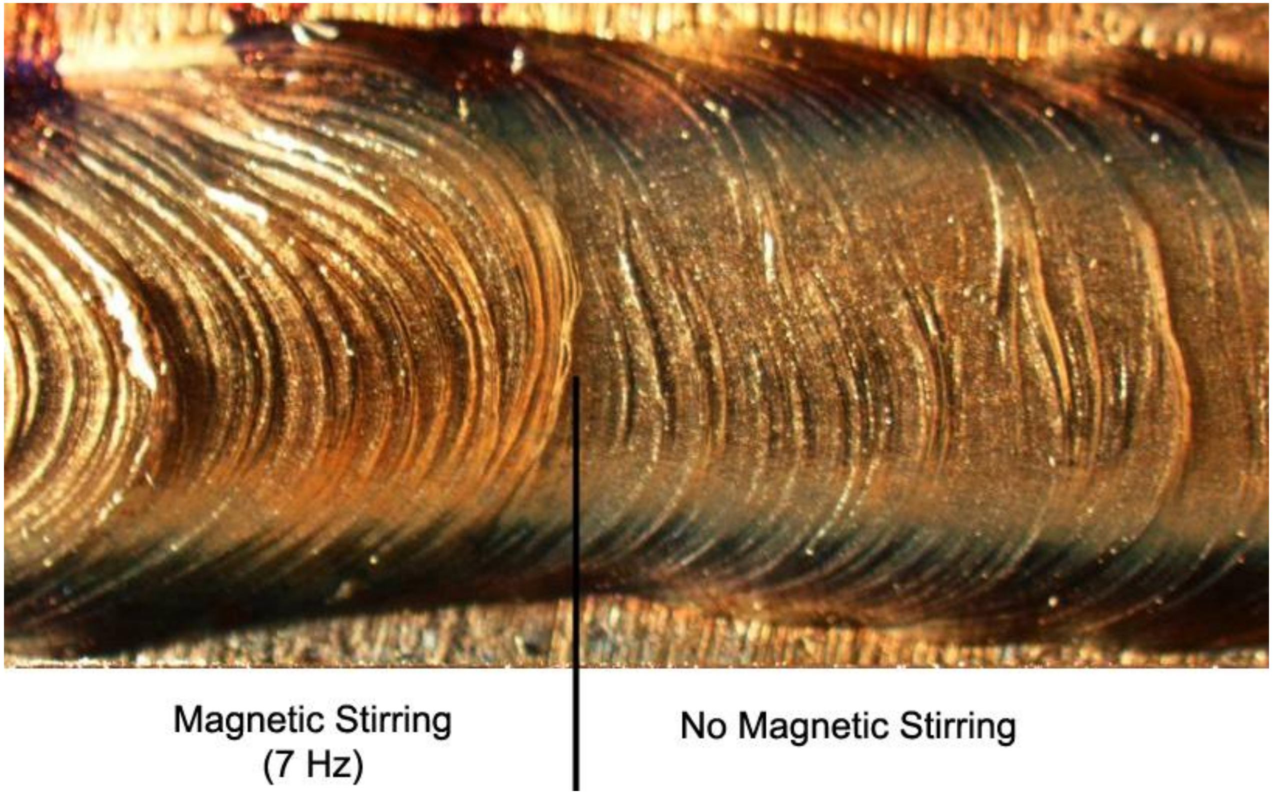
- **Cyclomatic Model 90A used for feasibility testing**
  - Stirring set to circular arc stirring pattern
  - Testing included autogenous beads and 52M weld pads
  - Standard GTAW torch





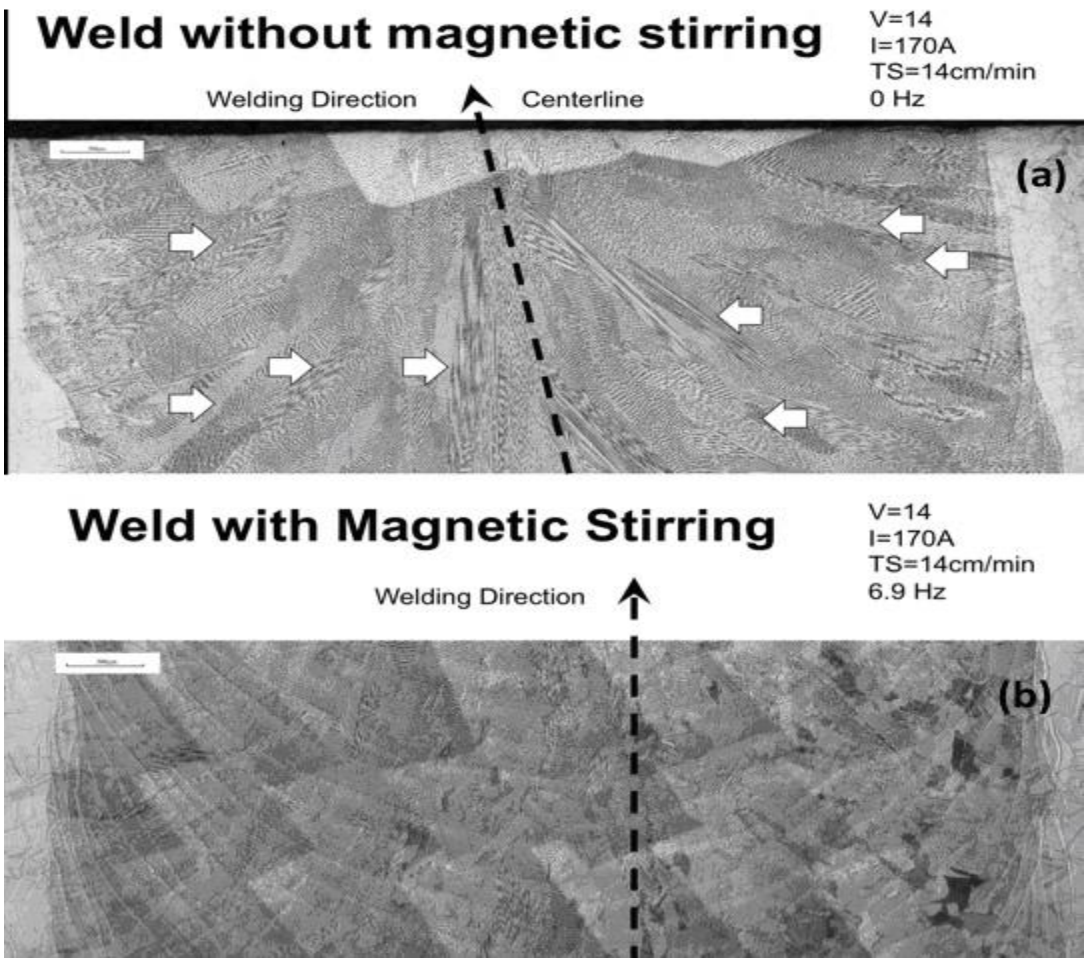


Magnetic Stir GTAW Bead



- 170 to 190 amp, 11 volt, 4 to 5.5 ipm travel, 40 to 50 ipm, 7 Hz stir frequency
- 0.035” 52M filler metal on Alloy 690 plate

Grain Size and Orientation with Mag Stir



- Magnetic arc stirring breaks up long columnar grains
- 6.9 Hz circular stirring at 14 cm/min travel speed are most effective
- Reversal in weld metal solidification direction is what breaks up the weld metal grain growth

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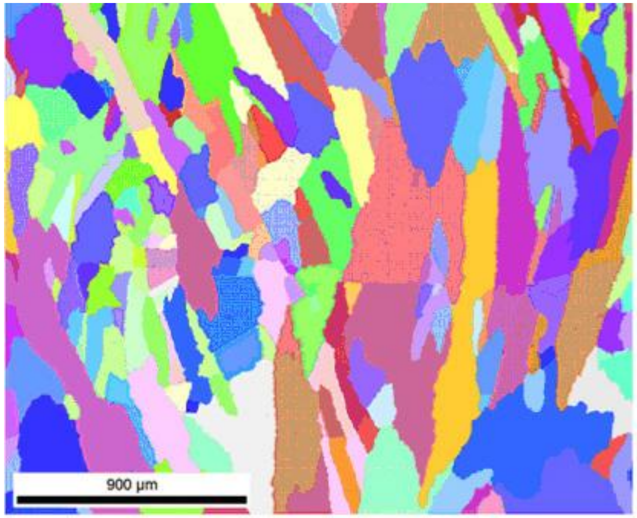
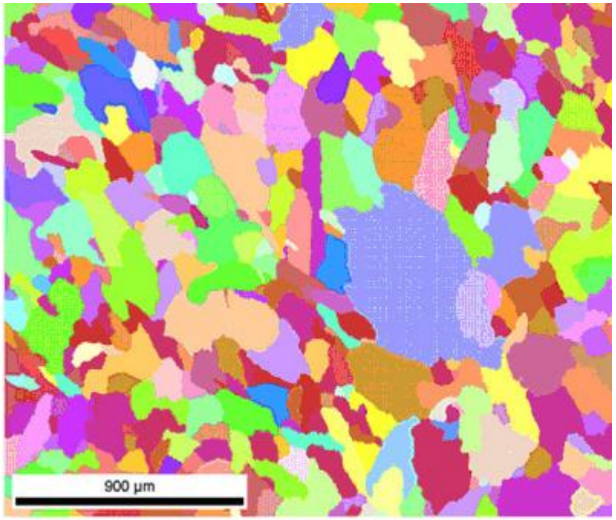
Results - Electron Back Scattered Diffraction

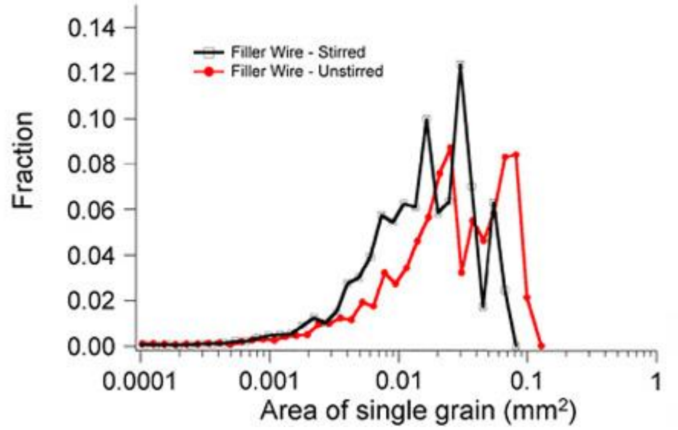
- Electron Back Scattered Diffraction
  - Method to look at grain size
  - Significant reduction in grain size with 6.9 Hz circular magnetic stirring



Unstirred (0 Hz)



Stirred 6.9 Hz



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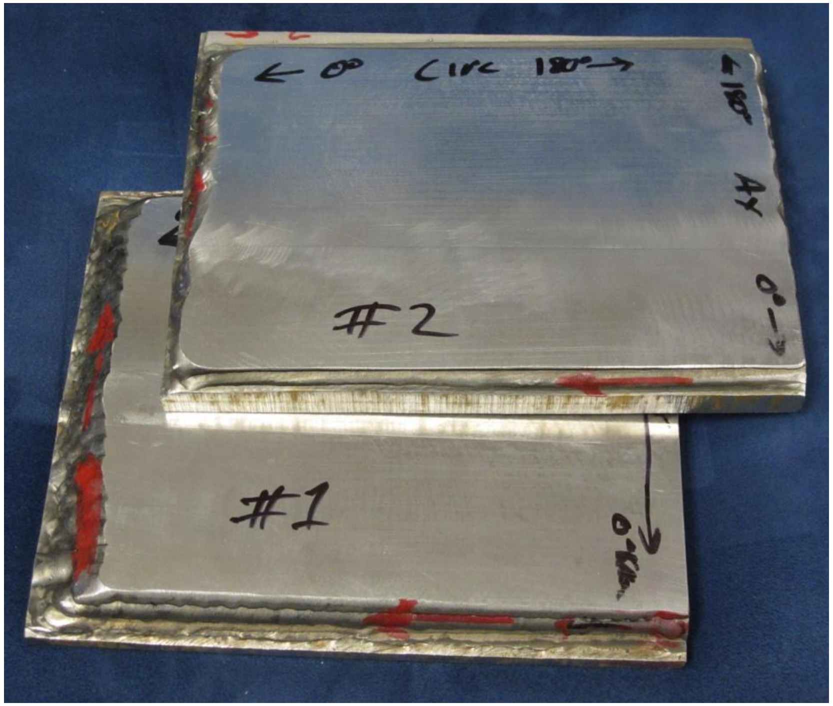
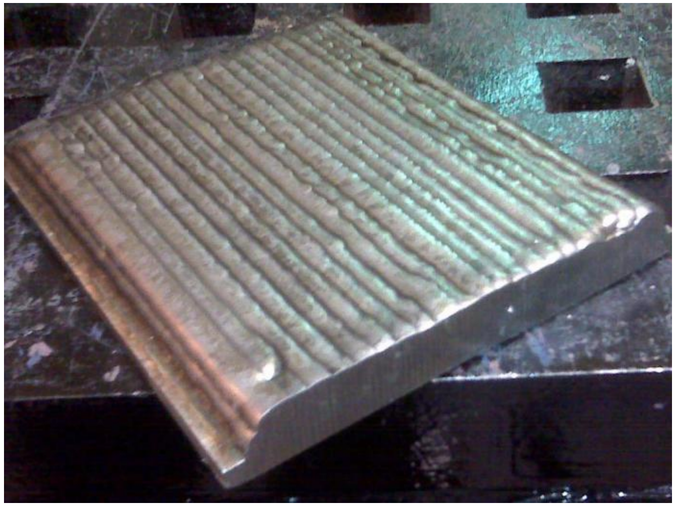
Specimens for Ultrasonic Examination

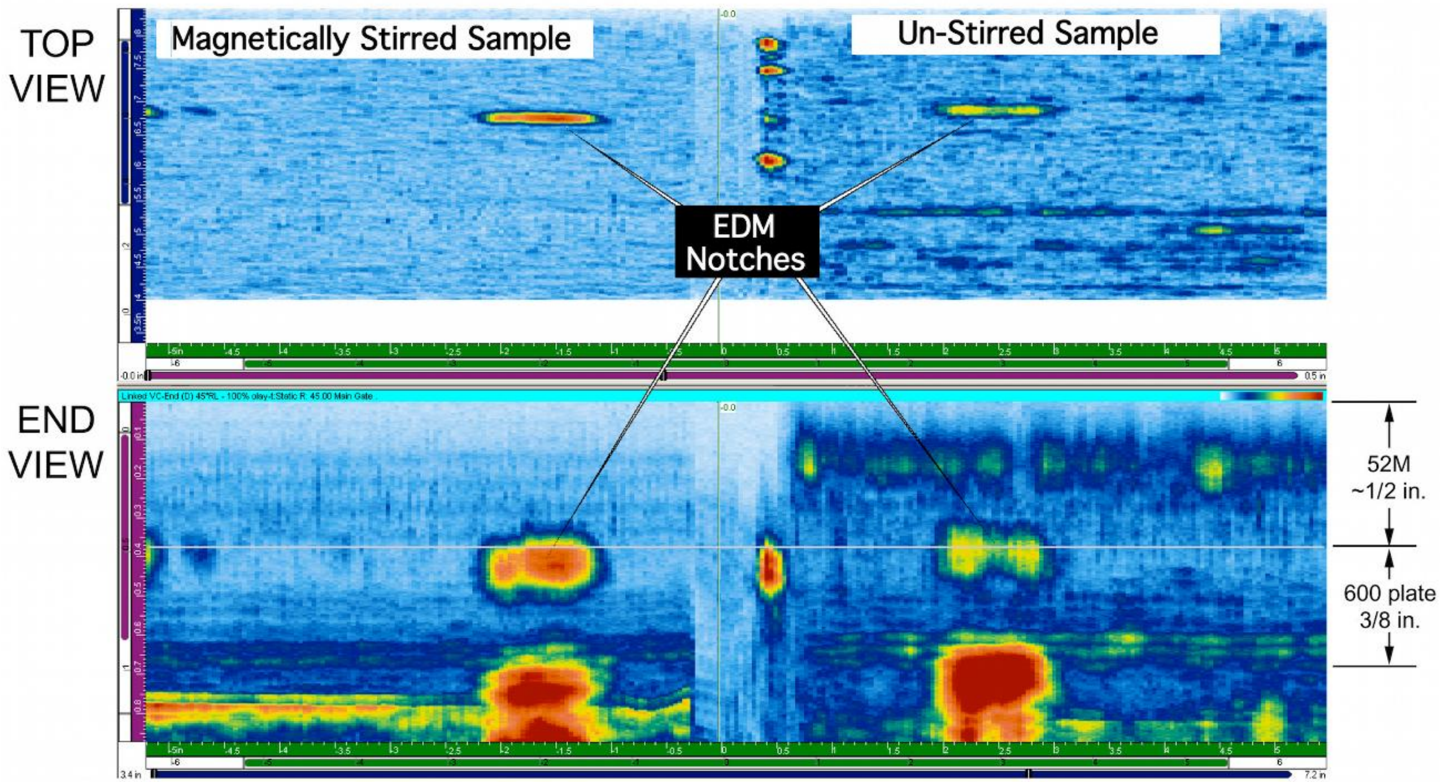
- Two weld 52M pads on 690 plate
  - #1 non-pulse GTAW parameters
  - #2 with optimized magnetic stirring





- Weld pads prepared for UT examination
  - Machined flush with ~3/8” 52M thickness
  - Circ & axial EDM notches machined on plate back surface to 52M fusion line depth

Improved Ultrasonic Response



- 45 RL Axial Scan
  - 13:1 to 20:1 *(+ & - scan direction)* signal-to-noise ratio with stirring
  - 5:1 & 8:1 *(+ & - scan direction)* signal-to-noise ratio without stirring

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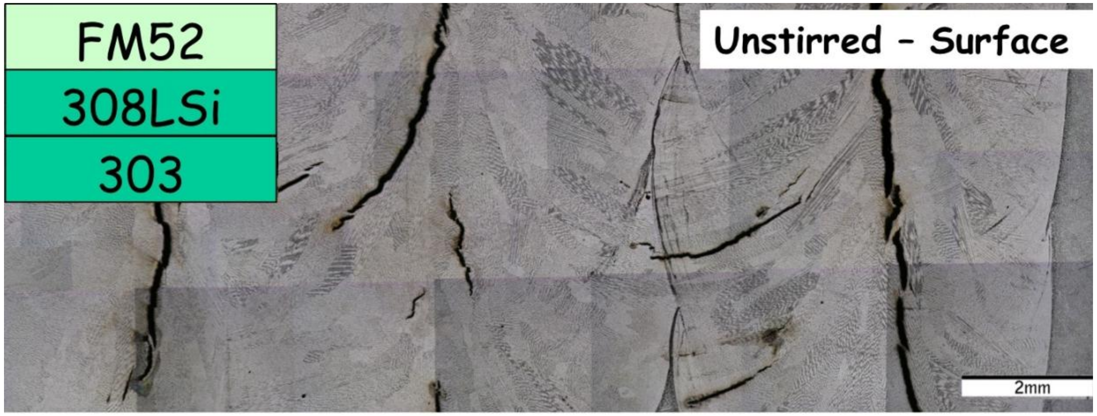
Improved Resistance to Solidification Cracking

- 52M weld pad on Type 303 plate clad with ER308L-Si weld metal
- Surface micrographs with & without magnetic arc stirring

- Standard GTAW without stirring
  - 11.5 Volt
  - 240 Amp
  - 4 ipm travel speed
  - 58 ipm wire feed speed (0.045" dia.)
- GTAW with magnetic stirring
  - Parameters same as above with 7Hz stirring



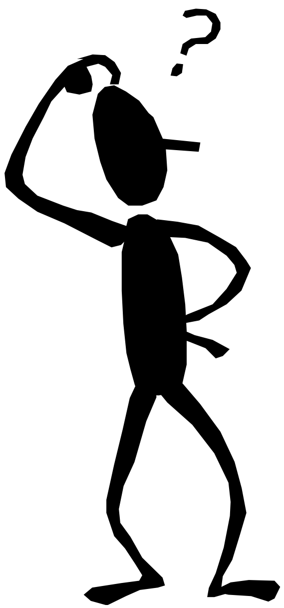
Magnetic Stir GTAW – Proven Potential

- Testing indicates that GTAW with optimized magnetic stirring:
  - Interrupts the solidification pattern at the weld puddle fusion line
  - Breaks up large columnar grains typical of nickel-base welds
- Testing shows that GTAW with magnetic arc stirring:
  - Improves ultrasonic examination response due to weld metal grain refinement (lower sound attenuation with smaller grains)
  - Improves resistance to solidification cracking

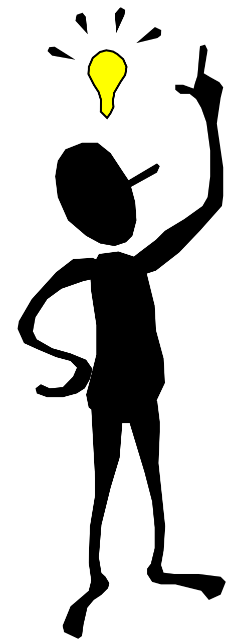
Magnetic Stir GTAW – Future Work & Potential

- Computer modeling developed for magnetic stir study
  - Considers solidification properties (solidification rate, temperature gradient, nucleation, cooling rate, etc.)
- Project for 2012 is to expand magnetic stir model to GTAW welding for optimizing standard controls
  - Goal of new computer model is to identify optimum GTAW parameters to control weld metal solidification in similar manner as magnetic stirring
    - Pulse parameters, oscillation, dwell, travel speed, etc.
- Evaluation of variable polarity GTAW to mitigate/minimize solidification cracking is in progress with Liburdi-Dimetrics in Canada

Thank You – Questions or Comments?



Welding and Repair Technology Center



Together…Shaping the Future of Electricity

EPRI Welding Residual Stress Validation Project

Final Report and Modeler's Handbook

John Broussard
Senior Engineer, Dominion Engineering

Industry-NRC Public Meeting on Welding Residual Stress

January 25, 2012

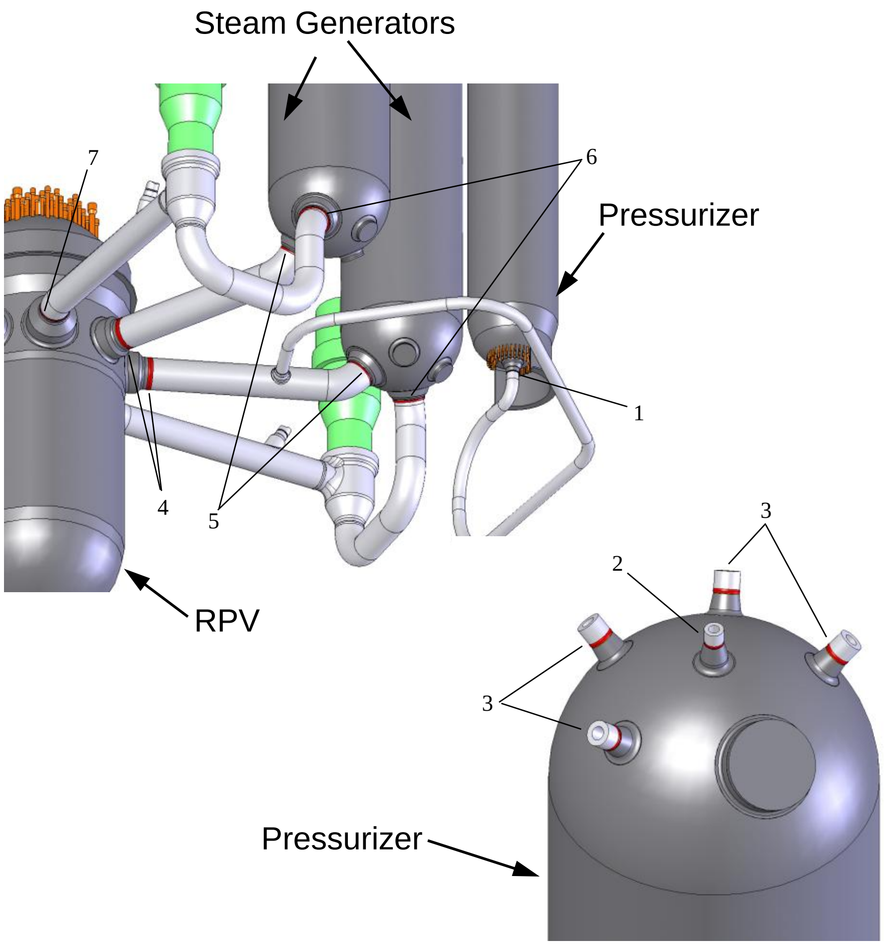
Contents

- Background
- Project Phases
- Residual Stress Measurement Techniques
- Phase 1 Discussion
- Phase 2 Discussion
- Phase 3 Discussion
- Modeling Handbook

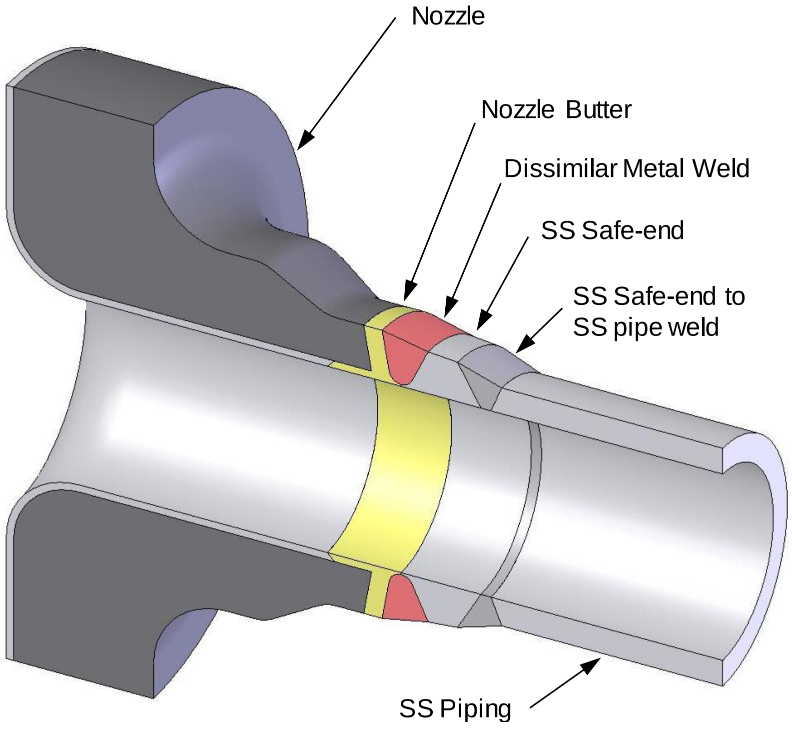
PWSCC in PWR Fleet Dissimilar Metal Welds

- Primary Water Stress Corrosion Cracking (PWSCC) observed in Alloy 600 and 82/182 dissimilar metal welds at 15 plants (11 US) via leaks, cracks or indications, primarily since 2000
- Primary driver for DM weld PWSCC is residual stress in the weld material itself
- Prediction of residual stress using computer modeling is a key part of evaluating PWSCC in DM welds
  - Support K-based crack growth rate calculations
  - Design and validation of remedies/repairs

Dissimilar Metal Butt-welds in PWRs



Example Illustration of Westinghouse Design Plant



Example DMW Configuration

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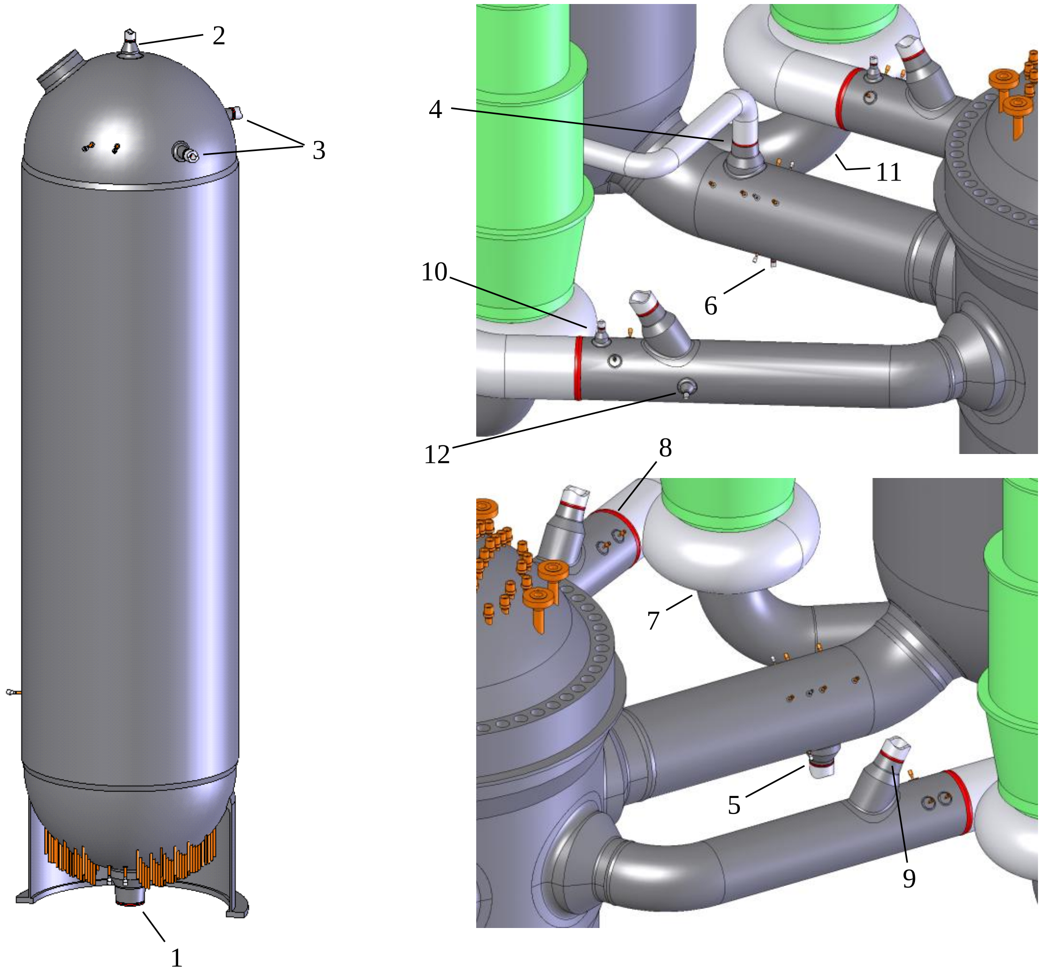
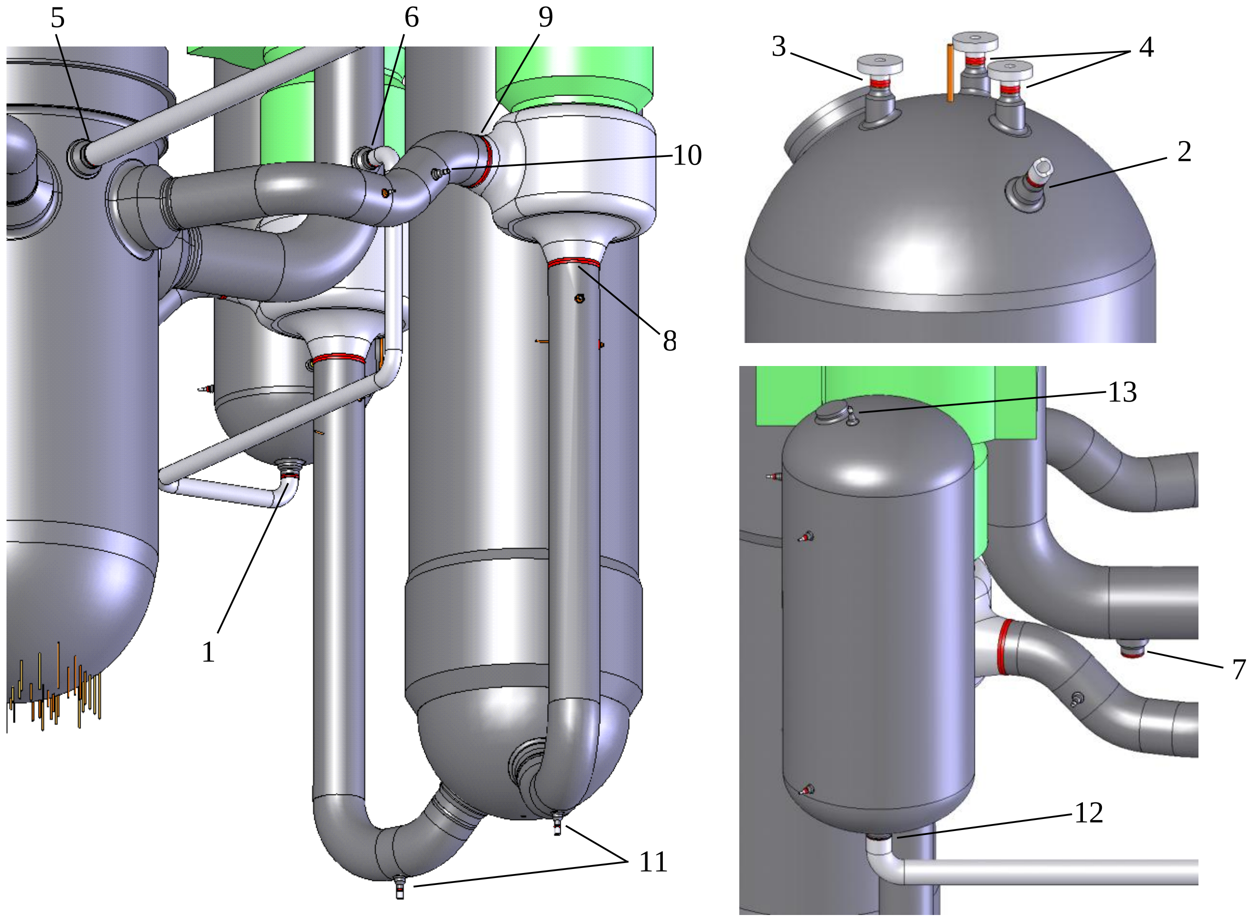
Dissimilar Metal Butt-welds in PWRs



Example Illustration of CE Design Plant

Dissimilar Metal Butt-welds in PWRs



Example Illustration of B&W Design Plant

Wolf Creek Fall 2006 Circumferential Indications

- 5 circumferential indications in 2006 were the first observation of multiple, long, circumferential indications.
- The observation had implications for PWR plants (9) with inspection requirements to complete by end of 2007
- Significant effort in 2007 by industry and NRC to evaluate the impact of the Wolf Creek indications on safety assessment of DM welds
  - More refined approach to crack growth calculations
  - Desire for validation of welding residual stress distributions used as input for crack growth

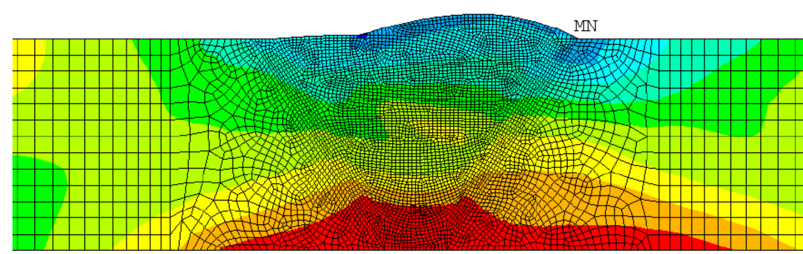
DMW WRS Validation R&D Program

- Basis:
  - ACRS letter dated 10/19/07 supported further research to validate WRS FEA models
  - NRC/EPRI MOU Addendum for Cooperative Research 10/22/09
- Purpose:
  - Refine WRS FEA model development for DMW through sequential development from Phase I to IV
  - Develop reasonable assurance that WRS FEA are defensible through blind validation of well controlled mockups and real components to various WRS measurement testing techniques

Approach to Validation

- Validation of WRS models comes from comparing laboratory measurements and analytical model results
- Both measurement and analysis are considered in this project
- Measurement efforts
  - Compare complimentary techniques
  - Two or more techniques each for through-wall and surface stresses

- Modeling efforts
  - Explore model variations to determine sensitivity of results to changes



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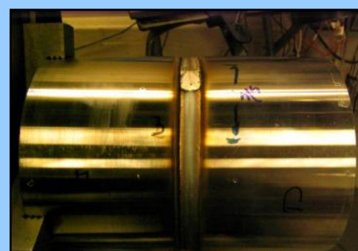
Summary of Project Phases

Phase 1

Scientific Weld Specimens

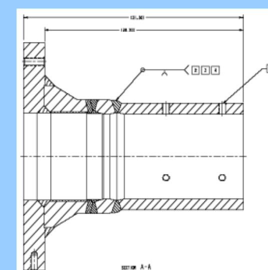
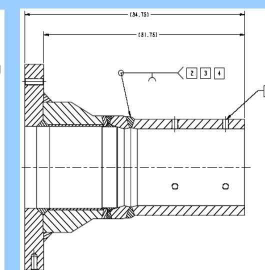
- **Phase 1A:** Restrained Plates
- **Phase 1B:** Small Cylinders
- Purpose: Develop FE models

Phase 2

Fabricated Prototypic Nozzles

- Type 8 Surge Nozzles
- Purpose: Prototypic scale under controlled conditions. Validate FE models

Phase 3

Plant Components

- WNP-3 S&R PZR Nozzles
- Purpose: Validate FE models


Phase 4

Plant Components

- WNP-3 CL Nozzle
- RS Measurements by NRC
- Purpose: Effect of overlay on ID

Residual Stress Measurement

Techniques Considered

- Techniques researched and classified based on level of destructiveness
  - **Nondestructive:** leaves sample unchanged from previous condition
  - **Semi-destructive:** local region of sample modified by measurement – overall sample still remains intact
  - **Destructive:** entire sample irrevocably changed by measurement

- Techniques also categorized by depth of penetration (e.g., through-wall, surface) and by advantages/disadvantages

Residual Stress Measurement

Techniques Summary

- Neutron Diffraction (ND)
  - Diffraction (crystal lattice spacing) strain measurement
  - Through wall stress in three directions at each gauge vol
  - Difference in spacing between loaded and unloaded sample is imposed strain
  - Unloaded sample must be cut into small pieces
  - Diffraction peaks in DM welds can be difficult to resolve
- X-ray Diffraction (XRD)
  - Similar principle as ND, but at surface (microns deep)
  - Sample cutting not needed since normal stress = 0
  - Large grain sizes present difficulty

Residual Stress Measurement

Techniques Summary

- Deep Hole Drilling (DHD)
  - Mechanical release strain measurement
  - Through-wall stress in two directions along line
  - Measures change in size for reference hole as it is trepanned from sample
  - Incremental technique (iDHD) added to resolve plasticity
- Contour Method
  - Mechanical release strain measurement
  - Through-wall stress in one direction for entire plane
  - Measures deflection on cut faces

Residual Stress Measurement

Techniques Summary

- Hole Drilling / Ring Core
  - Mechanical release strain measurement
  - Surface and near surface stress measurement
  - Hole drilling measures strain change around hole versus depth of drill
  - Ring core measures change in size for reference hole as it is trepanned from sample
  - Hole drilling typically limited to largest principal stress less than 70% of material yield
  - Ring core has larger gauge volume than hole drilling

Phase 1 Discussion

Phase 1

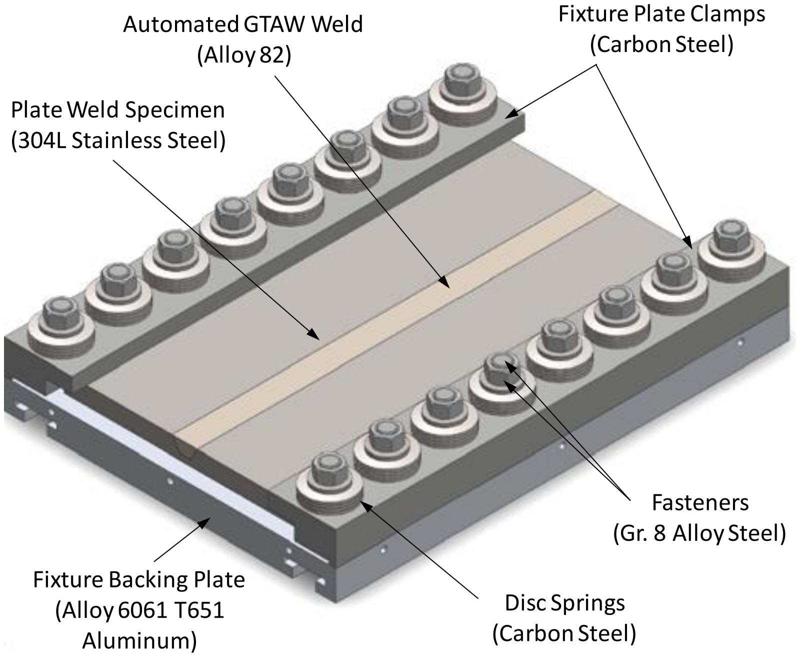
Scientific Weld Specimens

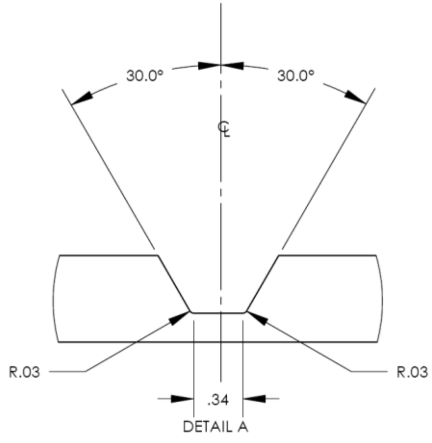
- **Phase 1A:** Restrained Plates
- **Phase 1B:** Small Cylinders
- Purpose: Develop FE models

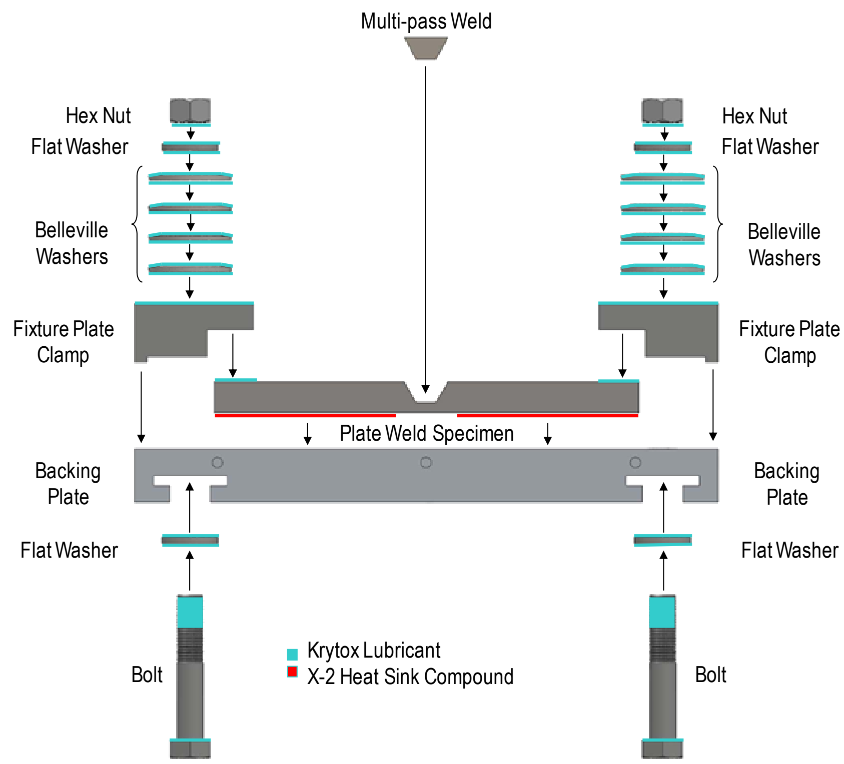
Phase 1 Specimen Design Goals

- Fabricate and measure weld residual stress in simple experimental specimens
- Multiple smaller size specimens for lower cost and logistics (shipping among measurement vendors, handling, etc.)
- Representative materials (A82 welds, stainless steel, buttered carbon steel)
- Multiple weld passes in weld cavity

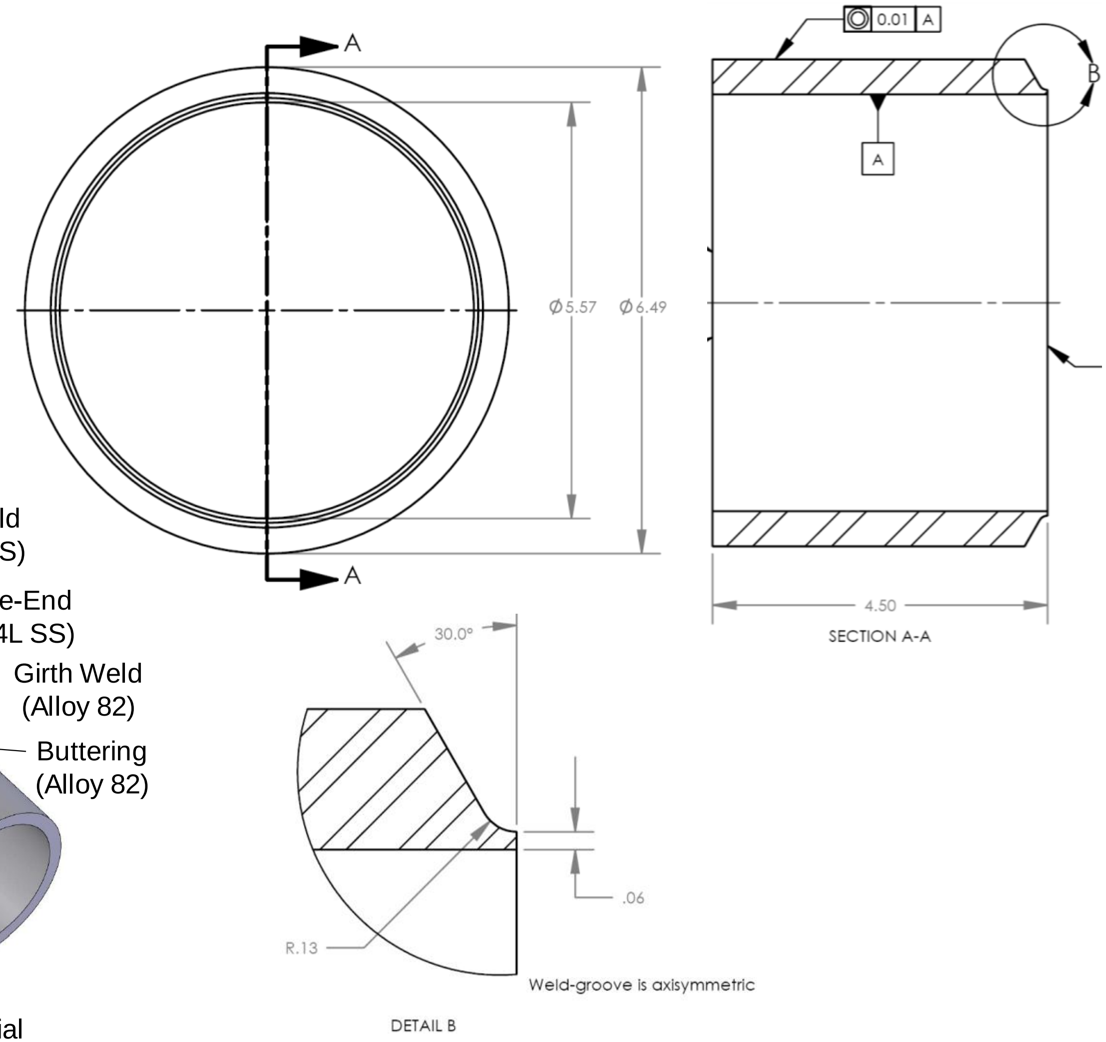
Phase 1A Plate Specimens

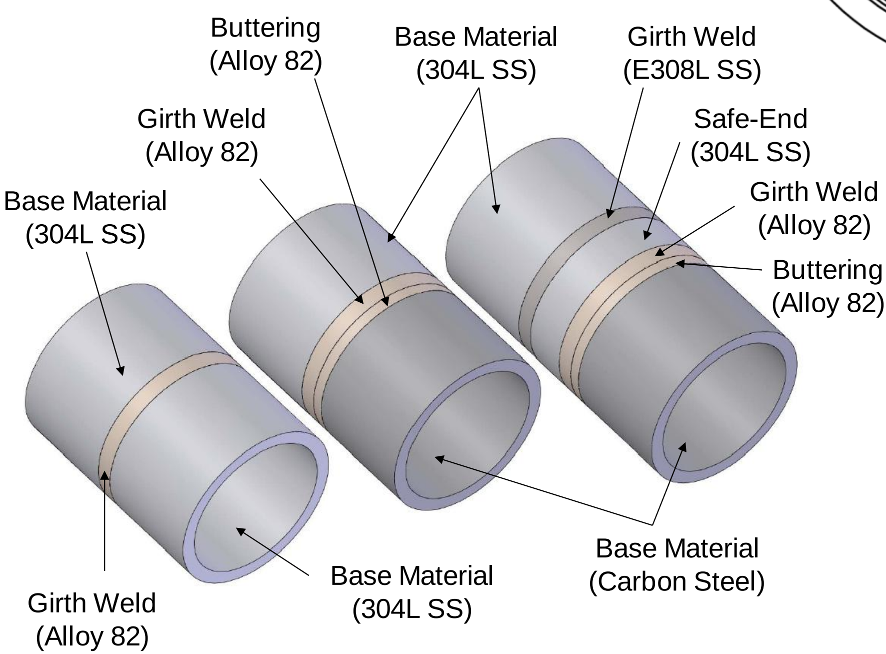






Phase 1B Cylinder Specimens





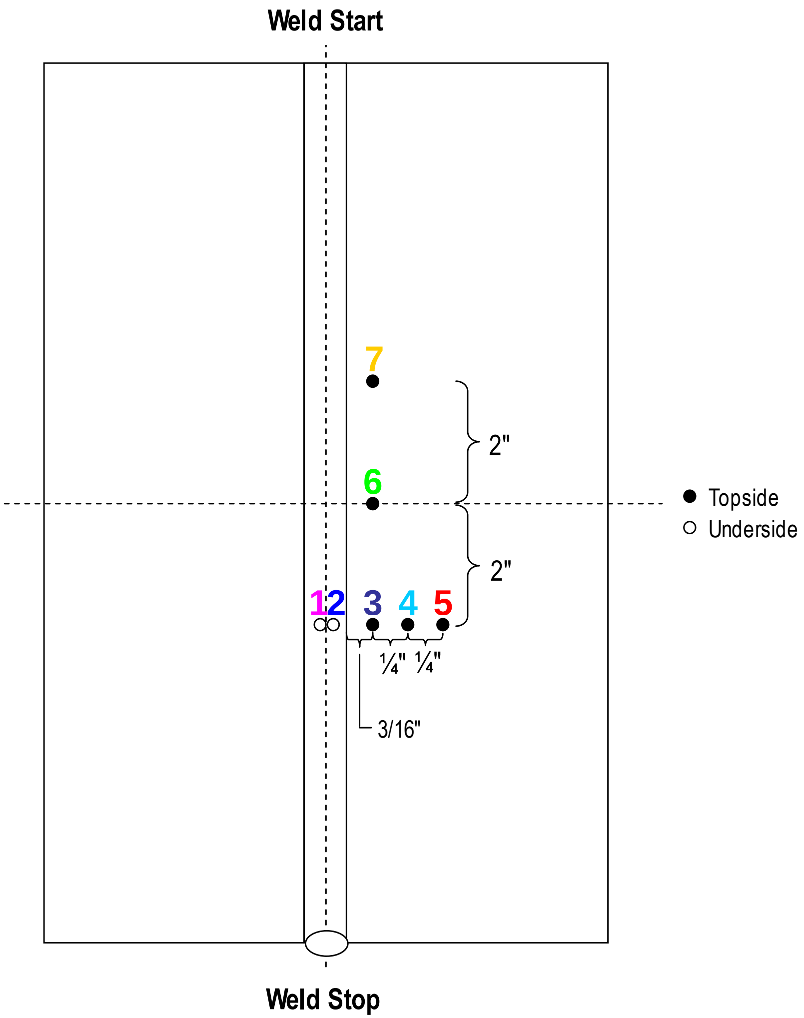
Phase 1A Plate Specimens Weld Parameters

	ID	Variable Tested	No. Passes	Current	Voltage	Travel Speed (in/min)	Wire Feed Speed (in/min)	
							Root Passes	Remaining Passes
Phase 1A Plates	P-3	Plate Base Case	11	275/225	11.5	6.0	76	96
	P-4	Decrease Travel Speed	7	275/225	11.5	3.5	76	96
	P-5	Increase Amperage and Wire Feed Rate	7	375/325	11.8	6.0	136	136
	P-6	Decrease Amperage and Wire Feed Rate	23	175/125	10.8	6.0	39	39

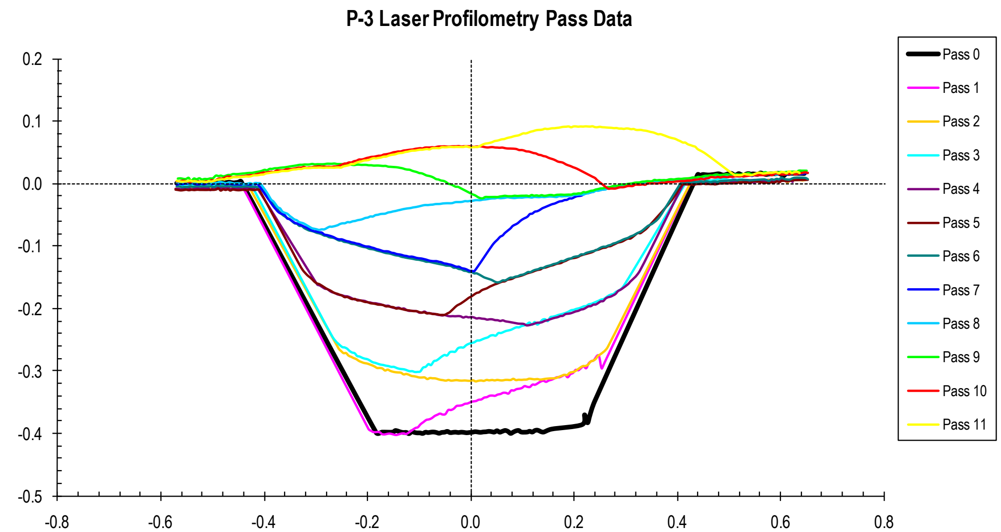
Phase 1B Cylinder Specimens Weld Parameters

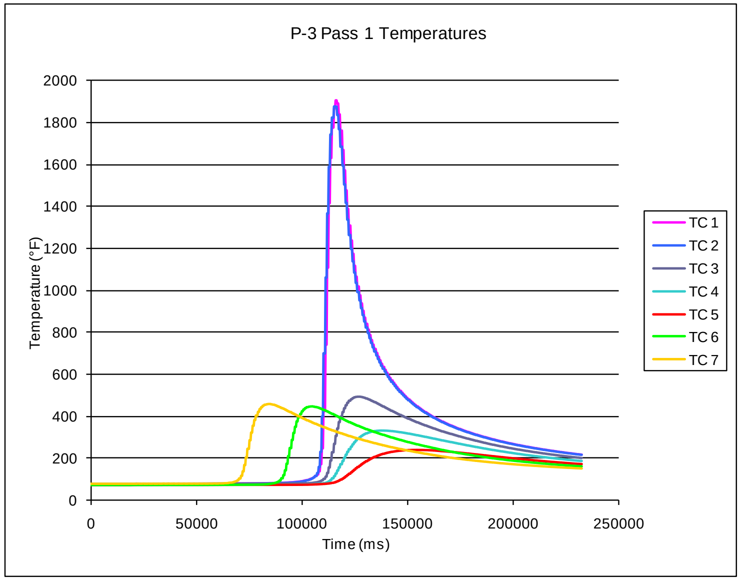
	Weld Passes	Current (A)	Voltage Range (V)	Travel Speed Range (in/min)	Wire Feed Speed (in/min)
SS-A82-SS	1	210/160	9.0-9.8	5.7-6.2	22 ± 2
	2	210/160	9.0-9.8	5.7-6.1	52.5 ± 5
	3	250/220	9.4-9.8	5.5-5.9	100 ± 5
	4 and up	350/300	10.5-11.5	5.5-5.9	96 ± 5
ButterCS-A82-SS	1	190/150	9.4-10.0	5.7-6.2	25 ± 2
	2	210/160	9.0-9.8	5.7-6.1	57 ± 6
	3	250/220	9.4-9.8	5.5-5.9	80 ± 5
	4 and up	300/270	10.5-11.5	5.5-5.9	96 ± 5
SS-ER308L-SS	1	190/150	9.4-10.0	5.7-6.2	25 ± 2
	2	190/150	9.0-9.8	5.7-6.1	47 ± 5
	3	250/220	9.4-9.8	5.5-5.9	75 ± 5
	4 and up	300/270	10.5-11.5	5.5-5.9	96 ± 5

Phase 1A Fabrication Measurements



Thermocouples





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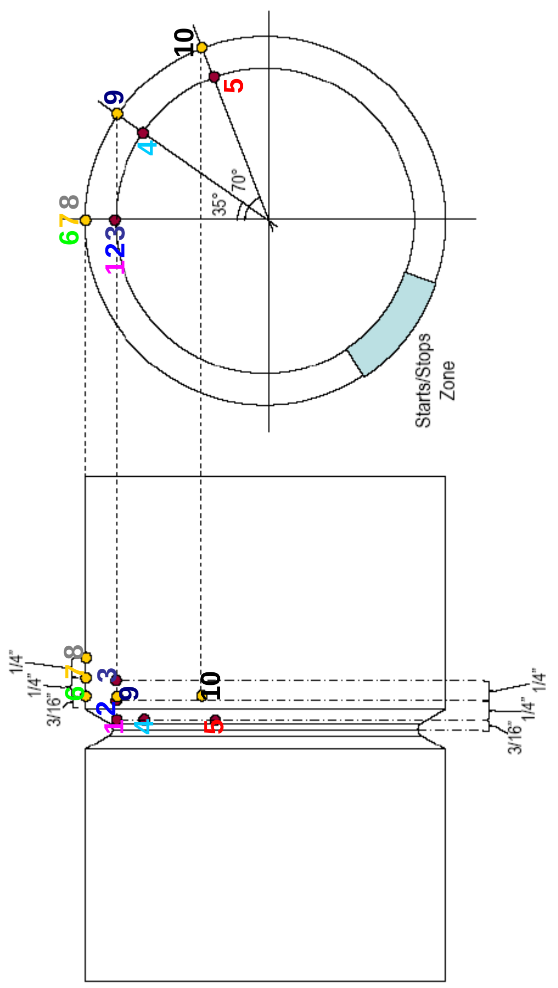
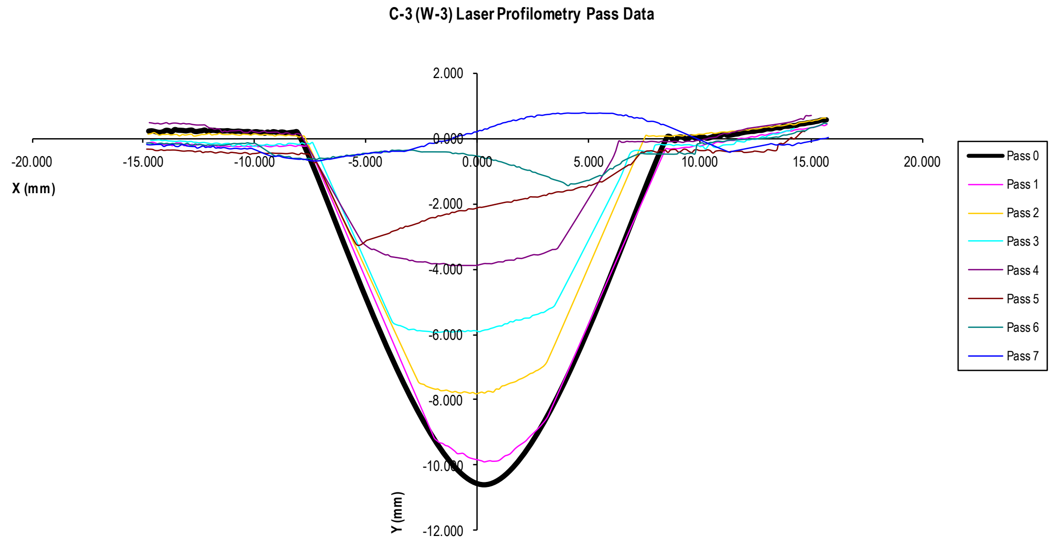
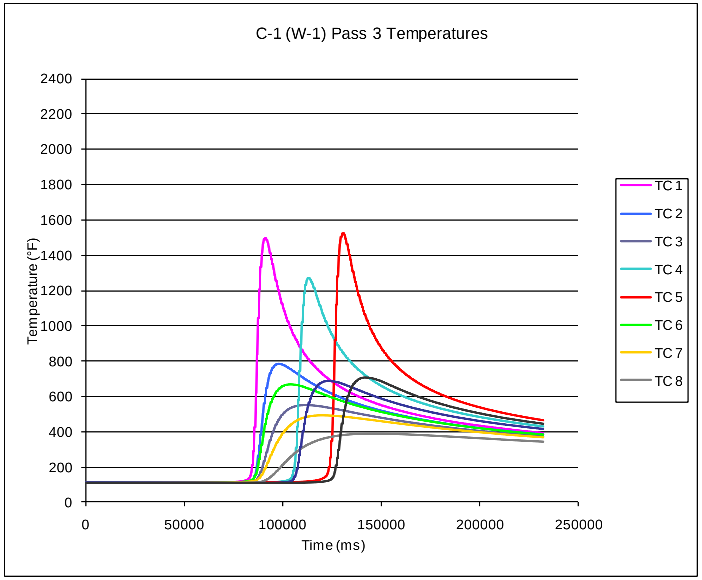
Phase 1B Fabrication Measurements



Thermocouples





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Phase 1A Residual Stress Measurements

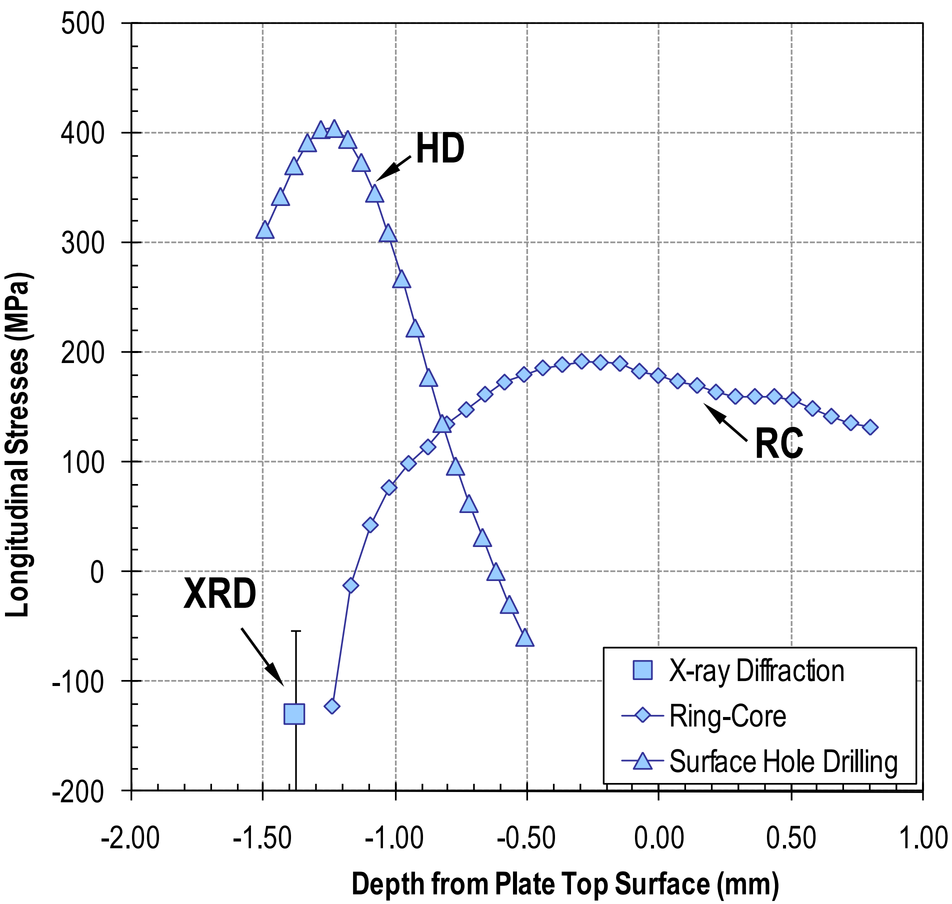
RS Measurement Method	Vendor	Location	Directions Measured	Measured Specimens P-3	P-4	P-5	P-6
Neutron Diffraction: Basic Measurements	**ORNL**	45 Point Grid in 7 Lines on Cross-section Plane	Longitudinal Transverse Normal	X	X	X	X
Neutron Diffraction: Full Strain Tensor	**ORNL**	7 Depths along Weld Centerline 2 Depths in Base Metal	6 Directions			X	
Neutron Diffraction: Longitudinal Traverse	**ORNL**	8 Longitudinal Positions, 3 Depth in WM & 3 Depths in BM	Longitudinal Transverse Normal	X			
Contour	**Hill Eng.**	1 Longitudinal Measurement Slice 1 Transverse Measurement Slice	Longitudinal Transverse			X	
X-ray Diffraction	**TEC**	7 Surface Points Across Weld On Topside of Specimen	Longitudinal Transverse	X	X	X	X
Surface Hole Drilling	**LTI**	7 Surface Points Across Weld On Topside of Specimen	Longitudinal Transverse In-plane Shear	X	X		X
Ring-Core	**LTI**	2 Longitudinal Positions, Both at Weld Centerline on Topside of Specimen	Longitudinal Transverse In-plane Shear	X	X		
Slitting	**Hill Eng.**	4 Transverse Measurement Slots	Transverse			X	

Phase 1B Residual Stress Measurements

RS Measurement Method	Vendor	Location	Directions Measured	Measured Specimens C-1	C-3	C-4	C-5	C-5 R
Neutron Diffraction: Basic Measurements	**ORNL**	80 Point Grid on Cross-section Plane	Hoop Axial Radial	**X**	**X**	**X**	**X**	**X**
Deep Hole Drilling	**VEQTER**	1 Hole through Centerline of Weld	Hoop Axial In-plane Shear	**X**	**X**		**X**	**X**
Contour	**Hill Eng.**	2 Longitudinal (Hoop) Meas. Slices 2 Transverse (Axial) Meas. Slices	Hoop Axial		**X**			

Surface Stress Measurement Results

Plate P-4, Weld Centerline



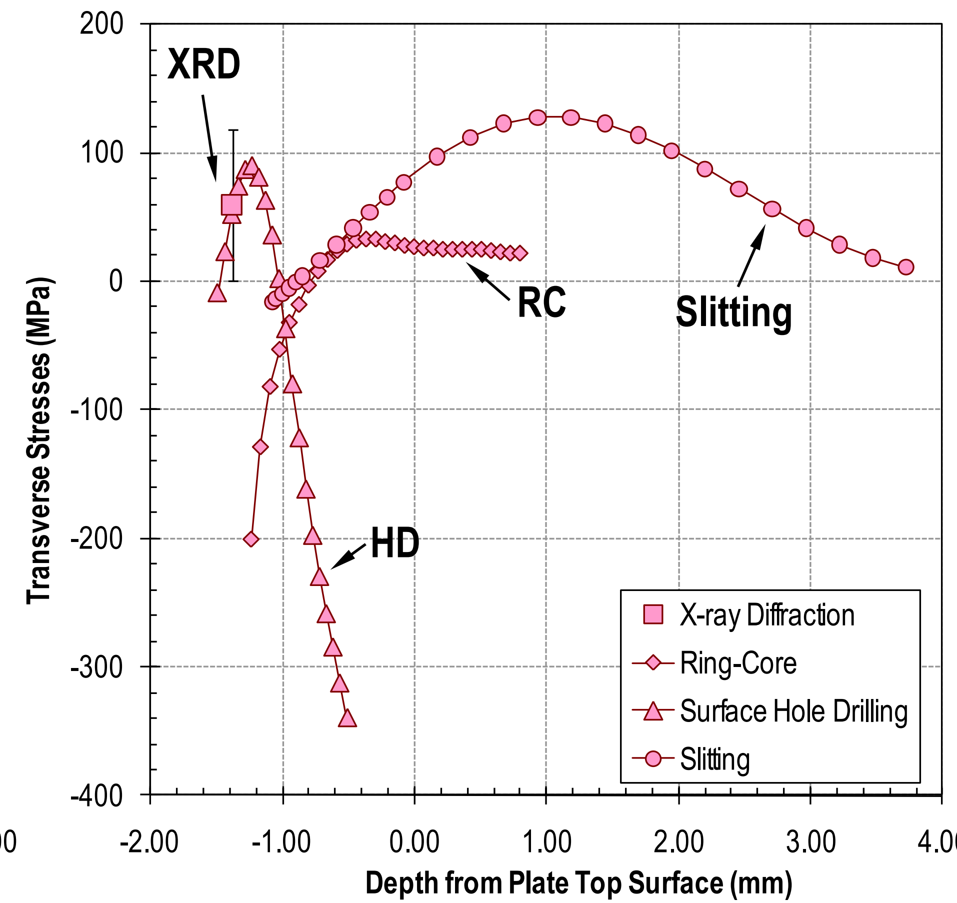


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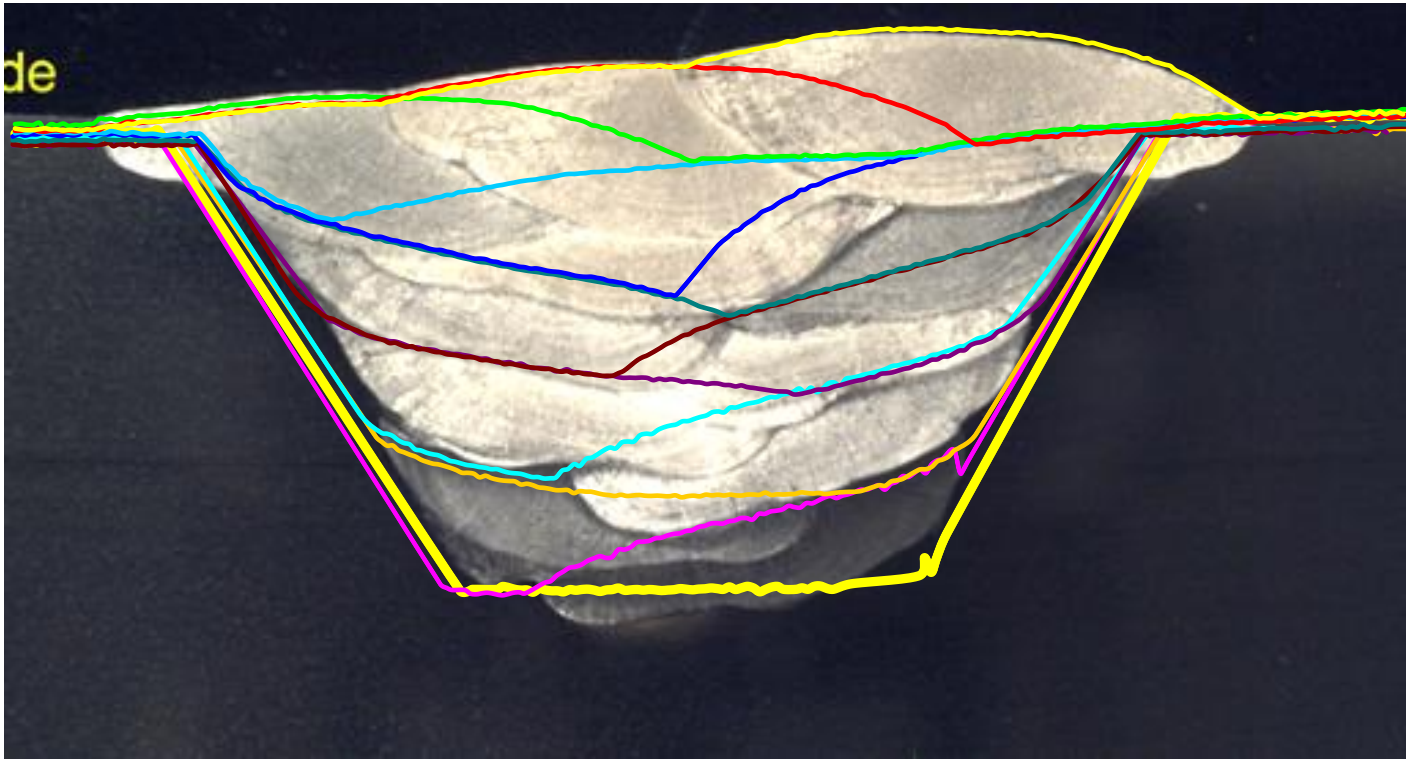
Plate P-3 Laser Profile and Etched Section



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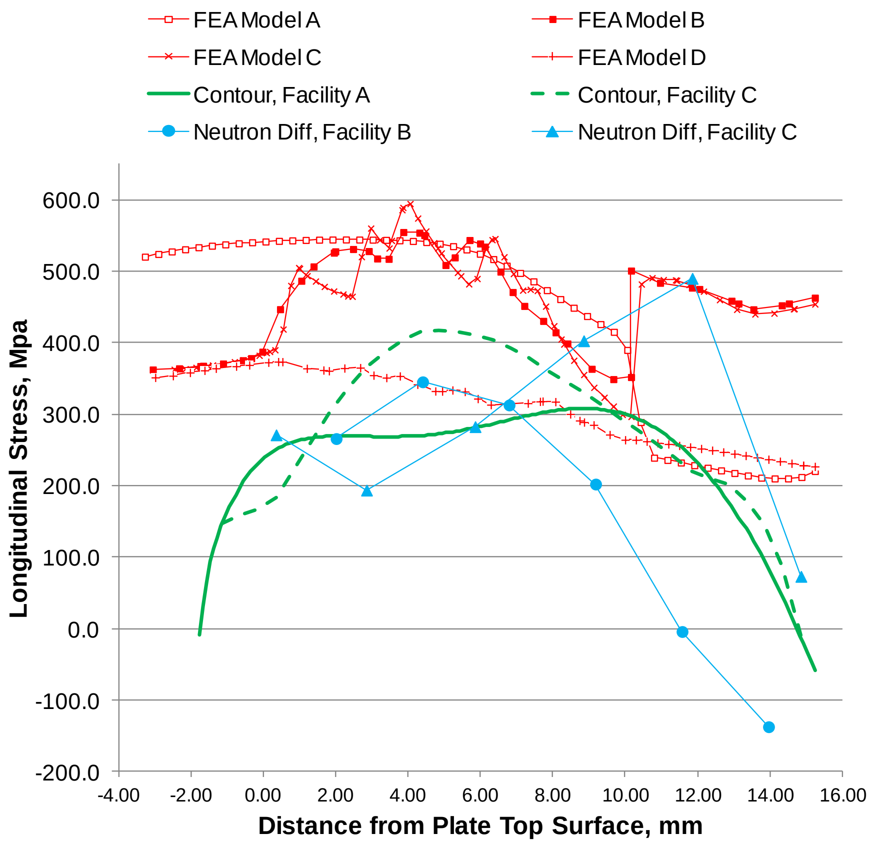
Stress Measurements and FEA Predictions

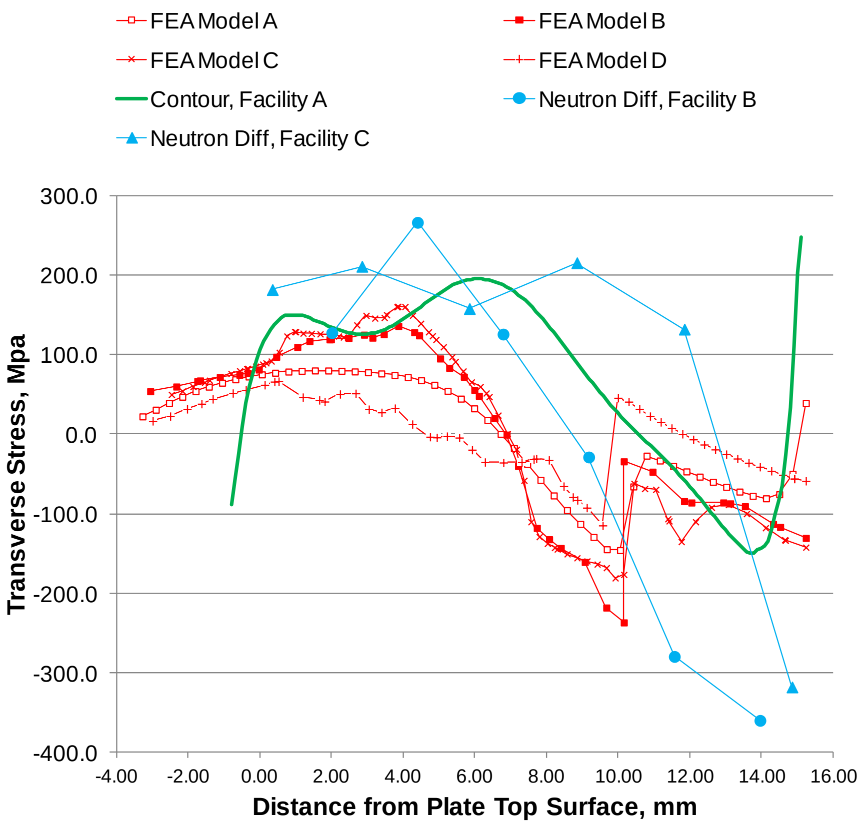
- Results from Plate P-4 and Cylinder C-3 presented
- Four sets of model results compared identified “A” through “D”
  - All models two dimensional plane strain (plate) or axisymmetric (cylinder)
  - Modeler’s best judgment for mesh, thermal inputs based on fabrication data
  - All models apply power generation as a function of time for thermal model
    - Roughly same amount of total energy input → consistent with weld process

Stress Measurements and FEA Predictions

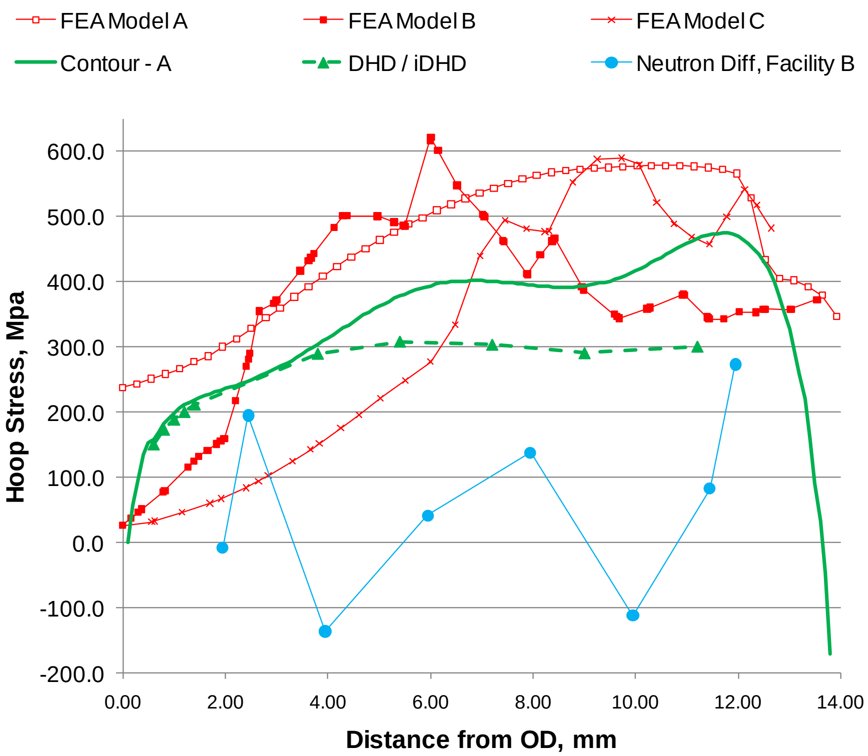
- Four sets of model results compared identified “A” through “D”
  - Model A: ANSYS, elastic perfectly-plastic hardening
  - Model B: ABAQUS, isotropic hardening law
  - Model C: ABAQUS, isotropic hardening law
  - Model D: ABAQUS, kinematic hardening law
- Measurements performed at facilities identified “A” through “C”
  - No correlation between modelers “A” through “D” and facilities “A” through “C”
  - Facility A: contour method only
  - Facility B: neutron diffraction only
  - Facility C: contour method and neutron diffraction

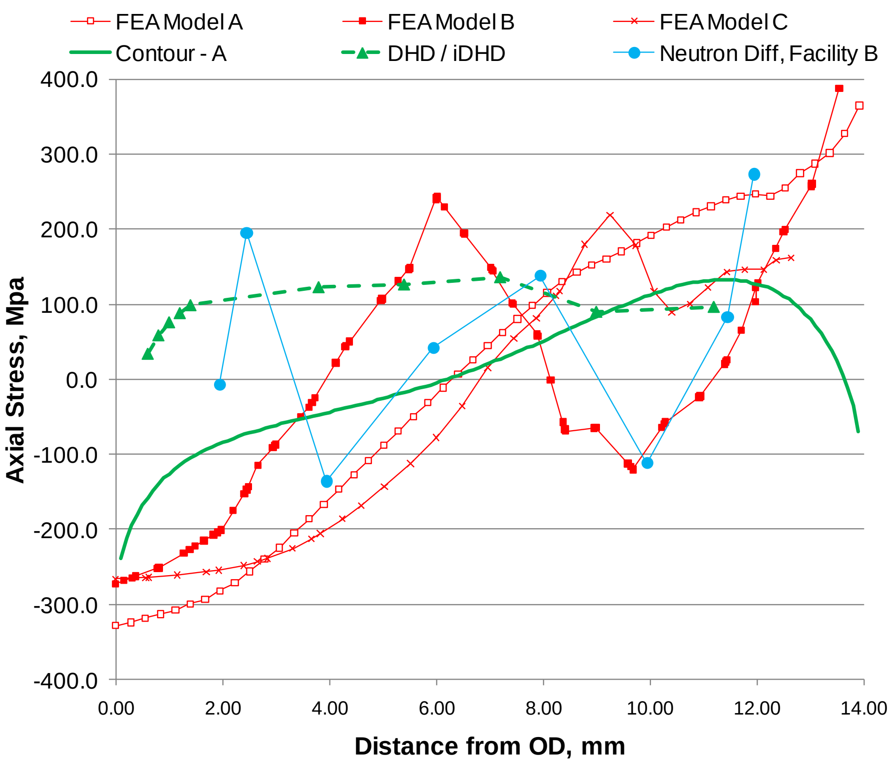
Plate P-4 Measurement and FEA Results





Cylinder C-3 Measurement and FEA Results





Stress Results Comparisons – Plate P-4

- Isotropic hardening models (B and C) have similar results
- Transverse (“axial”) direction: generally good agreement among all four models
- Longitudinal (“hoop”) direction: elas perf plas (A) has good agreement with isotropic hardening in body of weld, but not in last weld bead nor base metal
- Longitudinal: kinematic (D) agrees w/ isotropipc hardening in first bead and with elas perf plas in base metal
- Longitudinal measurements indicate A, B, and C over predict residual stress in body of weld
- Transverse measurements good agreement with models

Stress Results Comparisons – Cylinder C-3

- Less agreement between isotropic hardening models than in plate model
  - Elas perf plas (A) agrees better with iso C than iso B
  - Modeler assumptions on weld cavity changes with bead progression likely affected result
- Hoop stress: mechanical relaxation measurement methods and models agree on trend
  - Isotropic hardening and elas perf plas models tend to over predict measurment, similar to plates
- Axial stress: mech relaxation methods less agreement in trend than hoop

Phase 1 Conclusions

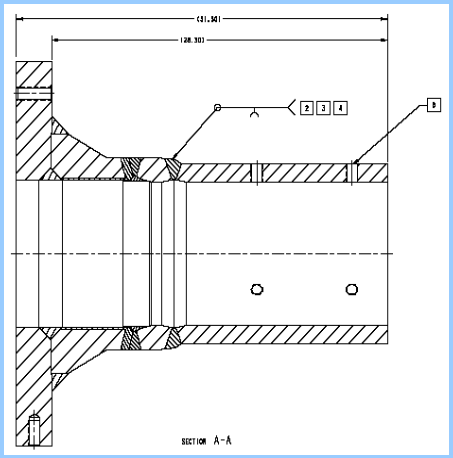
- By starting with small, easily handled specimens, a variety of measurement methods were able to be explored
- Analysis model results generally had good agreement with measurement trends
- Small number of weld beads relative to typical PWR DM weld cross section emphasized assumptions surrounding bead size and arrangement
  - These assumptions do not play as large a role in larger cross section welds

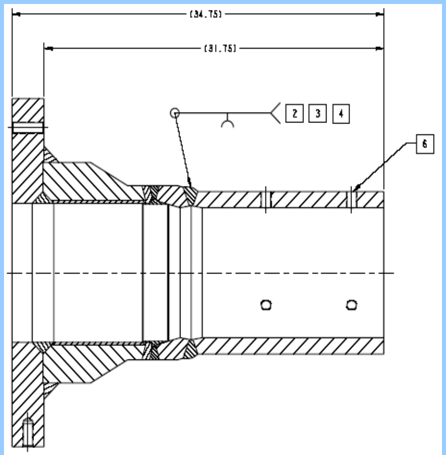
Phase 2 Discussion

Phase 2

Fabricated Prototypic Nozzles

- Type 8 Surge Nozzles
- Purpose: Prototypic scale under controlled conditions. Validate FE models





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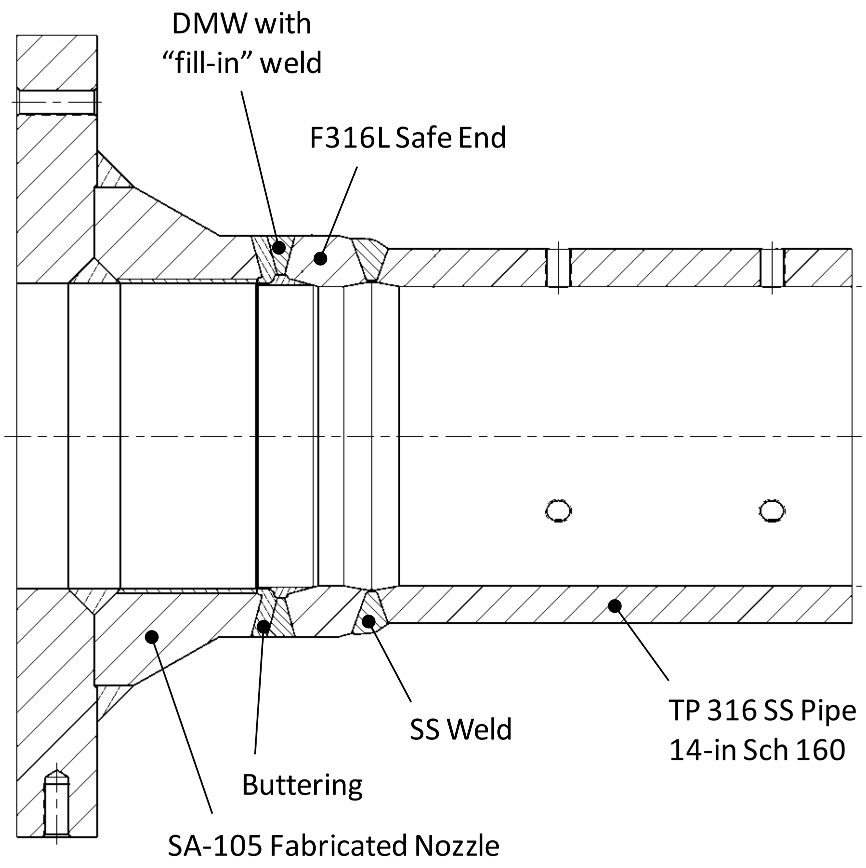
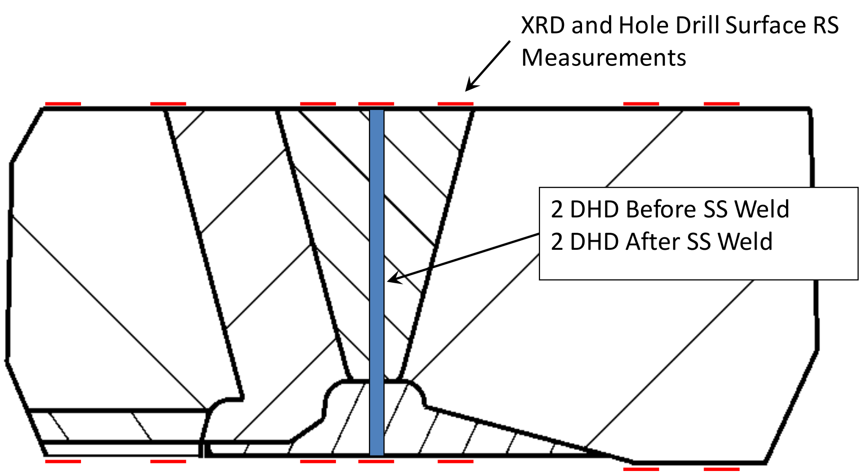
Phase 2 Configuration and RS Measurement





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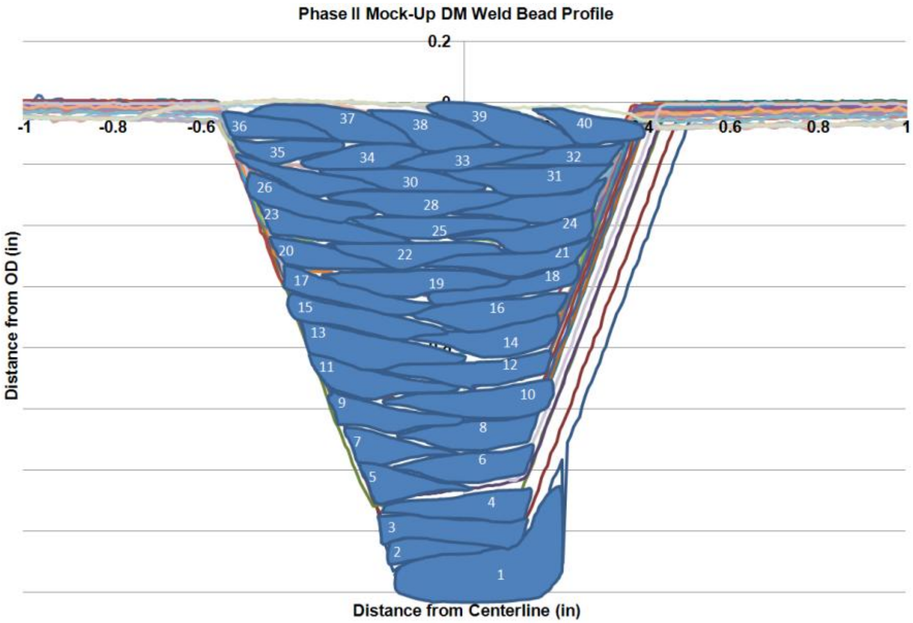
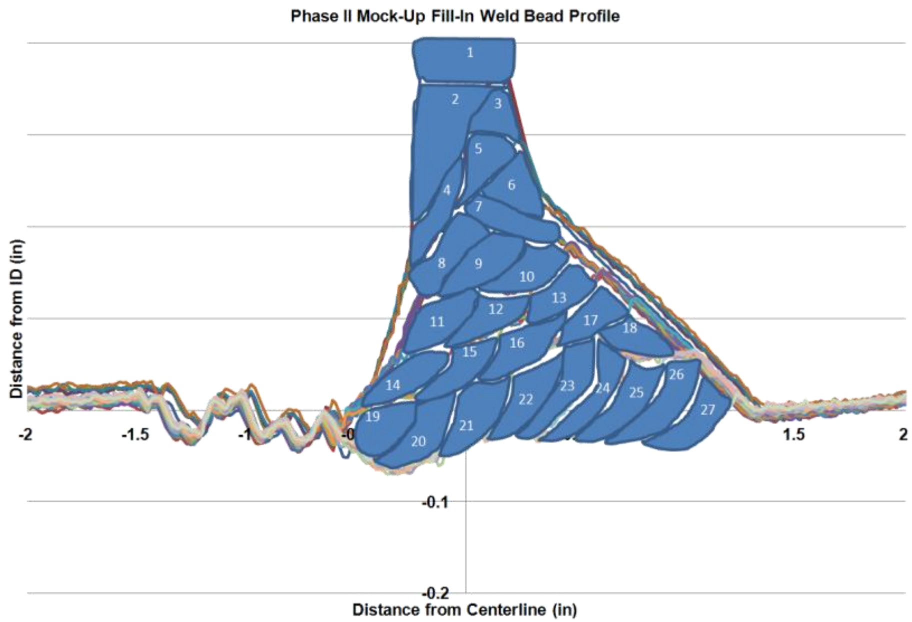
Phase 2 Laser Profilometry Results



V-Groove Weld



“Fill-in” Weld

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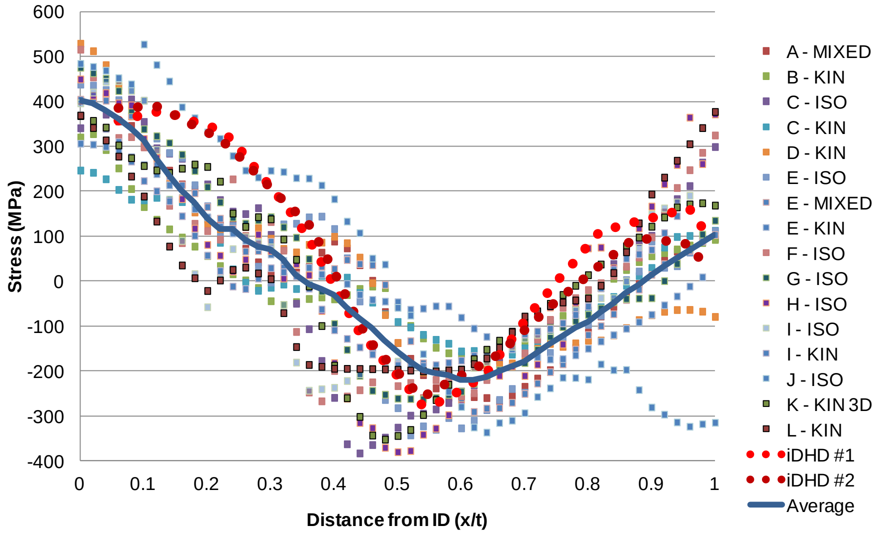
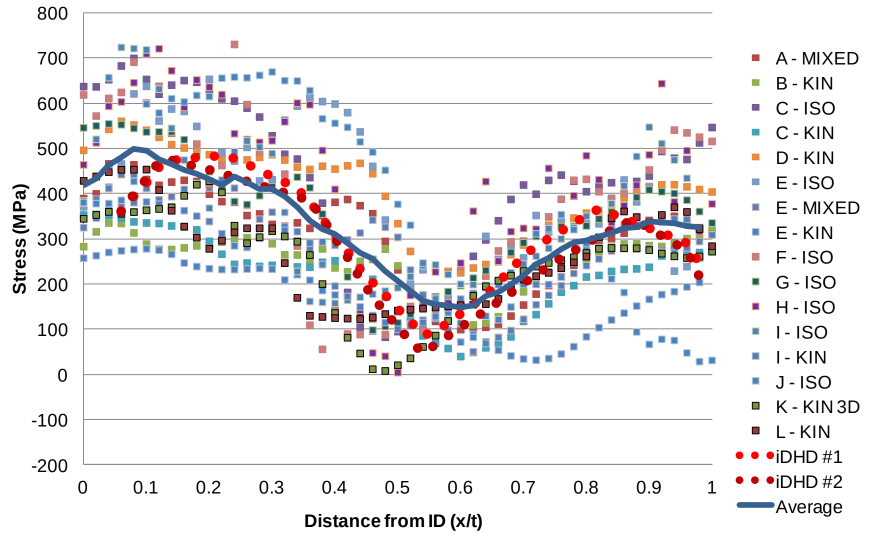
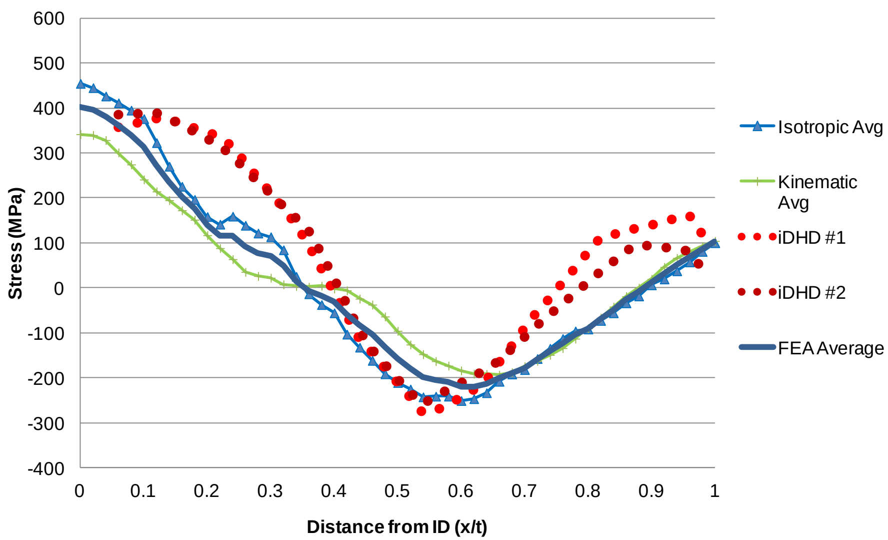
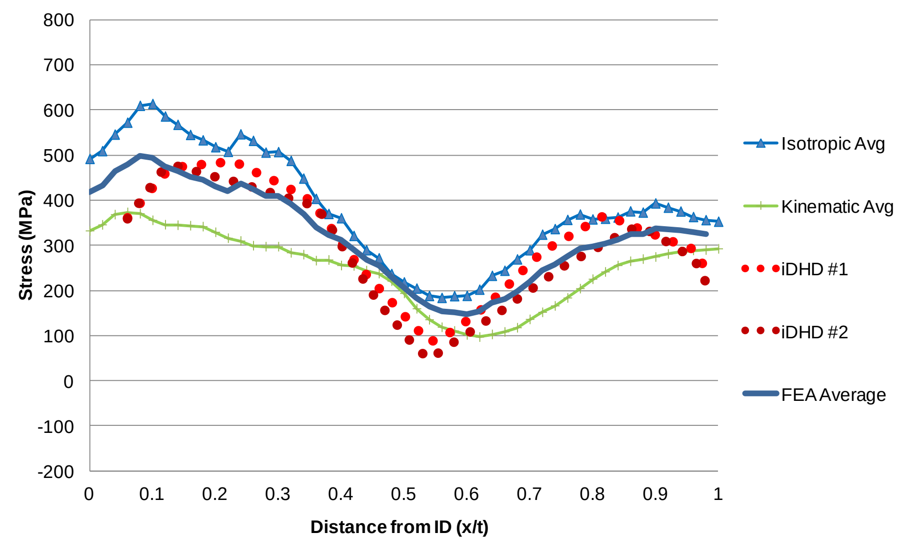
Phase 2 Stress Data – Prior to SS Weld





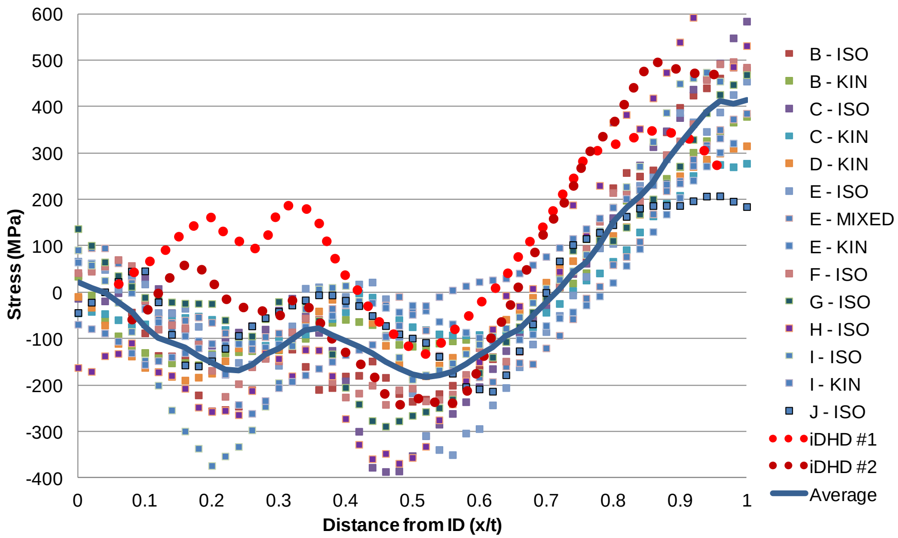


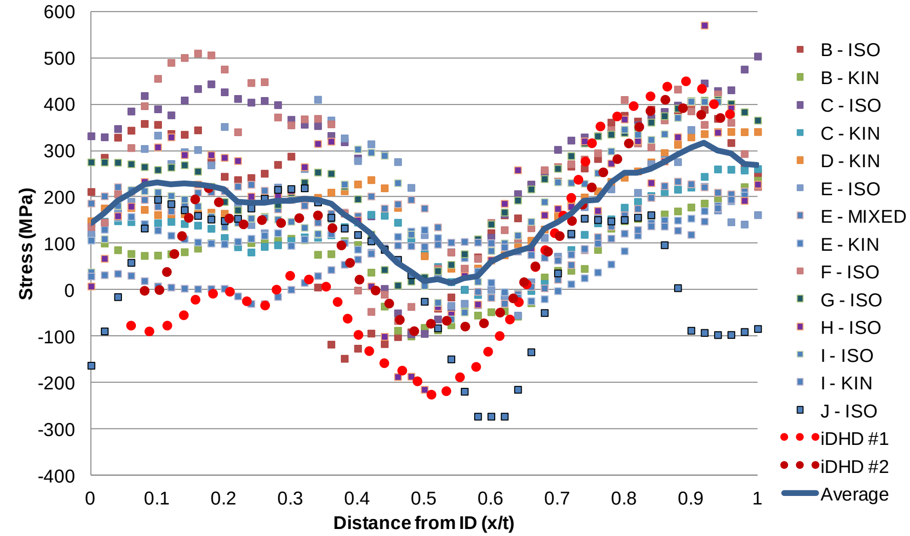
Axial Stress

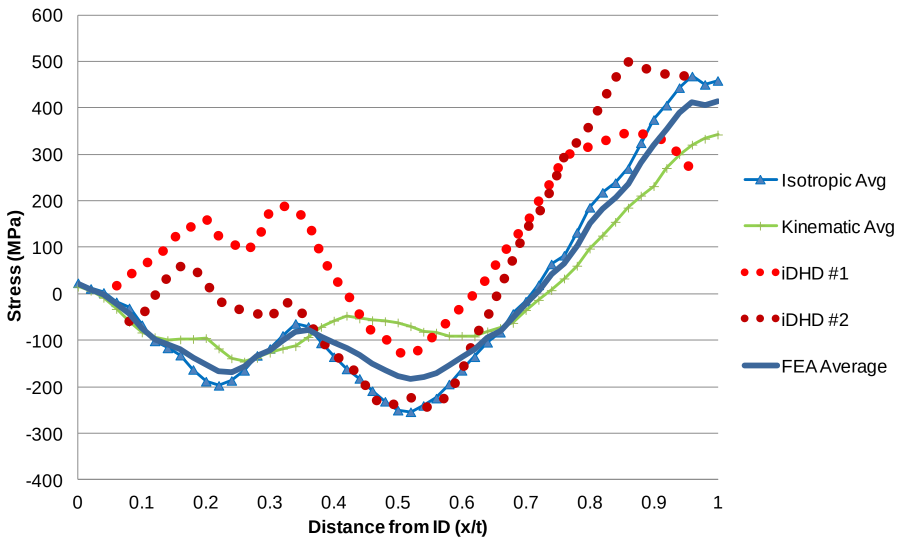


Hoop Stress

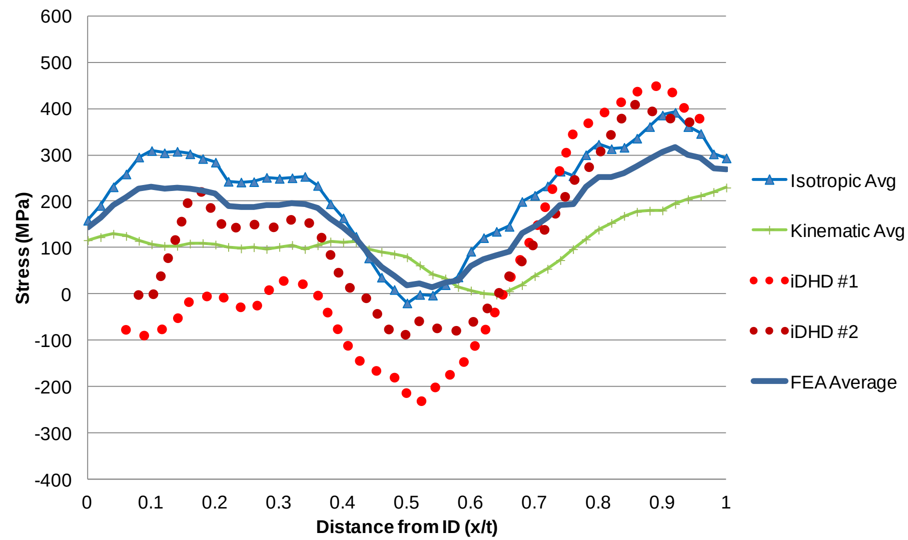
Phase 2 Stress Data – After SS Weld







Axial Stress



Hoop Stress

Phase 2 Results Discussion

- Stress improvement effect of SS weld at ID region demonstrated in model and measurement
- Substantial amount of scatter among the results of different modeling techniques for a fairly well-defined problem set
- Unquantified aspect of these differences is the degree to which the full set of modelers faithfully reproduced the analysis inputs provided in the problem set
- Result from prior to SS weld (Problem 1a), average of all modeling results agrees well with measurement data
  - Only a single measurement technique for comparison
  - A second technique such as contour method is desirable
  - Agreement not as good for after SS weld (Problem 2)

Phase 3 Discussion

Phase 3

Plant Components

- WNP-3 S&R PZR Nozzles
- Purpose: Validate FE models

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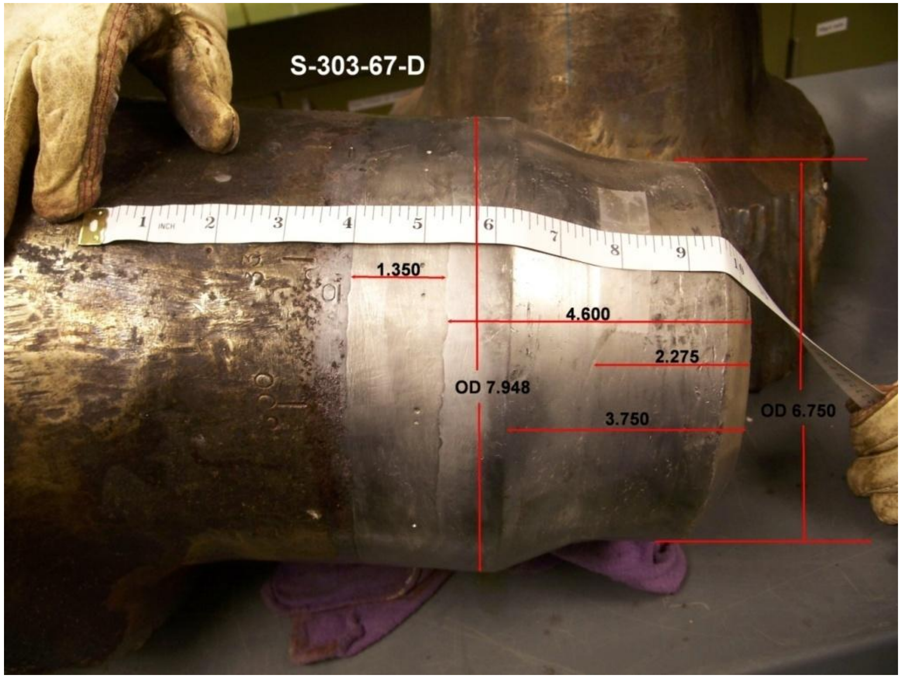
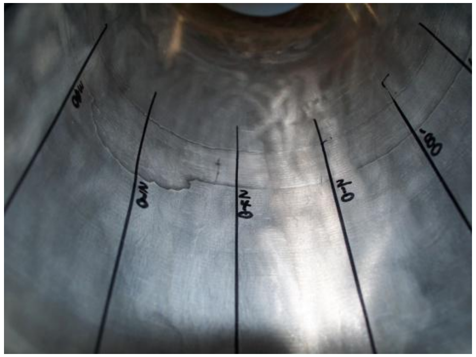
Phase 3 Nozzles

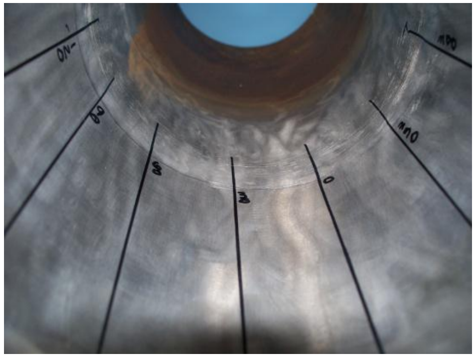
- Three pressurizer safety/relief nozzles, nominally identical in configuration, were taken from a cancelled plant prior to installation
- Nozzles had been rough cut from the pressurizer itself and were identified by markings on the nozzle body as nozzles “B”, “C” and “D”
  - In some cases, Nozzle B = Nozzle 1, etc.
- Nozzles present an opportunity to examine the as-fabricated condition of DM welds that were made during original plant construction
- Nozzle B sacrificed for materials characterization
- Residual stress measurements performed on Nozzles C, D

Phase 3 Nozzles Configuration



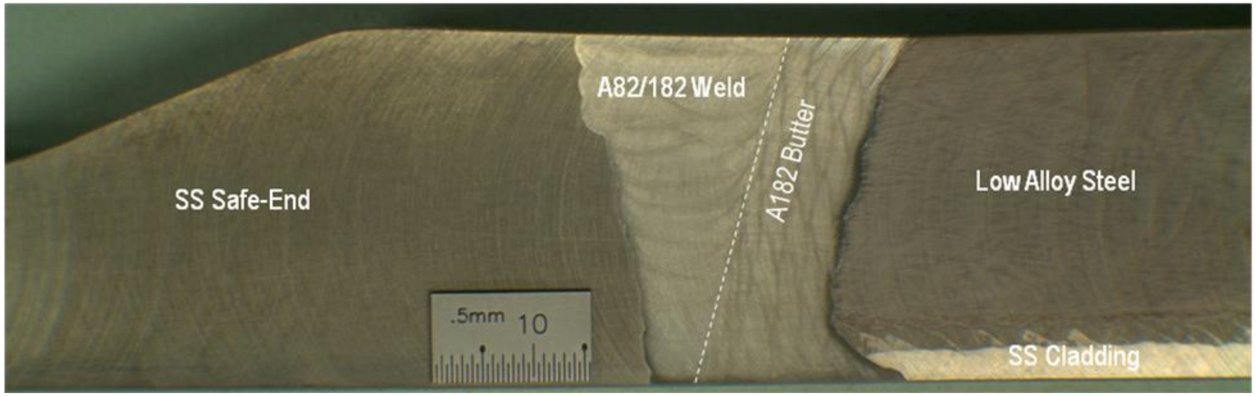


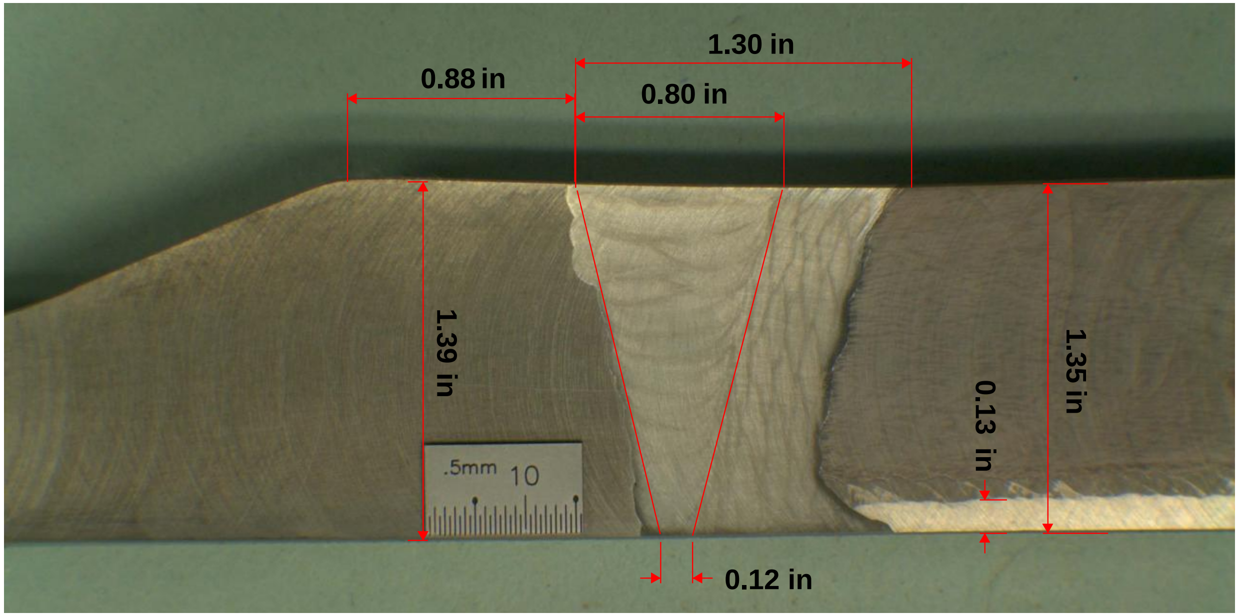
Nozzle C



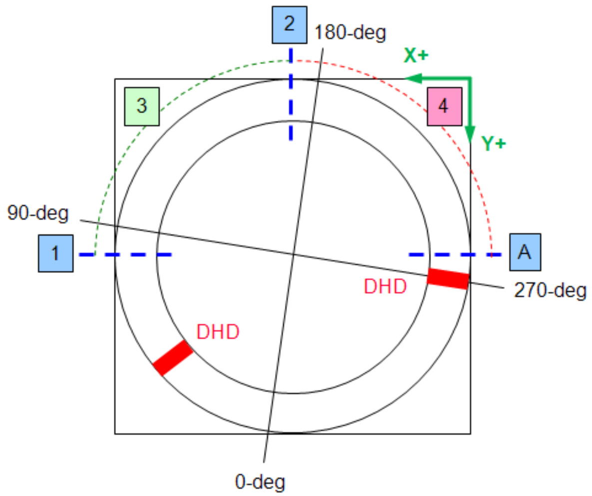
Nozzle D

Phase 3 Nozzle B Etched Cross Section



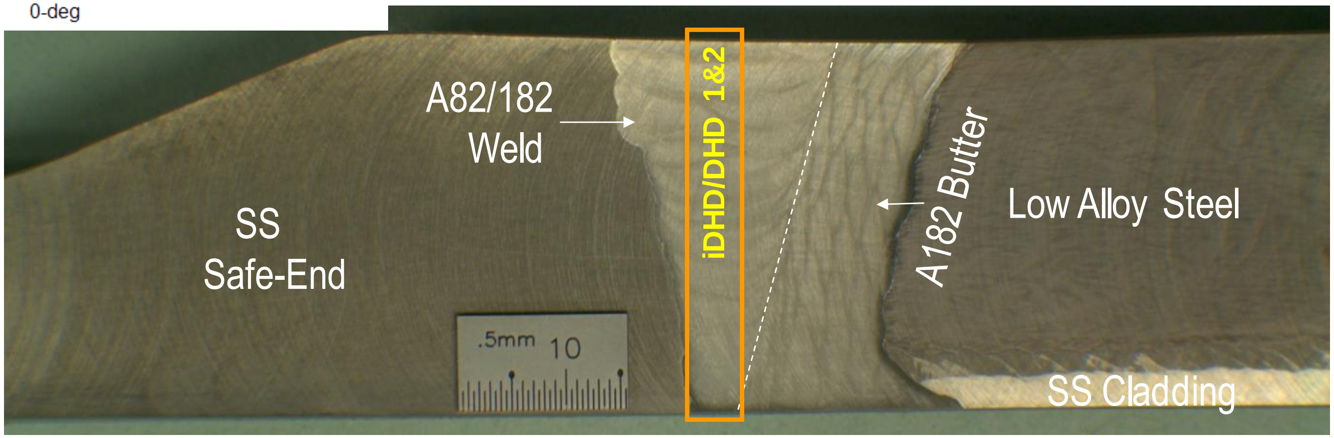


Nozzle C Measurement Locations



1, 2 = Contour Method Hoop Stress

3 = Contour Method Axial Stress



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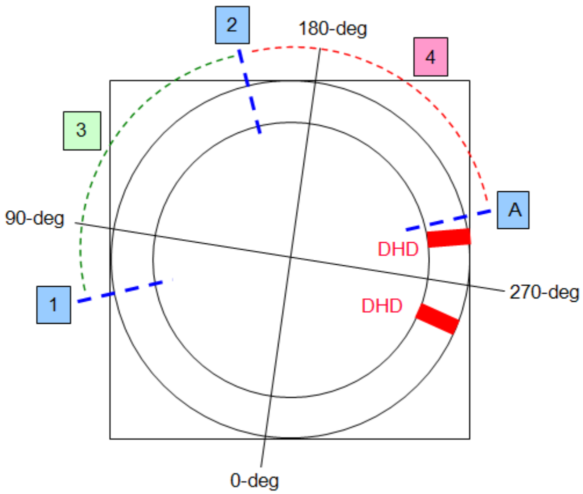
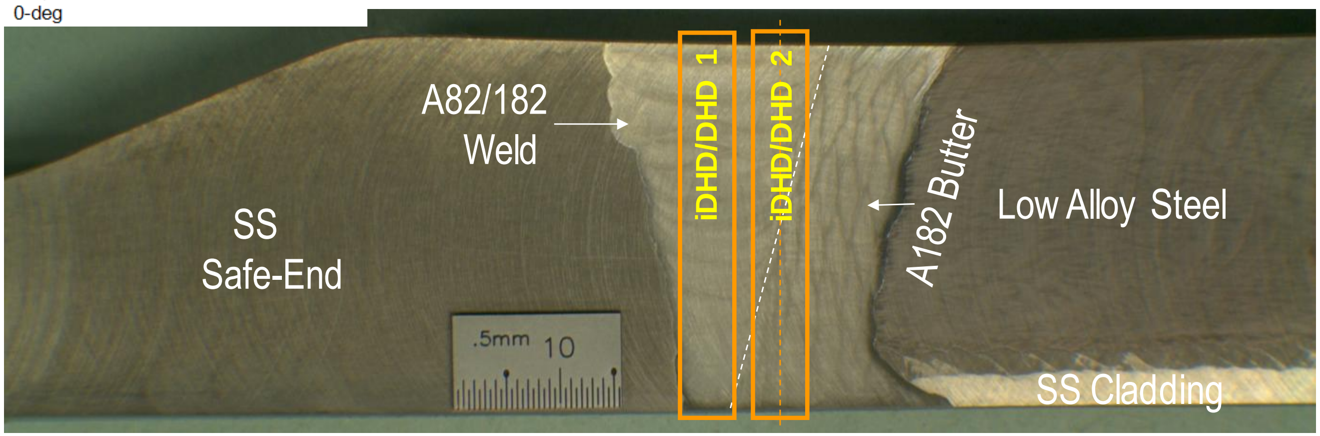
Nozzle D Measurement Locations



1, 2 = Contour Method Hoop Stress

3 = Contour Method Axial Stress



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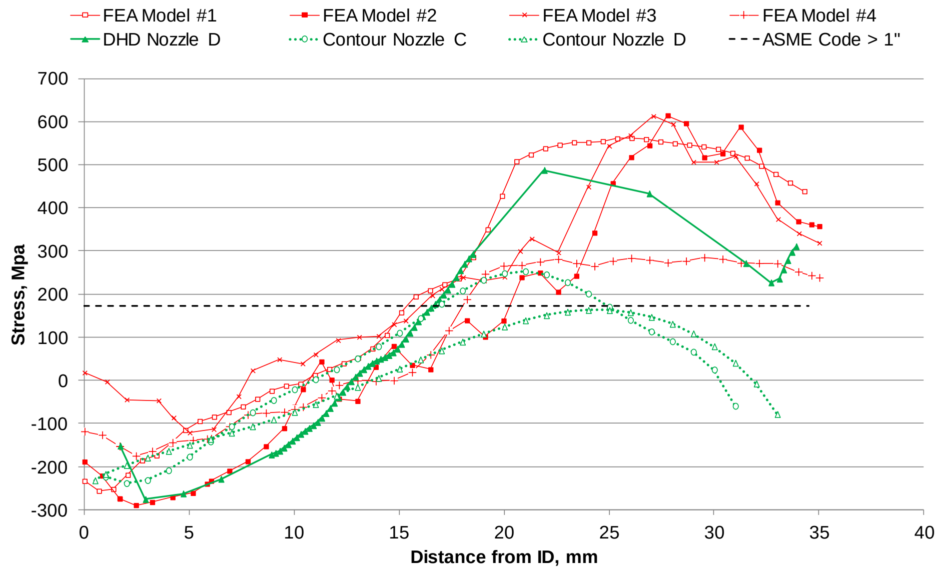
Stress Measurements and FEA Predictions

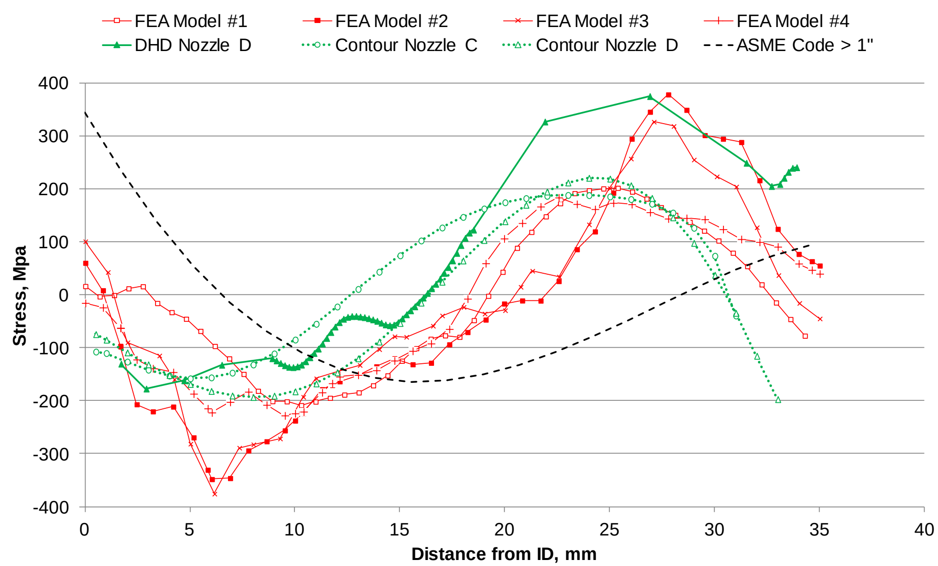
- Four sets of model results compared identified "Model #1" through "Model #4"
  - All models two dimensional axisymmetric (cylinder)
  - Modeler's best judgment for mesh, thermal inputs based on available data
  - All models apply power generation as a function of time for thermal model
    - Roughly same amount of total energy input → consistent with typical SMAW weld process

Stress Measurements and FEA Predictions

- Four sets of model results compared identified “Model #1” through “Model #4”
  - Model 1: ANSYS, elastic perfectly-plastic hardening
  - Model 2: ABAQUS, isotropic hardening law
  - Model 3: ABAQUS, isotropic hardening law
  - Model 4: ABAQUS, kinematic hardening law
- Model results compared to measurements
- Also shown are the stress distributions obtained from empirical models based on analysis and testing of butt welds in stainless steel piping, labeled ASME > 1"

Phase 3 Measurement and FEA Results





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Phase 3 Results Discussion

- Overall, the trends of the measurement results match well to all four analysis models for both hoop and axial stresses, and reflect previous trends identified in Phase 1
  - Elas perf plas and isotropic hardening tend to over predict hoop stress
  - Kinematic has good overall agreement with hoop and axial stress measurements
- Empirical model results based on stainless steel piping butt welds do not match well to either the measurement or analysis data

Summary and Conclusions – Project Phases

- By starting with easily replaceable simple specimens (Phase 1), confidence was gained in measurement techniques without the risk of damaging or losing access to the one of a kind mockups or plant components
- Drawback for Phase 1 was too much variation was introduced among them
  - Four identical plates rather than four unique plates would have investigated repeatability of measurements
- Broad variety of measurement techniques investigated and compared in Phase 1 specimens and Phase 3 nozzles

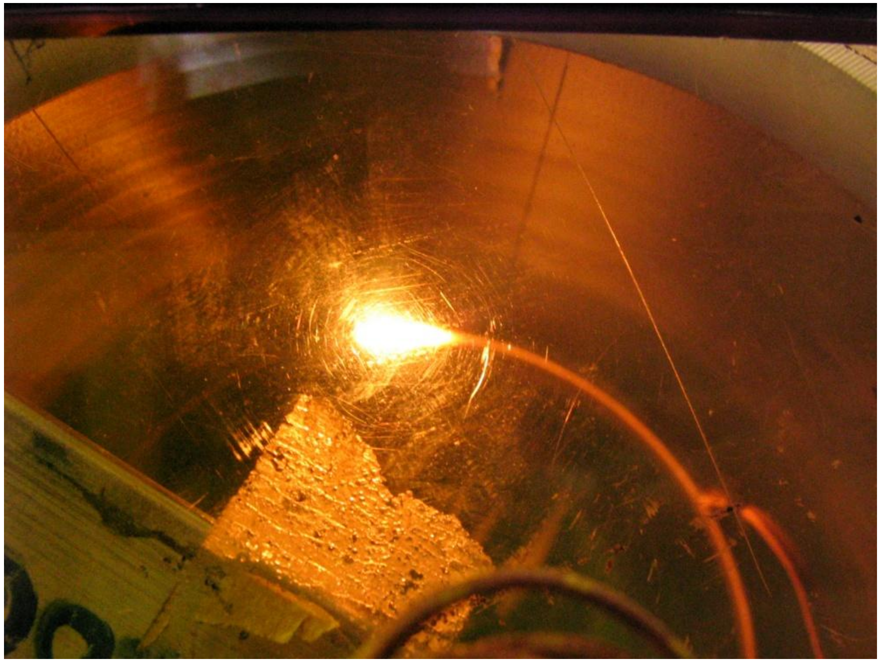
Summary and Conclusions – FEA Modeling

- FEA modeling investigated thermal models and hardening laws in particular
- Overall, a large spread in analysis results was observed for the models in all three project phases
- Even when similar or identical material property values are used, assumptions about the model geometry and thermal model behavior can lead to a significant spread in analysis results data

Summary and Conclusions – Validation

- Research effort demonstrated that reasonable agreement in trend and magnitude exists between measurement techniques and FEA models
- Challenges not fully resolved within the timeline of this project include
  - Differences between measurement results
  - Significant differences in modeler's results
- Work performed did improve the understanding and confidence in welding residual stress analysis models
  - Quantified the potential variation in model results relative to the potential variation in measured stresses

WRS Modeler's Handbook



Introduction

- Desired product from project beginning has been a WRS modeling handbook
- Overall program results provided in greater detail in the final technical report
- Modeling handbook intended to distill work performed and provide conclusions and recommendations for WRS models
- Similar to guidance provided in BEGL R6
- Uses results of sensitivity studies performed by DEI and NRC-RES during WRS validation project

Handbook Contents

- Scope
- Analytical Model Definition
- Material Properties
- Thermal Model
- Structural Model
- Validation
- Sample WRS Model Thermal and Structural Properties
- Measured Residual Stresses for Use in Model Validation

Scope

- (Currently) limited to DM welds between carbon/low alloy steel component and stainless steel component
  - Stainless steel welds are of a similar nature, so are generally covered as well
- Phase transformation effects not considered
- SMAW (MMA) and GTAW (TIG) welding methods

Analytical Model Definition

- Model geometry selection
  - Consider all aspects of fabrication sequence
    - Safe end ring machining
  - Weld cavity shrinkage affects bead sizes
- Bead geometry selection
  - Trapezoidal / rectangular shape vs rounded beads
  - Small number of weld beads may be more accurately described with rounded profiles
  - Otherwise trapezoidal / rectangular shapes work fine

Analytical Model Definition

- Element mesh considerations
  - Linear element types provide similar results to quadratic elements
  - Using linear elements
- Bead sequence
  - Layers and bead combination can be used to provide comparable results to bead by bead
  - Left/right vs right/left has some effect, but not large effect

Material Properties

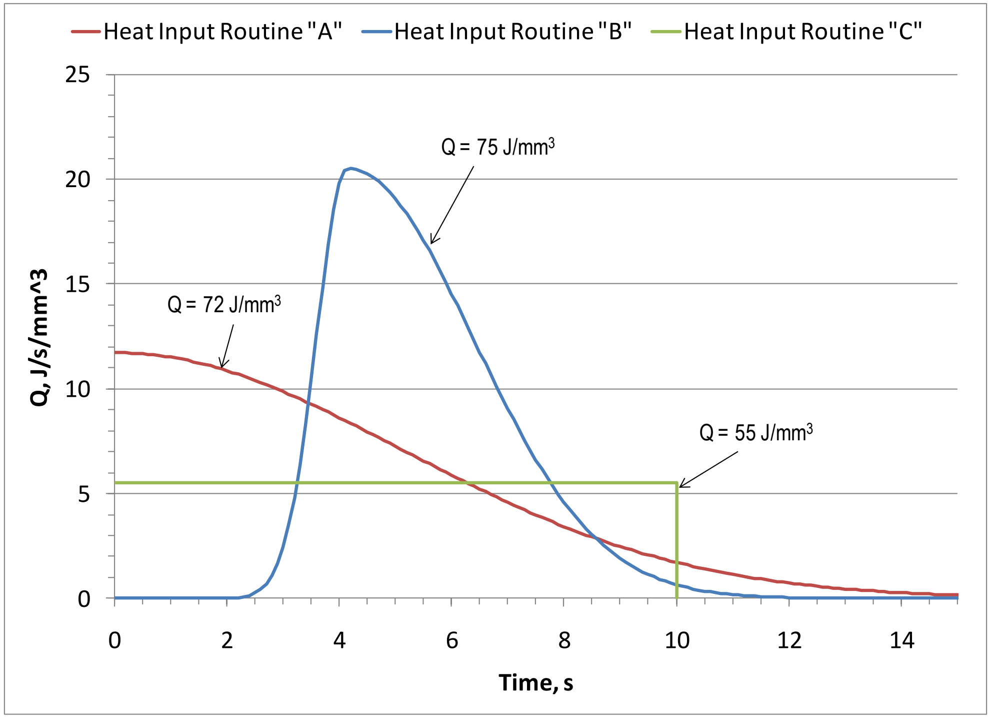
- Sensitivity studies shown for thermal properties and structural properties
  - Thermal model properties
    - Density, conductivity, specific heat
  - Structural model properties
    - Coefficient of thermal expansion, modulus of elasticity, hardening rule, stress-strain data input
- Most important inputs are hardening rule and associated stress-strain data input
  - Models not apparently sensitive to other properties inputs within range of available data

Thermal Model

- Different types of heat input models
  - Prescribed temperature
  - Static heat source
    - All 2D models are static heat source models
    - 3D models may also be static heat source – “block dumped”
  - Moving heat source
- Frequently used thermal model is static heat source model
  - Application of thermal energy based on welding parameters

Thermal Model

- Static heat source power versus time input routines examined
- Different power vs time but similar energy
- Energy consistent with weld energy in KJ/in



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Thermal Model

- Constant energy but varying power
  - High power over short time frame vs low power over long time frame
  - Factor of 100 shorter doesn't change structural model results
  - Factor of 10 longer changes structural model results
- Constant power but varying energy
  - Same power over shorter vs longer time period = different energy
  - Decrease energy by 15% → no change in through-wall model results
  - Decrease energy by 40% → beginnings of change in through-wall model results

Structural Model

- ANSYS and ABAQUS calculate thermal strain differently
  – ABAQUS adds additional term such that thermal strain at initial temperature is zero
  – Affects ability for ANSYS and ABAQUS to predict identical results for identical inputs
- Annealing in ABAQUS can be adequately represented by element birth/death in ANSYS
- Annealing affects expansion of yield surface
  – Annealing has no effect on through-wall results when using kinematic hardening

Validation

- MRP-287 (PWSCC evaluation guidelines) recommends validation approach based on crack tip SIF versus depth using through-wall distribution
  - Compare model result to measured values
  - Will eliminate apparent differences in some distributions, but may amplify small differences in others
- Handbook includes appendix describing Phase 2, Phase 3 models and measurement data results for validation

Weld Residual Stress Finite Element Analysis Validation

January 25, 2012

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

**** The views expressed herein are those of the authors and do not represent official positions of the USNRC***

Overview

- Brief summary of WRS validation program and findings
- Technical Letter Report
  - Measurement & FEA Results
  - Sensitivity studies
- K evaluations
- NUREG Report and revisions to Technical Letter Report

WRS Validation Program Aspects

- Program developed with input from industry, NRC staff and contractors
  - Peer developed and reviewed

- Only double blind study with engineering scale components with DM weld

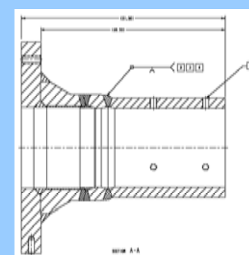
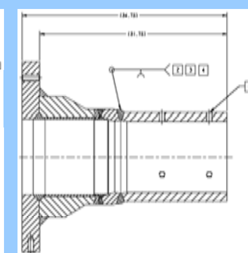
WRS Validation Program Overview

Phase 1 - EPRI

- Scientific Weld Specimens
- Phase 1A: Restrained Plates (QTY 4)
- Phase 1B: Small Cylinders (QTY 4)
- Purpose: Develop FE models.


Phase 2 - NRC

- Fabricated Prototypic Nozzles
- Type 8 Surge Nozzles (QTY 2)
- Purpose: Prototypic scale under controlled conditions. Validate FE models.

Phase 3 - EPRI

- Plant Components
- WNP-3 S&R PZR Nozzles (QTY 3)
- Purpose: Validate FE models.


Phase 4 - EPRI

- Plant Components
- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.

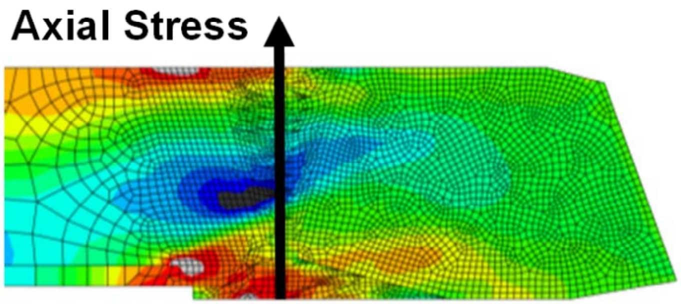
Phase 2 Participants

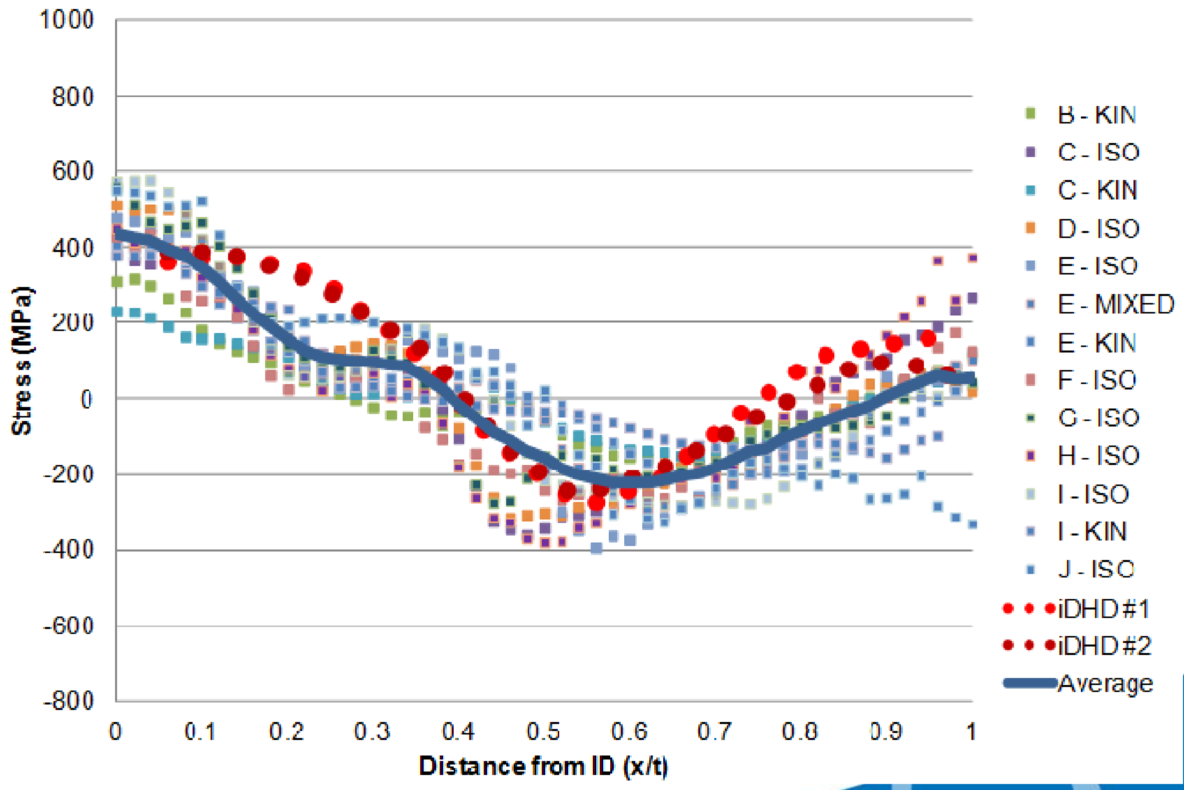
International WRS Round Robin

- ANSTO (Australia)
- AREVA (USA and EU)
- Battelle (USA)
- Dominion Engineering (USA)
- Goldak Technologies (Canada)
- ESI Group (USA)
- EMC^2 (USA)
- Inspecta Technology (EU)
- Institute of Nuclear Safety System (Japan)
- Osaka University (Japan)
- Rolls Royce (UK)
- Structural Integrity Associates (USA)
- Westinghouse Electric Company (USA)

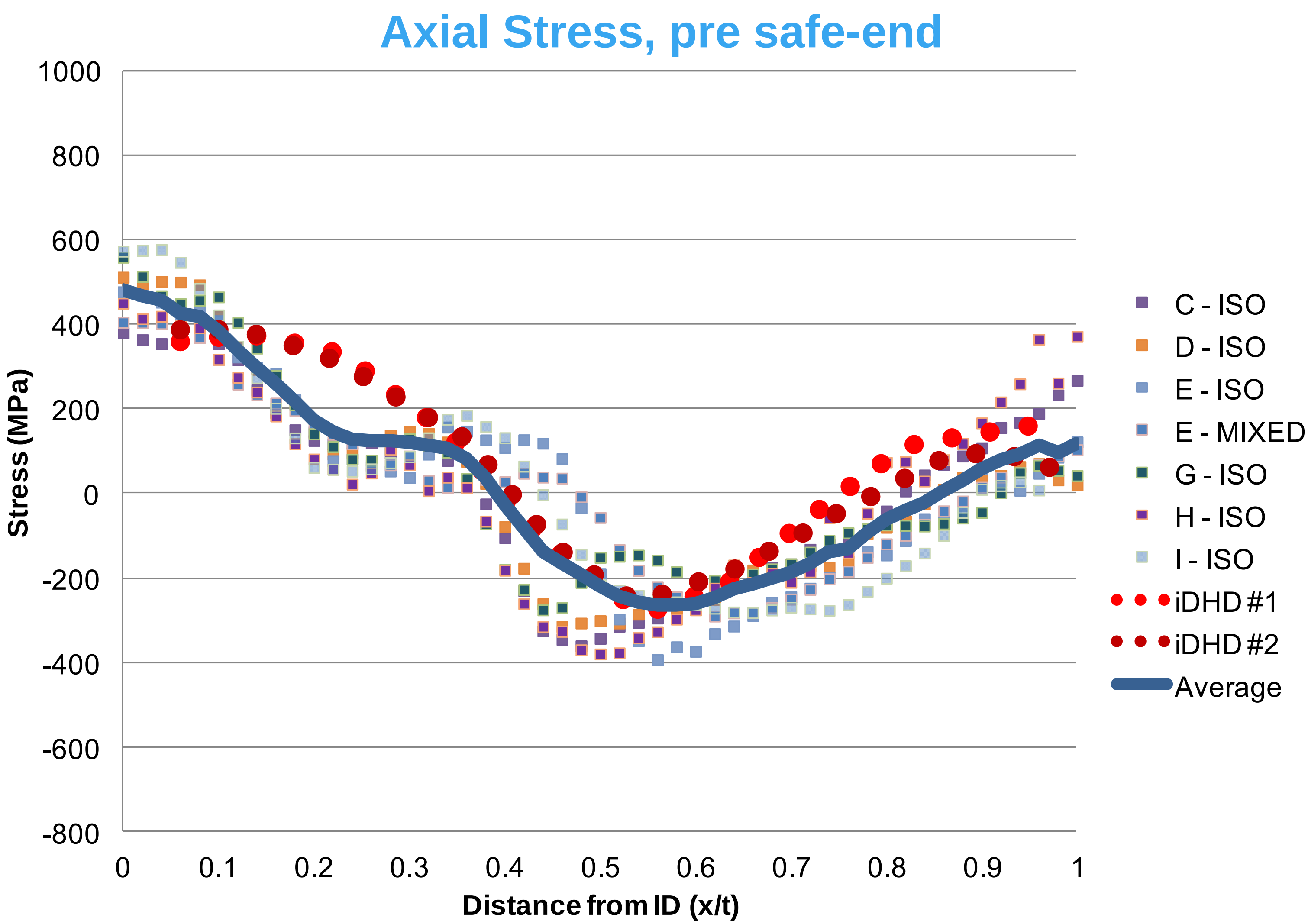
Example Results: Phase II Mean & Scatter

Axial Stress, pre safe-end





Domestic Participant Results



Sensitivity Study Parameters

- Thermal
  - Magnitude and duration of heat input
  - Density
  - Latent heat
  - Conductivity
  - Specific heat
  - Convective heat transfer coefficient
- Mechanical
  - Coefficient of Thermal Expansion
  - Elastic Properties
  - Plastic Properties
  - Hardening law

- Note:

  (highlighted) = Important

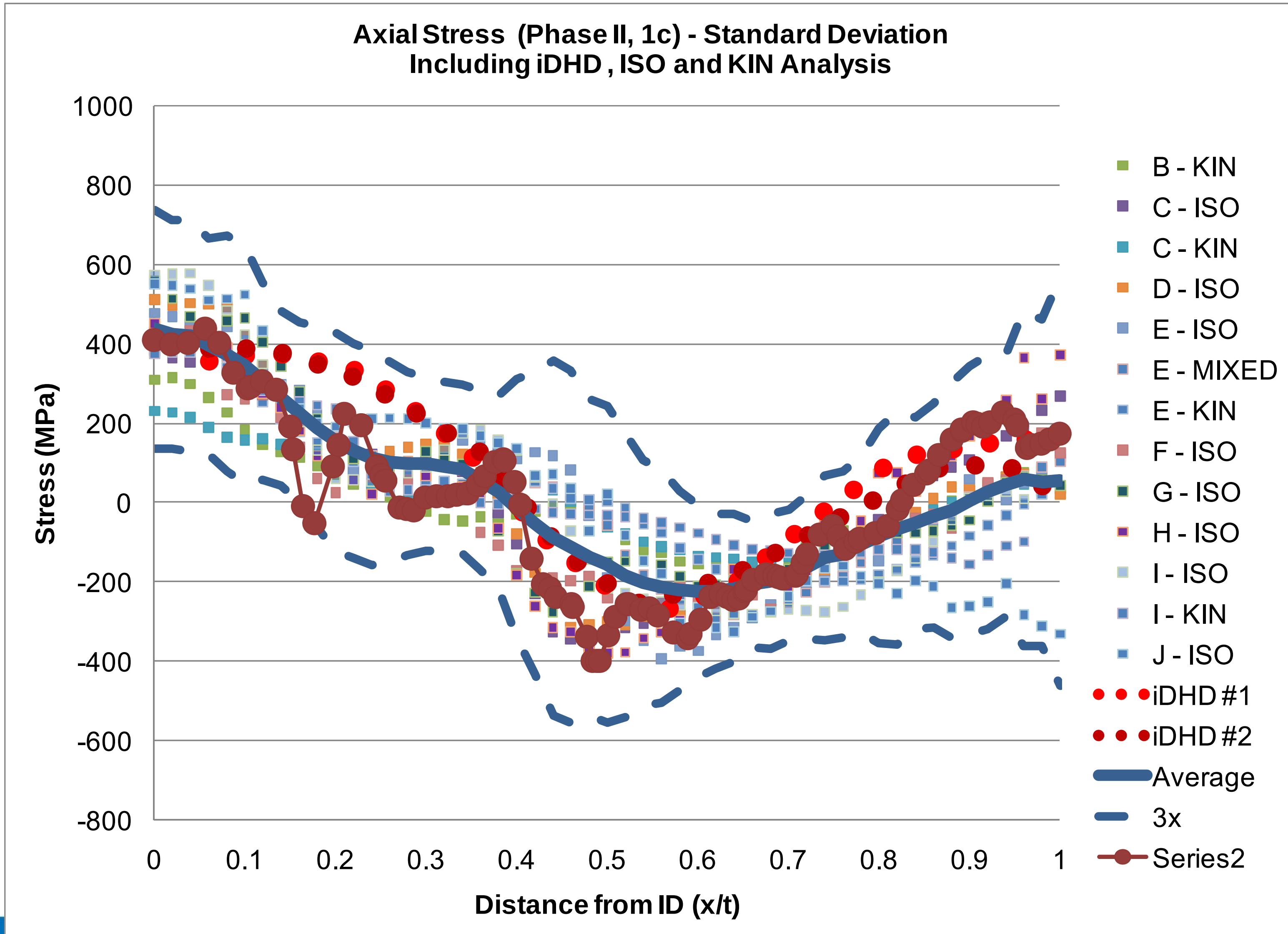
Sensitivity Studies

Joint NRC/EPRI WRS Validation Program

- Start with a "validated model"
  - Agrees with measurements and average of FEA results
- Systematically vary single variables:
  - Coefficient of thermal expansion, CTE
  - Modulus of Elasticity, E
  - True stress vs. plastic strain behavior
  - Hardening type (isotropic, kinematic)
  - Magnitude and duration of heat input
  - Weld pass order of deposition

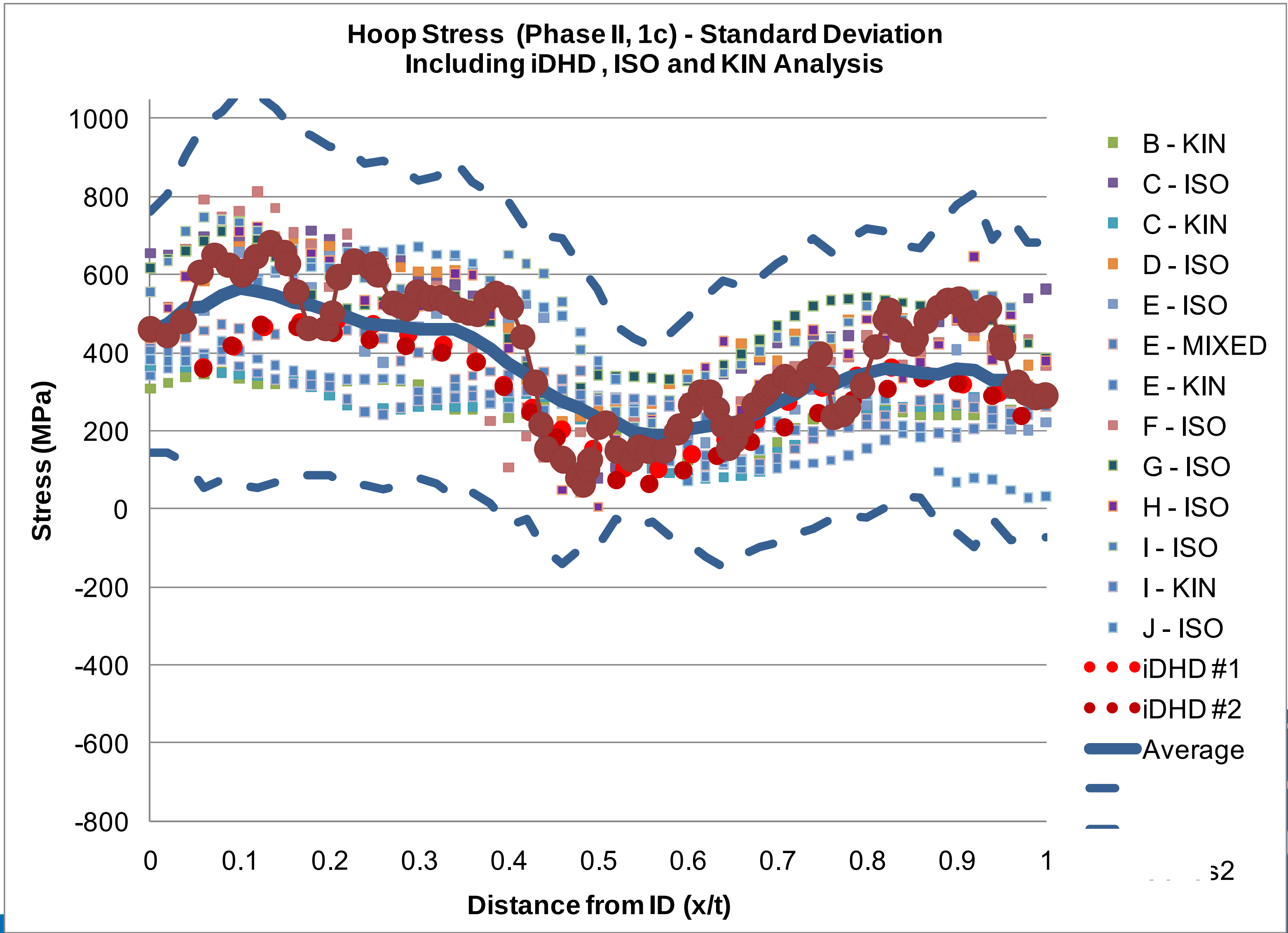
Sensitivity Studies

Baseline case – Axial pre-ss weld results



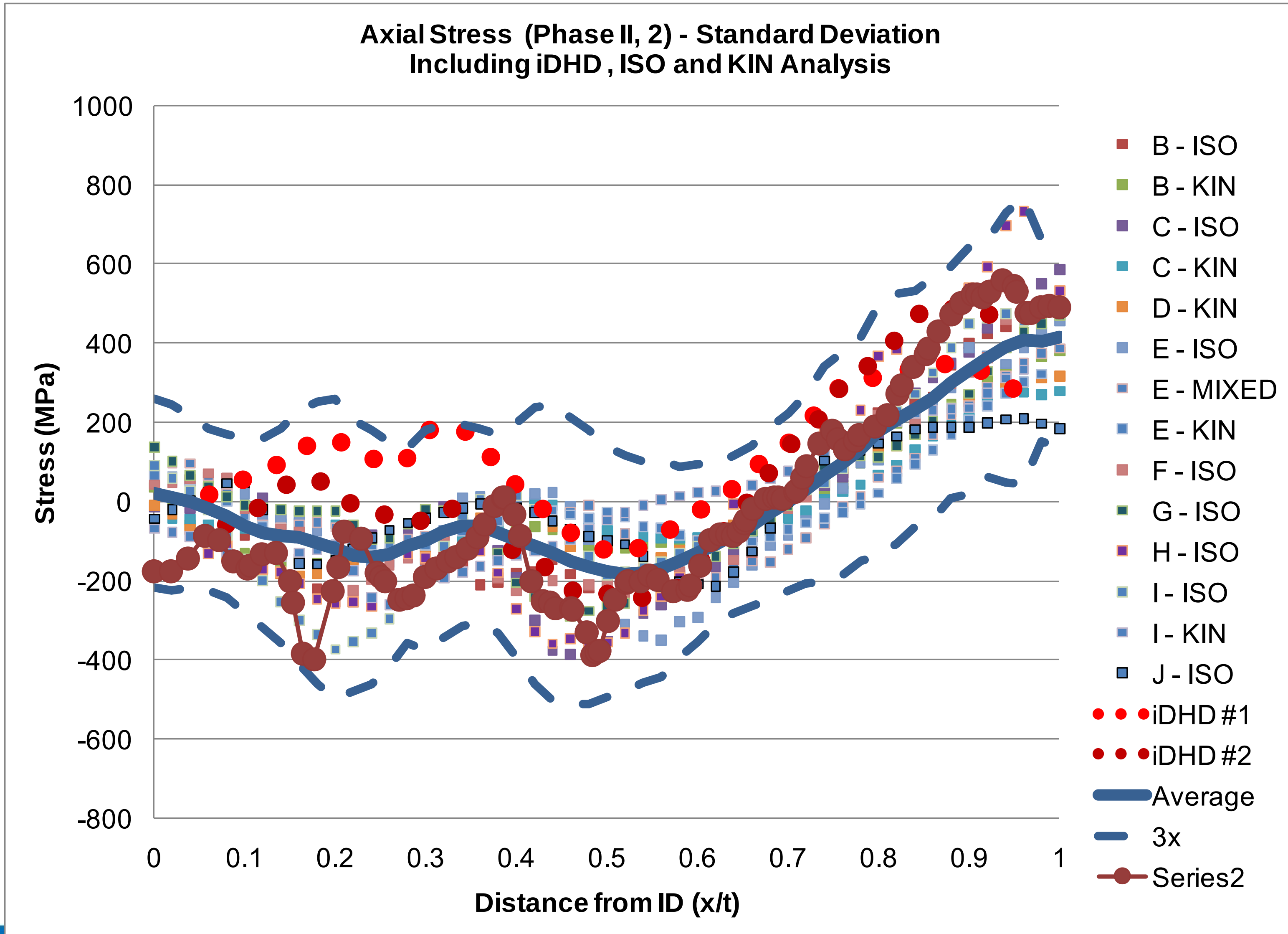
Sensitivity Studies

Baseline case – Hoop pre-ss weld results



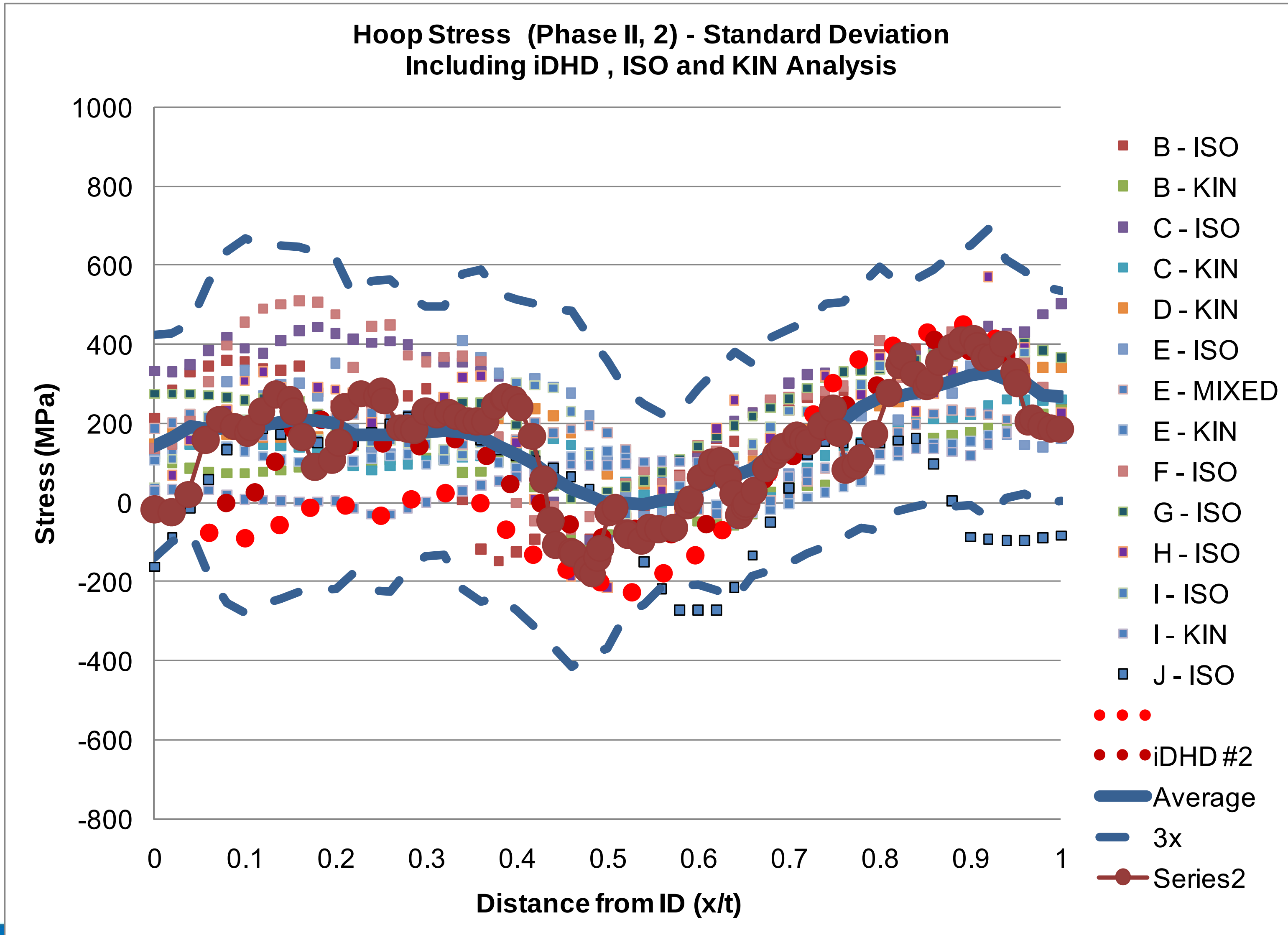
Sensitivity Studies

Baseline case – Axial post-ss weld results

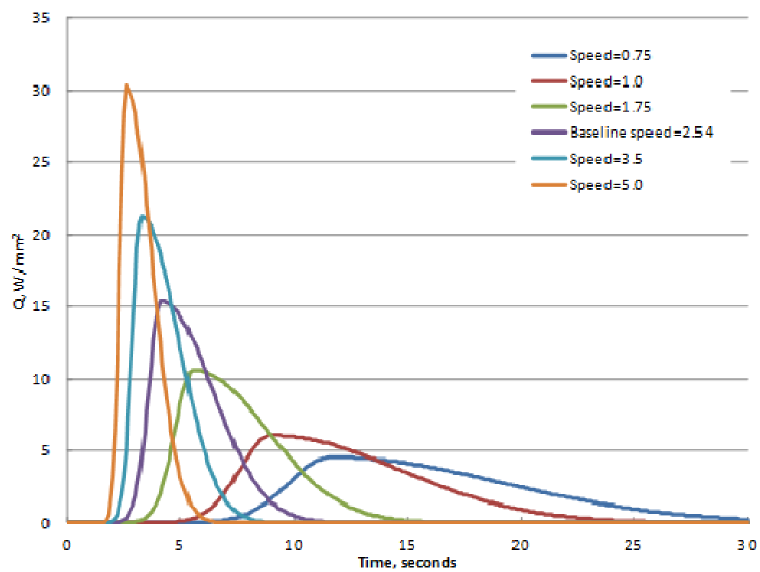


Sensitivity Studies

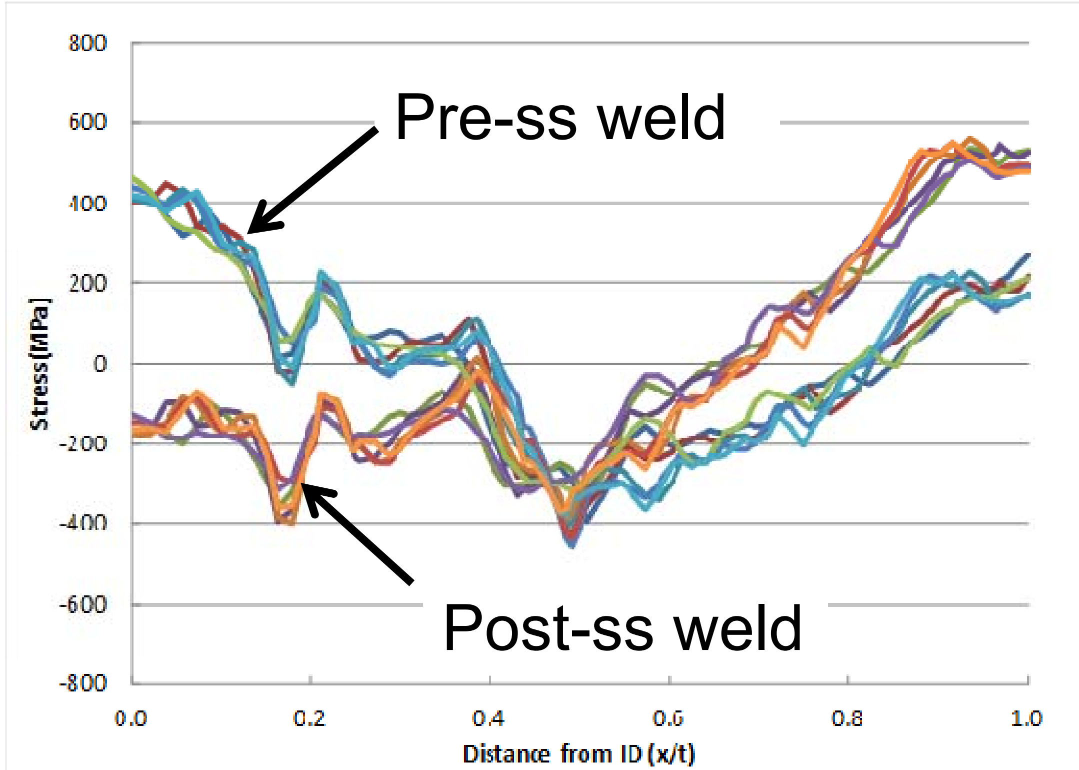
Baseline case – Hoop post-ss weld results



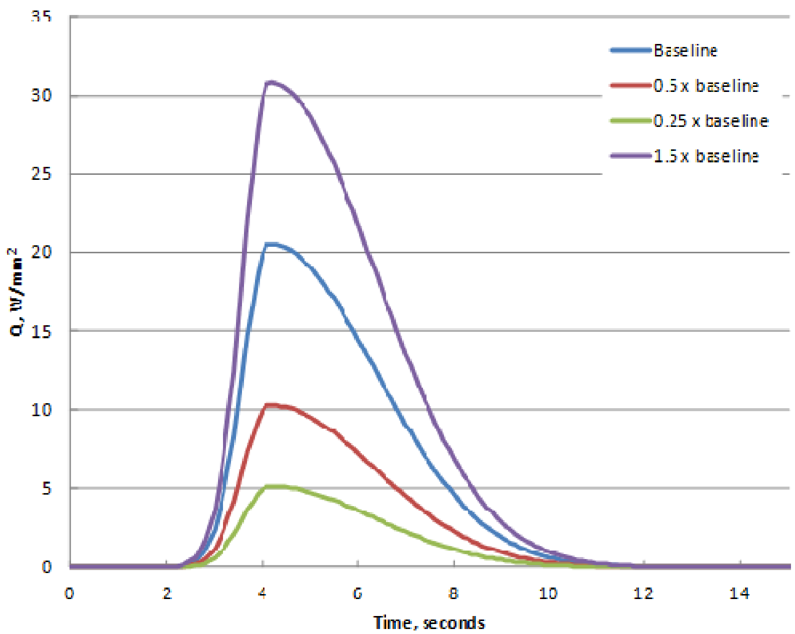
Sample Result: Thermal Input Duration



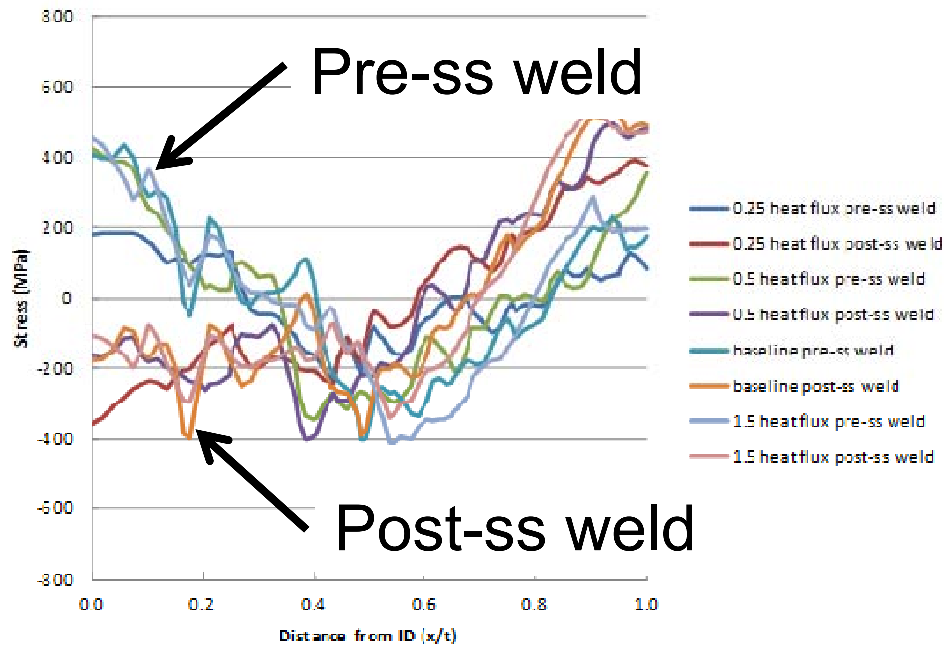
Axial Stress



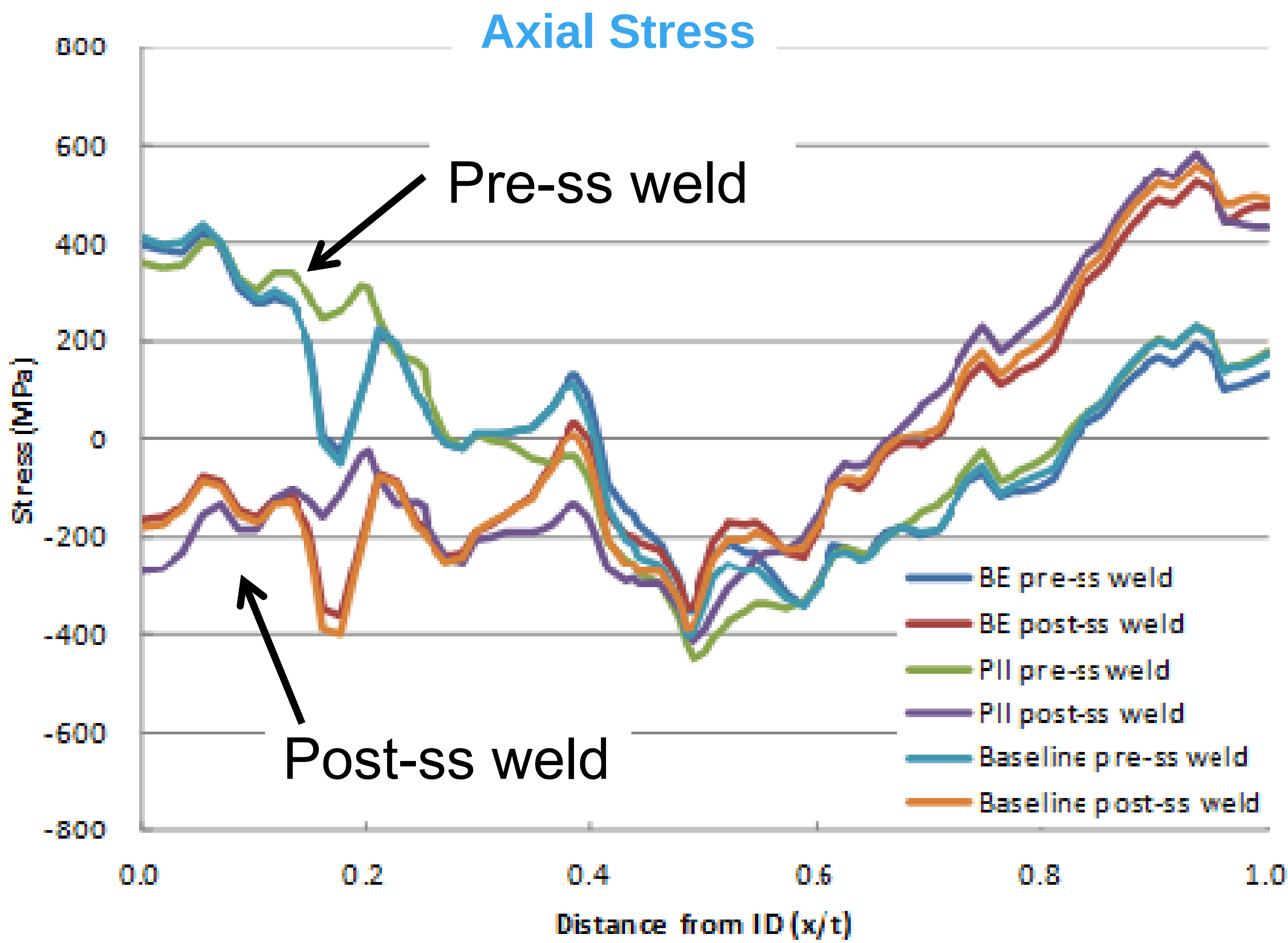
Sample Result: Thermal Magnitude



Axial Stress

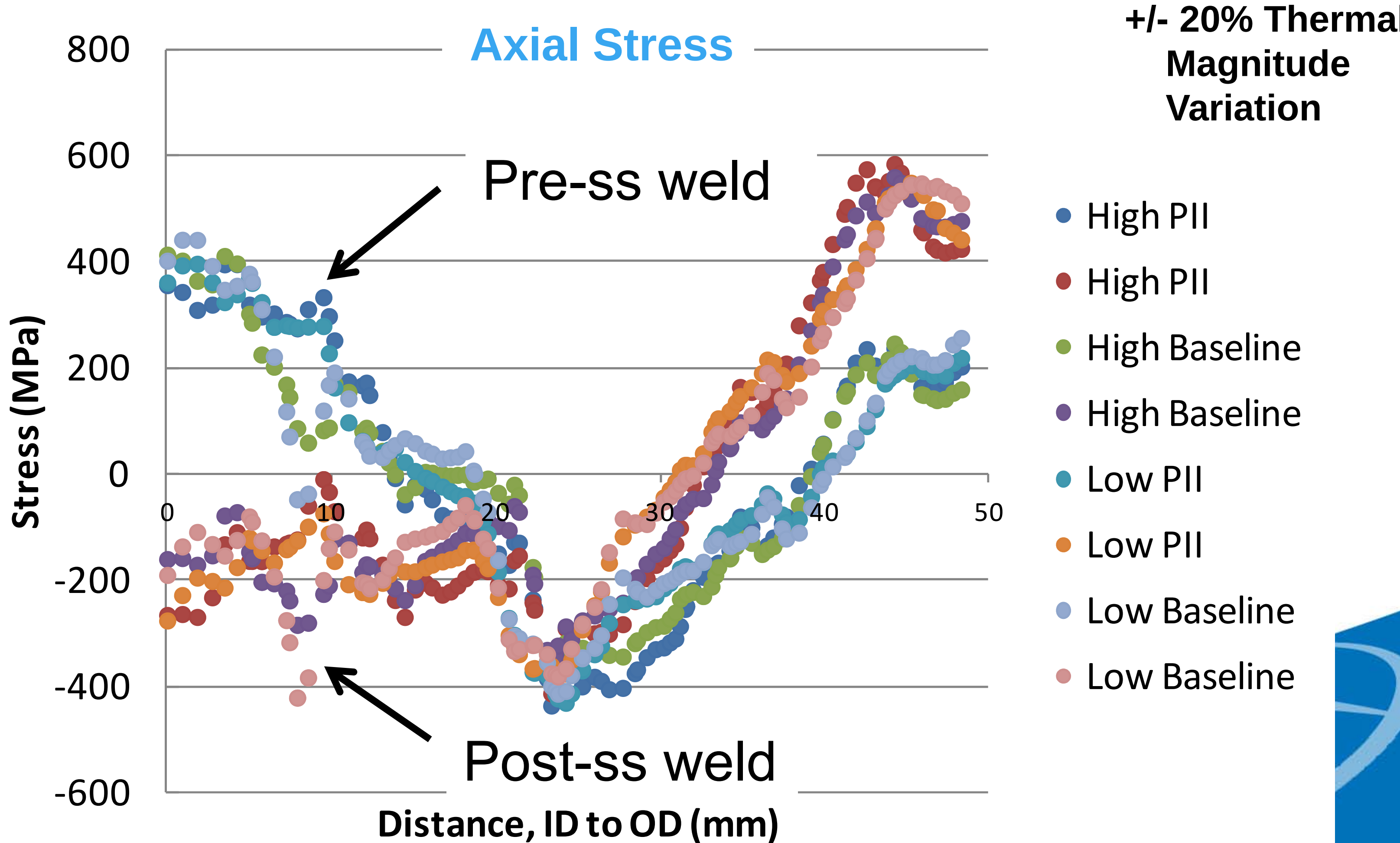


Sample Result: Plastic Stress-Strain Properties



Consolidated Sensitivity Study

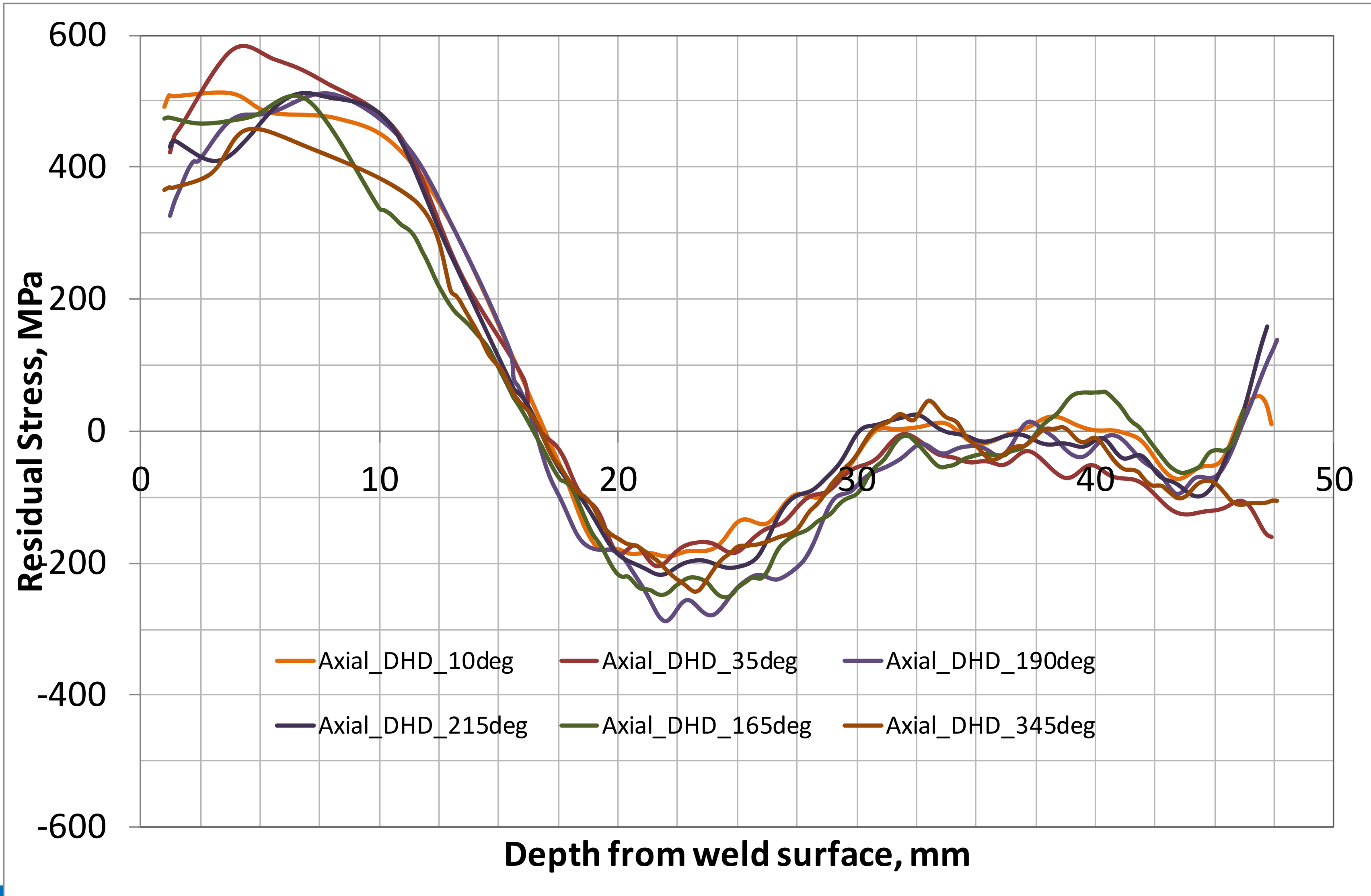
- Variation in reasonable modeling choices can lead to significant scatter in calculated WRS results



Recent Additional Deep Hole Drilling Results on Phase 2a Nozzle

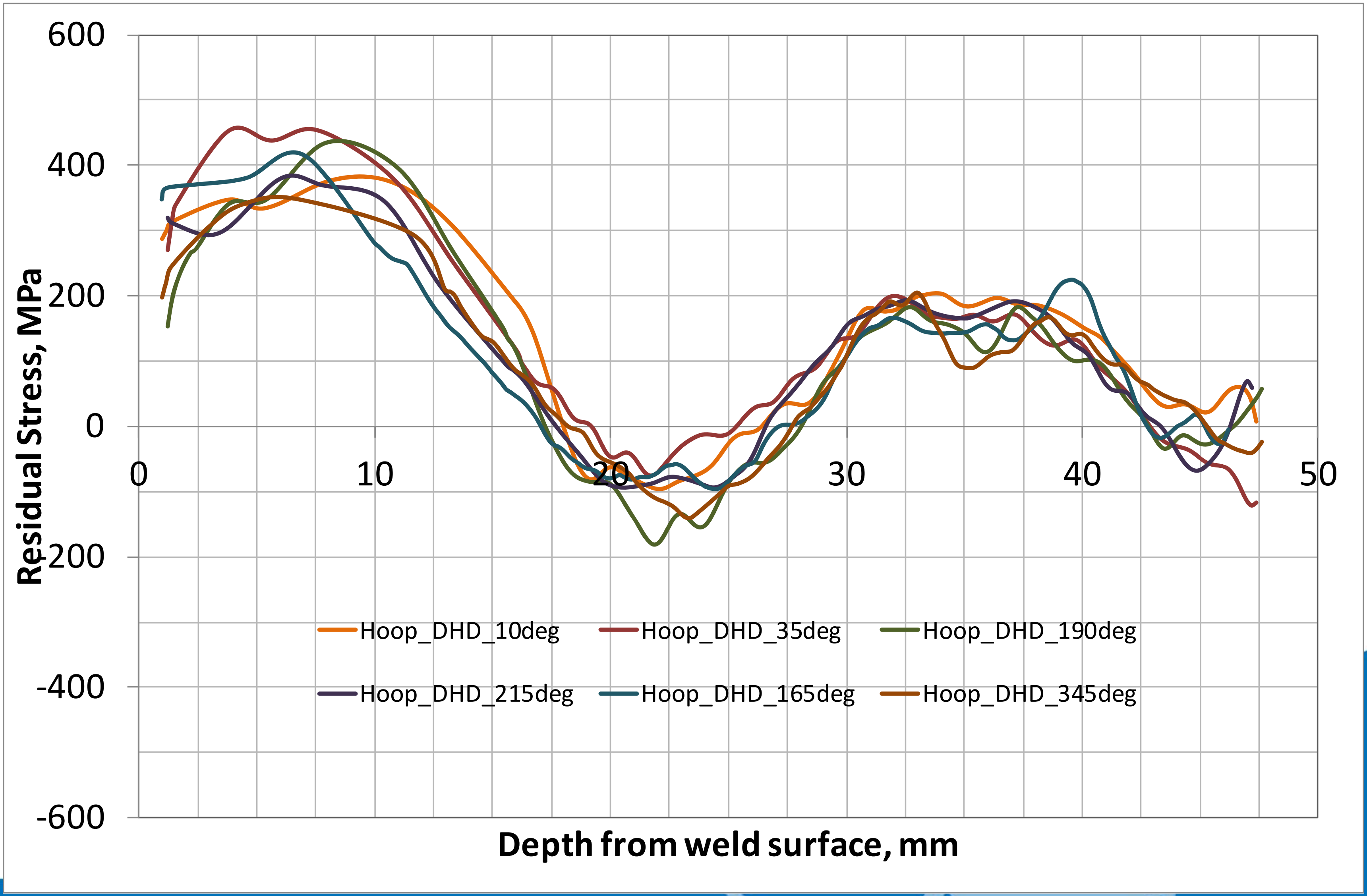
Phase 2a DHD/iDHD Results

Axial Stress, post safe-end, plotted OD to ID



Phase 2a DHD/iDHD Results

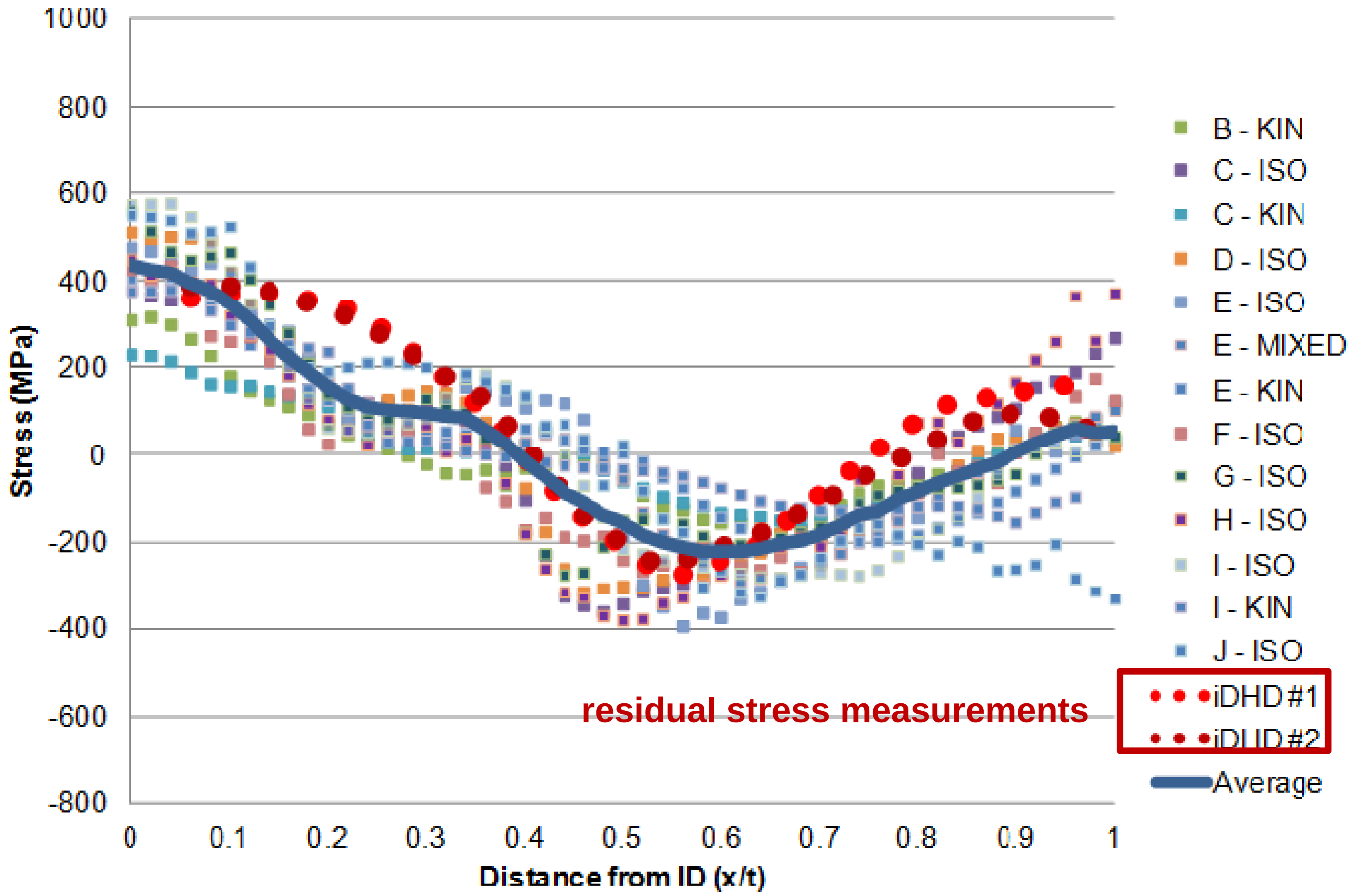
Hoop Stress, post safe-end, plotted OD to ID



K Evaluation - Phase 2

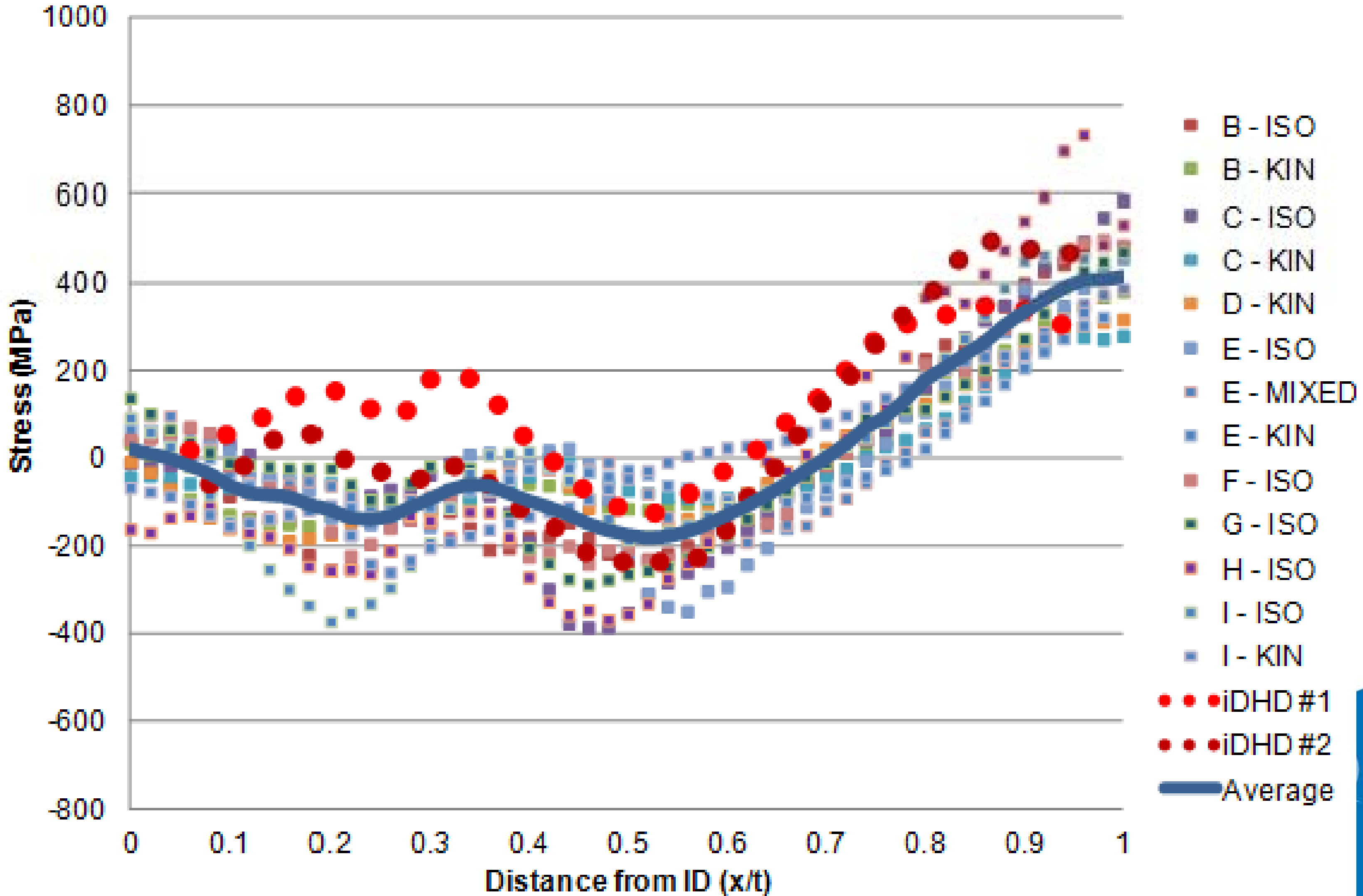
Phase 2 Analysis 1c

Axial Stress, pre safe-end



Phase 2 Analysis 2

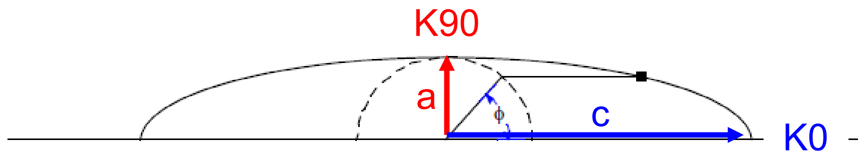
Axial Stress, post safe-end



Phase 2

K-Solution Analysis Details

- Geometry assumed for Phase 2 analysis
  - r/t of 3
  - c/a of 5
  - Circumferential flaw



- K-Solution API 579 (2001)
  - kSurf implementation from xLPR Version 1.0
  - Also used in PRO-LOCA
  - And confirmatory flaw evaluation work in support of NRR

- WRS representation
  - 4^{th} order polynomial
  - Constrained to pass through ID stress

Phase 2

K-Solution Analysis Details

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Polynomial WRS representation

$$\sigma(x) = \sigma_o + \sigma_1\left(\frac{x}{t}\right) + \sigma_2\left(\frac{x}{t}\right)^2 + \sigma_3\left(\frac{x}{t}\right)^3 + \sigma_4\left(\frac{x}{t}\right)^4 \quad (9.6)$$

where t is the section thickness. Figure 9.5 illustrates the nonuniform stress distribution and defines the x coordinate. If we introduce a surface crack at the location where the above stress distribution applies, the application of the principle of superposition leads to the following expression for K_I:

Closed form K-solution

$$K_I = \left[\sigma_o G_o + \sigma_1 G_1\left(\frac{a}{t}\right) + \sigma_2 G_2\left(\frac{a}{t}\right)^2 + \sigma_3 G_3\left(\frac{a}{t}\right)^3 + \sigma_4 G_4\left(\frac{a}{t}\right)^4\right]\sqrt{\frac{\pi a}{Q}} \quad (9.7)$$

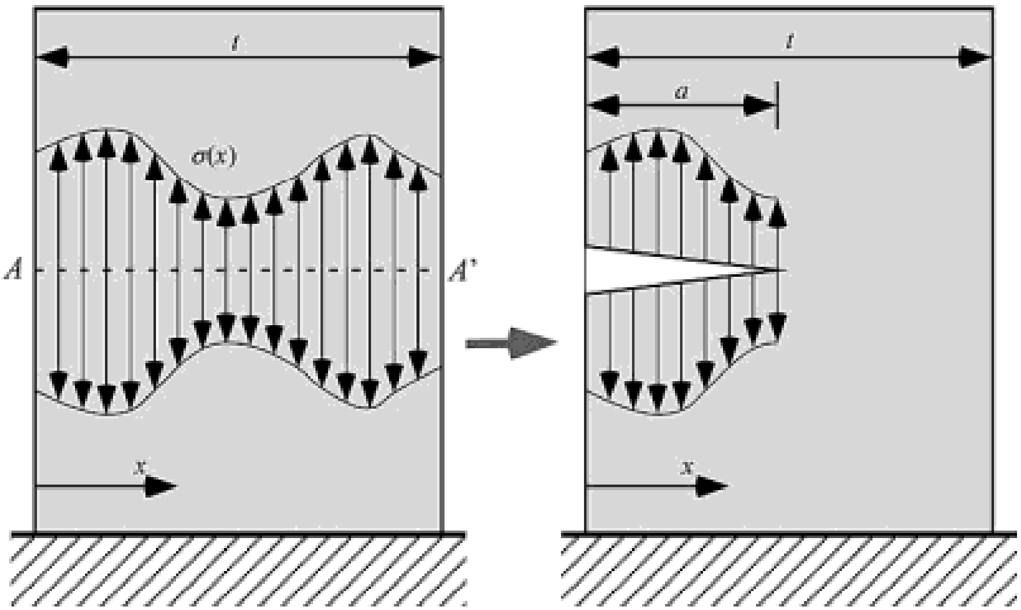


FIGURE 9.5 Nonuniform stress distribution that can be fit to a four-term polynomial (Equation (9.6)).

Phase 2

K-Solution Analysis Details

- API 579 K-Solutions

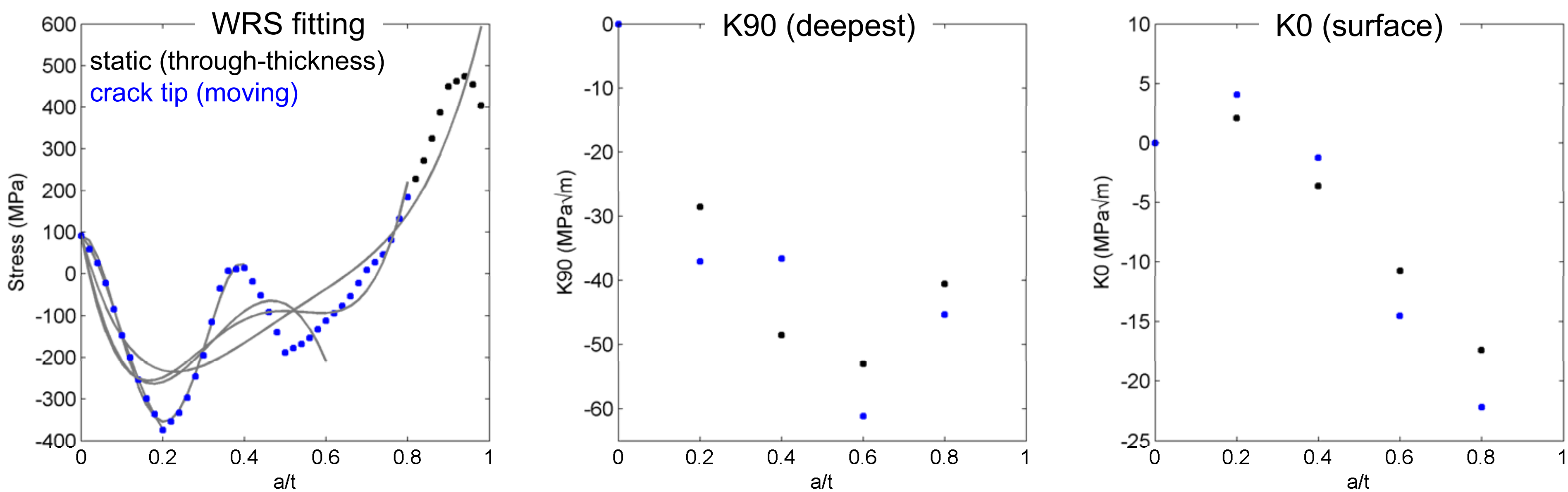
$$K = \left(\sigma_0 G_0 + \sigma_1 G_1 \left[\frac{a}{t} \right] + \sigma_2 G_2 \left[\frac{a}{t} \right]^2 + \sigma_3 G_3 \left[\frac{a}{t} \right]^3 + \sigma_4 G_4 \left[\frac{a}{t} \right] + \sigma_b G_5 \right) \frac{\sqrt{\pi a}}{Q}$$

  – K (MPa√m) calculated at surface (K0) and deepest point (K90)
  – σ_n (MPa) is the through-thickness stress components
  – a/t is the crack length normalized by the wall thickness
  – c/a is the crack width normalized by the crack depth
  – G_n are the influence function coefficients (function of a/t, c/a, and order of the polynomial fit), derived from finite element solutions

Anderson, T.L., Thornwald, G., Revelle, D.A., and Lanaud, C., "Stress Intensity Solutions for Surface Cracks and Buried Cracks in Cylinders, Spheres, and Flat Plates," Structural Reliability Technology final report to The Materials Property Council, Inc., March 14, 2000.

Phase 2

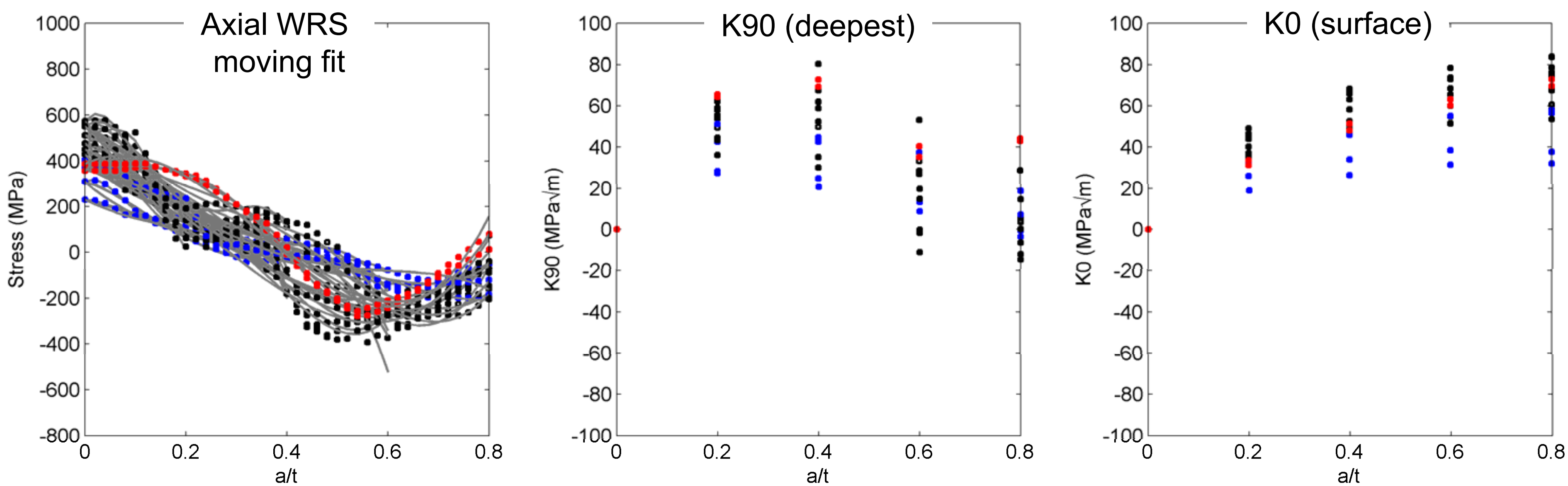
K-Solution Analysis Details



- Polynomial fits are not always a good representations of WRS profiles
  - Stress magnitudes can be under or over estimated
  - Fitting through-thickness and to crack tip can have an effect
  - Difficult to qualify the uncertainty associated with polynomial fitting
  - Multiple inflections and stress discontinuities potentially produce fitting artifacts

Phase 2 Analysis 1c

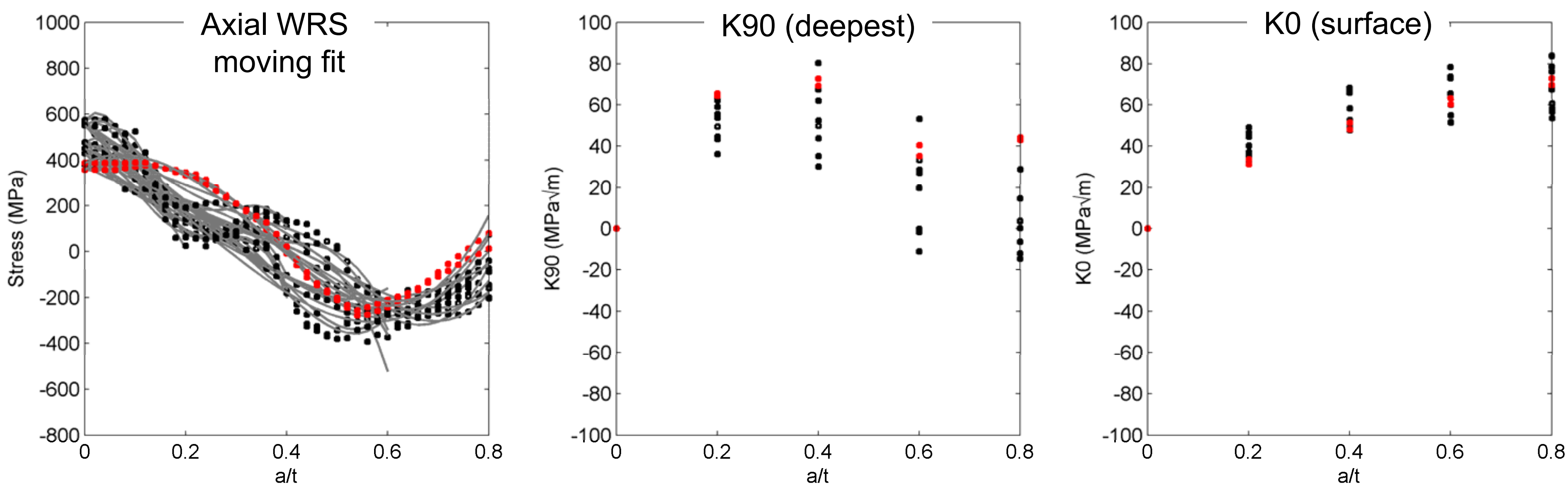
K-Solution, axial stress, pre-safe end



- All Phase 2 data segregated by **DHD**, **ISO**, **KIN**
  - Distinction made in the Phase II WRS analysis
  - Scatter in WRS distributions is not reduced by K evaluation
  - DHD results bounded by FE results

Phase 2 Analysis 1c

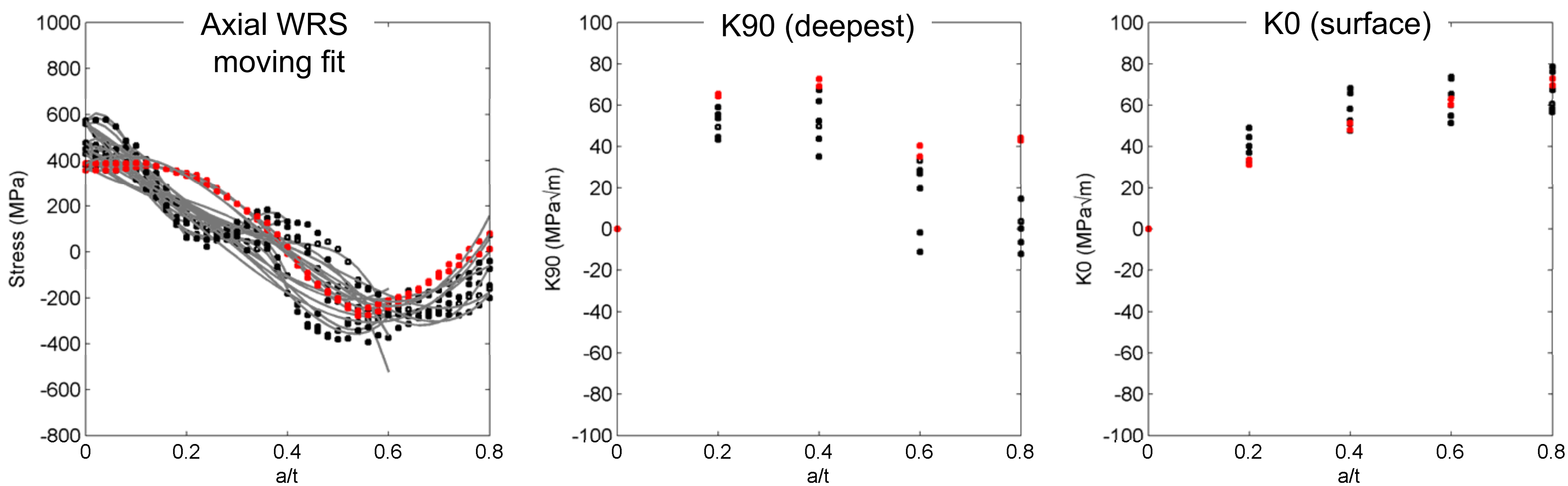
K-Solution, axial stress, pre-safe end



- **ISO** Phase 2 data
  - Some reduction in K90 scatter
  - Significant reduction in K0 scatter
  - DHD results bounded by FE results

Phase 2 Analysis 1c

K-Solution, axial stress, pre-safe end



- **ISO** Phase 2 data from US Vendor/NRC Contractor
  - Some reduction in K90 and K0 scatter
  - DHD data slightly high with respect to FE data for K90
  - DHD data bounded by FE data for K0
- Summary of FE results
  - K90 ±25 MPa√m
  - K0 ±15 MPa√m

Phase 2 Analysis 2

K-Solution, axial stress, post-safe end

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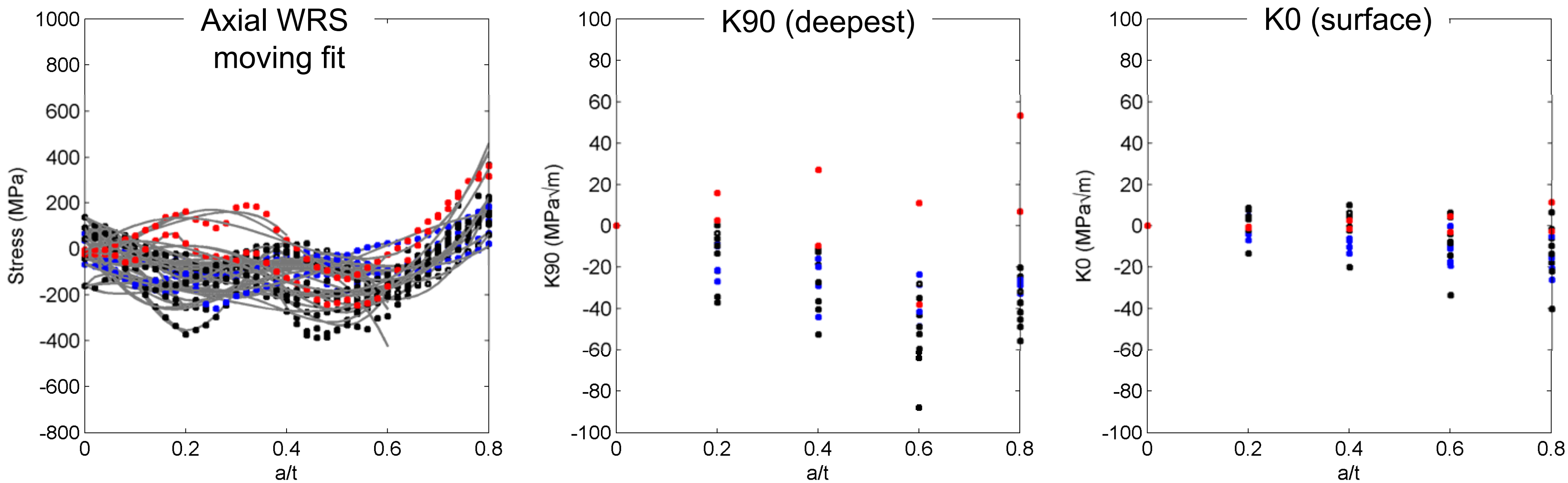
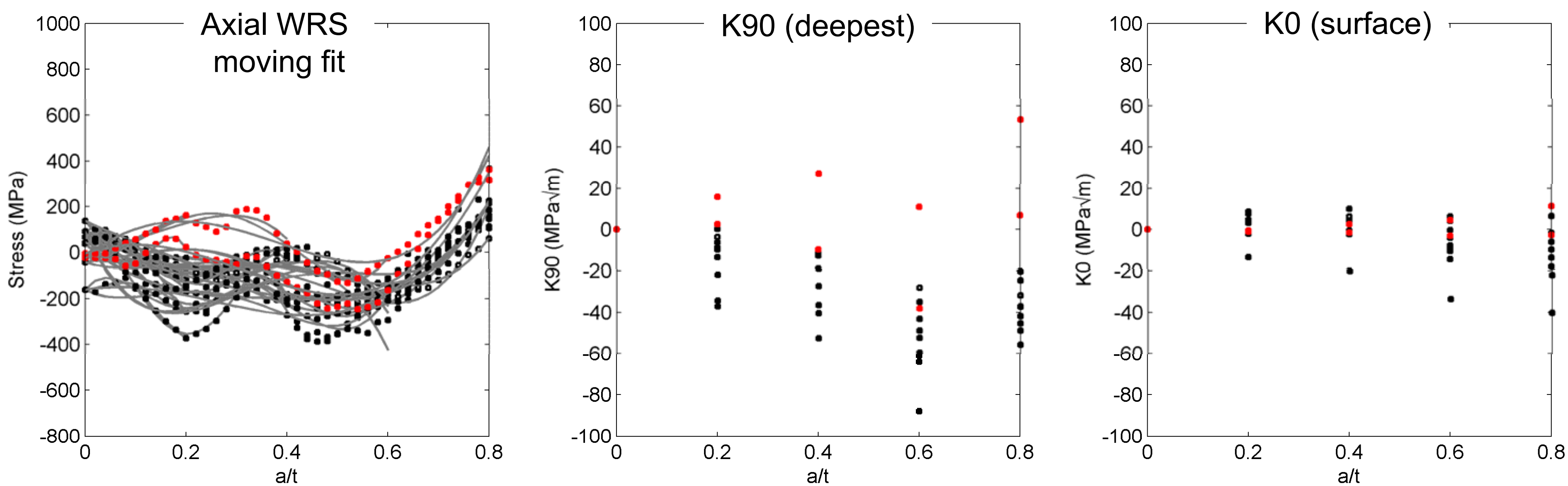


- All Phase 2 data segregated by **DHD**, **ISO**, **KIN**
  - DHD data consistently outlies FE results for K90
  - DHD data bounded by FE results for K0

Phase 2 Analysis 2

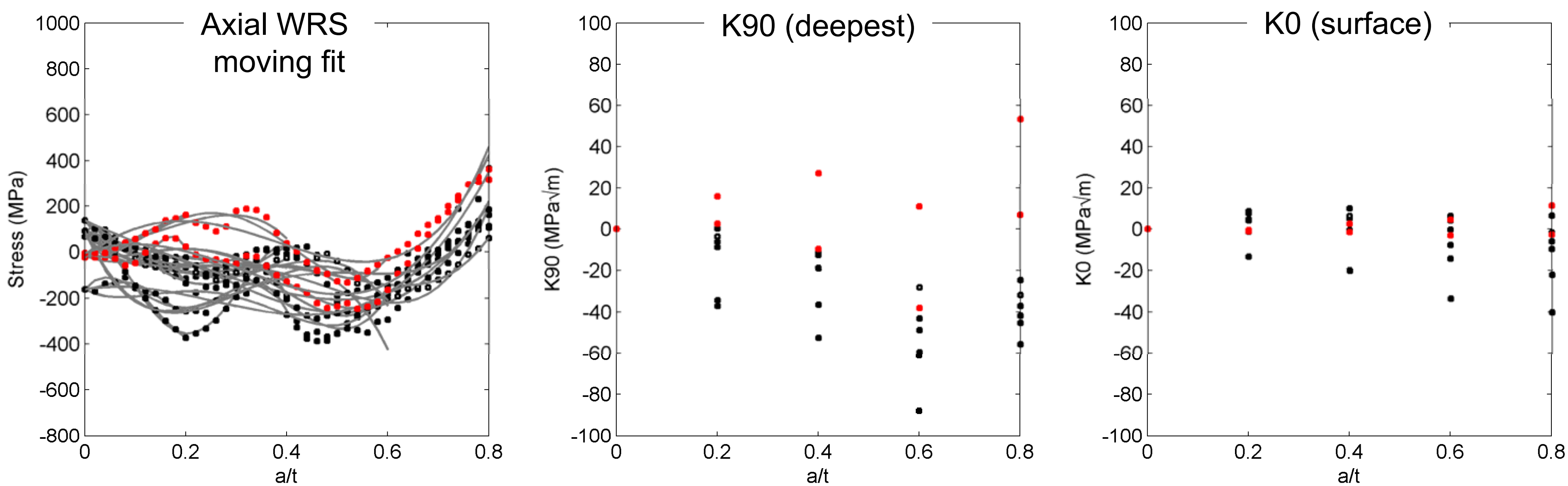
K-Solution, axial stress, post-safe end



- **ISO** Phase 2 data
  - No change in scatter for K90 or K0

Phase 2 Analysis 2

K-Solution, axial stress, post safe-end



- **ISO** Phase 2 data from US Vendor/NRC Contractor
  - No change in scatter for K90 or K0
- Summary of FE results
  - K90 ±30 MPa√m
  - K90 ±20 MPa√m
  - Similar to pre safe-end

K Evaluation – Phase 4

MRP-287

Industry Flaw Evaluation Guidelines

- Simulate actual weld configuration and fabrication sequence
- Include ID weld repair
  - Phase 4 contained a 30° partial arc repair to 1/4*t*
- Include safe-end weld
  - Phase 4 included safe-end analysis
- Benchmark and validate analysis
  - Based on K, ±10 MPa√m criteria suggested
  - Suggests methodology can be validated
- Account for operating conditions
  - Temperature and pressure

MRP-287

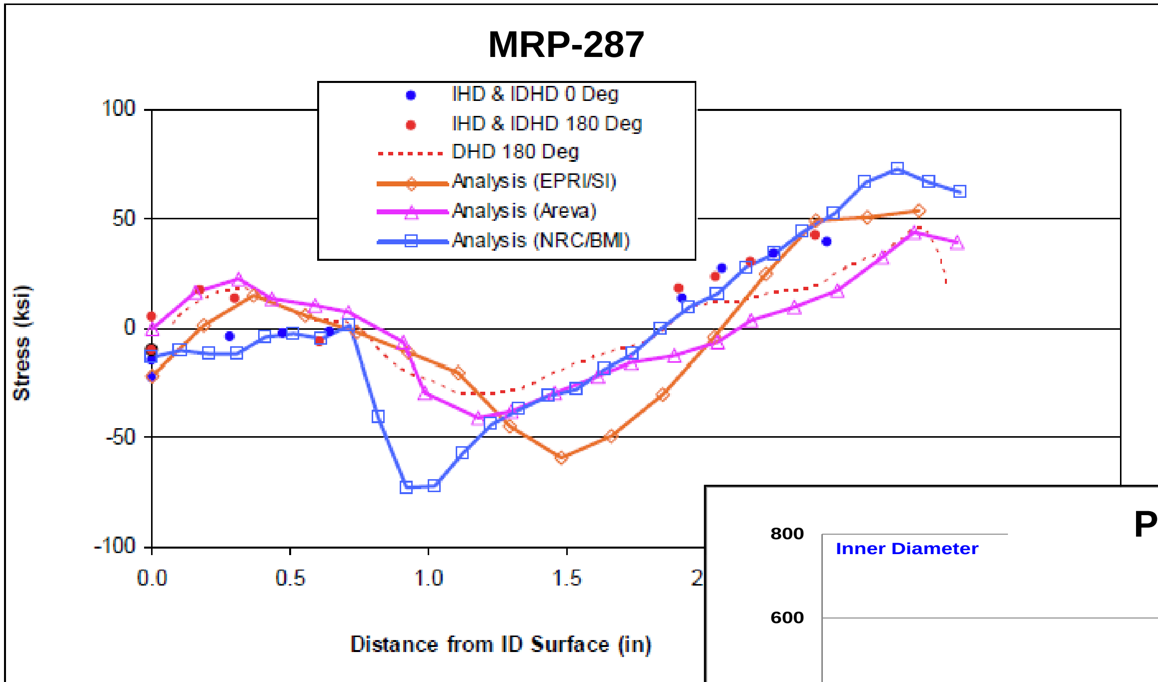
Flaw Evaluation

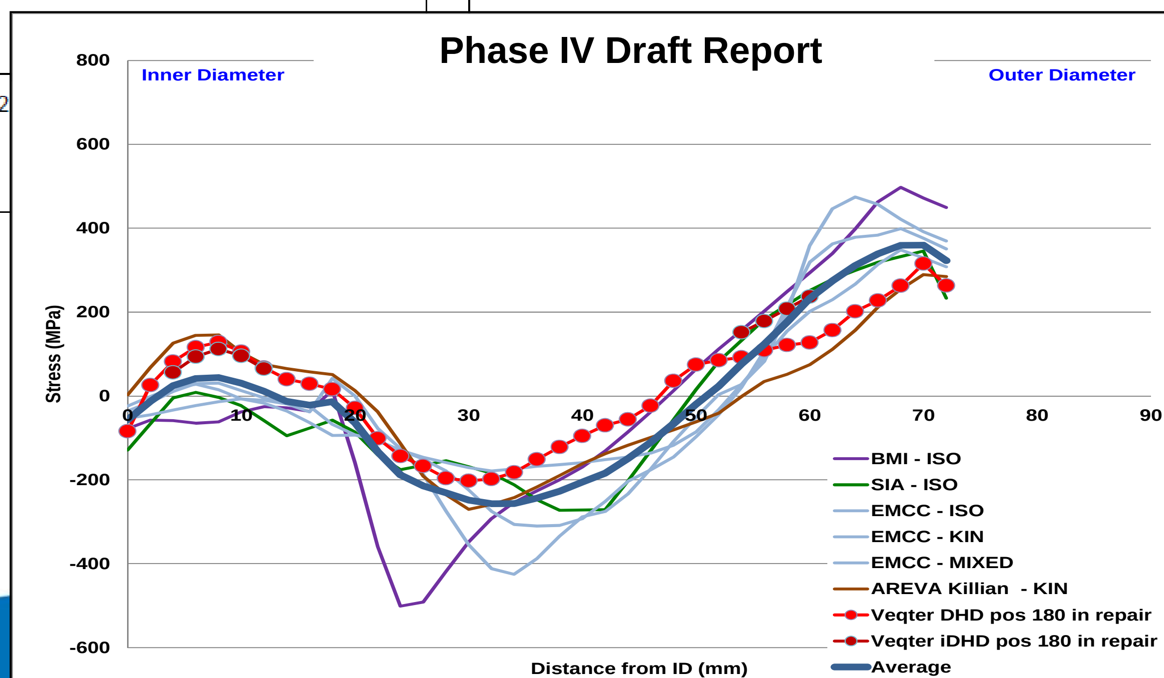
- WRS profiles from Phase 4 used
  - SIA results updated, submitted results did not include main DM weld
  - Results from SIA, Battelle, and Areva used
  - Polynomial WRS representation

- Phase 4 geometry
  - Cold leg nozzle
  - r/t = 5
  - Axisymmetric circumferential flaw (axial stress)
  - Axial flaw also considered (hoop stress)

Phase 4

Axial Stress, repair weld

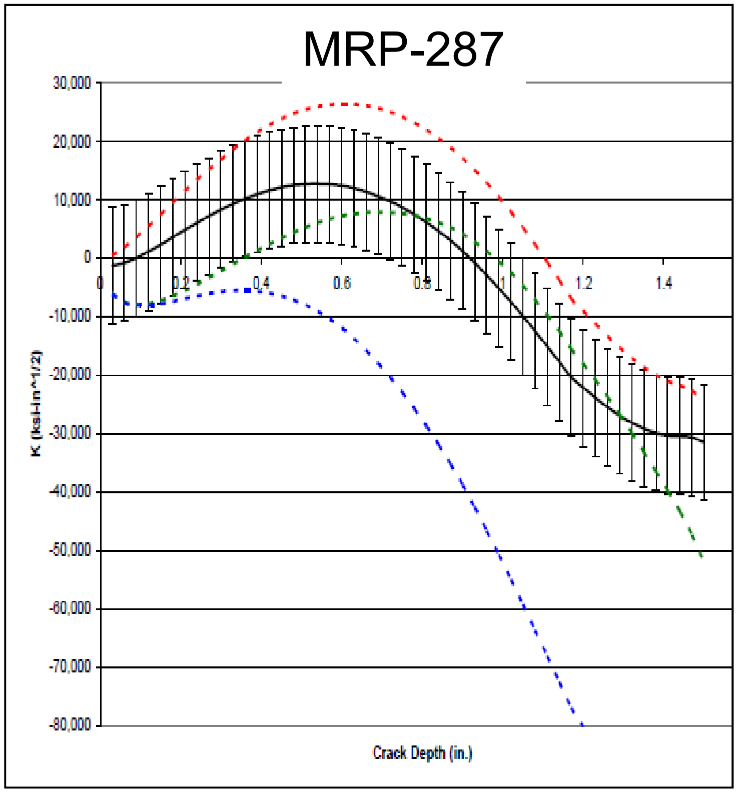


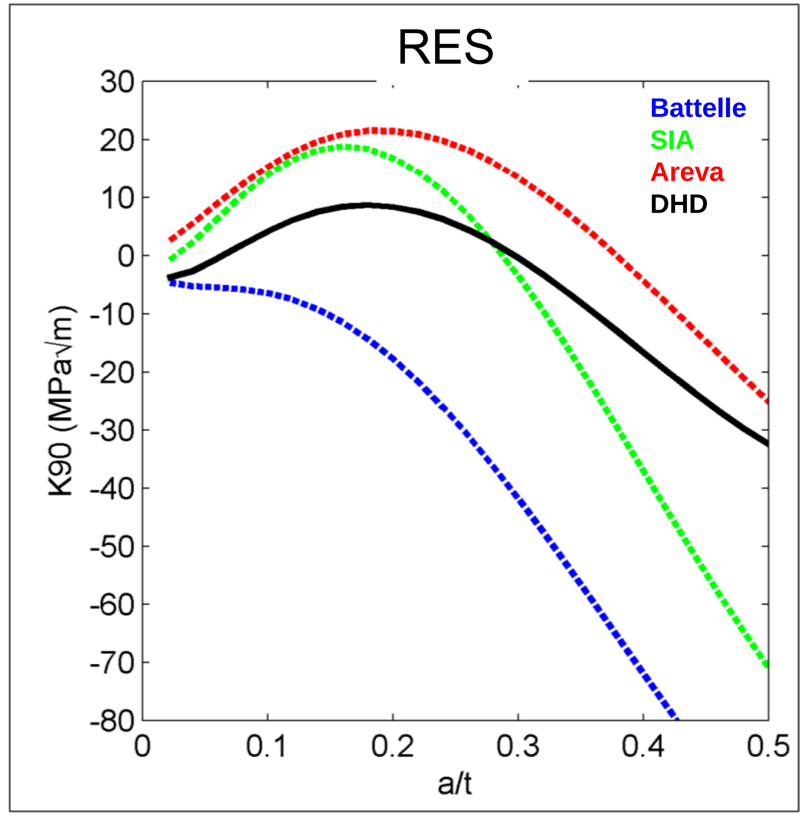


Axial WRS profiles reported in Phase 4 are similar to those used in MRP-287.

MRP-287

Circ. Flaw, repair, post safe-end

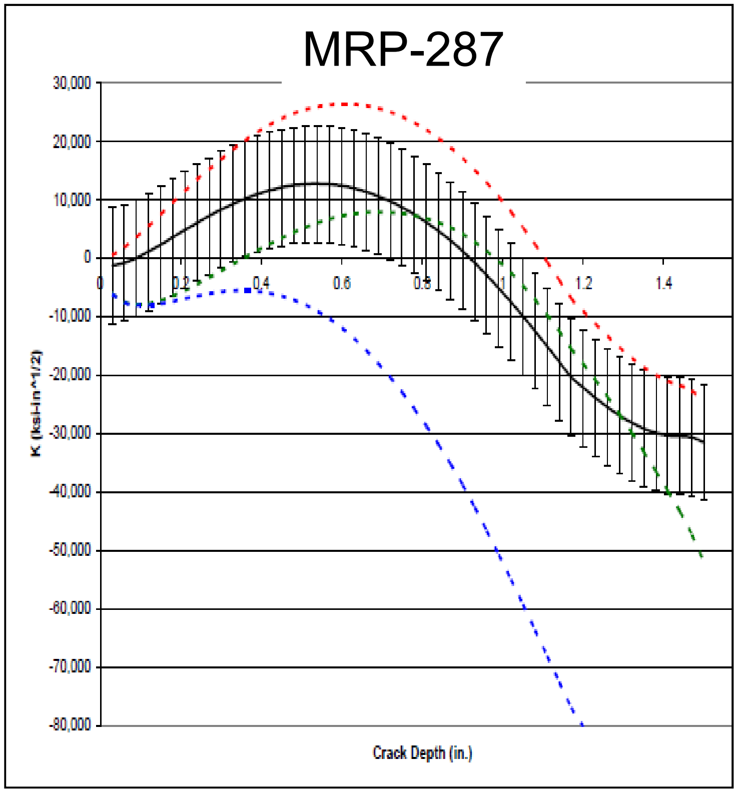


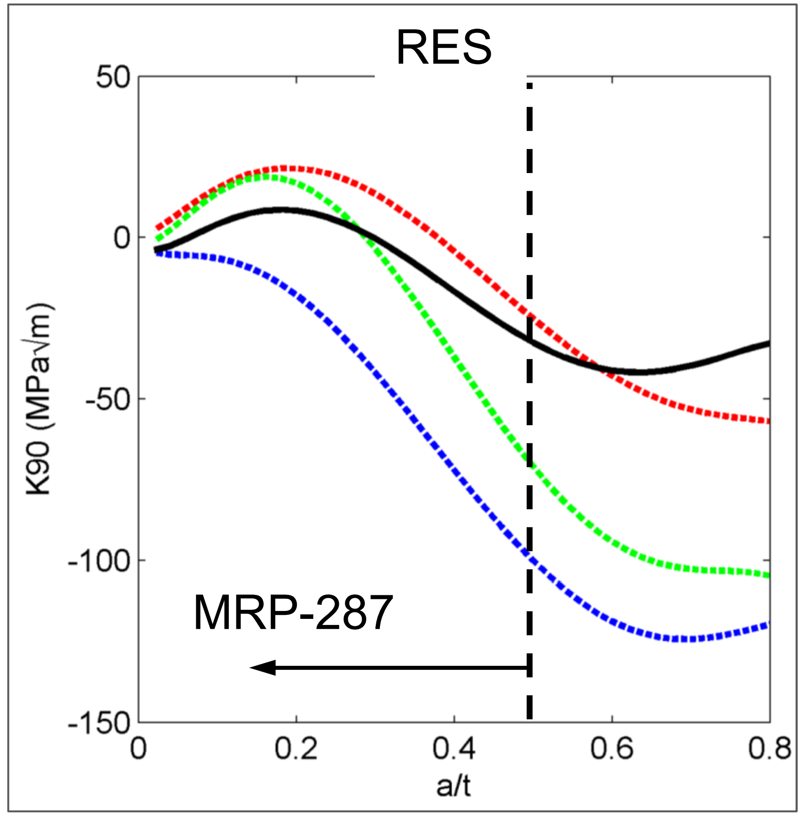


- RES analysis using the Phase 4 dataset is similar to results reported in MRP-287 …

MRP-287

Circ. Flaw, repair, post safe-end

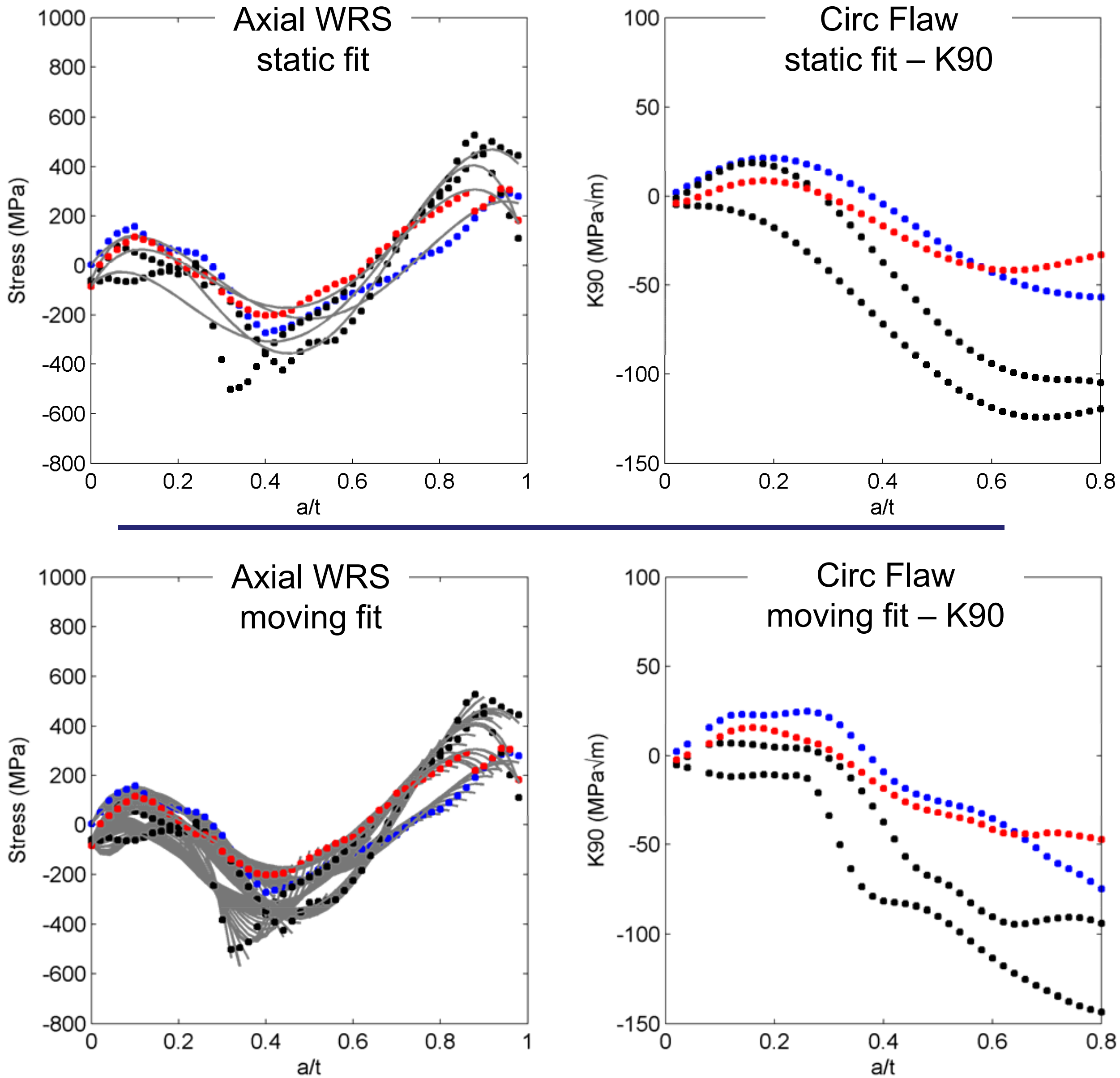




- … BUT MRP-287 does not calculate K through-thickness

RES Analysis (MRP-287)

Circ. Flaw, repair, post safe-end

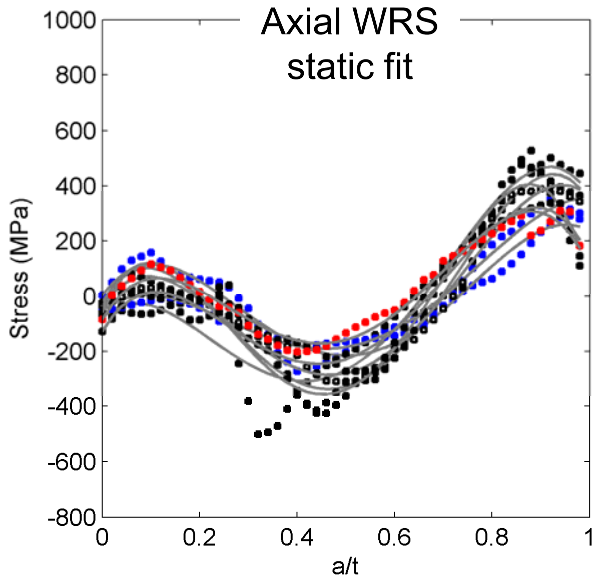


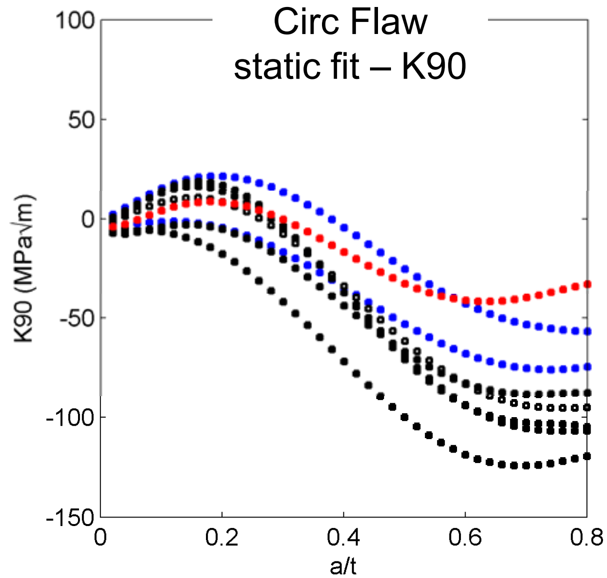
Moving fits produce slightly different profile shapes

K results are similar in magnitude

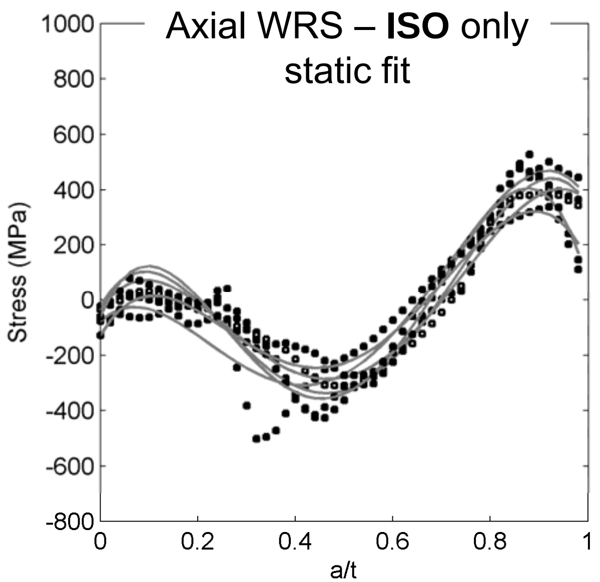
RES Analysis (Phase 4)

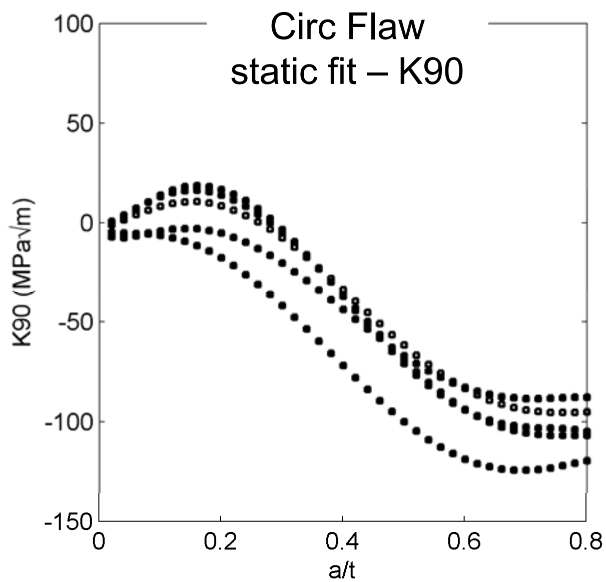
Circ. Flaw, repair, post safe-end





Full Phase 4 results plotted, bounded by subset used in MRP-287

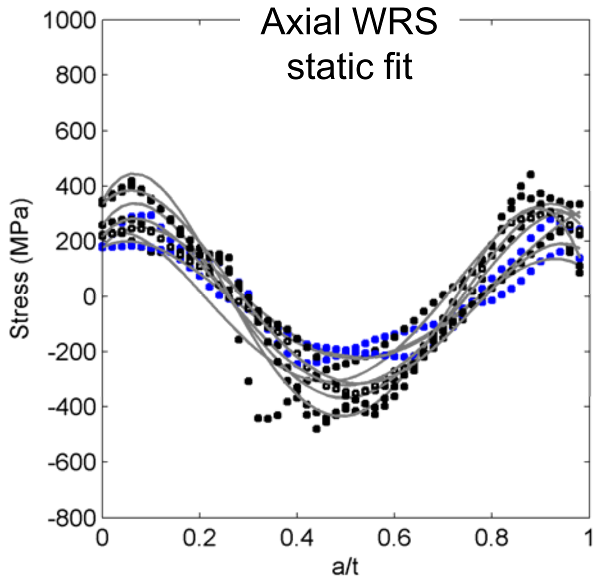


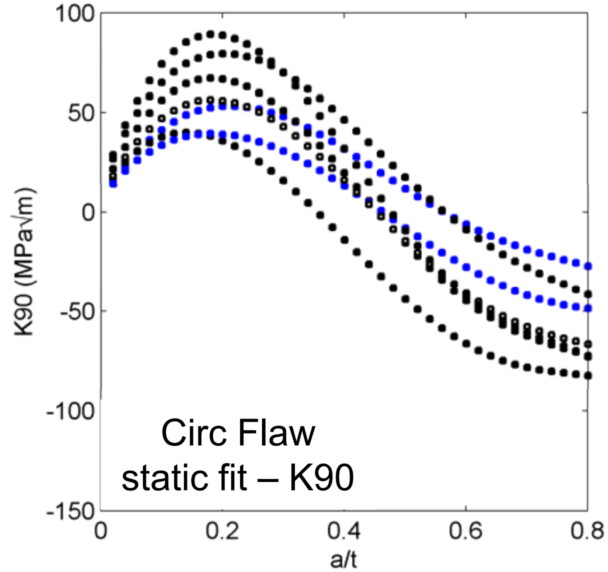


ISO only Phase 4 results show similar scatter to Phase 2

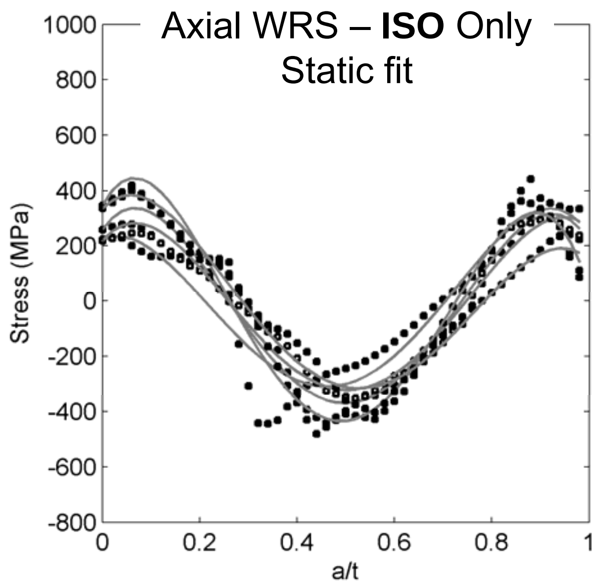
RES Analysis (Phase IV)

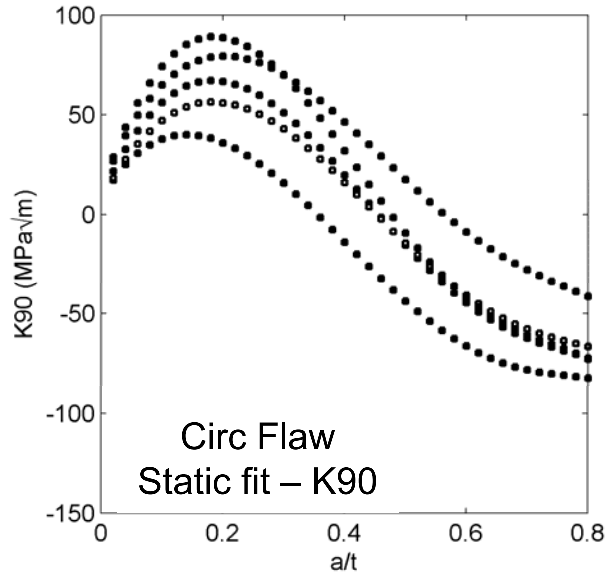
Circ. Flaw, repair, pre safe-end





Higher K values prior to application of safe-end weld



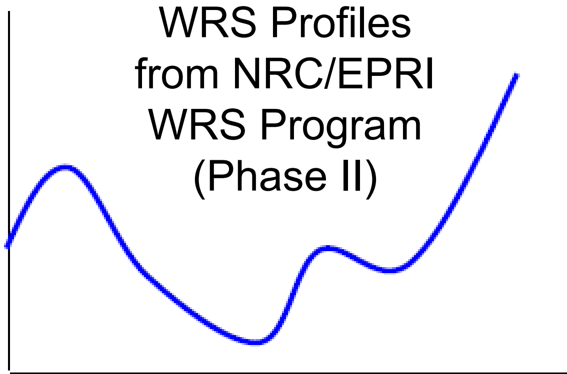


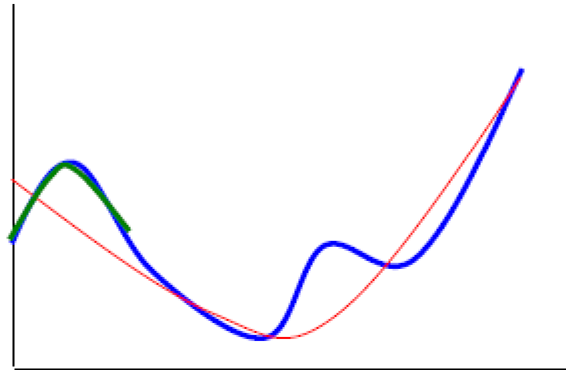
ISO only Phase 4 results show similar scatter to Phase 2

K Evaluation Benchmarking

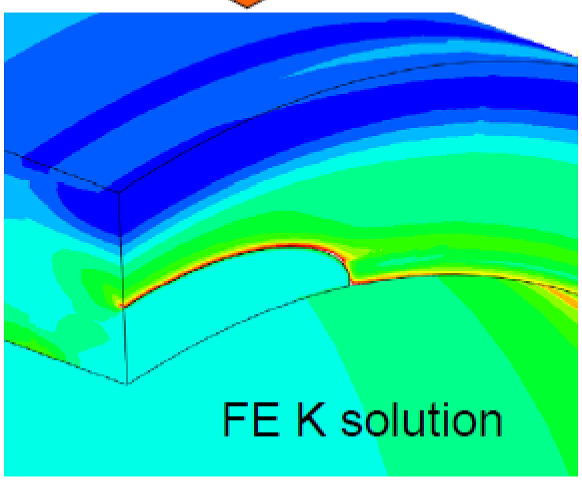
Phase 2 Analysis 2

K-Solution benchmarking





- API solution
  - Entire polynomial fit
  - Partial polynomial fit
- UWFM solution
  - Various fits

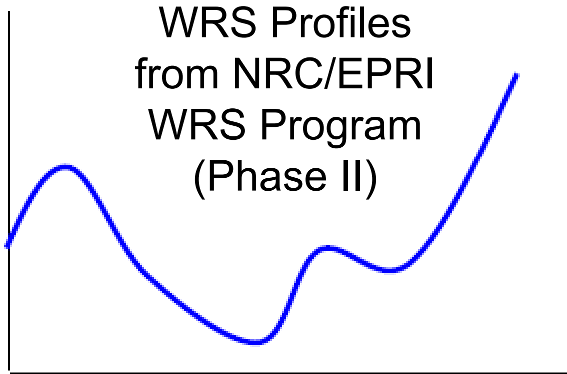


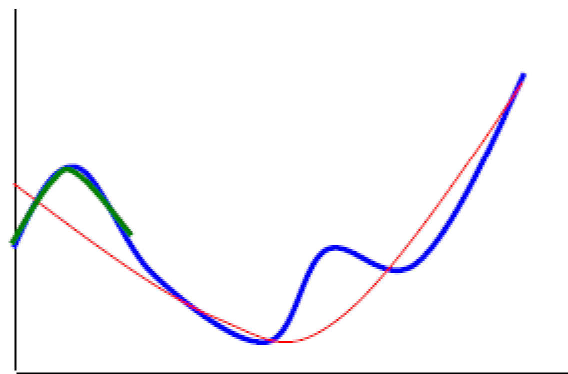
Compare

- K solutions for various semi-elliptical crack sizes:
  - a/t=0.2, 0.4, 0.6, 0.8 (fix c/a=5, R_i/t=3)
  - K values at deepest and surface points

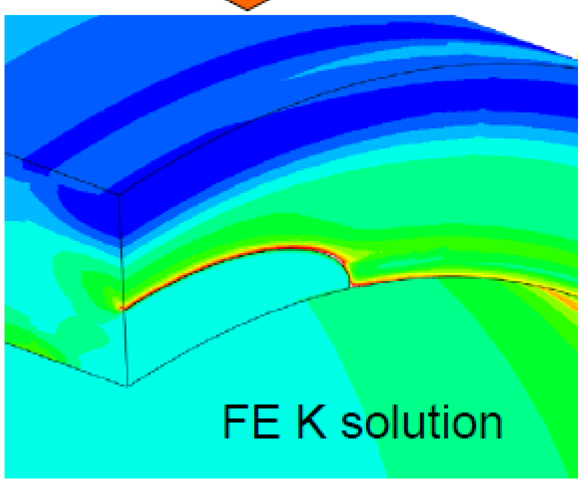
Phase 2 Analysis 2

K-Solution benchmarking

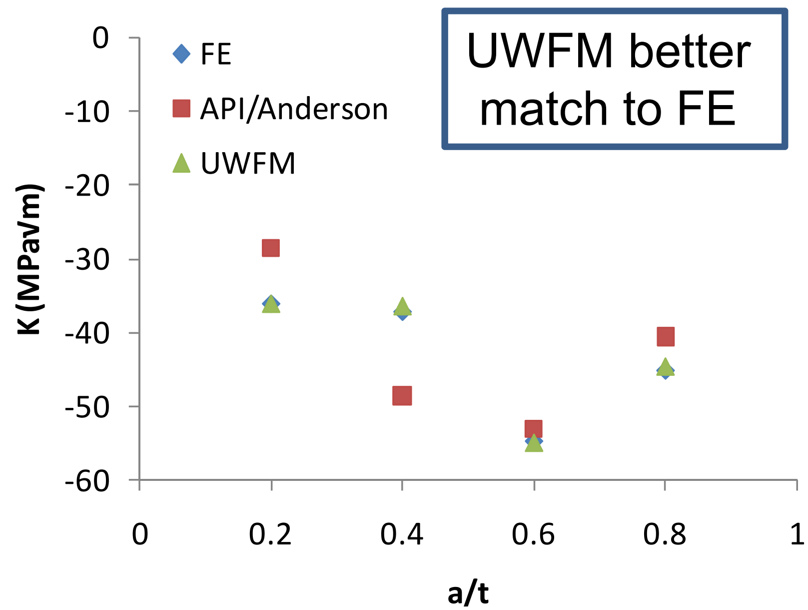




- API solution
  - Entire polynomial fit
  - Partial polynomial fit
- UWFM solution
  - Various fits



Compare



Summary
WRS Stress Intensity Factor Evaluation

- Presentation briefly summarized the following
  - K evaluation of the WRS Program Phase 2 dataset
  - Industry flaw evaluation guidelines (MRP-287)
  - K evaluation of the WRS Program Phase 4 dataset
  - Current K-solution benchmarking efforts
- WRS scatter is not reduced by K evaluation
  - Subset of ISO result for US vendor/NRC contractors show similar scatter for all analyses (Phase 2 and 4)
  - Supports the sensitivity analyses used in confirmatory flaw evaluation work in support of NRR

Technical Letter Report for Phase 2a

- Current contents
  - Summary of Round Robin
  - Analysis of measured and calculated results
  - Sensitivity studies

- Additional related work
  - Through-wall K calculations
  - More mockup DHD measurements

- Current milestone for TLR is 12/31/11
  - Inclusion of through-wall K & add'l measurement results will be include in Revision 1

Action Items and Schedule

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- Technical Letter Reports

Phase	Date
2. Pressurizer Surge Nozzle	4th Quarter, CY 2011 √ Rev. 1 1st Quarter, CY 2012
3. Safety / Relief Nozzles	1st Quarter, CY 2012
4. Cold Leg Nozzle	4th Quarter, CY 2011 √ Rev. 1 1st Quarter, CY 2012

Action Items and Schedule (cont'd)

- NUREG consolidating NRC WRS Program Results
  - 1st Quarter, CY 2012
- ACRS briefing
  - Fall 2012 (tentative)

Weld Residual Stress Follow-On Research

January 25, 2012

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**** The views expressed herein are those of the authors and do not represent official positions of the USNRC***

Overview

- Phase 2b Analysis Mini-Round Robin
- Additional WRS Measurements
- Topics for Further Research

WRS Validation Program

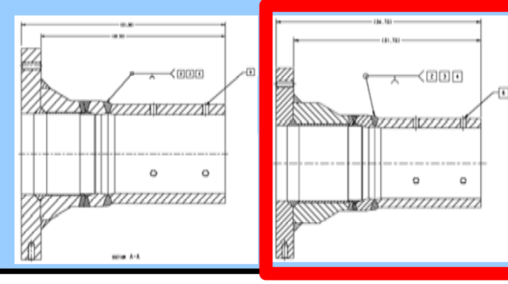
Phase 1 - EPRI

- Scientific Weld Specimens
- Phase 1A: Restrained Plates (QTY 4)
- Phase 1B: Small Cylinders (QTY 4)
- Purpose: Develop FE models.

Phase 2 - NRC

- Fabricated Prototypic Nozzles
- Type 8 Surge Nozzles (QTY 2)
- Purpose: Prototypic scale under controlled conditions. Validate FE models.

Phase 2b nozzle



Phase 3 - EPRI

- Plant Components
- WNP-3 S&R PZR Nozzles (QTY 3)
- Purpose: Validate FE models.

Phase 4 - EPRI

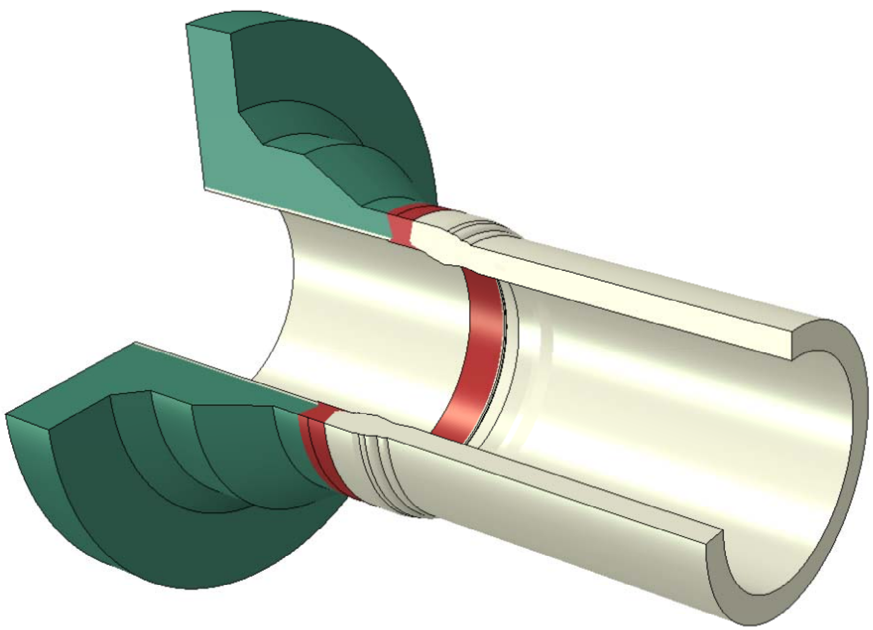
- Plant Components
- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.

Phase 2b Mini-Round Robin

- Motivation
  - Significant variability in FEA results from Phase 2a
  - With uniform modeling guidelines, would variability be reduced?
- Plan
  - FEA modeling of Phase 2b nozzle by multiple participants
  - Employ industry WRS FE guidelines
  - Perform WRS measurements on nozzle
  - Analyze and compare results
- Status
  - Nozzle model completed by H. Rathbun
  - Need to resolve a few questions with EWI
  - Will be ready to send out modeling package by 1/31/12

Phase 2b Mini-Round Robin

- Nozzle is similar to Phase 2a
  - Approximately ½ the number of passes in Main DMW and Re-weld
  - Phase 2b used stick weld vs. automated welding in Phase 2a
  - About the same number of passes in SS weld
  - Pipe wall thickness is about 3/4 that of Phase 2a



Phase 2b Mini-Round Robin

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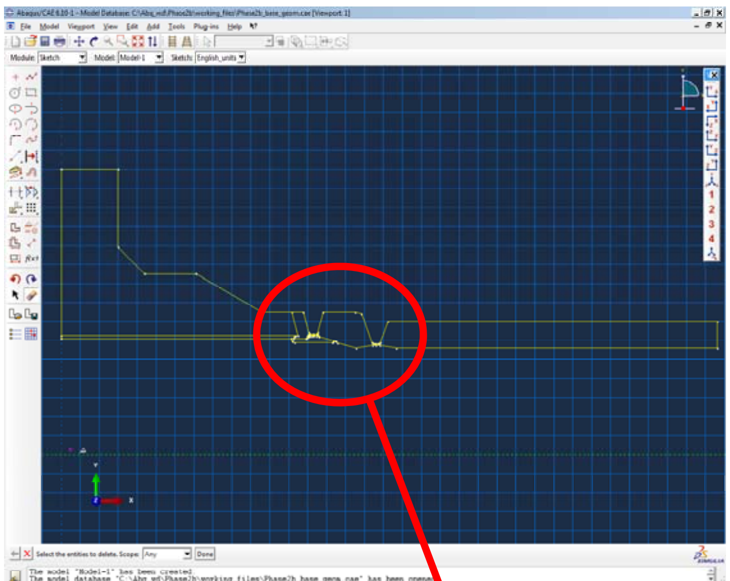
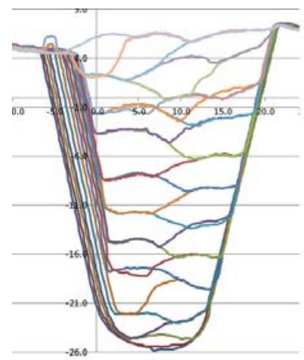
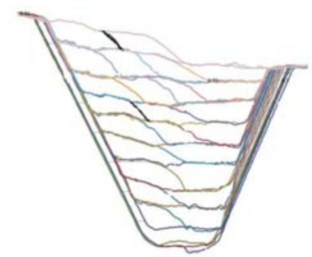
- Fabrication Diagrams & Profilometry



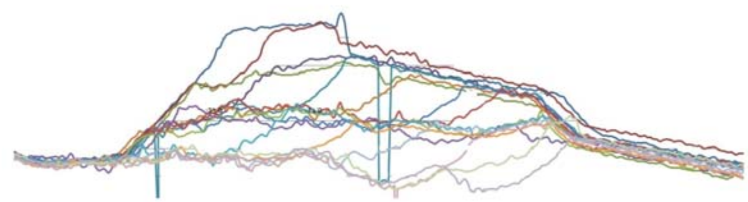
Main DMW



SS Weld



Re-Weld



Phase 2b Sources of Information

- Geometry
  - Fabrication / machining drawings
  - CAD drawing in lieu of complete set of drawings
- Laser profilometry
  - Consolidated diagrams, in lieu of excel spreadsheets
- Thermocouples
  - Excel spreadsheets & description of TC placement
- Material properties
  - Use Phase 2a properties
- Weld parameters (voltage, current, pass speed)
  - Text file

Phase 2b Results Requested

- Form of thermal model
- Magnitude of heat input, e.g. arc efficiency
- Mesh
- Boundary conditions
- Axial and hoop stresses along centerline of DMW from ID to OD, before & after SS weld
- Material properties (if different from Phase 2a properties)
- Hardening law assumptions

Phase 2b Possible Participants

- AREVA (USA)
- Battelle
- Dominion Engineering
- EMC^2
- ORNL
- Structural Integrity Associates
- U.S. NRC
- Westinghouse Electric Company

- EPRI Charlotte? (use of Sysweld?)
- Bettis / KAPL?

Tentative Phase 2b Schedule

- Modeling package to be issued: February 1, 2012
- Results requested by April 30, 2012
- WRS measurements simultaneous with modeling
- Analyze data and presentation of results – Fall 2012

Possible Additional WRS Measurements & Analyses

- Welding parameter study
- Phase 2b Nozzle
  - DHD/iDHD
  - Contour
  - Excavate and Weld Repair
  - Peening
- Contour measurements on Phase 2a
- Repair Welds
- Vessel Penetration Nozzles
- Effects of Peening

Possible Additional WRS Measurements & Analyses (cont'd)

- K-evaluation appears not to reduce scatter
- Effect of WRS variability on Flaw Evaluation
  - …in an xLPR sense
    - Time to leakage
    - Magnitude of leakage
    - And distributions thereof
  - …in an ASME Section XI Appendix C sense
    - Final crack size
    - Applied stress

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Welding Residual Stress Modeling Improvement Tasks 2012-2013

Paul Crooker
Mitigation and Testing Technical Advisory Committee Project Manager

Nuclear Regulatory Commission Staff and Representatives of the Nuclear Power Industry PWR Materials Reliability and Weld Repair Research Meetings

January 24-26, 2012

Issue

- Recently completed WRS validation project improved understanding of FEA model results and residual stress measurements
- Substantial differences still exist when comparing
  - 1) model to model
  - 2) measurement to measurement
  - 3) model to measurement.

Objective

- Improve understanding of modeling variations and residual stress measurement differences
- Improve agreement for
  - Model to model comparisons
  - Measurement to measurement comparisons
  - Model to measurement comparisons
- Support key inputs to the xLPR project
- Advance welding residual stress models through cooperative R&D program

Scope

- Additional modeling and measurement comparisons performed in cooperation with NRC-RES
- Modeling of DM weld locations to develop standardized through-wall stress distributions
  - Support xLPR
  - Potentially support deterministic calculations
- Benchmarking of NRC-RES crack tip SIF (K) versus depth calculations

R&D Tasks Planned for 2012-2013

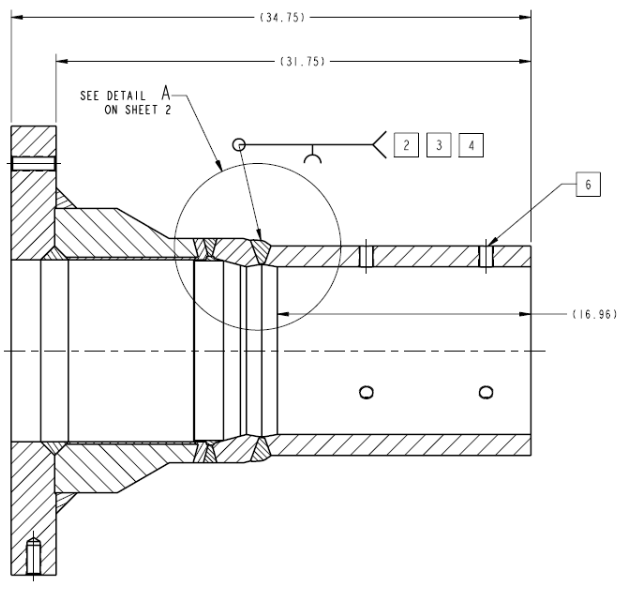
- Incorporate new strain hardening information into welding residual stress models
- Cooperate with NRC-RES to perform residual stress measurements of existing pressurizer surge nozzle mockup
- FEA modeling for surge nozzle mockup round robin, including review of input listings when consistency of inputs is desired
- Perform additional FEA analysis for WRS distribution cases required for xLPR model inputs
- Validation of WRS predictions for CRDM/BMN nozzle geometries
  - Additional measurements, consider new mockup
- Neutron diffraction measurements of WRS for removing d_0

Use of R&D Results

- Compare analysis model results from round robin and identify sources of modeling differences
- Additional measurements will be used to increase confidence in measurement and modeling
- Participation in ASME Code Committee on welding residual stress modeling
- WRS distributions for specific cases will be used as inputs to xLPR
- WRS distributions will be investigated for application as generic inputs to deterministic calculations

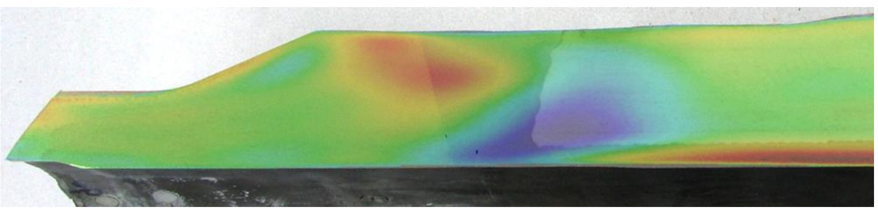
Residual Stress Measurements

- Expand data sets using available assets
  - Phase II mock-up (pressurizer surge)
  - CRDM or BMN sections
  - Other assets as available or useful



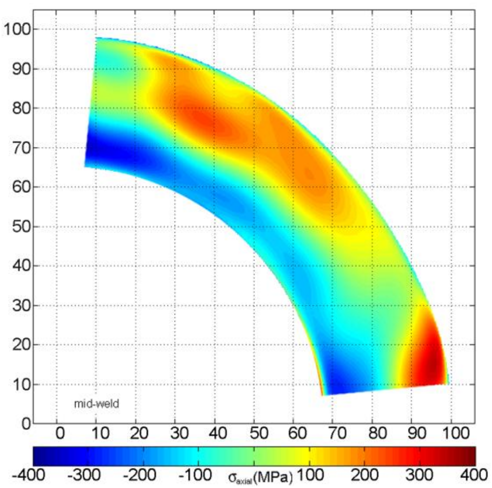
Residual Stress Measurements

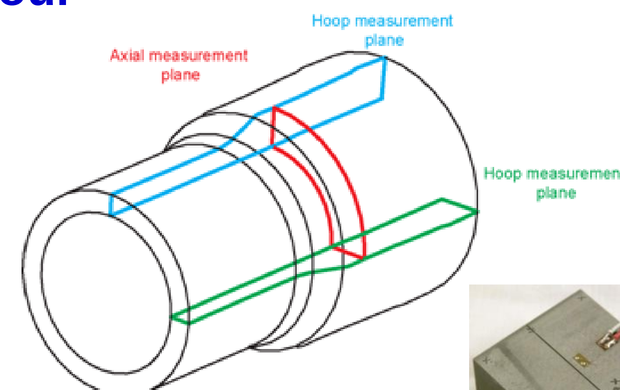
- Reduce uncertainty in residual stress measurements
  - Normalize established techniques
  - Define best practices

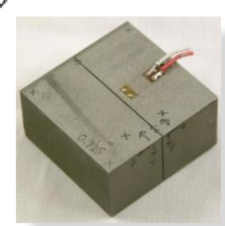


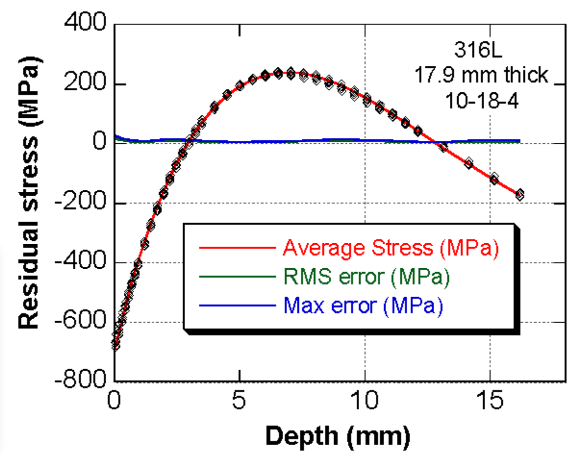
Contour

Deep Hole









Slitting

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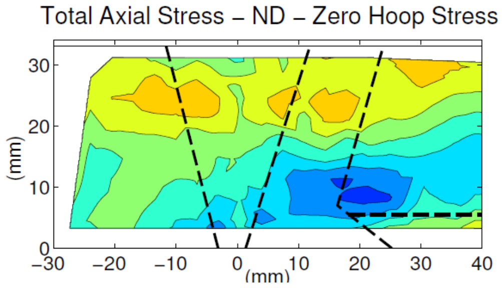
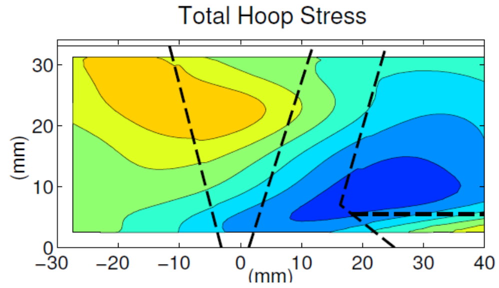
Residual Stress Measurements

- Where possible
  - Apply related methods (e.g., triaxial stress mapping)
  - Benchmark measurement techniques
  - Leverage through cooperative program

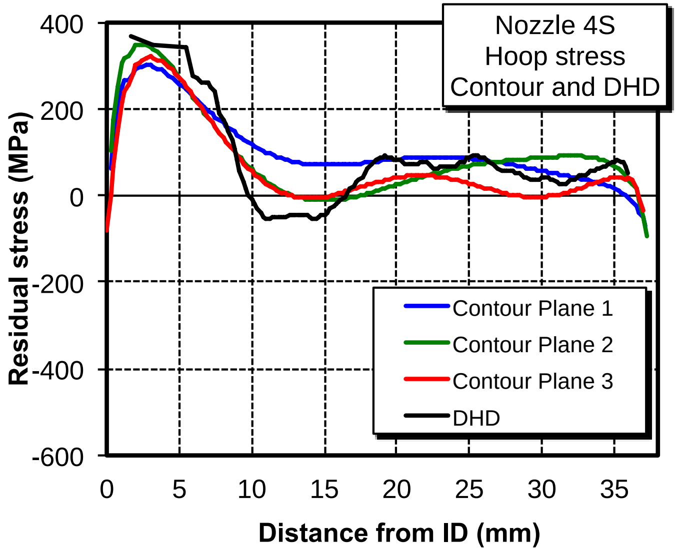
Triaxial Stress Maps in Phase III Nozzle 2



Axial Stress



Hoop Stress



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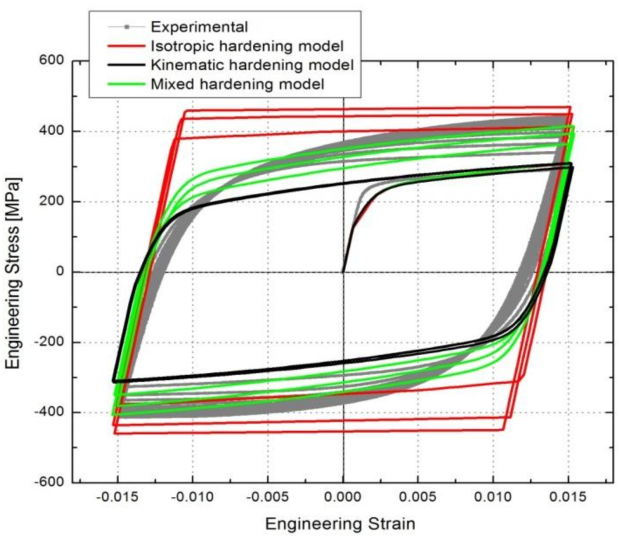
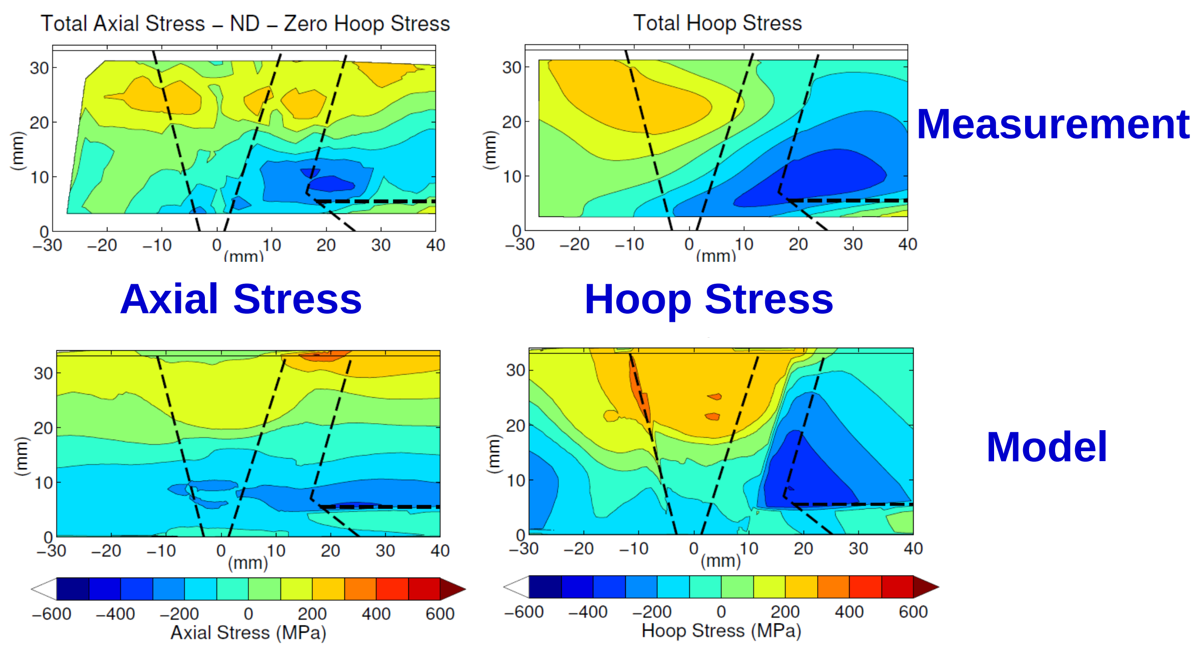
Improve Measurement to Model Agreement

- Work to close gap between measurements and models
  - Use full-field residual stress measurement data for
  - Improvements in weld material models





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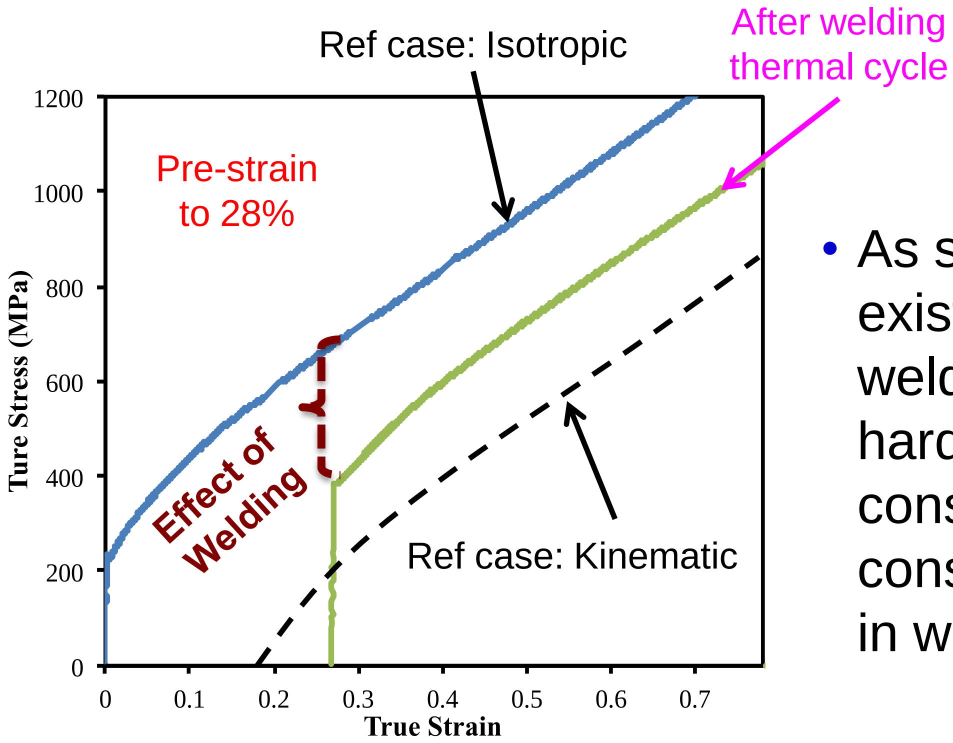
Possible Future R&D Areas

Considerations for R&D to Improve Models and Reduce Uncertainty

1. Gleeble experiments for improving strain hardening relations
2. Studies on transition zone between carbon steel and nickel alloy in DMWs
3. 3D modeling of repair weld scenarios
4. Surface measurements R&D for improving models and reducing uncertainty

Gleeble Experiments for Improving Strain Hardening Laws - Background

- For austenitic stainless steels and nickel-base superalloys exhibiting strong work hardening, the dynamic recovery of dislocation can occur rapidly at evaluated temperatures.



- As shown in the right figure, there exists a significant influence of welding thermal cycle on the strain hardening behavior that is not considered in the rate-independent constitutive relations commonly used in weld residual stress modeling.

Extending Materials and Testing Conditions for Strain Hardening Relations

- Development of a comprehensive knowledge and material property database:
  - 304L SS (ongoing) and possibly another heat of 304L SS for assessing the heat-to-heat variability
  - Alloys 82 / 182
  - Weld metal comprising different mixtures between 304L SS and Alloy 82
  - Wider temperature and cooling rate ranges
  - Other relevant materials: Alloys 152, 316L SS, etc.
- Implementation of strain hardening relations including dynamic recovery in the form of user materials

Transition Zone between Carbon Steel and Nickel Alloy in DMWs

- The structural carbon steel side of the dissimilar metal weld involves complex microstructural changes that have yet been adequately considered in the current WRS modeling practice.
- The objective of this task is to determine the microstructural changes and their special distribution, and devise an effective modeling approach to include such complex microstructural changes in the WRS model.

Carbon Steels

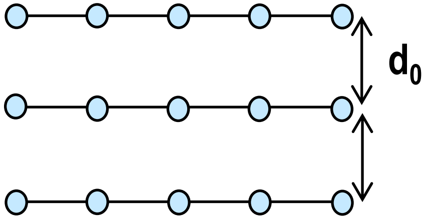
- Characterize the microstructure at the interface between the carbon steel and the nickel alloy to identify the new phases and microstructures in this transition zone as a function of the position.
- Determine the local property (tensile strength) variation in the transition zone by automated indentation test (i.e., micro-hardness mapping).
- Investigate the phase transformation kinetics in the transition zone using Gleeble and/or other techniques such as in-situ neutron/synchrotron diffraction.
- Formulate an effective strategy for predicting the phase transformation in DM welds (carbon steel side) and its influence on weld residual stresses.

3D Modeling of Repair Weld Scenarios

- 3D model necessary to address the deficiency of current 2D model especially for repair welds, and the weld start and stop effect.
- Addressing computational expensive issue in 3D modeling:
  - Brute force with parallel computing
  - Effective and fast 3D modeling approach including computational fluid dynamics (CFD) weld pool model for the weld temperature distribution

Neutron Diffraction Measurements of WRS - Background

- One of the most widely used experimental techniques for determining through-thickness residual stresses.
- Advantages:
  - Direct, precise measurement of elastic strains
  - Can be non-destructive
- Unique challenge in DM weld:
  - Difficulty in reliably determining the stress-free lattice spacing (d_0), a prerequisite for calculating residual stresses

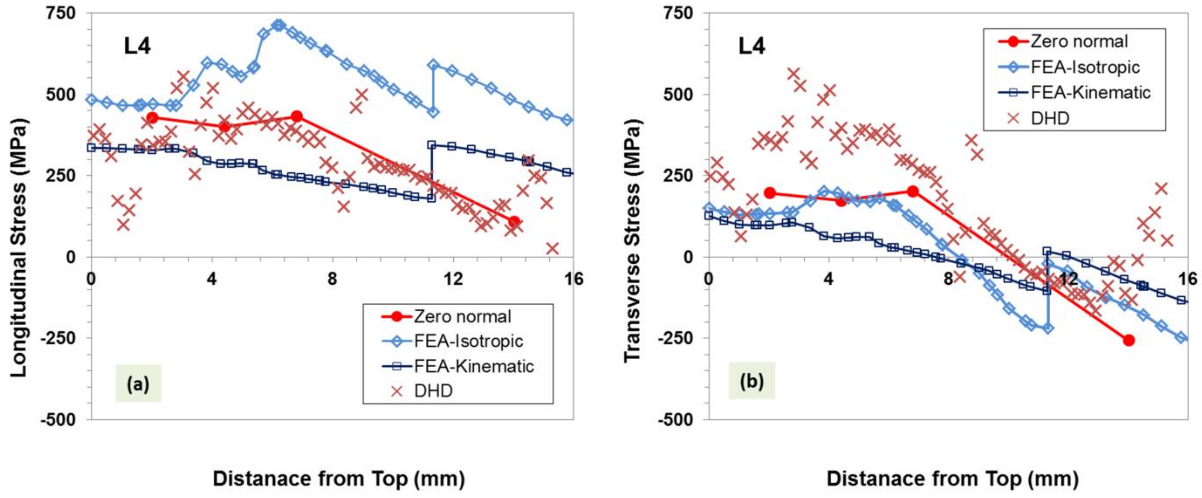


$$\varepsilon_{hkl} = \frac{d_{hkl} - d_0}{d_0}$$

No residual stress

Eliminating d_0

- Built on the previous work of two d_0-less methods:
  - Plane-stress condition for thin plates and pipes
  - Low bound check for the flow (von Mises) stress



Thanks to Dr. Dave Rudland at U.S. NRC for FEA results and Prof. Dave Smith at University of Bristol, UK, for deep-hole drilling data.

- New task aiming at developing a new d_0-less method for thick pipe DM welds

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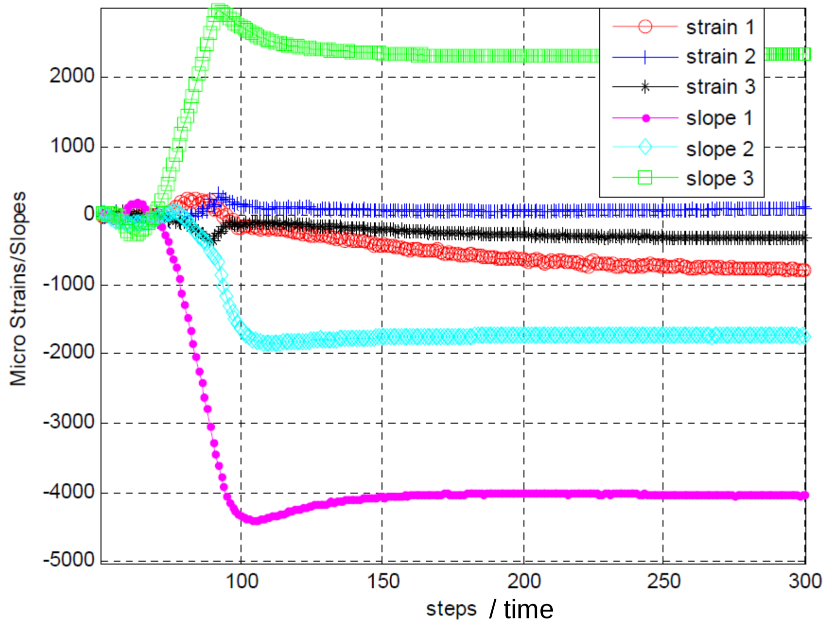
Surface Measurements R&D for Improving Models and Reducing Uncertainty

- Current surface residual stress measurement techniques such as x-ray diffraction and incremental hole drilling are not effective or reliable for surface residual stress measurement as they are sensitive to surface conditions.
- ORNL will investigate and develop a new technique based on laser-interferometry to record the entire stress evolution history during welding (i.e. in-situ stress measurement), which would provide much more information for WRS model validation.



Preliminary work by ORNL showing in-plane strains can be directly measured in real-time during welding, which in turn, can be used to calculate the in-plane stresses.

Summary - Possible Additional R&D

Task	1st	2nd
Gleeble experiments for improving strain hardening relations	• Completion of 304L SS • Nickel alloys 82 / 182 • Weld metal	• Weld metal (cont'd) • Other materials
Transition zone between carbon steel and nickel alloy in DMWs	• Microstructure characterization • Local properties	• Phase transformation kinetics modeling
Considerations for 3D modeling of repair weld scenarios	• Brute force with parallel computing	• Effective and fast 3D modeling approach
Surface measurements R&D for improving models and reducing uncertainty		• In-situ surface strain and stress during welding using laser interferometry

Deliverables

Deliverables, Schedule and NRC Interactions
- Pressurizer surge mock-up

- Deliverables: Reports summarizing work scope and results
- Schedule:
  - 1Q 2012 – Measurements and define analysis round robin scope
  - 2Q/3Q 2012 – Compare results and measurements, work on profile compendium
  - 4Q 2012 – Summary technical report
- NRC Interactions:
  - Like previous WRS validation work, NRC-RES and EPRI will cooperate on measurements and modeling
  - Independent evaluation of common set of results data

Deliverables and NRC Interactions
- Additional 2012 activities

- Deliverables:
  – Gleeble experiments test report
  – Measurement articles and work plans
  – Measurements
  – Summary of results in technical reports
- Anticipated NRC Interactions:
  – Like previous WRS validation work, NRC-RES and EPRI cooperates on measurements and modeling
  – Independent evaluation of common set of results data

xLPR - Pilot, Version 2, WRS Validation, PWSCC Mitigation

David Rudland, U.S. NRC
Craig Harrington, EPRI

PWR Materials Reliability and Weld Repair Research Meetings
January 25, 2012

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Outline

- xLPR Program Background and Need
- xLPR Pilot Study Summary
- xLPR Version 2.0 Plans and Schedule
- WRS and Mitigation in xLPR

GDC-4 and LBB

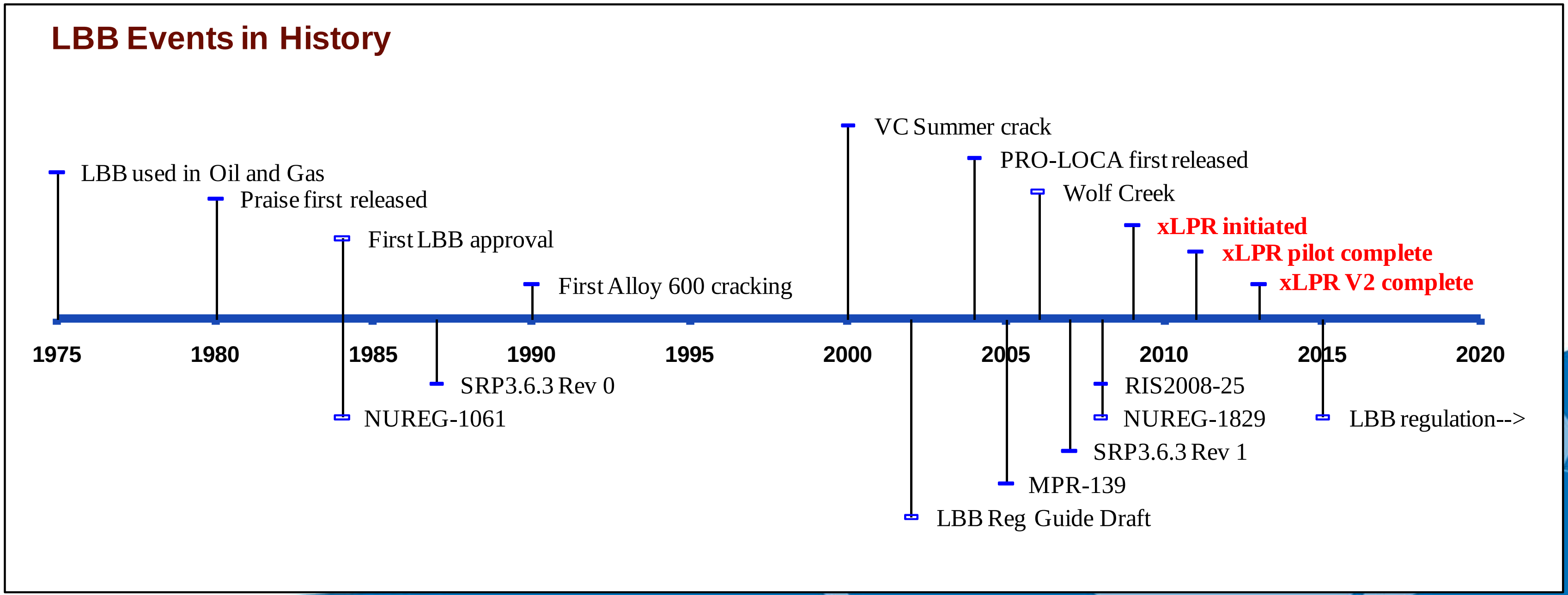
- 10CFR50 Appendix A GDC-4 allows local dynamic effects of pipe ruptures to be excluded from design basis if pipe ruptures have extremely low probability of occurrence

- Local dynamic effects include pipe whipping and discharging fluids. Effect is to eliminate need for whip restraints

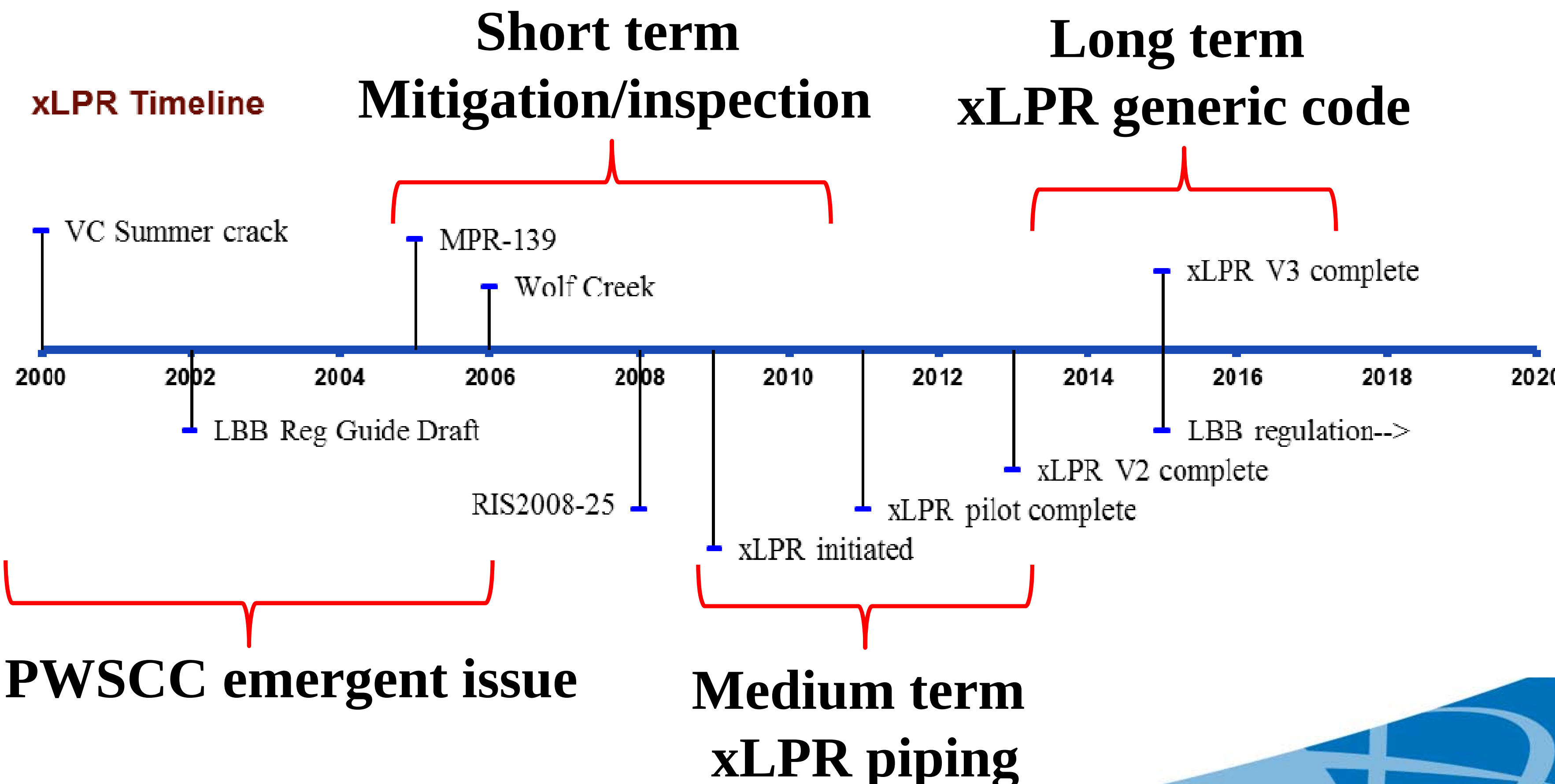
- Conservative flaw tolerance analyses developed and incorporated in SRP3.6.3 to demonstrate leak-before-break and satisfy GDC-4

LBB Historical Review

- PWRs have LBB approvals for reactor coolant loop (RCL) piping
  - Some PWRs have LBB for RCL branch piping
- SRP 3.6.3 stipulates no active degradation. PWSCC is active in LBB approved lines
- Qualitative: mitigations and inspections – **Short Term**
- Quantitative: probabilistic evaluation – **Long Term**



xLPR Timeline

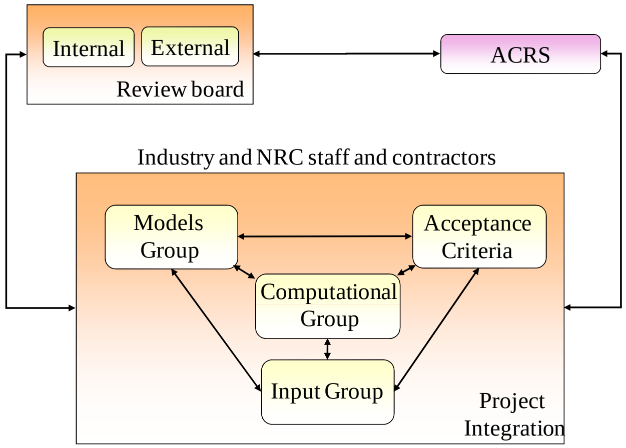


Longer Term

- Develop a ***probabilistic*** assessment tool that can be used to ***directly*** assess compliance with 10CFR50App-A GDC-4
- Tool will be
  - **Comprehensive** with respect to known challenges and loadings
  - **Vetted** with respect to scientific adequacy of models and inputs
  - **Flexible** to permit analysis of a variety of in service situations
  - **Adaptable** – able to accommodate
    - evolving / improving knowledge
    - new damage mechanisms

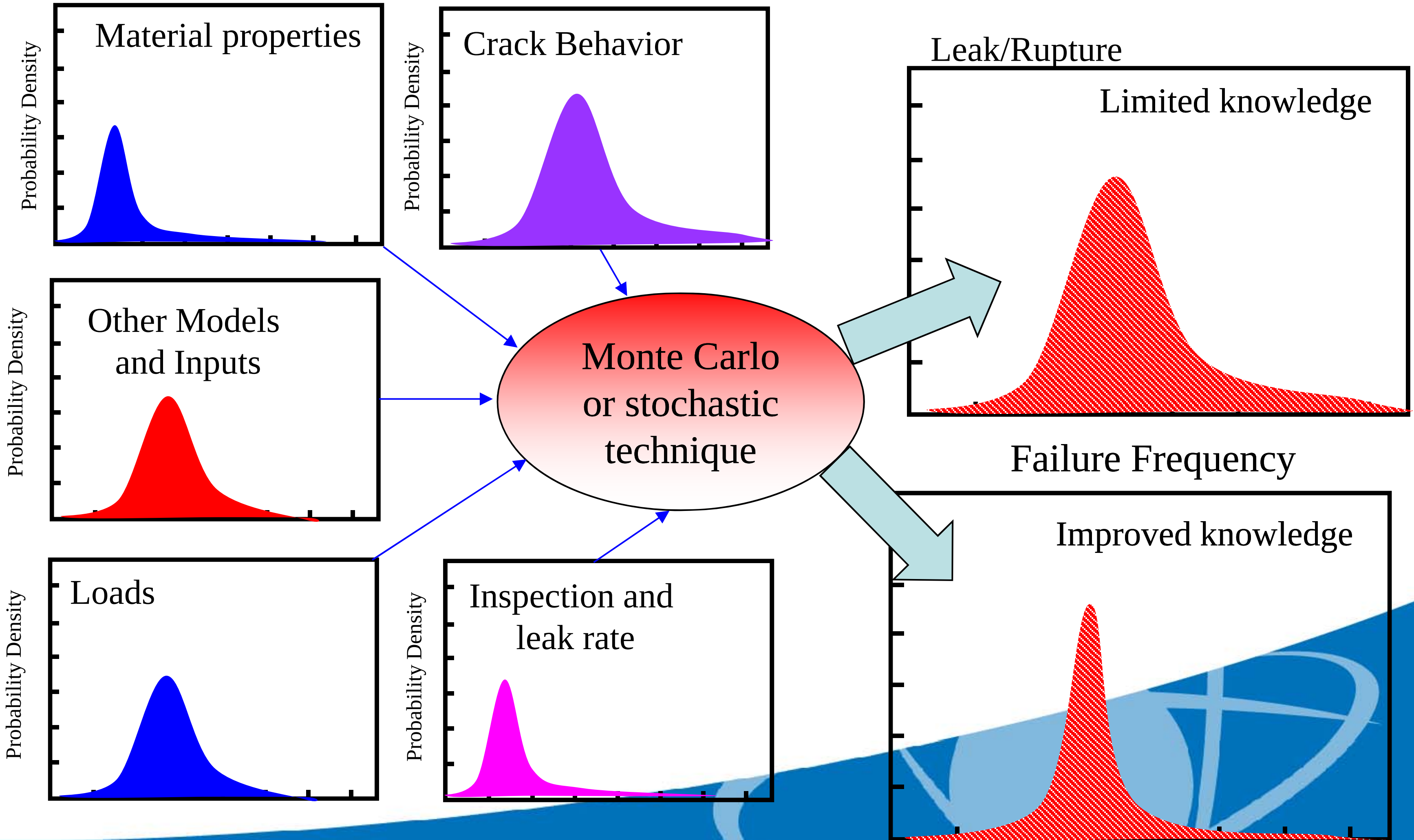
xLPR Development

- NRC goal to develop "modular" code for evaluating the risk of pressure boundary integrity failure
- Currently focusing on piping issues
  - LBB
  - <u>May be applicable to other needs</u>
- Working cooperatively with EPRI through MOU addendum



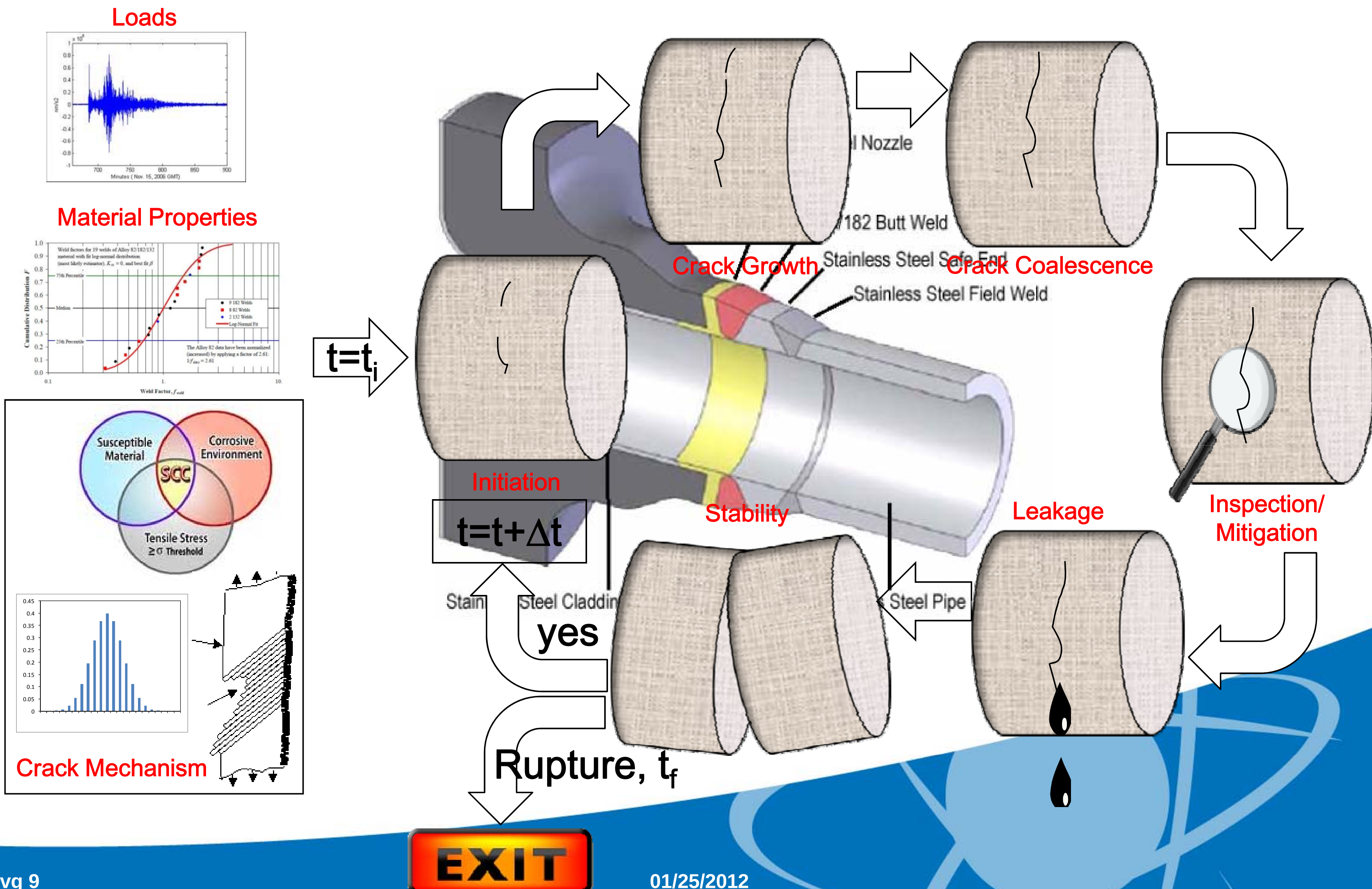
- Initial pilot study to assess effectiveness of approach

PFM Process



Material properties
Probability Density
Crack Behavior
Probability Density
Other Models
and Inputs
Probability Density
Loads
Probability Density
Inspection and
leak rate
Probability Density
Monte Carlo
or stochastic
technique
Leak/Rupture
Limited knowledge
Failure Frequency
Improved knowledge

PFM Technical Flow



Using xLPR

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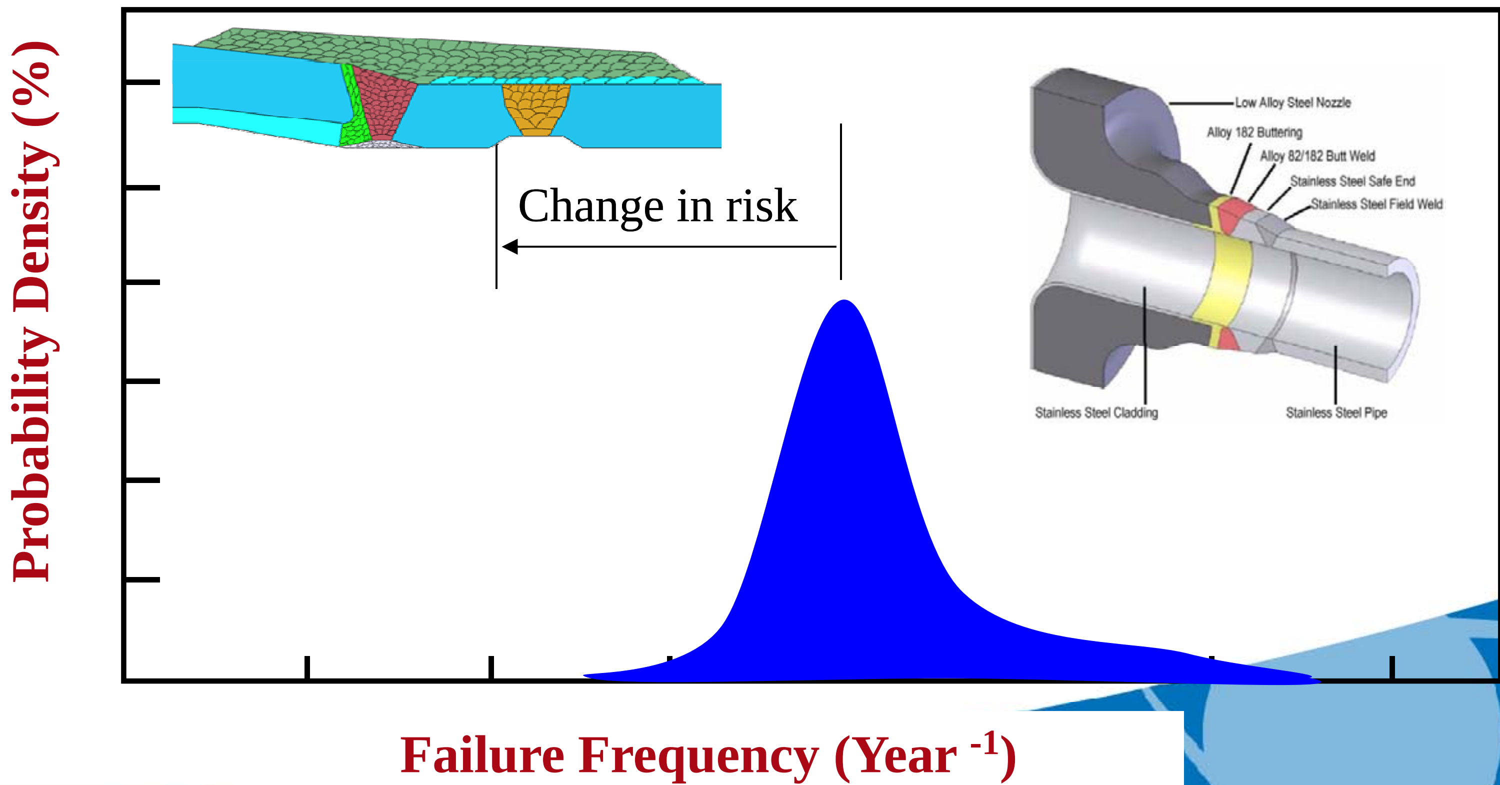
Conduct analyses with typical parameters

Conduct analyses with typical parameters and overlay



Team Members

Computational Group
David Rudland – U.S. NRC
Bruce Bishop – Westinghouse
Nathan Palm – Westinghouse
Patrick Mattie – Sandia National Laboratories
Cedric Sallaberry – Sandia National Laboratories
Don Kalinich – Sandia National Laboratories
Jon Helton – Sandia National Laboratories
Hilda Klasky – Oak Ridge National Laboratory
Paul Williams – Oak Ridge National Laboratory
Robert Kurth – Emc^2
Scott Sanborn – Pacific Northwest National Laboratory
David Harris – Structural Integrity Associates
Dilip Dedhia – Structural Integrity Associates
Anitha Gubbi – Structural Integrity Associates

Inputs Group
Eric Focht – U.S. NRC
Mark Kirk – U.S. NRC
Guy DeBoo – Exelon
Paul Scott – Battelle
Ashok Nana – AREVA NP Inc.
John Broussard – Dominion Engineering
Nathan Palm – Westinghouse
Pat Heasler – Pacific Northwest National Laboratory
Gery Wilkowski – Emc^2

Acceptance Group
Mark Kirk – U.S. NRC
Glenn White – Dominion Engineering Inc.
Aladar Csontos – U.S. NRC
Robert Hardies – U.S. NRC
David Rudland – U.S. NRC
Bruce Bishop – Westinghouse
Robert Tregoning – U.S. NRC

Models Group
Marjorie Erickson – PEAI
Gary Stevens – U.S. NRC
Howard Rathbun – U.S. NRC
David Rudland – U.S. NRC
John Broussard – Dominion Engineering
Glenn White – Dominion Engineering
Do-Jun Shim – Emc^2
Gery Wilkowski – Emc^2
Bud Brust – Emc^2
Cliff Lange – Structural Integrity Associates
Dave Harris – Structural Integrity Associates
Steve Fyfitch – AREVA NP Inc.
Ashok Nana – AREVA NP Inc.
Rick Olson – Battelle
Darrell Paul – Battelle
Lee Fredette – Battelle
Craig Harrington – EPRI
Gabriel Ilevbare – EPRI
Frank Ammirato – EPRI
Patrick Heasler – Pacific Northwest National Laboratory
Bruce Bishop – Westinghouse

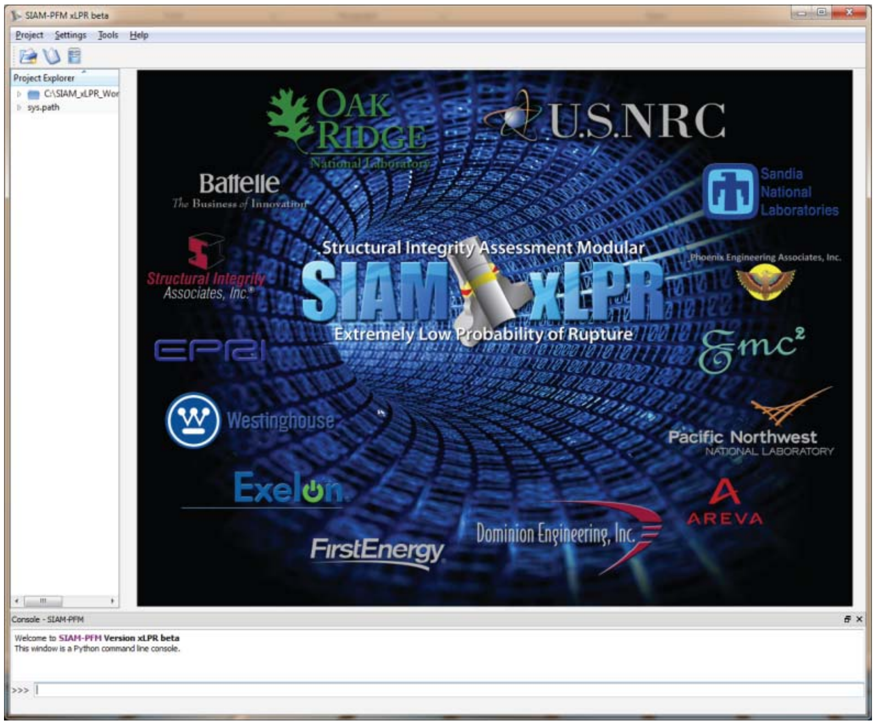
Program Integration Board
Craig Harrington – EPRI
Aladar Csontos – U.S. NRC
Robert Hardies – U.S. NRC
Denny Weakland - Ironwood Consulting
David Rudland – U.S. NRC
Bruce Bishop – Westinghouse
Eric Focht – U.S. NRC
Guy DeBoo – Exelon
Marjorie Erickson – PEAI
Gary Stevens – U.S. NRC
Howard Rathbun – U.S. NRC
Mark Kirk – U.S. NRC
Glenn White – Dominion Engineering Inc.

xLPR Pilot Study

- Pilot study objectives
  - Develop and assess xLPR management structure
  - Determine the appropriate probabilistic framework
  - Assess the feasibility of developing a modular-based probabilistic fracture mechanics computer code
- Focused on pressurizer surge nozzle DM weld with PWSCC
- Development of Version 1.0 code using comprehensive configuration management
- Developed detailed program plan (objective, schedule, deliverables, budget, communications) for Version 1.0 and Version 2.0 code

xLPR Version 1.0 Framework

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment



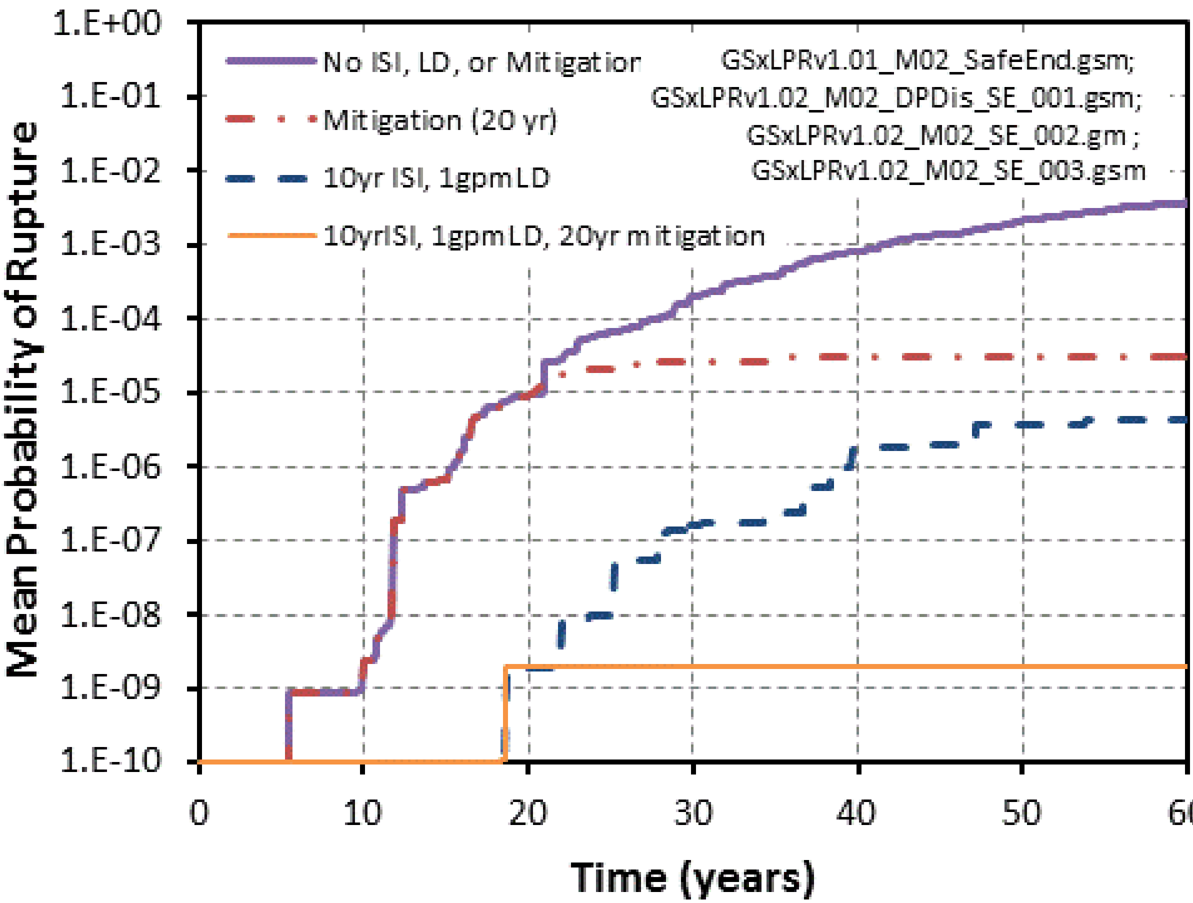
Fully Open Source

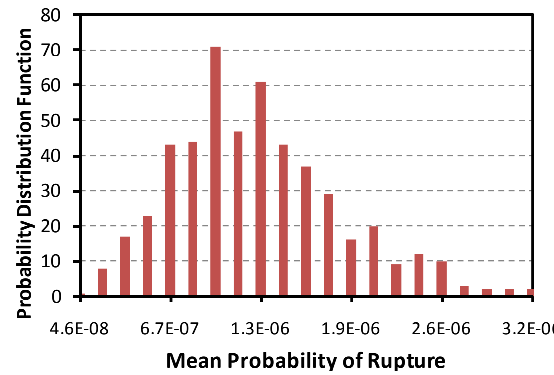
GoldSim Commercial Code

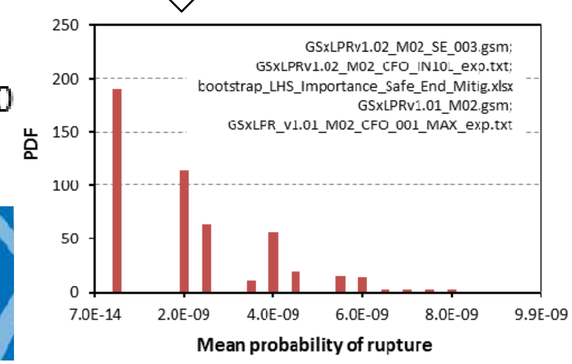
Two framework structures considered
Same calculation modules used
Both gave similar results

xLPR Code Feasibility

Westinghouse-type pressurizer surge nozzle dissimilar metal weld







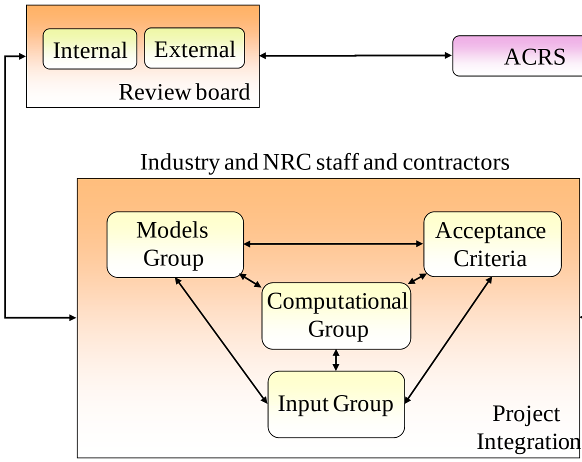
Pilot Study Results

- The project team demonstrated that **<u>it is feasible</u>** to develop a modular-based probabilistic fracture mechanics code within a cooperative agreement while properly accounting for the problem uncertainties

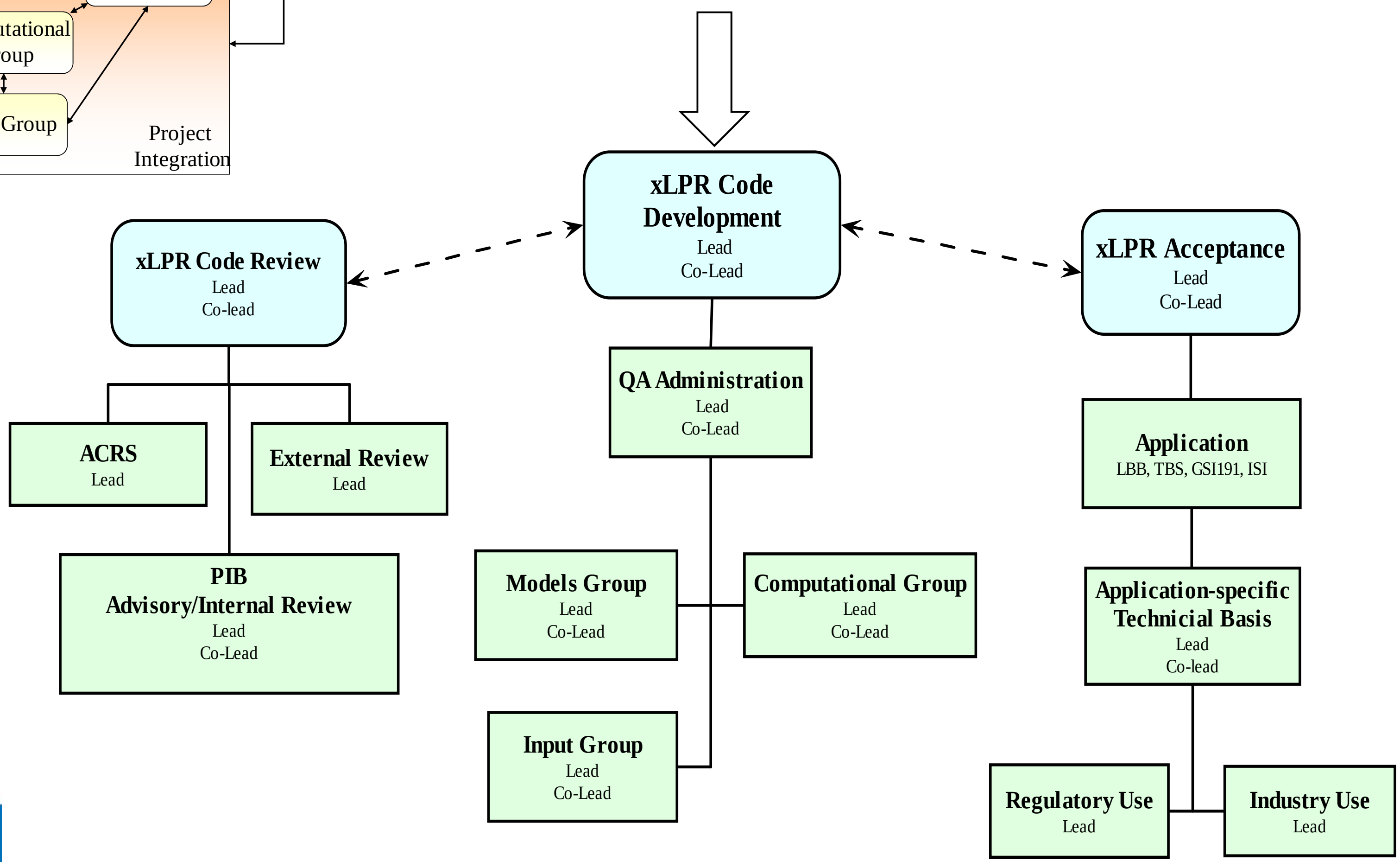
- Identified potential efficiency gains in the program management structure

- Selected commercial software as the computational framework

xLPR Management



Pilot study structure circular in nature
Project Integration Board too large
Reorganization required



xLPR Version 2.0 Scope

- xLPR Version 1.0 was developed as part of a feasibility study and focuses on PWSCC in a Westinghouse-style pressurizer surge nozzle DM weld
- Version 2.0 is being expanded to handle welds within piping systems approved for LBB
- Capabilities of Version 2.0 will meet requirements for LBB lines, but <u>must stay</u> within available cost and schedule limitations
- The lessons learned from the pilot study provided many areas where improvement was needed

Version 2.0 Scope

- Pilot study demonstrated several shortcomings in Version 1.0 scope

- xLPR Groups have developed work plans that selected scope recommendations that fit within available resources and overall xLPR timeframe – Scope decided by majority vote of team leads and PIB

- Model inclusion in xLPR Version 2.0 does not guarantee regulatory approval. Process for obtaining approval of xLPR models is under discussion

Version 2.0 Scope Modifications

- Framework
  - Investigate advanced methodologies to improve sampling efficiency and solution accuracy
  - Revisit uncertainty propagation methodology
  - Modify code output structure
  - Update post processing
  - Modify GoldSim for additional user capability
- Models
  - Revisit PWSCC initiation – Expert panel
  - Update WRS model – more generic, better uncertainty
    - Weld repairs
  - Update K-solution to be consistent with updated WRS model

Red font represents high priority items

Version 2.0 Scope Modifications

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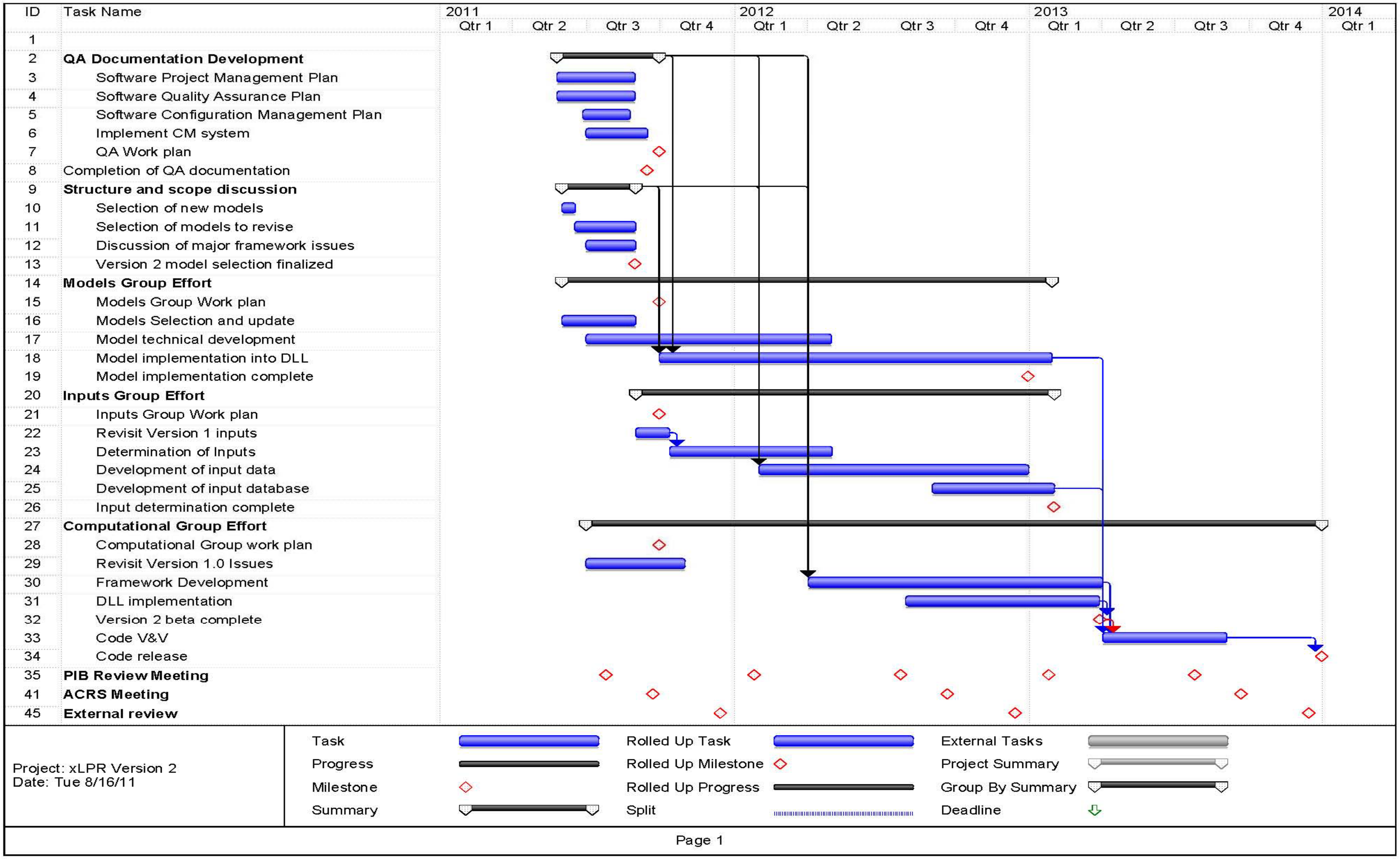
- Models
  - Update mitigation to include FSWOL,OWOL, Inlay, surface treatment, and other chemistry
  - Update ISI model – sizing, POD, simplified model
  - Update crack stability – Surface crack EPFM
  - Update leak rate model –SQuIRT, bound leak rate calc
  - Update COD tension and bending blended solution.
- Inputs
  - Update load definition to include transients
  - Retrieve all relevant data for
    - One reactor coolant loop - Westinghouse PWR
    - One reactor coolant loop - Babcock & Wilcox (B&W) PWR
    - Others may be considered

Version 2.0 Scope Additions

- Framework
  - Microsoft Access dB for inputs
- Models
  - Environmental fatigue
  - Axial cracks
  - IGSCC
  - Surface crack-to-through wall crack transition
  - Manufacturing defects

Version 2.0 Schedule



WRS and Mitigation in xLPR

WRS in Version 1.0

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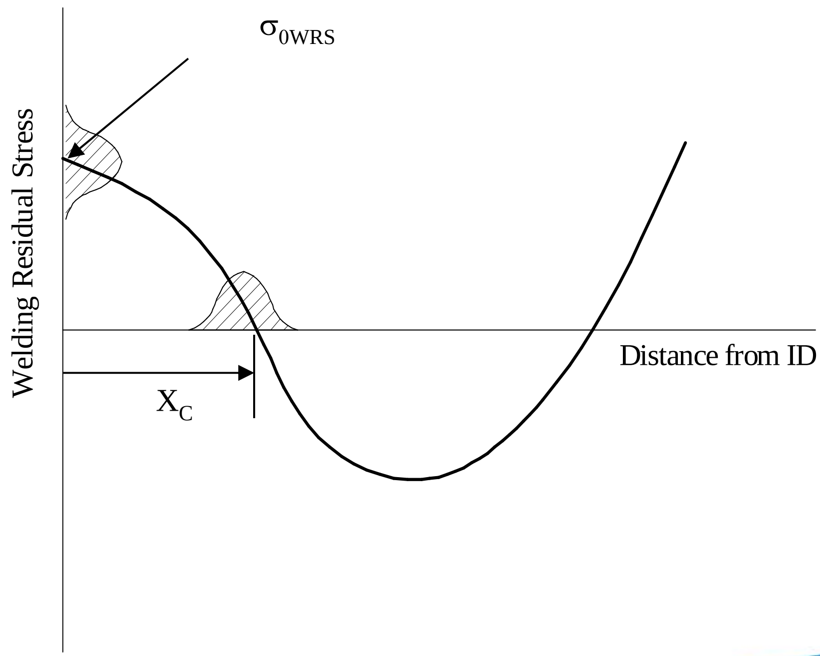
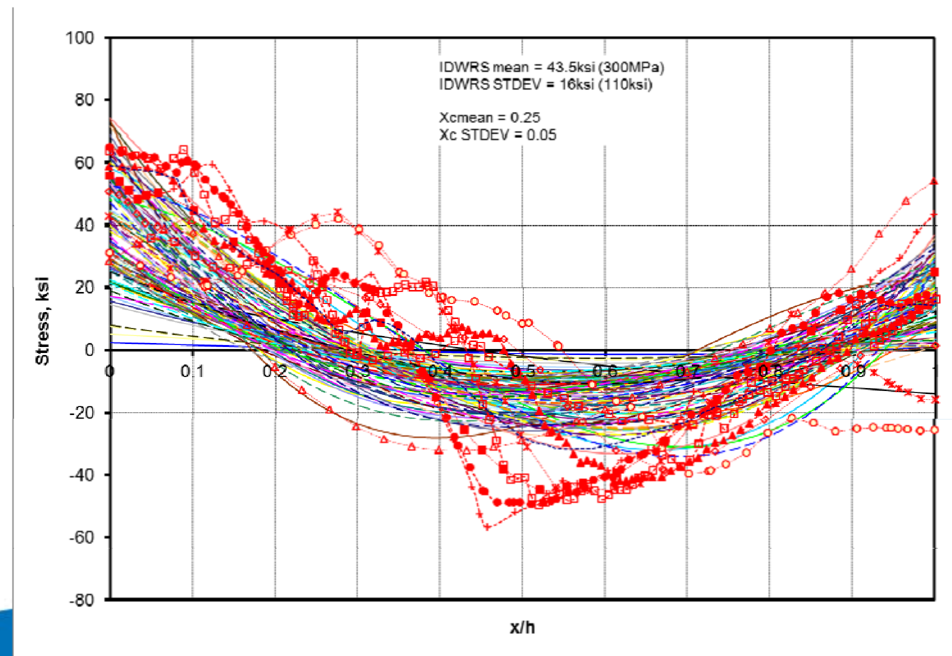
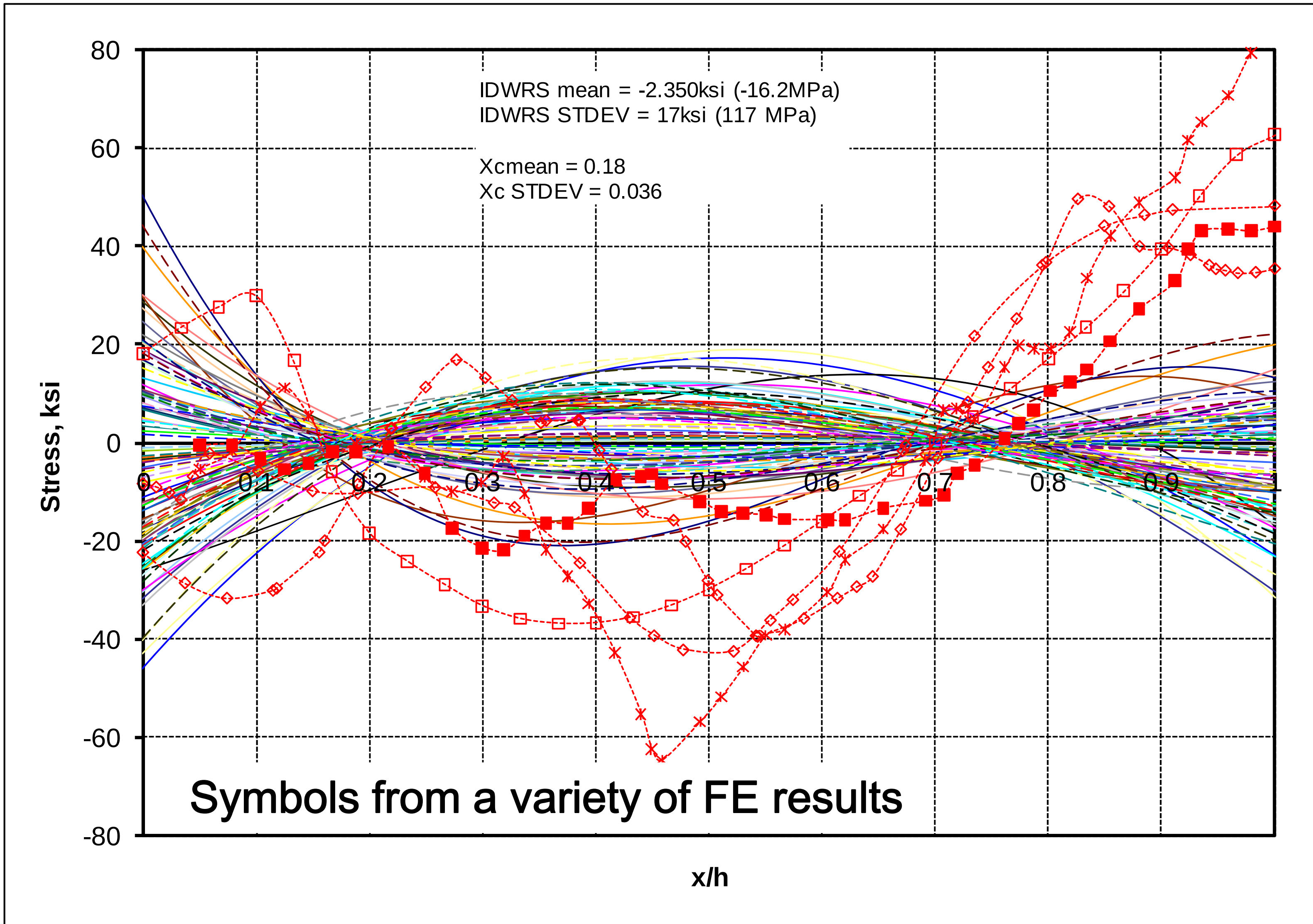
- The weld residual stress is assumed to be a 3rd order polynomial with uncertainty in ID WRS and distance when stress passes through zero

$$\sigma_{WRS} = \sigma_{oWRS} + \sigma_{1WRS}\left[\frac{x}{t}\right] + \sigma_{2WRS}\left[\frac{x}{t}\right]^2 + \sigma_{3WRS}\left[\frac{x}{t}\right]^3$$





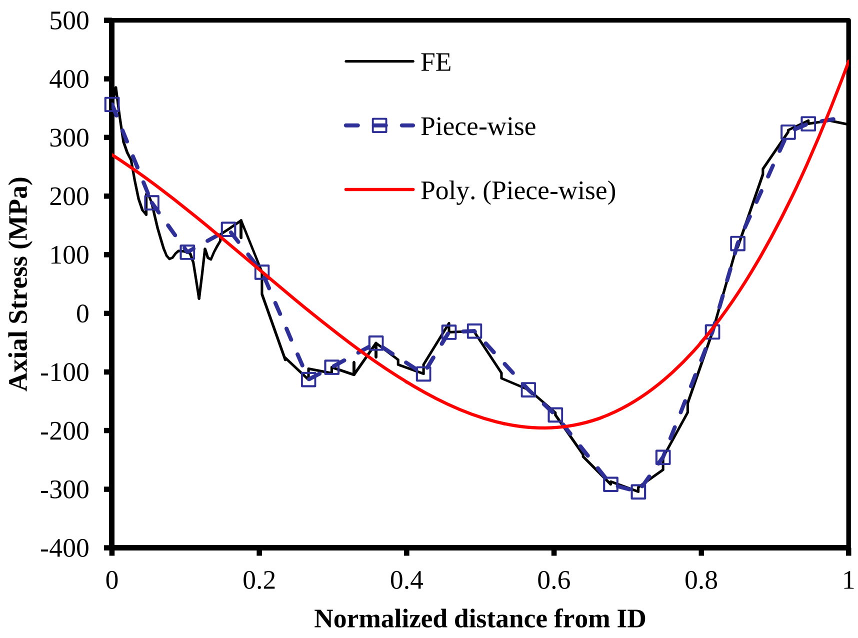
Version 1.0 WRS Issue



WRS in Version 2.0

- Issues with assuming a polynomial WRS distribution lead xLPR team to consider piece-wise linear representation
- Universal Weight Function Method will be used for K-solutions to be consistent with piece-wise WRS approximation

Mean Stress (Mpa)	Distance from ID x/t
σ_1	0
σ_2	0.05
σ_3	0.1
σ_4	0.15
σ_5	0.2
σ_6	0.25
σ_7	0.3
σ_8	0.35
σ_9	0.4
σ_{10}	0.45
σ_{11}	0.5
σ_{12}	0.55
σ_{13}	0.6
σ_{14}	0.65
σ_{15}	0.7
σ_{16}	0.75
σ_{17}	0.8
σ_{18}	0.85
σ_{19}	0.9
σ_{20}	0.95
σ_{21}	1



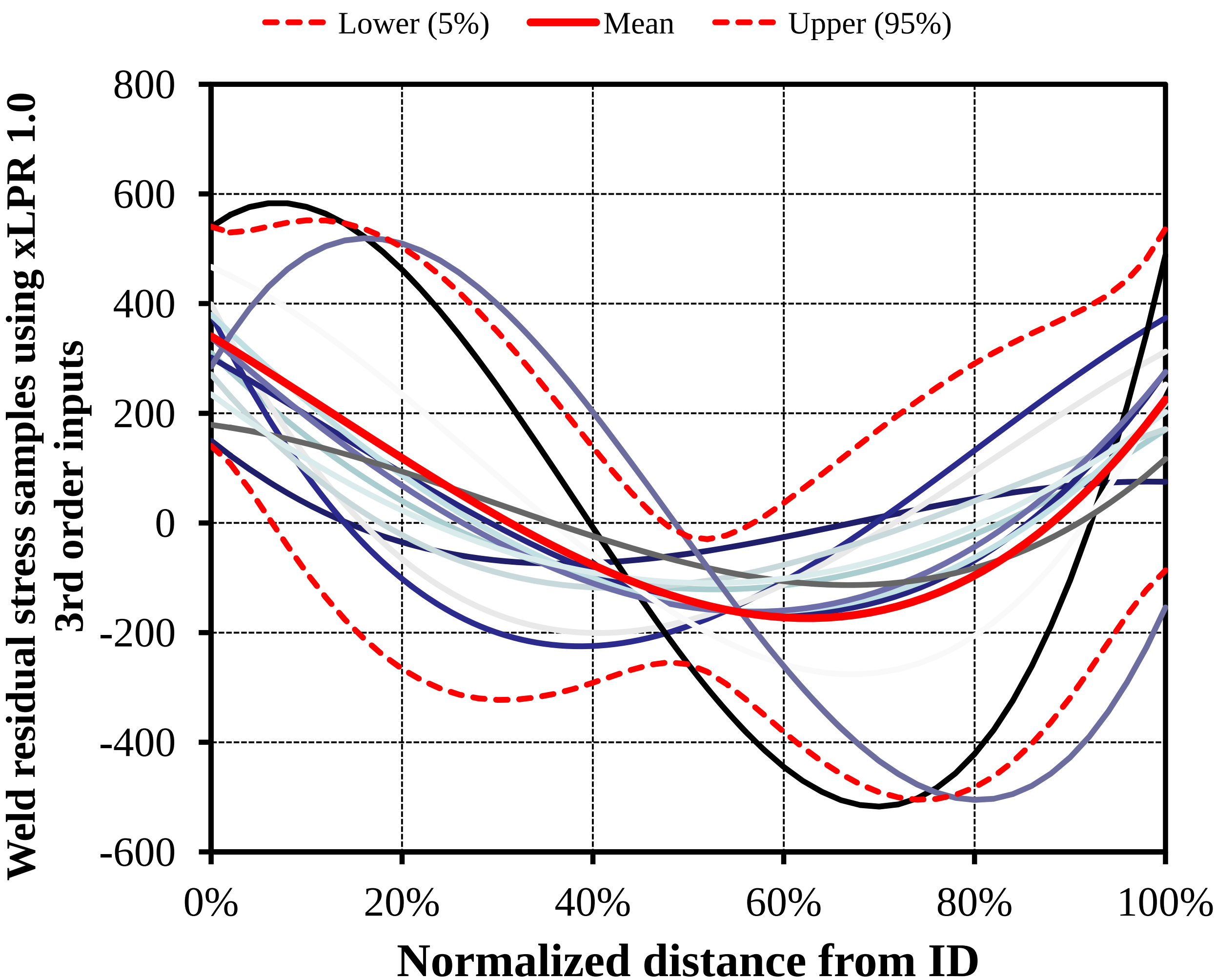
WRS in Version 2.0

- FE analyses will be conducted to develop WRS database of solutions
- Solutions will be benchmarked against mock-up solutions
- Both Model and Parameter uncertainty will be developed from these analyses
- Sampling scheme required

No.	Nozzle Type	Before Stainless Steel Weld			After Stainless Steel Weld		
		Repair Depth (% thickness)			Repair Depth (% thickness)		
		0	15	50	0	15	50
1	Surge (mock-up)	X			X		
2	Surge	X	X	X	X	X	X
3	Hot leg	X	X	X	X	X	X
4	B&W plant surge line nozzle at hot leg end. This nozzle has a 10" ID	X	X	X			
5	CE plant reactor coolant pump inlet or outlet nozzle. This nozzle has a 28" ID	X	X	X			

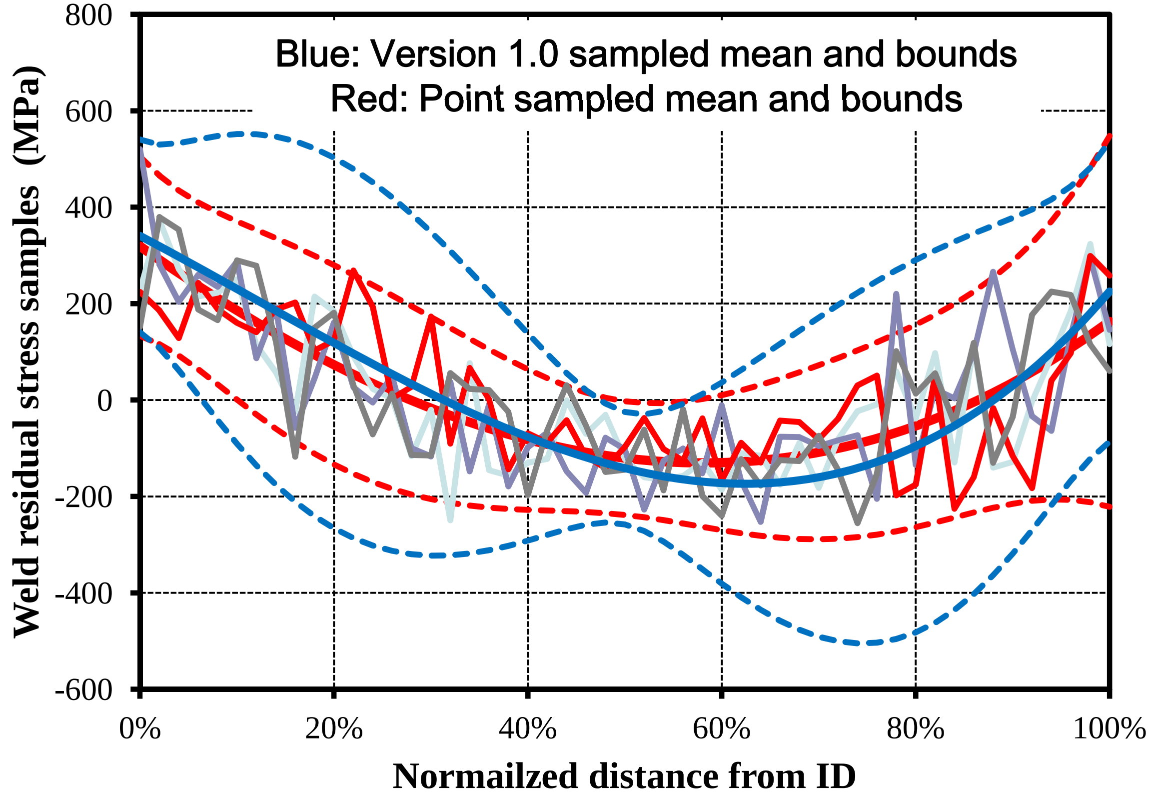
- Welds, 360 deg and partial arc repairs and mitigations will be considered

WRS example



- Version 1.0 samples from distribution similar to surge nozzle mock-up
- Point-by-point samples can be taken from this distribution

WRS – Version 2.0



- Sampled from Version 1 example
- Demonstrates
  - Calculation of point by point variability in the WRS samples
  - Sampling from the uncertainty at each point
  - Constructing the WRS sample based on these **independently** sampled points

Work is still needed to correlate samples to avoid irregular behavior

Mitigation in Version 1.0

- Mechanical mitigation is a pre-emptive mitigation which is defined by a change in the WRS at a fixed time (MSIP)

- This change in WRS affected the crack initiation and crack growth rates

- Placeholders for mitigation by zinc and hydrogen are included. Hydrogen mitigation for crack growth per MRP-263 was implemented. Zinc models were not implemented

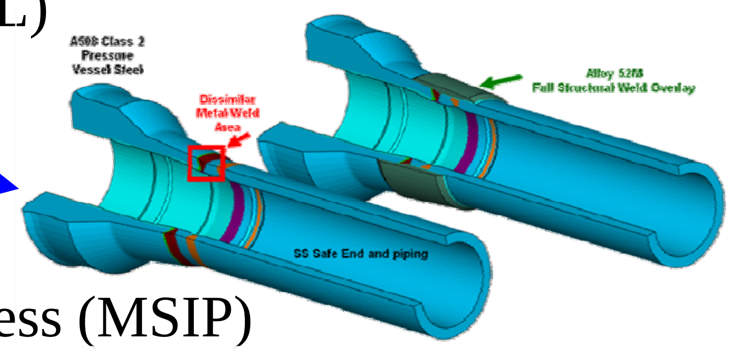
Version 2.0 Mitigation

- For xLPR Version 2.0 the effect of a variety of mitigations techniques will be implemented in a realistic fashion

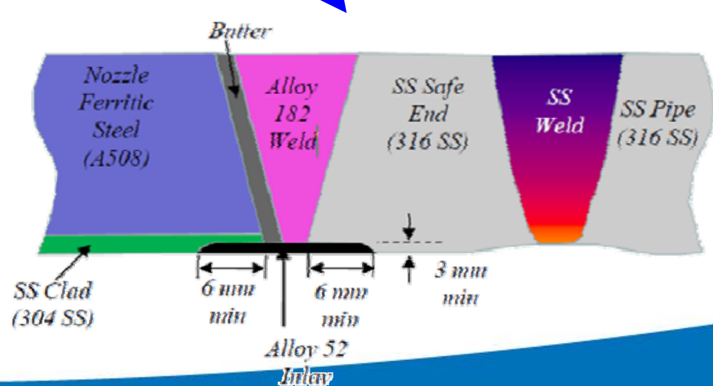
- The xLPR team has developed a whitepaper to provide a high level description of mitigation techniques and how they will be incorporated into the code

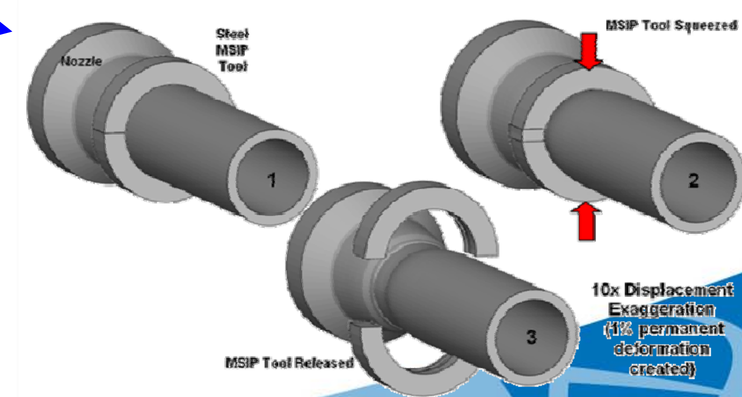
Version 2.0 Mitigation Plan

- Stress and Material Mitigations
  - Full Structural Weld Overlay (FSWOL)
  - Optimized Weld Overlay (OWOL)



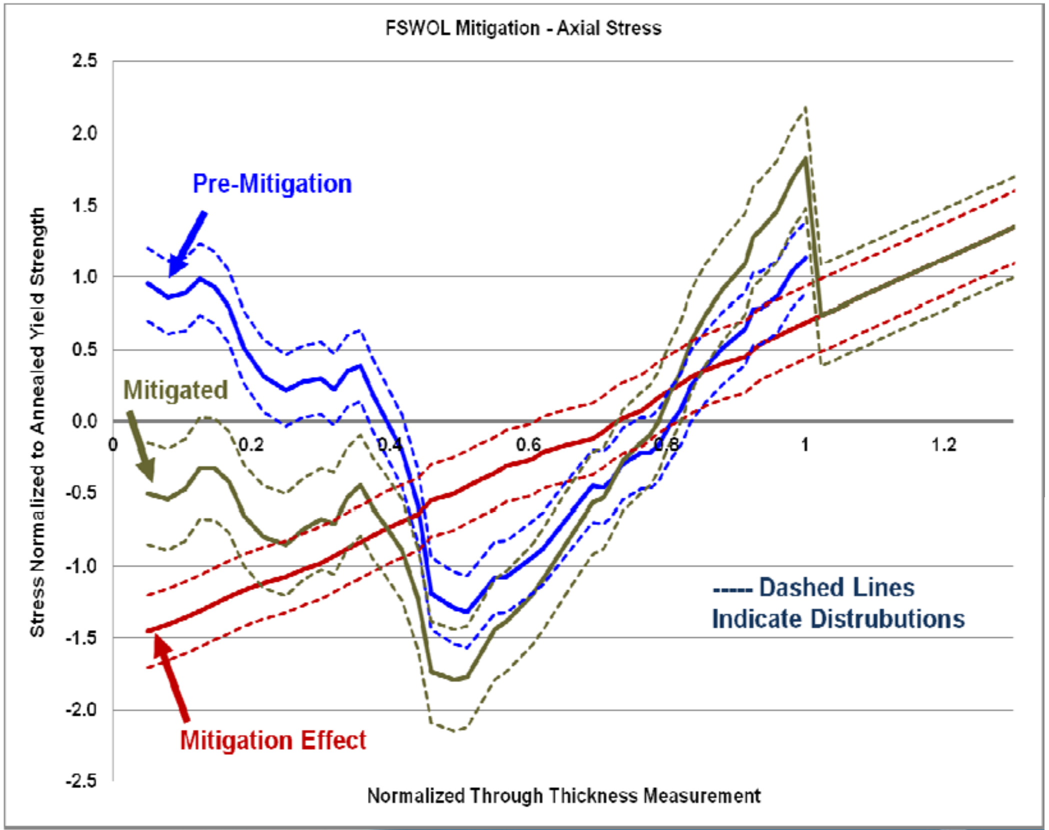
  - Mechanical Stress Improvement Process (MSIP)
  - Inlay/Onlay





Version 2.0 Mitigation Plan

- Stress-based and material replacement mitigation
  - Incorporation of a mitigation effect with a statistical distribution to the pre-mitigated stress profile.



Axial stress concept example

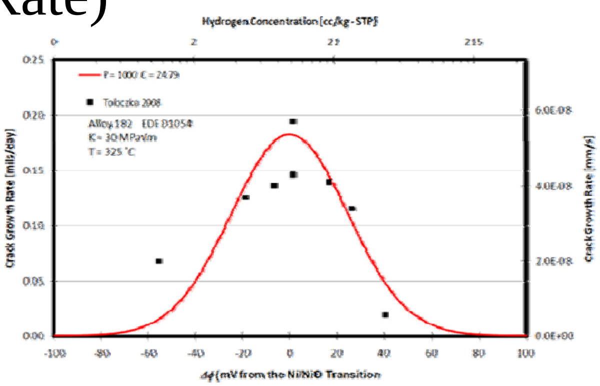
Pre-Mitigation + Mitigation Effect = Mitigated Profile

Profiles and distribution to be determined

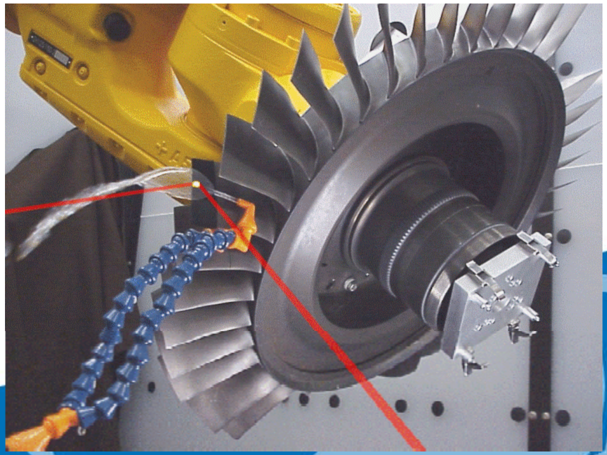
- **Stress field modified**
- **Strength/toughness modified**
- **Initiation and growth rates modified**
- **Cracking mechanisms modified as needed**

Version 2.0 Mitigation Plan

- Chemical and Surface Stress Modification Techniques
  - Chemical Mitigation
    - Hydrogen Optimization (Crack Growth Rate)
    - Zinc Application (Initiation Delay)



  - Surface Stress Modification (Peening)
    - Water Jet Peening (WJP)
    - Fiber LASER Peening (FLP)



From LSP Technologies' website

Version 2.0 Mitigation Plan

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- Mitigation Incorporation – Chemical Mitigation
  - MRP-263 equations to be further improved for Version 2.0. – xLPR team has not reviewed technical basis
    - Output would be crack growth rate that varies with time and temperature over the plant life.
  - Zinc Application – xLPR team has not reviewed technical basis
    - Proposed equation to adjust the time of crack initiation based on the time of zinc addition.
    - Equation is currently based on data from steam generator and laboratory studies.
    - Time between zinc application and the predicted crack initiation modified by the zinc improvement caused by zinc.
    - Only applicable when the zinc addition occurs before the predicted initiation

Version 2.0 Mitigation Plan

- Mitigation Incorporation – Surface Stress Modification
  - At this point, no technical basis has been reviewed by xLPR team
  - May include:
    - Water Jet Peening (WJP)
    - Fiber LASER Peening (FLP)
  - May be a modification of through-wall stress distribution or a simple modification to initiation models

Mitigation Implementation

Mitigation Strategy		Models Group				Inputs Group		Comp Group
		WRS	ISI	Initiation*	Crack Growth	Analysis Specific Input	Loads Module	Framework
Mechanical	FSWOL/ OWOL	Tech basis to generate mitigated WRS profiles	Effect on POD	Surface stress from mitigated WRS	New material	Pipe geometry, material properties, mitigated WRS, ISI (POD, Inspection Interval)	Piping system loads (?)	WRS, ISI, Initiation, Crack Growth
Mechanical	MSIP	Tech basis to generate mitigated WRS profiles	Effect on POD	Surface stress from mitigated WRS		Mitigated WRS, ISI (Inspection Interval)		WRS, ISI, Initiation
Mechanical	Inlay/ Onlay	Tech basis to generate mitigated WRS profiles	Effect on POD	Surface stress from mitigated WRS	New material	Pipe geometry, material properties, mitigated WRS, initiation (if stress dependent), ISI (POD, Inspection Interval)		WRS, ISI, Initiation, Crack Growth
Mechanical	Surface Stress	Review tech basis for surface stress modifications (?)		Surface stress appropriate for surface stress modification		Surface stress, initiation (if stress dependent), ISI (Inspection Interval)		ISI, Initiation
Chemical	Hydrogen				H term in crack growth equation	Crack growth, ISI (Inspection Interval)		ISI, Crack Growth
Chemical	Zinc			Zn crack initiation equation		Initiation, ISI (Inspection Interval)		ISI, Initiation

Benefits of xLPR

- Quantified solution to LBB issue
  - Regulation guide
  - Update to SRP3.6.3
- Fully QA'ed modular probabilistic fracture mechanics code for reactor pressure boundary integrity
  - LBB including evaluation of mitigation for DM welds
  - Research tool for prioritization
  - TBS – 50.46a
  - Risk informed ISI
  - GSI 191
  - Easily adaptable to other applications
    - CRDM ejection probabilities
    - RPV

Path Forward

- Version 2.0 Development underway
- Ongoing meetings
  - ACRS meeting - March 2012 (yearly updates)
  - NRC and EPRI Management (as needed)
  - External reviews (annually)
  - Internal reviews (bi-annually)
- Version 2.0 release – End 2013
- Technical basis and Regulatory Guide for LBB - 2015

Finite Element Analysis of Weld Residual Stress

Efforts and Benchmarking

Francis H. Ku

January 24-26, 2012

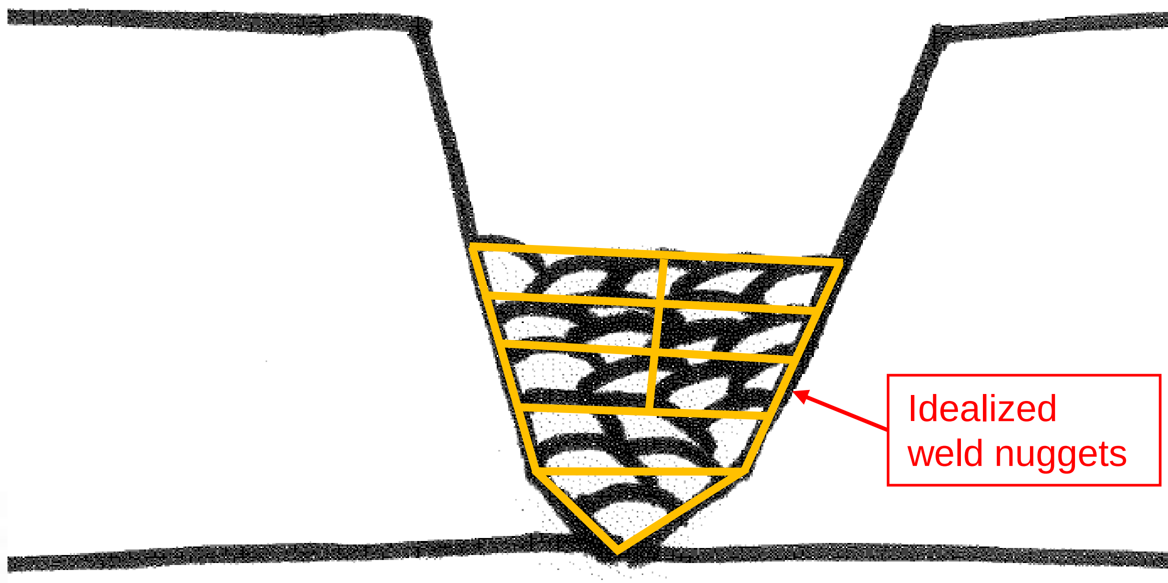
PWR Materials Reliability and Weld Repair Research Meeting, Charlotte, NC

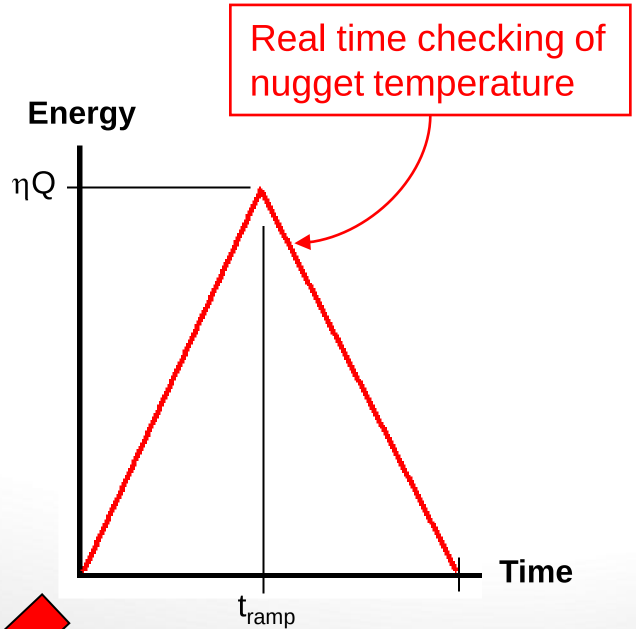
www.STRUCTINT.com
877-4SI-POWER

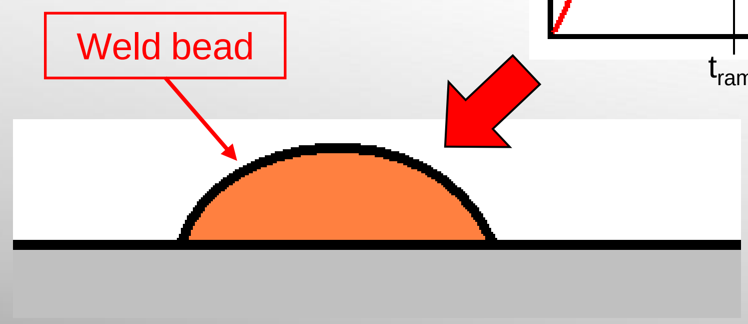
FEA Methodology Used at SI

- Using ANSYS Mechanical APDL
- Procedures are standard industry practice
- Decoupled Thermal and Stress analyses
- Thermal pass to calculate welding temperature history
- Weld bead deposition simulated via body heat generation
- Export temperature history to Stress pass
- Utilize large deformation option

Weld Bead Idealization and Deposition

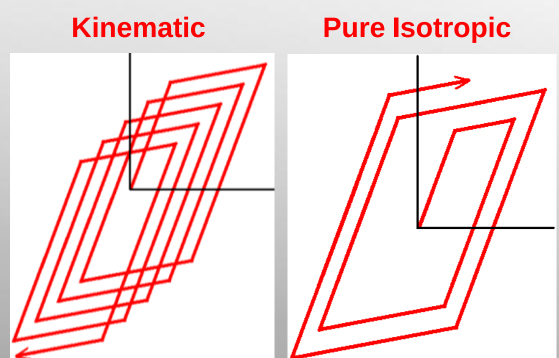






Modified SS Curve + Isotropic Hardening

- Kinematic hardening not suitable for large strain and high cycle load/unload WRS analyses due to premature shakedown
- Pure isotropic hardening causes too much expansion
- Modified stress-strain curve caps the maximum stress at flow stress: Sf = (Sy+Su)/2
- Balances isotropic hardening model for WRS analyses
- Avoids early shakedown while limiting over expansion
- Faster and more stable solution convergence
- Results in similar behavior to mixed mode hardening

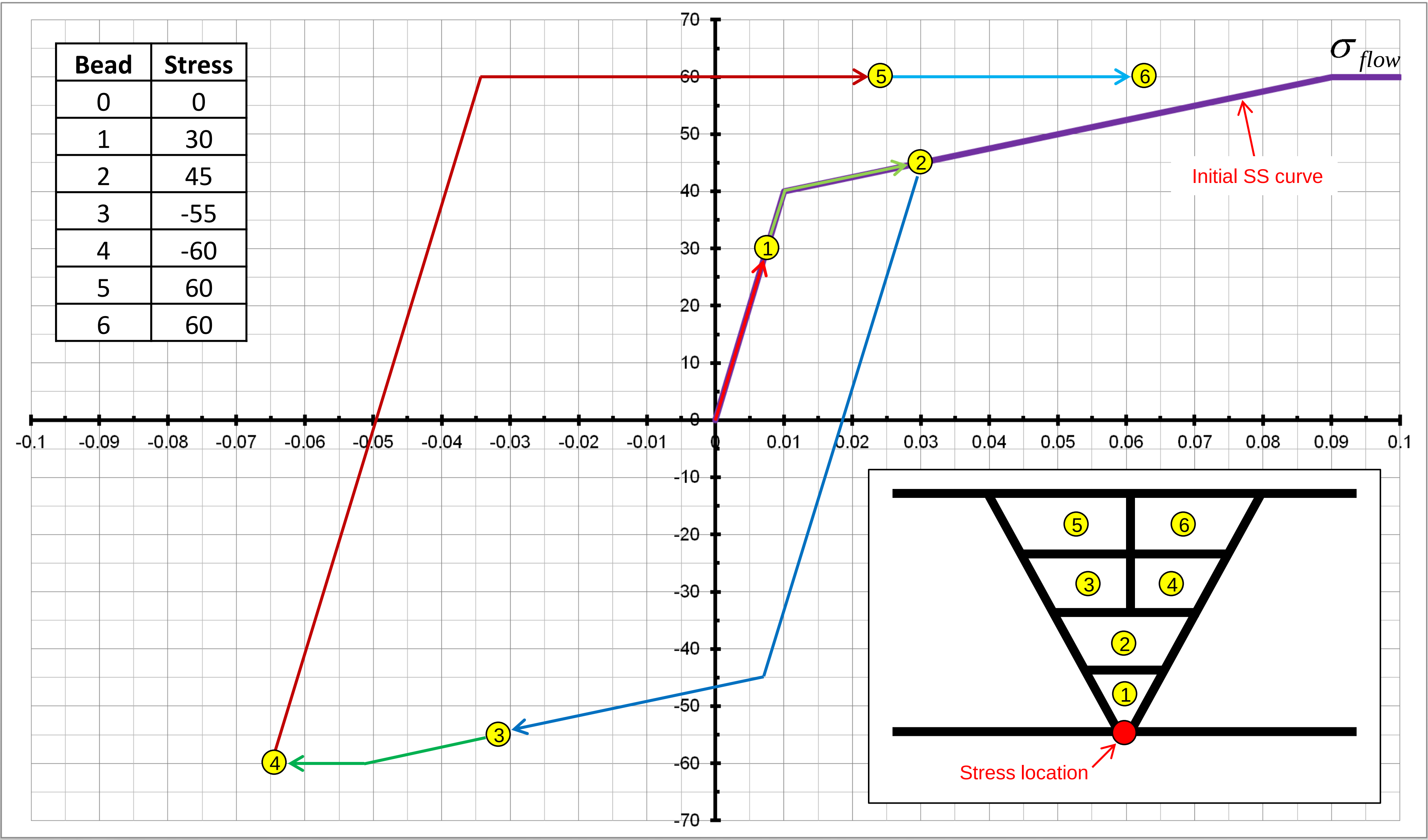


** Not to Scale **

Structural Integrity Associates, Inc.®

Hysteresis Loops for Isotropic Hardening

Bead	Stress
0	0
1	30
2	45
3	-55
4	-60
5	60
6	60



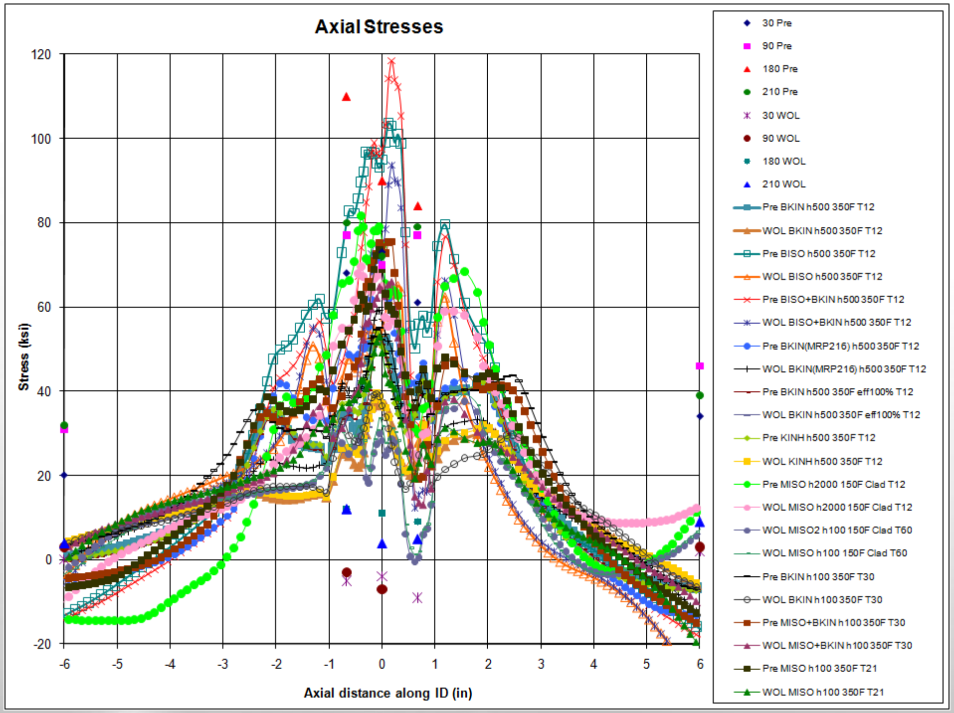
Sensitivity Studies

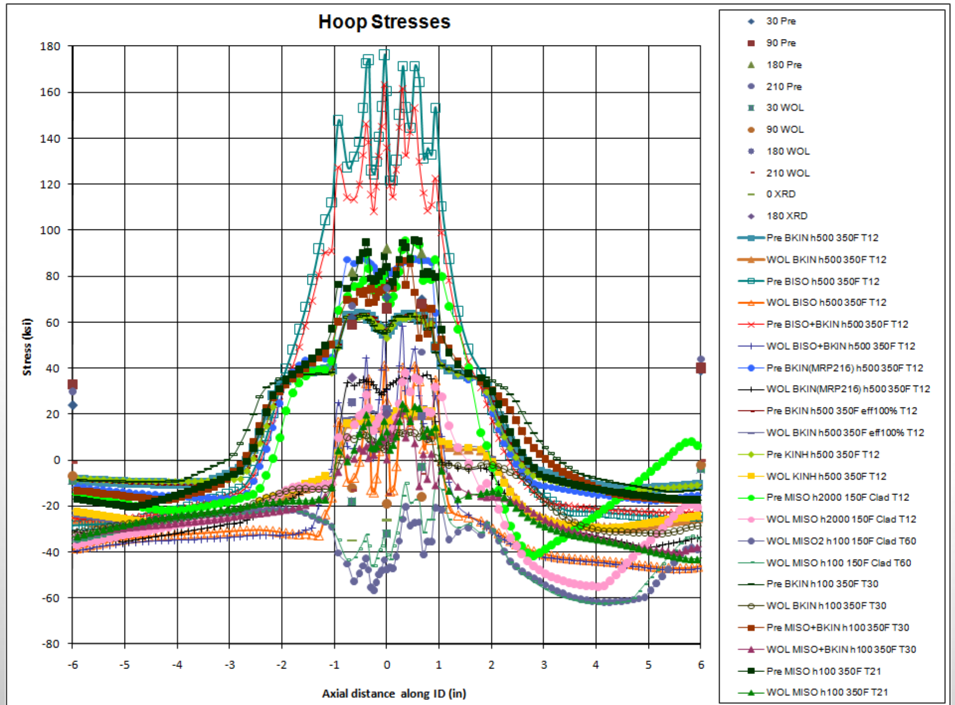
- Proven engineering approach through sensitivity studies
- MRP-169 (Rev. 0, Oct 2005) used bilinear kinematic strain hardening law
- Best practices for WRS simulations via FEA
  - Kinematic vs. Isotropic vs. Modified SS Curves
  - Two-dimensional (2D) vs. three-dimensional (3D)
  - Moving heat source vs. lumped segments
  - Heat inputs
  - Weld bead size and sequencing
  - Weld skipping (a weld overwhelmed by the next one)
  - Welding direction
  - Flow conditions

Structural Integrity Associates, Inc.®

Evolution of Strain Hardening Laws

- Extensive analyses performed to evaluate sensitivity of SS curves, strain hardening laws, and welding parameters
- Modified SS curve combined with isotropic hardening law is a good balance between measurements and FEA predictions, while retaining conservatism





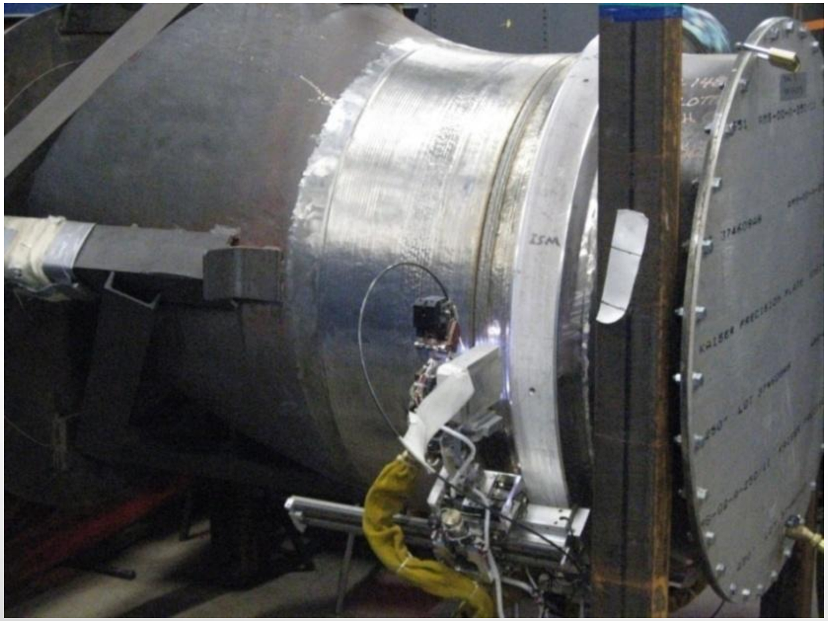
SI WRS FEA Benchmarking Efforts

FEA Predictions vs. Measurements

(1) EPRI WOL Mockups

- EPRI sponsored WOL mockups
- 14” diameter nozzle with FSWOL
- 36” diameter elbow with FSWOL
- Multiple welds including a partial arc ID repair

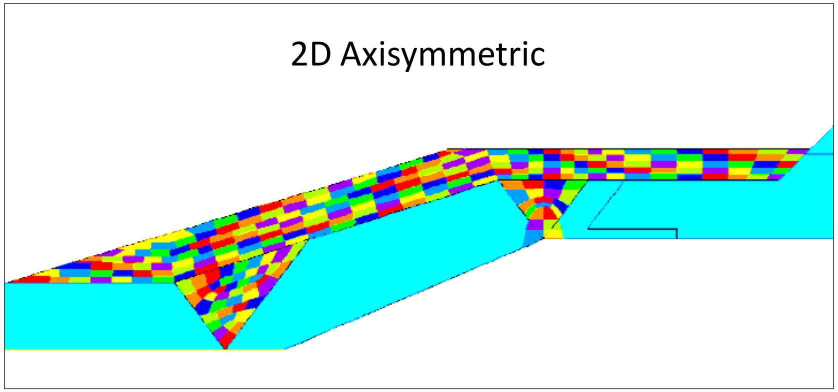
14” Surge Nozzle WOL Mockup

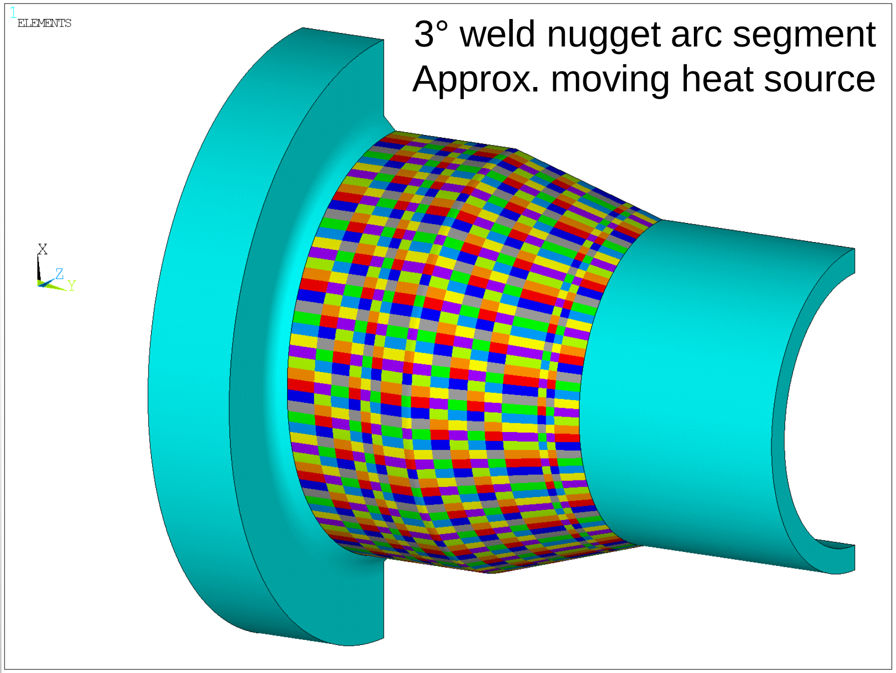


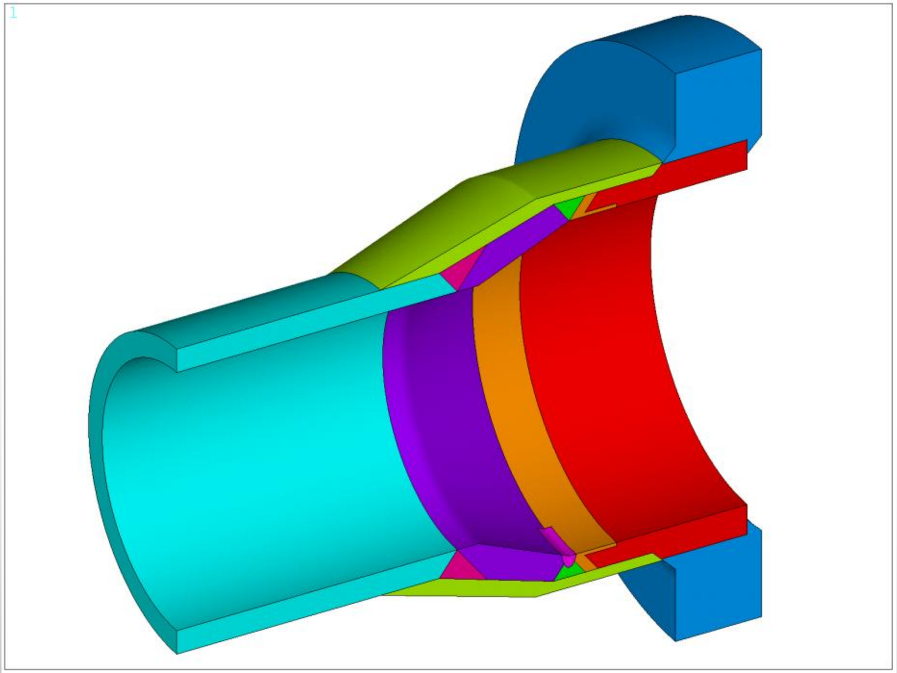
36” Large Bore WOL Mockup

(1) 14” Nozzle PWOL Mockup

- 2D and 3D WRS FEA
- Various 3D nugget arc lengths
  - 3°, 30°, 90°, 180°
- ID surface RS results compared to measurements



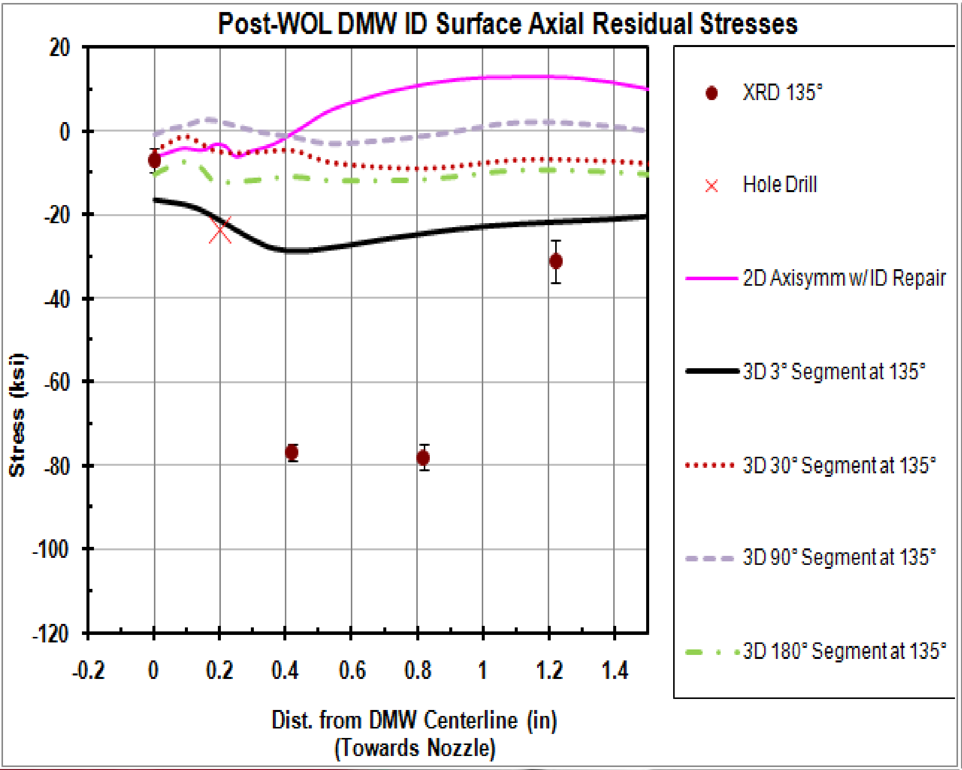


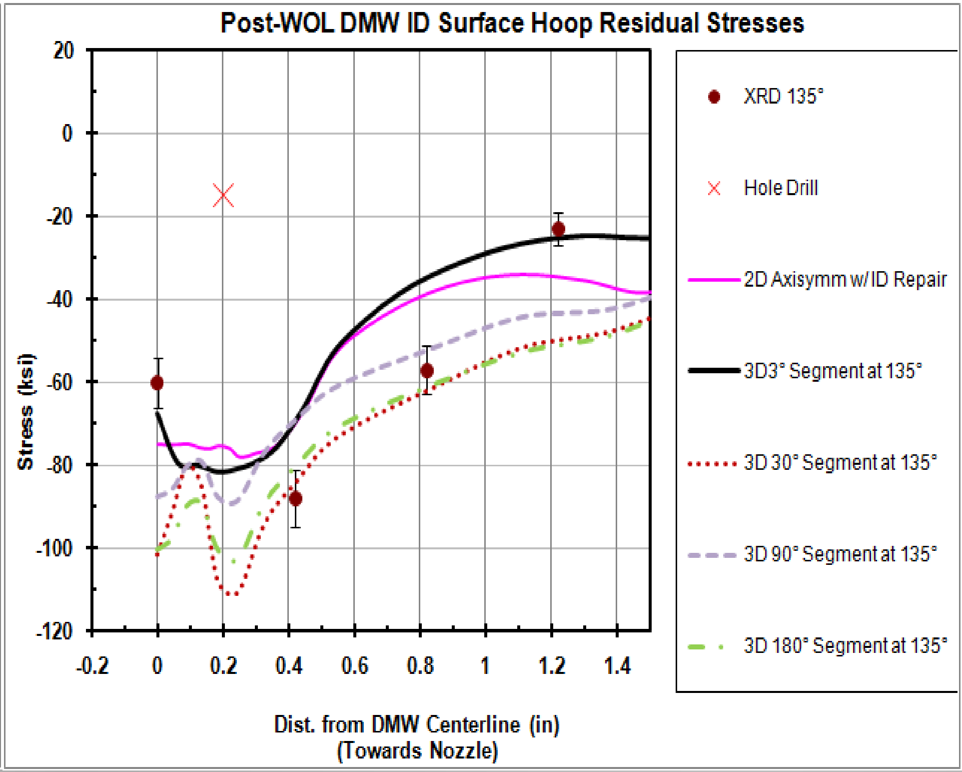


Click Image to Play/Pause

(1) 14" Nozzle Mockup Benchmarking

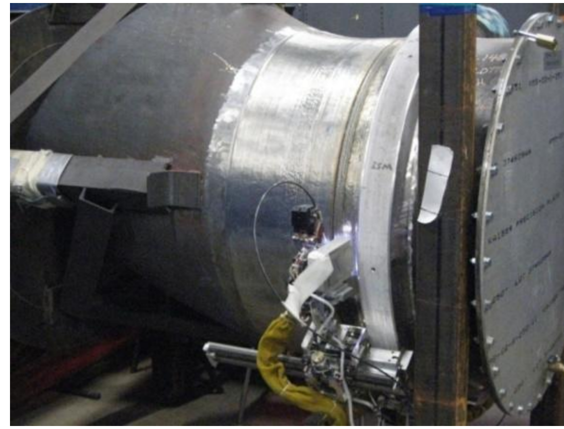
- Modified SS curve + isotropic hardening does not over-predict compressive RS
- 3D produces best results
- Similar hoop results 2D vs. 3D
- 2D predictions are more conservative

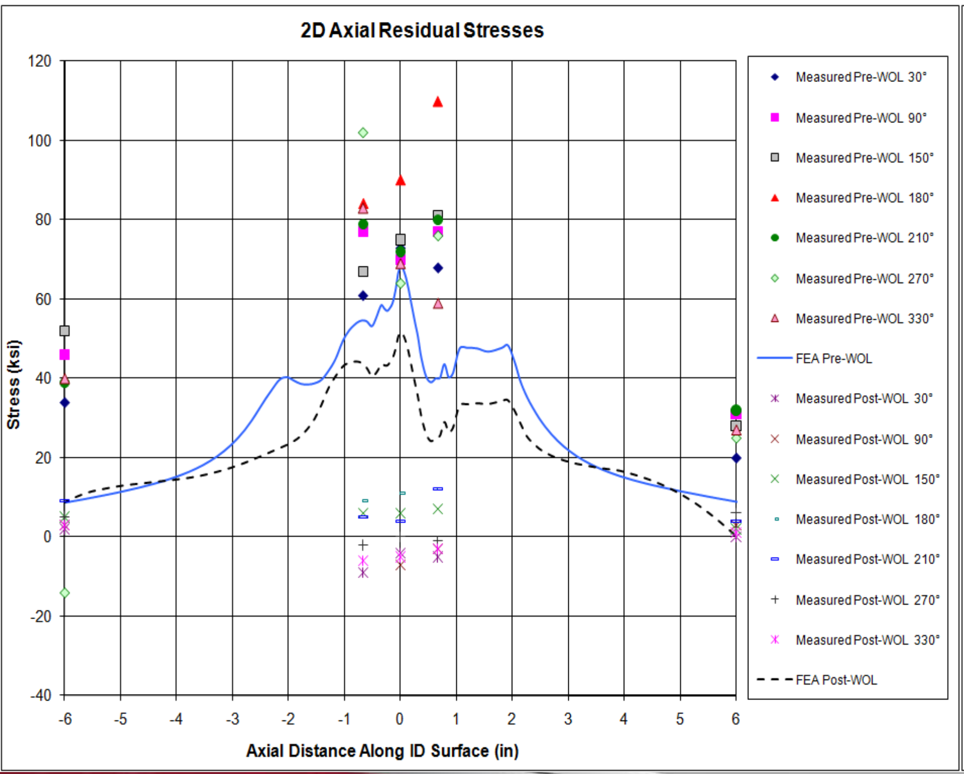


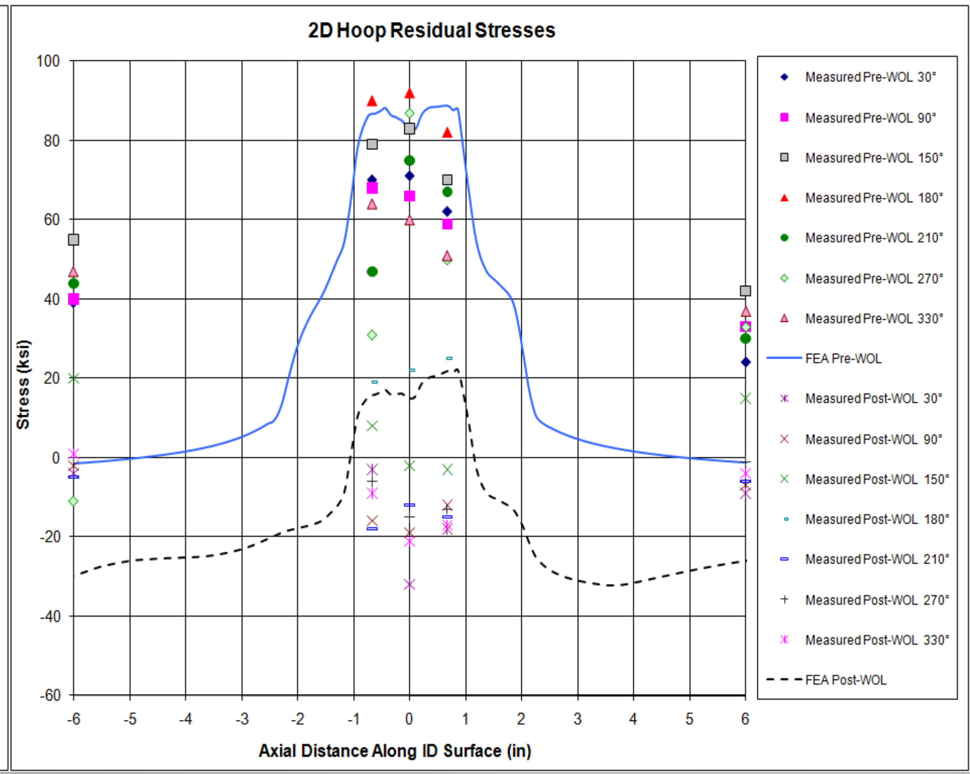


(1) 36" Elbow Mockup Benchmarking

- Modified SS curve + isotropic hardening yields conservative predictions
- Post-WOL hoop stress on upper bound
- Results remain at under-predicting WOL axial stress benefits

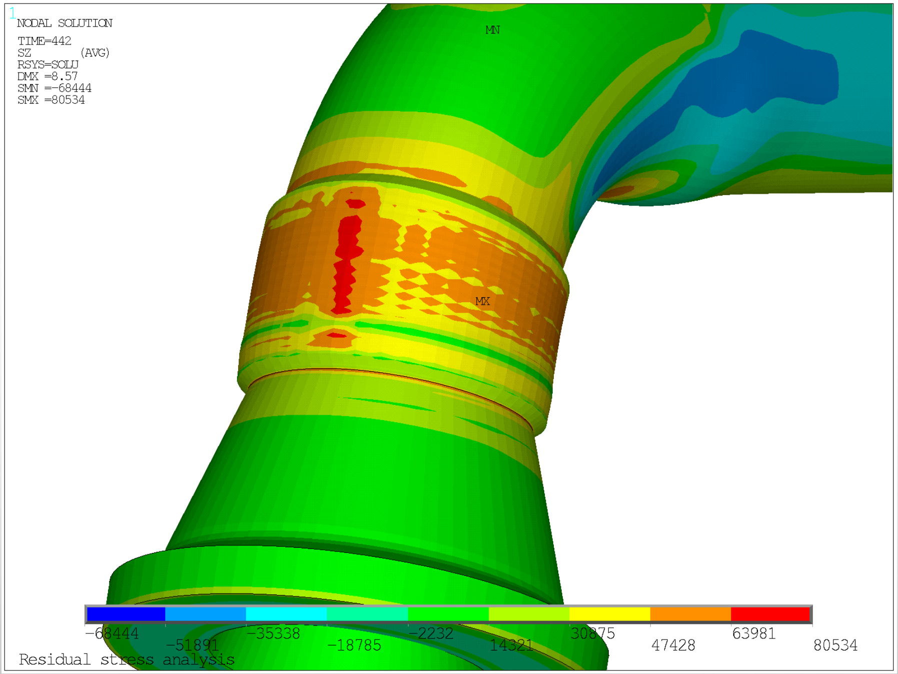


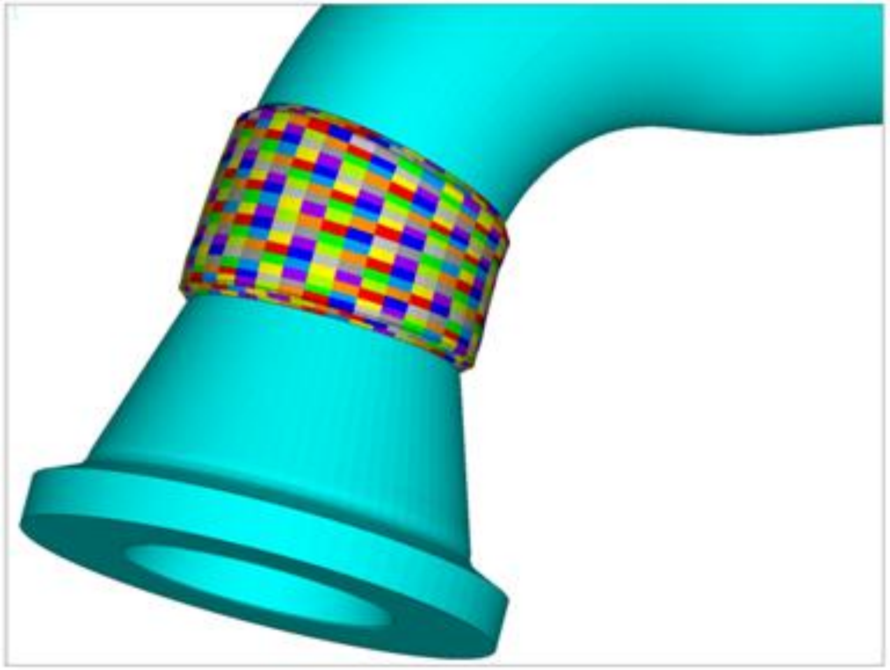




(2) Feeder Tube WOL Repair

- Pure isotropic hardening used to capture large strain from elbow forming
- No modification of SS curves in analysis
- 10° weld nugget arc segments



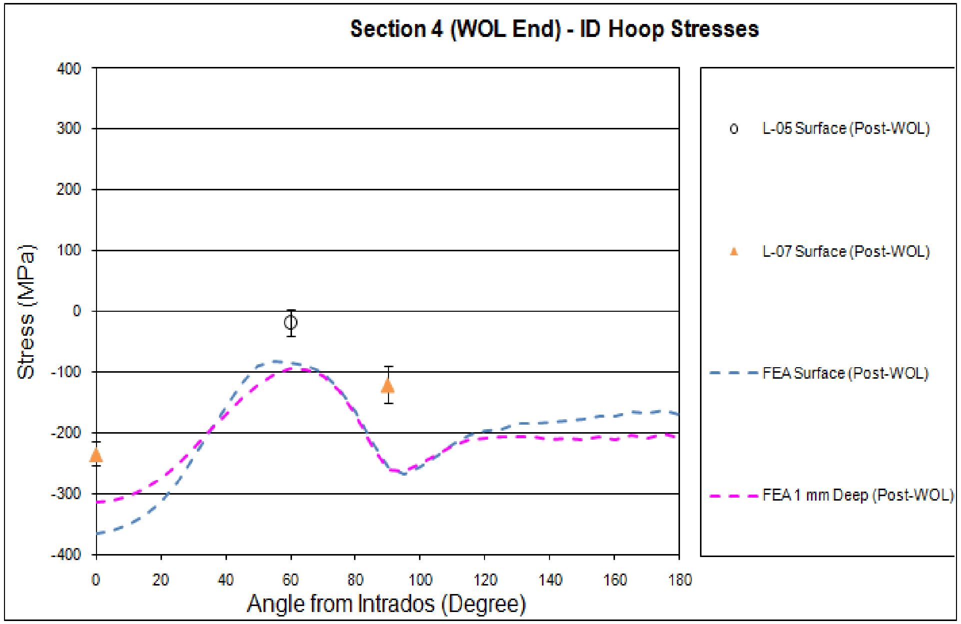


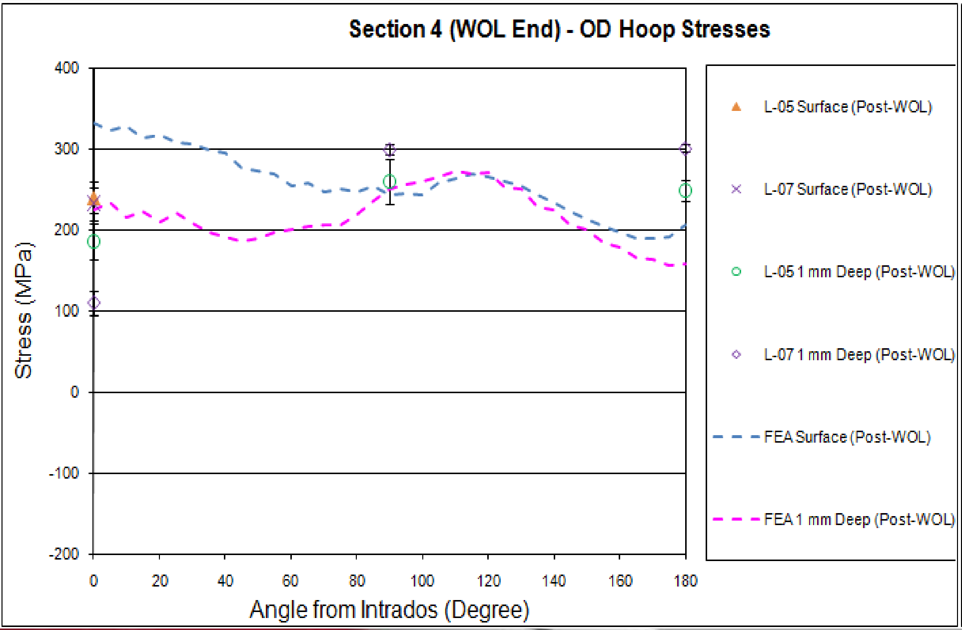
Click Image to Play/Pause

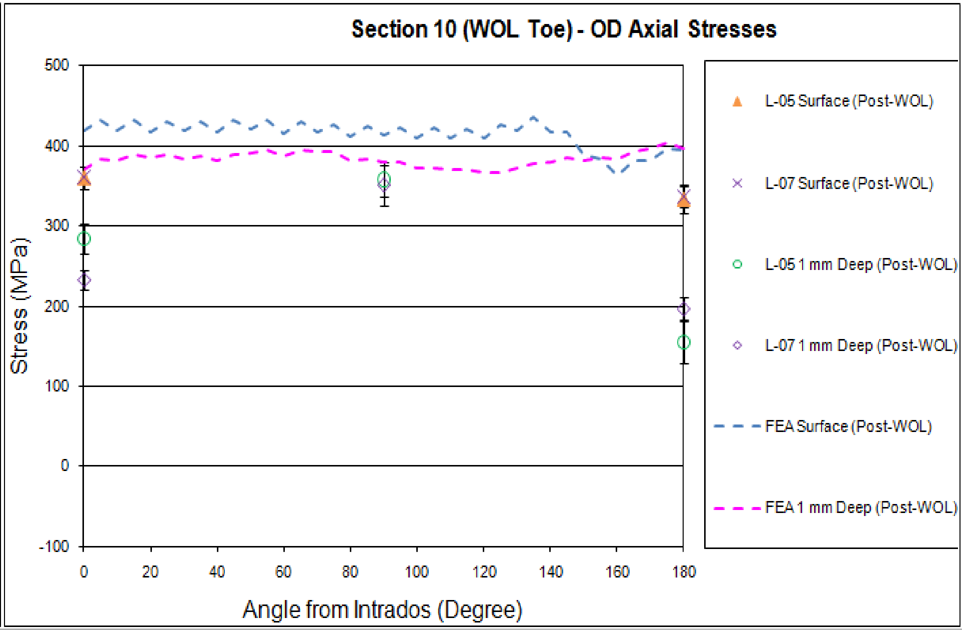
Structural Integrity Associates, Inc.®

(2) Feeder Tube WOL Benchmarking

- Even with pure isotropic hardening, post-WOL results still compare reasonably will with measurements
- No significant RS over-predictions





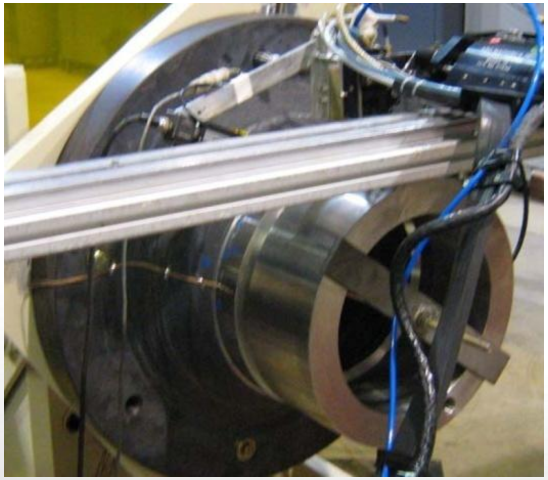


(4) NRC Phase II Nozzle DMW Mockup

- NRC Phase II International Round Robin
- 14” nozzle mockup, DMW, SSW, no WOL
- 2D and 3D WRS FEA
- Compare Case 2 results to measurements

Phase 2 Participants
International WRS Round Robin

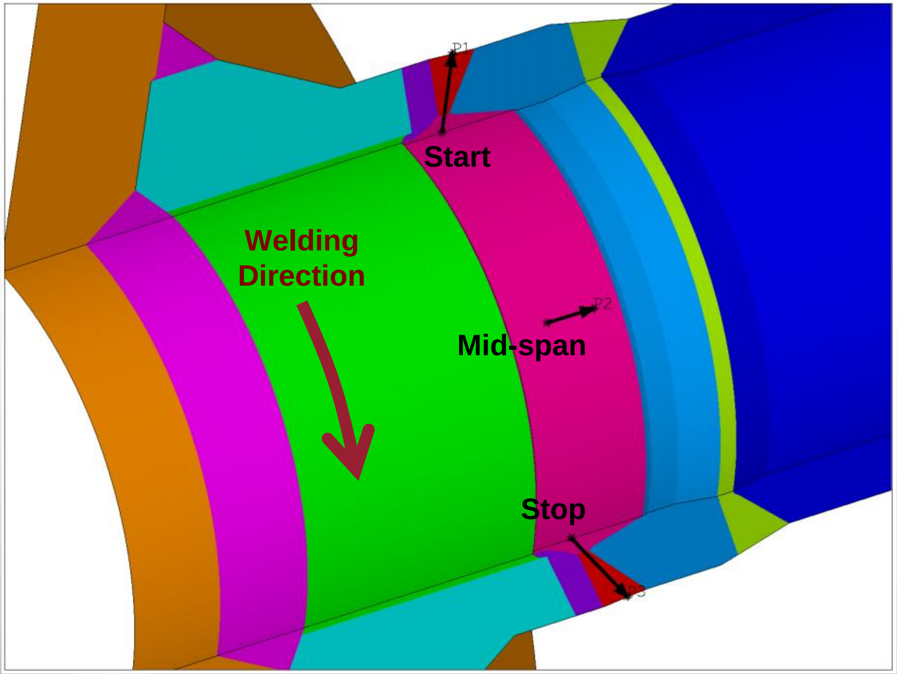
- ANSTO (Australia)
- AREVA (USA and EU)
- Battelle (USA)
- Dominion Engineering (USA)
- Goldak Technologies (Canada)
- ESI Group (USA)
- EMC^2 (USA)
- Inspecta Technology (EU)
- Institute of Nuclear Safety System (Japan)
- Osaka University (Japan)
- Rolls Royce (UK)
- Structural Integrity Associates (USA)



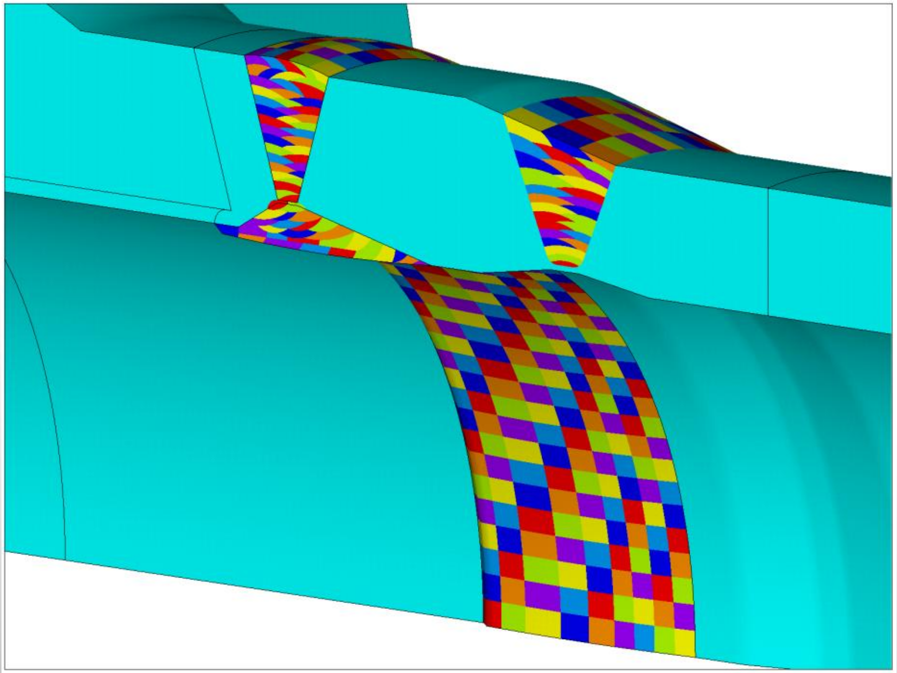
Source: NRC Public Documents

(4) Phase II Finite Element Models

- 2D model is axisymmetric, 3D model is 90° quarter model
- 3D results taken at three azimuth locations
  - Weld bead start location (0°)
  - Mid-span (45°), remote from start/stop
  - Weld bead stop location (90°)



3D 3° weld nugget arc segment
Approximate moving heat source



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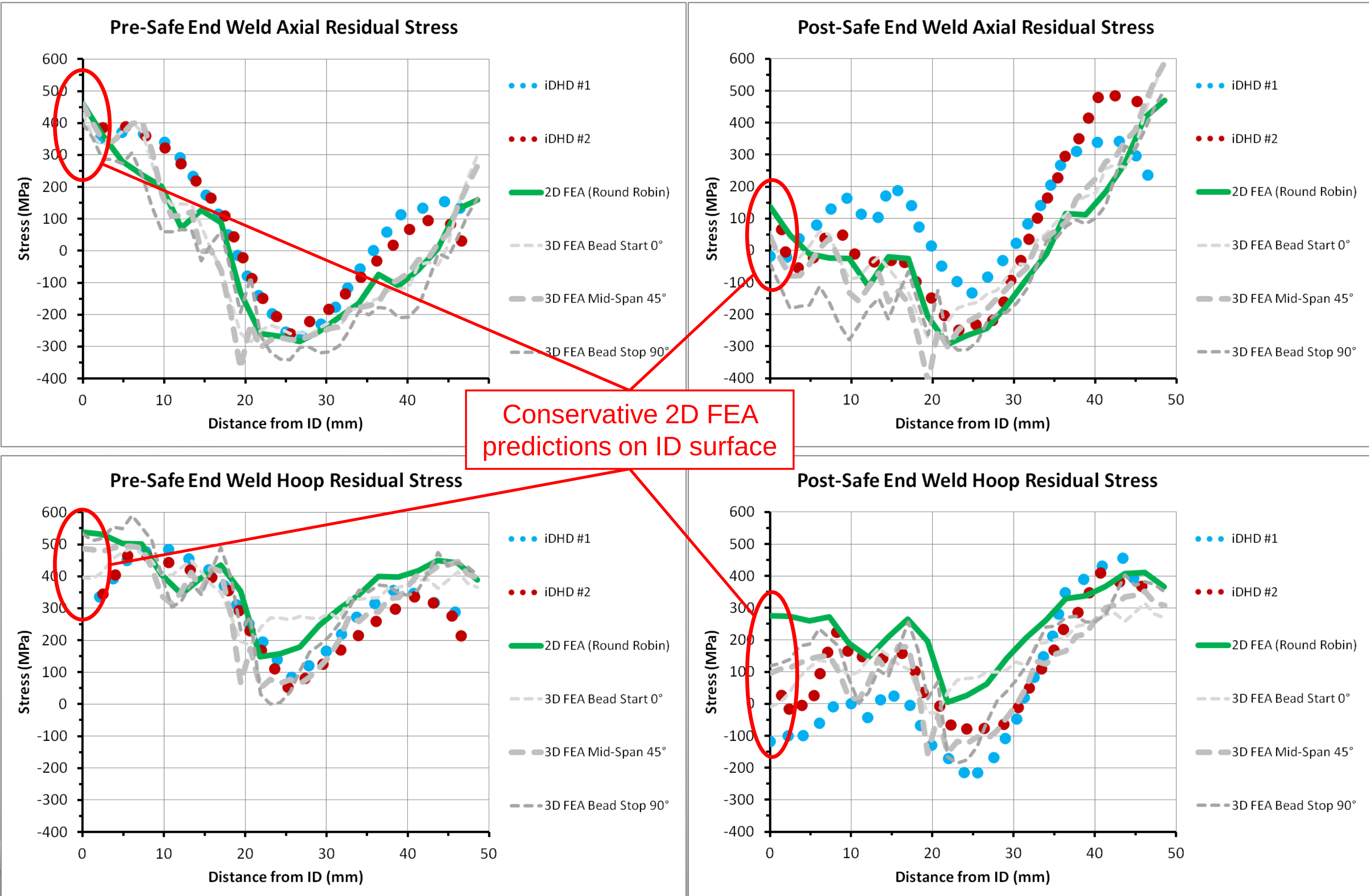
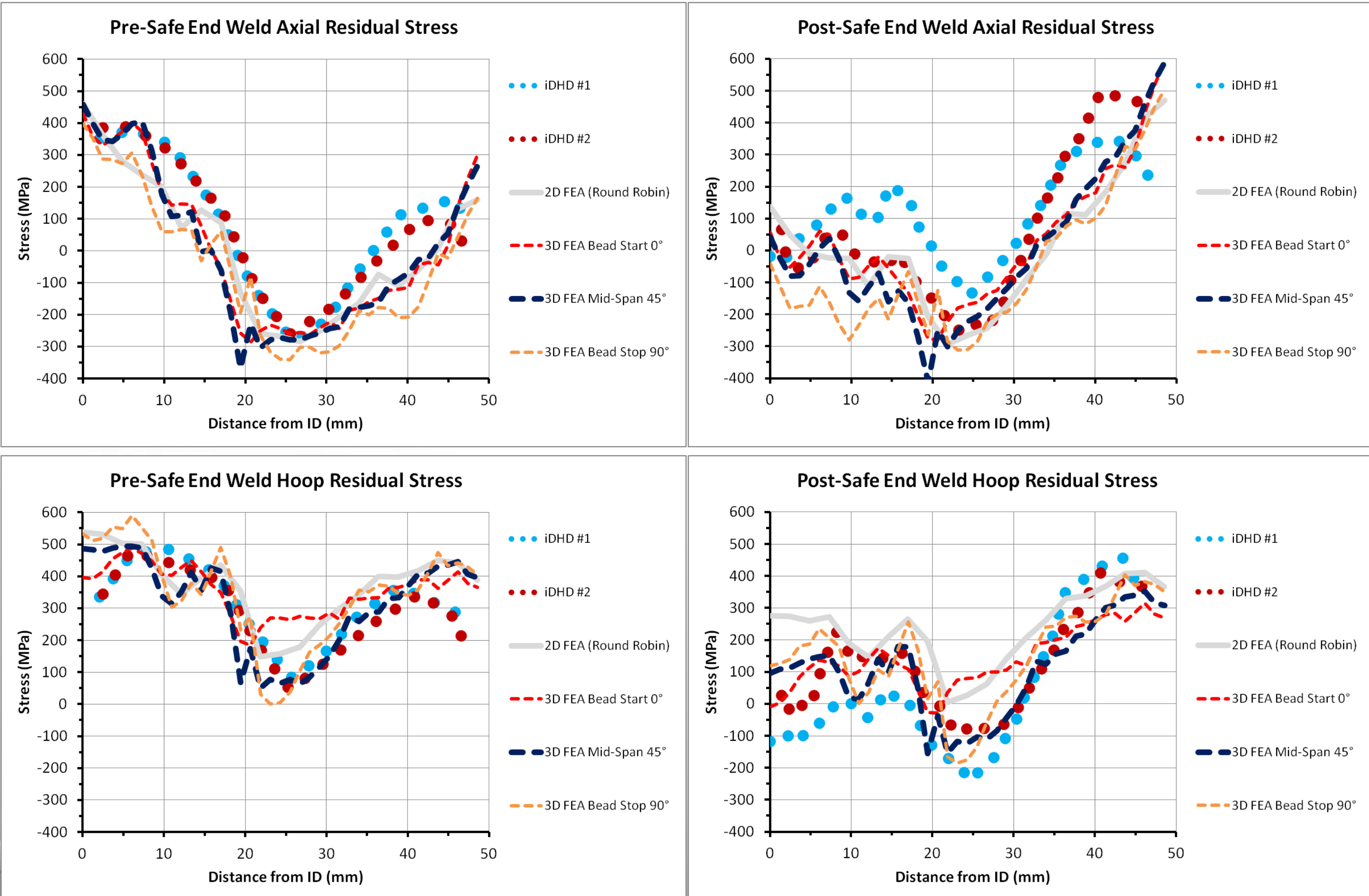
(4) 2D Residual Stress Benchmark



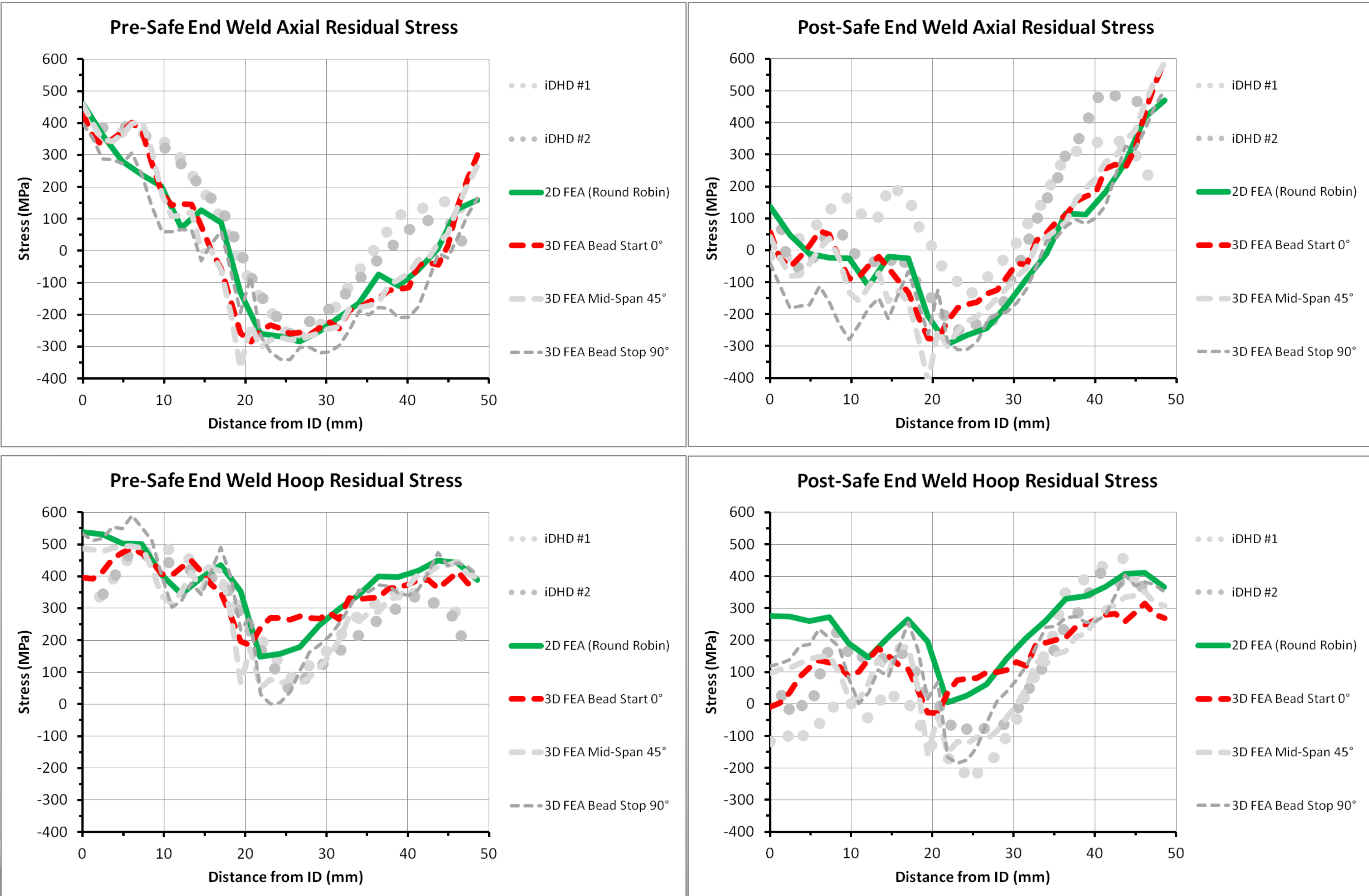
- 2D results compare fairly well with data

(4) 3D Residual Stress Benchmark



- 3D mid-span results compare best with data

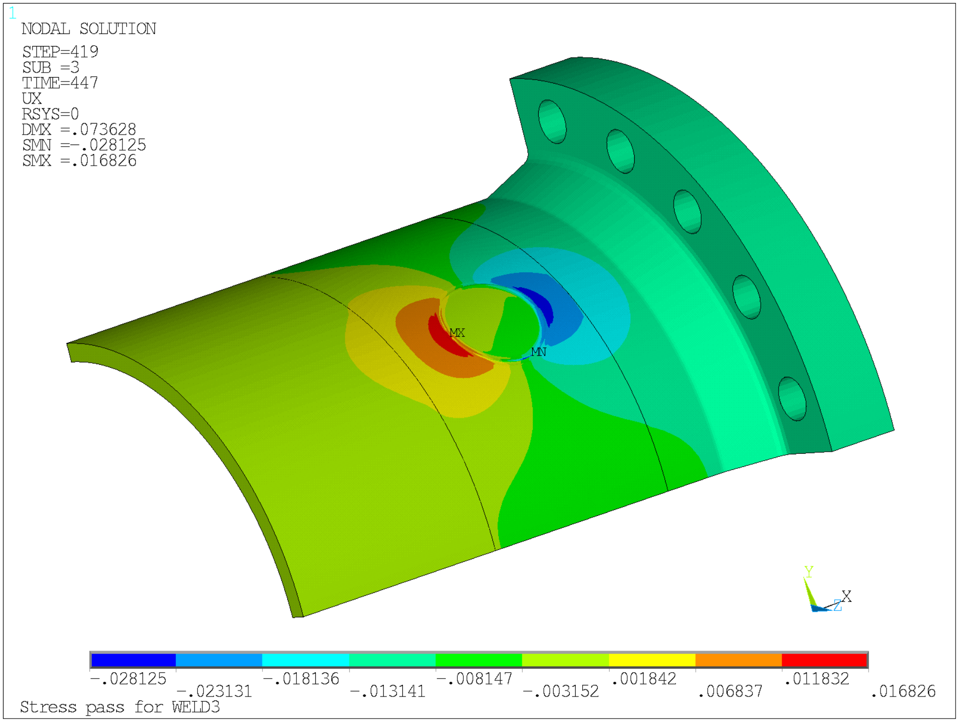
(4) 2D vs. 3D Residual Stress Benchmark

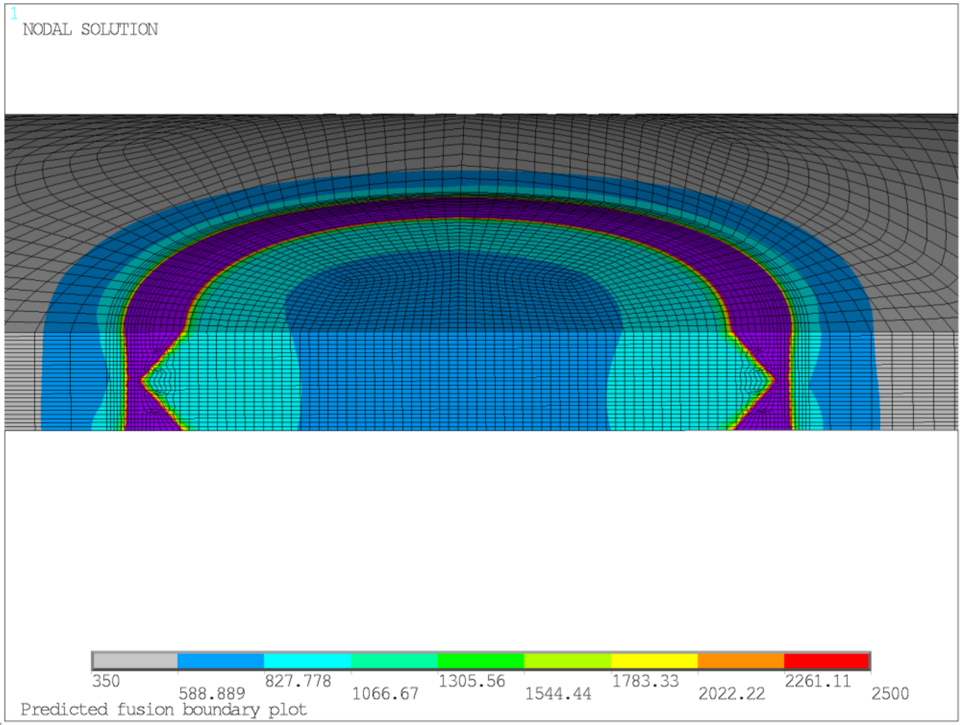


- 2D results closer to that for 3D Bead Start

(5) Hydro Plant Penstock Plug Repair

- Low alloy steel, 40” OD, 1” thick
- “Hockey puck” insert plug welded to penstock shell
- K-groove weld around plug disc edge
- WRS FEA and benchmark shrinkage
- Axial shrinkage at flange 0.011” FEA vs. 0.009” Measured





Overall Conclusions

1) 2D FEA typically yields conservative results, esp. for WOL
2) 3D FEA yields better predictions to measurements
3) Strain hardening laws have significant effects on results
   a) Pure isotropic hardening tend to over-predict WRS benefits
   b) Pure kinematic hardening tend to under-predict WRS benefits
   c) Modified SS curve (stress capped at flow stress) with isotropic hardening offers improvements over either hardening laws
4) Modified SS curve with isotropic hardening is suitable for WRS FEA
   a) Easy to obtain or derive stress-strain data
   b) More stable and faster solution convergence than kinematic and combined hardening laws
   c) More realistic prediction of actual weld residual stress profile
   d) Does not over-predict residual stresses
   e) Stress predictions remain conservative

EMC^2 Materials Characterization Program and WRS Work in Support of xLPR

NRC Materials Reliability and Residual Stress Research

F. W. Bud Brust, D. J. Shim, G. Wilkowski, T. Zhang, S. Kalyanam
D. Rudland, M. Kerr, H. Rathbun

Innovative Structural Integrity Solutions

Material Properties for Weld Analysis

Prior Testing

- ***Tensile testing for WRS material modeling***
  - ***NRC/EPRI Phase II Mock-up's ('long nozzle' and 'short nozzle')***
  - ***Tensile data and Chaboche parameters for mixed hardening (Alloy 182)***
  - ***Alloy 52M tensile properties for WRS analysis***
  - ***Alloy 690 tensile properties for WRS***
  - ***A508/A516 and Stainless steel WRS data from literature***
  - ***Stainless Steel tensile properties (including Chaboche) from literature***

Material Property Testing for xLPR

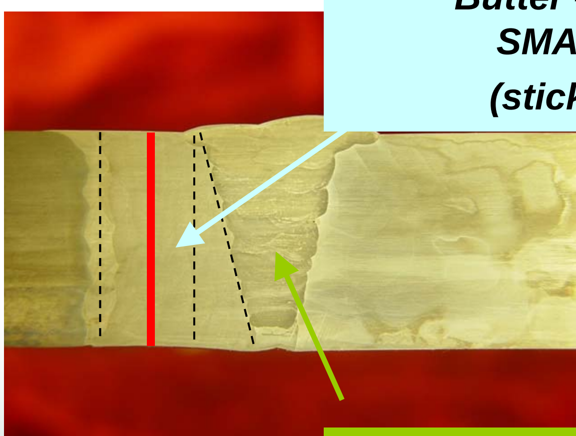
Fracture Test Plans

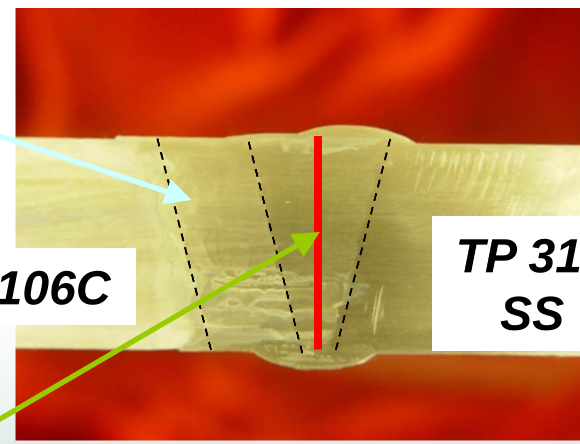
- Specimen testing for NRC/Battelle DMW pipe fracture test program
  - C(T), SENT, CCT

- Additional testing in planning stage
- Hoping to obtain additional material to test

From Plate (NRC/Battelle DMW Tests)

Butter – Inconel 182 SMAW process (stick) - PWHT





A106C

TP 316 SS

DMW-170

Main weld – Inconel 82 GTAW process (wire)

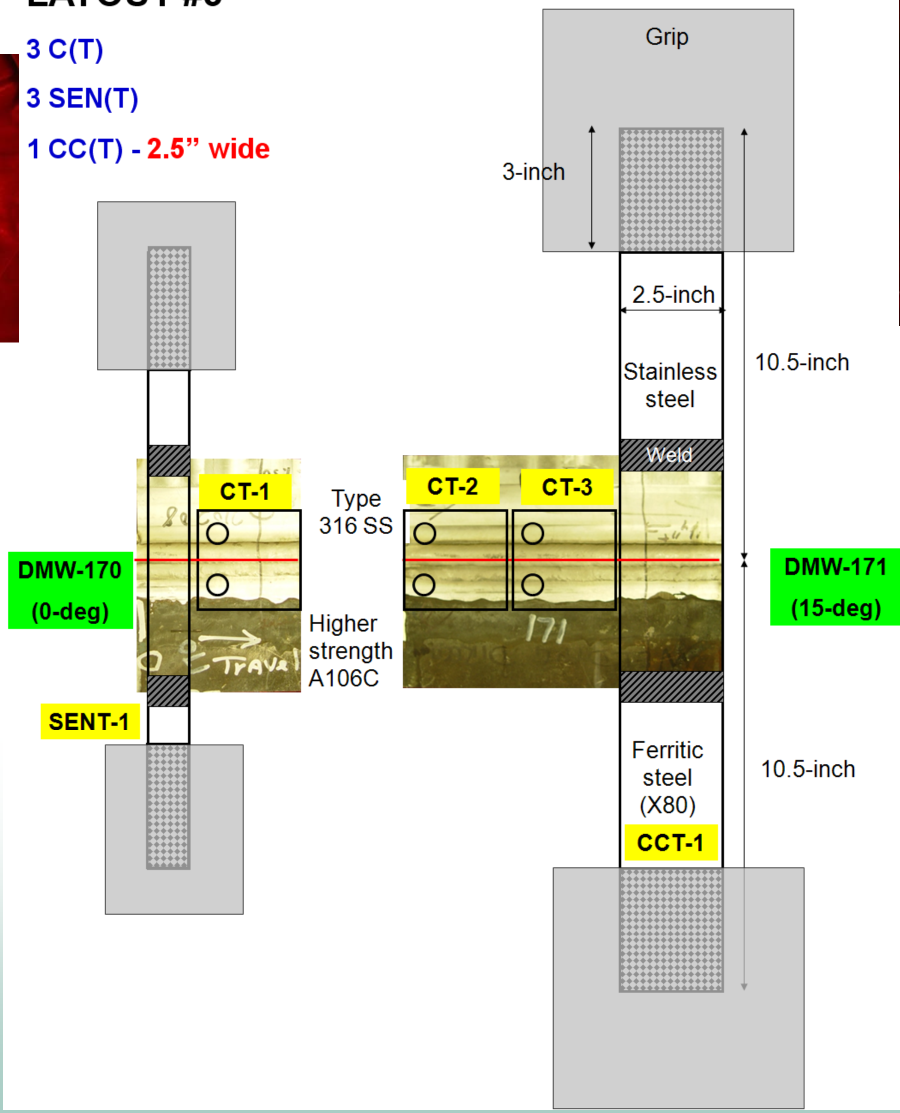
Plate (NRC/Battelle DMW Tests): Layout

LAYOUT #3

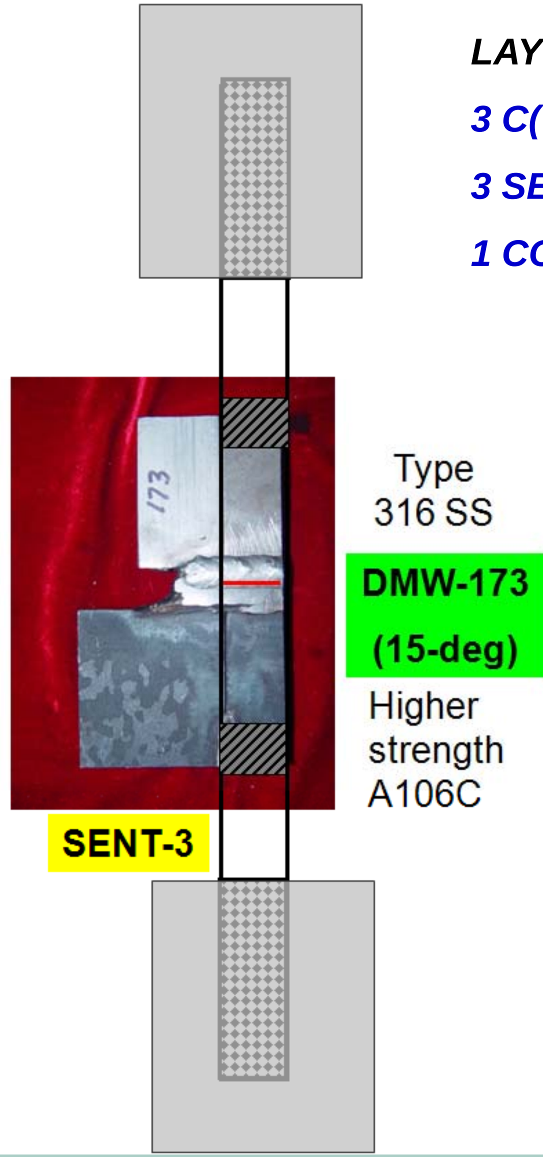
3 C(T)

3 SEN(T)

1 CC(T) - 2.5” wide



From Plate (Battelle DMW Tests): Layout



LAYOUT #3

3 C(T)

3 SEN(T)

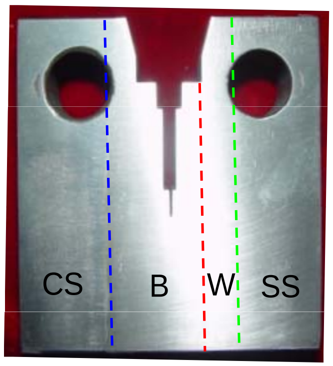
1 CC(T) - 2.5" wide

Test matrix for fracture toughness testing of DMW material

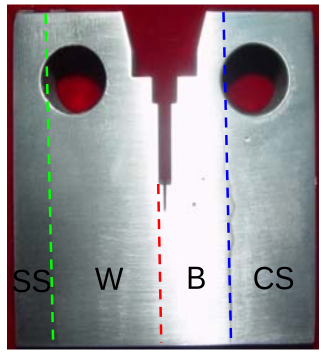
Emc^2 material ID	Specimen ID	CS and butter bevel	Crack location	Crack type (fatigue-precrack, SMN, etc.)
170	CT-1	0-deg	Butter	Fatigue precrack and SG
171	CT-2	15-deg	Weld center	Fatigue precrack and SG
171	CT-3	15-deg	Weld center	Fatigue precrack and SG
170	SENT-1	0-deg	Butter	Fatigue precrack and SG
172	SENT-2	0-deg	Weld center	Fatigue precrack and SG
173	SENT-3	15-deg	Weld center	Fatigue precrack and SG
171	CCT-1	15-deg	Weld center	No fatigue pre-crack/chamfered corner

Battelle DMW Tests: CT Specimens

ID view

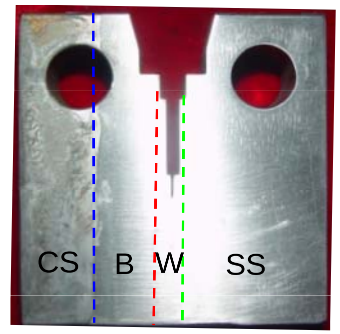


OD view

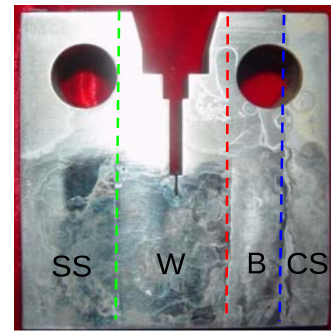


Specimen CT-1

ID view

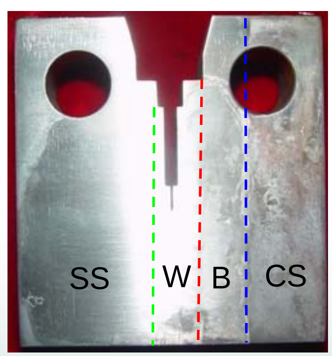


OD view

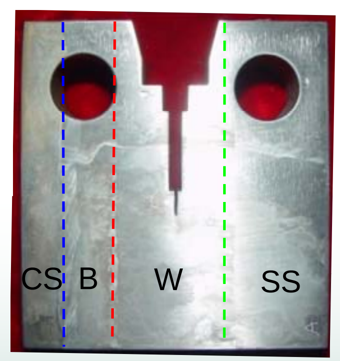


Specimen CT-2

ID view

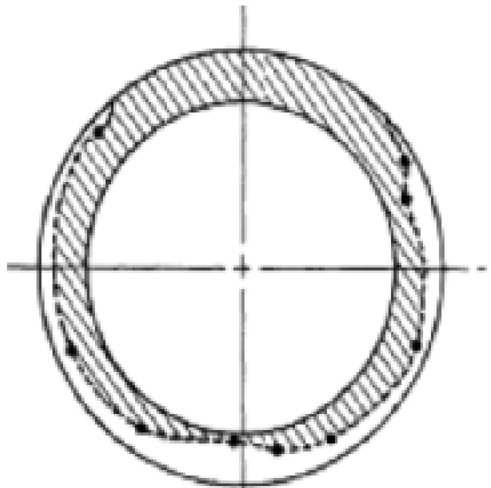


OD view

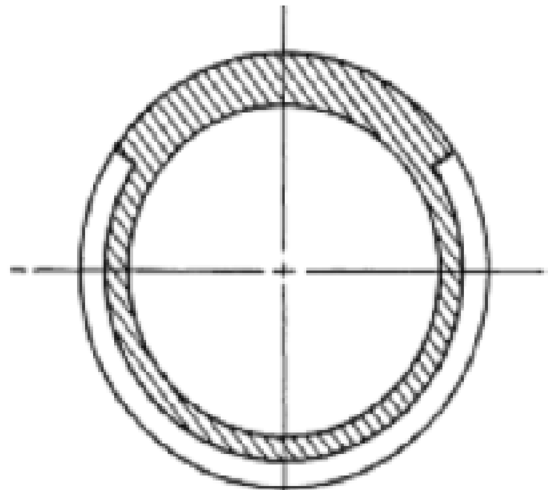


Specimen CT-3

Complex Crack Pipe and specimen

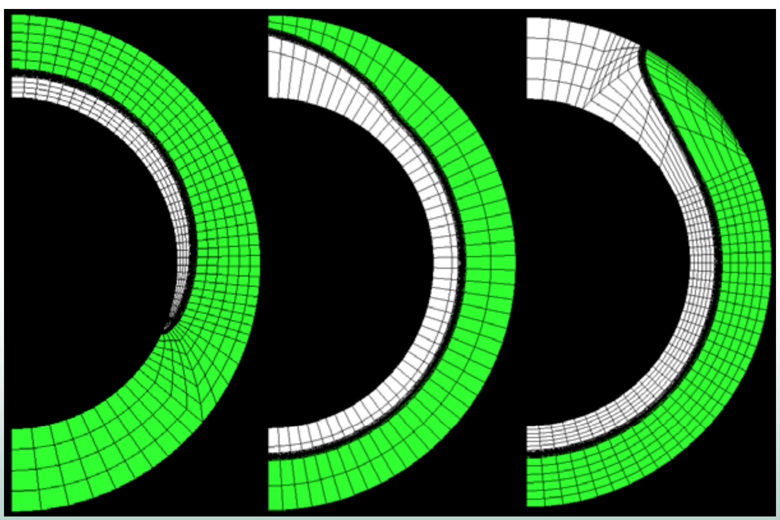


Duane Arnold safe end crack

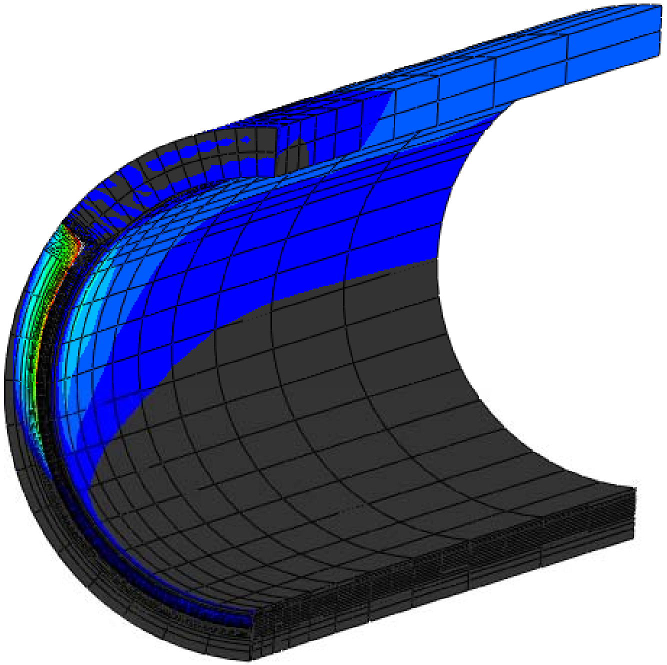


Simplified complex crack

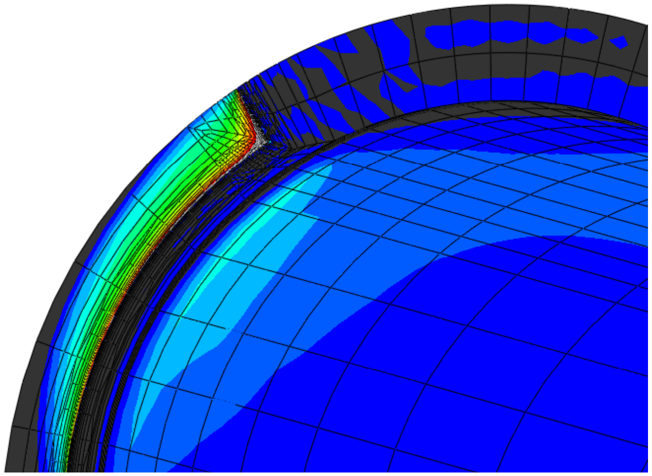
- Measured crack depth
- Estimated crack depth
- IGSCC Area



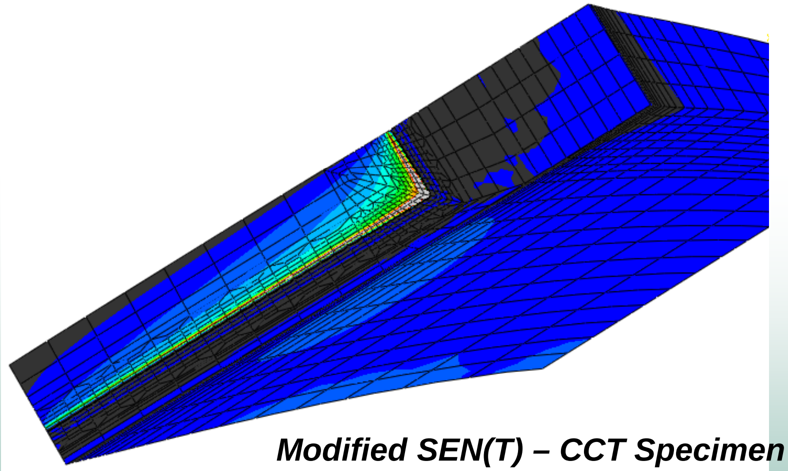
Complex Crack Pipe and specimen



Complex crack pipe

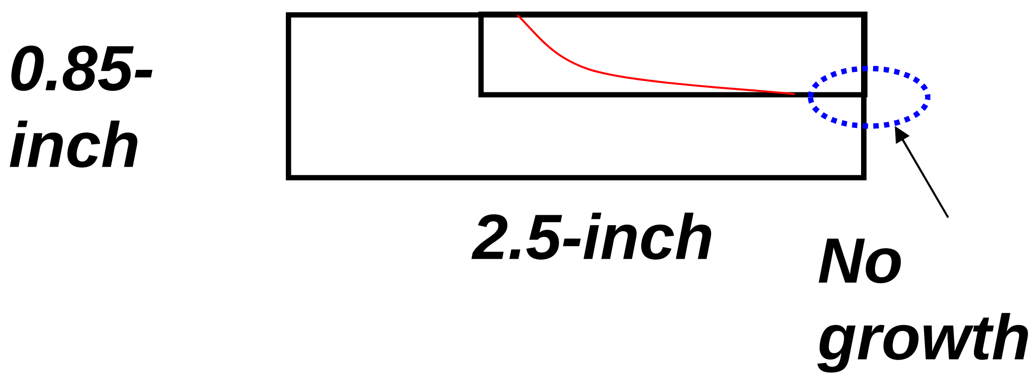


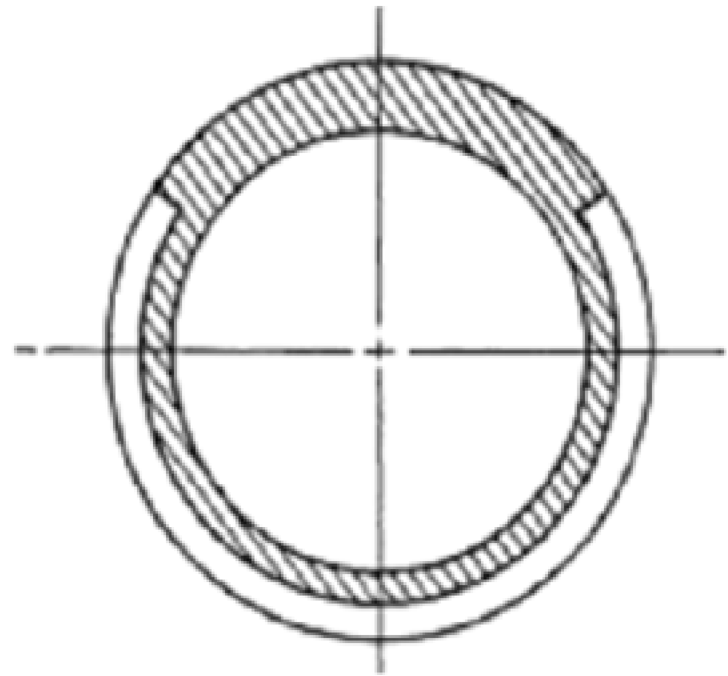
Complex crack pipe (magnified view)



Modified SEN(T) – CCT Specimen

Complex Crack specimen





Similar to prior work for Another program

Material for Additional Testing

Pressurizer nozzles from St. Lucie Unit-1 were obtained through NRC. Decommissioned and decontaminated.

Spray nozzle - SA-508 Cl 2 forged alloy steel with type 304 SS cladding and fitted with an SA-182 F-316 SS safe end

Surge nozzle - SA-508 Cl. 2 forged alloy steel with type 304 SS cladding and fitted with an SA-351 GR CF8M SS safe end.

Additional Testing

- ***Would like material for A152/52, Alloy 690, Alloy 600, and other DM material***
  - ***Alloy 52/152 weld. Preferably a bimetal weld between ferritic nozzle and stainless steel.***
    - ***Produce toughness (J-R) curves for cracks placed in the weld near the ferritic material (fusion zone), in the center of the weld, and near the SS fusion zone.***
    - ***Most likely will be C(T) tests but may perform some SENT type (for surface crack toughness) if enough material is available.***
  - ***Perform additional tensile tests as well (Chaboche along with additional tensile data for WRS)***

WRS Support (Model Group)

- ***The WRS subgroup - responsible for developing all of the mathematical models and solutions needed to calculate the weld residual stresses (WRS) and corresponding loads which drive subcritical crack growth in welded nuclear piping.***
  - ***WRS do not affect stability – except for materials that are not ductile***
  - ***WRS does affect COD under some circumstances – leak rate***
  - ***WRS important for crack initiation***
  - ***These results feed into the stress intensity factor calculation solution procedure using UWF methods***
  - ***This combination (WRS/K solutions), are used for the subcritical crack growth mechanisms (stress corrosion crack growth, fatigue crack growth, etc.), materials (Alloy 600/82/182/132, austenitic stainless steels, and ferritic steels), and environments (PWR, BWR) designated for inclusion in xLPR 2.0.***

WRS Support (Model Group)

- ***Development of WRS solutions***
- ***Development of WRS Distributions Post Mitigation***
- ***Accounting for service loading over top WRS fields and safe-end length effects***
- ***Account for the Effect of Partial Repairs on WRS Profiles***
- ***Development of a WRS sampling scheme***
- ***Module-Level Verification and Validation of WRS Module 2.0 and Coordination of Support of Code Review***

ELECTRIC POWER RESEARCH INSTITUTE

Welding Residual Stress Research at Oak Ridge National Laboratory

Zhili Feng, Dongxiao Qiao, Wei Zhang

Materials Science and Technology Division
Oak Ridge National Laboratory (ORNL)
Oak Ridge, Tennessee

Presented in Nuclear Regulatory Commission Staff and Representatives of the Nuclear Power Industry PWR Materials Reliability and Weld Repair Research Meetings, January 24-26, 2012

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Two-Part Presentation

- Part 1: Progress update of ongoing ORNL project sponsored by EPRI
  - ➢High-temperature dynamic recovery and its influence on materials hardening behavior
- Part 2: Other weld residual stress research at ORNL
  - ➢Helium-induced cracking during weld repair of irradiated materials
  - ➢Fracture mechanics analysis of welds
  - ➢Weld pool fluid flow
  - ➢Microstructure modeling

High-Temperature Dynamic Recovery – Motivation from Round-Robin WRS Modeling

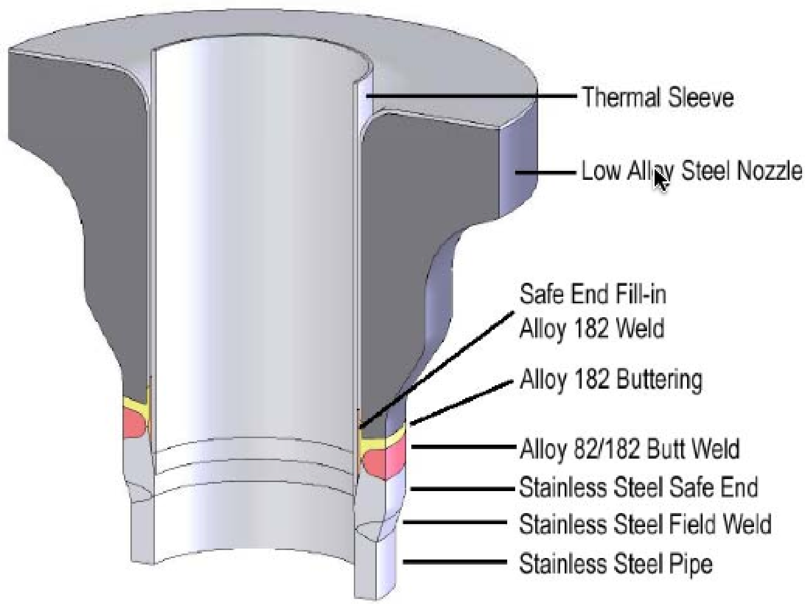
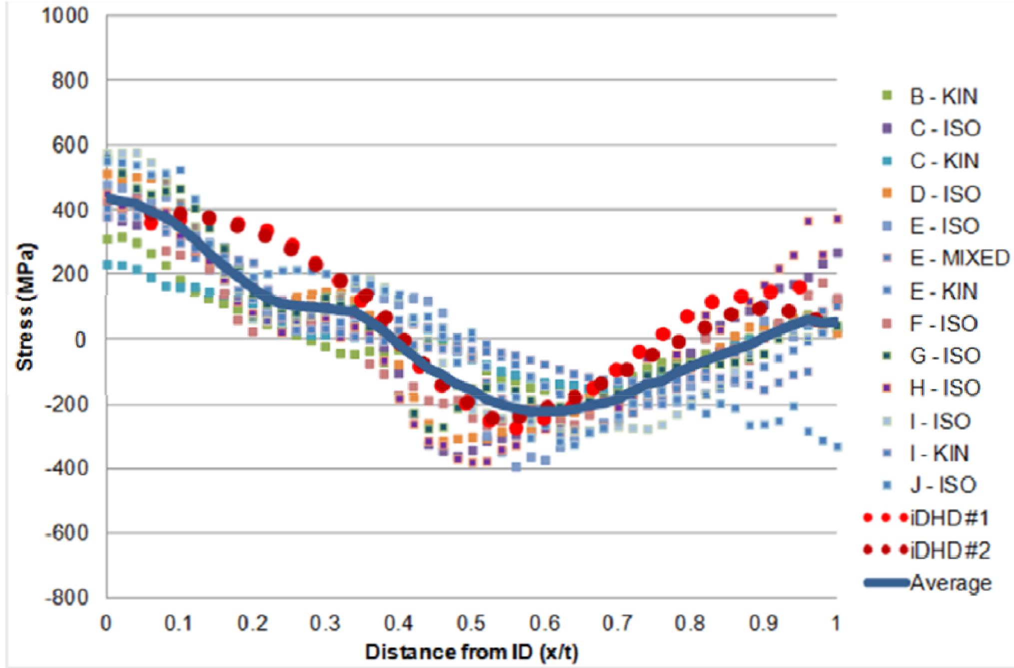


Figure 1. Representative Nozzle Cross Section

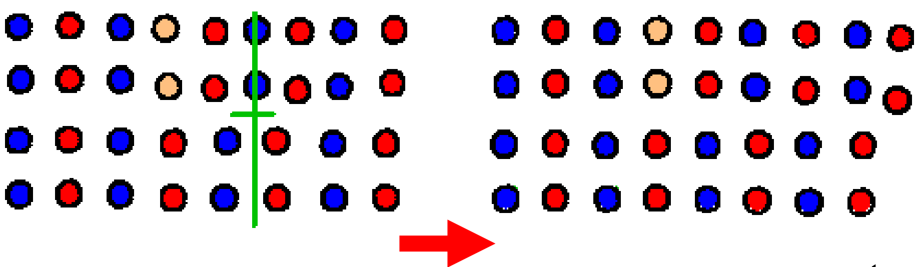


"In reviewing input parameters provided by round robin participants, the stress results are highly sensitive to some parameters and models, and relatively insensitive to others. *Of highest significance is the assumed weld material hardening behavior.* Generally, analysts who apply an isotropic strain hardening law calculate higher stresses than those who apply kinematic hardening"

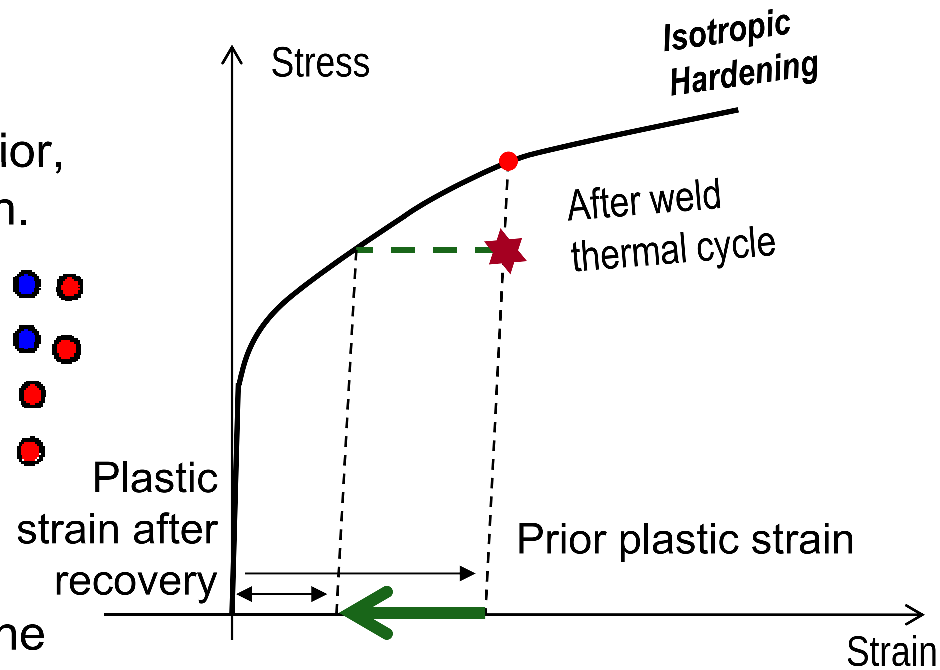
- *H.J. Rathbun et al., "NRC Welding Residual Stress Validation Program International Round Robin Program and Findings" ASMP PVP 2011, Paper No 57642.*

Influence of High-Temperature Dynamic Recovery on Strain Hardening Behavior

- Austenitic stainless steels and nickel alloys common to DM welds exhibit strong strain (work) hardening behavior, which is caused by dislocation motion.



- The isotropic, kinematic and mixed strain hardening models adopted in the current WRS modeling practices are based on the classic rate-independent elastic-plasticity theory.
- These models ignore the high-temperature dynamic dislocation annihilation (recovery and/or recrystallization) process.



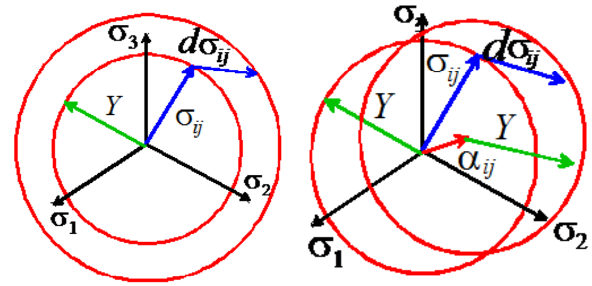
- The dynamic dislocation recovery occurred during welding can partially anneal the effective plastic strain (i.e., partially resetting the active yield surface).
- Extent of recovery is dependent on the "strength" of weld thermal cycle (i.e., time at high temperature).

Limitation of Rate-Independent Hardening Rules

- The active yield surface for isotropic, kinematic, or mixed strain hardening rules is:

$$F = f(\sigma - \alpha) - Y = 0$$

where the strain hardening behavior (F, yield criterion) is determined by α (center) and Y (yield stress). Although specific values of these two parameters depend on the specific hardening rules, both are a function of the equivalent plastic strain (ε^p).

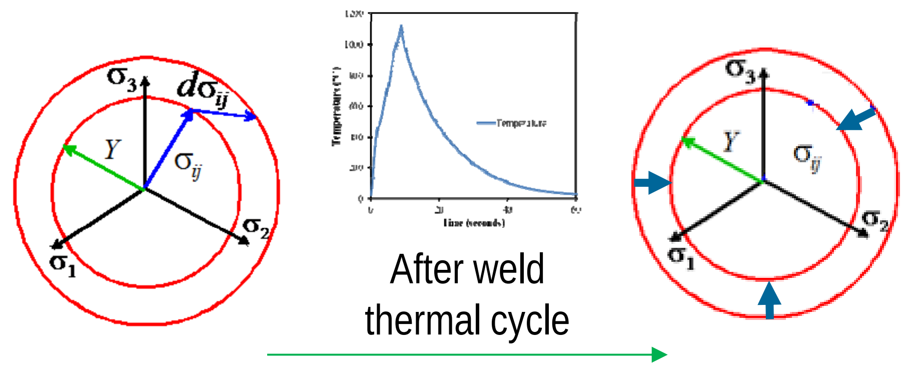


A.F. Bower: Applied Mechanics of Solids.

- The total strain consists of three components.

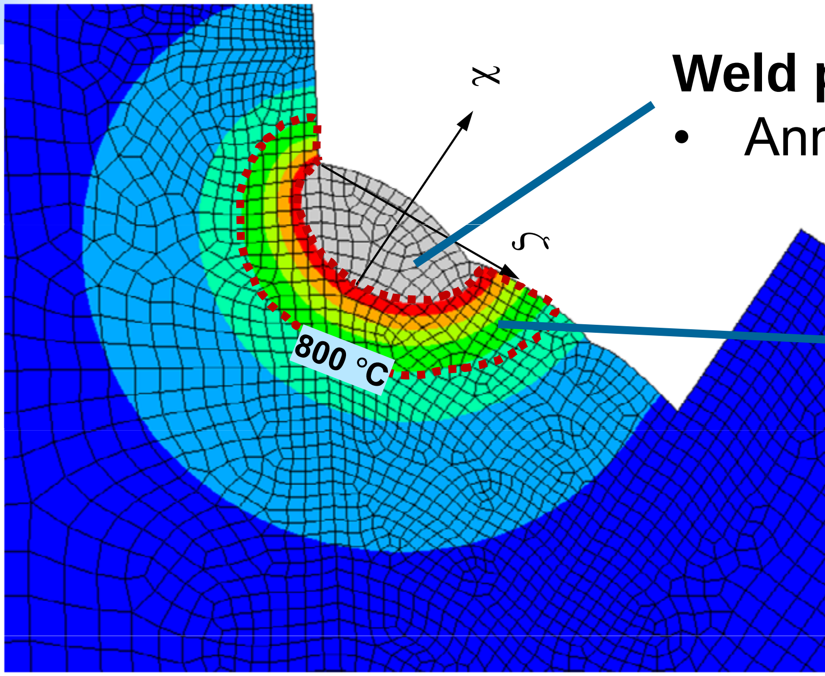
$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p + \boldsymbol{\varepsilon}^{th}$$

In rate-independent hardening rules, there is not consideration of the effect of dynamic dislocation recovery on ε^p.



- The equivalent plastic strain can be over-predicted using conventional hardening rules, which can significantly influence the calculated residual stress values.

Applicability to Multi-Pass DM welds



Weld pool:
- Annealing due to melting

High-temperature HAZ (base metal and reheated weld metal):
- Dynamic recovery with varying extent depending on the local temperature and strain histories

- To put it simply, the dynamic recovery in the weld heat-affected zone (HAZ) is analogous to the annealing due to melting in the weld pool.
- Although it is a relatively common practice to consider the annealing of plastic strains the weld pool, there has been very limited understanding of the extent of dynamic recovery in the high-temperature HAZ.

Goal of this Study

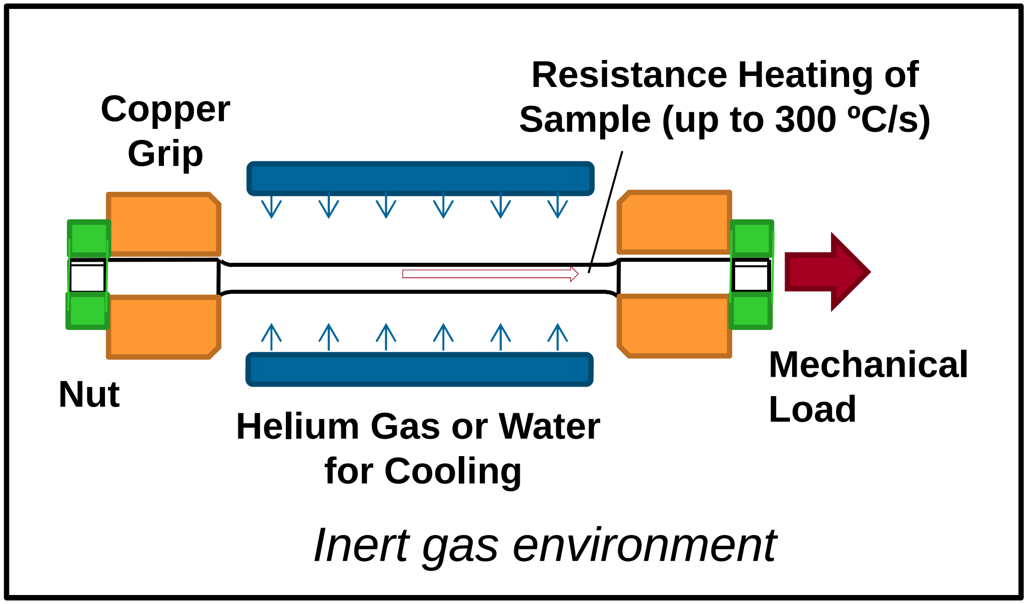
- Funded by EPRI, ORNL has developed a special experimental procedure to quantify the reduction of equivalent plastic strain due to the dynamic recovery effect (or to quantify the over-calculation of equivalent plastic strain based on the elasto-plasticity and the three plasticity based hardening rules).

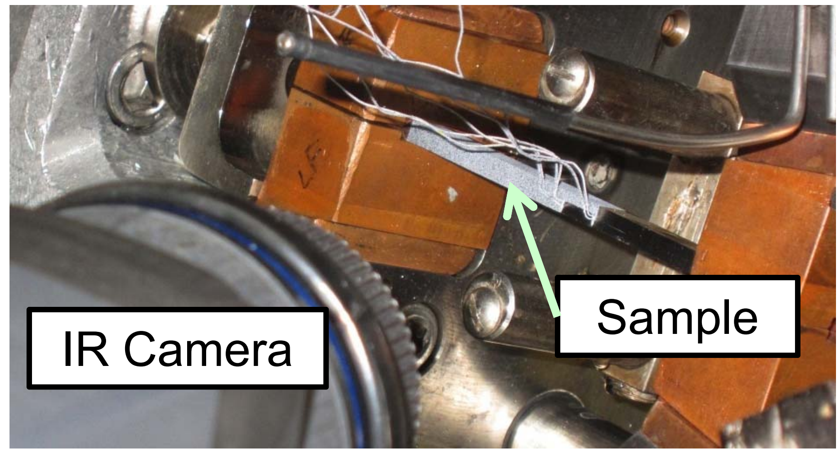
Approach

- High-temperature mechanical testing using Gleeble with special data collection techniques:
  - Ensuring the accuracy of temperature and strains
  - Mimicking the welding heating and cooling cycles and mechanical cycling conditions
- Materials of interest: austenitic stainless steels and nickel alloys for DM welds
- Implementation of new “user materials” incorporating strain hardening laws with dynamic recovery for weld residual stress modeling.

Special Testing Tool using Gleeble

- Gleeble used for applying user-defined thermal and mechanical loads





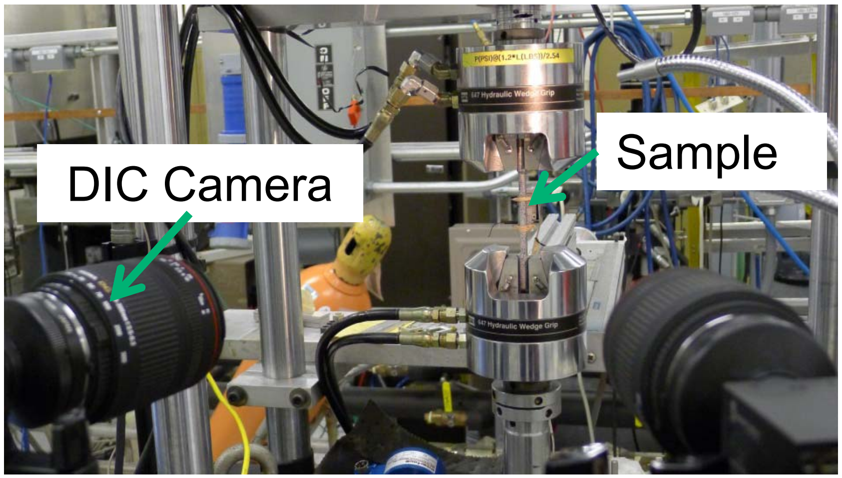
Temperature recorded by thermocouples and infrared (IR) camera

Mimicking the temperature and stress histories experienced by materials in welding in a controlled manner:

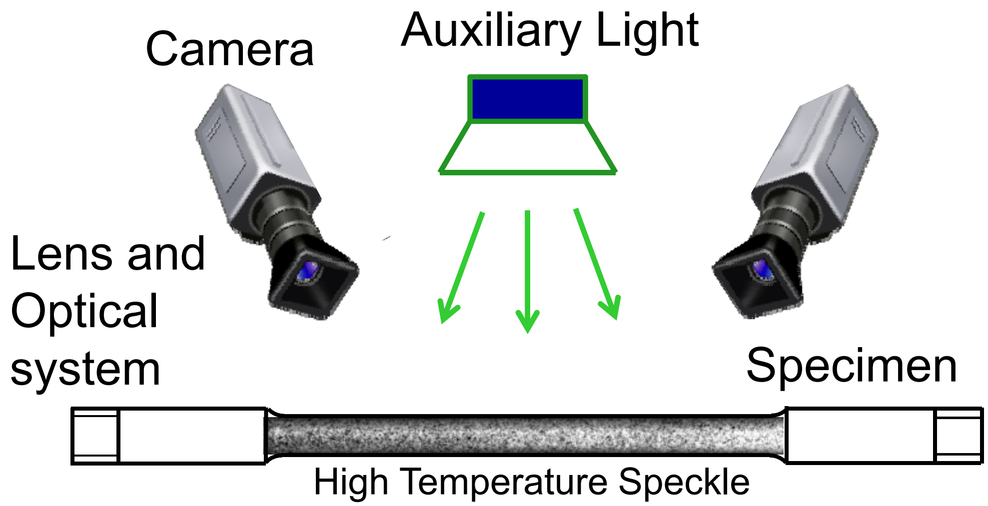
- *Controlled resistance heating and/or gas/water quenching for achieving user-defined temperature profiles*
- *A servo hydraulic system for applying user-defined mechanical loads*

Strain Measurement using 3D Digital Image Correlation (DIC)

- Recording strain history of every point on the specimen surface

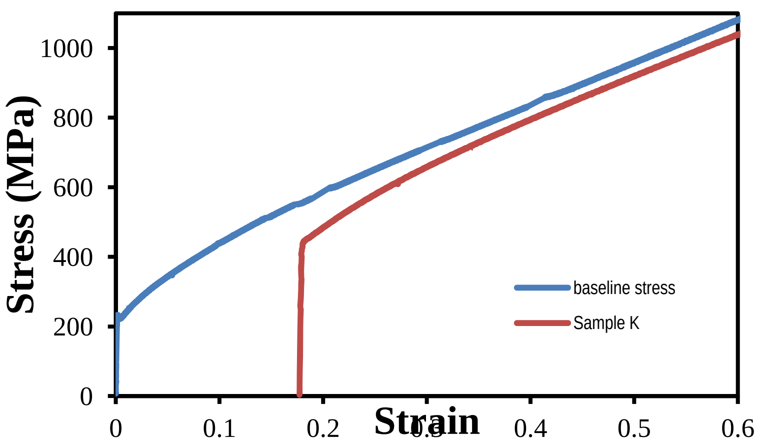


Room temperature DIC setup

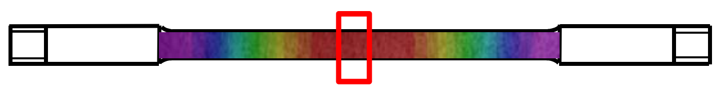


High temperature DIC setup

- True stress vs. true strain data for quantifying the extent of recovery



- True strain obtained for the region of interest from the DIC measured non-uniform strain field



- True stress calculated using the force and the cross-section area

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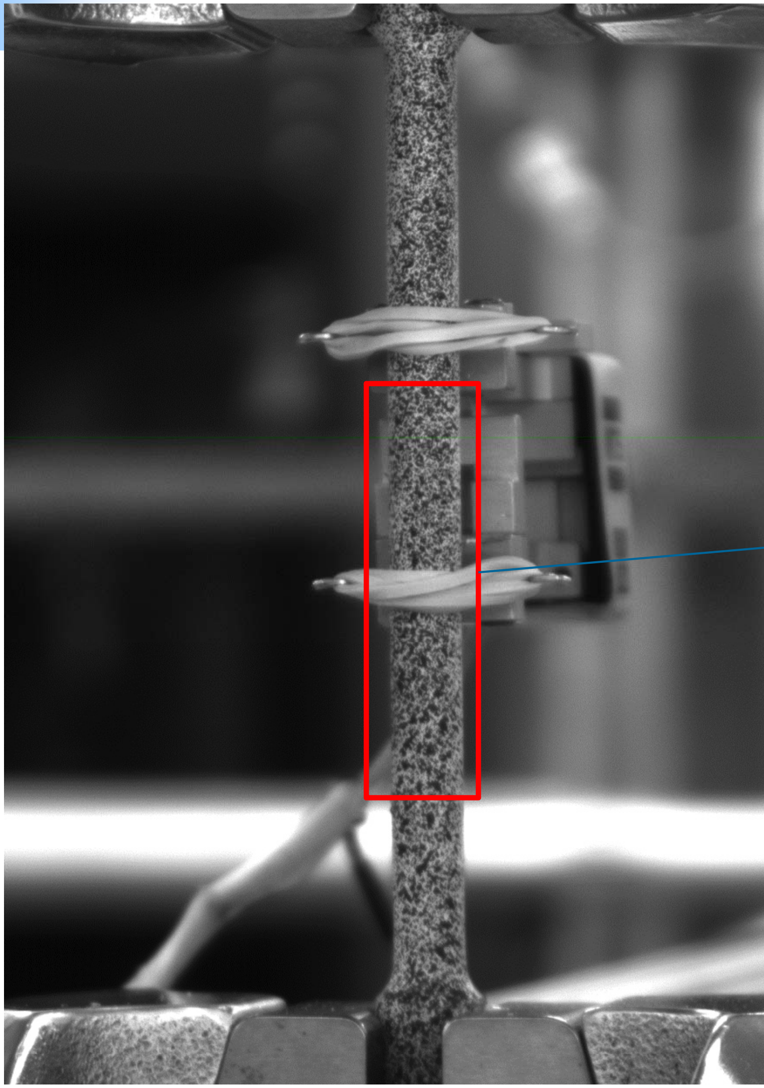
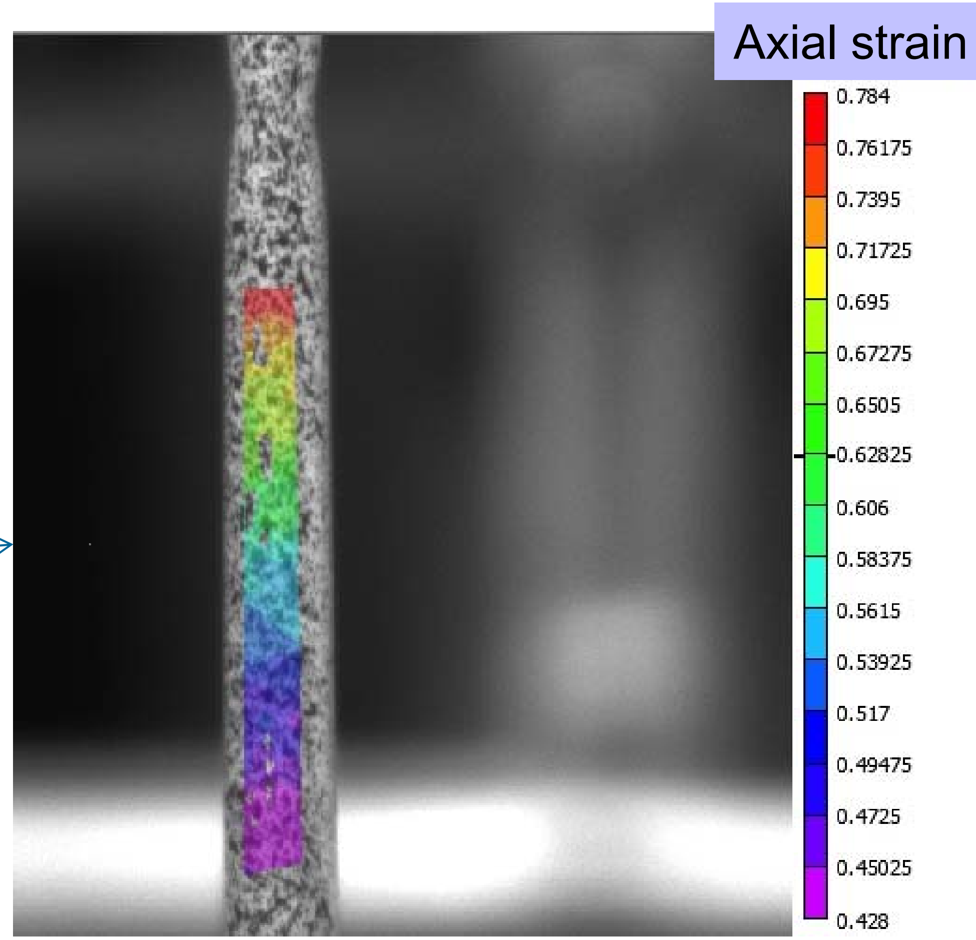
Example of Room-Temperature DIC





- Highly non-uniform strain distribution captured by DIC.

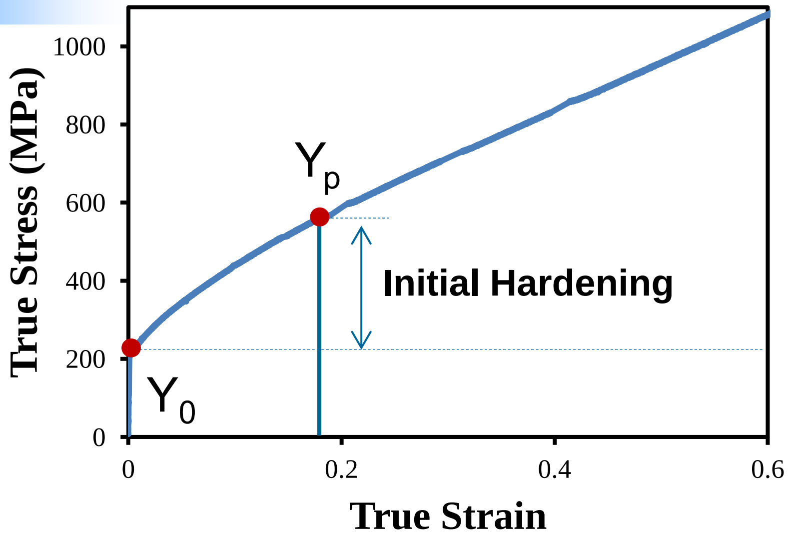
Overview of Testing Procedure

Case 1: Room temperature plasticity	Case 2: High temperature plasticity	Case 3: Simultaneously varying temperature and plasticity
Room temperature tensile plastic strain → Isothermal annealing for different times at different temperatures	High temperature deformation at constant temperatures	Deformation during heating and cooling to simulate real welding process

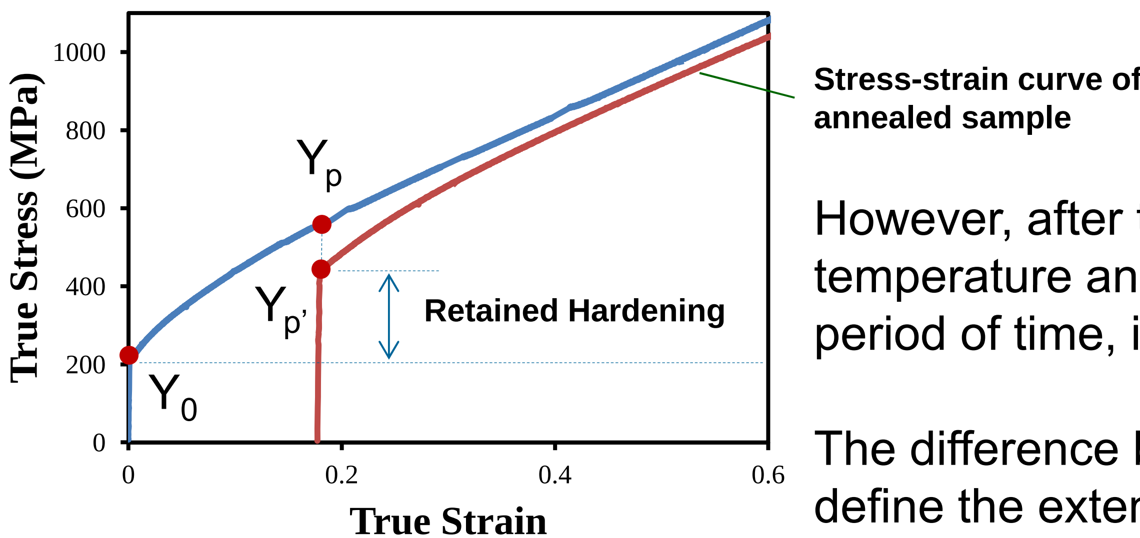
- Final room temperature tensile test to generate the stress-strain curves of processed materials, which are used to reveal the influence of annealing on strain hardening

- Uniaxial tensile tests of annealed 304L austenitic stainless steel.
- Cases 1 and 2 are used to produce the data needed for the constitutive model, as only one variable is changed in a single test of those cases.
- Case 3, mimicking the temperature and strain histories in welding, is used to validate the constitutive model for non-isothermal conditions.

Quantifying the Extent of Recovery



As the material is cold worked, its yield point is shifted to Y_p. Assuming there is no dislocation recovery, when it is subject to subsequent tensile loads, the material will deform plastically only after the applied stress is higher than Y_p.



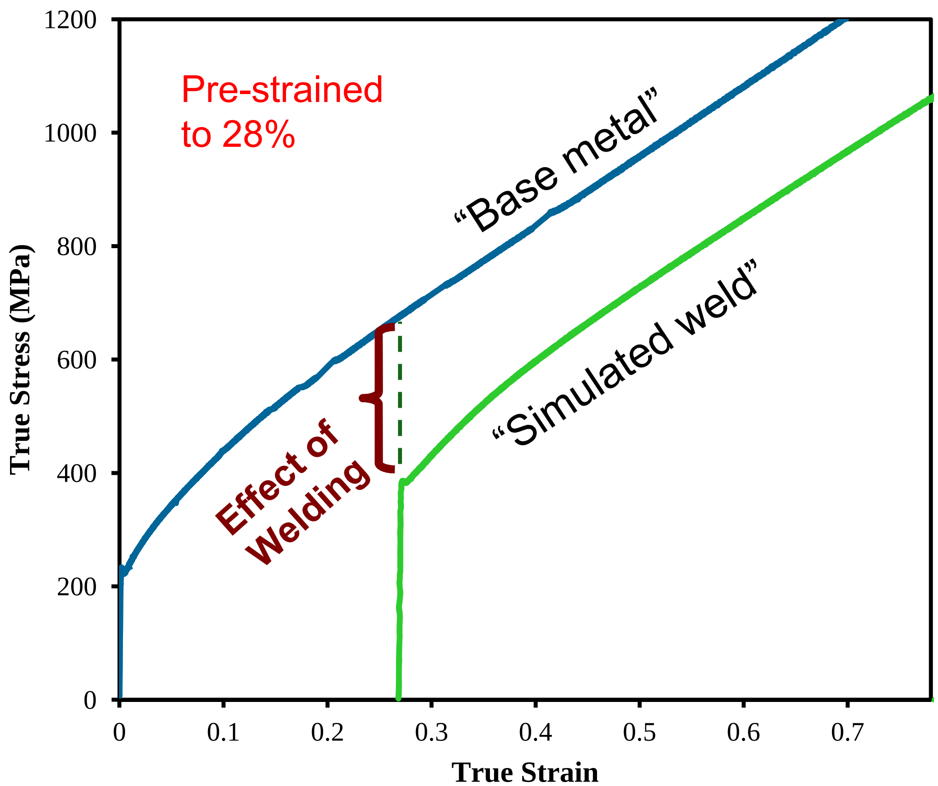
Annealing temperature: 900 °C
Annealing time: 6 sec

However, after the sample is subject to high-temperature annealing even over a short-period of time, its yield point drops to $Y_{p'}$.

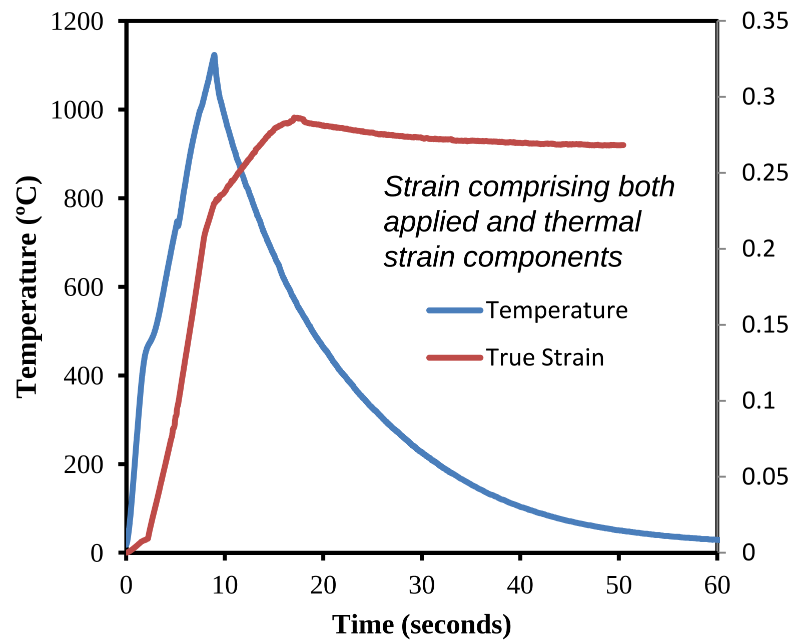
The difference between $Y_{p'}$ and Y_p is used to define the extent of high-temperature recovery.

Case 3 simulating Extent of Recovery during Welding

- Applying ~28% strain during a weld thermal cycle. Then performing room temperature tensile test.



Room-temperature tensile stress-strain curves for base metal and simulated weld



* Temperature history based on that from Material Reliability Program: Welding Residual Stress Dissimilar Model Validation (MRP-316).

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Case 1: Isothermal Annealing

Testing procedure

1. Room temperature tensile strain of about 20%
2. Isothermal annealing in Gleeble
3. Final room temperature tensile test of Gleeble-processed sample to failure

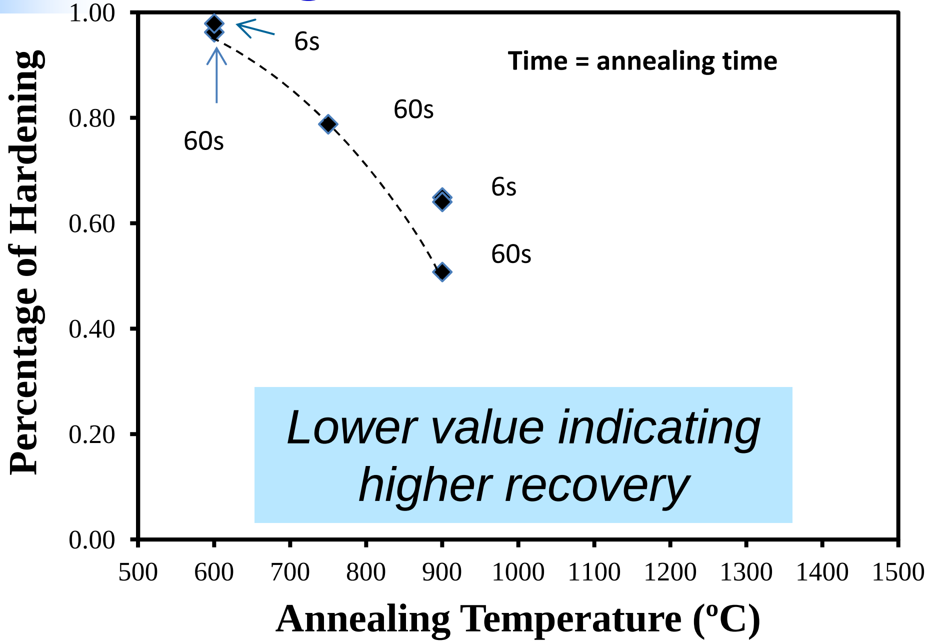
Testing matrix

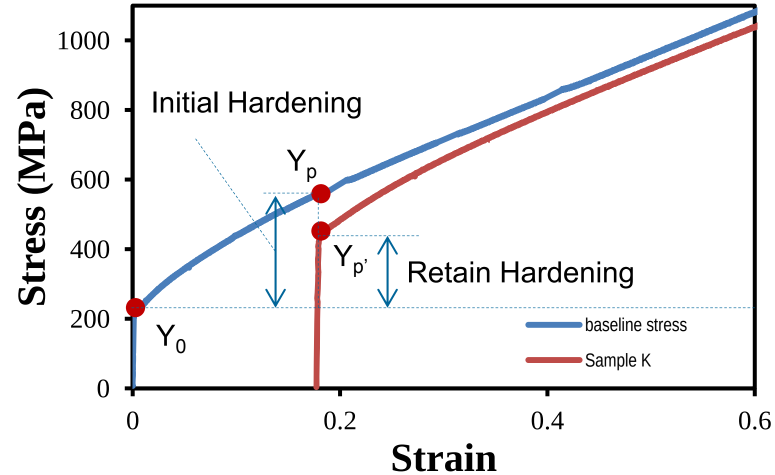
Annealing time	Annealing temperature (°C)						
	600	700	750	800	900	1000	1100
3s							
6s	A		S		O, P		
15s							
60s	N				K		

Other levels of pre-strains are under consideration.

* Letters indicating the ID of samples that have been tested.

Preliminary results of Case 1 - Isothermal Annealing



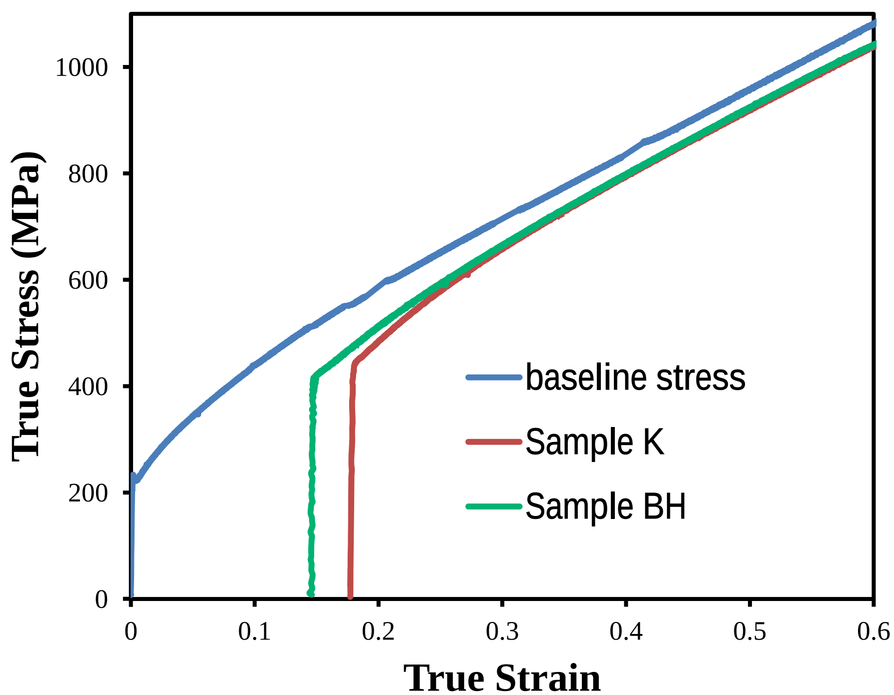


Percentage of hardening $= \dfrac{Y_{p'} - Y_0}{Y_p - Y_0}$

Sample	Annealing Time (seconds)	Annealing Temperature (°C)	Initial strain	Initial yield stress (Mpa)	As annealed yield stress (Mpa)	Stress of softening (yield stress, Mpa)	Percentage of hardening (%)
O	60	900	0.176	559	397	162	0.51
P	6	900	0.172	549	437	112	0.65
K	6	900	0.174	550	435	115	0.64
S	60	750	0.179	560	490	70	0.79
N	60	600	0.169	549	537	12	0.96
A	6	600	0.177	561	554	7	0.98

Preliminary results of Case 2

1. Deformation at a constant, elevated temperature;
2. Quenching to room temperature using helium or water;
3. Room temperature tensile test



- **Baseline:** No heat-treatment
- **Sample BH** of Case 2: Tension to 14.6% plastic strain in 0.5 sec at 900 ºC
- For comparison, **Sample K** of Case 1 is superimposed. It has a 17.7% plastic strain at room temperature, followed by annealing for 60s at 900 ºC.

Summary

- Testing results clearly revealed the effect of welding thermal cycle on the strain hardening behavior. Suggest that the constitutive laws used in the current WRS modeling practices can be inadequate to capture the reduction of strain hardening.
- There is a physic basis for such behavior – recovery and/or recrystallization (annihilation of dislocations).
- Comprehensive experimental testing is under way to develop new constitution rules to adequately quantify the effect of welding thermal and mechanical cycling on the strain hardening behavior, in order to improve the quality of calculation result of weld residual stresses.

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  - Fracture mechanics analysis of welds
  - Weld pool fluid flow
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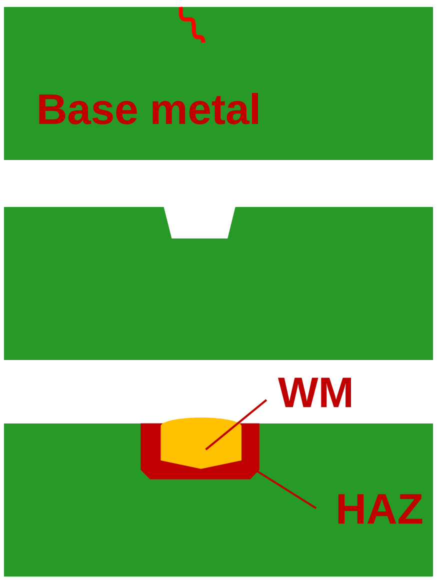
- Zhili Feng, Eric Willis and Ken Wolfe: *A Computational Modeling Tool for Welding Repair of Irradiated Materials*, AWS Professional Program 2011, Chicago, IL.

Challenges for Nuclear Power Plant Life Extension and Power Up-rate

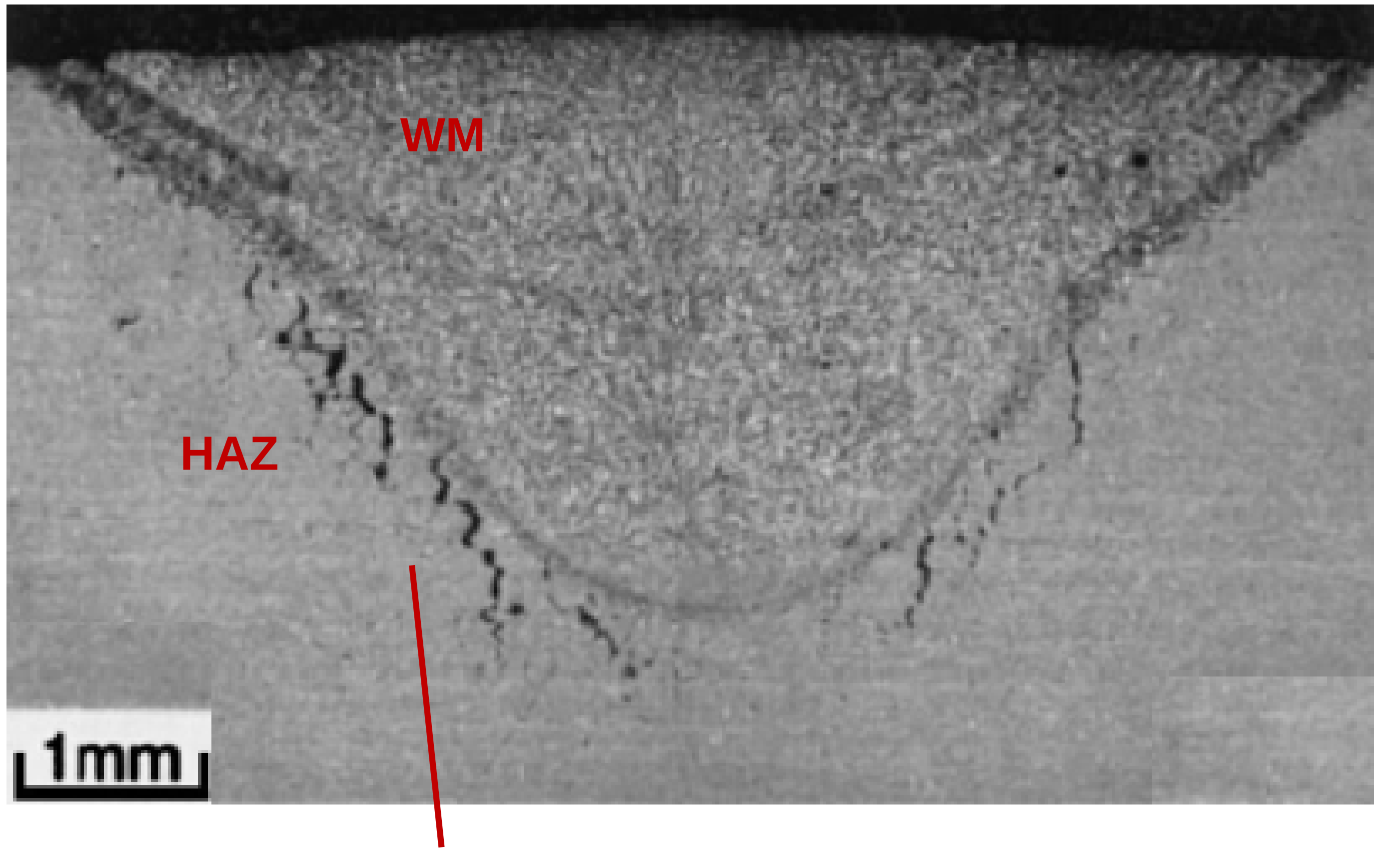
- ***Materials aging and degradation*** due to prolonged lifetime and power up-rate leading to increased exposures to radiation, thermal and stress extremes.
- U.S. Department of Energy (DOE) sponsored **Light Water Reactor Sustainability (LWRS)** Program (aka life beyond 60).
- **Weld repair of nuclear reactor structures** is identified as a key enabler for life extension and power up-rate.

The Problem: Helium Induced Weld Cracking of Irradiated Materials significantly Reducing Repair Weldability

One scenario of welding repair



- *WM - Weld metal*
- *HAZ – Heat affected zone*



- Cracking in HAZ due to helium bubble coalescence driven by the weld temperature and tensile stress.

Reference: Asano et al., J. Nucl. Mat., 264 (1999) 1-9.

Fundamentals: Where does Helium originate?

- Helium is generated as a result of irradiation of boron and nickel in reactor internals materials:
  - $^{10}B(n, \alpha) \rightarrow {}^{7}Li + He$
    - Occurs early in the component's life-cycle until boron burn-up is completed
  - $^{58}Ni(n, \gamma) \rightarrow {}^{59}Ni(n, \alpha) \rightarrow {}^{56}Fe + He$ (2-step reaction)
    - Continues through the component's life

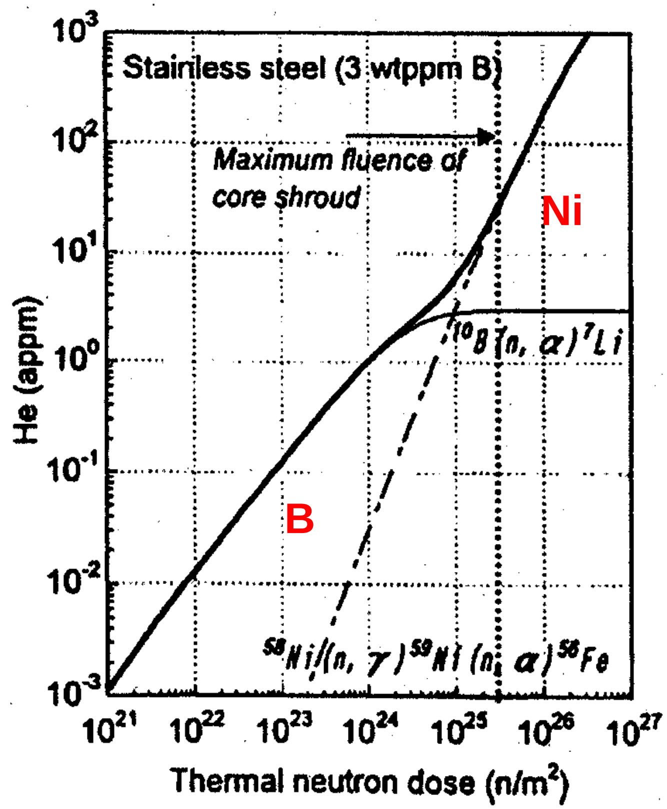
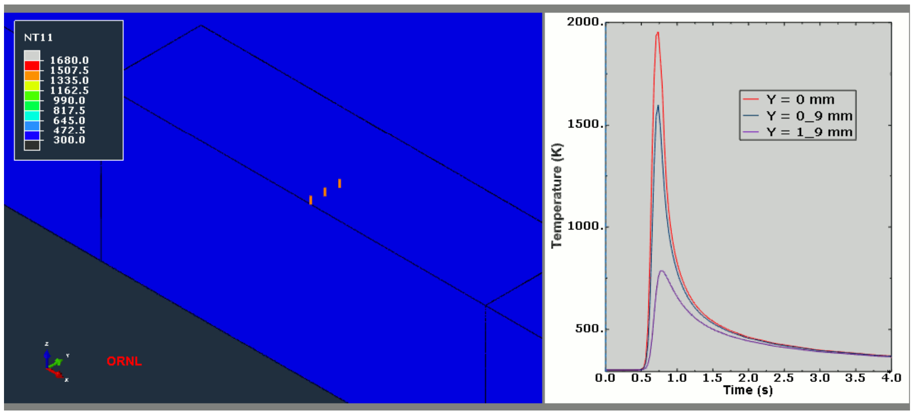
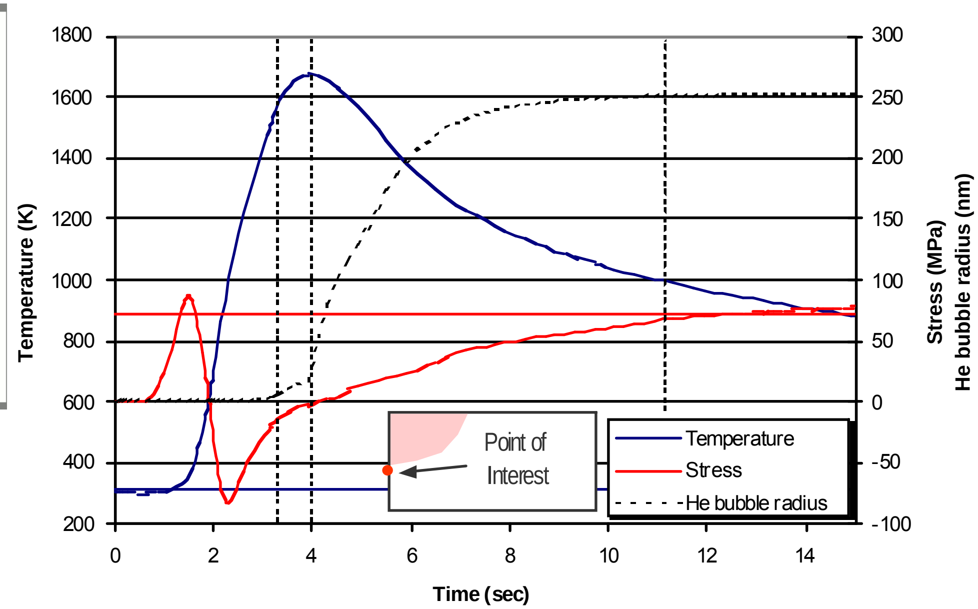
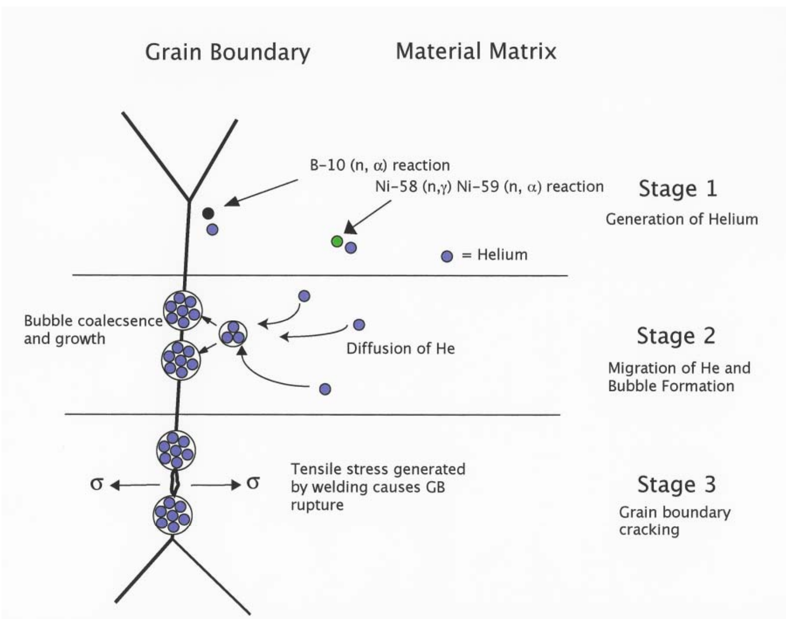


FIG 5.4.2-42 Neutron Dose vs. Amount of He Generated

Fundamentals: Helium Induced Weld Cracking







- Upon heating during welding, helium bubbles form and coalesce at the grain boundaries
- Upon cooling cracking in the HAZ of the weld occurs
- Conditions required for cracking depend on helium concentration, time at temperature, and stress state during cooling from welding

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Helium Bubble Growth Model (After Kawano et al.)

- Basic variables:
  - Bubble density (N), radius (r), and spacing (L)
- Initial He bubble at grain boundary:
  - Already nucleated prior to welding
  - Density is proportional to the He concentration

$$N_0 = \alpha C_{He}$$

  - Initial He bubble radius, r_i is 1 nm (after Lin and Grossbeck et al.)
- Differential equations
  - Density change due to bubble migration and coalescence (after Olander)

$$\frac{dN}{dt} = -2\pi D_s \left(\frac{a}{r}\right)^4 \frac{N^2}{\ln(L/2r)}; \quad L = 1/\sqrt{N}$$

  - Radius change (after Lin and Grossbeck et al.)

$$\frac{dr}{dt} = \begin{cases} \dfrac{\delta\Omega D_{gb} C_v^e}{2r^2}; & for\ \sigma \leq 0 \\ \dfrac{2\pi\delta\Omega D_{gb}}{LrkT}\sigma; & for\ \sigma > 0 \end{cases}$$

Helium Bubble Growth Model (Cont'd)

- Cracking Criterion (after Mclintock's ductile fracture model)
  - Ductile fracture occurs when the tensile strain in welding (ε_w) exceeds the fracture strain (ε_f):

$$\varepsilon_w \geq \varepsilon_f = \frac{(1-n)\ln(L/2r)}{\sinh\left(\sqrt{3}(1-n)/2\right)}$$

    - n = plastic work hardening rate (0.3)

Unlike WRS modeling where the final stress distribution is of interest, the modeling of helium-induced cracking requires the entire temperature and stress histories to be accurately predicted.

Modeling Example – Single Pass Weld

- TIG Bead-on-Plate, with filler, 4kJ/cm, single pass
- Initial helium concentration = 3.4 appm
- Cracking observed in experiment

Peak Temperature, K

Bubble radius, r_{max}=329 nm

Bubble spacing, nm

ε_w-ε_f =0.83 > 0, cracking

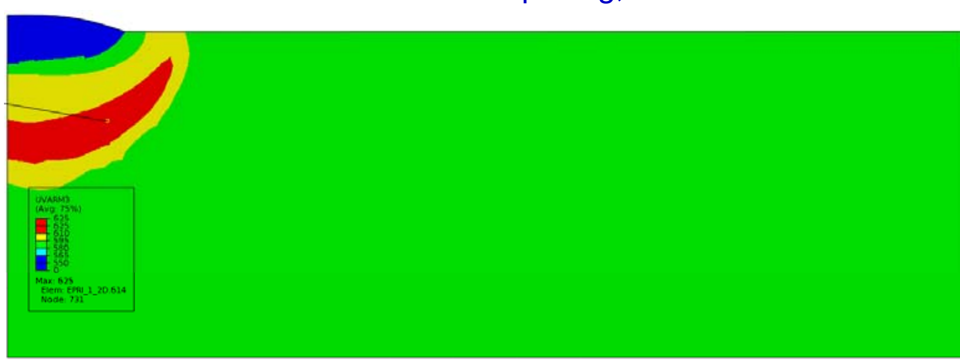
Modeling Example – Single Pass Weld (cont’d)

- TIG Bead-on-Plate, with filler, 4kJ/cm, single pass
- Initial helium concentration = <u>1.1 appm</u>
- No cracking observed in experiment

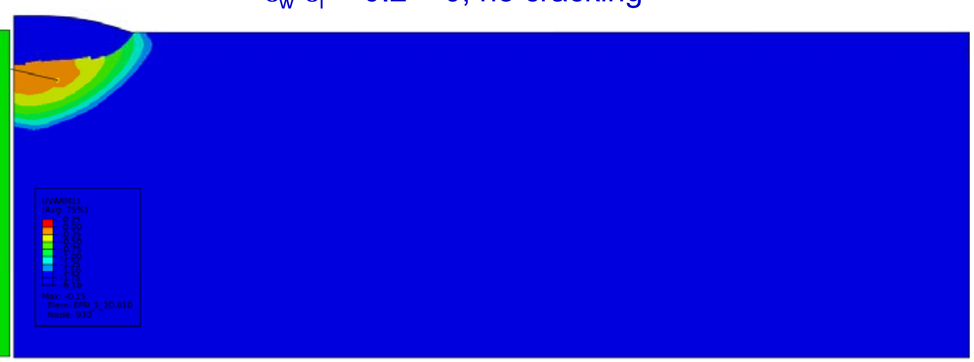
Peak Temperature, K

Bubble radius, r_{max}=256 nm

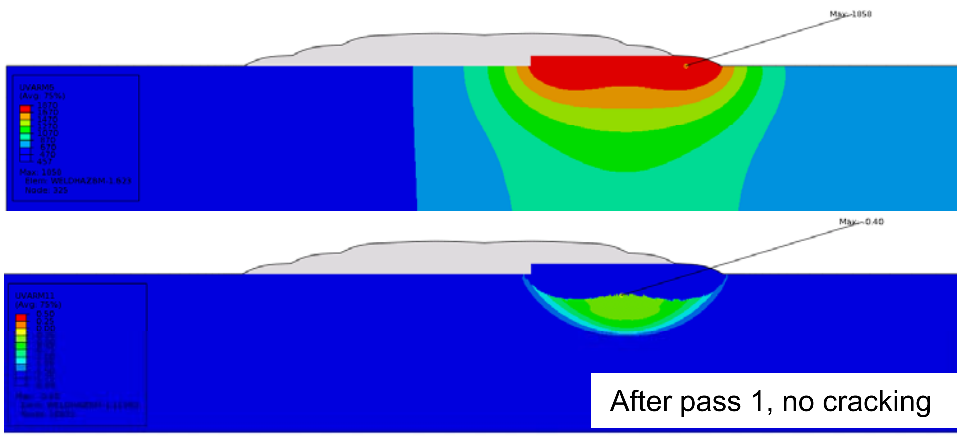
Bubble spacing, nm

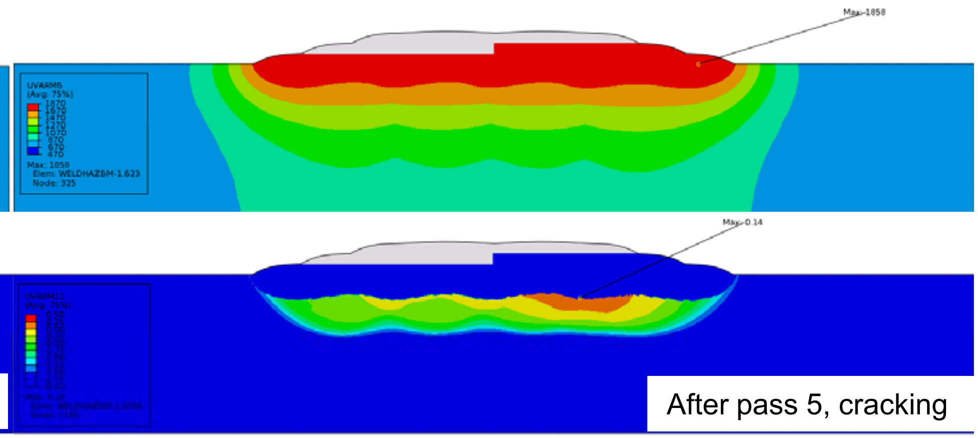


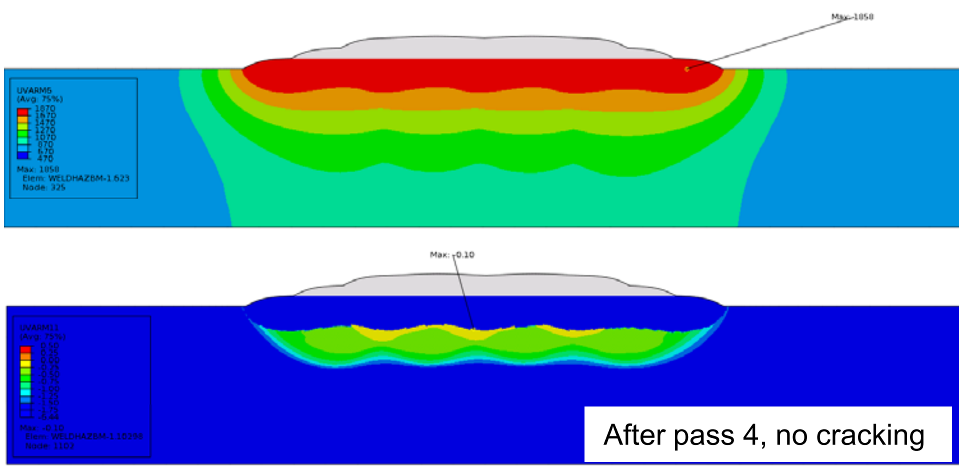
ε_w-ε_f =-0.2 < 0, no cracking

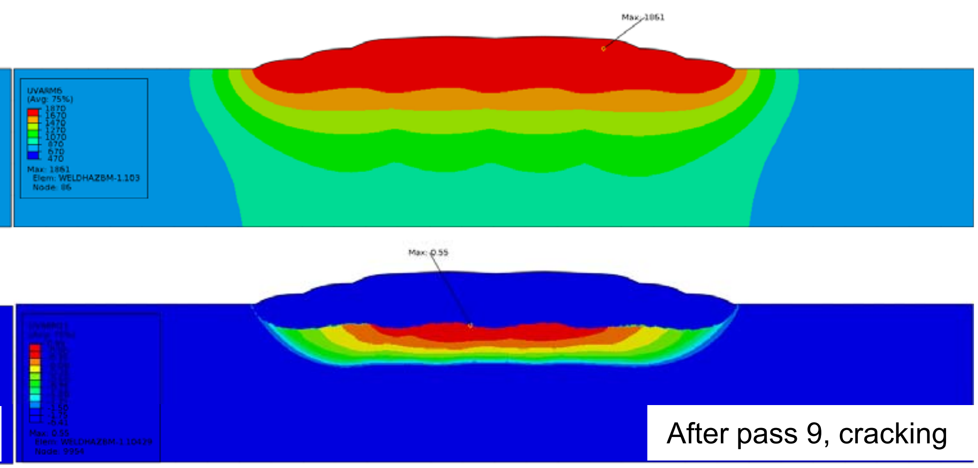


Modeling Example – Multi-pass Weld Overlay (10kJ/cm, 0.45 appm He)









Cracking observed in experiment

EPRI LTO and DOE LWRS Collaboration: Advanced Welding-Repair Technologies

Special welding cell at ORNL

- Ability to safely handle irradiated materials
- Major welding capabilities:
  - Laser and laser-arc hybrid
  - Friction stir welding
- To be completed by 2014

- Eric Willis and Zhili Feng : *Advanced Welding-Repair Technologies for Irradiated Reactor Materials*, 2011 Second Workshop on U.S. Nuclear Power Plant Life Extension and Development, Washington, DC.

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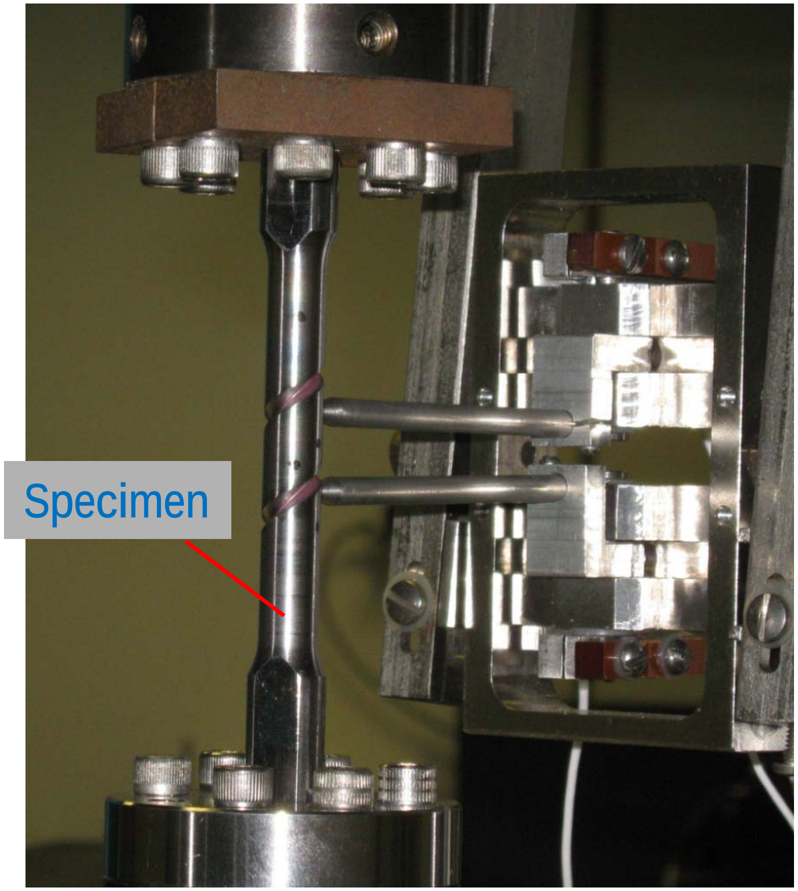
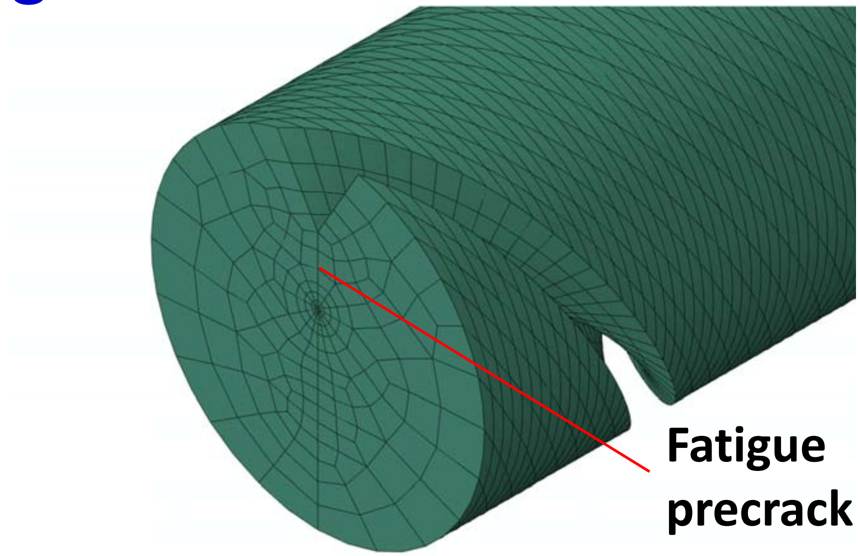
Automated Mesh Generation around Spiral-Shaped Crack for Fracture Toughness Calculation



During spiral notch torsion testing (SNTT), a torque is applied at the ends of the sample subjecting the entire sample to pure shear forces.



Automated meshing script

- Rings of elements centered on the spiral crack tip line to facilitate the contour integral calculation
- Element: 20-node quadratic brick

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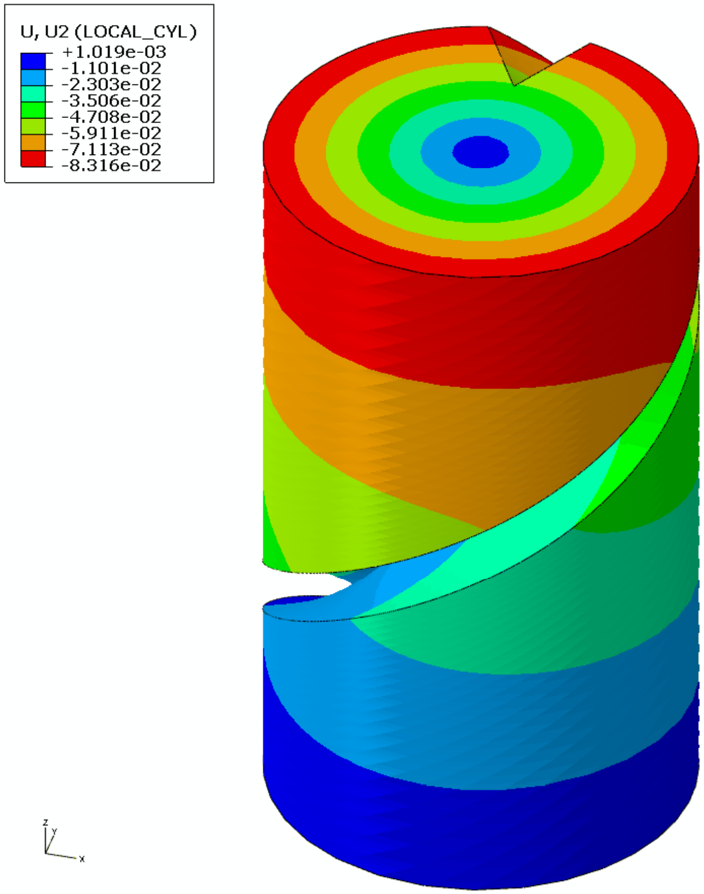
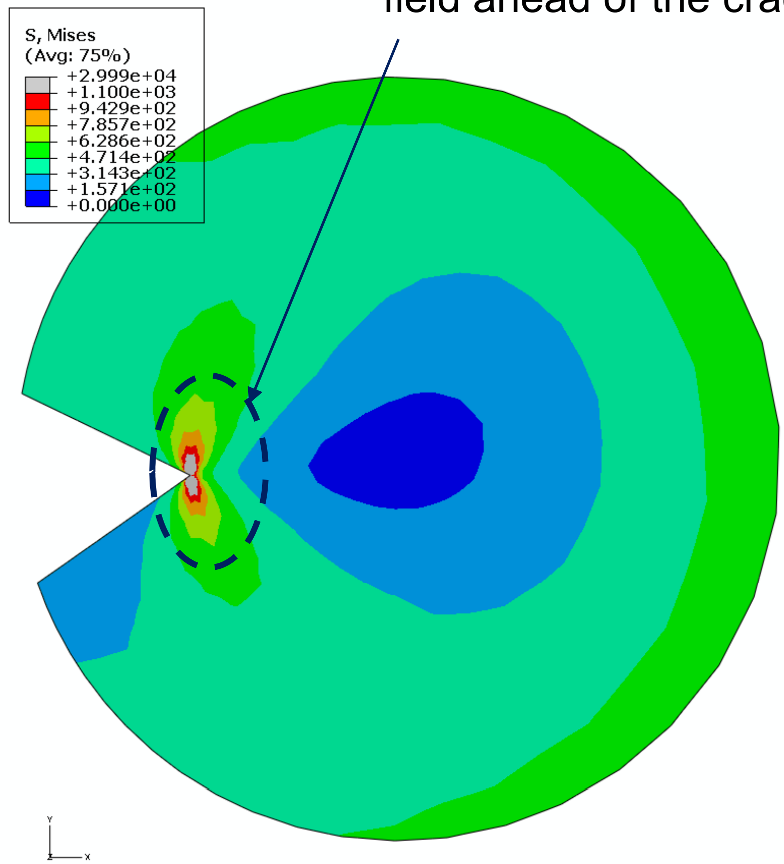
Example of Calculated Results after Applying Torque

Classic butterfly shape of stress field ahead of the crack tip



Circumferential displacement (mm)



von Mises stress at a cross-section (MPa)

From the strain and stress fields, the contour integration method is used to calculate the fracture toughness (J_{Ic} and K_{Ic}).

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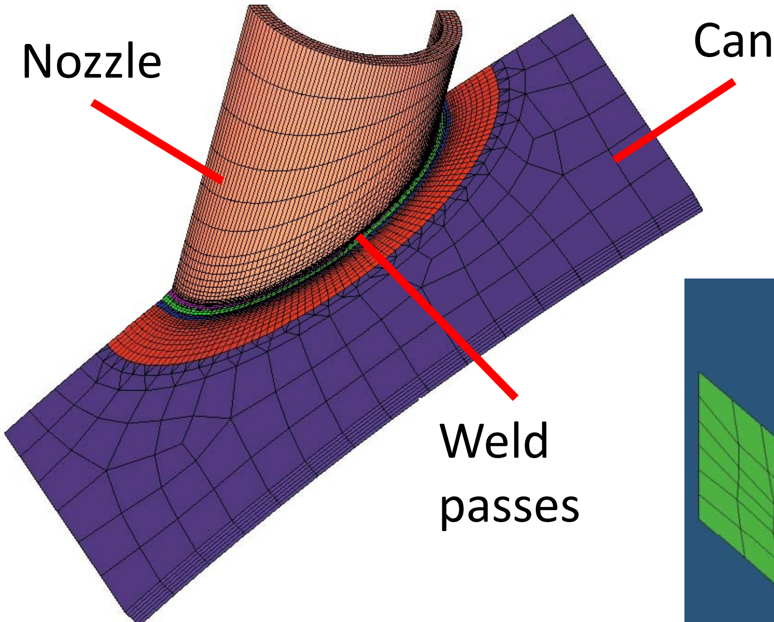
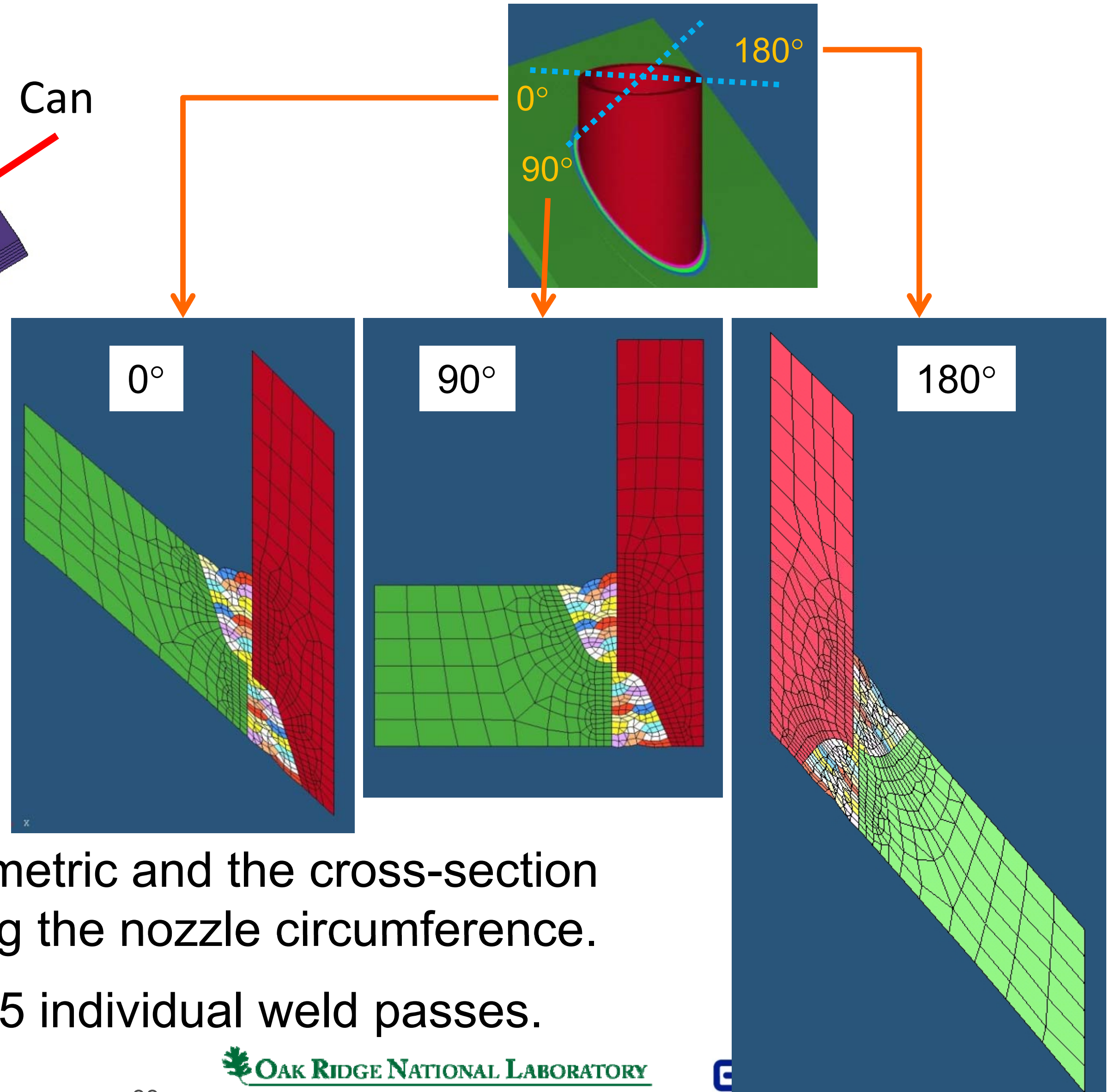
Mesh Generation of Complex Structure for WRS and Distortion Modeling





- Geometry is not axisymmetric and the cross-section varies continuously along the nozzle circumference.
- Final mesh consists of 25 individual weld passes.

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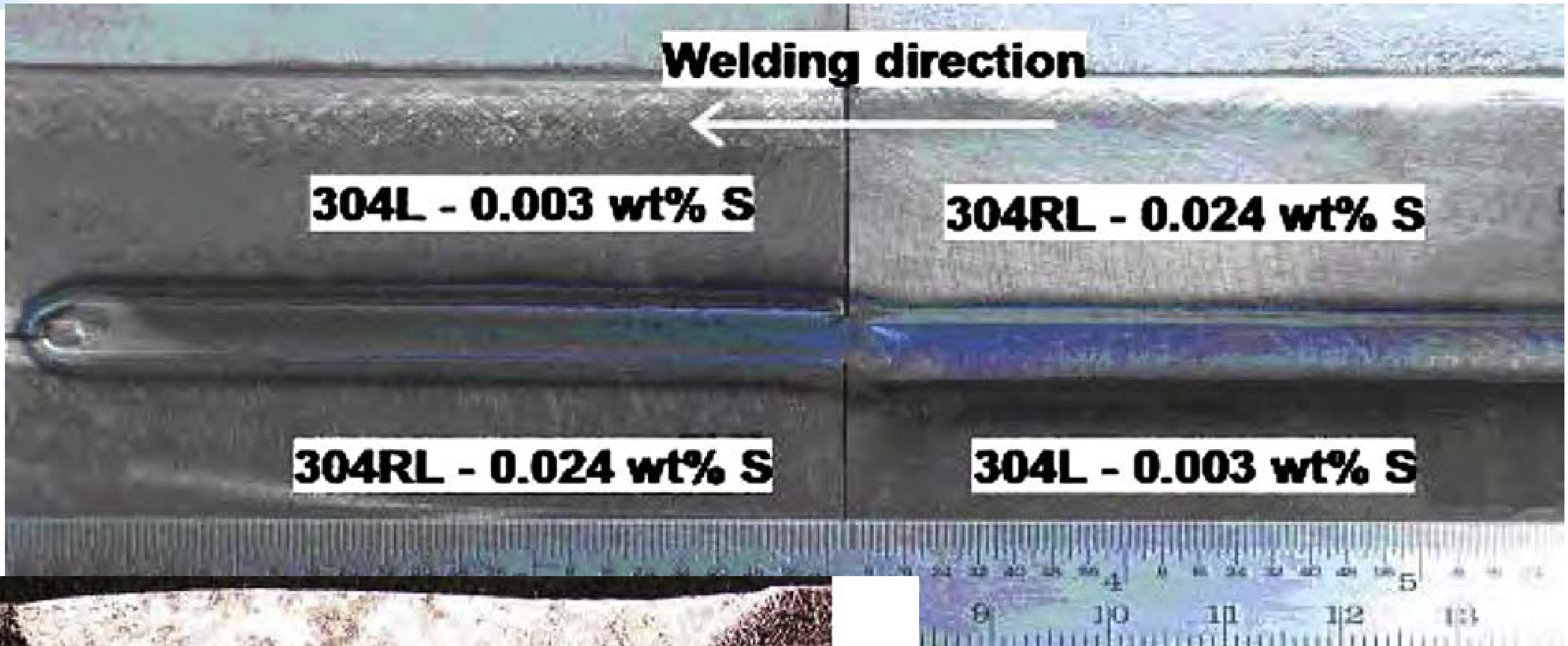
Why're We interested in Weld Pool Fluid Flow?

From Mishra, et al., Acta Materialia, 2008.

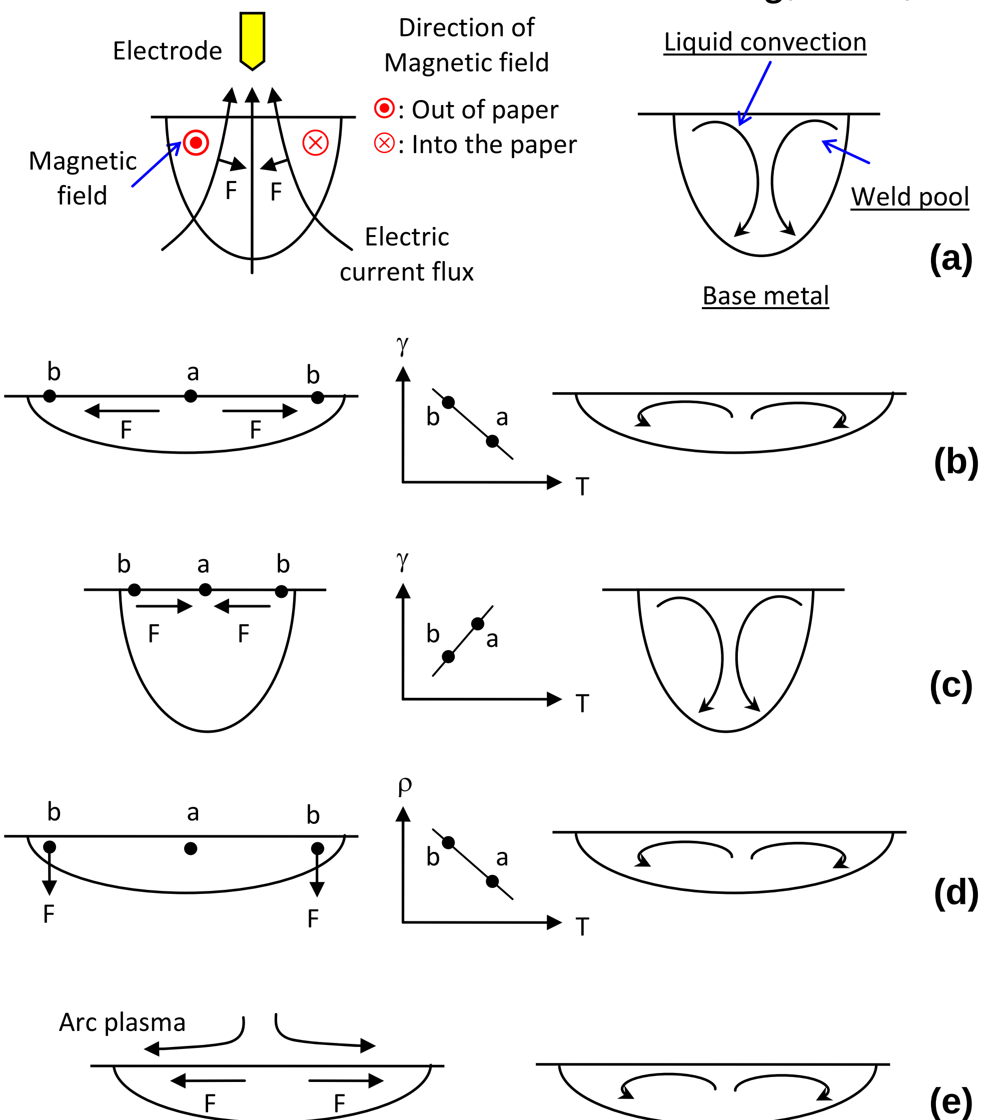


Sulfur = 0.003 wt% Sulfur = 0.024 wt%

- A heat conduction model cannot explain the weld penetration shifted to the low sulfur side.
- Moreover, the heat conduction model cannot accurately describe the temperature in the weld HAZ.

Driving Forces for Fluid Flow in the Weld Pool

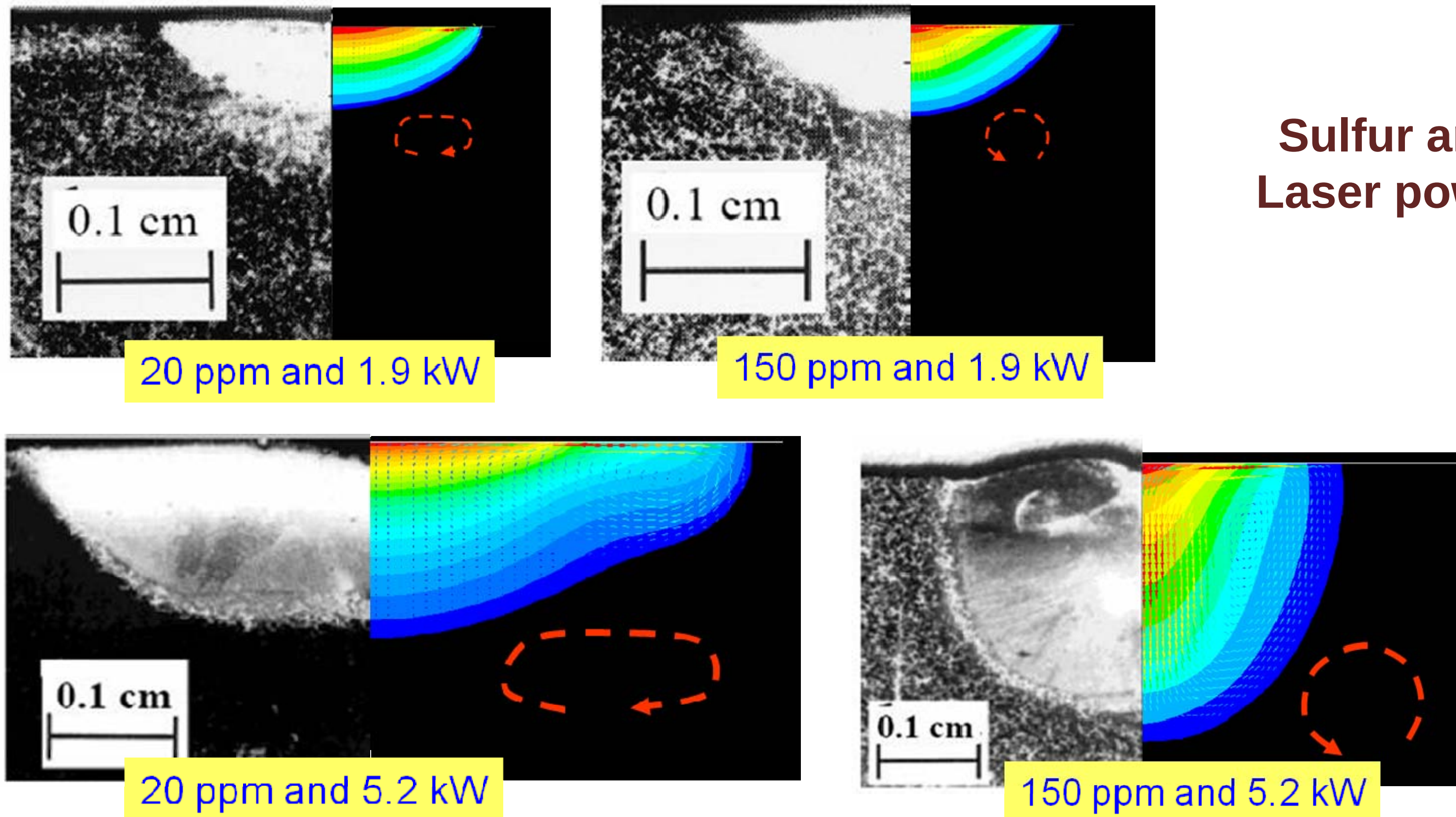
From Zhang, et al., ASM Handbook Vol. 6A, 2011.



Various driving forces and the resulting liquid convection in a gas tungsten arc weld pool:
(a) Electromagnetic force.
(b) Surface tension gradient force with negative $\partial\gamma/\partial T$.
(c) Surface tension gradient force with positive $\partial\gamma/\partial T$.
(d) Buoyancy force.
(e) Plasma jet shear stress.

The symbol γ is the surface tension, $\partial\gamma/\partial T$ is the temperature coefficient of surface tension, T is the temperature, ρ is the density, a and b are two locations in the weld pool, and F is the driving force.

Weld Pool Fluid Flow affecting Bead Shape and Temperature Distribution



Sulfur and Laser power

- Sulfur and other impurities can significantly affect the fluid flow by changing the surface tension.
- Such effect is especially significant for high input welding conditions.

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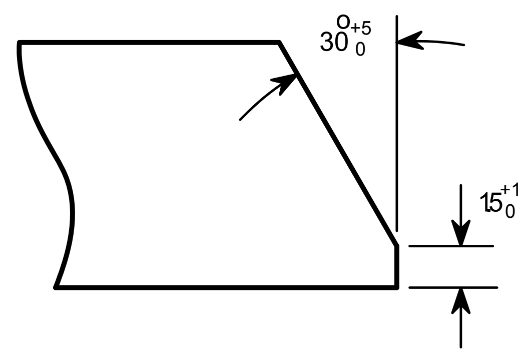
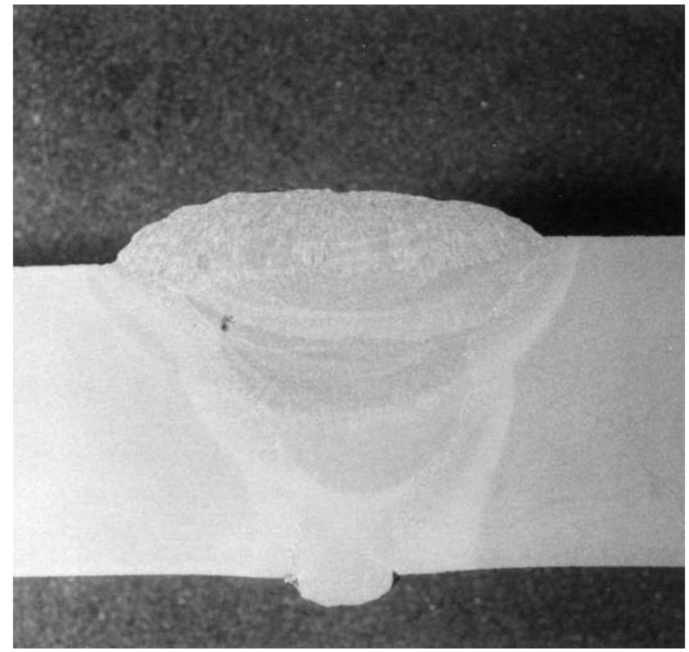
Modeling of Weld Residual Stress in X65 Pipe Girth Welds (Feng & Chauhan, 2002)

- API 5L Grade X65 pipe
  - 0.13-0.2%C, 1.3-1.6%Mn, 0.31-0.33%Si
  - 3-m long
  - 36-in OD
  - Wall thickness: 5/8 and ½ in
- Manual SMAW girth weld
  - Six passes
  - 60 deg V-groove
- AWS E6061 electrode for root and second pass, and E8010 for other 4 passes

Pass No.	Travel Speed cm/min)	Interpass Temp. (ºC)	lectrod Size (mm)	Electrode Type AWS	Heat Input (kJ/mm)
1	26	50	4	E6010	0.84
2	35	60	4	E6010	0.76
3	24	80	5	E8010	1.26
4	12	50	5	E8010	2.16
5	13	70	5	E8010	1.86
6 (cap)	13	90	5	E8010	1.59



Predicted Microstructure Distributions



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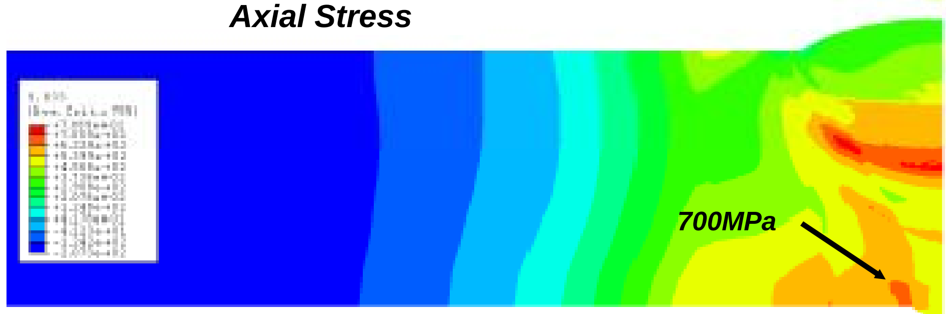
Residual Stresses in X65 Girth Welds

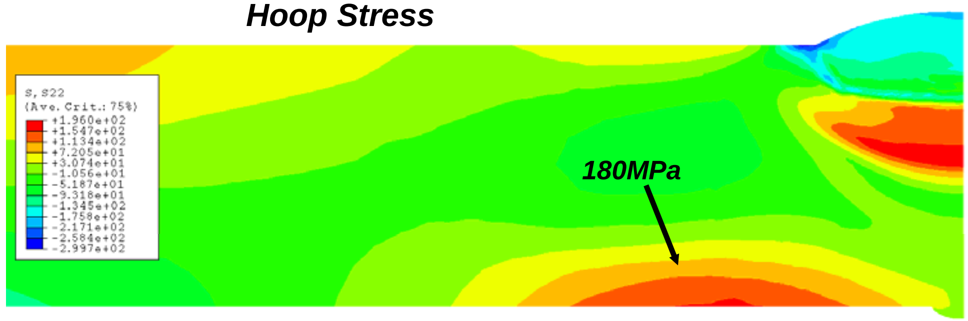
As-welded

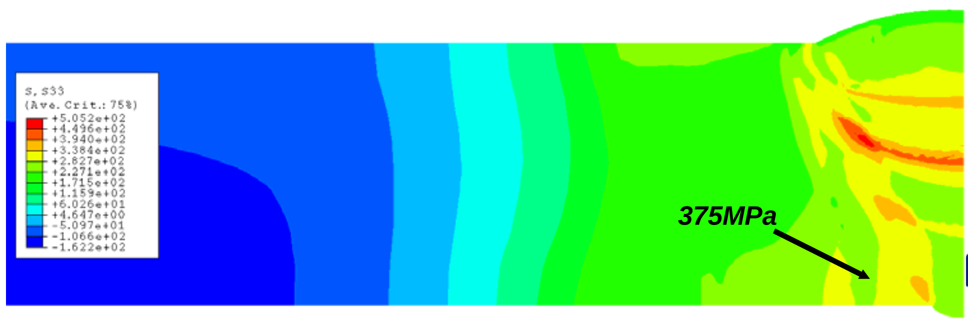
Axial Stress



Hoop Stress

After hydro-test





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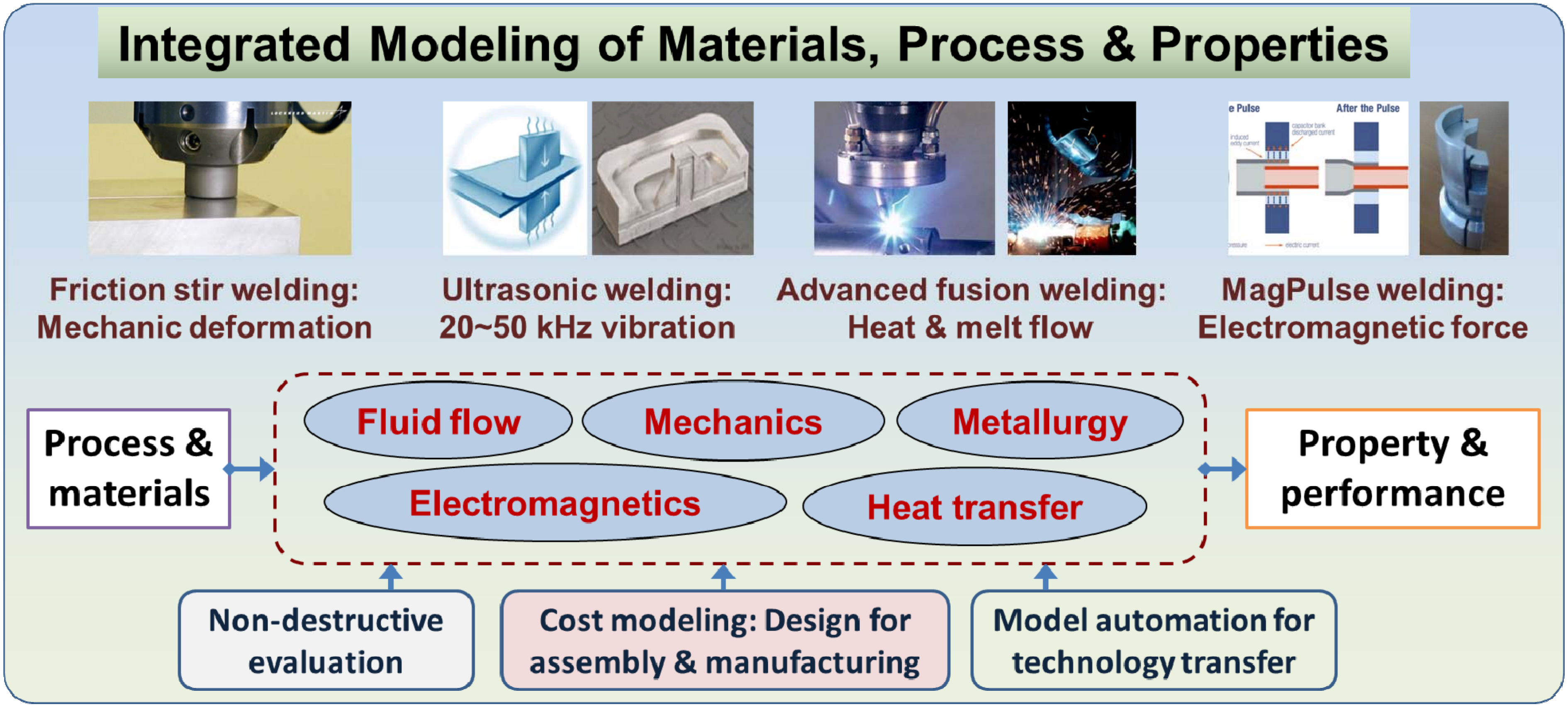
Summary

- Welding is an inherently multi-disciplinary subject.
- Integrated, multi-physics solution at ORNL:



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Academic and International Programs for Residual Stress

January 2012
Charlotte, NC

Michael R. Hill

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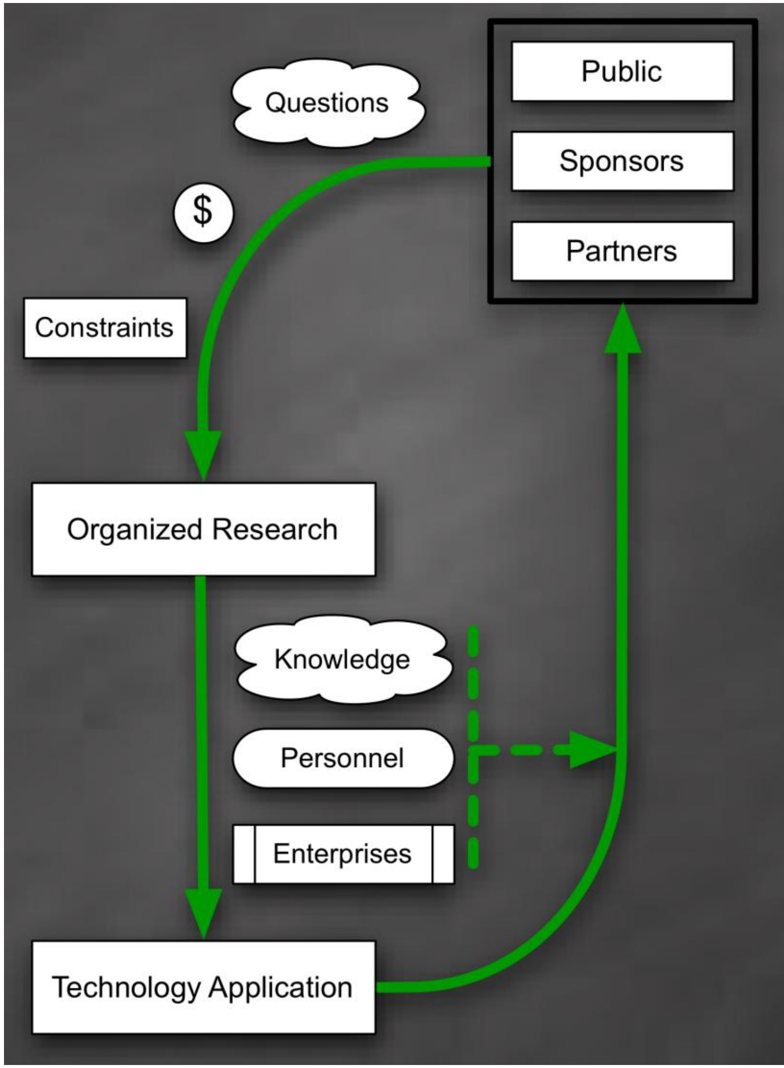
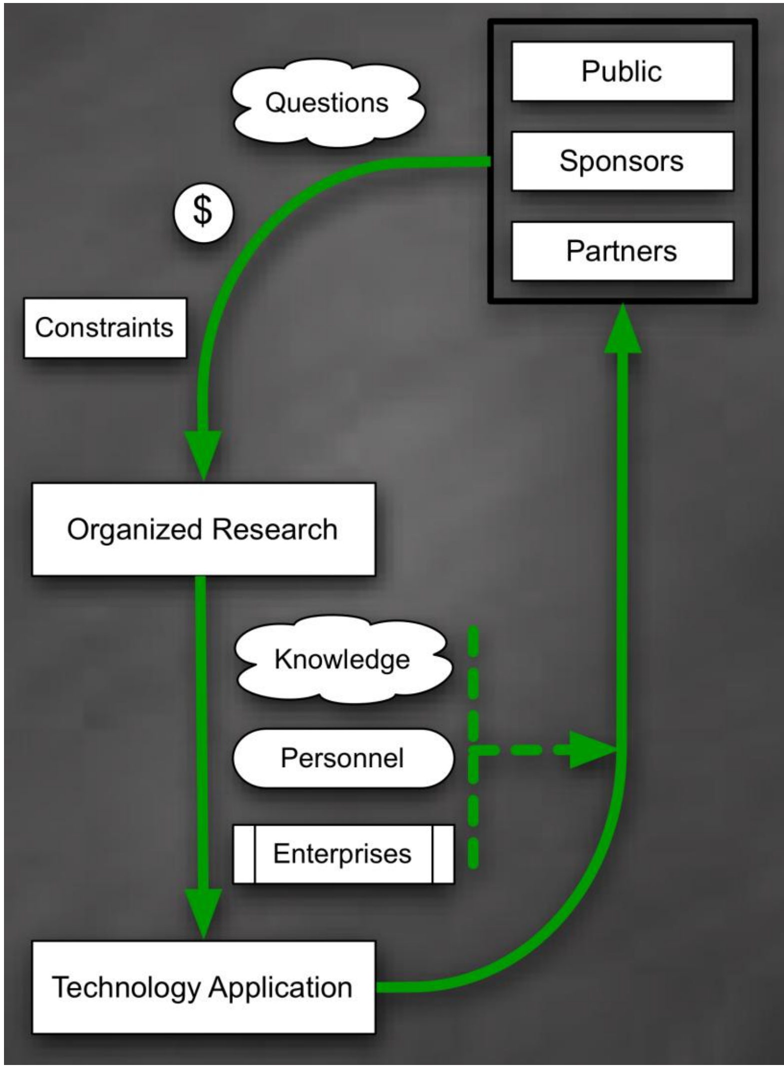
Academic and International Programs for Residual Stress

- Experience driven presentation
- Aviation Residual Stress Technology Development
  - Fatigue life improvement (aircraft)
    - Government funded programs
  - Cost and lifetime savings by understanding residual stress in aircraft structural forgings
- Residual Stress in DM Welds
  - NRC/EPRI Cooperative Program
  - Potential areas for further work
  - International collaborations



Aviation residual stress technology development

- **Partners**
  - End-user: Military Aircraft Programs
    - SPOs: F-22, A-10, F-16, F-35
    - OEMs: Boeing, Lockheed-Martin, Sikorsky
  - Process developer (LSP): LLNL and MIC
  - Certification: USAF, FAA
- **Sponsors**
  - LLNL, MIC, LSPT
  - FAA, AFRL, NAVAIR
  - DoD SBIR Programs
- **Research Questions**
  - Reliable residual stress measurements
  - Experiments to demonstrate fatigue life improvement from LSP
  - Design tools for residual stress
  - Derive cost and lifetime savings by understanding residual stress in aircraft structural forgings

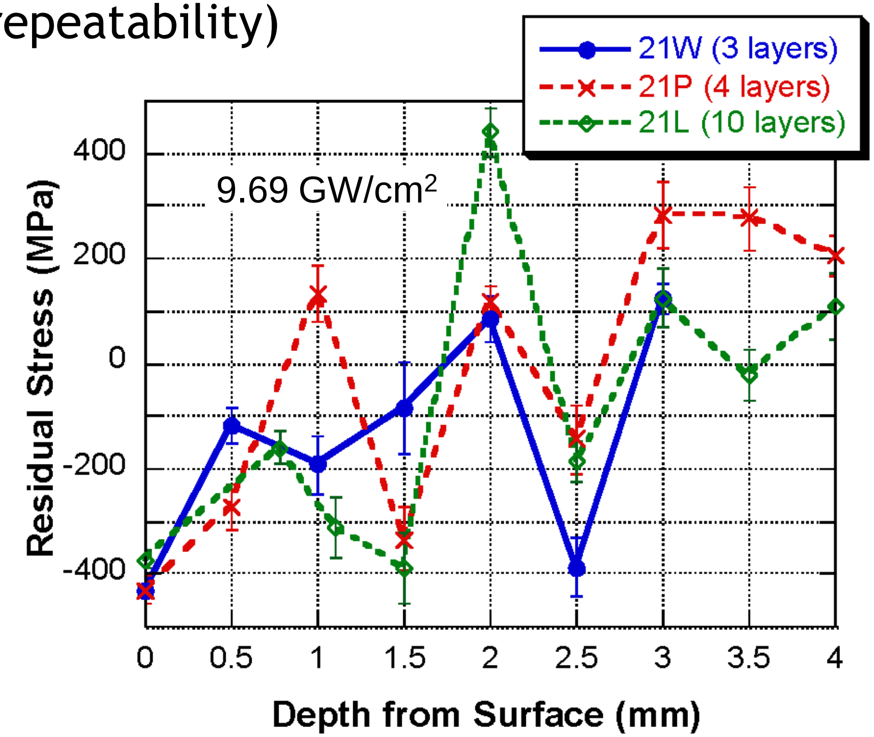


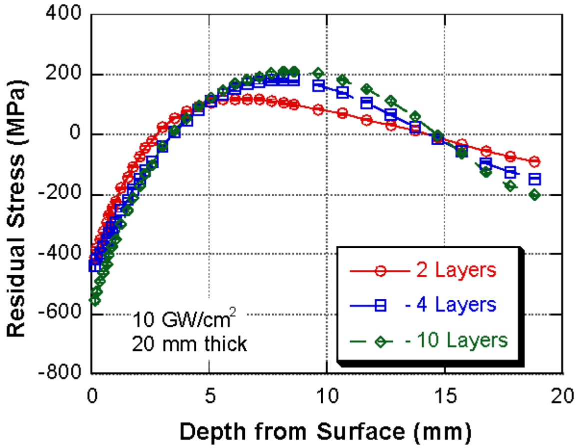
Example technology spiral: Reliable RS measurements

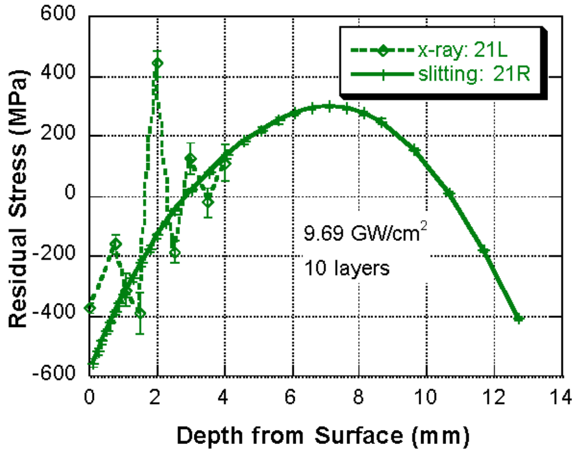
- **Technological need: reliable RS measurements in LSP materials**
  - X-ray diffraction (XRD) stress vs depth profiles not useful (scatter, repeatability), worse for deeper stress fields
- **Pursued mechanical measurement: Slitting**
  - "Crack compliance method", now called slitting
    - Credit: Ian Finnie, Weili Cheng (UC Berkeley, sponsored by EPRI in 1980s)
  - Reduced to practice in University setting
  - Validation and verification of method
    - Repeatability
    - Cross-correlation
    - Correlation of residual stress with mechanical behavior (fatigue and fracture)
- **Technology transfer**
  - Support industry adoption (people and know-how): MIC, Boeing, Alcoa
  - Supported standardization (ASTM TG E28.13.02)

Example technology spiral: Reliable RS measurements

- Technological need: reliable RS measurements in LSP materials
  - X-ray diffraction (XRD) depth profiles not useful (scatter, repeatability)



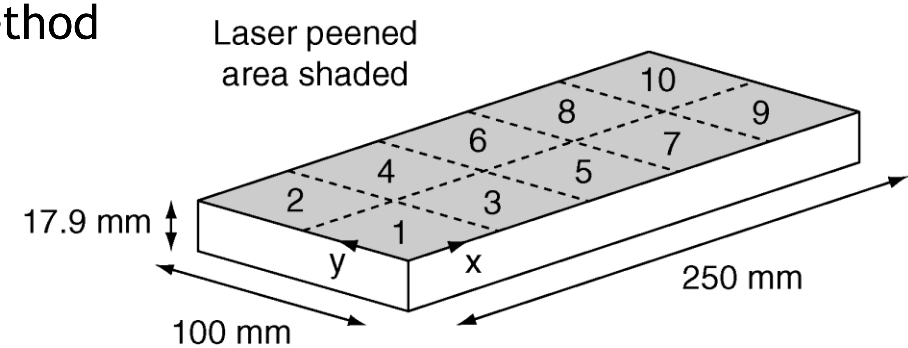




- Slitting provides RS measurements consistent with process physics
  - Enables process decisions

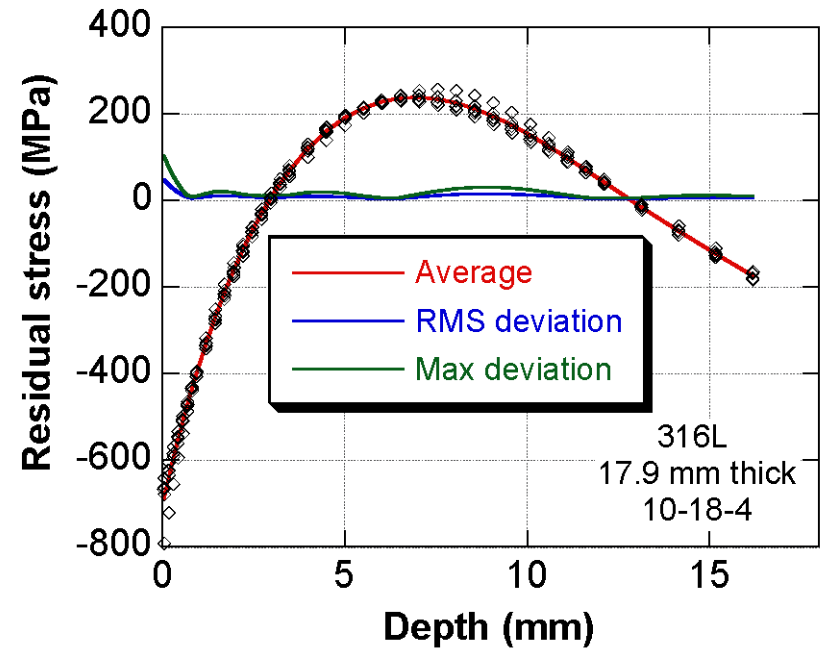
Example technology spiral: Reliable RS measurements

- **Pursued mechanical measurement: Slitting**
  - Validation and verification of method
    - Repeatability
    - Cross-correlation
    - Correlation of residual stress with mechanical behavior (fatigue and fracture)



- **Repeatability assessment**
  - Uniformly LSP entire surface of 316L stainless steel plate
- **Cut into 10 block coupons**
  - Each 50 x 50 x 17.9 mm
  - Each block should have similar RS
    - Variability in LSP process, material properties, and RS measurement

Demonstrated repeatability error < 5% of peak stress

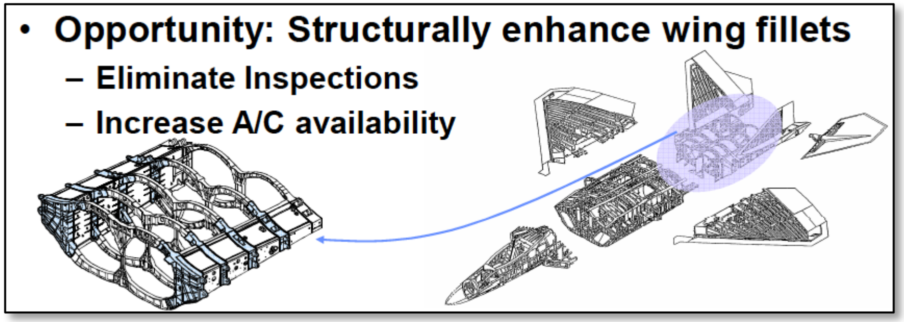


Example technology spiral: Fatigue life improvement

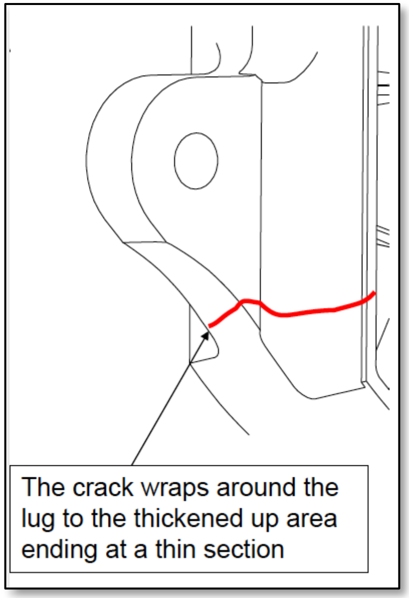
- **Technological need: short-fall of fatigue capability, F-22**
  - Critical structural feature: wing-attach lugs
  - Monolithic (one-piece) airframe, limited repair options
- **Supported application of LSP for service life improvement >5X**
  - MIC/LLNL laser peening capability
  - Required new residual stress measurement capability: Contour method
  - Demonstrated service life improvements in simple coupons
  - Developed residual stress design capability (eigenstrain analysis)
    - Enables first-principles prediction of service life improvement
- **Technology transfer via SBIR funding**
  - Established residual stress engineering firm (Hill Engineering, LLC)
  - Validation and verification of design capability
    - Simple coupons
    - Full scale hardware
    - Verified crack growth assessment capability

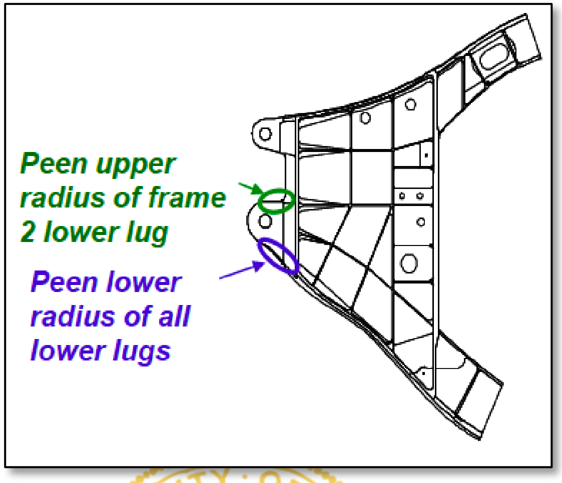
Example technology spiral: Fatigue life improvement

- **Technological need: short-fall of fatigue capability, F-22**
  - Critical structural feature: wing-attach lugs
  - Monolithic (one-piece) airframe, limited repair options
  - Sheri Welsh, ASIP 2004: Fatigue cracking, 1.2x life
  - Bob Bair, ASIP 2009: GBP/LSP solution



  - LeAnn Polin, ASIP 2011: Full-scale test results
  - F-22 LSP production on-going since 2011





Example technology spiral: Fatigue life improvement

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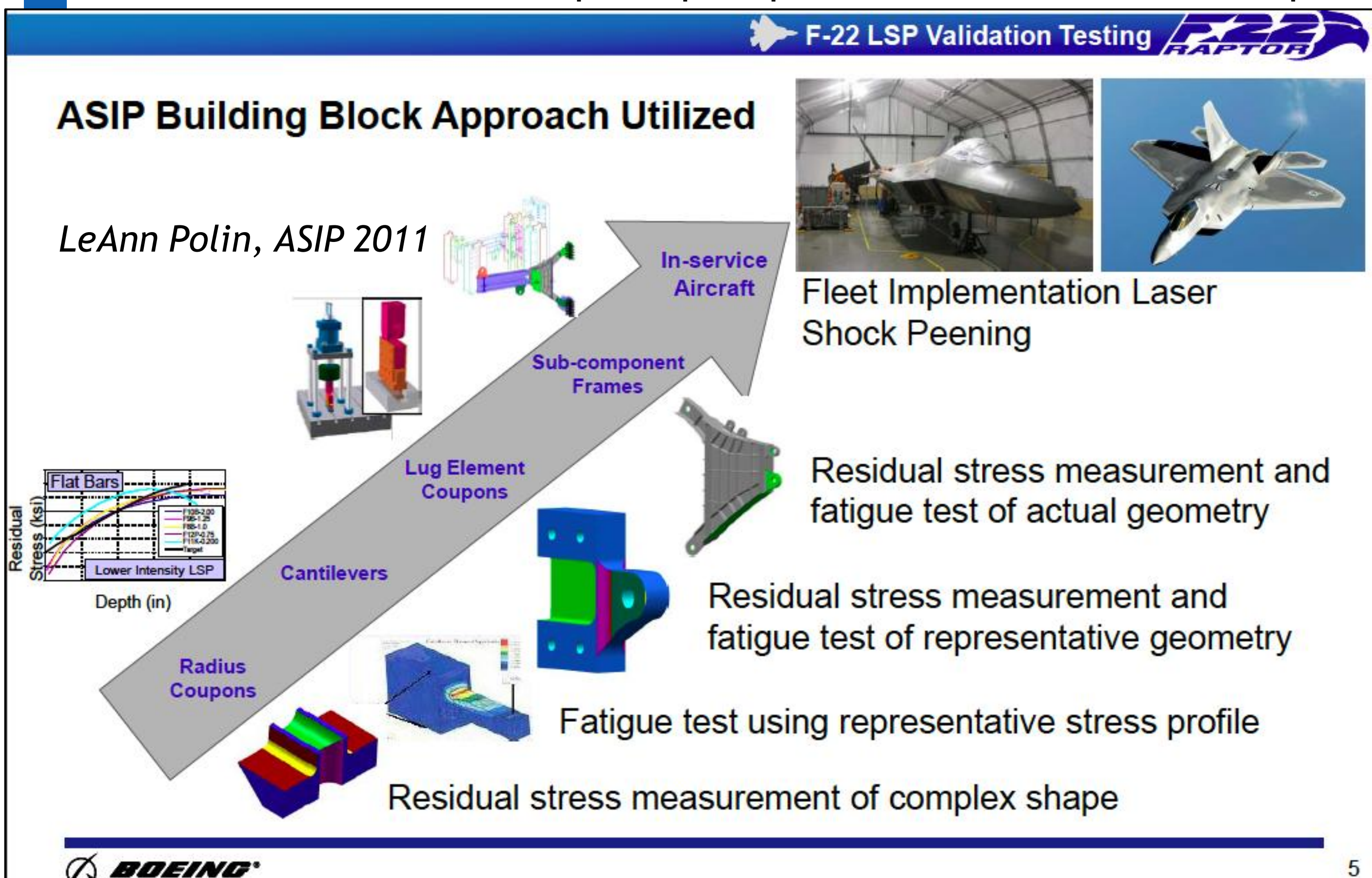
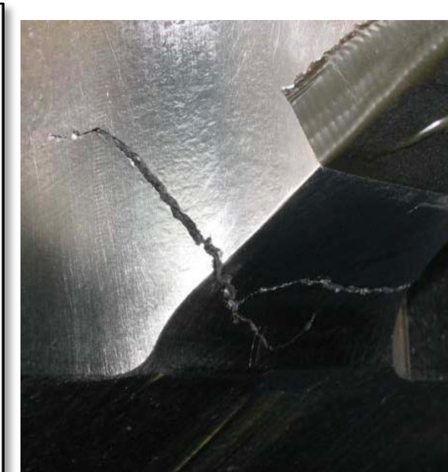
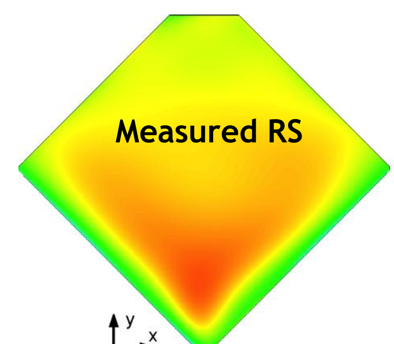


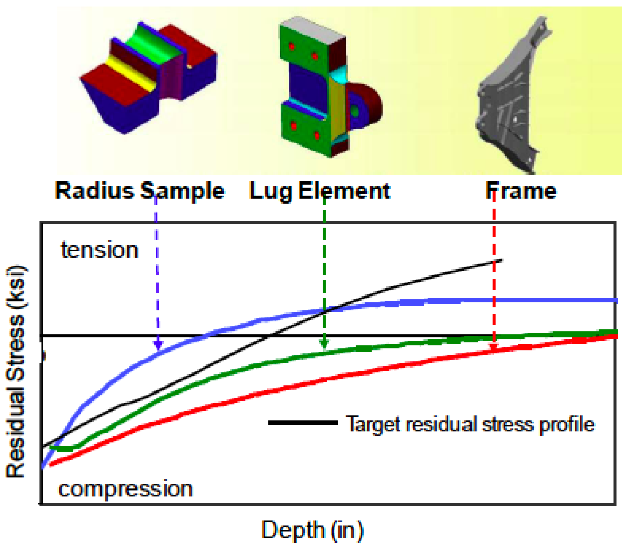




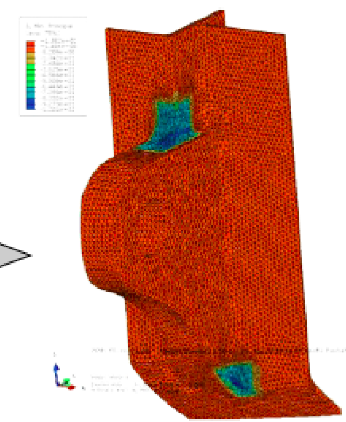
Example technology spiral: Fatigue life improvement

- **Technology transfer via SBIR funding**
  - Established residual stress engineering firm (Hill Engineering, LLC)
  - Validation and verification of residual stress design capability

F-22 LSP Validation Testing



- **Residual stresses modeled using empirical eigenstrain method**
  - **Method validated with structured ASIP test plan**
  - **"Blind" predictions validated by measurements**
  - **Specimens of increasing mass and complexity**
  - **Data populated empirical eigenstrain database**

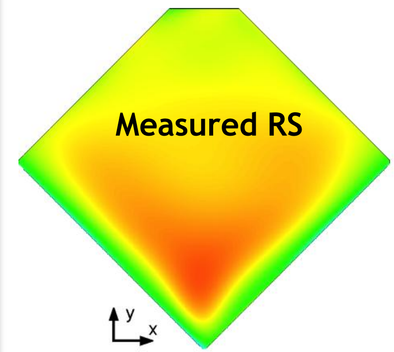


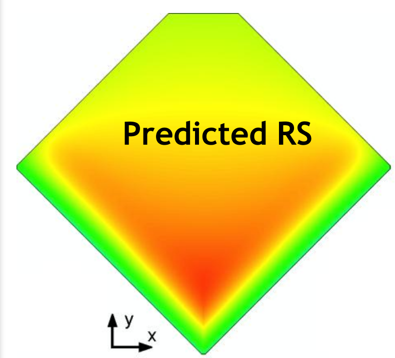
Result of structured test program: Validated method to model residual stresses in 3-dimensions

LeAnn Polin, ASIP 2011

BOEING

15

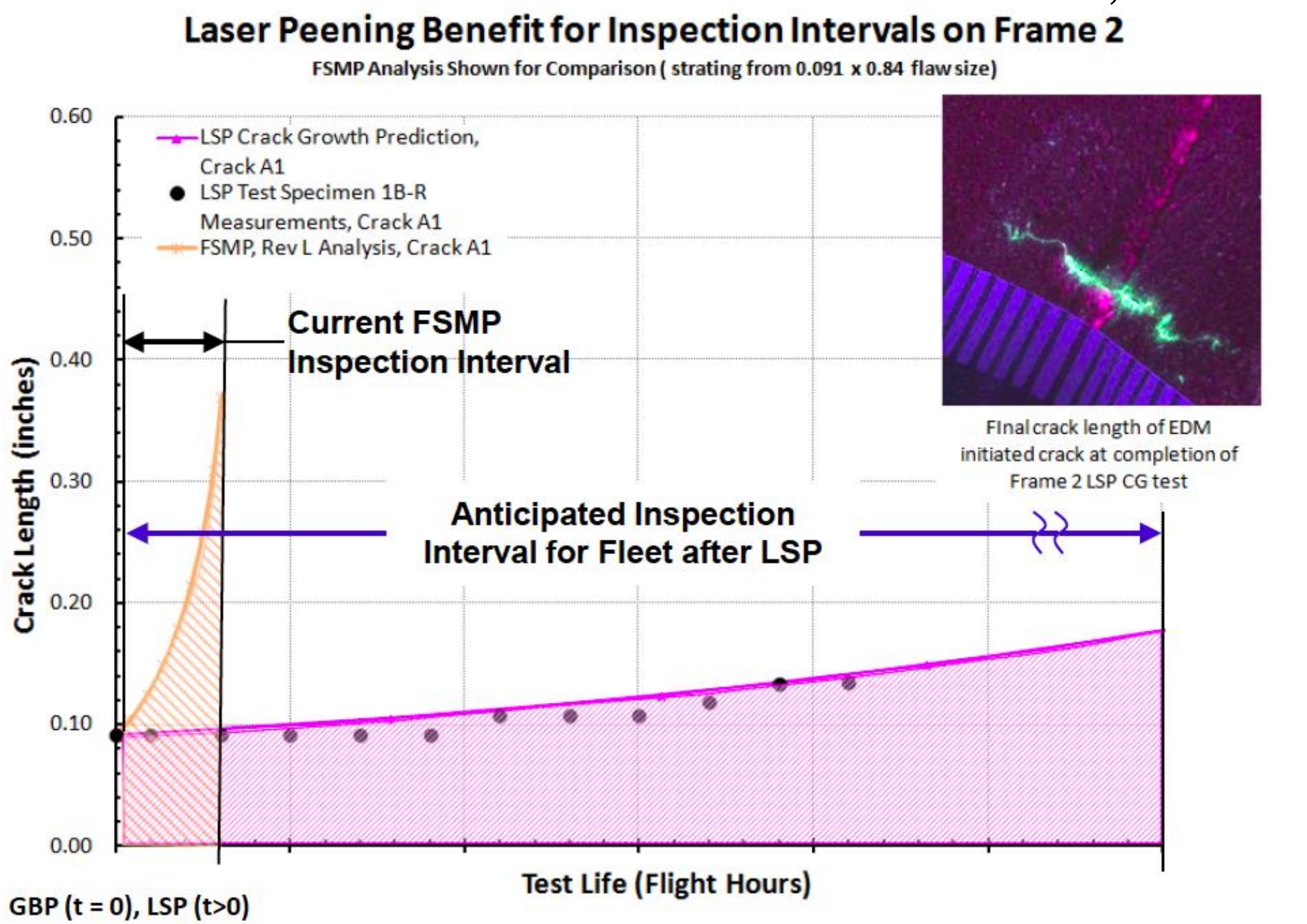




Example technology spiral: Fatigue life improvement

- **F-22 Program Pay-off**
  - Large service life extension
  - Anticipated inspection relief

LeAnn Polin, ASIP 2011



Residual stress fields validated through assessment.

Residual stress not the primary outcome.

Require useful forecasts of subcritical cracking.

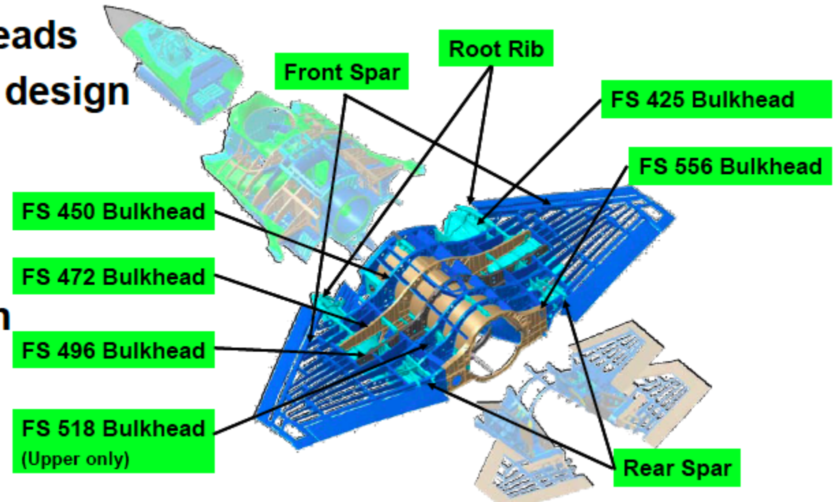
Industry Program on Forging RS (MAI BA-11, 2011-15)

- JSF Designer Perspective (Dale Ball, 2010 RS Summit)

Impact of Residual Stress on Life, Weight & Cost of A/C Structure:

Background

- **Large Forged Components for advanced fighter aircraft - Material of choice for wing substructure**
  - **One-piece forged bulkheads**
    - **Replaces multi-piece design**
    - **10 - 15% wt saved**
  - **Improved buy-to-fly**
    - **50% current design**
    - **More, next generation design**



- **10 major die-forgings per aircraft**

The Aggressive Pursuit of Structural Unitization

5

Industry Program on Forging RS (MAI BA-11, 2011-15)

- JSF Designer Perspective (Dale Ball, 2010 RS Summit)

Impact of Residual Stress on Life, Weight & Cost of A/C Structure:

Background

CONCERNS:

- **Durability – repair / replace capability**
- **Damage tolerance / crack arrest capability**
- **Presence of detrimental (tensile) residual stresses**

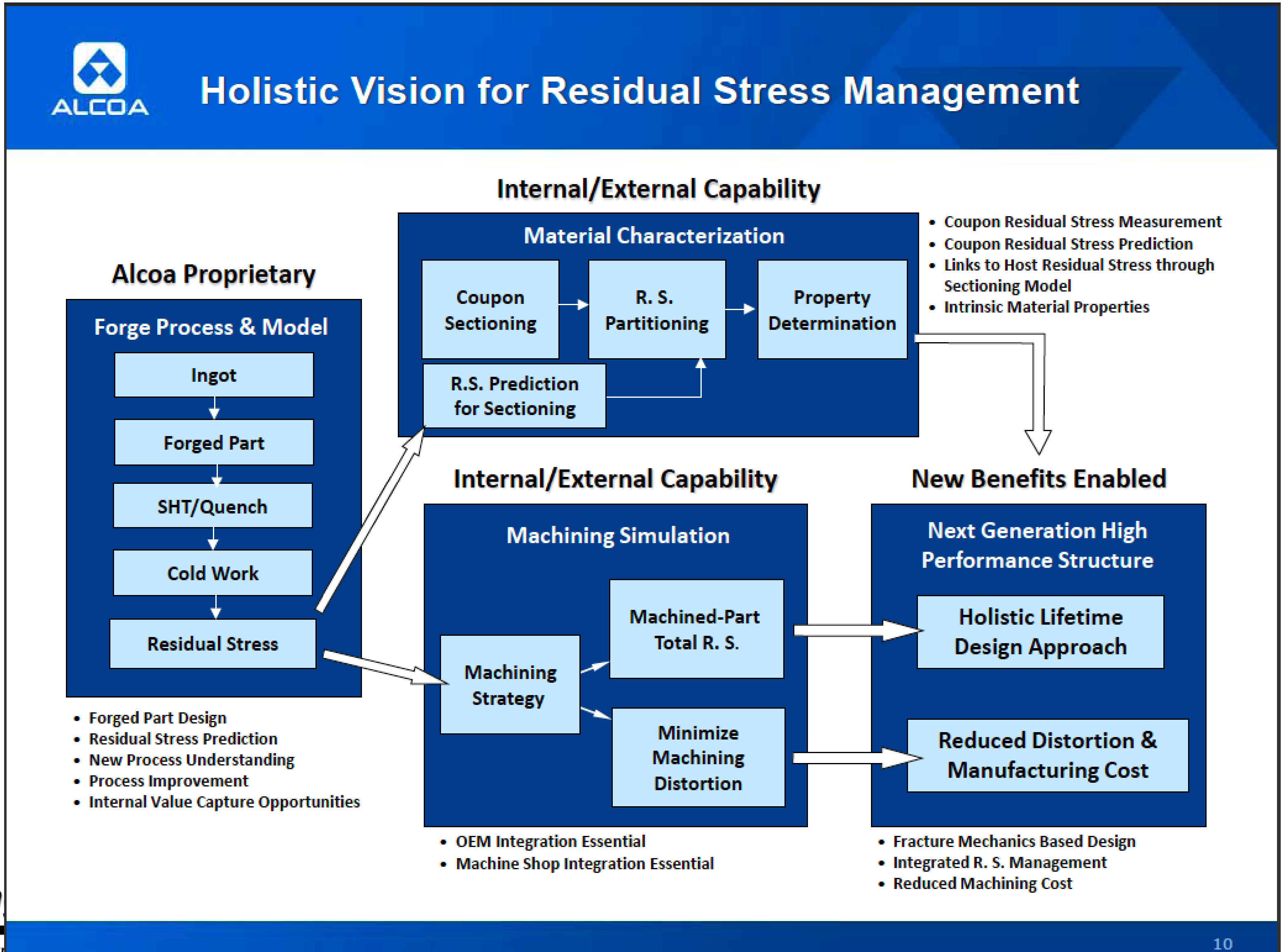
RESIDUAL STRESS ISSUES:

- **Large forgings can have residual stresses that generate significant distortion upon machining – this can lead to**
  - ***part rejection, detrimental rework***
  - ***assembly issues***
  - ***early failure***
- **Parts / components machined from large forgings have residual stresses present in some areas.**
- **Presence of residual stresses tends to confound fatigue crack growth rate data if not accounted for**
- **Presence of residual stresses in finished parts may result in premature cracking if not accounted for in design**

6

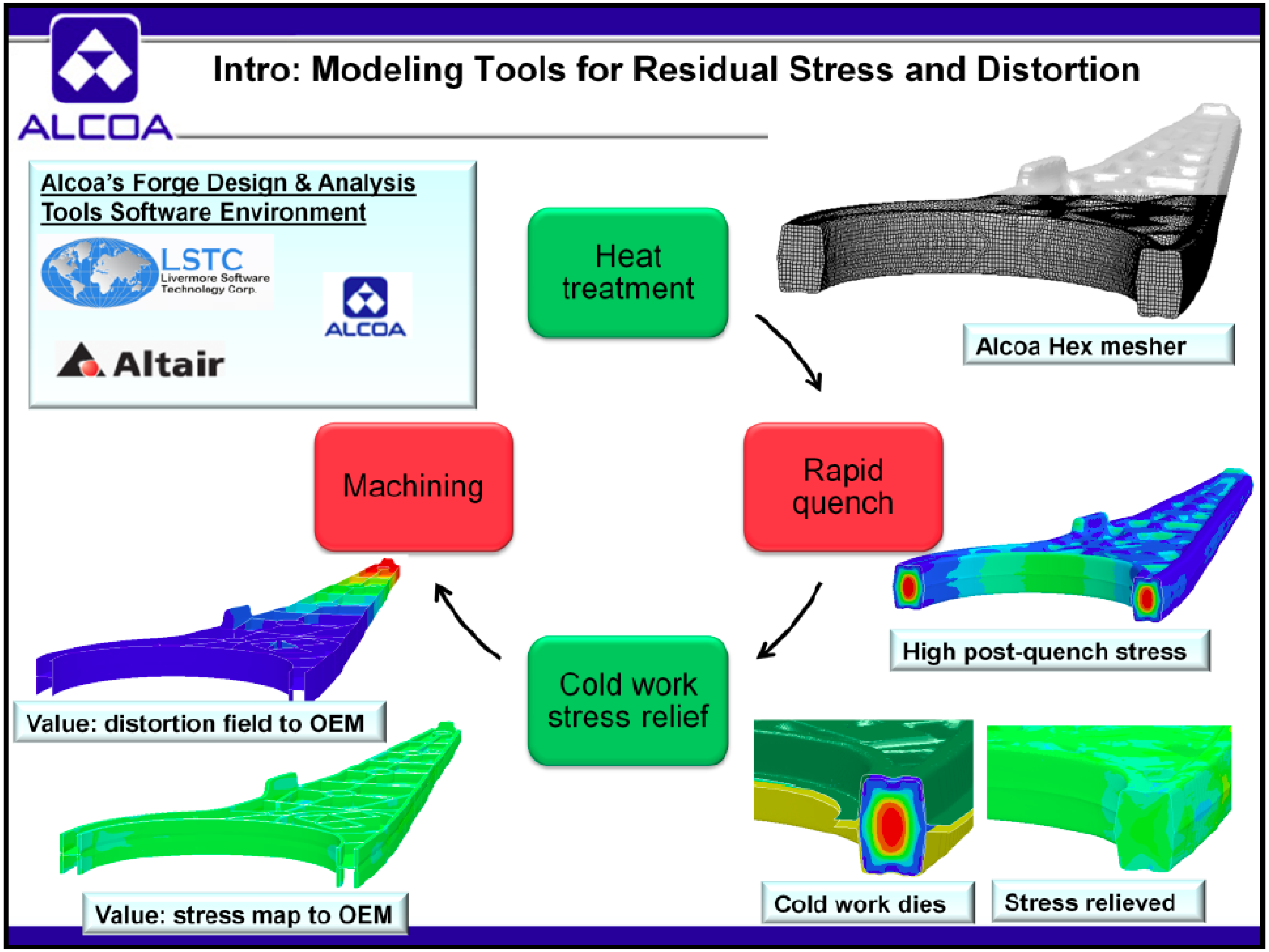
Industry Program on Forging RS (MAI BA-11, 2011-15)

- Material Producer Perspective (Mark James, Aeromat 2010)



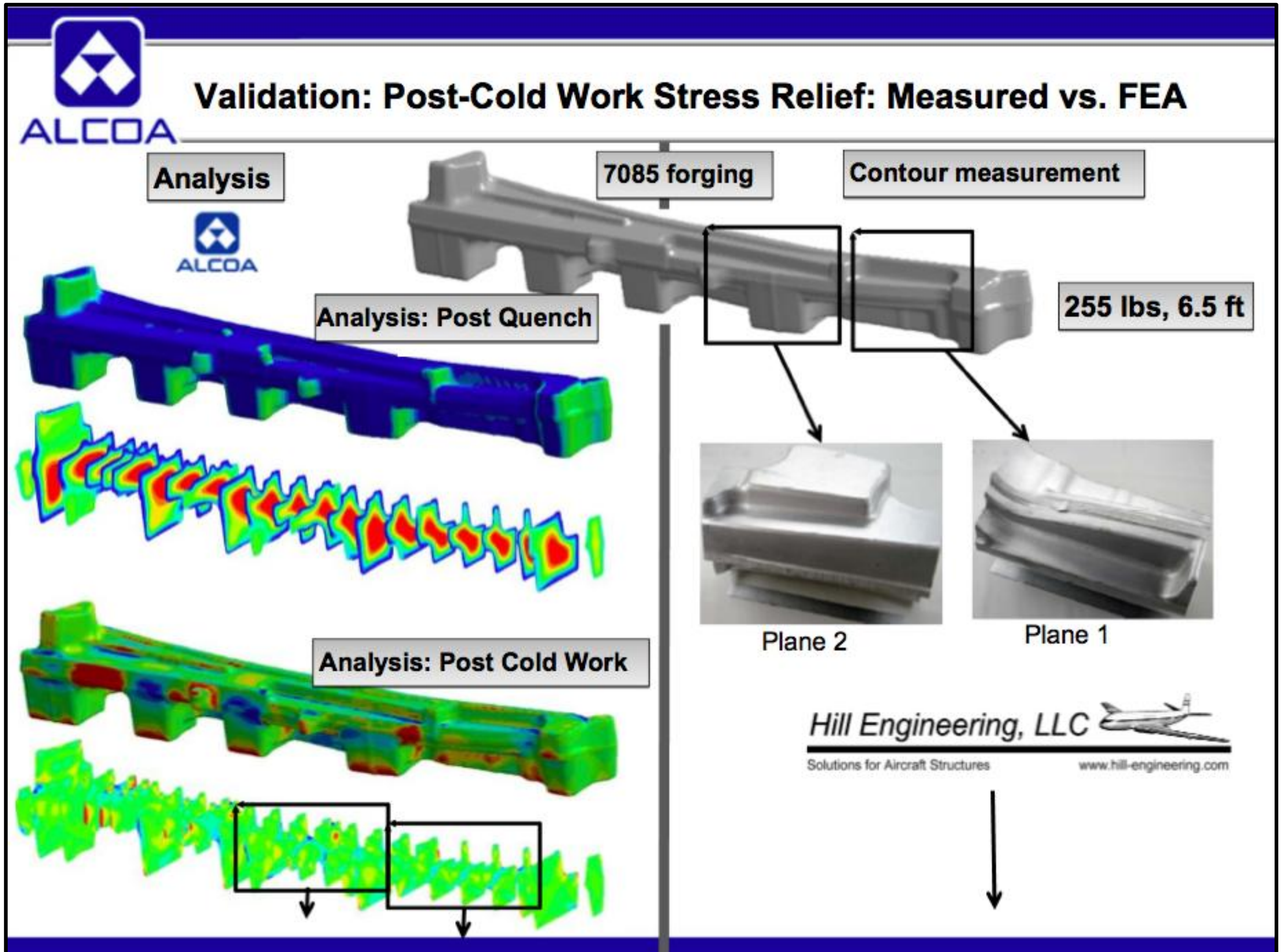
Industry Program on Forging RS (MAI BA-11, 2011-15)

- Material Producer Perspective (John Watton, 2010 RS Summit)



Industry Program on Forging RS (MAI BA-11, 2011-15)

- Early Program Demonstration (John Watton, 2010 RS Summit)



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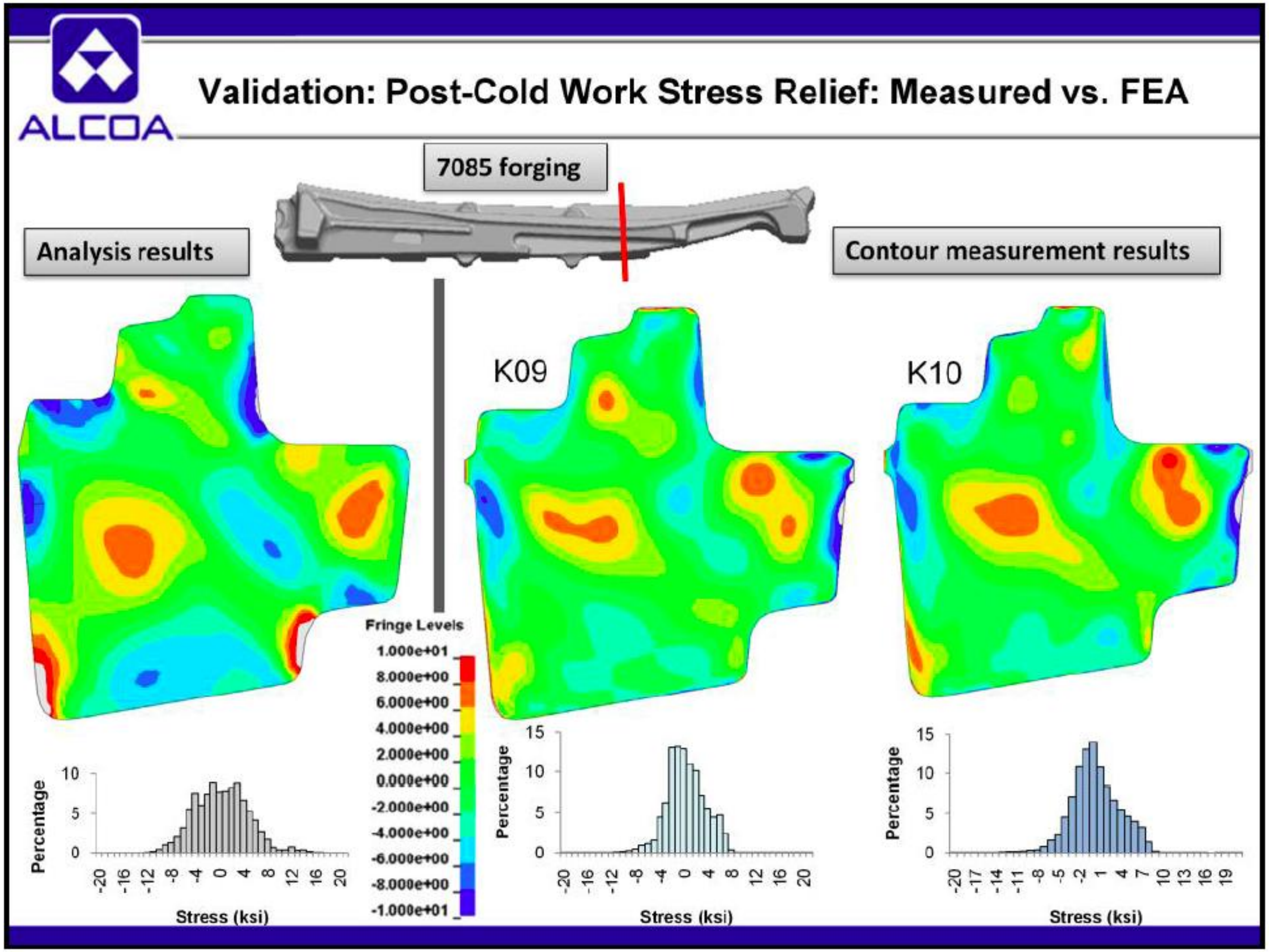

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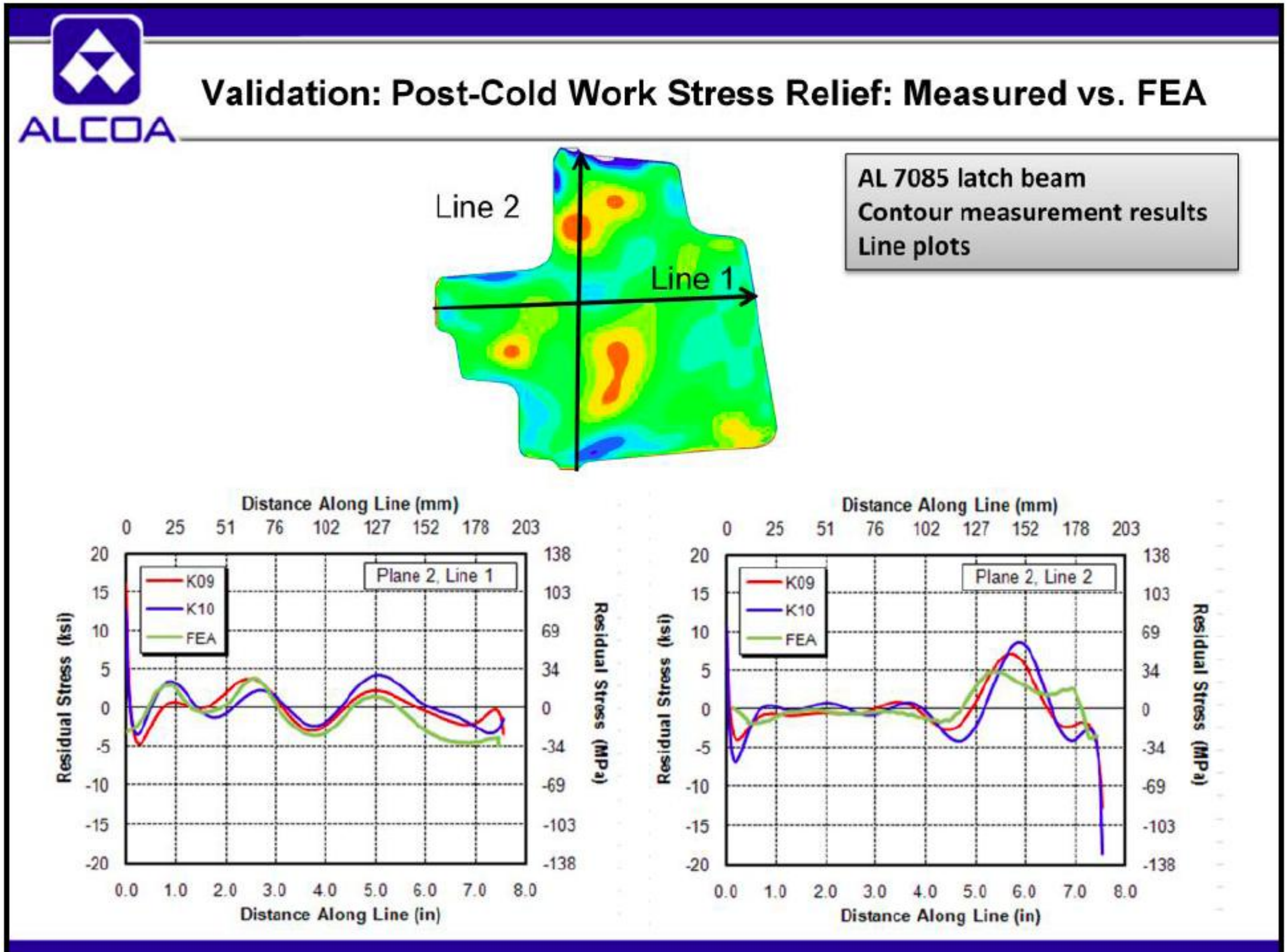


Industry Program on Forging RS (MAI BA-11, 2011-15)

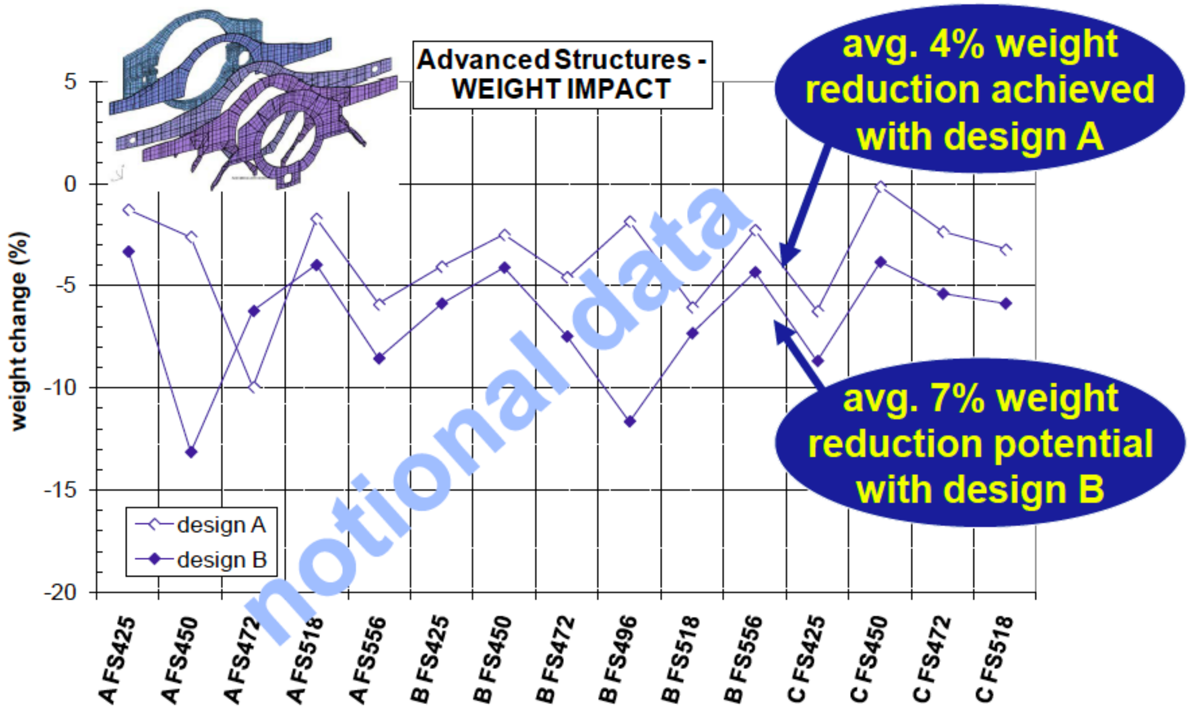
- JSF Designer Pay-off Concept (Dale Ball, 2010 RS Summit)

Impact of Residual Stress on Life, Weight & Cost of A/C Structure:

Life, Weight and Cost

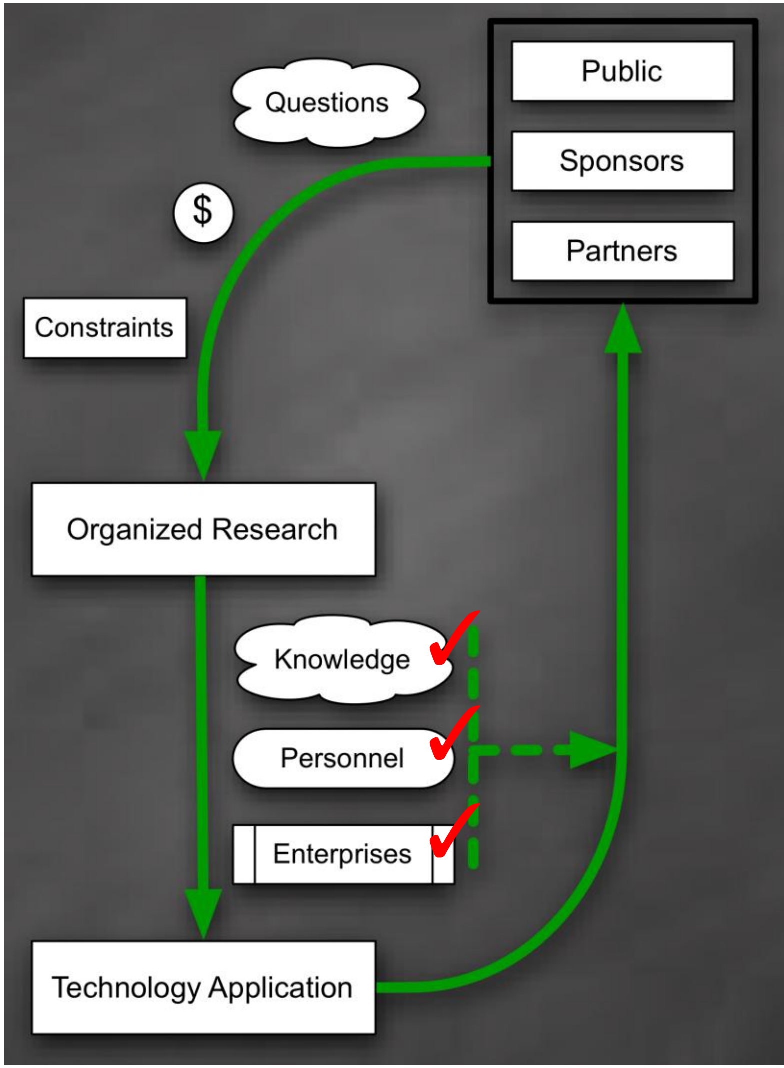
ANALYSIS OF FORGED BULKHEADS – WEIGHT SUMMARY

- **Estimated weight impact for all candidate bulkheads**



Academic and International Programs for Residual Stress

- Experience driven presentation
- Aviation Residual Stress Technology Development
  - Fatigue life improvement (aircraft)
    - Government funded programs
  - Cost and lifetime savings by understanding residual stress in aircraft structural forgings
- **Residual Stress in DM Welds**
  - NRC/EPRI Cooperative Program
  - Potential areas for further work
  - International collaborations



From: Crooker and Csontos, 2010 North American Residual Stress Summit

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Phase I-IV Program Overview

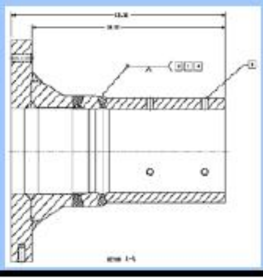
Specimens and Mockups

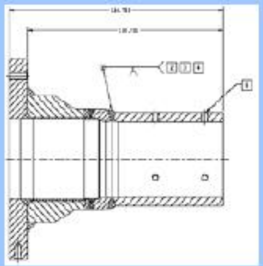
Phase 1 - EPRI

- **Scientific Weld Specimens**
- **Phase 1A:** Restrained Plates
- **Phase 1B:** Small Cylinders
- Purpose: Develop FE models.

Phase 2 - NRC

- **Fabricated Prototypic Nozzles**
- Type 8 Surge Nozzles
- Purpose: Prototypic scale under controlled conditions. Validate FE models.





Phase 3 - EPRI

- **Plant Components**
- WNP-3 S&R PZR Nozzles
- Purpose: Validate FE models.

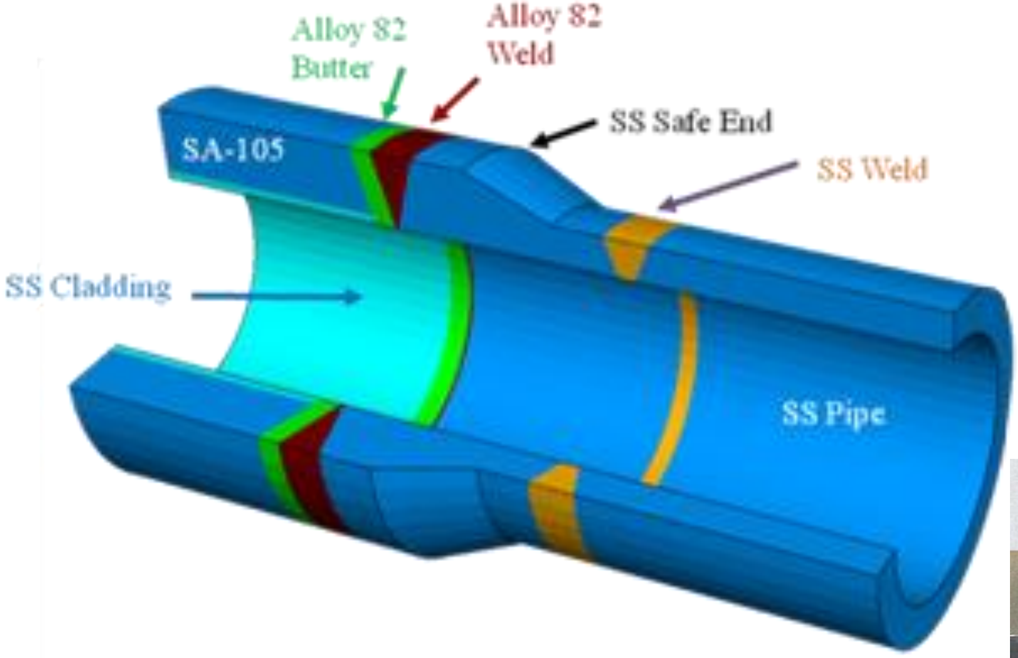
Phase 4 - EPRI

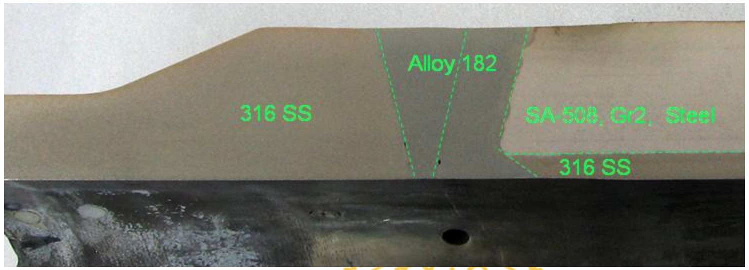
- **Plant Components**
- WNP-3 CL Nozzle
- RS Measurements by NRC
- Purpose: Effect of overlay on ID.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Exploited contour capability on Phase III nozzles

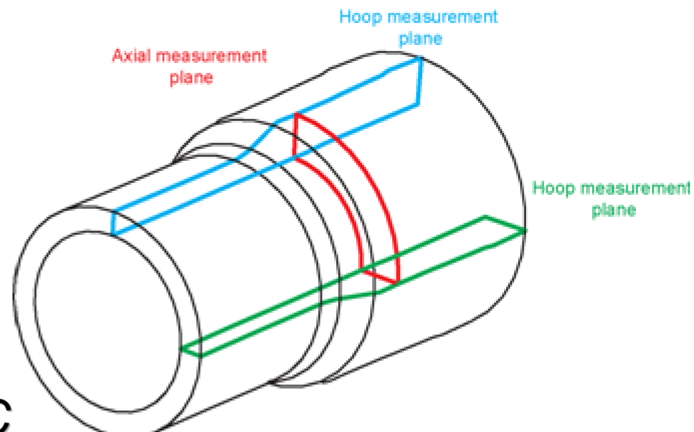
- Measurements performed on pressurizer safety & relief nozzles from cancelled plant
  - Dissimilar metal weld (stainless steel to carbon steel)
  - SS cladding
  - SS weld and SS pipe on one nozzle





Nozzle measurements – Contour method

- **Measurements performed on two nozzles (one with and one without additional SS piping)**
  - Nominally similar in dissimilar metal weld region
  - Minor differences in geometry
  - Expected to have “similar” residual stress
- **Measurement locations**
  - Hoop stress measurement on two planes (90-deg apart)
    - Expected to be similar
    - Some unknowns about welding (start/stops, repairs, etc…)
  - Axial stress measurement on 90-deg segment (at middle of weld)

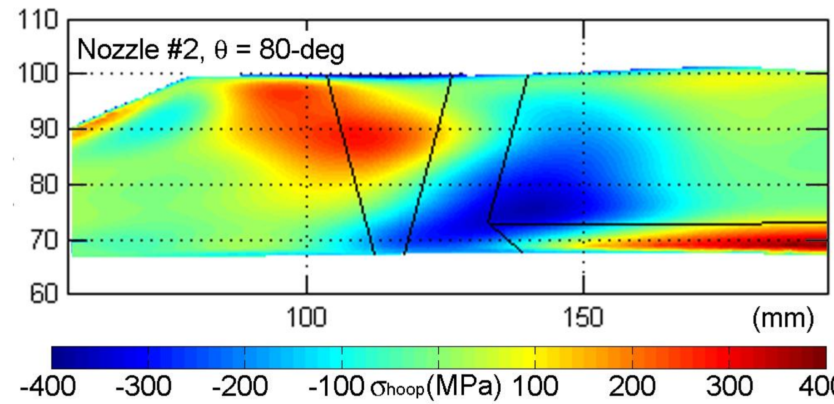


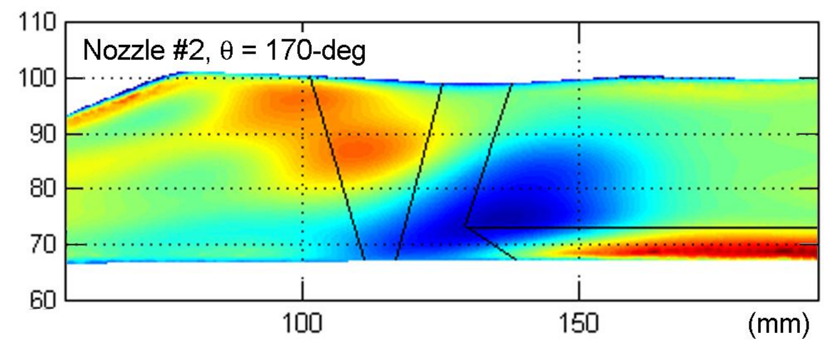
8.0”

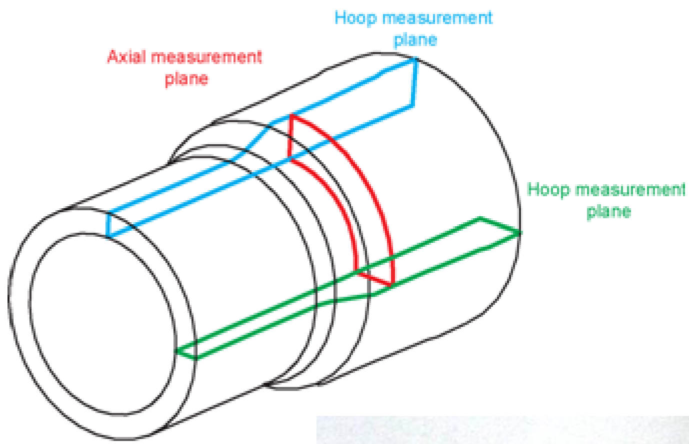
14.75”

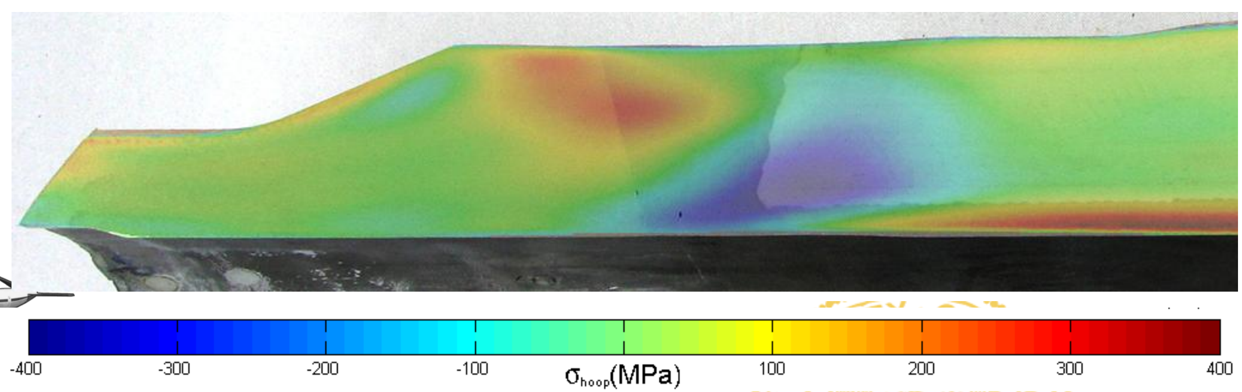
Nozzle #2 hoop stress

- Contour plots of hoop stress in nozzle
  - Tensile stress near OD in weld (shifted toward SS end)
  - Compressive stress near ID
  - Tensile stress in clad layer (at room temperature)



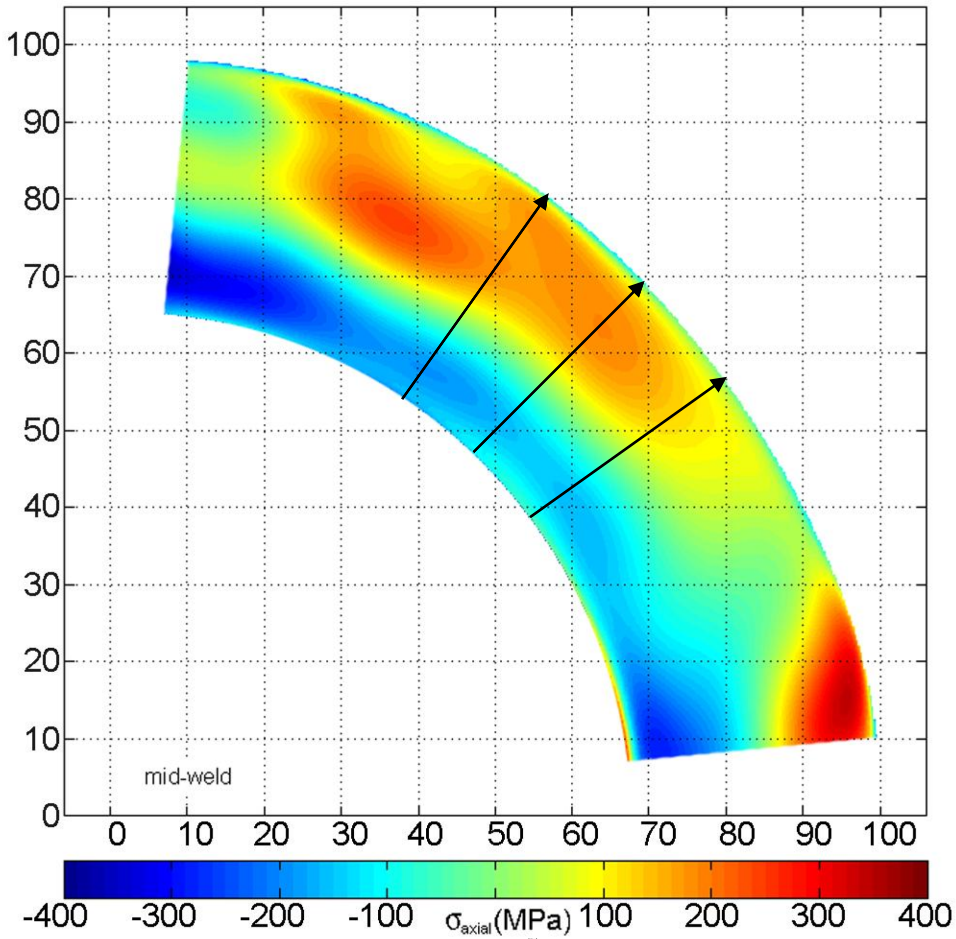


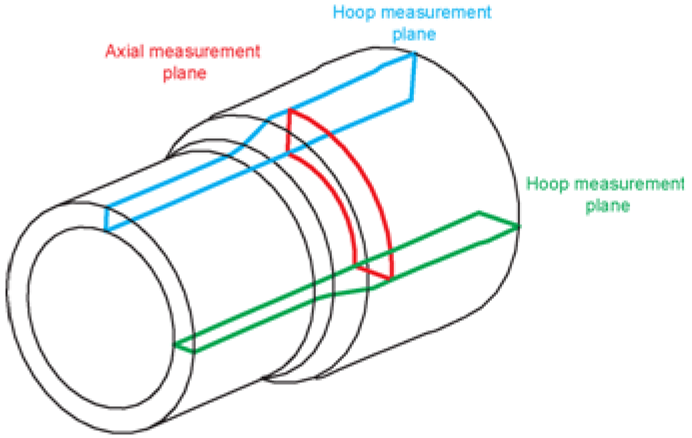


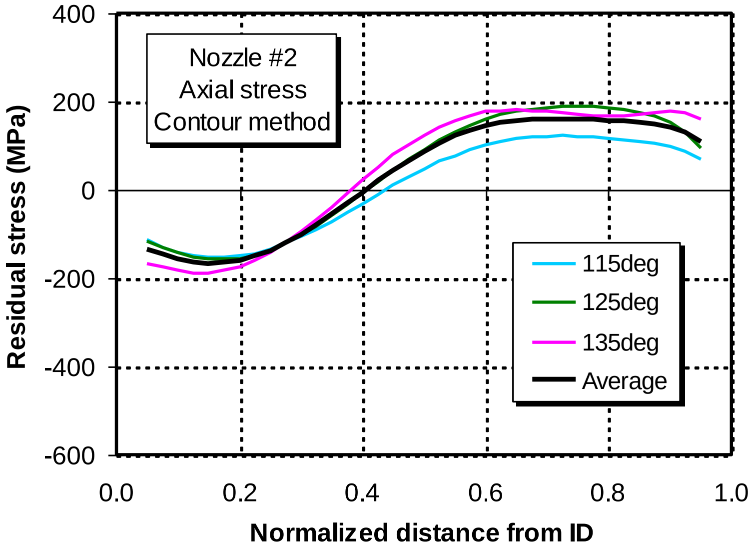


Nozzle #2 axial stress

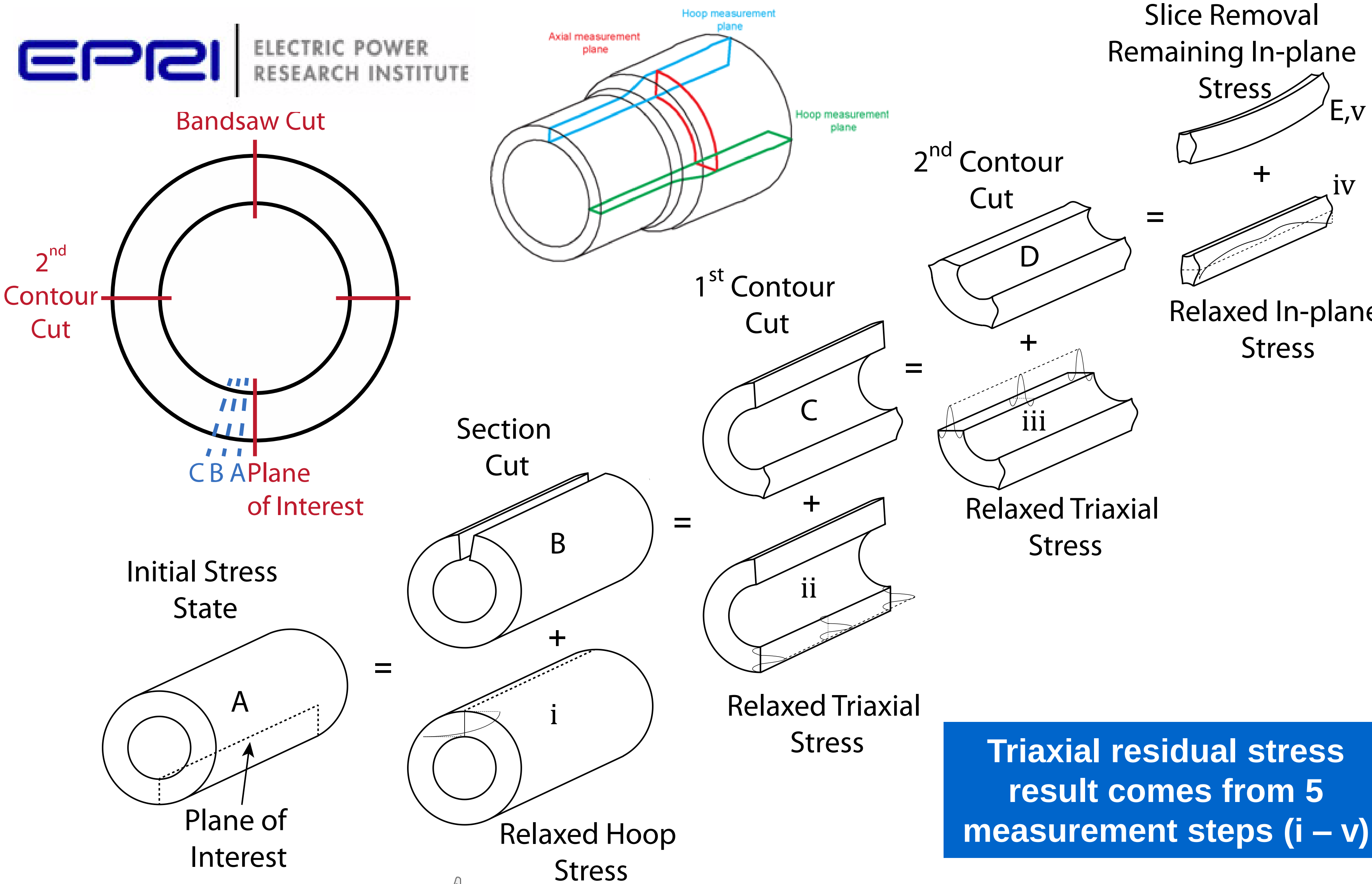
- Axial stress measurement on 90-deg section between hoop contour planes





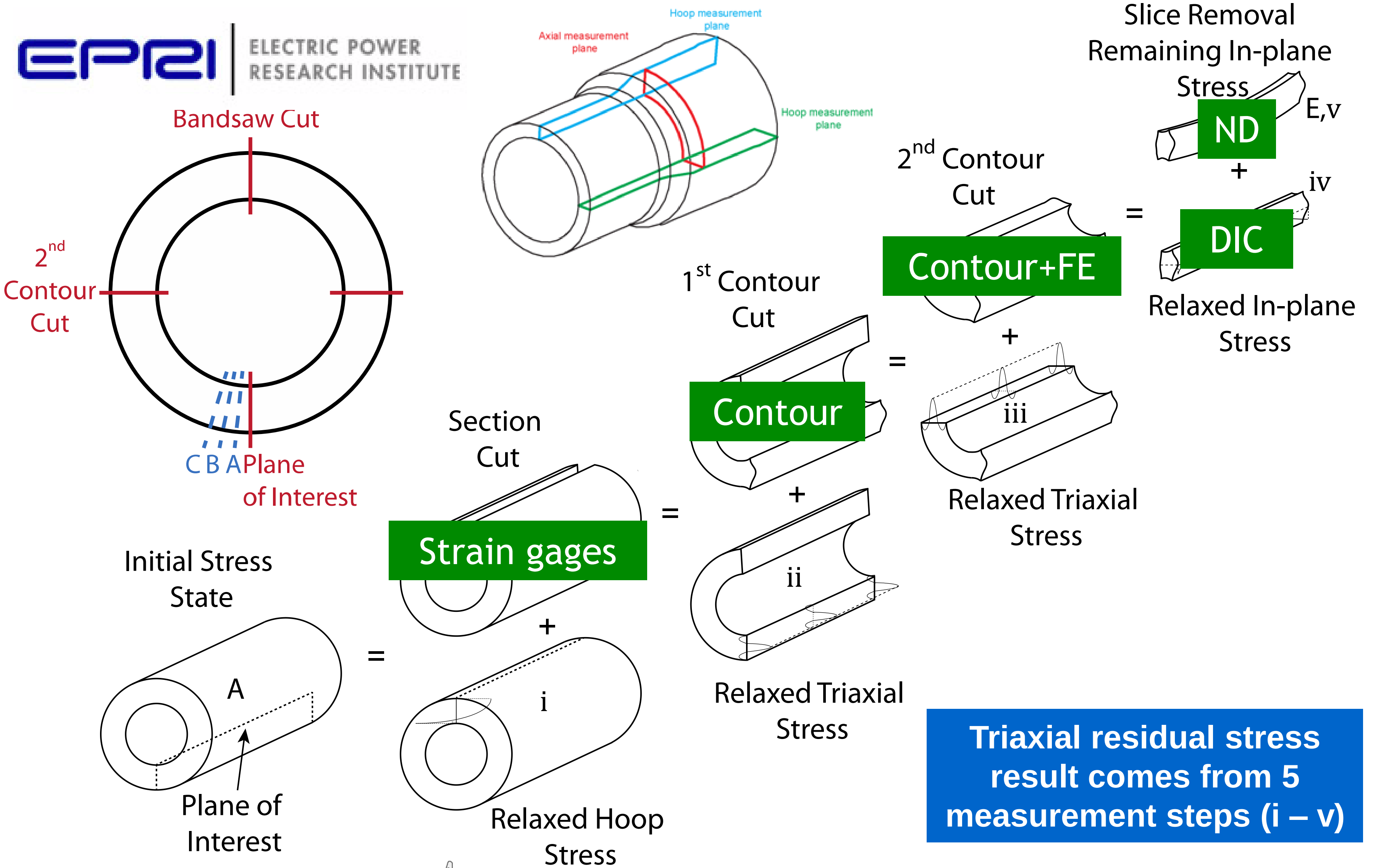


Trial of a novel triaxial RS measurement in Nozzle #2



Triaxial residual stress result comes from 5 measurement steps (i – v)

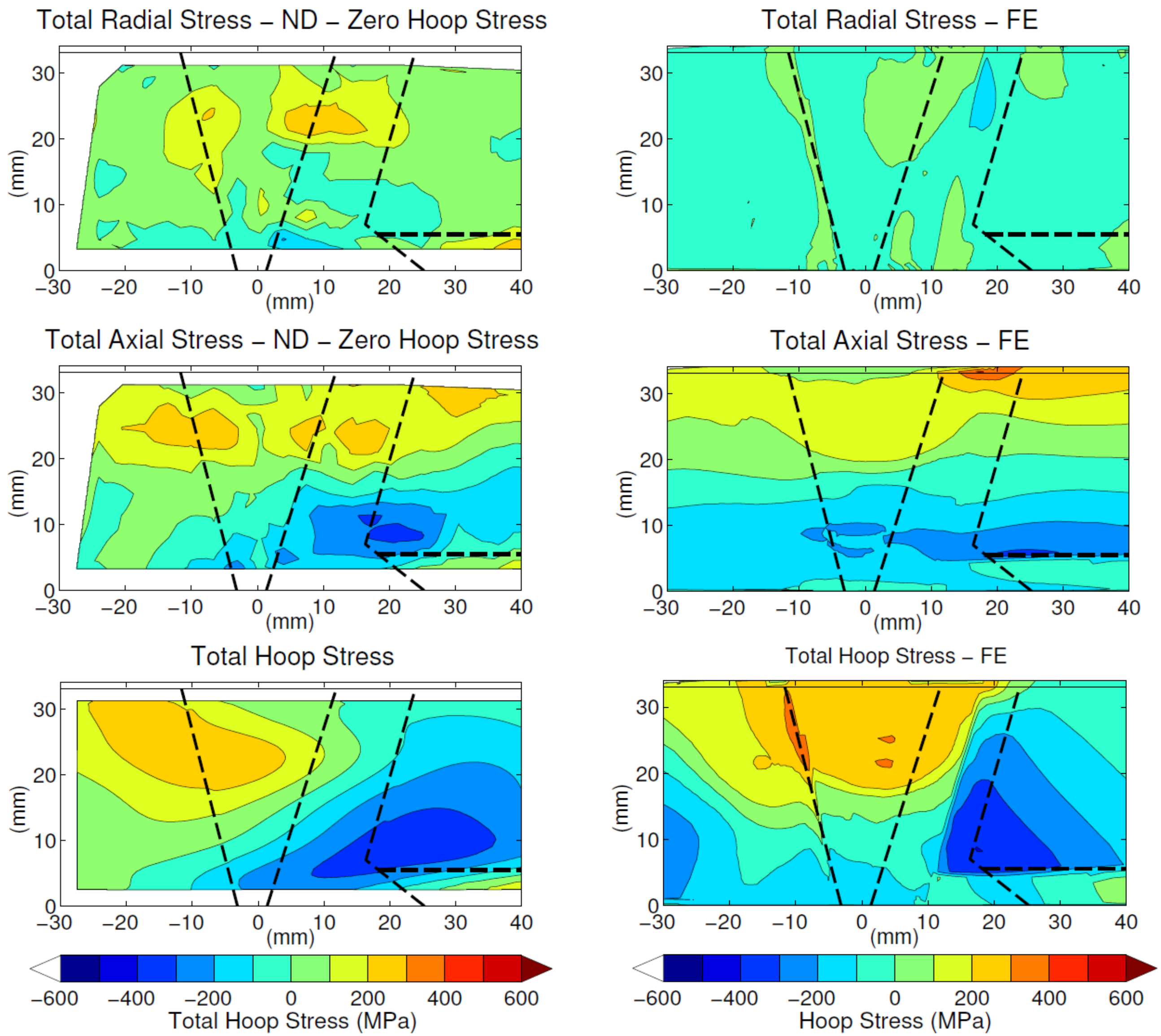
Trial of a novel triaxial RS measurement in Nozzle #2



Triaxial residual stress result comes from 5 measurement steps (i – v)

Trial of a novel triaxial RS measurement in Nozzle #2

- Results, compared to NRC FE (kinematic)

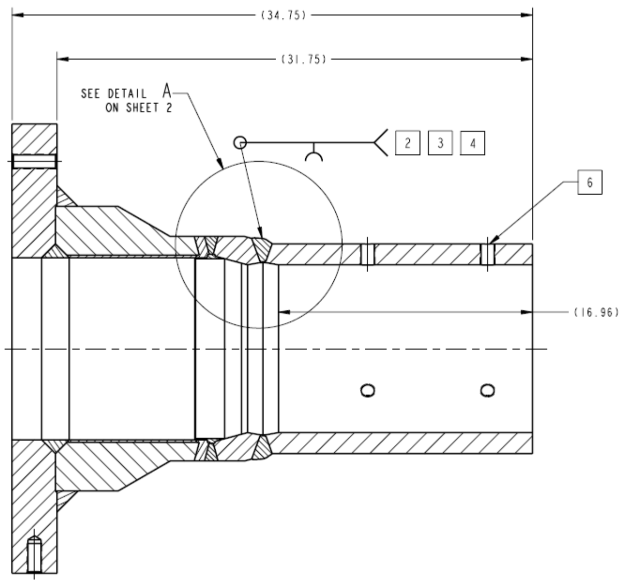


Long-term Program Outlook

- **Complementary use of measurement and modeling**
- **Improved measurement to model agreement**
  - Model improvements (e.g., material models)
  - Measurement improvements (experience, advanced methods)
- **Library of residual stress fields**
  - Models confirmed by Measurements
  - For existing plant
    - As-built
    - Stress mitigation techniques
  - Guidance for new build
    - Weld processes
    - New materials

Near term activities

- **Expand residual stress data using available assets**
  - Phase II mock-up (pressurizer surge)
    - Contour and triaxial measurements
  - Phase IV?
  - CRDM or BMN sections?
  - Other assets or mock-ups as available and useful

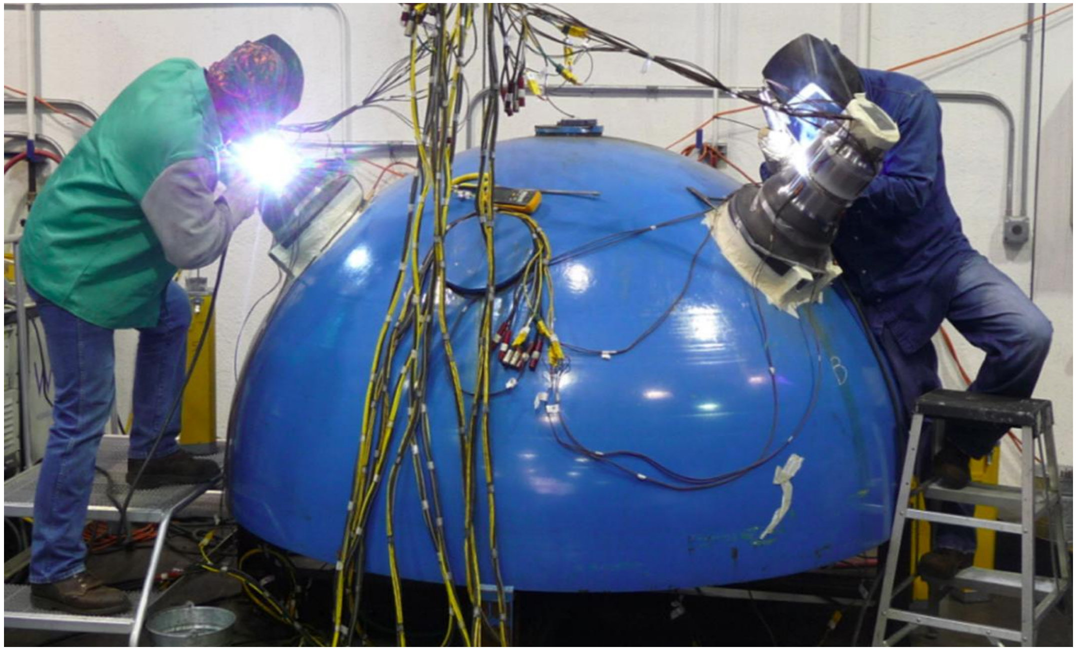


Sustainable Cooperative WRS R&D Program

- Potential Value from International Collaborations
- Example collaborators
  - UK
    - EDF/BE, Weld modeling
    - Univ of Bristol, Struct Integrity
  - Australia
    - ANSTO, Weld modeling
  - Japan
    - JAEA, Weld measurement
  - Korea
    - KAERI, Weld measurement
- Example programs
  - UK and Europe
    - NULIFE framework
      Nuclear plant life prediction
    - STYLE project
      Structural integrity for lifetime management
    - NeT project
      Weld modeling and measurement

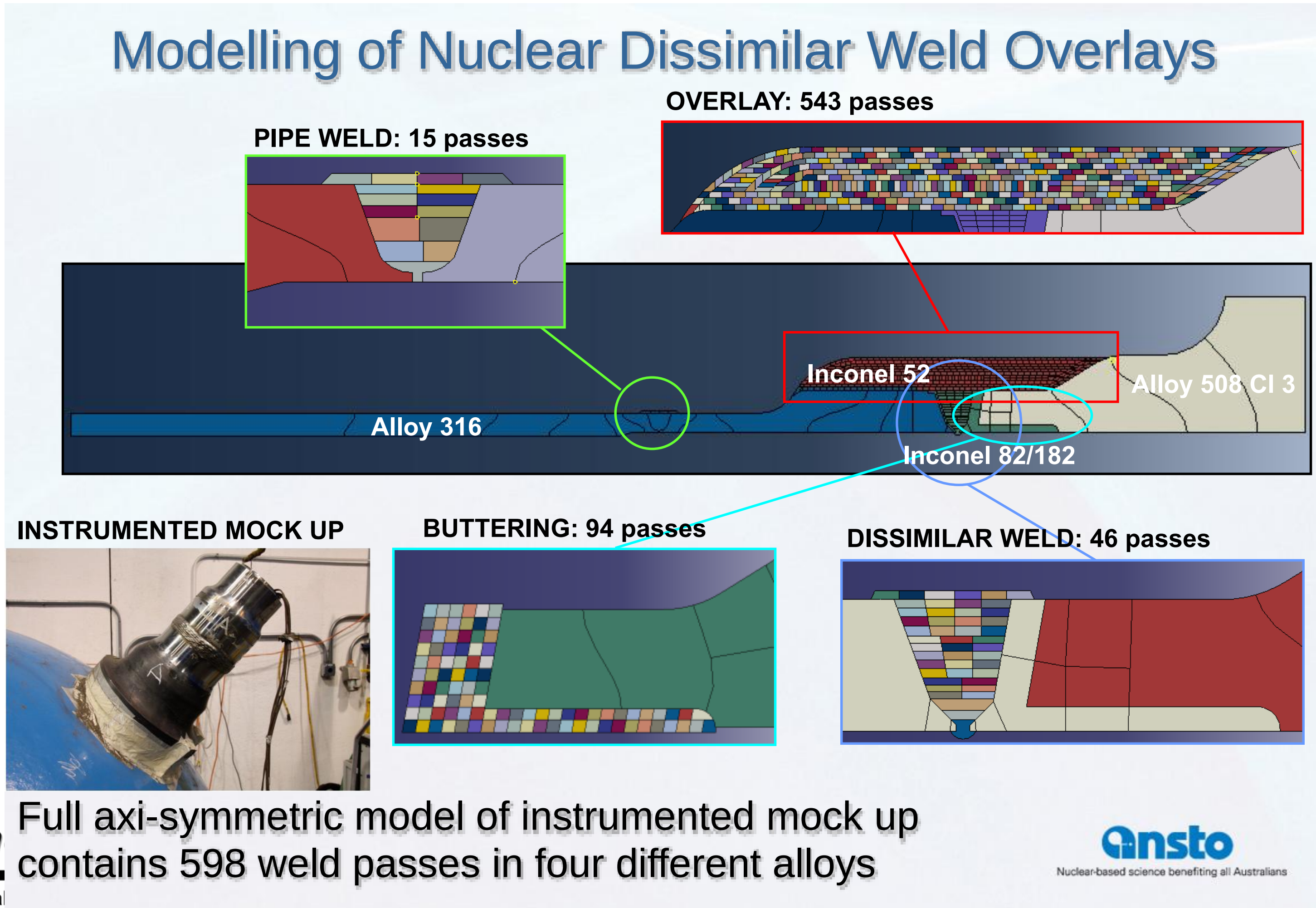
Sustainable Cooperative WRS R&D Program

- **Potential Value from International Collaborations**
- **EDF/BE, Weld modeling**
  - Pressurizer nozzle mock-ups
  - NeT project
    Weld modeling and measurement



Sustainable Cooperative WRS R&D Program

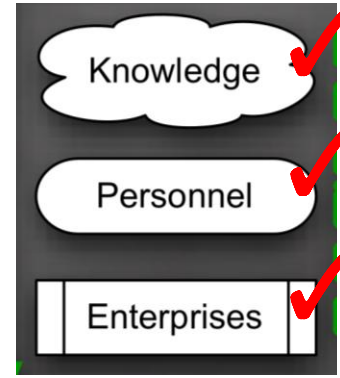
- Potential Value from International Collaborations
- ANSTO (Australian Nuclear Science and Technology Organization)
  - Weld modeling (partner with EDF/BE)



Sustainable Cooperative WRS R&D Program

- **Potential Value from International Collaborations**
- **Univ of Bristol**
  - Residual stress measurement (DHD)
  - Structural Integrity
  - EU nuclear programs
    - STYLE project
      Structural integrity for lifetime management
    - NeT project
      Weld modeling and measurement

Summary



- **Deep knowledge base in residual stress technology**
  - Measurements, Models, Engineering methods
  - Not all discipline specific … requires adaptation
- **Described residual stress measurements in DM welds**
  - Trial of novel triaxial stress mapping
- **Potential benefits from international collaboration**
  - Shared efforts, funding
  - Identified key potential partners (UCD, UoB, ANSTO)

Today

Residual Stresses are
managed consequences
that affect design performance

Future

Residual Stresses are part of
higher-order specifications
that ensure design performance

Acknowledgements

- **UC Davis work on laser peening (1999 to present)**
  Collaborations with LLNL and MIC
  Collaborations with Boeing and Lockheed-Martin (F-22)
- **US DoD SBIR Programs (Launched Hill Engineering, LLC)**
  - "Design Tools for Fatigue Life Prediction in Surface Treated Aerospace Components", 2004 to Present
  - "Design/Life Prediction Tools for Aircraft Structural Components with Engineered Residual Stresses", 2008
  - NAVAIR: Ravi Ravindranath
  - AFRL: Mike Shepard, Kristina Langer, Pam Kobryn, Stephanie Flanagan, Rollie Dutton
  - Pratt & Whitney: Bob Morris, Dave Murphy
  - Boeing F-22 Program: Jim Pillers, Jeff Bunch
  - Lockheed-Martin: Dale Ball
- **FAA Rotorcraft Damage Tolerance Program**
  - FAA: John Bakuckas; MS State: Jim Newman, Jr.; Sikorsky: Mike Urban

Acknowledgements

- **Nuclear Electric Power Materials Reliability**
  - EPRI: Paul Crooker, Eric Willis
  - US NRC: Al Csontos, Howard Rathbun, Matthew Kerr
  - ORNL: Cam Hubbard
  - LANL: Mike Prime, Don Brown, Bjørn Clausen

- **Present and former students at UC Davis**

- **Staff at Hill Engineering, especially**
  - Adrian DeWald
  - Brett Watanabe

Thank you.

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Probabilistic Assessment of Chemical Mitigation of PWSCC

Zinc Addition and Hydrogen Optimization

Presented To:

PWR Materials Reliability and Weld Repair Research Meetings
Charlotte NC

Presented By:

Chuck Marks
Dominion Engineering, Inc.

January 26, 2012

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Presentation Outline

- Introduction
- Description of the probabilistic model
- Summary of a few results
- General conclusions

Background

MRP-263 (EPRI 1019082, 2009) – Technical Bases for Chemical Mitigation

- Hydrogen optimization reduces crack growth rates
  - Rate decreases with distance from electrochemical potential of Ni/NiO transition
- Zinc addition reduces rate of new initiations
  - Concentration of zinc not important in applied range (2-40 ppb)
- Hydrogen has no effect on initiation over the range of interest
  - Very low hydrogen concentrations can lower initiation rate
  - No effect once above the Ni/NiO transition
- Zinc appears to have a limited effect on crack growth rate
  - Data mixed
  - Possible mitigative effect at low K (lab data for Alloy 600 plus SG tube experience)
- Recommended probabilistic approach:
  - Capture benefit on initiation from zinc
  - Address other uncertainties

Model Description

EPRI 1022852 – MRP-307

Overall Model (1/2)

- Partially based on xLPR work
- Monte Carlo simulation
- Distributed input parameters
- No separation of aleatory and epistemic uncertainty
- Reduced complexity of model output vs. xLPR (e.g., through-wall cracking, single initiation per weld, etc.)
- Output: Fraction (probability) of a given end point, for example:
  - Through-wall crack before end of life
  - End of life with no initiation
  - End of life with no through-wall crack
  - End of life with no 75% through-wall crack

Overall Model (2/2)

- Selected dissimilar metal butt welds for component specific analysis
  - Benefit of hydrogen temperature-specific
- Focused model on chemical mitigation effects
  - Used through-wall cracking as an endpoint
    - Strongly related to probability of rupture
    - Crack stability (rupture) not affected by chemistry
  - Used comparative assessments
    - Probability of leakage with versus without chemical mitigation
    - Identified risk-neutral inspection interval increase

Main Model Components

- Initiation
- Propagation
- Load
- Detection (not covered here, same as xLPR V1)

Initiation Model

- Simplified approach relative to xLPR, based on empirical plant data and one flaw per weld
- Step 1: select a reference initiation time using a Weibull distribution

$$F\left(t_{ref}\right)=1-e^{-\left(\frac{t_{ref}}{\theta}\right)^{\beta}}$$

- Step 2: adjust reference initiation time for stress and temperature

$$t_f = t_{ref}\left(\frac{\sigma_{ref}}{\sigma}\right)^{n} e^{\left(\frac{Q}{R}\right)\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}$$

- Step 3: adjust reference time for chemical mitigation (zinc)

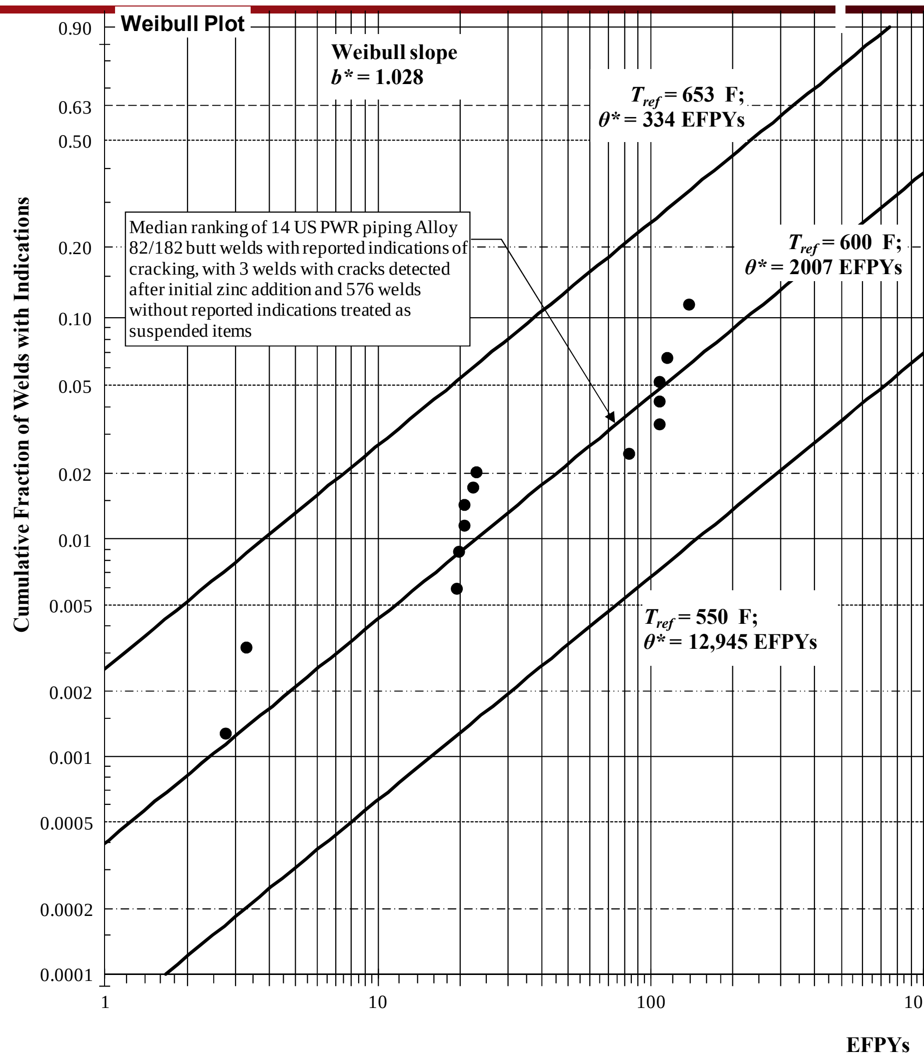
$$t' = t_{ZM} + FOI_{Zni}\left(t_f - t_{ZM}\right)$$

Initiation Model

Step 1: Weibull Distribution (Plant Data)

- Based on plant data
  - US plants
  - Alloy 82/182 piping butt welds with PWSCC tabulated in detail
  - Welds without indications treated as suspended samples

All inspection data adjusted to 600 F (Q = 44 kcal/mole)



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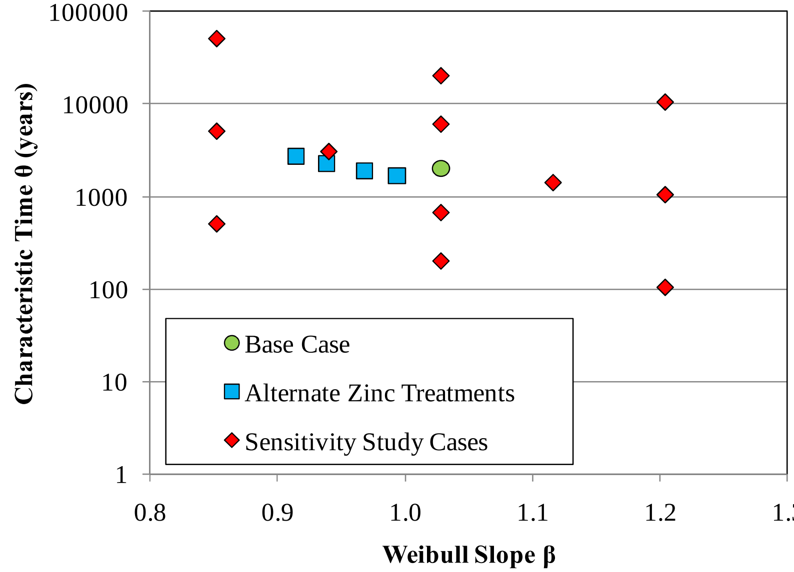
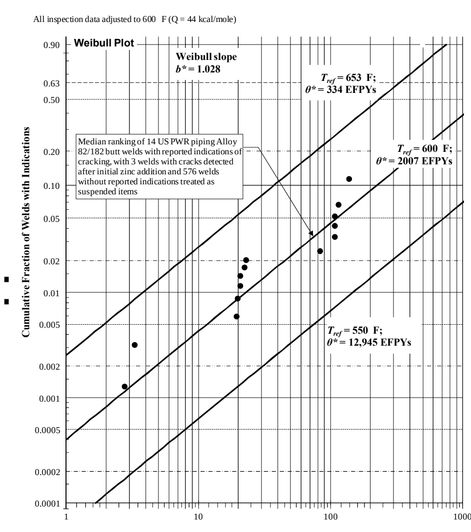
Initiation Model

Step 1: Weibull Distribution (Uncertainties)



- Weibull Slope
  - Normal distribution
  - μ = 1.028, σ = 0.088
  - Based on plant data
- Characteristic Time
  - Normal distribution on the linearized Weibull intercept (F=0.01)
  - Based on plant data
- Focus of a specific set of sensitivity studies
  - Weibull parameters
  - Treatment of data from plants already on zinc, for example:
    - No effect of zinc
    - Start of zinc program is a suspension
    - Time on zinc is discounted



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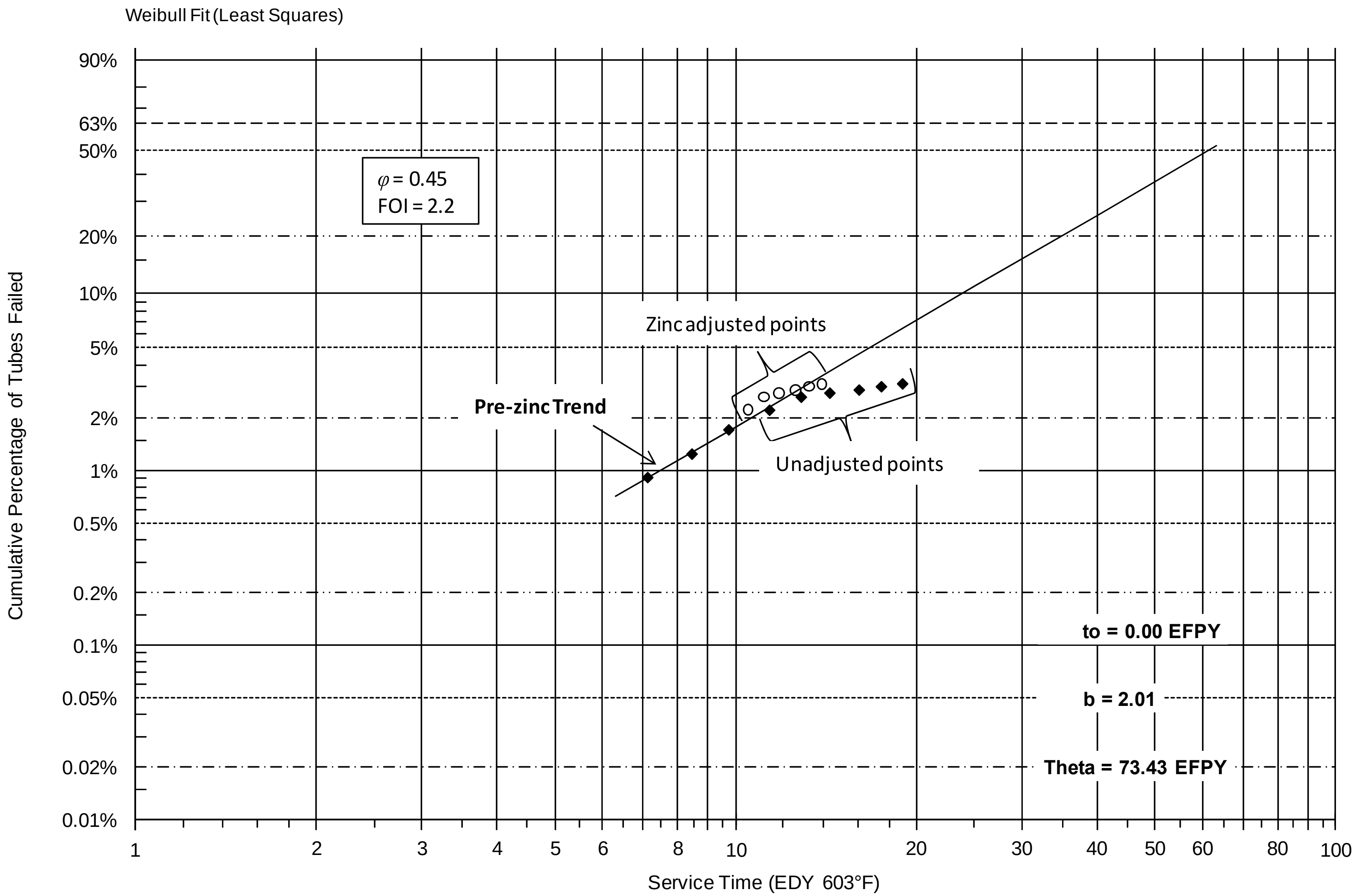
Initiation Model

Step 2: Temperature and Stress Adjustment

- Activation Energy
  - Normal distribution
  - μ = 184.23 kJ/mol, σ = 12.82 kJ/mol
  - Based on thick-wall laboratory data
    - σ set such that SG value is at 95^{th} percentile
  - Mean used in assessment of plant data to determine Weibull distribution
- Stress Exponent
  - Stress dependence of crack initiation not modeled (i.e., n = 0)
  - Little data on surface stresses for particular plant welds
  - Variation in initiation time due to stress captured by Weibull distribution
    - Assume surface stress distribution in 593 inspected welds is representative of total population
    - Fit to plant data incorporates aleatory and epistemic uncertainty
      - Surface stress = lack of knowledge (epistemic)
      - Stochastic initiation = inherent randomness (aleatory)

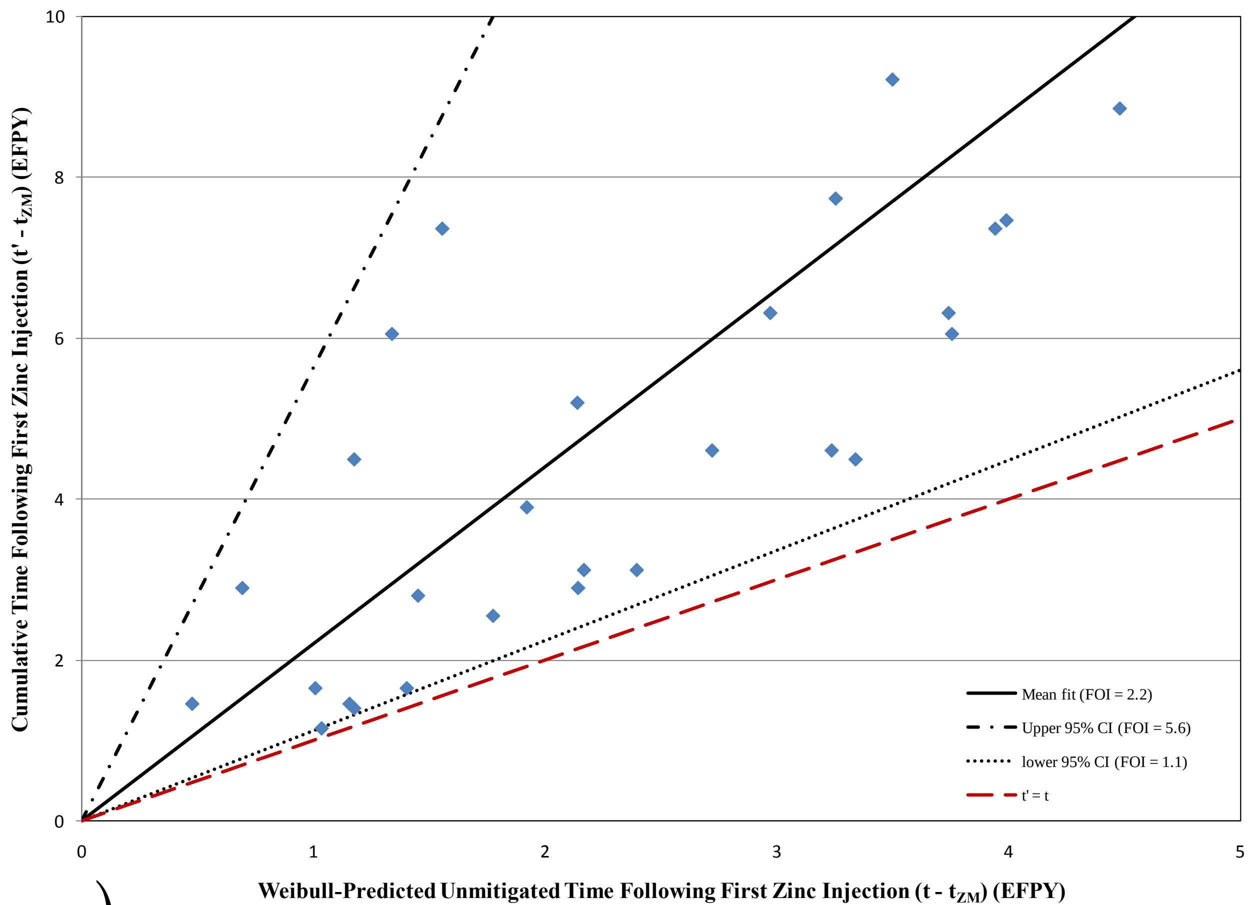
Initiation Model

Step 3: Adjustment for Zinc (1/3) – SG Data Used for Quantification



Initiation Model

Step 3: Adjustment for Zinc (2/3) – Improvement Factors



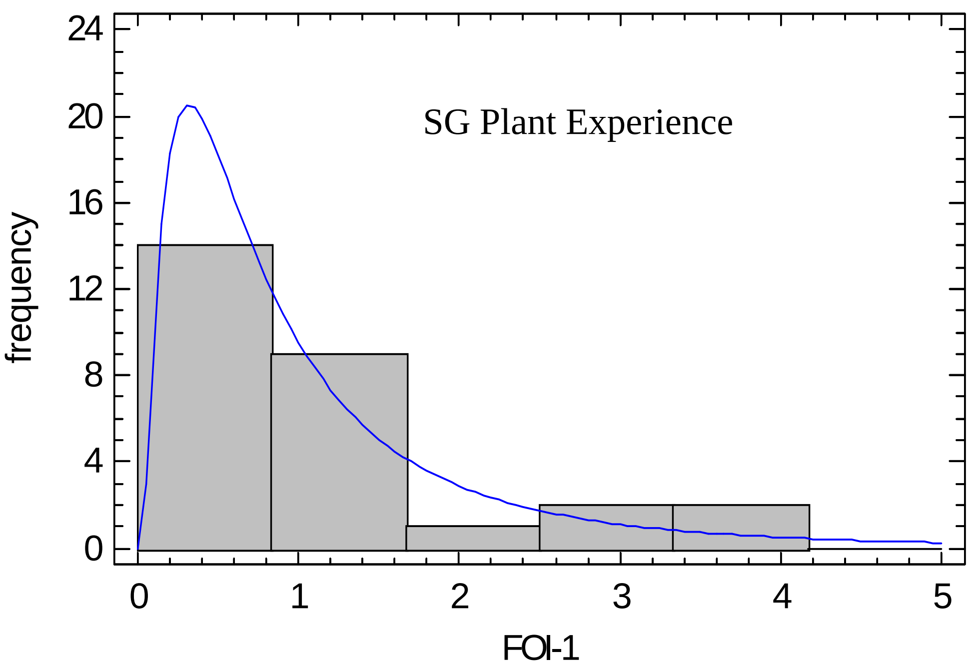
$$FOI_{Zni,j} = \frac{\left(t' - t_{ZM}\right)_j}{\left(t - t_{ZM}\right)_j}$$

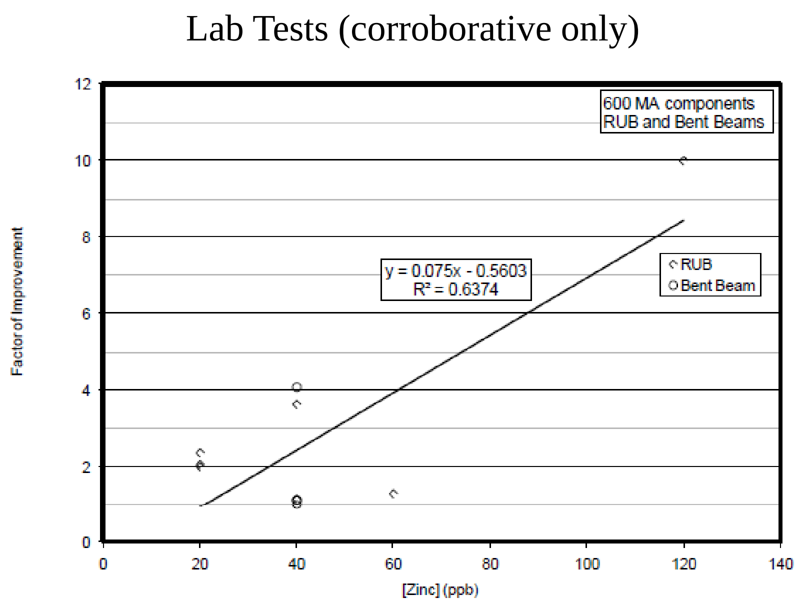
$$t' = t_{ZM} + FOI_{Zni}\left(t_f - t_{ZM}\right)$$

Initiation Model

Step 3: Adjustment for Zinc (3/3) – Actual Distribution and Corroboration

- Normal in ln(FOI-1)
  - $\mu = -0.29$, $\sigma = 0.93$ (mean FOI = 1.75)
  - Fit to plant data (SG tubes)
  - Lower truncation (FOI > 1) justified by corroborative lab data
    - All studies show some improvement





Initiation Model

Other Aspects

- Orientation (circumferential vs. axial) randomly selected
  - Matched to plant data
- Initial flaw depth
  - Flaw depth is assumed to be finite upon initiation
  - Normal distribution in ln(fraction through wall)
  - $\mu = -3$, $\sigma = 0.35$ (mean fraction = 0.05)
  - Results in SIFs greater than the assumed cut-off for zinc mitigation of propagation
    - Effectively, no mitigation of crack growth rates by zinc addition
- Initial aspect ratio
  - Normal distribution in ln(AR)
  - Based on data from plant inspections
  - Independently evaluated for circ and axial flaws

Propagation Model

MRP-263 Model with Hydrogen Effect

$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_{\mathrm{I}} - K_{\mathrm{I}th}\right)^b \left[\frac{1}{P} + \frac{(P-1)}{P} \exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^2\right)\right]$$

$$\Delta ECP_{Ni/NiO} = 29.58\left(\frac{T}{298.15}\right)\log_{10}\left(\frac{[H_2]}{[H_2]_{Ni/NiO}}\right)$$

$$[H_2]_{Ni/NiO} = 10^{(0.0111T_c - 2.59)}$$

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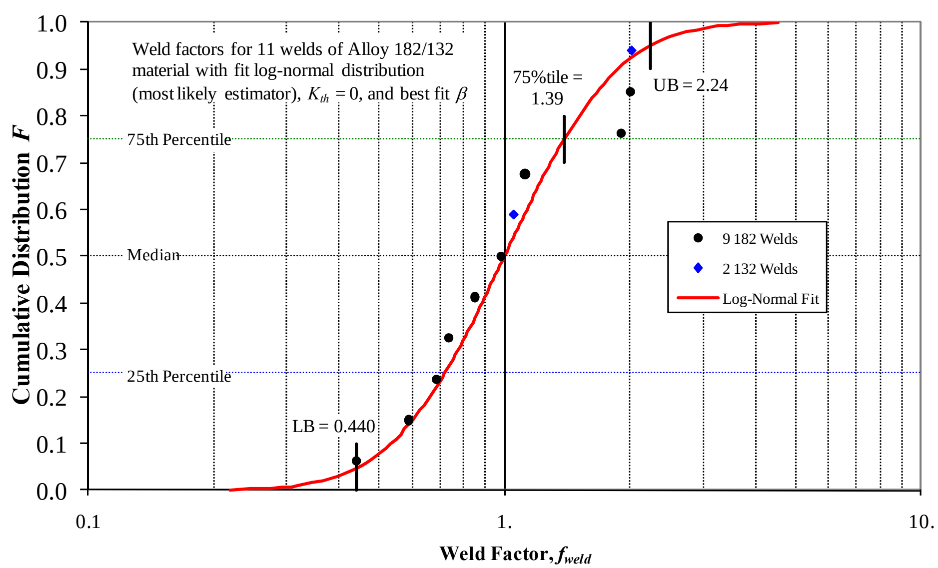
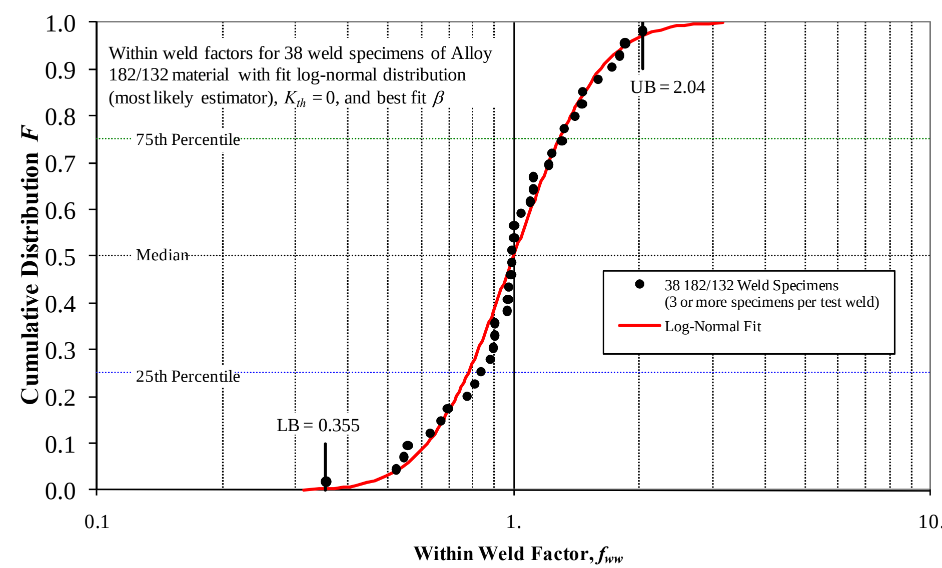
Propagation Model

Material Factors

Weld Factor, f_{weld}



Within Weld Factor f_{ww}



$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_{\mathrm{I}} - K_{\mathrm{I}th}\right)^b \left[\frac{1}{P} + \frac{(P-1)}{P}\exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^2\right)\right]$$

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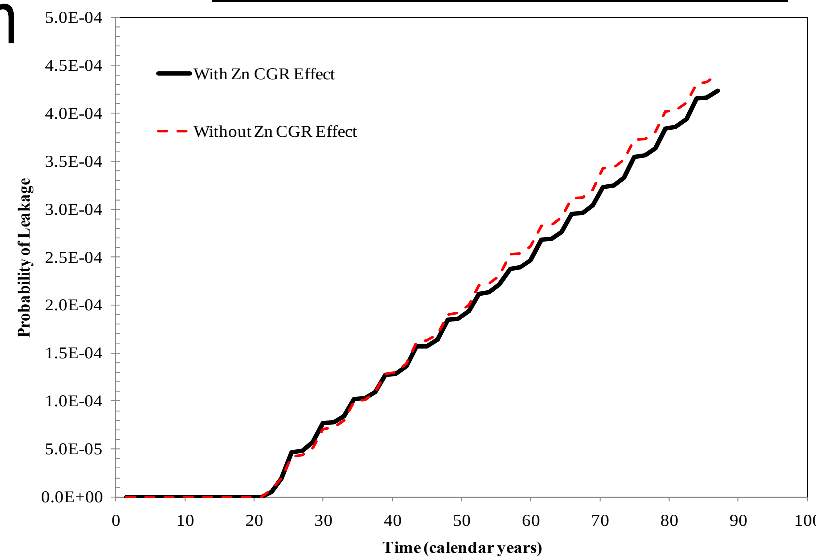
Propagation Model

Zinc Effect

- Normal distribution in $\ln(f_{Zn}-1)$
  - $f_{Zn} > 1$ corroborated by SG tube data
- Only applied for K<16.5 MPa√m
- Due to finite initial crack size, generally not applied during model run time

Data summary from MRP-263

K (Mpa√m)	Zinc (ppb)	FOI
27	57	1.25
27	22	0.64
22	108	1.08
16.5	50	5.67
16.5	50	2.83
16.5	50	1.00
16.5	50	1.00
27.5	50	0.62
27.5	150	1.72



$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_{\mathrm{I}} - K_{\mathrm{I}th}\right)^b \left[\frac{1}{P} + \frac{(P-1)}{P} \exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^2\right)\right]$$

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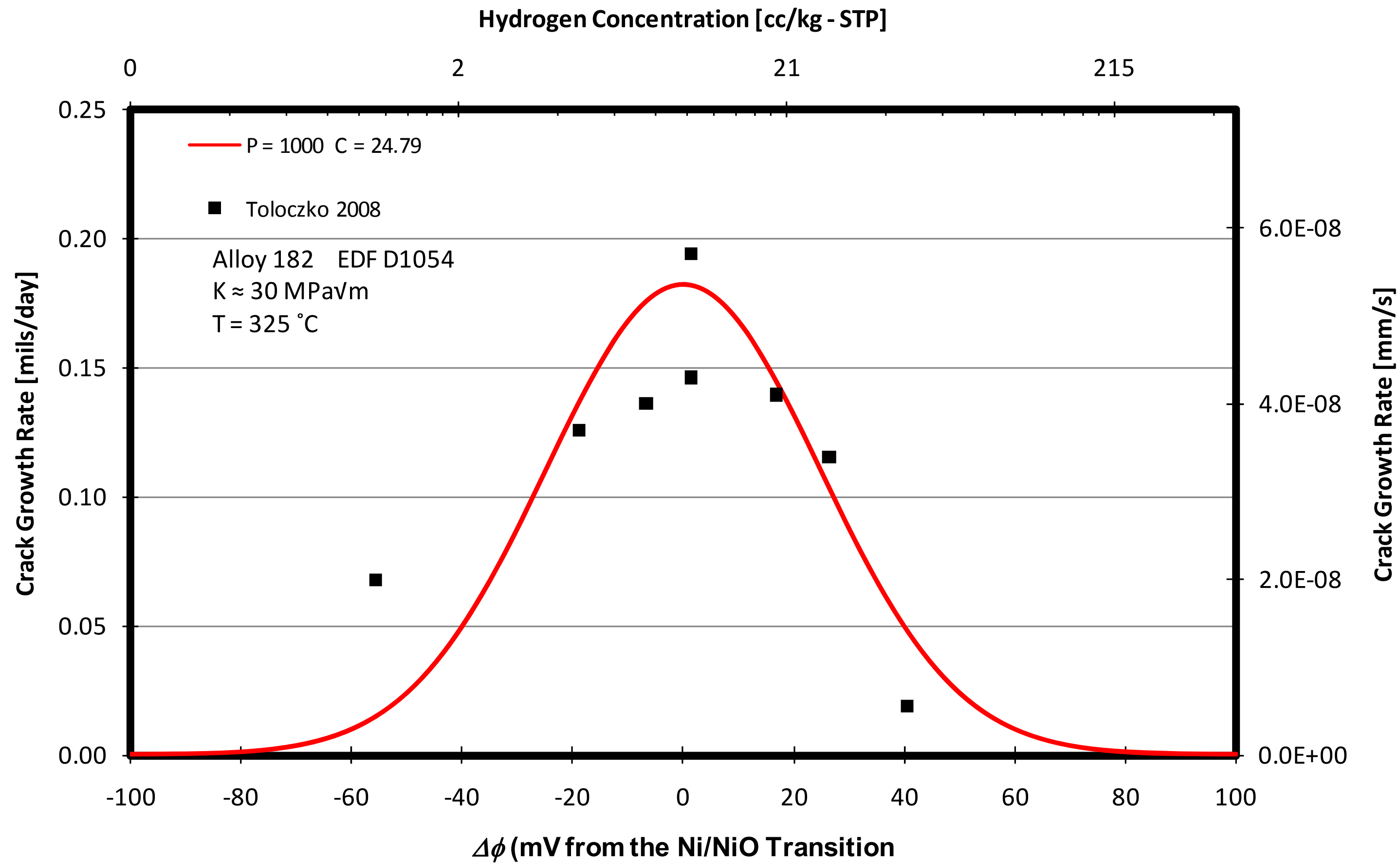
Propagation Model

Hydrogen Effect – Example Test Data



$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_I - K_{Ith}\right)^b \left[\frac{1}{P} + \frac{(P-1)}{P}\exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^2\right)\right]$$

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Propagation Model

Hydrogen Effect – Data Analysis

- Four test sets for Alloy 182
  - Qualitatively corroborated by additional Alloy 600 data
- Peak width parameter *c*
  - Normal distribution
  - $\mu = 18.5$, $\sigma = 5.5$
- Peak height parameter *P*
  - Normal distribution in ln(*P*-1)
  - $\mu = 4.52$, $\sigma = 2.75$ (mean $P = 93$)
  - $P > 1$ supported by data from other nickel alloys (600, 82, X750)
  - Form of equation used makes value of *P* unimportant if >~17

Data Set	Peak Width, *c* (mV)	Peak Ratio, *P*
A	20.2	1000
B	24.79	1000
C	12.06	10.5
D	15.81	8.6

$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_{\mathrm{I}} - K_{\mathrm{I}th}\right)^b \left[\frac{1}{P} + \frac{(P-1)}{P} \exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^2\right)\right]$$

Propagation Model

Other Aspects

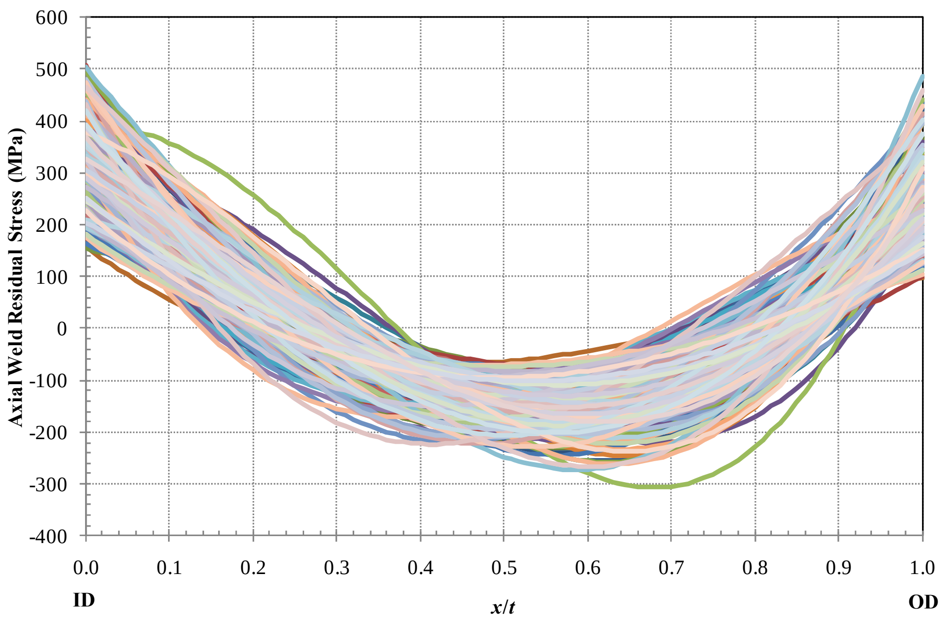
- Threshold $K_{Ith} = 0$
- Stress exponent *b* taken as a single value
  - 1.6 per MRP-115
- ΔECP taken as having no uncertainty
- During model run time, cracks grown in one month intervals

$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_{I} - K_{Ith}\right)^{b} \left[\frac{1}{P} + \frac{(P-1)}{P}\exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^{2}\right)\right]$$

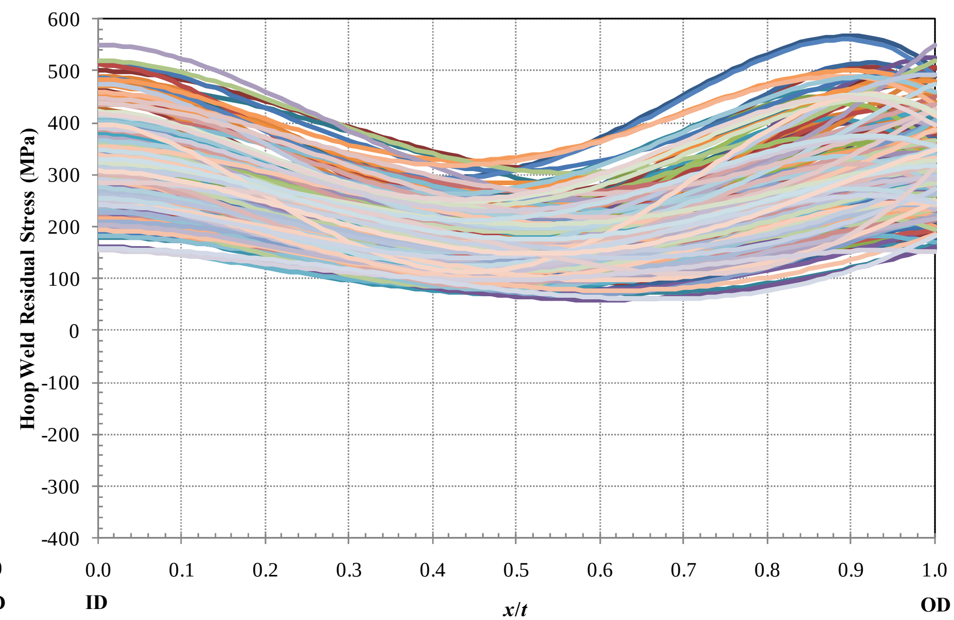
Loads

Examples

Axial Welding Residual Stress



Hoop Welding Residual Stress



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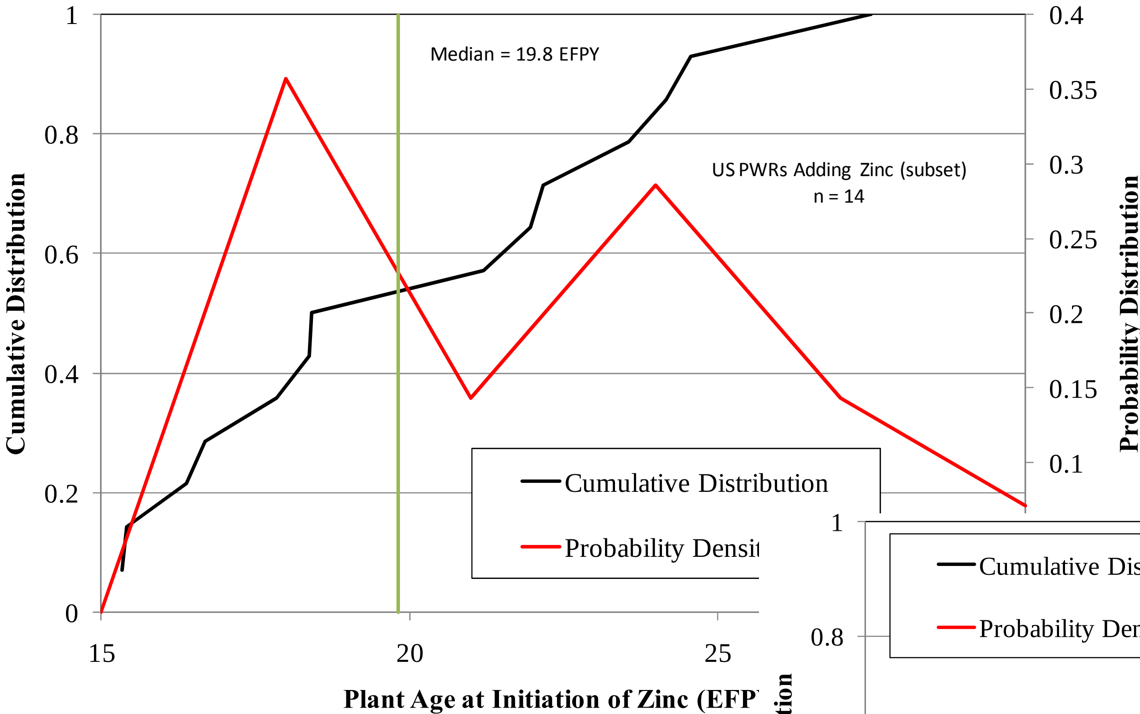
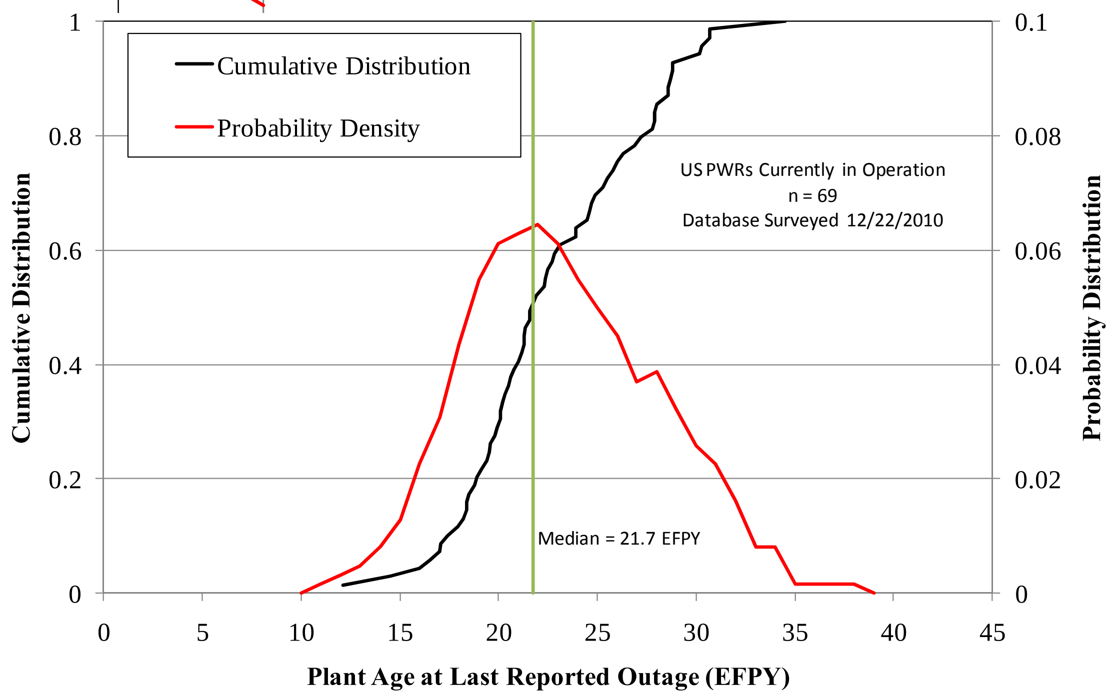
General Inputs

- Westinghouse RV Outlet Nozzle (RVON)
  - Others considered, but not presented here
- Typical geometry selected as fixed input
  - Thickness 2.75 in
  - Diameter 36 in
  - Width 1.75 in
- Aged component (see next slide)
- 315°C
- Un-optimized hydrogen = 37 cc/kg
  - Used for comparison basis

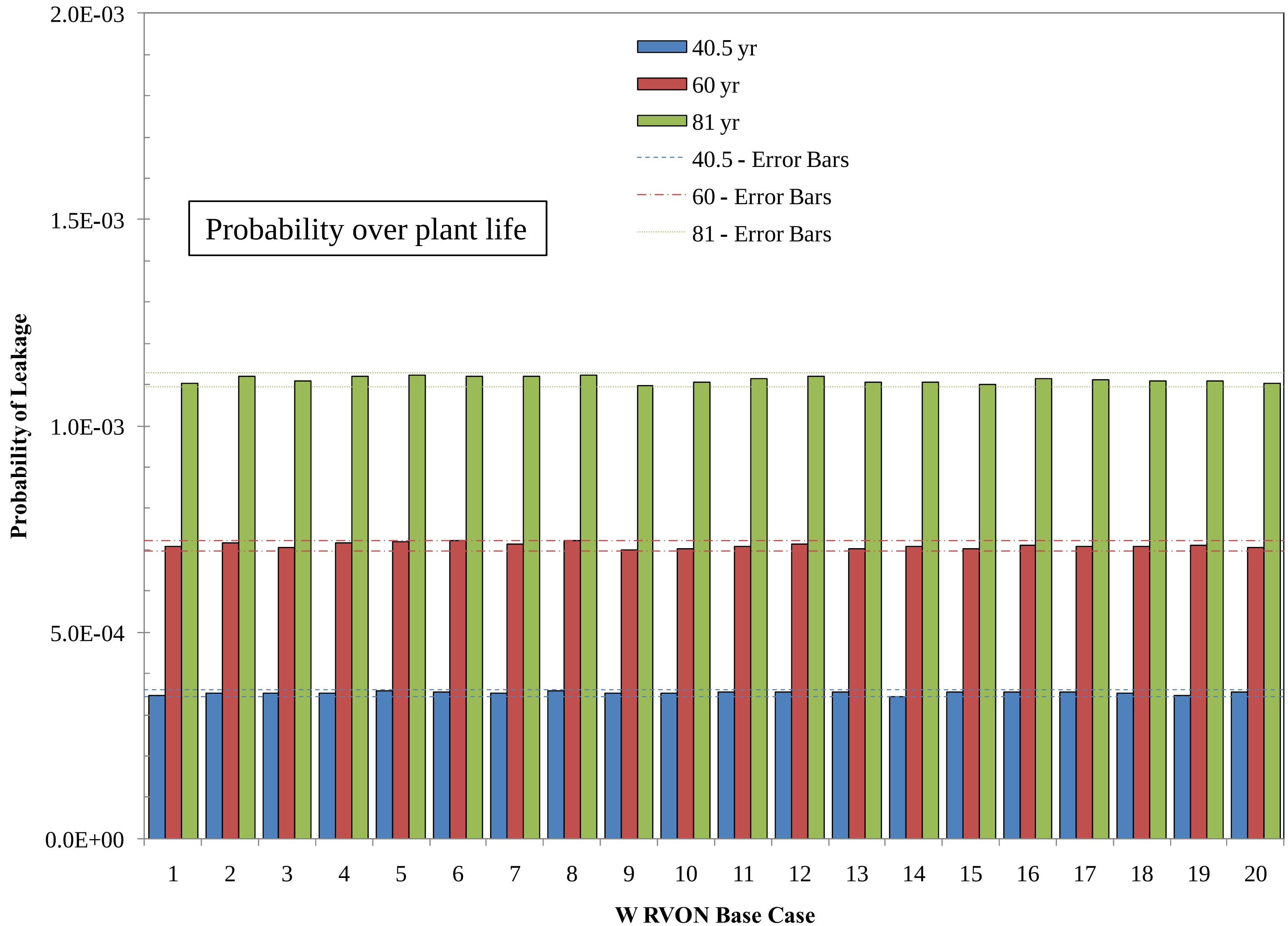
Aged Components



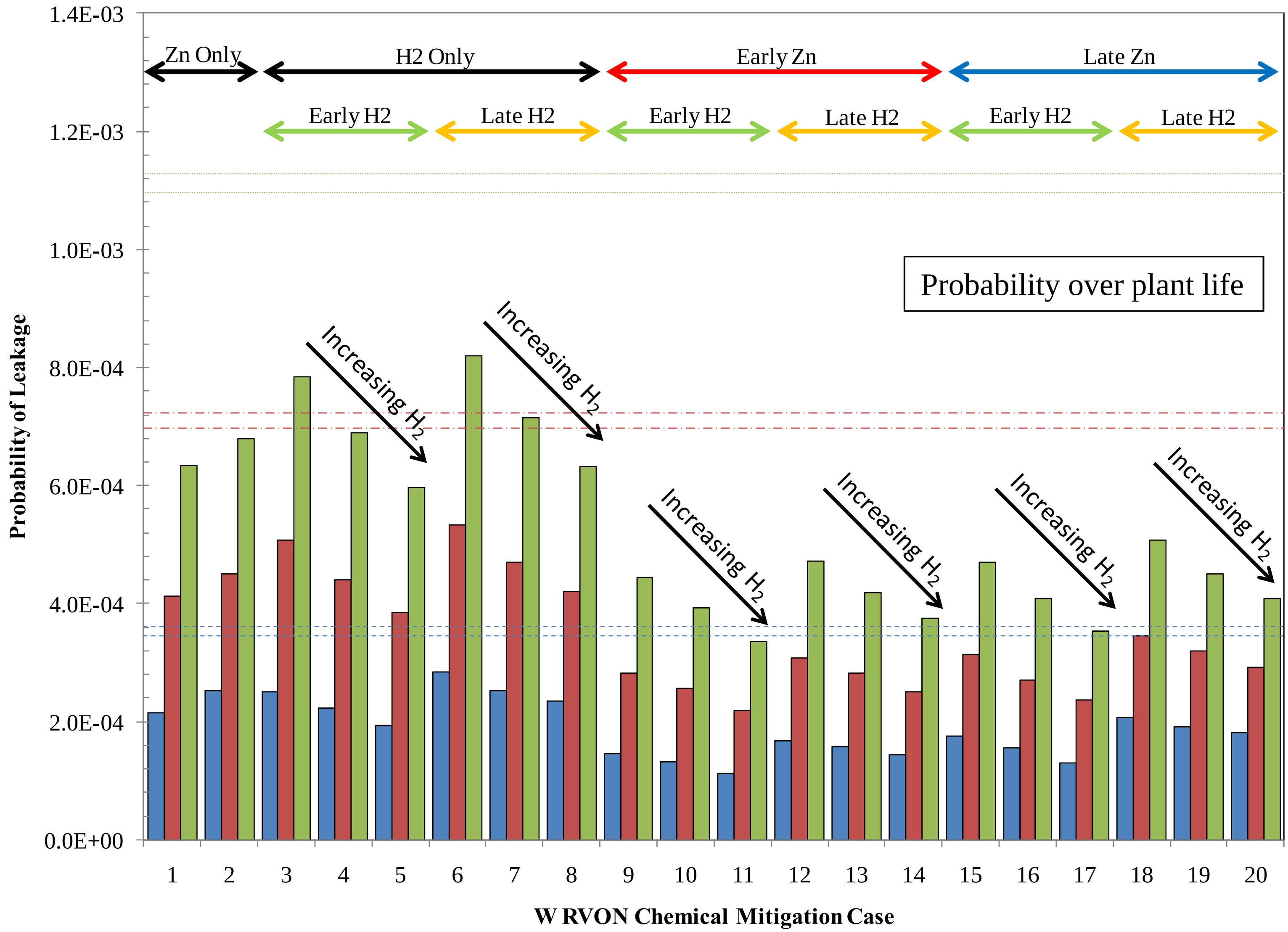


Example Results

Evaluation of Repeatability



Different Strategies Considered



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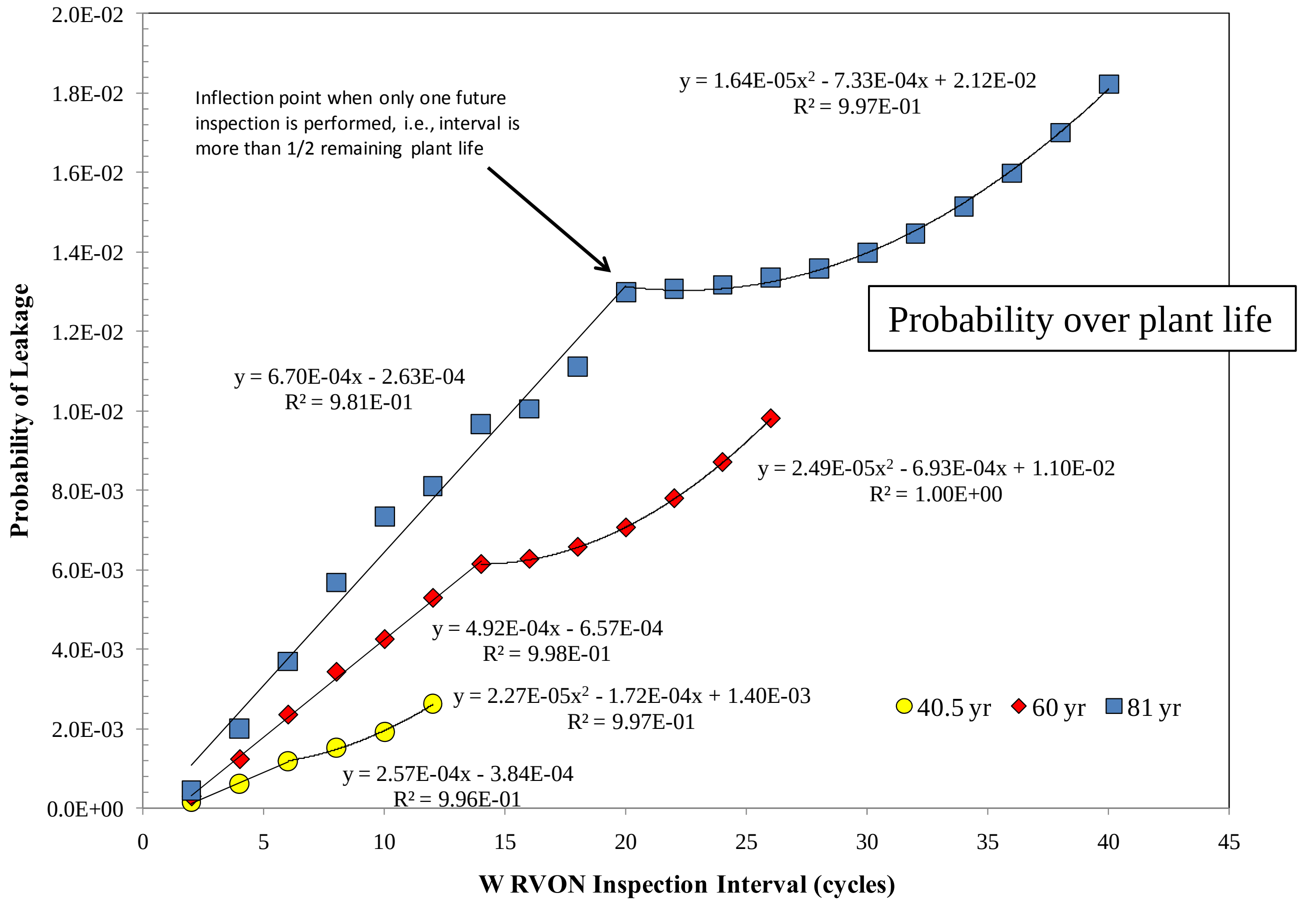
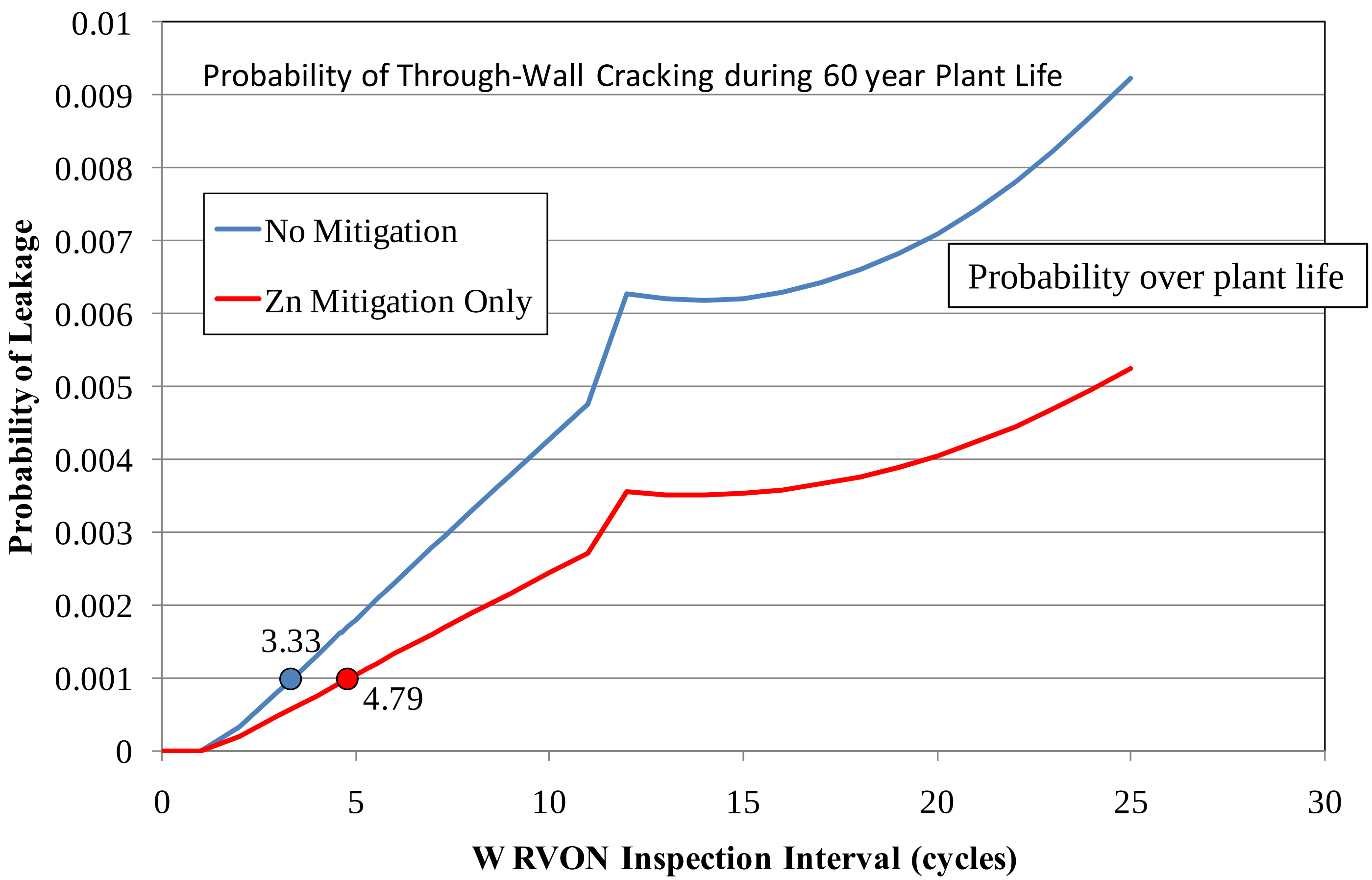
Dependence on Inspection Interval

No Mitigation



Dependence on Inspection Interval

Comparison of No-Mitigation with Mitigation – Zinc Only



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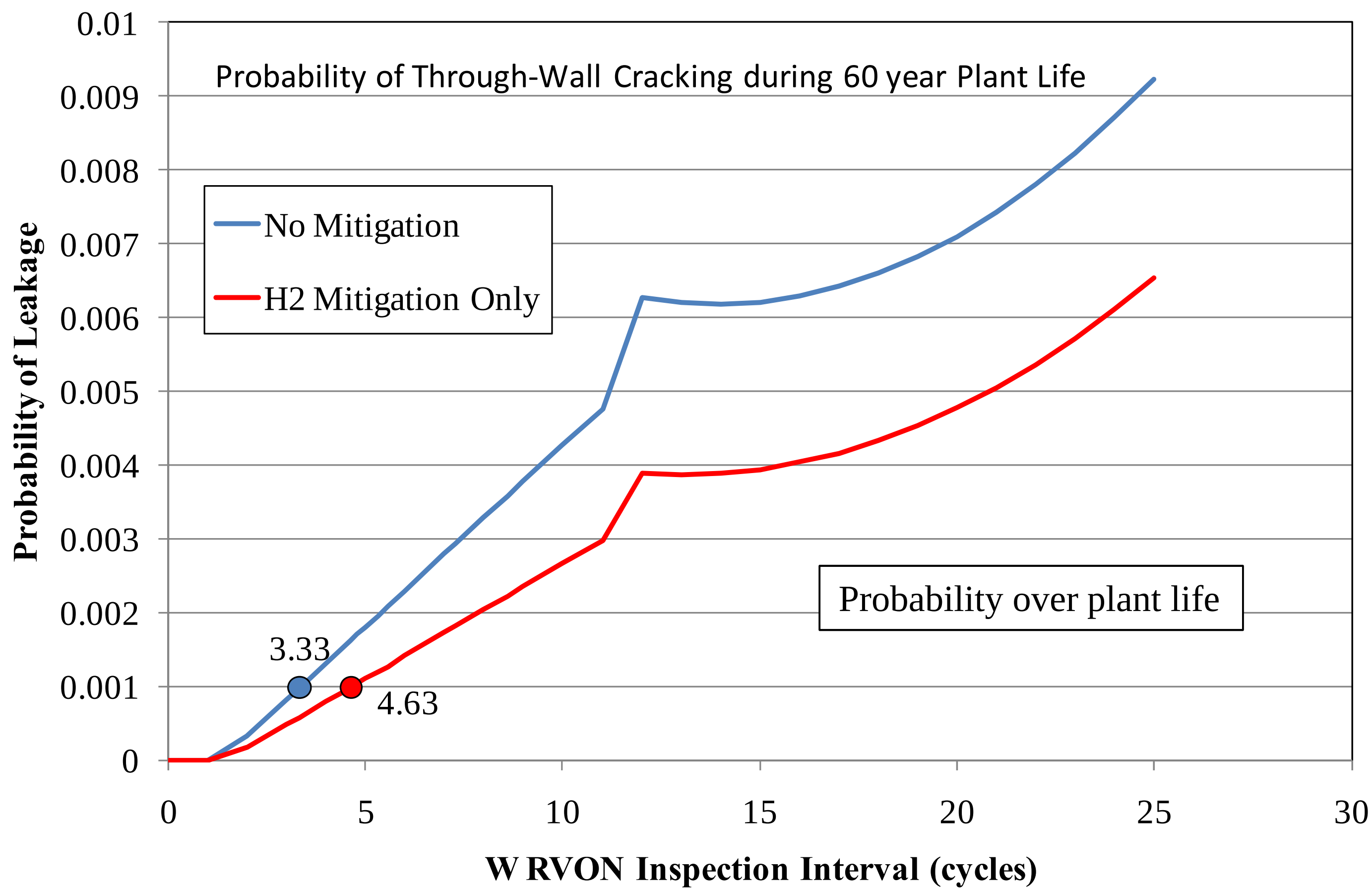
Dependence on Inspection Interval

Comparison of No-Mitigation with Mitigation – Hydrogen Only



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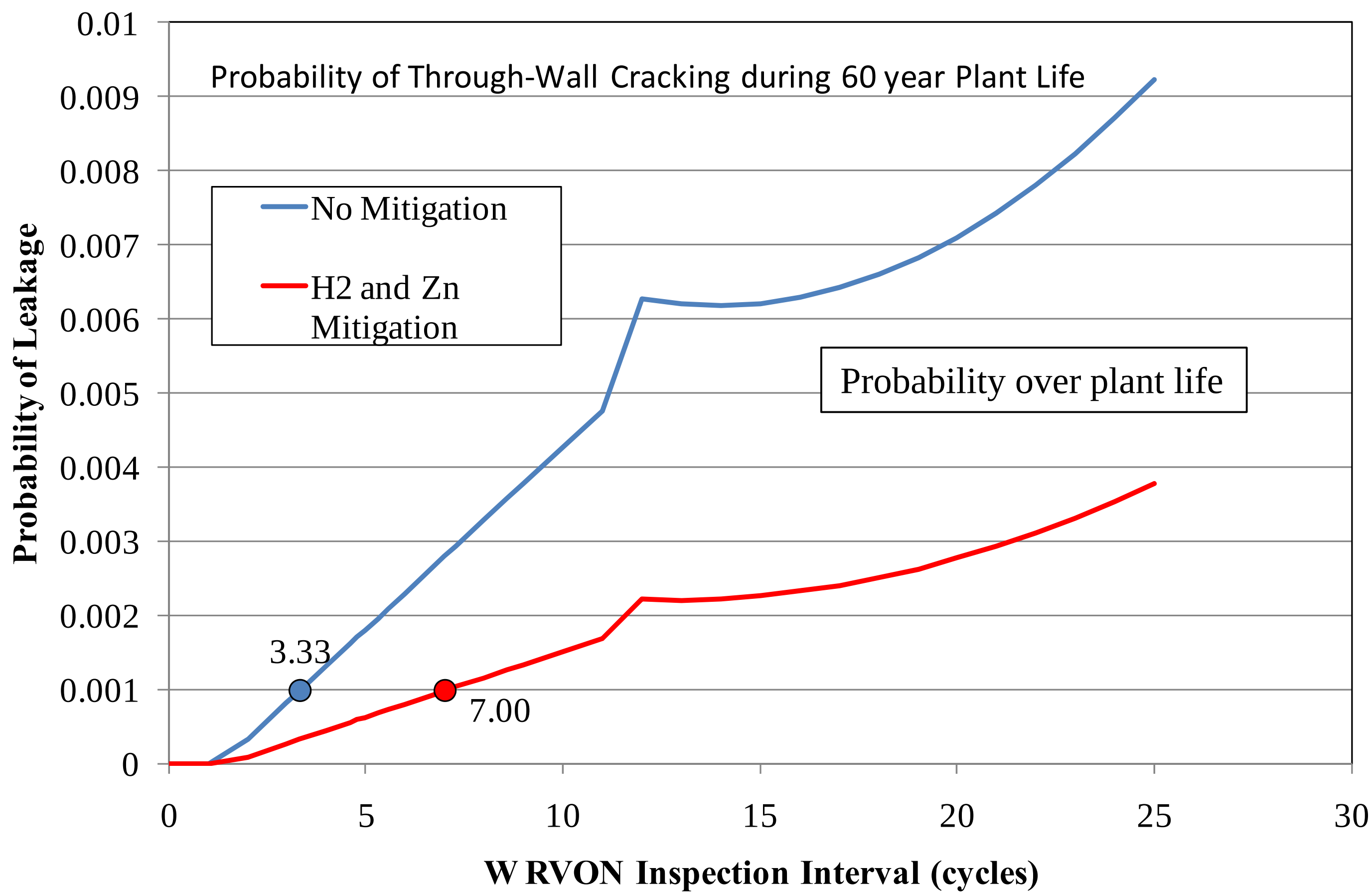
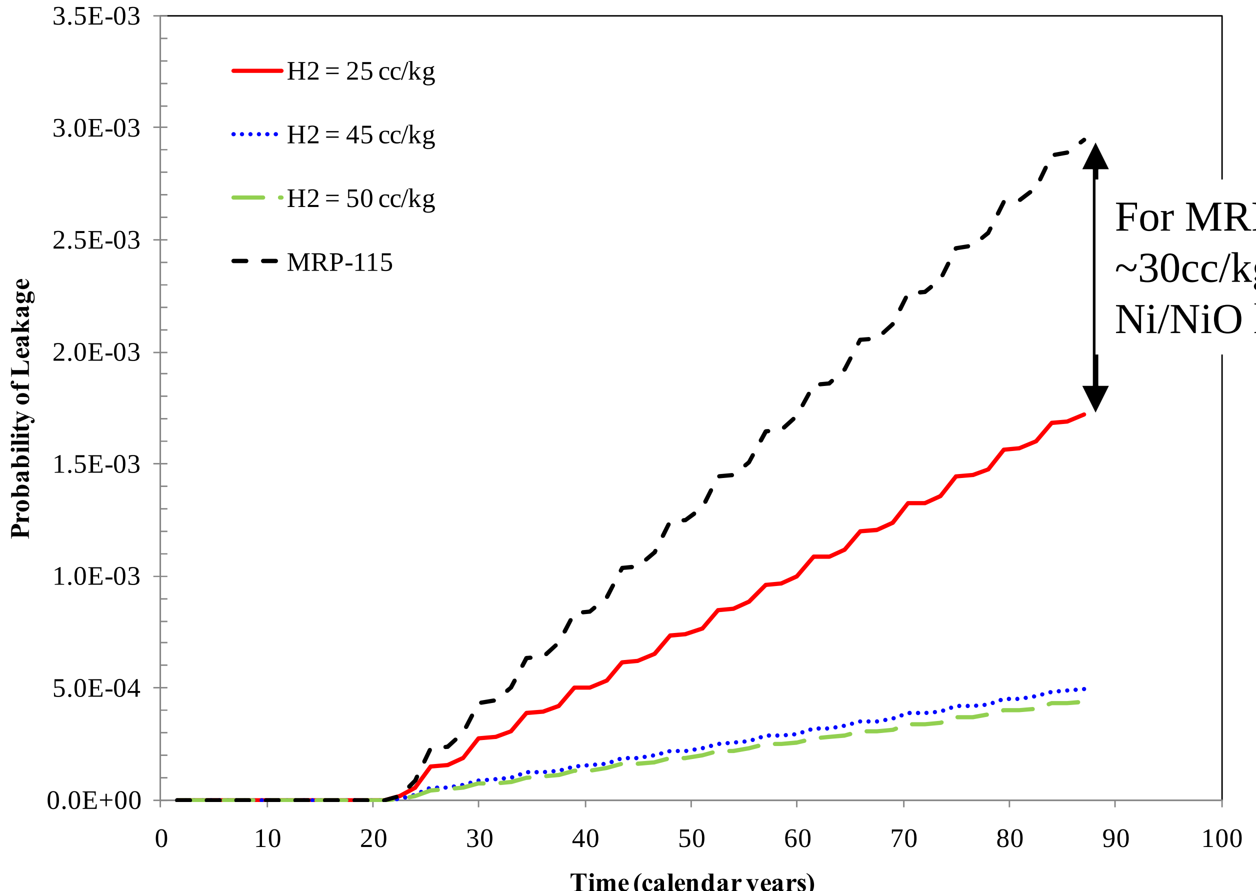
Dependence on Inspection Interval

Comparison of No-Mitigation with Mitigation – Hydrogen and Zinc



Sensitivity Study

Comparison to MRP-115



For MRP-115, most tests were at ~30cc/kg and 340°C, so much closer to Ni/NiO line (e.g., ~16cc/kg at 315°C)

MRP-115 is a conservative interpretation of the experimental data because the hydrogen effect makes the data seem more pessimistic than it really is.

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Conclusions (1/2)

- Results are favorable

Location	Current Interval (years)	Equivalent Interval with Chemical Mitigation								
		Zn Only			H2 Only			Zn+H2		
		41 EFPY	60 EFPY	81 EFPY	41 EFPY	60 EFPY	81 EFPY	41 EFPY	60 EFPY	81 EFPY
Westinghouse RVON DMW	5	6.9	7.2	8.3	6.9	6.9	8.0	10.9	10.5	12.9
B&W RCP Nozzle DMW	7	8.0	9.1	8.4	7.1	7.1	7.0	8.8	9.5	8.8

- Inspection interval increase of a factor of two for hot leg locations is justified when both zinc and hydrogen optimization are used.

Conclusions (2/2)

- Framework for quantitative incorporation of chemical mitigation (initiation and propagation) developed
  - A risk-neutral approach, i.e., determine increase in inspection interval that results in the same risk after chemical mitigation as risk with the current inspection interval without chemical mitigation
  - Allows for simplification of phenomena unrelated to chemical mitigation
- Industry considering best path forward
  - No defined plan for requesting inspection relief at this time
  - Models are being made available to xLPR for consideration
    - Hydrogen effect included in V1 CGR model

Technical Basis for PWSCC Mitigation by Surface Stress Improvement (MRP-267, Revision 1)

Glenn White and Iain Hamilton
Technical Leads – Dominion Engineering Inc.

William Sims
Assessment TAC Chairman – Entergy

Paul Crooker
Mitigation and Testing TAC PM - EPRI

PWR Materials Reliability and Weld Repair Research Meetings, EPRI, Charlotte, NC
January 26, 2012

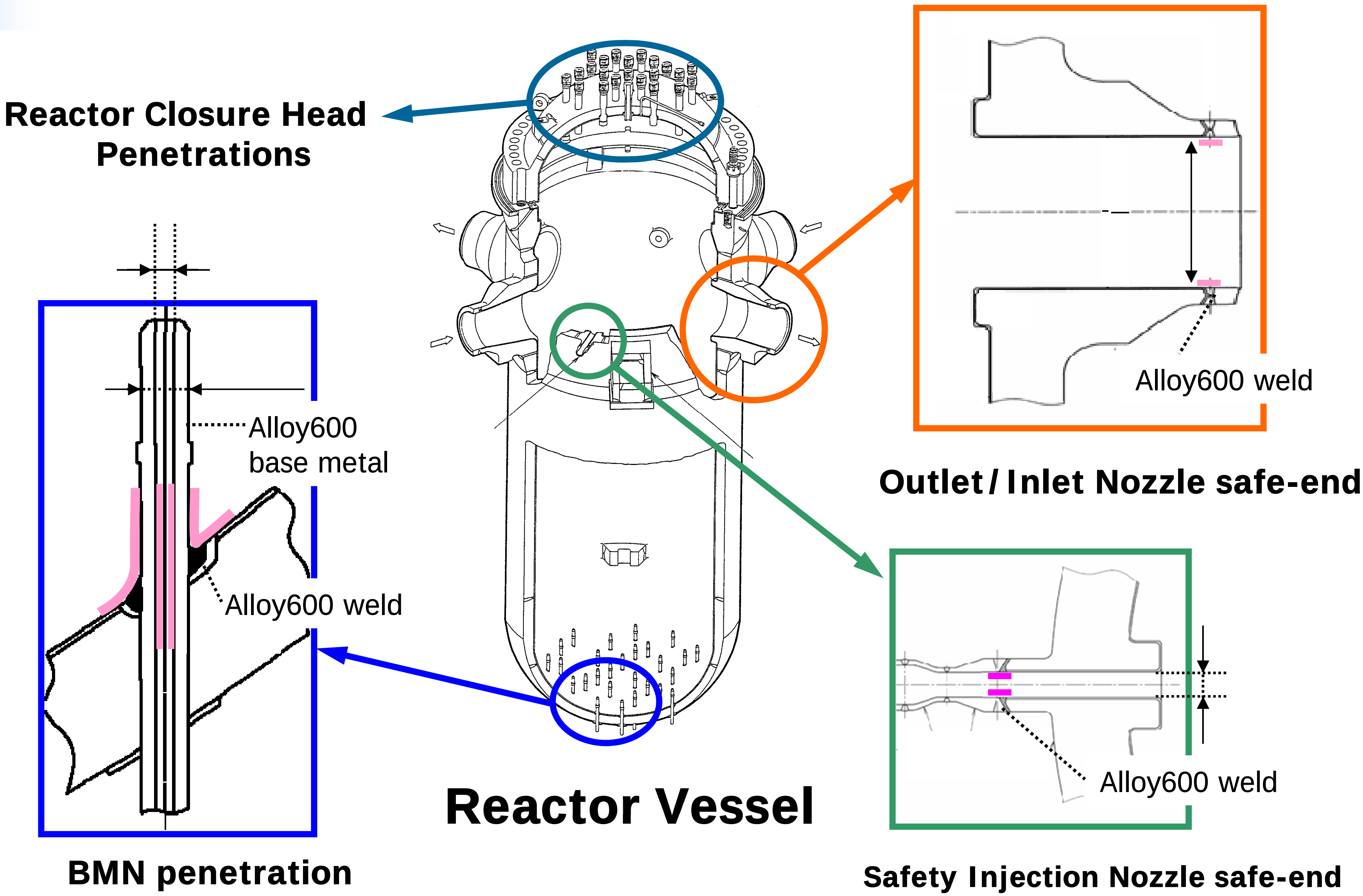
Outline

- MRP Support of Peening Mitigation of PWSCC
- MRP-267 Technical Basis Document
  - Contents of MRP-267
  - Purpose, Scope, Approach
  - Introduction to Peening Technology
  - Use of Peening Technology in Japanese LWRs
  - Effectiveness of Laser Peening and Water Jet Peening
    - Stress Measurements
    - SCC Testing
    - Stress Relaxation Testing
  - Peening Implementation
  - Conclusions

Project Team and Peening Vendors

- MRP Project Team:
  - Paul Crooker, EPRI Project Manager
  - William Sims, Entergy, Assessment TAC Chairman
  - MRP Peening Working Group (utility participants)
  - Glenn White, Technical Lead, Dominion Engineering, Inc.
- Peening vendors providing input to MRP effort
  - Hitachi GE (Water Jet Peening—WJP)
  - Metal Improvements Corp (Laser Shock Peening—LSP)
  - MNES/MHI (Water Jet Peening—WJP)
  - Westinghouse/Toshiba (Fiber Laser Peening—FLP)

Potential US PWR Locations for Application



Utility/Industry Perspective

Peening might be the only or preferred option

- Not Feasible / Practical Locations
  - Some Westinghouse plants due obstruction and limited space in sandbox, MSIP or Weld Overlay is not practical
    - ID welding under development but high risk
- Difficult/High Consequences Locations
  - B&W Core Flood location
    - ID remote welding required or substantial concrete removal
    - Core barrel removal required for inspection
  - BMNs – not feasible to replace all penetrations
- Option to mitigate RV Heads rather than replace
  - Cost effective and minimizes exposure to personnel
  - Shorter outage duration for mitigation than replacement
  - No Containment opening required
  - Eliminates the need for future repair contingency following mitigation

Utility/Industry Perspective

Protect Plant Assets and Reduce operating costs

- Avoid component replacement
- Avoid unnecessary costly repairs
- Eliminate repair dose
- Eliminates the need for contingencies
- Optimize inspection timing for Hot and Cold Legs DM welds to coincide with 10/20 year ISI frequency to minimize the number of core barrel movements
- <u>**Plants are planning proactive peening now with the desire for future inspection relief**</u>

MRP Support of Peening Mitigation of PWSCC

- MRP is supporting use of peening as an option to mitigate PWSCC in US and international PWRs:
  - Laboratory testing of peened samples independent of vendor testing
  - Detailed analytical models
  - Series of three documents supporting use of peening, including appropriate relaxation of inspection requirements after peening:
    - MRP-267 technical basis document presenting the extensive set of laboratory tests (to be submitted for NRC information)
    - MRP-335 topical report (to be submitted for NRC review)
    - MRP-336 specification guideline (for use by utilities)

Table of Contents of MRP-267 (Revision 1)

Need for Peening Mitigation

- Methods to mitigate PWSCC of dissimilar metal welds (DMWs) in primary piping systems have been developed:
  - Weld overlay
  - Weld in-lay and on-lay
  - Mechanical stress improvement
- Surface stress improvement (SSI) (i.e., peening) is another mitigation method that has been extensively used in Japan
  - For DMWs, SSI has the advantage that access is not required at the pipe exterior
  - Unlike other mitigation methods, SSI can be used to mitigate partial-penetration welded (i.e., J-groove) Alloy 600 nozzles including:
    - Reactor pressure vessel top head penetration nozzles (RPVHPNs)
    - Reactor pressure vessel bottom mounted nozzles (BMNs)

Purpose of MRP-267 Technical Basis Document

- To establish the technical basis for applying SSI treatments in mitigating PWSCC as a viable method to protect key PWR plant assets
  - To establish the effectiveness of SSI treatments (especially FLP, LSP, and WJP) as alternative mitigation options to be applied in the nuclear industry
  - To present information on implementation of these SSI treatments that EPRI members can consider in pursuing proactive mitigation options
  - To identify Alloy 600/82/182 locations for which relaxation of inspection requirements is appropriate after applying SSI mitigation treatments

Scope of MRP-267

- Peening methods that have been commercialized or are near commercialization for use in PWRs:
  - Fiber Laser Peening (FLP)
  - Laser Shock Peening (LSP)
  - Water Jet Peening (WJP)
- The Alloy 600/82/182 components of focus are:
  - Alloy 82/182 DMWs in primary system piping
    - Large diameter DMWs in main loop piping
    - Other DMWs mainly on branch connections
  - RPVHPNs including CRDM, CEDM, top head instrumentation (ICI), and head vent nozzles
  - BMNs (i.e., BMI, ICI, and IMI nozzles)
- The SSI treatment is applied to the entire area of the wetted surface that is susceptible to PWSCC

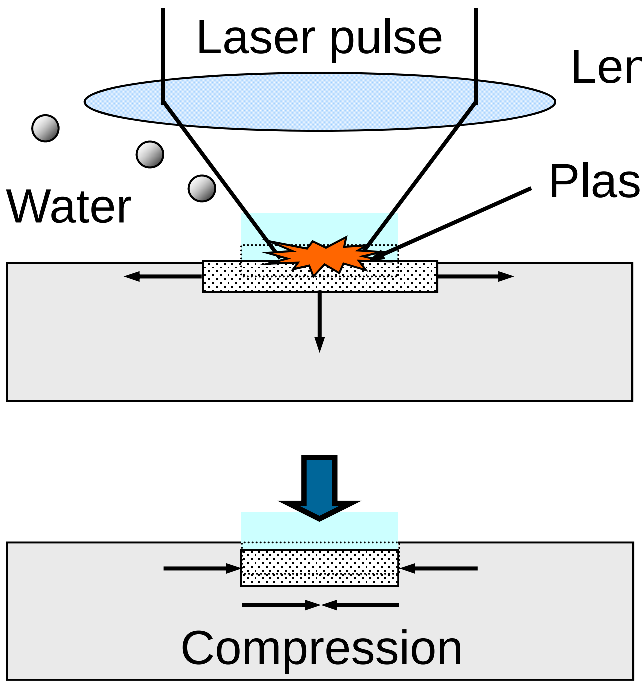
Approach of MRP-267

- SSI mitigates PWSCC by reversing the tensile stress at the surface exposed to reactor coolant to compressive residual stress
  - Initiation of PWSCC flaws requires as a necessary condition tensile stress at the surface
  - Any existing flaws that are in the surface compressive stress zone when the SSI process is applied cannot grow via PWSCC
- Present the results of extensive experimental studies supporting the long-term effectiveness of the SSI mitigation methods without any unacceptable side effects
- Present additional reference information supporting the viability of the SSI methods:
  - Use of methods in Japanese BWRs and PWRs
  - Principles of operation
  - System design basics
  - Field implementation issues

Fiber Laser Peening (FLP)

Process

- *Process performed underwater*
- *Focused high-energy laser pulse irradiates metal surface in water*
- *High-pressure plasma forms on the metal surface*
- *Shock wave forms, impinges on metal surface, and creates permanent local strains*
- *Compressive residual stress is produced by constraint of surrounding material*
- *Vendor: Toshiba/Westinghouse*



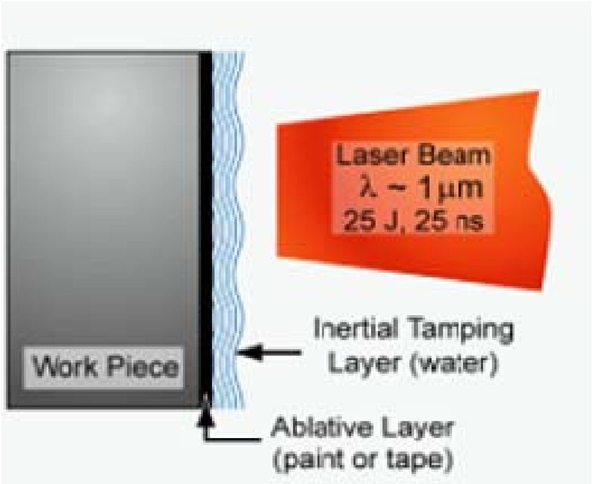
- **Plasma pressure ~ 725 ksi**
- **Alloy 600 Yield Strength ~ 35-42 ksi**

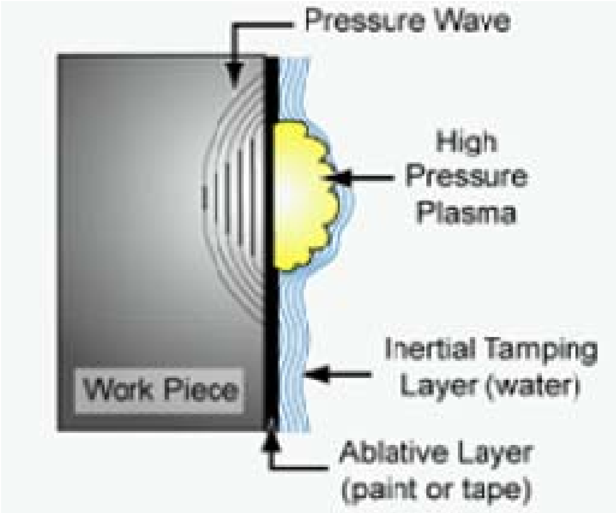
(Schematic provided by Toshiba)

Laser Shock Peening (LSP)

Process

- *Process not performed underwater (although a thin layer of de-ionized water is applied to surface)*
- *The basic physics of the process are the same as for FLP*
- *The ablative layer is optional*
- *Vendor: Curtiss-Wright Metal Improvement Company (MIC)*
- *The LSP technology is currently being used in critical aerospace and other applications:*
  - *Commercial jet engine blades*
  - *Aircraft structural parts*
  - *Boeing 747-8/777/787, Gulfstream V/VI, Airbus A340, F-22 Fighter, Navy T-45*
  - *Commercial gas and steam turbine blades*



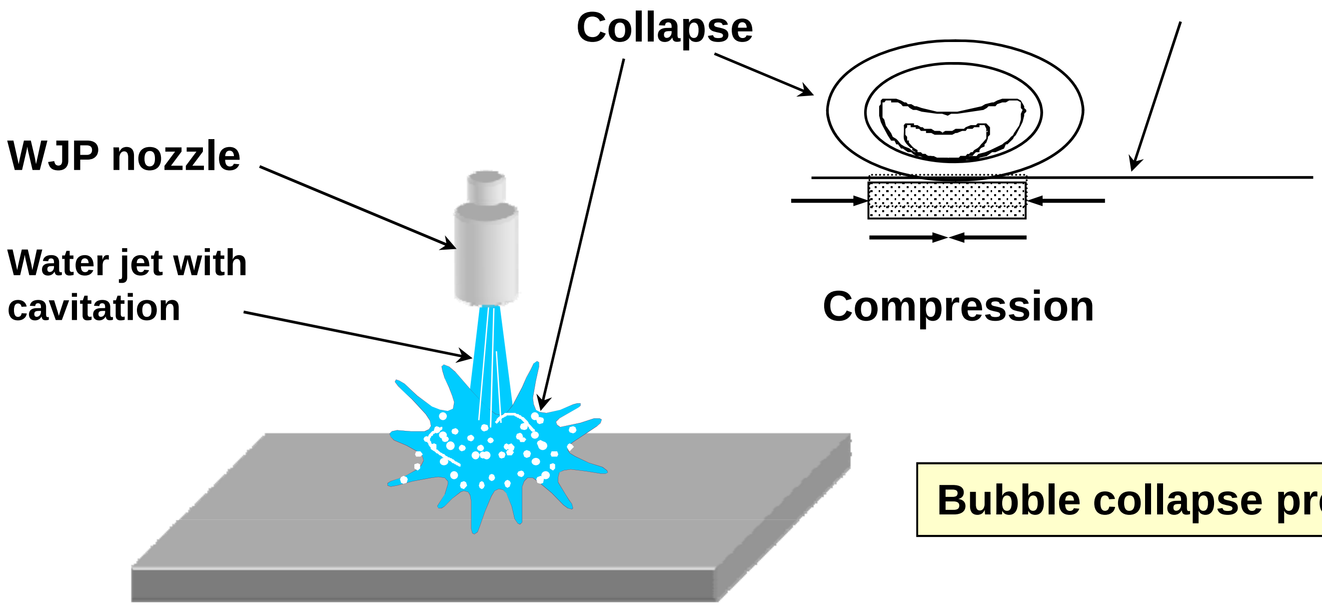


(Schematic provided by MIC)

Water Jet Peening (WJP)

Process

- *Process performed underwater*
- *High-speed jet results in local pressure dropping below the vapor pressure of water*
- *Water is locally evaporated to form cavitation bubbles due to pressure drop*
- *Bubbles collapse at surface generating high pressures*
- *Compressive residual stress is produced after the shock wave*
- *Vendors: Hitachi-GE, MNES*



Bubble collapse pressure ~ 150 ksi

(Schematic provided by Hitachi-GE)

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Use of FLP and WJP Peening Mitigation in Japan

For PWR plants:

- Currently, 21 out of 24 PWR units have applied WJP or FLP to BMNs and RV inlet/outlet nozzle DMWs
- The remaining three PWR units have plans to apply peening
- Peening has also been applied to RV safety injection nozzles
- The current status is shown on the next slide

For BWR plants:

- As of 2009, 20 BWR units have applied WJP or FLP to core shrouds and bottom head penetrations (i.e., CRD stud tubes)
- Plans to perform peening at other BWR plants
- Applying to new ABWR units during the fabrication and construction phases

Use of FLP and WJP Peening Mitigation in Japan (cont.)

Utility	Plant - Unit	Number of Loops	Peening application to Alloy 600/82/182 locations of RV				
			BMN (BMI Nozzle)		Outlet/Inlet Nozzle		Safety Injection Nozzle
			Tube ID	Tube OD and J-Groove Weld	Outlet Nozzle	Inlet Nozzle	
Kansai Electric Power Co.	Mihama - 1	2	✓	✓	✓	✓	✓
	Mihama - 2	2	✓	✓	✓	✓	✓
	Mihama - 3	3	✓	✓	✓	✓	—
	Takahama - 1	3	✓	✓	✓	✓	—
	Takahama - 2	3	✓	✓	**INLAY**	**INLAY**	—
	Takahama - 3	3	✓	✓	✓	✓	—
	Takahama - 4	3	✓	✓			—
	Ohi - 1	4	✓	✓	✓	✓	—
	Ohi - 2	4	✓	✓	✓	✓	—
	Ohi - 3	4	✓	✓	**✓/ INLAY**	✓	—
	Ohi - 4	4	✓	✓	**INLAY**	✓	
Kyusyu Electric Power Co.	Genkai - 1	2	✓	✓	✓	✓	✓
	Genkai - 2	2	✓	✓	✓	✓	✓
	Genkai - 3	4	✓	✓	✓	✓	—
	Genkai - 4	4					—
	Sendai - 1	3	✓	✓	✓	✓	—
	Sendai - 2	3	✓	✓	✓	✓	—
Shikoku Electric Power Co.	Ikata - 1	2	(FLP)	(FLP)	**INLAY**	(FLP)	(FLP)
	Ikata - 2	2	(FLP)	(FLP)	**INLAY**	(FLP)	(FLP)
	Ikata - 3	3					—
Hokkaido Electric Power Co.	Tomari - 1	2	✓	✓	✓	✓	✓
	Tomari - 2	2					
	Tomari - 3	3	✓	✓	✓	✓	—
Japan Atomic Power Co	Tsuruga - 2	4	✓	✓	✓	✓	—

"✓": WJP applied by Mitsubishi; "(FLP)": FLP applied by Toshiba; "—": N/A; "Blank": under planning

Demonstrating Peening Effectiveness

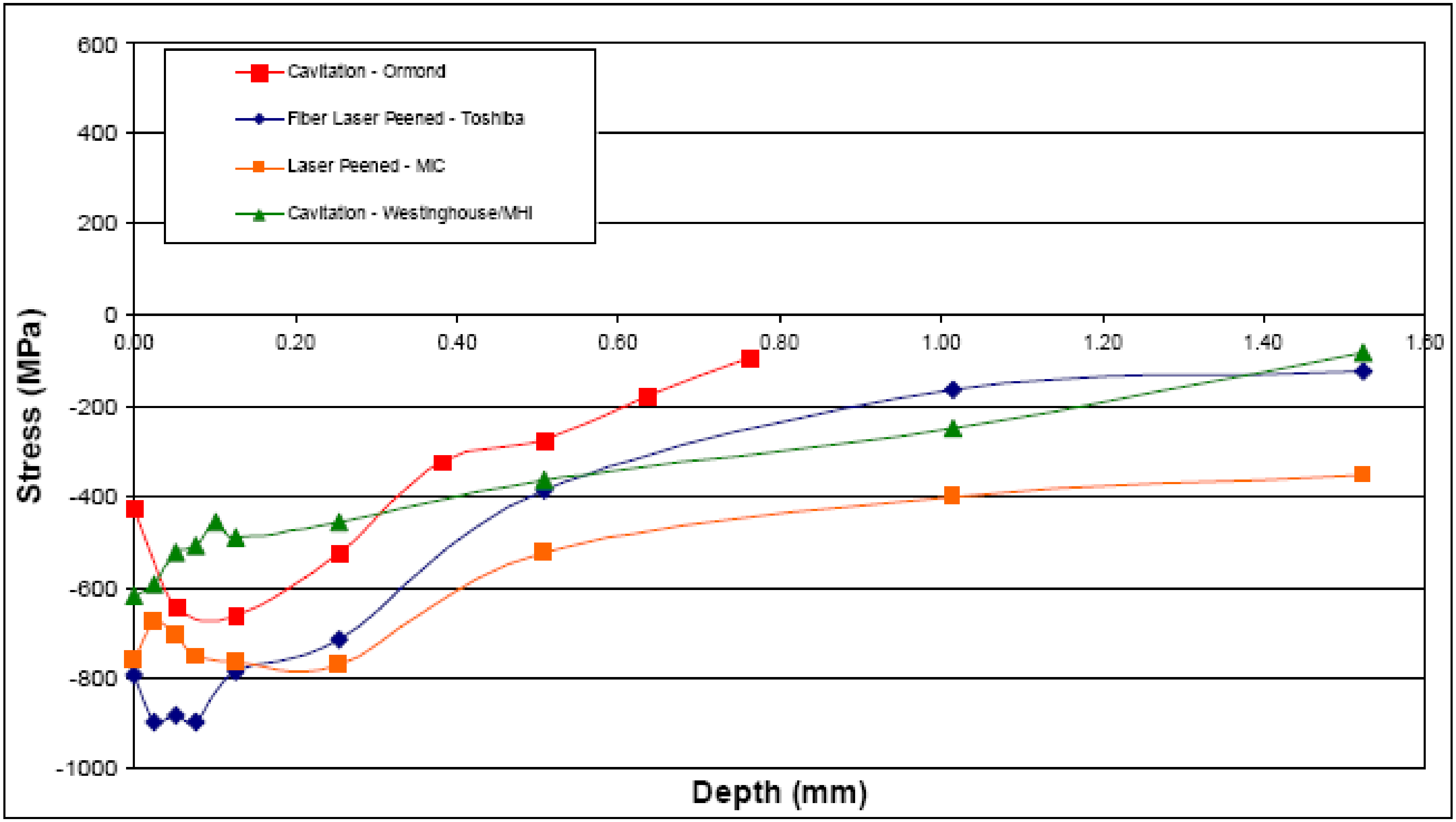
- The goal of an SSI application is to reliably mitigate the PWSCC concern for a plant component for long-term operation. The following mitigation effectiveness criteria may be used to assess this goal:
  - The stress in the surface region following the SSI treatment is compressive to a specified depth, including the effect of normal operating stress
  - Lab tests confirm the resistance to PWSCC initiation on the treated surface, as well as growth of pre-existing flaws located in the specified compressive stress zone
  - The compressive stress condition is maintained to the specified depth for the intended mitigation period (e.g., remaining plant operating period) given the effects of operating temperature (mainly 285-320°C (545-608°F)) and load cycling
- The process must also be confirmed not to produce any unacceptable side effects

Effectiveness of Peening Mitigation: Residual Stress Measurement

- Stress measurements by XRD with progressive electropolishing and strain gauge adjustment
- The measured samples represented a wide range of initial residual stress conditions prior to peening
- Flat plate samples of nickel-based alloys (Alloy 600, Alloy 132, Alloy 182) and stainless steels (304 and 316L) were peened with FLP, LSP, or WJP
  - Plate and weld plate samples
  - Residual stress was compressive to a depth of at least 1.0 mm
- Mock ups of BMNs were constructed of Alloy 600/82/182 and the BMN ID, OD, and J-groove weld were peened with FLP or WJP
  - Residual stress was compressive to a depth of at least 1.0-1.5 mm in most cases
  - For WJP of the inner surface of BMNs, the residual stress was compressive to a depth of about 0.5 mm

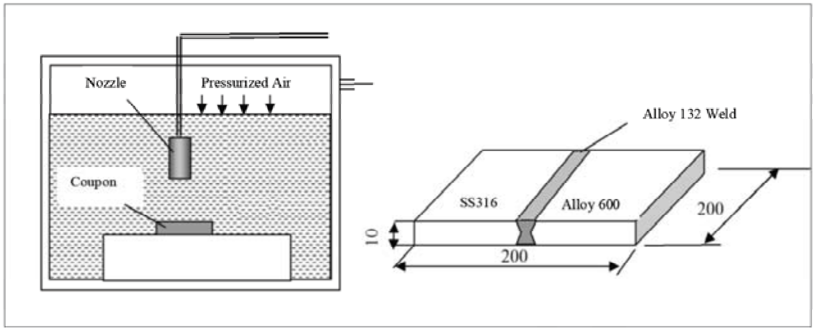
Flat A600 Plate Residual Stress Measurements

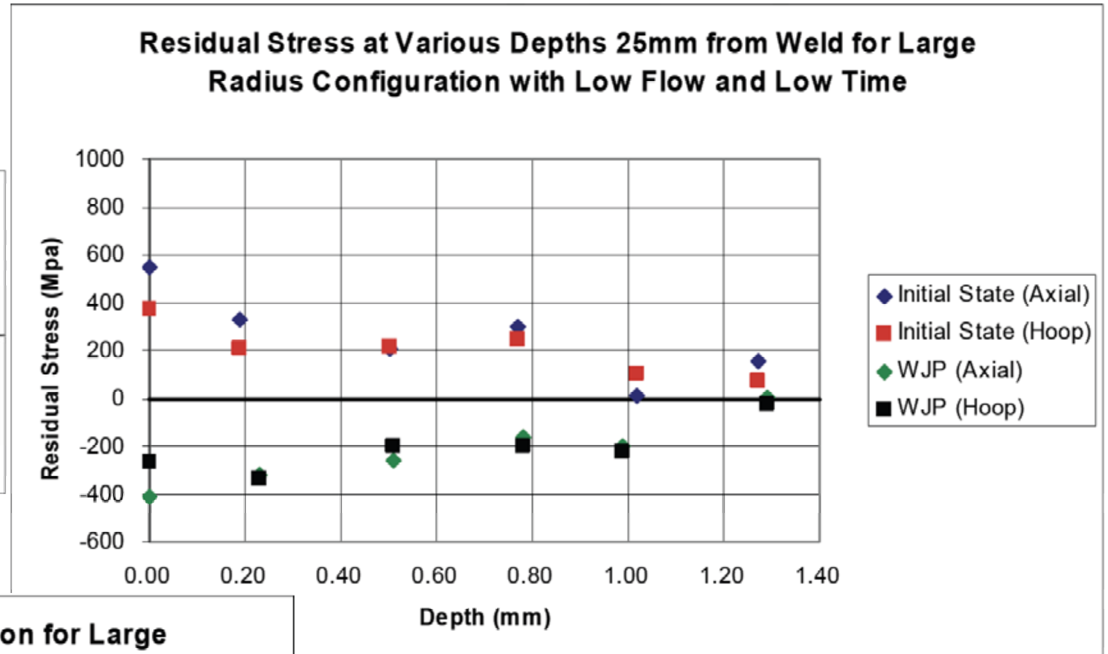
(Data from MRP-162 EPRI Study)

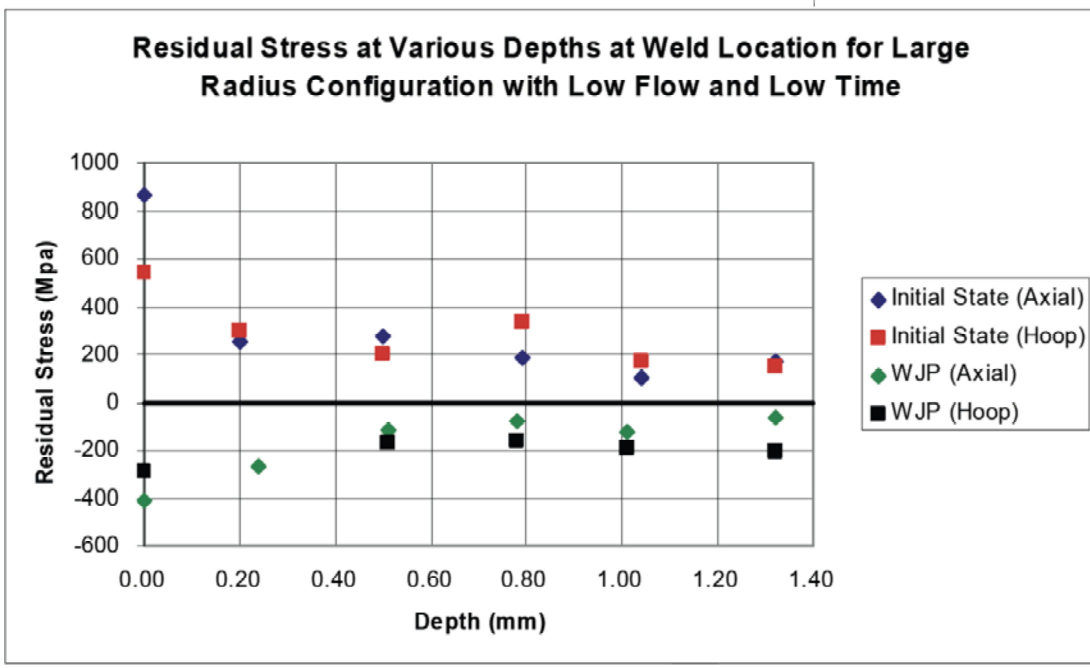


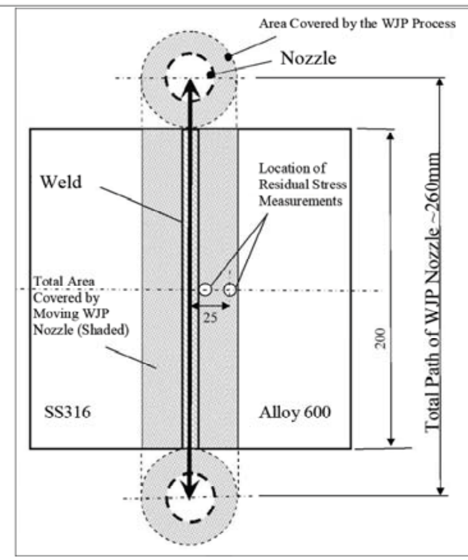
Weld Plate Residual Stress Measurements

(Data provided by MHI)



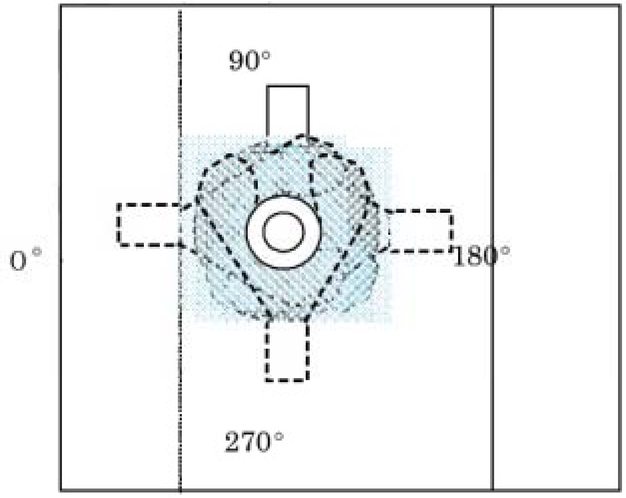


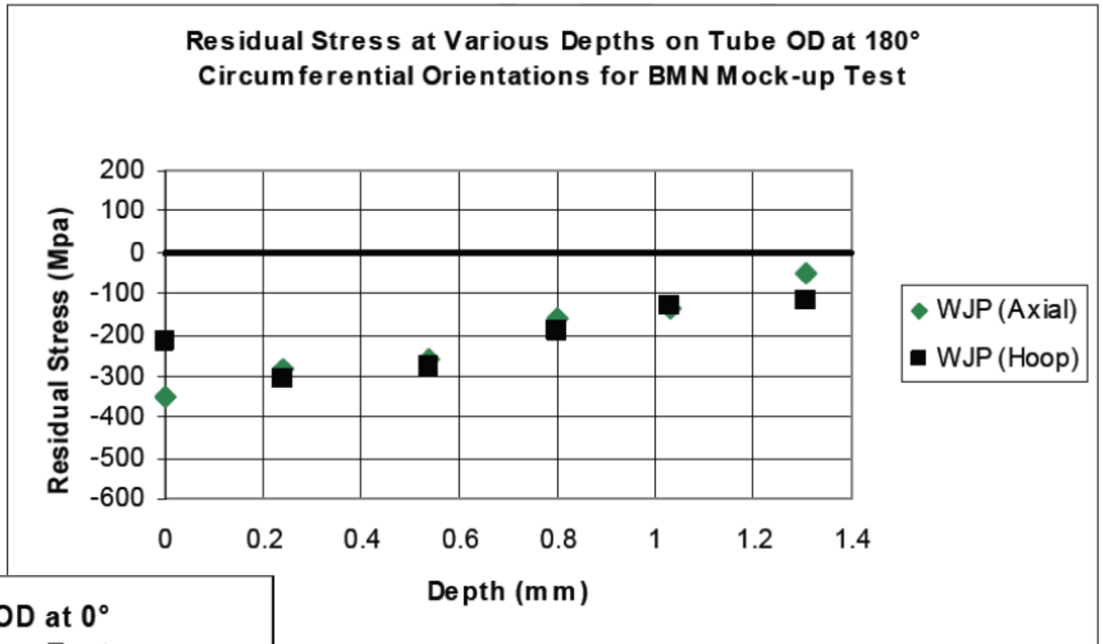


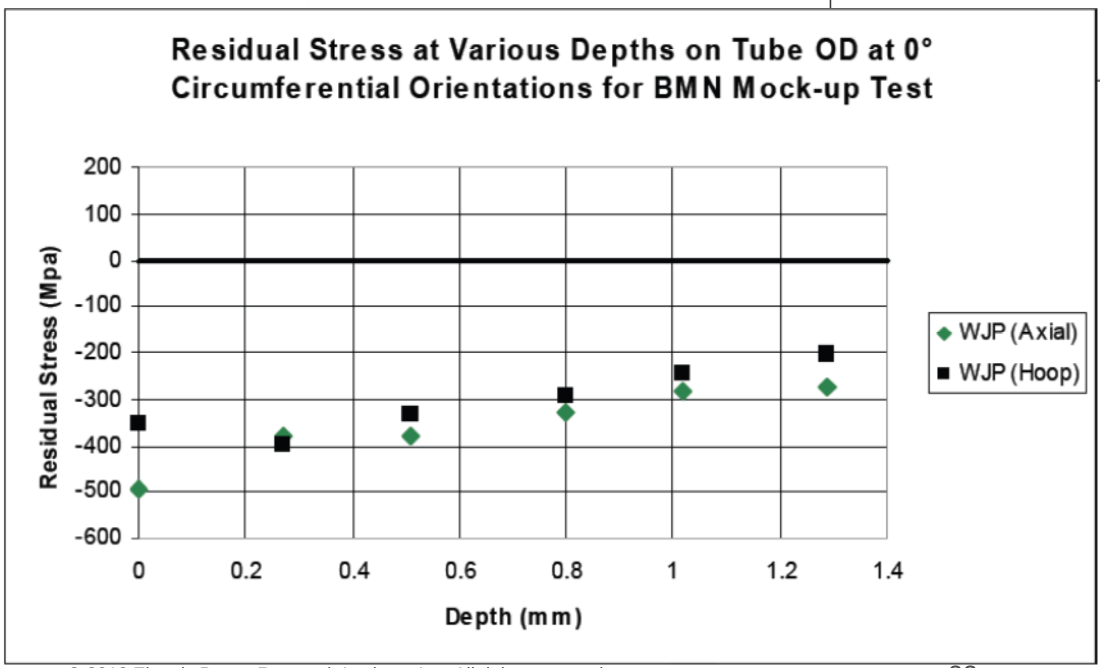


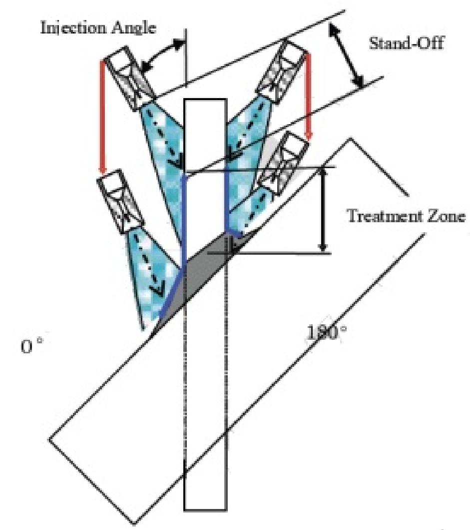
BMN Mockup OD Residual Stress Measurements

(Data provided by MHI)









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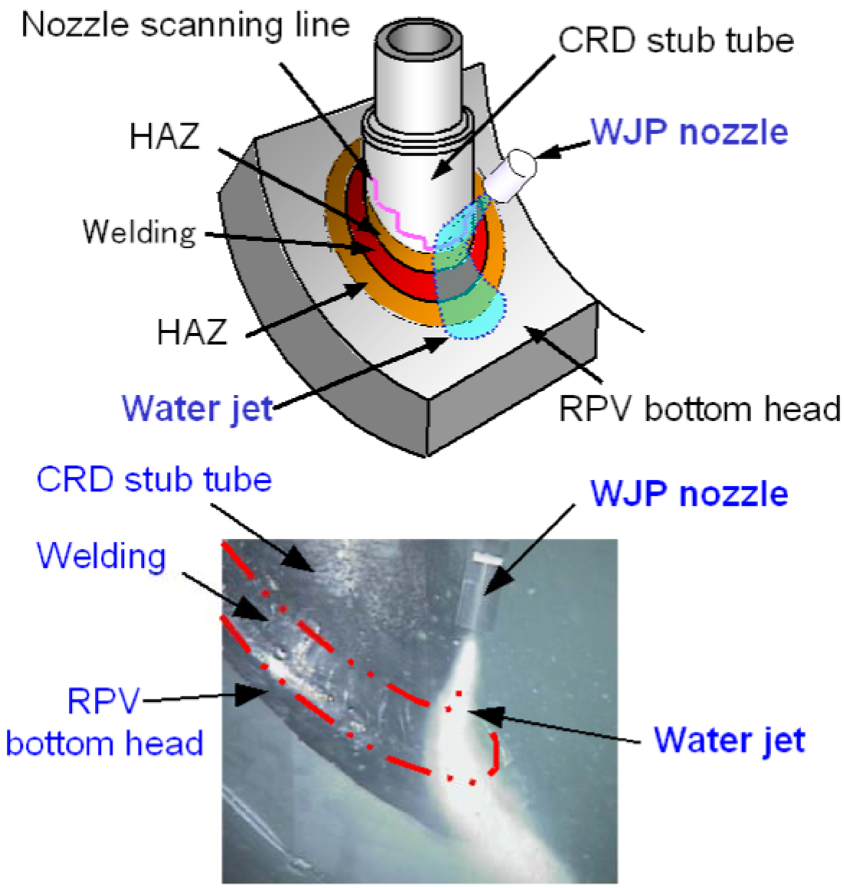
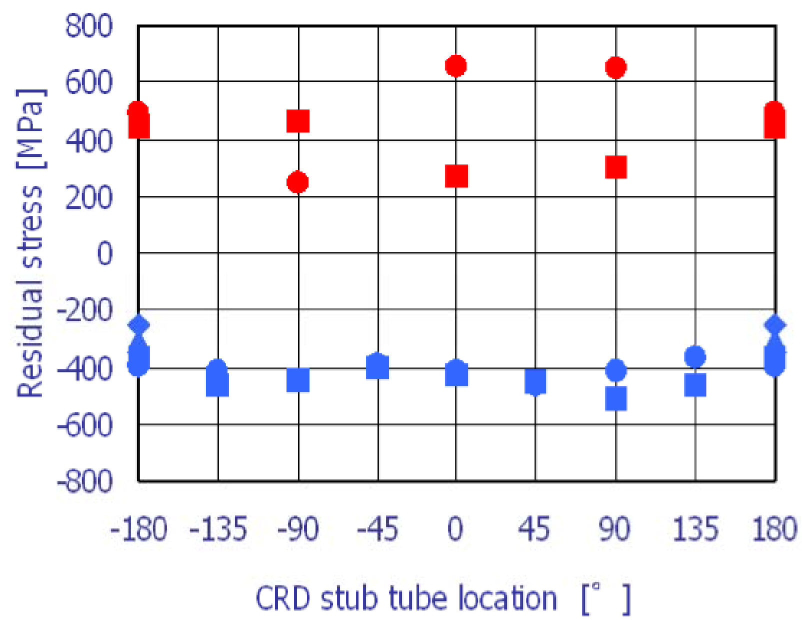
BMN Mockup OD Residual Stress Measurements

(Data provided by Hitachi-GE)



WJP treatment in a mockup test

	Before WJP	WJP treated	
	Residual stress (on the surface)		Residual stress (0.2mm subsurface)
σ y	● (red)	● (blue)	▲ (blue)
σ x	■ (red)	■ (blue)	◆ (blue)



Residual stress before/after WJP

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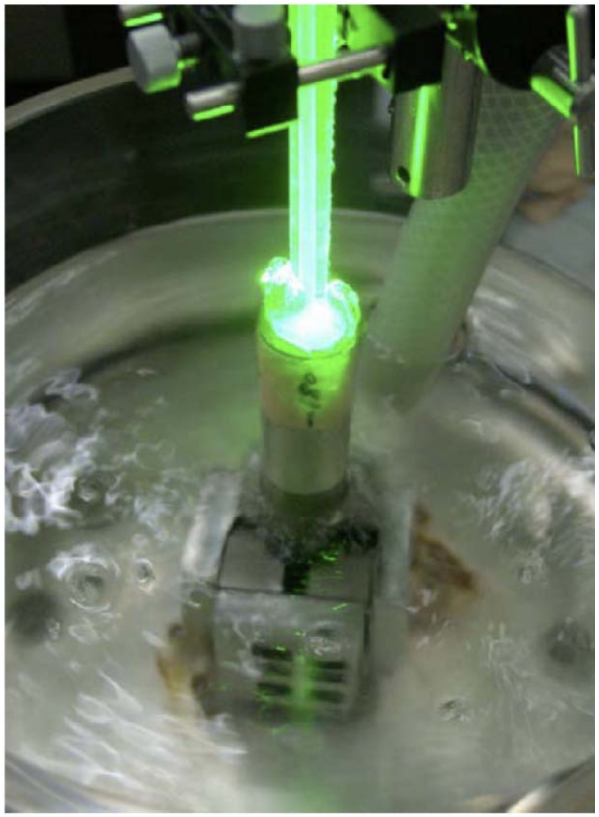
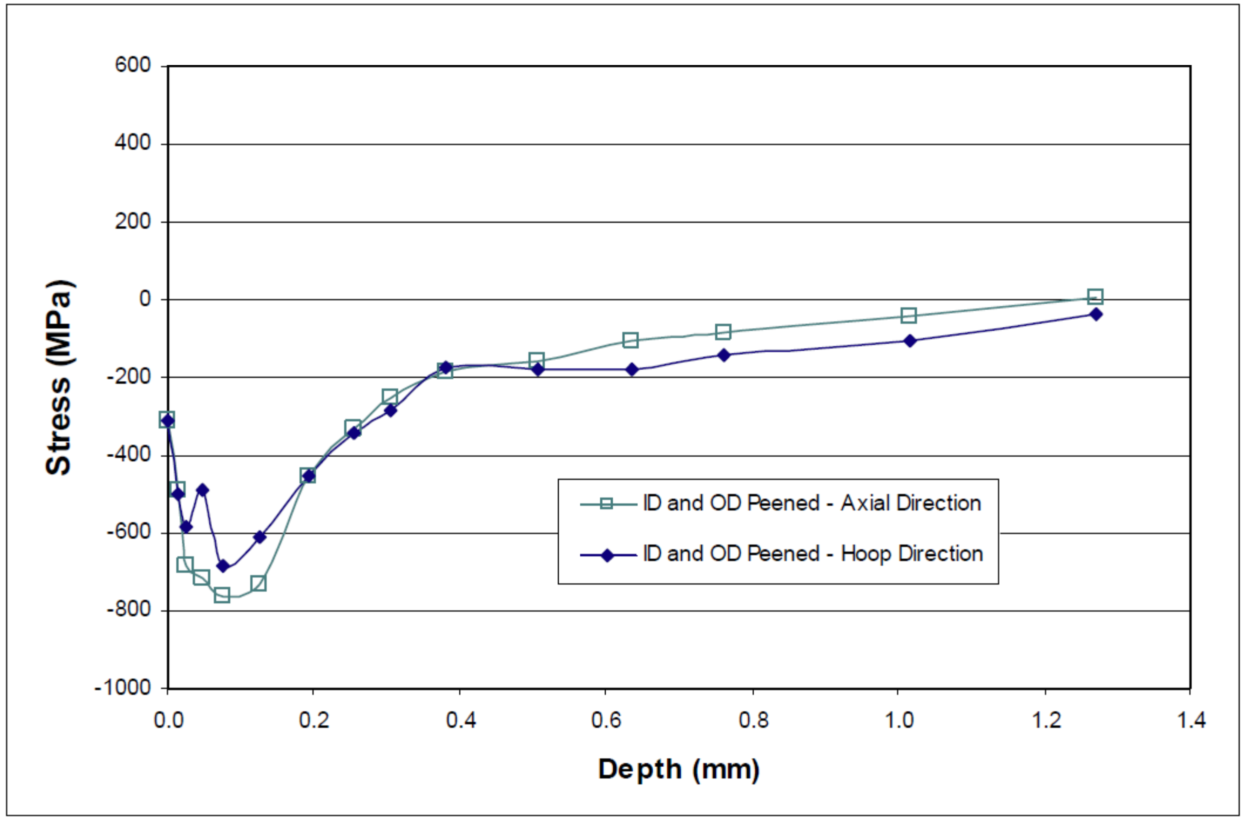
BMN Tube ID Residual Stress Measurements

(Data provided by Toshiba)





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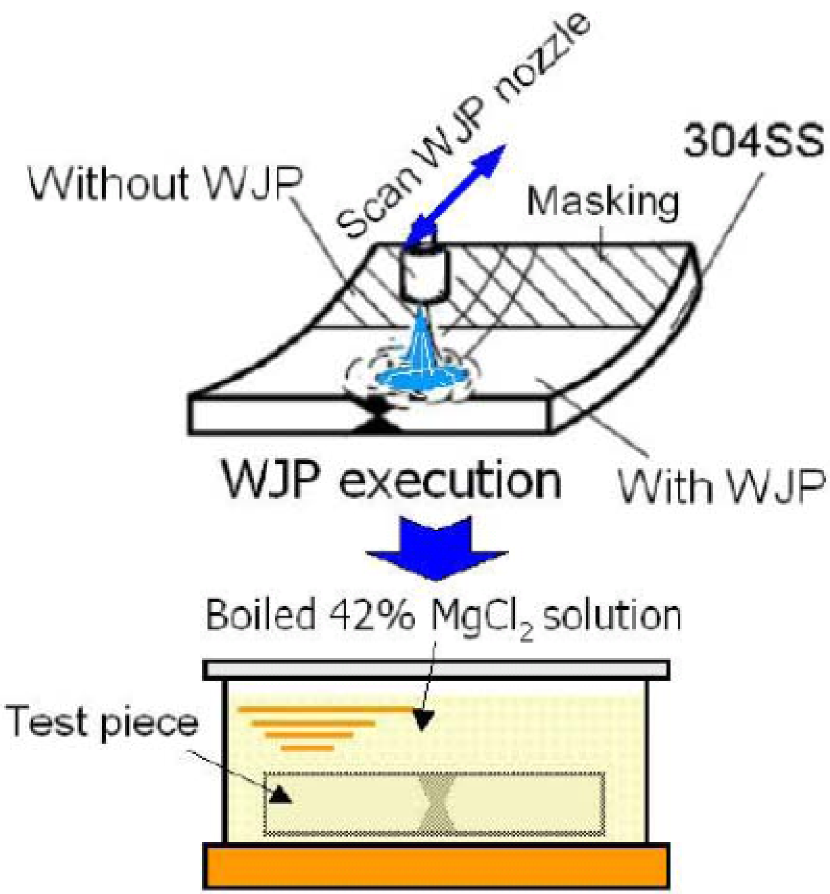
Effectiveness of Peening Mitigation: SCC Testing

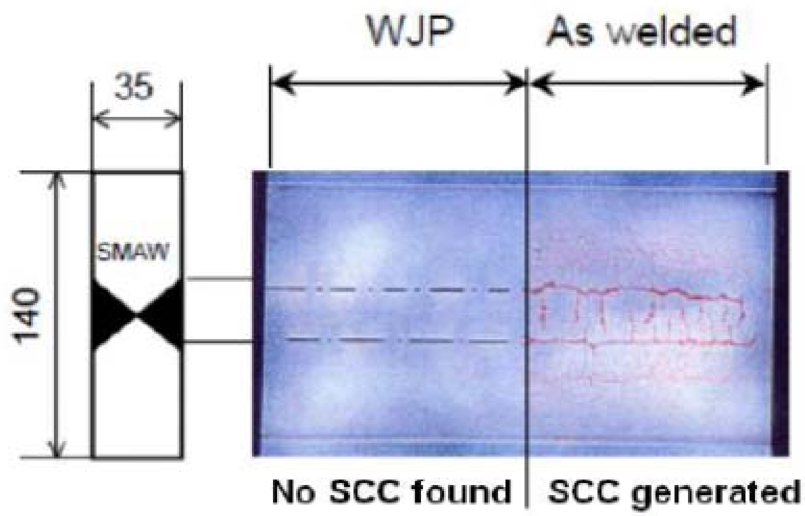
- Testing was performed by the FLP, WJP, and LSP vendors, as well as by an independent lab sponsored by EPRI
- Various samples with no pre-existing flaws were tested in various corrosive environments
  - SCC was detected in unpeened samples but not peened samples
- Various pre-cracked coupons were peened and subjected to various SCC environments
  - Shallow cracks located in the compressive stress zone were effectively mitigated
  - Cracks significantly deeper than the compressive zone tended to grow at a rate similar to that for unpeened samples
- WJP was applied to temper-colored, pre-cracked coupons
  - No growth of the pre-existing cracks due to the WJP application itself was observed

Mitigation of SCC Initiation

(Data provided by Hitachi-GE)



$MgCl_2$ test



Result of penetrant test

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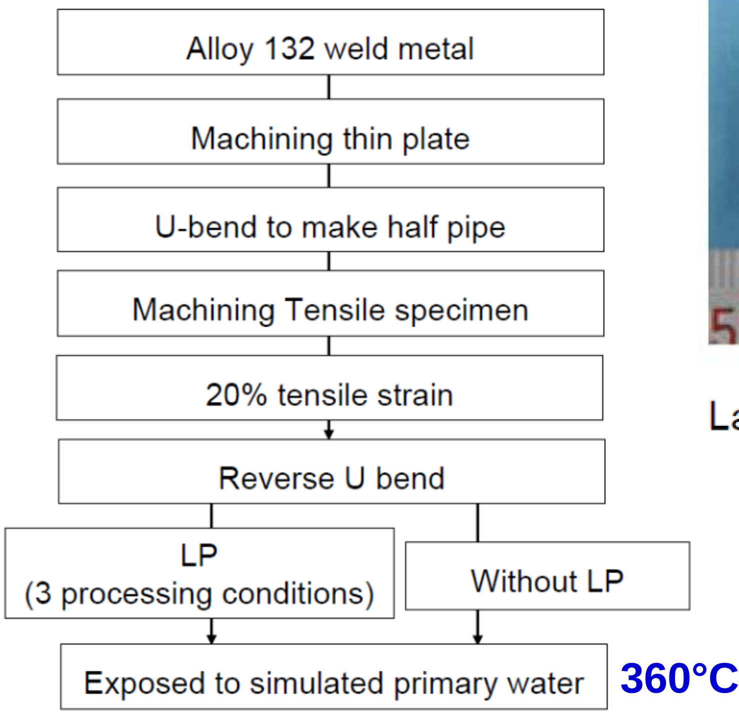
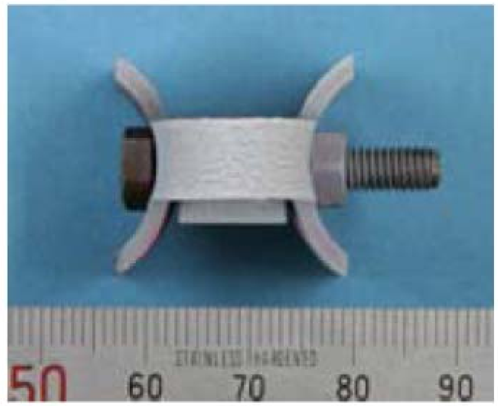
Mitigation of SCC Initiation
(Data provided by Toshiba)

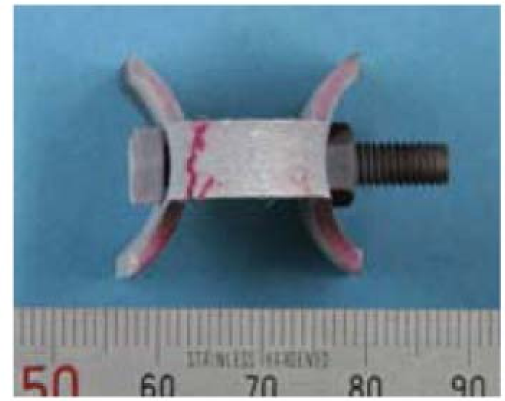
FLP



Alloy 132 U-Bend Samples



Laser peening / condition 3



Without laser peening

Summary of PWSCC test

	LP conditions	Cracked specimens /total specimens	
		500h	1000h
LP	1	0/7	
	2	0/7	
	3	0/7	
Without LP	–	3/7	5/7

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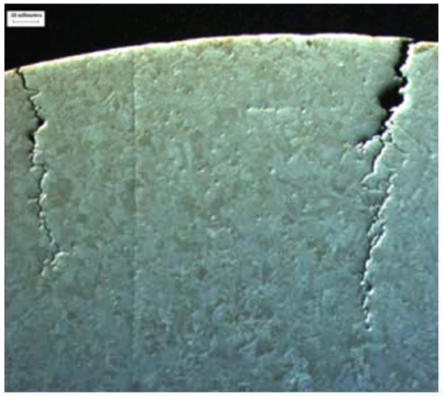
Mitigation of Growth of Shallow SCC Cracks

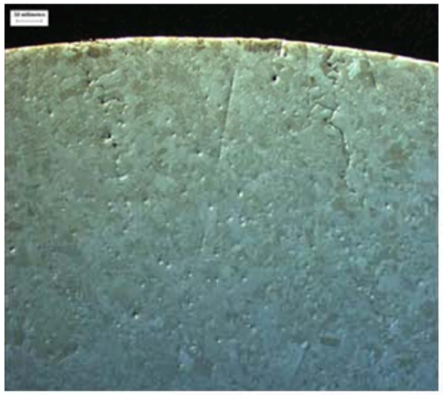
(Data provided by MIC)

Alloy 600 U-Bend Samples Treated by LSP

U-bend samples tensioned and exposed to Thiosulfate to enhance SCC



Pre-cracked, no laser peening → Extensive Cracking



Pre-cracked, then laser peened → Cracking arrested

No pre-cracking, laser peened → No Cracking

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Lack of Growth of Pre-Existing Cracks During WJP *(Data provided by MHI)*

Produce SCC crack in the coupon

(in polythionate water)

Crack size

(1) 0.6 mm
(2) 0.8 mm
(3) 1.3 mm
(4) 2.0 mm

↓

Applying WJP

↓

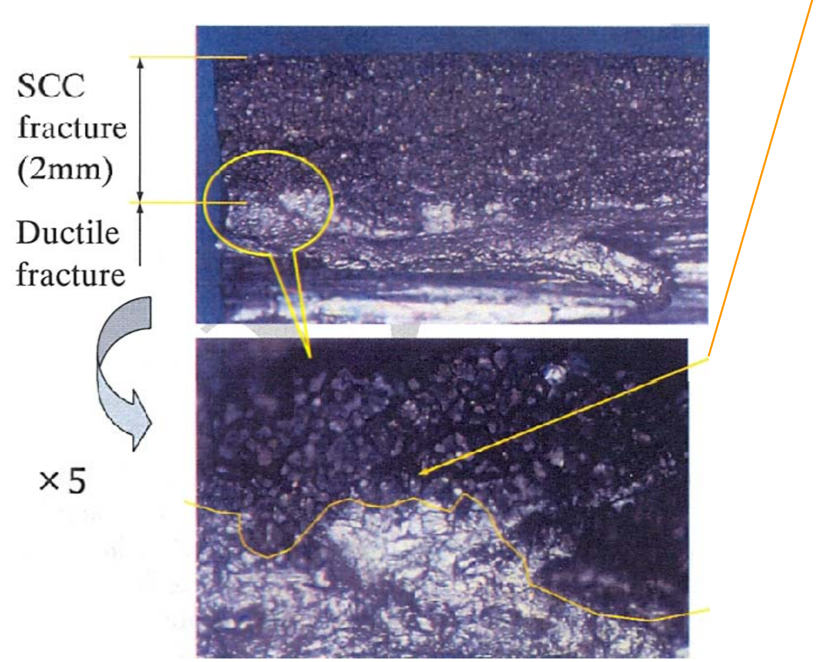
- **Color by heat tempering**
- **Open up the fracture**

Examine fracture surfaces

- If only SCC fracture → Peening does not advance crack
- If SCC + ductile fracture → Crack propagate due to peening process

There are no ductile fracture in the temper colored region.

No indication of crack advancing due to peening operation



Effectiveness of Peening Mitigation: Long Term Sustainability of Residual Stress

- Testing was performed by the FLP and WJP vendors, as well as by an independent lab sponsored by EPRI
- Effect of operating temperature on peening residual stress
  - Peened plate samples of nickel-based alloys were subjected to elevated temperatures (320-450°C) for up to ~2700 hours
  - After testing surface stress at least ~275 MPa compressive
- Effect of load cycling on peening residual stress
  - Peened plate samples of nickel-based alloys were subjected to oscillating stress (stress amplitude 245-300 MPa) for up to 2000 cycles
  - After testing surface stress at least ~275 MPa compressive
- The testing demonstrates the long-term sustainability of a substantial compressive residual stress at the surface treated by SSI

Thermal Relaxation Test

(Data provided by Toshiba)

Material: Alloy 600

Heating: 360°C for 1000 hrs

20% pre-strained reverse U bend specimen (Alloy 600)

↓

Surface residual stress measurement

↓

Laser peening (3 processing conditions)

↓

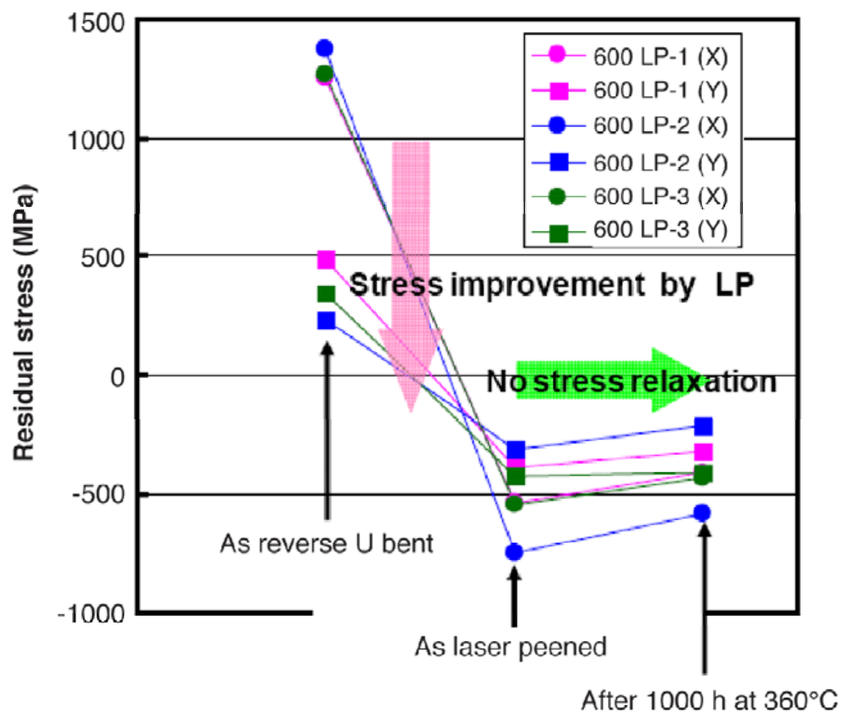
Surface residual stress measurement

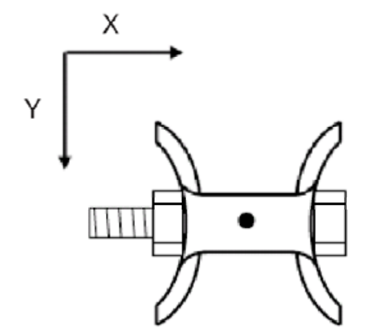
↓

Exposed to simulated primary water for 1000 h at 360°C

↓

Surface residual stress measurement





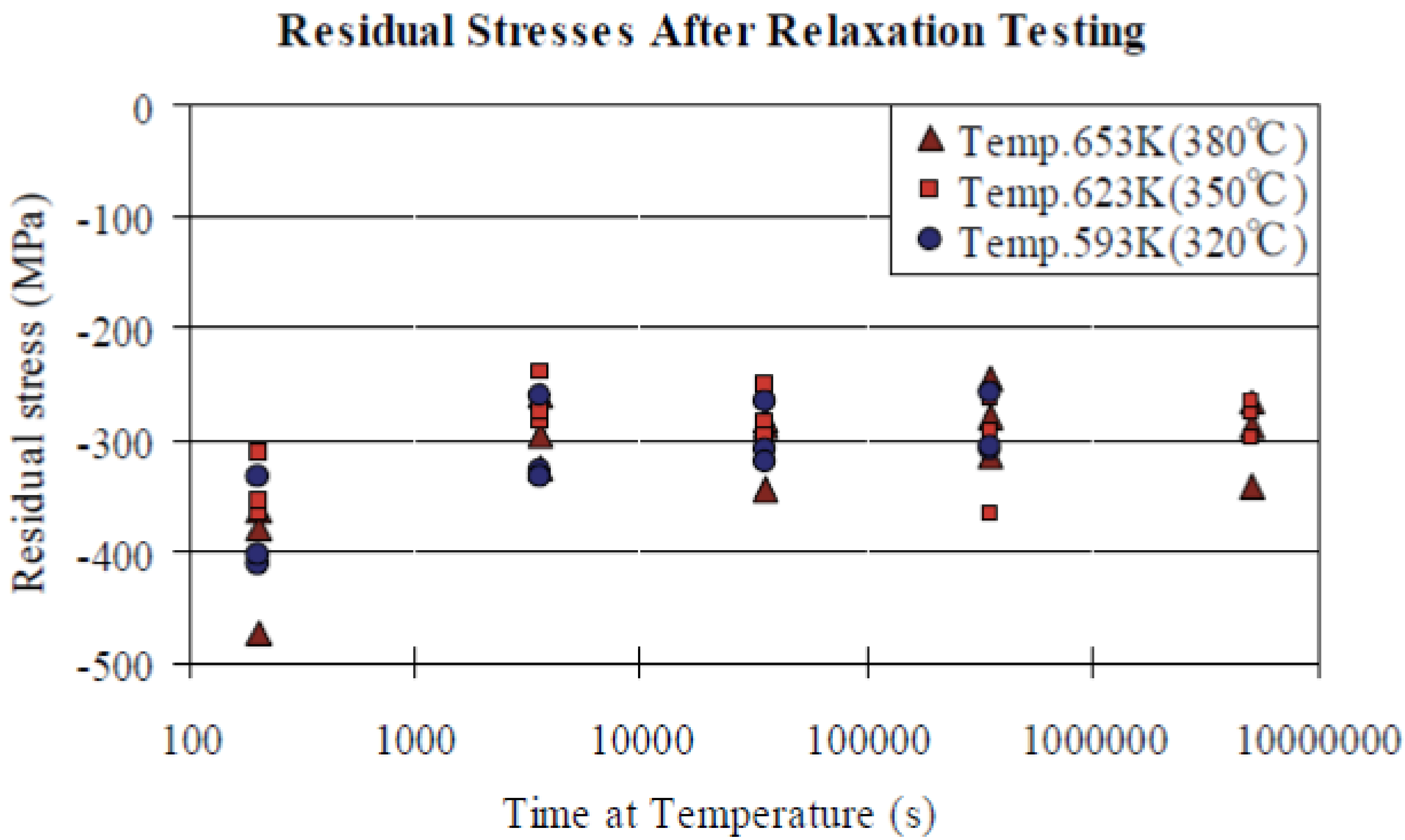
Stress measurement

Thermal Relaxation Test

(Data provided by MHI)

Materials: Alloy 132 weld trough in Alloy 690

Heating: 320-380°C for up to 10^7 s (2700 hrs)



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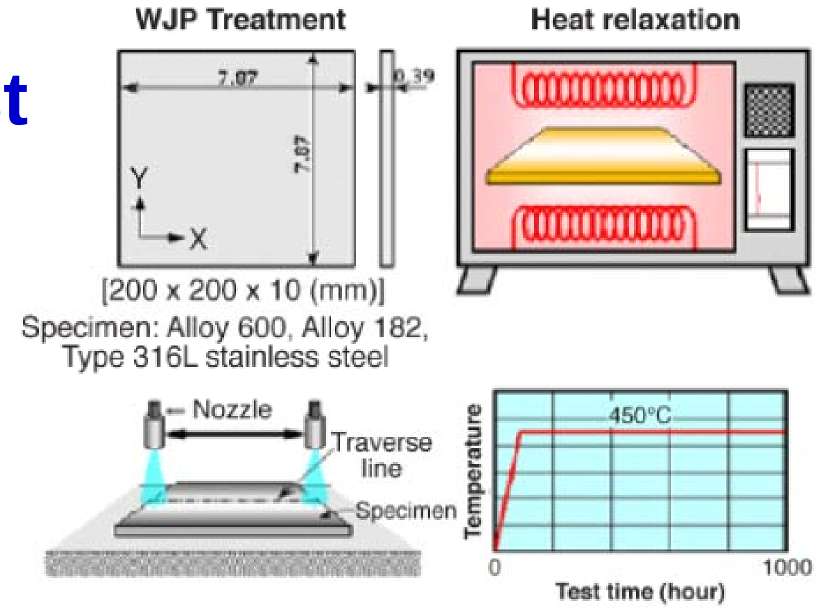
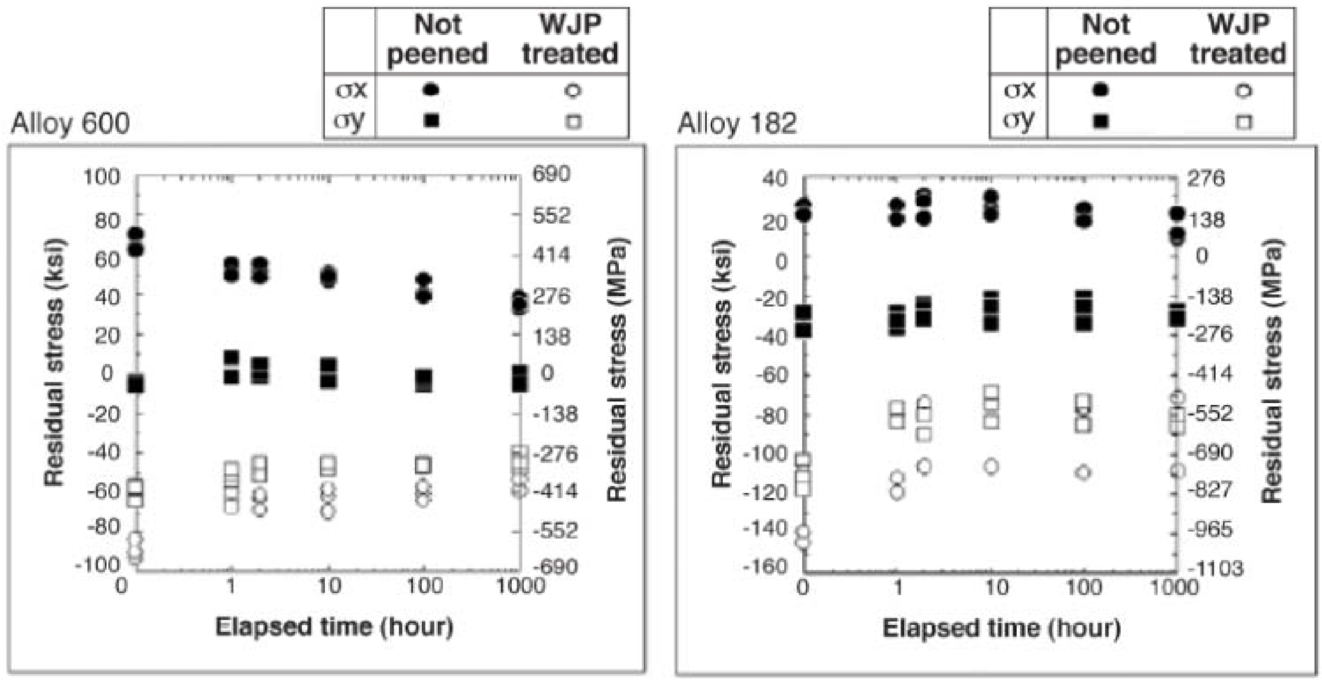
Thermal Relaxation Test

(Data provided by Hitachi-GE)



Materials: Alloy 600, Alloy 182

Heating: 450°C for up to 1000 hrs



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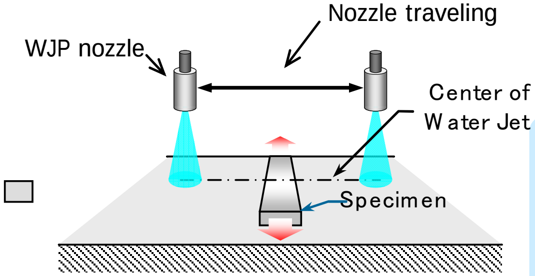
Load Cycling Stress Shakedown Test

(Data provided by Hitachi-GE)

WJP treatment

Specimen

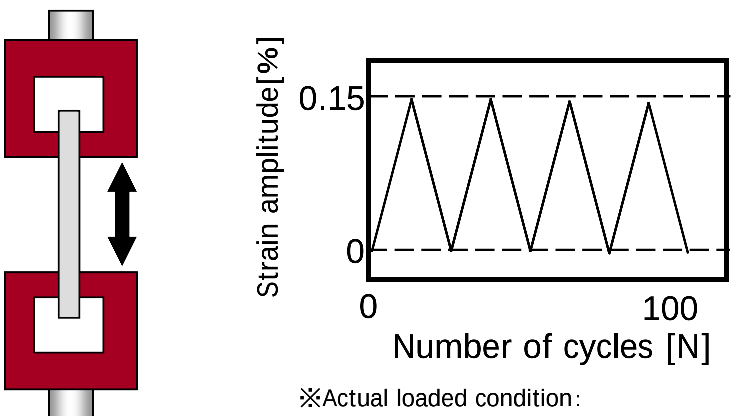


Dimensions(mm): 100×8×6t

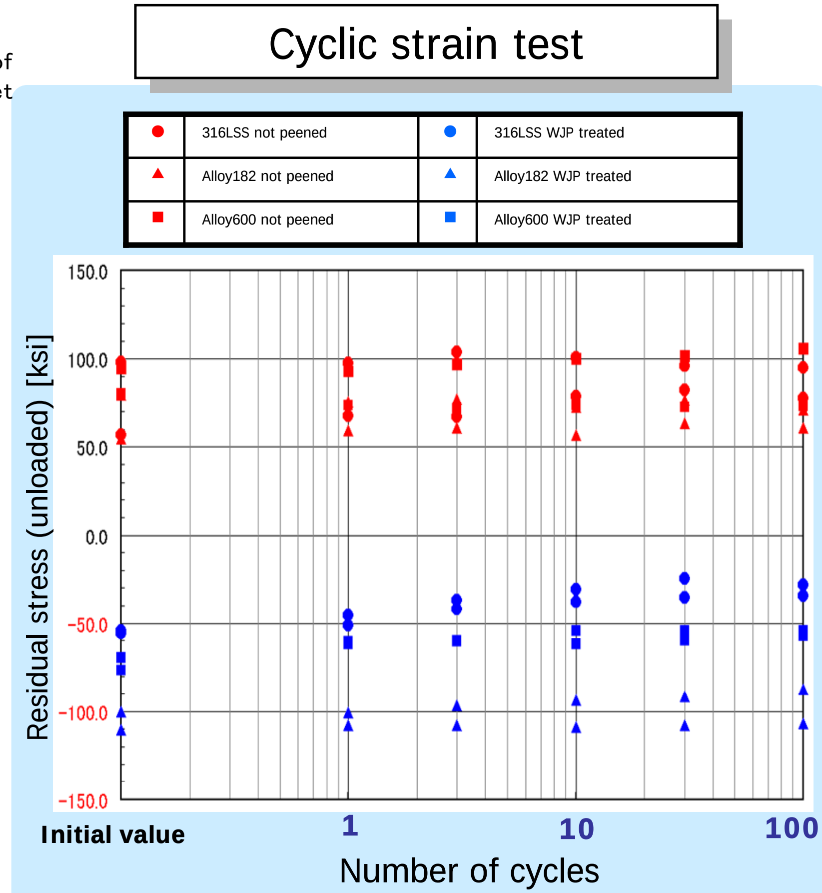
Materials: 316LSS, Alloy182, Alloy600

WJP treatment under tensile strain loaded (equivalent to 300MPa)

Cyclic strain test



※Actual loaded condition: around 0.1% strain amplitude at a maximum



Cyclic strain relaxation test

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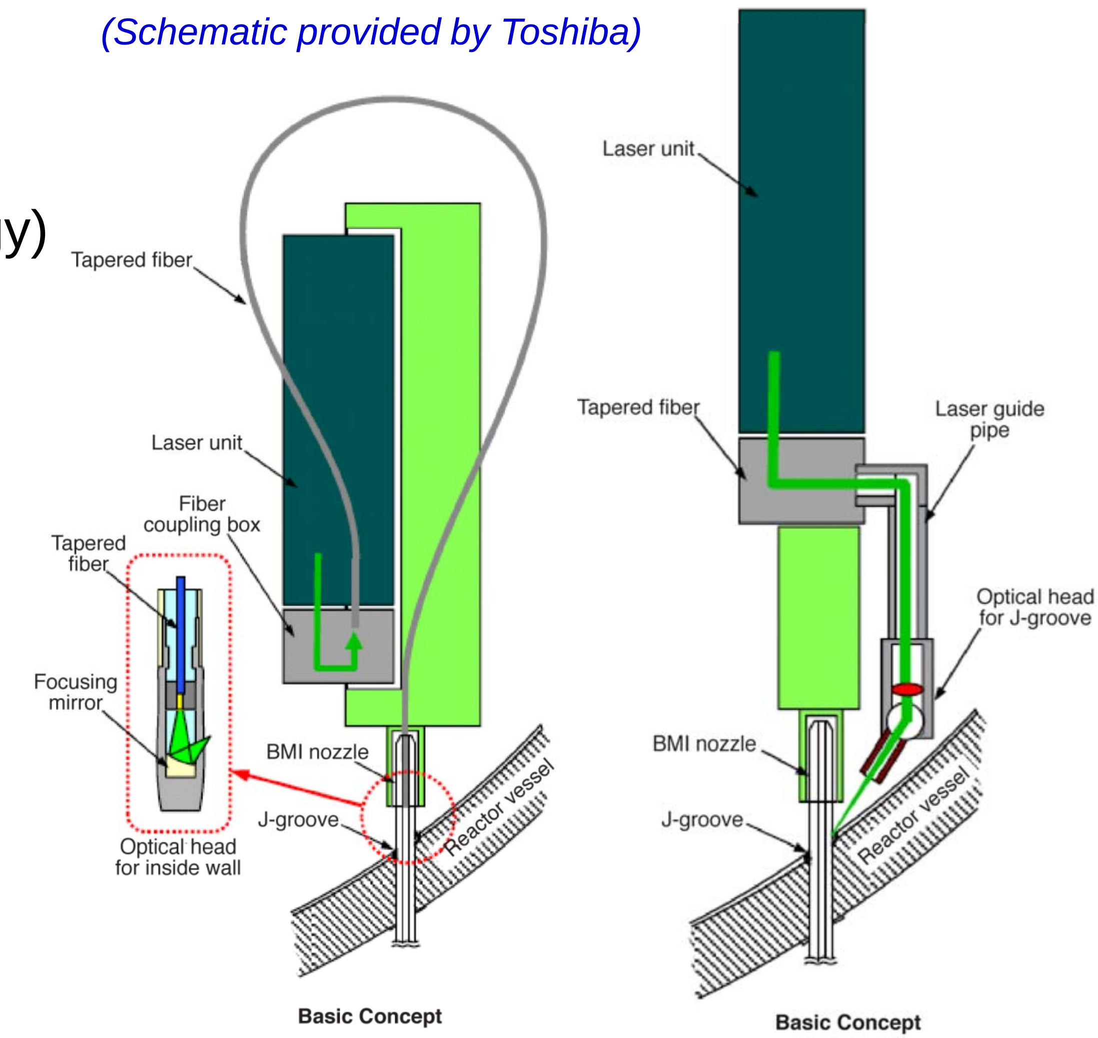
Peening Implementation: Fiber Laser Peening (FLP)

- FLP control parameters
  - Laser power (pulse energy)
  - Laser scanning speed
  - Driving motor torque
  - Irradiation head distance
- Main equipment
  - Portable laser peening system
  - Laser power unit
  - Laser cooling system
  - Water cleaning pump
- To treat BMNs, reactor internals are removed to allow access

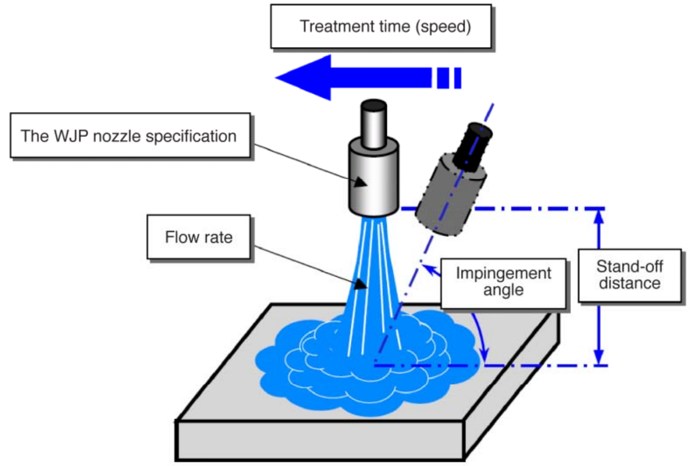
(Schematic provided by Toshiba)



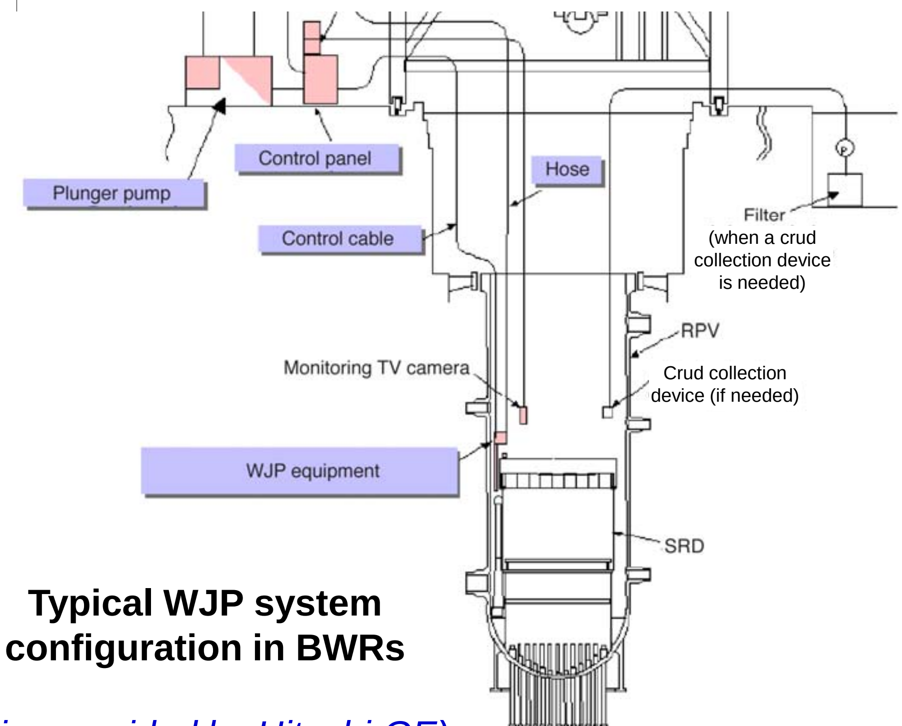
BMN Inner Surfaces

BMN Outer Surfaces

Peening Implementation: Water Jet Peening (WJP)



- WJP control parameters
  – WJP nozzle specification
  – Flow rate
  – Stand-off distance
  – Impingement angle
  – Treatment time (speed)
- Main equipment
  – WJP delivery tool
  – Control panel
  – Plunger pump
  – High-pressure hose
- To treat BMNs, reactor internals are removed to allow access

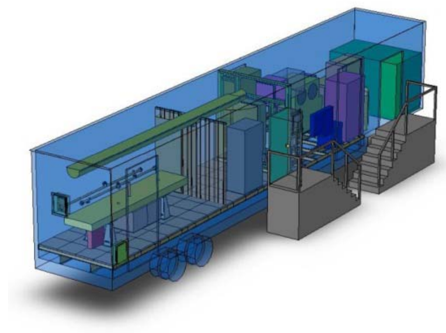


Typical WJP system configuration in BWRs

(Schematics provided by Hitachi-GE)

Peening Implementation: Laser Shock Peening (LSP)

- Key LSP parameters
  - Pulse energy
  - Pulse width
  - Laser spot shape
  - Optional ablative layer
- Main equipment
  - Transportable laser system
  - Beam transport system
  - Robotic beam delivery head
- LSP technology is readily adaptable to nuclear power plant applications



Concept of laser system trailer and beam transport pipes routed into reactor building

(Schematics provided by MIC)

Conclusions

- FLP, LSP, and WJP are viable options for effective long-term mitigation of PWSCC of Alloy 600/82/182 components
- These SSI methods are already commercialized or near commercialization for use in PWRs:
  - FLP and WJP have been implemented in dozens of BWRs and PWRs in Japan
  - LSP is currently being applied in critical aerospace applications, and is readily adaptable to PWRs
- The extensive experimental results demonstrate that SSI treatments are effective measures in preventing or mitigating PWSCC:
  - FLP and WJP methods typically result in a compressive residual stress layer that is at least 1 millimeter (0.040 in.) deep
  - The LSP process is capable of inducing deeper compressive residual stress layers, up to several millimeters deep

Conclusions (cont.)

- SSI techniques are a key option for locations such as
  - RPVHPNs and BMNs, for which other mitigation methods have not been demonstrated
  - For piping DMWs with limited access at the pipe exterior
- The different SSI techniques have complementary capabilities:
  - All three techniques are applicable to treatment of RPVHPNs, BMNs, and piping DMWs
  - Unlike LSP, FLP and WJP are performed underwater
  - Specialized tooling would be necessary to apply FLP or WJP to the outer surfaces of RPVHPNs while the head is located on its storage stand
  - Use of LSP for BMN or piping DMW locations would require that these areas be drained during the maintenance outage

Schedule for MRP-267 Submittal to NRC

- Draft of MRP-267, Revision 1 has been completed
- Revision 1 of MRP-267 to be finalized for submittal to NRC with the MRP-335 topical report in July 2012

Questions & Discussion

Together…Shaping the Future of Electricity

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Topical Report Outline and Submission Plan for PWSCC Mitigation by Surface Stress Improvement

Glenn White and Iain Hamilton

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Outline

- Purpose and Scope
- Draft Topical Report Table of Contents
- Schedule
- Approach
  - Process Requirements and Information
  - Verification of Peening Effectiveness
  - Examination Requirements
  - Deterministic Analyses and Probabilistic Assessments for
    - Dissimilar Metal Welds (DMWs) in Primary Piping
    - RPV Top Head Penetration Nozzles (RPVHPNs)
- Conclusions

Need for Topical Report and NRC Review

- Surface stress improvement (SSI) (i.e., peening) is a key option for mitigating PWSCC of Alloy 600/82/182 locations
  - For DMWs, SSI has the advantage that access is not required at the pipe exterior
  - Unlike other mitigation methods, SSI can be used to mitigate partial-penetration welded (i.e., J-groove) Alloy 600 nozzles including:
    - Reactor pressure vessel top head penetration nozzles (RPVHPNs)
    - Reactor pressure vessel bottom mounted nozzles (BMNs)
- Inspection requirements for these locations are defined in ASME Code Cases N-770-1, N-729-1, and N-722-1
  - Made mandatory by 10CFR50.55a(g)(6)(ii)(D) through (F) with conditions
- NRC approval is required for relaxation of inspection requirements with peening mitigation

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Purpose of MRP-335 Topical Report Document

- To establish application-specific requirements for use of SSI to mitigate PWSCC of Alloy 600/82/182 pressure boundary components in PWRs
- To establish appropriate relaxation of inspection requirements after SSI mitigation
- It is anticipated that:
  - MRP-335 will be part of the technical basis for further revision of ASME Code Cases N-729-1 and N-770-1 to include SSI mitigation
  - MRP-335 may serve as a basis for requests for relaxation of inspection requirements to NRC per 10CFR50.55a

Scope of Topical Report (MRP-335)

- Peening methods that have been commercialized or are near commercialization for use in PWRs:
  - Fiber Laser Peening (FLP)
  - Laser Shock Peening (LSP)
  - Water Jet Peening (WJP)
- The Alloy 600/82/182 components of focus are:
  - Alloy 82/182 DMWs in primary system piping
    - Large diameter DMWs in main loop piping
    - Other DMWs mainly on branch connections
  - RPVHPNs including CRDM, CEDM, top head instrumentation (ICI), and head vent nozzles
  - BMNs (i.e., BMI, ICI, and IMI nozzles)
- The SSI treatment is applied to the susceptible area

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Table of Contents of Topical Report (MRP-335)

Schedule for Topical Report Submittal to NRC

- Initial feedback requested on MRP approach
- Draft to be completed for MRP review and revisions:
  - End of April 2012
- Final topical report submitted for NRC review:
  - July 2012
- Final technical basis document (MRP-267, Revision 1) to be submitted to NRC for information with the topical report

Section 2: Process Requirements & Information

2.1 Process overview and description

2.2 Process field experiences

2.3 Basis for no unacceptable side effects

2.4 Stress improvement (including depth attained)

2.5 Inspectability (before and after treatment)

2.6 Assessment of potential crack growth during operation after peening

2.7 Geometric application limitations

2.8 Surface condition limitations (if any)

2.9 Coverage verification

2.10 Summary of key process application variables

Section 2: Process Requirements & Information
Process Overview and Description

- Objective is to apply peening to PWSCC susceptible wetted surfaces to develop high compressive stresses at the surface
- Known to inhibit initiation of SCC in many material-environment systems
- Three main peening processes under consideration
  - Fiber Laser Peening (FLP)
  - Water Jet Peening (WJP) – aka Cavitation Peening
  - Laser Shock Peening (LSP)

Section 2: Process Requirements & Information Process Field Experience

- FLP used in Japan since 1999 for BWRs and 2004 for PWRs
- WJP used in Japan for both BWRs and PWRs
  - For BWRs started ~2000, with 14 units treated as of June 2010
  - For PWRs applied at 19 units as of early 2011
- No reports of subsequent problems

Section 2: Process Requirements & Information Basis for No Unacceptable Side Effects

- None identified by tests or analyses
- None identified by over 10 years plant experience
- Careful monitoring of process during application

Section 2: Process Requirements & Information Stress Improvement

- Development of high compressive residual stresses shown by tests
- FLP and WJP methods typically result in a compressive residual stress layer that is at least 1 millimeter (0.040 in.) deep
- The LSP process is capable of inducing deeper compressive residual stress layers, up to several millimeters deep

Section 2: Process Requirements & Information Inspectability

- UT inspection methods have been developed, qualified, and used on key target areas
  - RPVHPNs
  - BMNs
  - DMWs
- Basis for no adverse effects of peening on inspectability

Section 2: Process Requirements & Information Crack Growth Considerations

- Tests demonstrate that peening does not aggravate growth of pre-existing cracks during the peening application
- Tests demonstrate that peening inhibits subsequent growth of cracks that do not penetrate to below the compressive stress zone
- Tests and SG tube experience show that subsequent growth of pre-existing cracks that extend beyond compressive stress field can occur

Section 2: Process Requirements & Information
Geometric Application Limitations

- FLP and WJP have been demonstrated as being able to be used for all target locations
  - Depth of compressive field may be less on inner surface of small ID nozzles
- LSP has not yet been applied to nuclear plant components, but is readily adaptable to treatment of outer surfaces of RPVHPNs

Section 2: Process Requirements & Information Surface Condition Limitations (if Any)

- None currently identified by test or by plant experience

Section 2: Process Requirements & Information Coverage Verification

- Key requirement of process qualification and of QA/QC monitoring during application
- In-process monitoring and data automatically recorded to provide verification
- Vendor-specific procedures ensure 100% coverage of intended area

Section 2: Process Requirements & Information
Key Process Variables

- Fiber Laser Peening (FLP)
  - Type of laser
  - Pulse energy
  - Pulse duration
  - Pulse delivery rate
  - Spot size
  - Driving motor torque
  - Irradiation head distance
  - Delivery method (fibers, mirrors, lenses)
- Water Jet Peening (WJP)
  - Nozzle type
  - Flow rate
  - Stand-off distance
  - Impingement angle
  - Treatment time (speed)
- Laser Shock Peening (LSP)
  - Type of laser
  - Irradiance (GW/cm^2)
  - Pulse duration
  - Optional ablative layer
  - Layers of coverage
  - Delivery method (mirrors, lenses)

Section 3: Verification of Peening Effectiveness

3.1 Depth of residual compressive stresses

- 3.1.1 Experimental results
- 3.1.2 Analytical results

3.2 Plant/application-specific factors

3.3 Peening performance criteria

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Section 3: Verification of Peening Effectiveness Depth of Residual Compressive Stresses

- Needs to be verified for each specific application
  - Peening process
  - Application parameters
  - Application geometry
- Based on Japanese experience including work performed using mockups, satisfactory results demonstrated for FLP and WJP
- Experience with LSP shows that it will also provide satisfactory results
  - Extensive manufacturing experience in other critical applications
  - Extensive lab testing including tests on Alloy 600 samples peened by LSP

Section 3: Verification of Peening Effectiveness Experimental and Analytical Results

- Tests using mockups such as welded 316SS in boiling magnesium chloride show that cracks develop at untreated part of weld, no cracks at treated part
- Analytical results
  - If total stress is below threshold for initiation (e.g., 0.8 times elastic limit), no initiation will occur. Compressive stress of hundreds of MPa ensures that such high tensile stresses do not develop – thus initiation cannot occur
  - If stress intensity factor at tip of pre-existing crack is zero, then no crack growth expected

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Section 3: Verification of Peening Effectiveness Plant/Application–Specific Factors

- Process qualification needs to be verified as covering each specific application
- Need to consider geometry, interferences, surface condition, inspection results
- These factors have already been addressed for Alloy 600/82/182 locations treated by peening in Japan

Section 3: Verification of Peening Effectiveness
Peening Performance Criteria

- Performance criteria will establish the formal requirements for demonstrating that a peening process effectively mitigates PWSCC
- The performance criteria will address, for example:
  - Compressive stress magnitude and depth for long-term cyclic operation
  - Complete coverage of target area

Section 4: Current Inspection Requirements for Unmitigated Locations

- RPVHPNs, Code Case N-729-1 (volumetric and visual for leakage)
  - Alloy 600 nozzles: volumetric exams every 8 calendar years or before Reinspection Years (RIY) = 2.25
  - Non-cold heads with Alloy 600 nozzles: usually every one or two RFOs
  - Cold heads with Alloy 600 nozzles: usually every 4 or 5 18-month fuel cycles or every 3 or 4 24-month fuel cycles
- RV BMNs, Code Case N-722-1 (visual for leakage)
  - Direct visual exam for leakage every other RFO
- DMWs, Code Case N-770-1 (volumetric and visual for leakage)
  - Hot leg temperature (≤ 625°F (329°C)): volumetric every 5 years
  - Cold leg temperature: every second inspection period not to exceed 7 years
  - The SSI methods are not clearly defined in Code Case N-770-1 although SSI is similar to stress improvement without welding, which is addressed in N-770-1. For Category D (uncracked weld mitigated with stress improvement), there is a single exam within 10 years following mitigation, followed by a program of sample inspections

Section 4: Examination Requirements

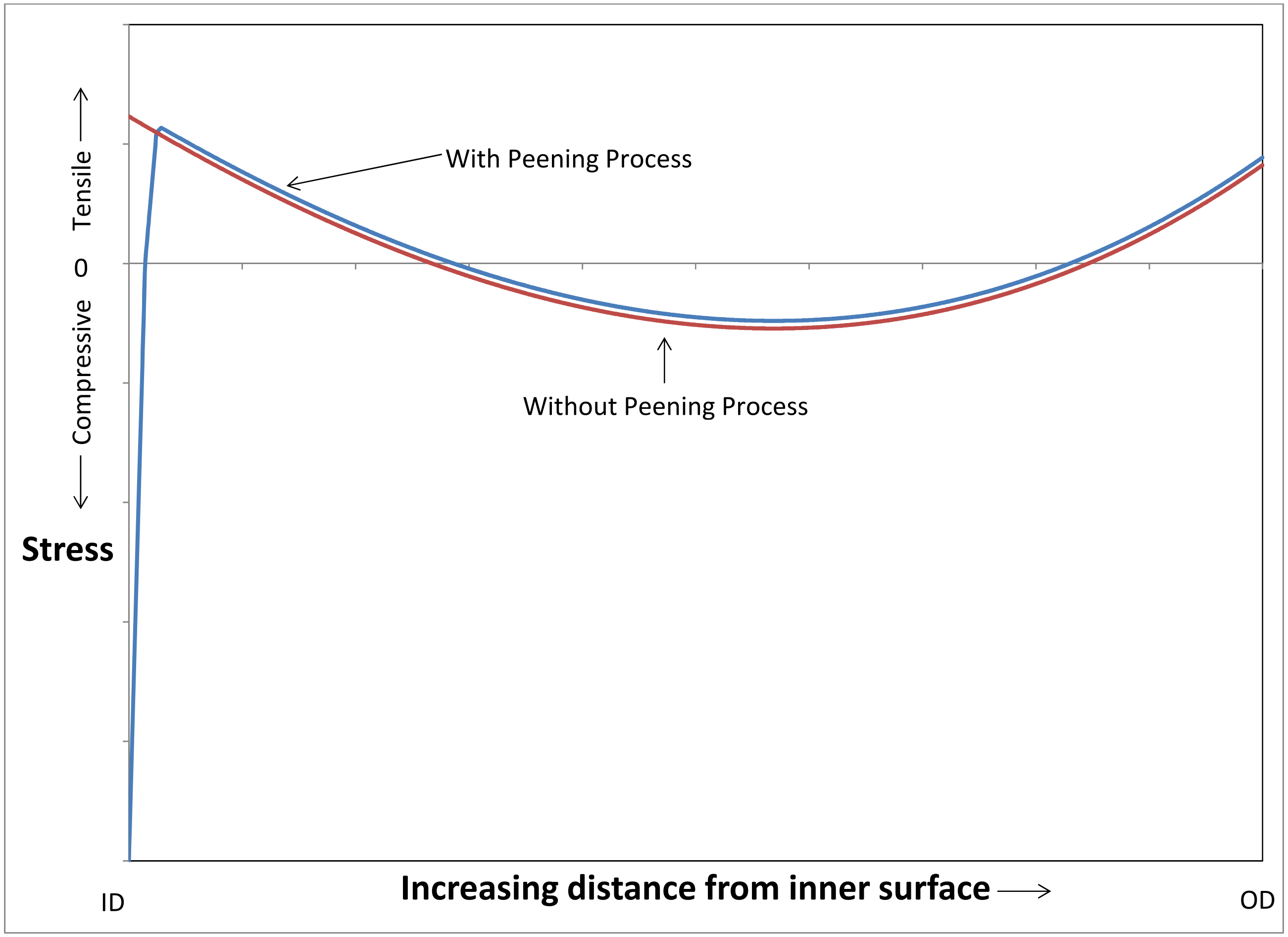
- The topical report will include calculations to determine appropriate inspection requirements after SSI treatment for:
  - RPVHPNs
  - DMWs
- These calculations will include the following elements:
  - Probability of crack initiation prior to peening
  - Effect of SSI on residual stress profiles, crack-tip stress intensity factors, and crack growth
  - Effect of exposure to operating temperature and load cycles on compressive residual stresses
  - Possibility of growth of pre-existing flaws by fatigue
  - Detectability of flaws as function of depth and length
  - Probability of through-wall cracking (i.e., leakage)
  - Probability of nozzle ejection (for RPVHPNs)

Crack Growth Modeling

- Load and stress model
  - Internal pressure
  - Piping loads (DMWs)
  - Weld residual stress before peening
  - Residual stress after peening
  - Effect of operating temperature and load cycling
- Flaw types considered
  - Axial and circumferential (DMWs)
  - Axial on ID, axial on OD below weld, flaw on weld surface, circumferential in tube above weld (RPVHPNs)
- Stress intensity factor calculation using standard weight function method
- Crack growth equations
  - Same probabilistic approach as xLPR Version 1.0: MRP-55 for Alloy 600 and MRP-115 for Alloy 182 with heat and weld factor distributions

Effect of SSI on Residual Stress Profile

- Conceptual example (axial stress for DMW)



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Crack Initiation Modeling

- RPVHPNs
  - Weibull approach to probability of cracking based on empirical plant experience
  - MRP Weibull assessment of top head inspection experience was revised in 2011 and submitted to NRC for information (MRP letter 2011-034)
  - The past inspection results for the particular head to be mitigated are a key factor
- DMWs
  - Use empirical Weibull model of time to crack initiation based on plant experience similar to crack initiation model used in MRP-307 for assessments of chemical mitigation
  - Frequency of axial and circumferential cracking based on empirical experience (same as MRP-307)
  - Sensitivity cases used to investigate effect of uncertainty in Weibull distribution describing probability of initiation

Crack Detection Modeling

- Probabilistic approach allows simulation of different inspection options
  - UT
  - ET
  - BMV
- RPVHPNs
  - Simulate UT/ET exams from nozzle ID such as for follow-up exam
  - Credit lack of leakage detected in BMV exams
- DMWs
  - Simulate UT exams based on xLPR approach (MRP-262, Revision 1)

Probabilistic Model End Point

- RPVHPNs
  - Calculate probability of nozzle ejection (net section collapse) using the critical size of circumferential flaw in nozzle tube located above the weld (MRP-105 approach)
  - Acceptance criteria for probability of nozzle ejection per MRP-105 approach
- DMWs
  - Calculate probability of through-wall cracking (i.e., leakage)
  - Probability of leakage is used to compare risk before and after peening given assumed inspection requirements before and after peening (MRP-307 approach)

Section 6: Conclusions

6.1 Basis for effectiveness of peening

6.2 Basis for no unacceptable side effects

6.3 Basis for appropriate relaxation of inspection requirements after peening

Conclusions

- The technical basis study (MRP-267) shows that SSI is a viable method for mitigating PWSCC of Alloy 600/82/182 components in PWRs
  - The SSI methods reliably produce a substantial compressive residual stress zone that is sustained for long-term operation
  - The SSI methods do not produce unacceptable side effects
- The technical basis (MRP-267) and topical report (MRP-335) documents are being prepared to support use of SSI at US PWRs, including appropriate relaxation of inspection requirements after peening
  - US NRC review of the topical report
  - Input to ASME Code committees
- MRP-335 will include calculations that consider:
  - The effect of SSI on the stress profile of the component
  - The possibility of pre-existing flaws deeper than the compressive stress

Questions & Discussion

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