NRC Perspectives on WRS Uncertainty, Predictions, and Use in Regulated Nuclear Applications

Patrick Raynaud, Michael Benson, Rob Tregoning
U.S. Nuclear Regulatory Commission

-

ASTM-E08.04

Workshop on Incorporating Residual Stress Into Structural Design and Sustainment

Disclaimer

This presentation was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed in this presentation, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission.

Outline

- History of WRS research at the NRC
- WRS uncertainty for measurements and predictions
- WRS impact on crack growth predictions
- Exploratory criteria for WRS modeling acceptance
- WRS modeling in nuclear applications
- Conclusions

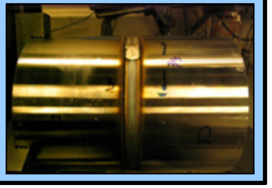
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

EPRI/NRC WRS Validation Program

- Conducted between 2008-2015
- Identify, quantify, and minimize sources of model uncertainty
- Develop reliable and consistent modeling procedures
- Develop recommendations for validation of WRS models

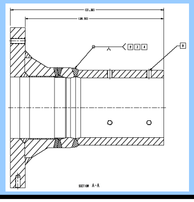
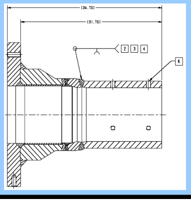
Phase 1 - EPRI

- 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 1: Scientific Weld Specimens

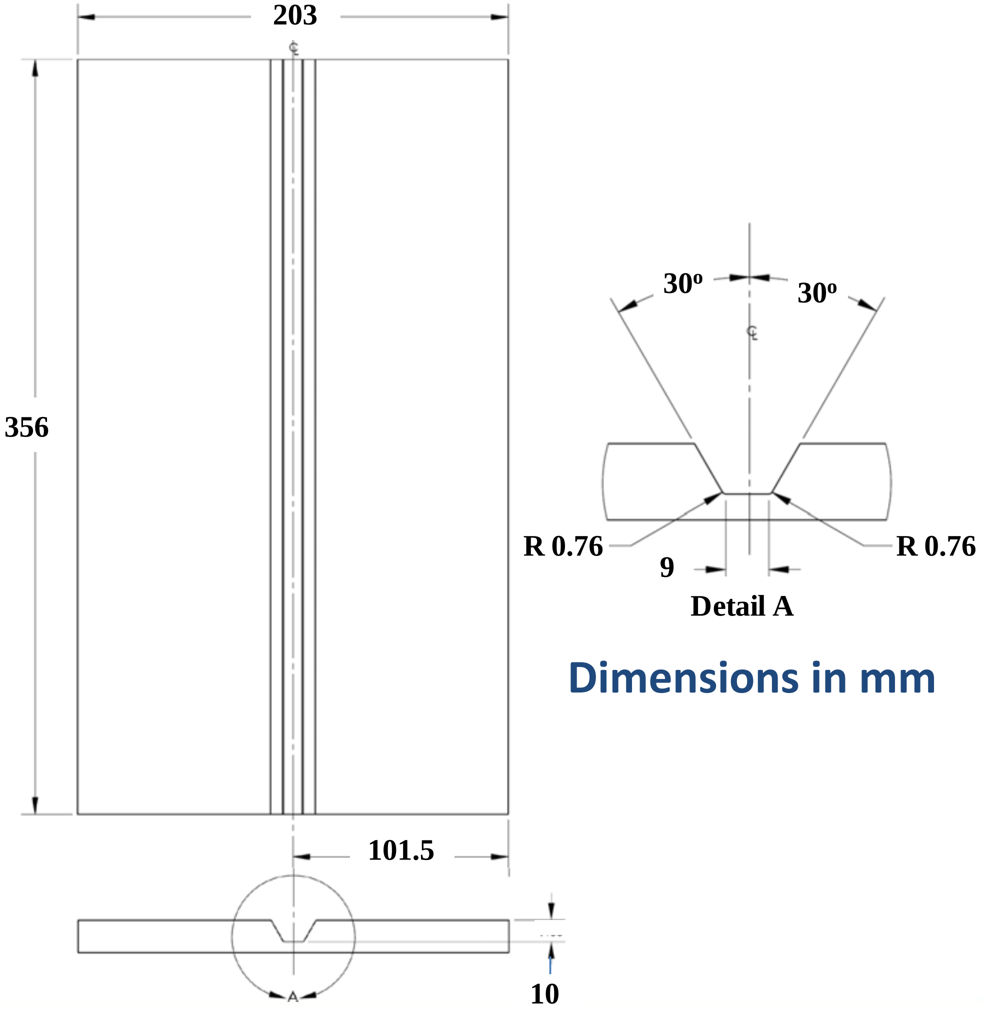
- Simple, light-weight specimen geometries
  - Grooved plate
  - Butt-welded cylinders
- Objective
  - To demonstrate/develop WRS measurement and modeling capabilities

Phase 1 - EPRI

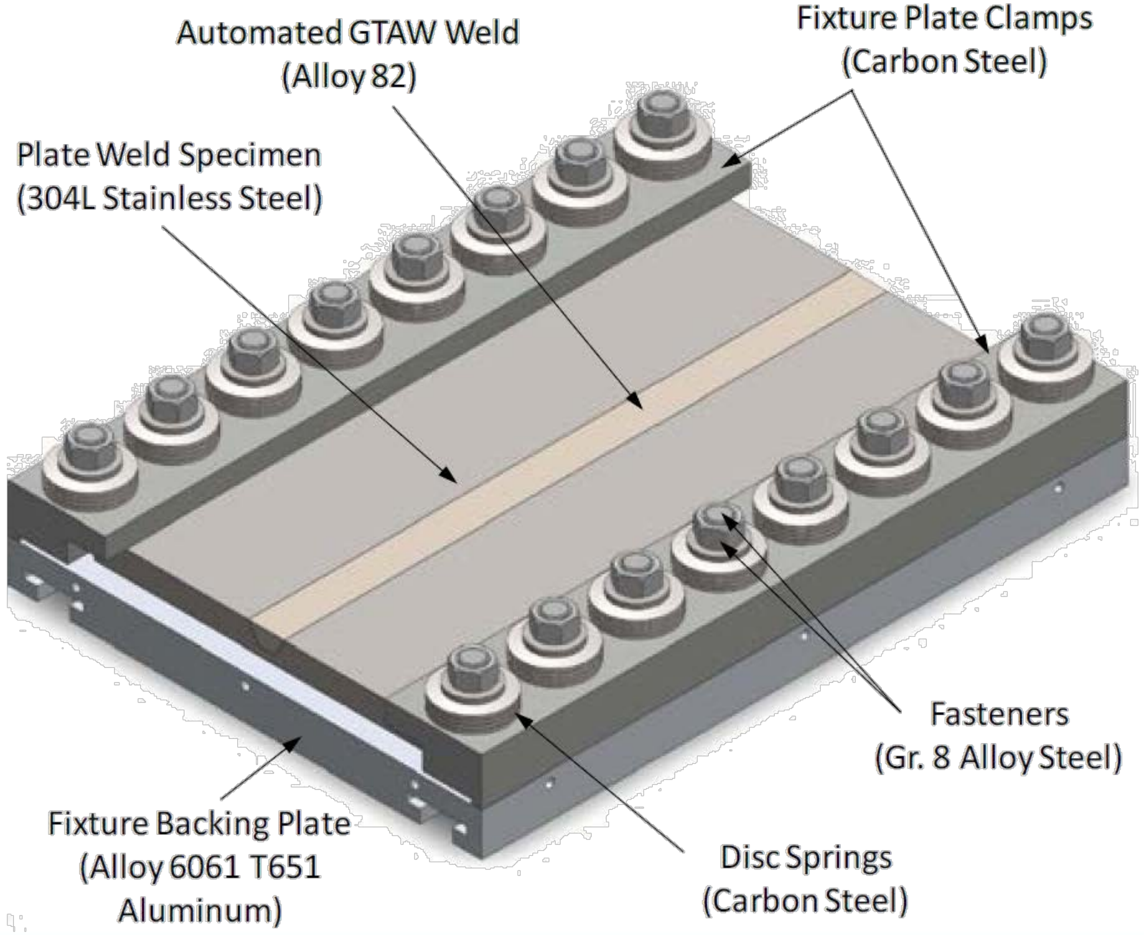
- Scientific Weld Specimens
- Phase 1A: Restrained Plates (QTY 4)
- Phase 1B: Small Cylinders (QTY 4)
- Purpose: Develop FE models.

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

Phase 1 Plate Specimens



Dimensions in mm

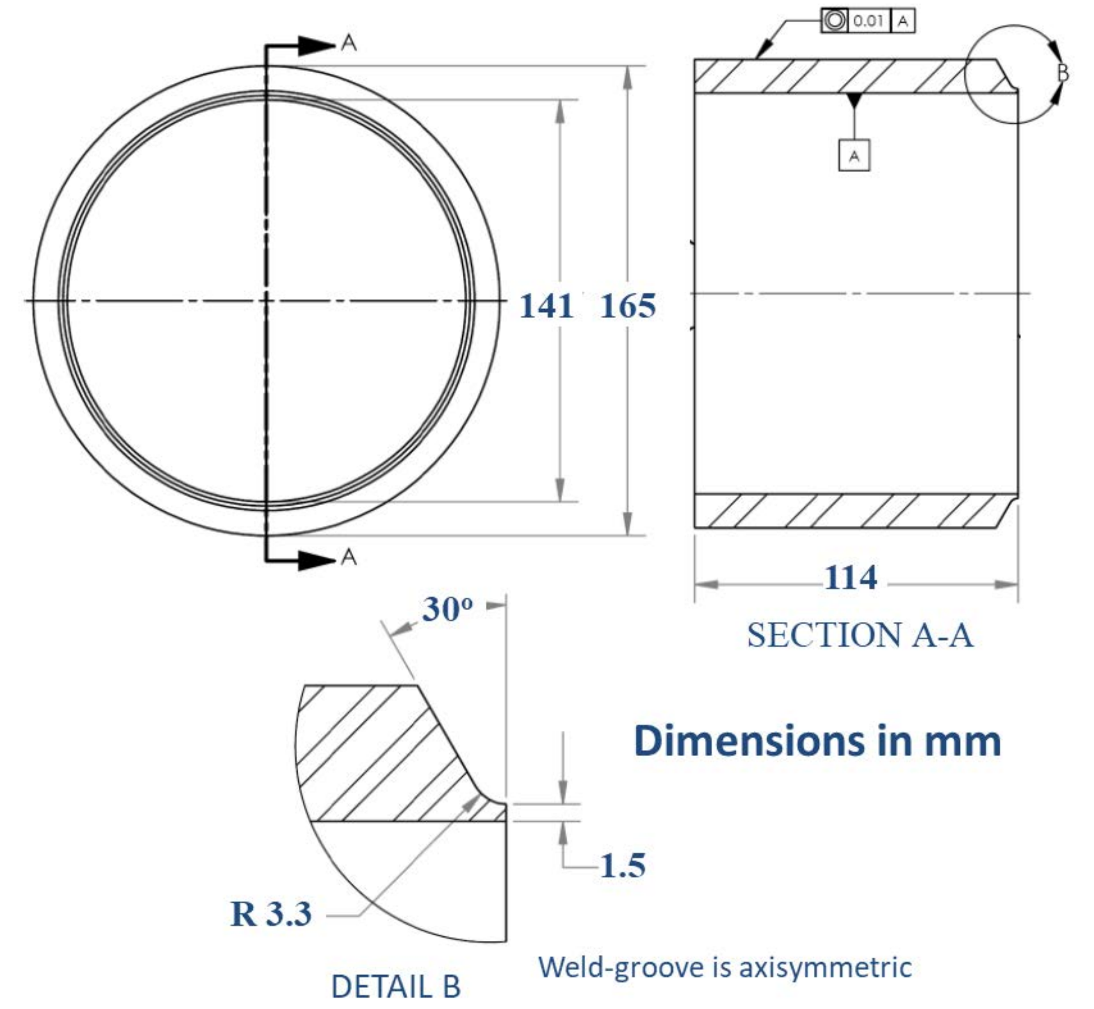


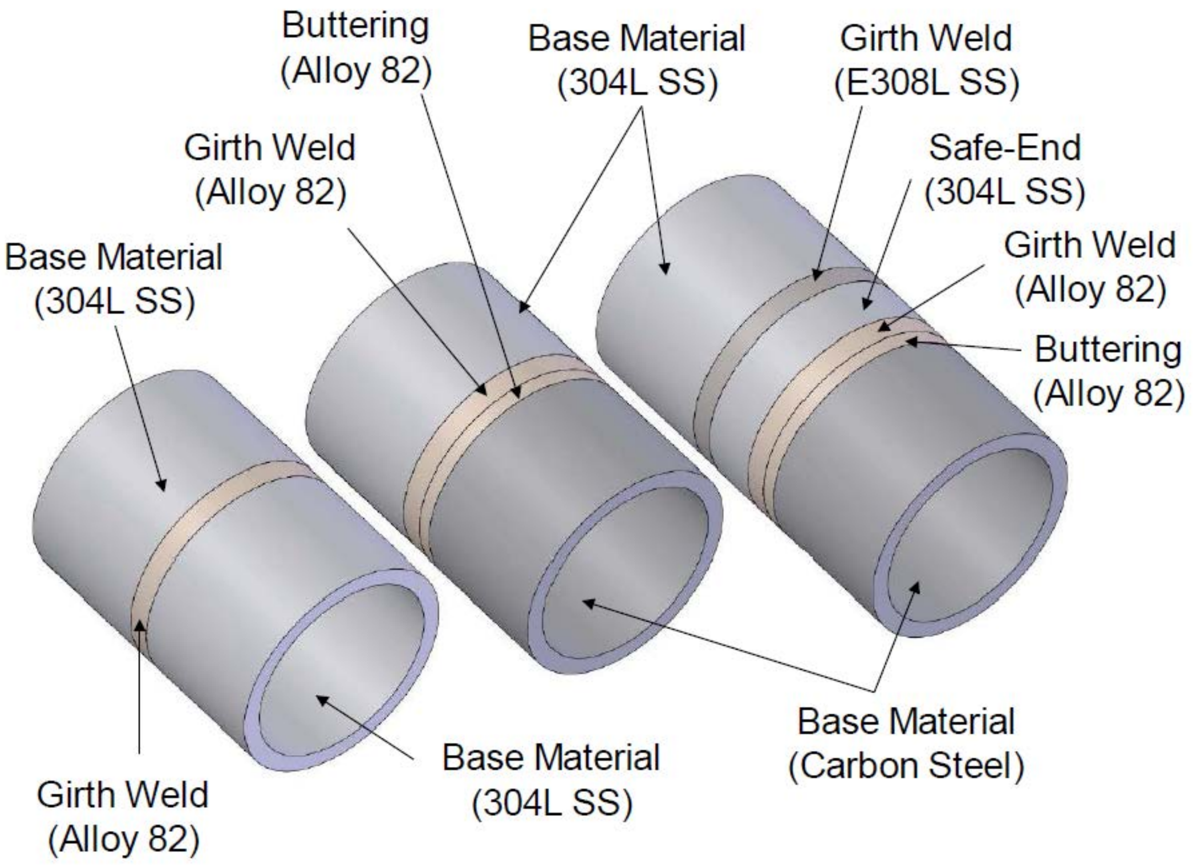
Source: MRP-316, EPRI, 2011

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

Phase 1 Cylindrical Specimens

Source: MRP-316, EPRI, 2011



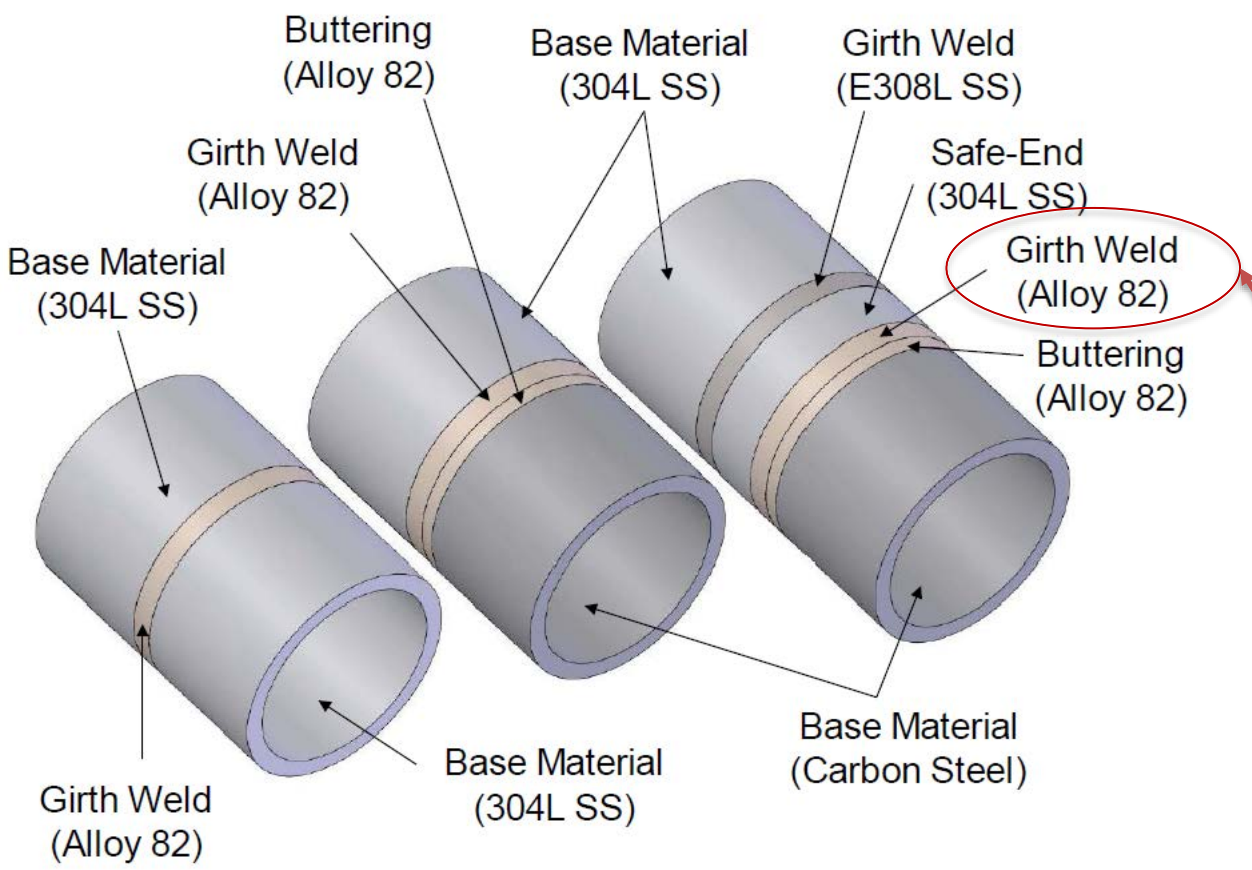


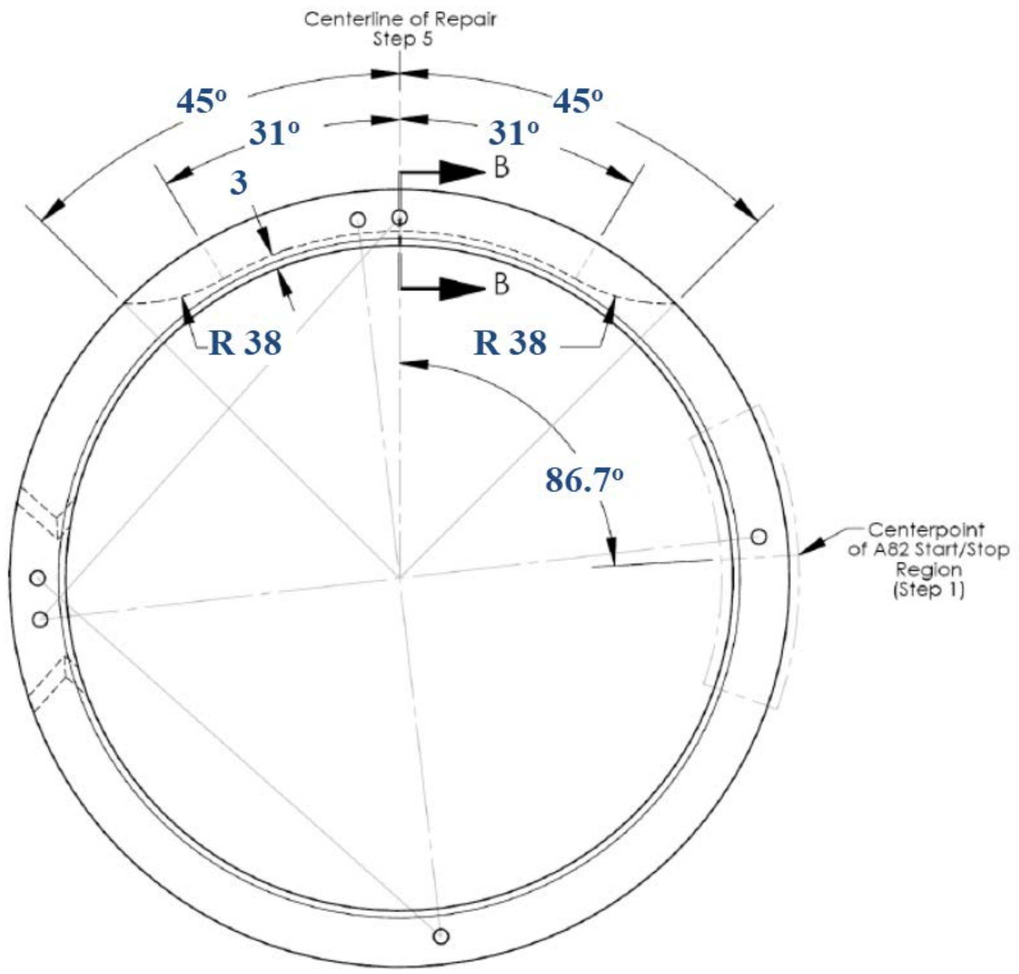
Source: MRP-316, EPRI, 2011

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

Phase 1 Cylindrical Specimens with Weld Repair

Source: MRP-316, EPRI, 2011

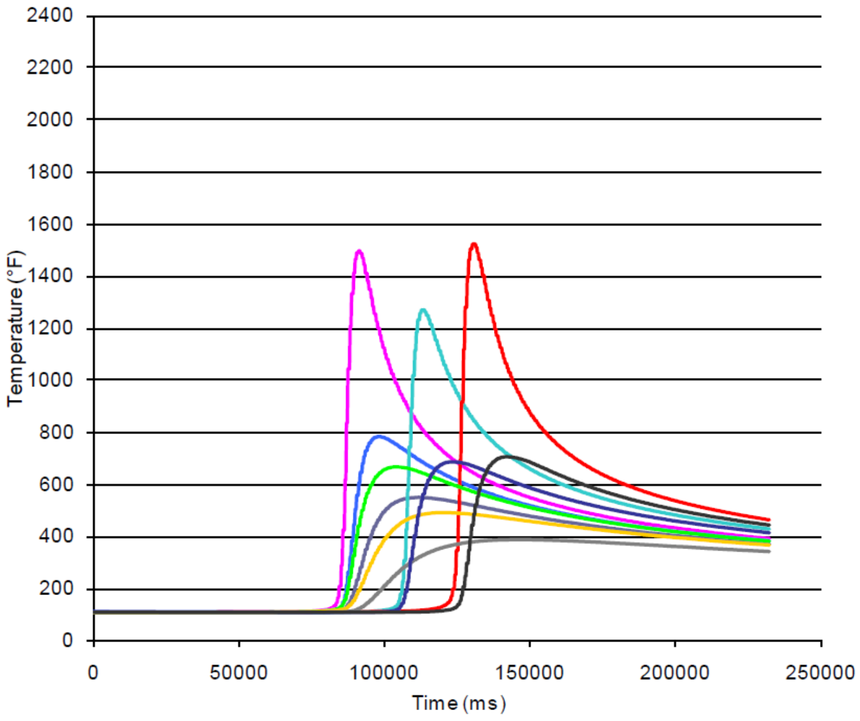


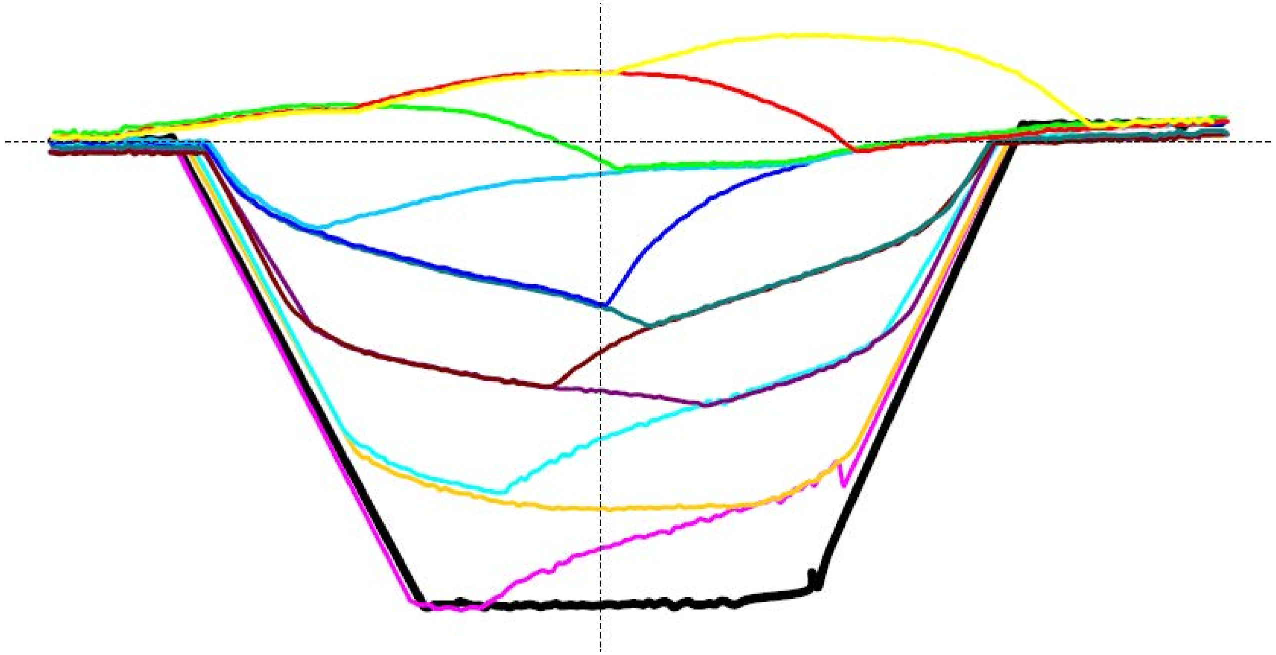


Source: MRP-316, EPRI, 2011

Characterization of Phase 1 Specimens

- Thermocouples were spot welded on the specimens to characterize temperature history at different locations
- Laser profilometer was used to measure individual weld beads



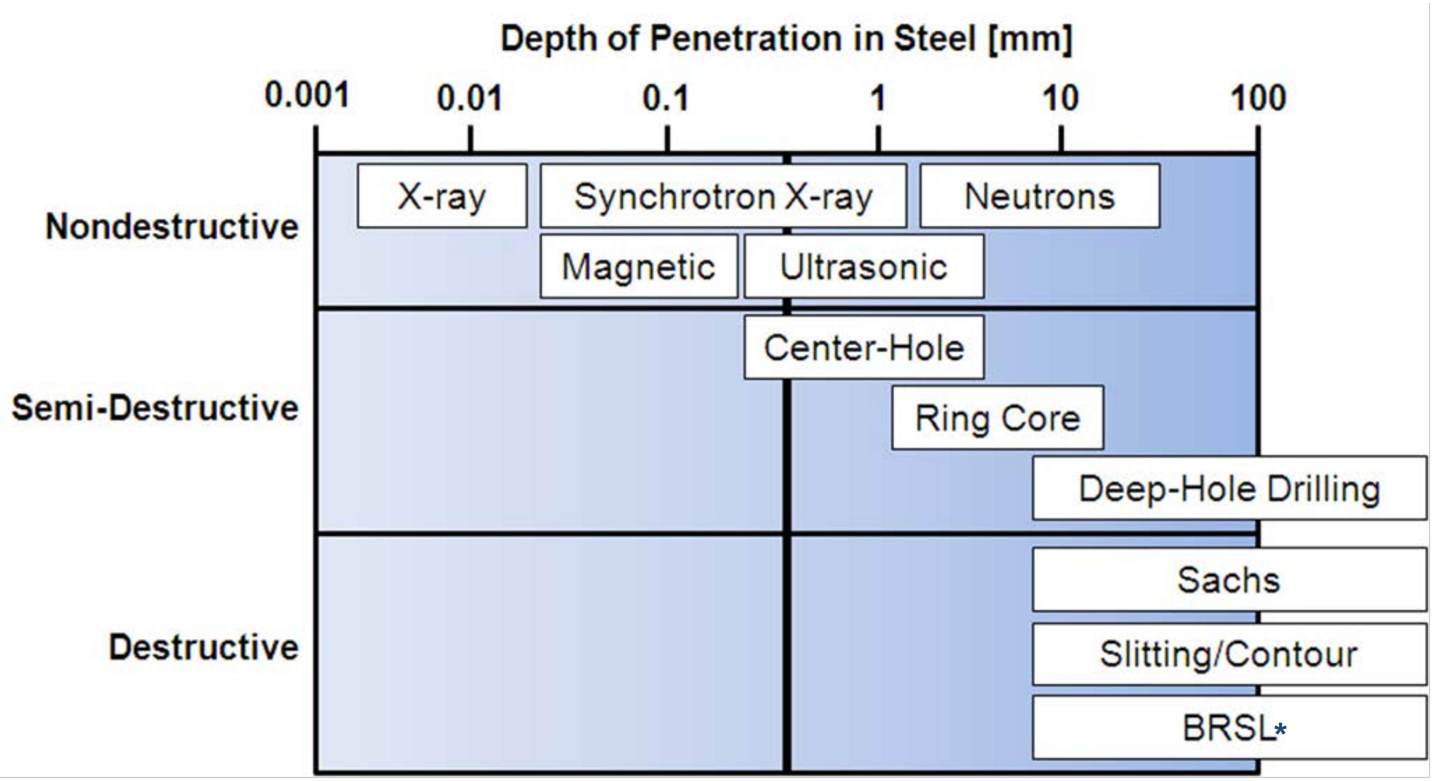


 Source: MRP-316, EPRI, 2011

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

Phase 1 WRS Measurement Techniques

- Neutron diffraction - ORNL
- Contour - Hill Engineering
- X-ray diffraction - TEC
- Surface Hole Drilling - LTI
- Deep Hole Drilling - VEQTER
- Ring-Core - LTI
- Slitting - Hill Engineering



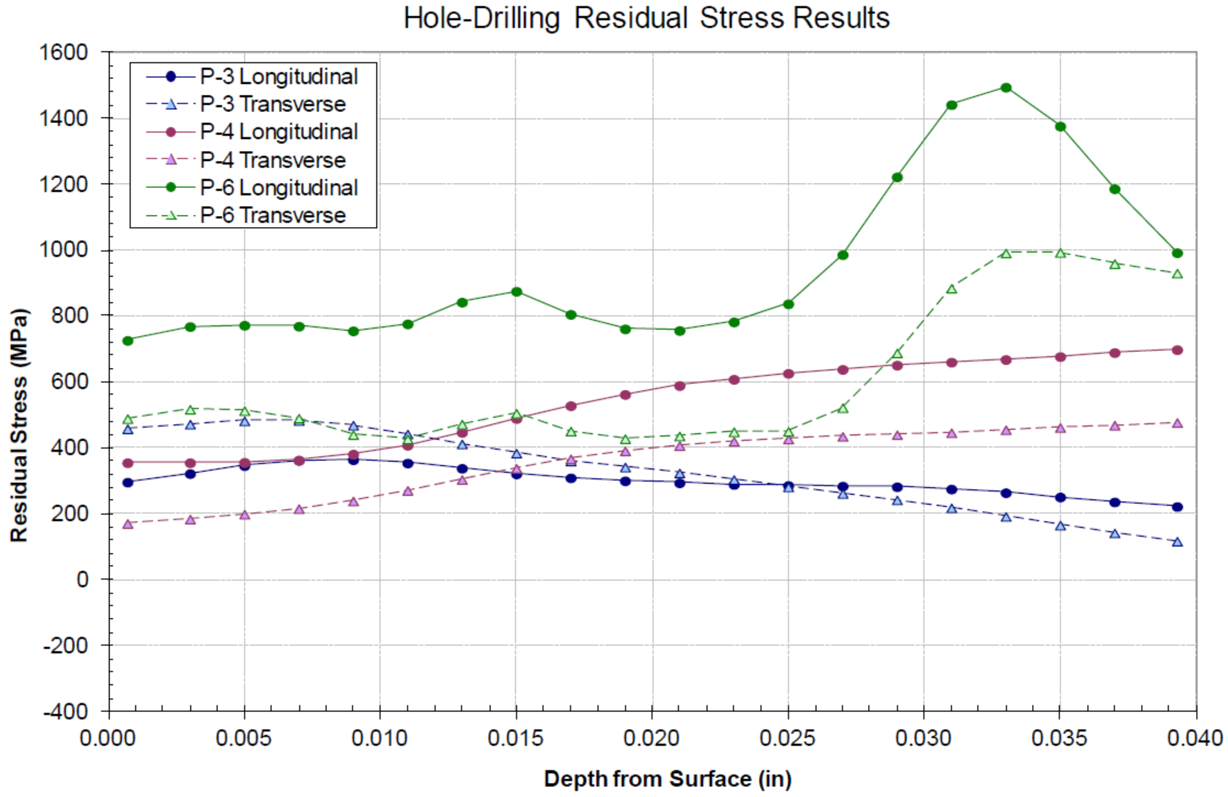
* Block Removal and Surface Layering

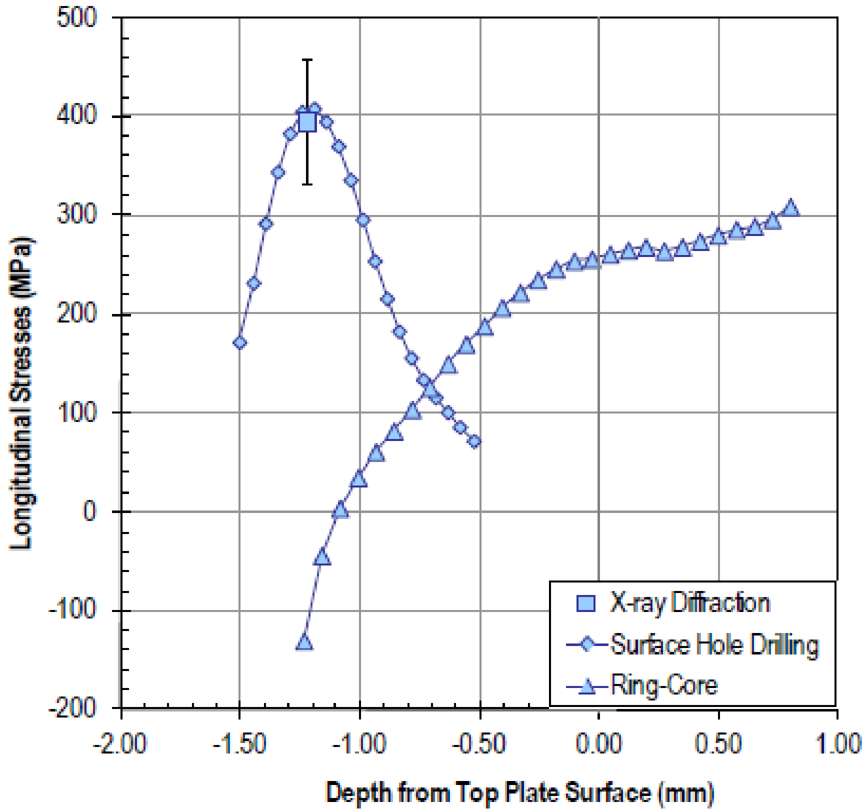
Source: Veqter, Ltd.

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

Phase 1 Surface WRS Measurements

- Surface hole drilling
- Unrealistically large values: e.g., 1500 MPa
- Independent techniques did not compare well with each other



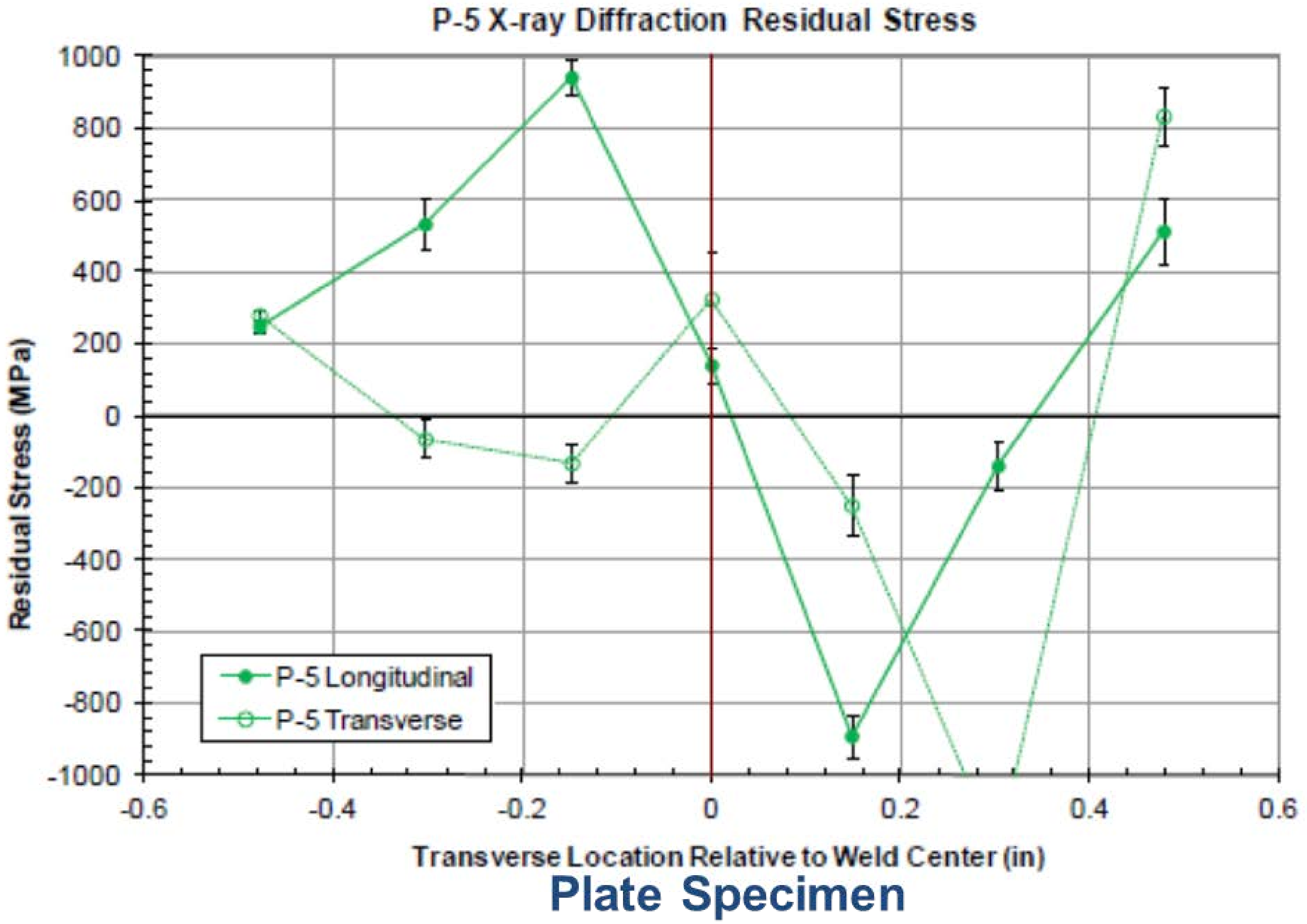


Source: MRP-316, EPRI, 2011

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

Phase 1 Surface WRS Measurements

- X-ray diffraction showed large fluctuations in the data: e.g., from 950 to -950 MPa
- Data is asymmetric for a similar metal weld



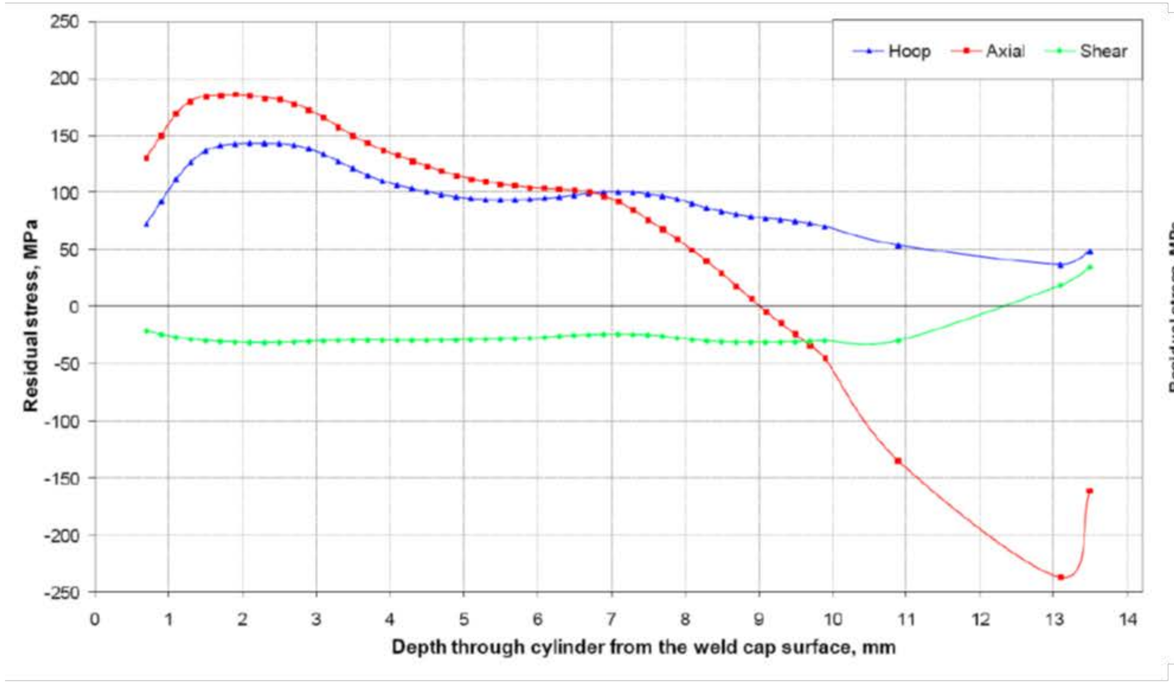
Source: MRP-316, EPRI, 2011

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

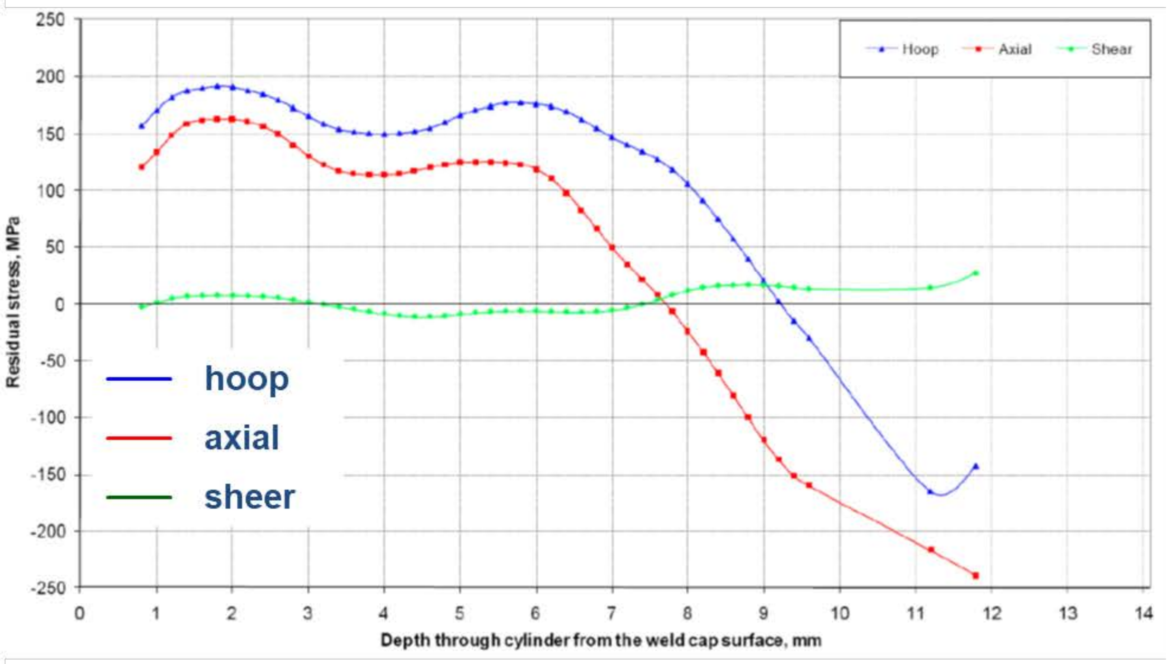
Phase 1 Bulk WRS Measurements

- Smooth trends and reasonable magnitudes: e.g., -250 to 200 MPa
- Repair weld significantly affected the hoop stress

Weld Centerline



Repair Weld Centerline

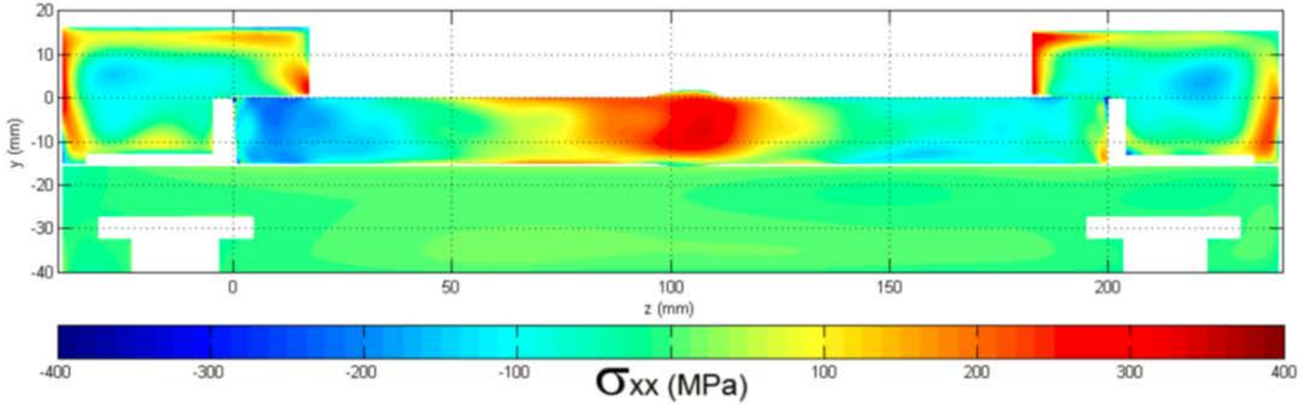


Cylinder Specimen – Deep Hole Drilling

Source: MRP-316, EPRI, 2011

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

Phase 1 Bulk WRS Measurements



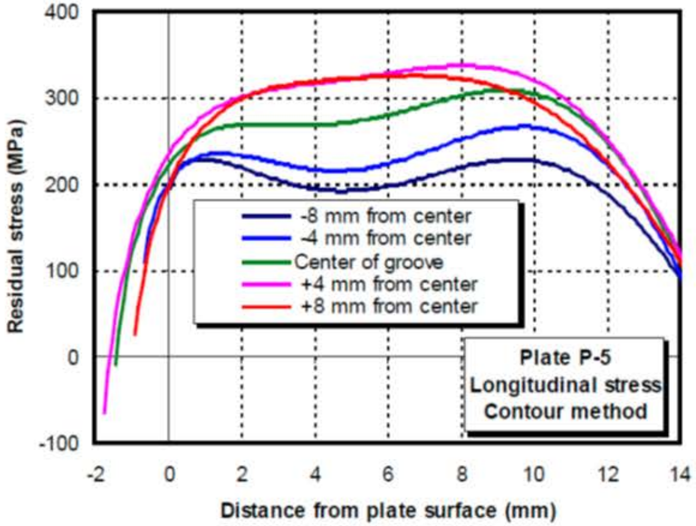
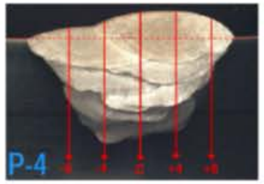


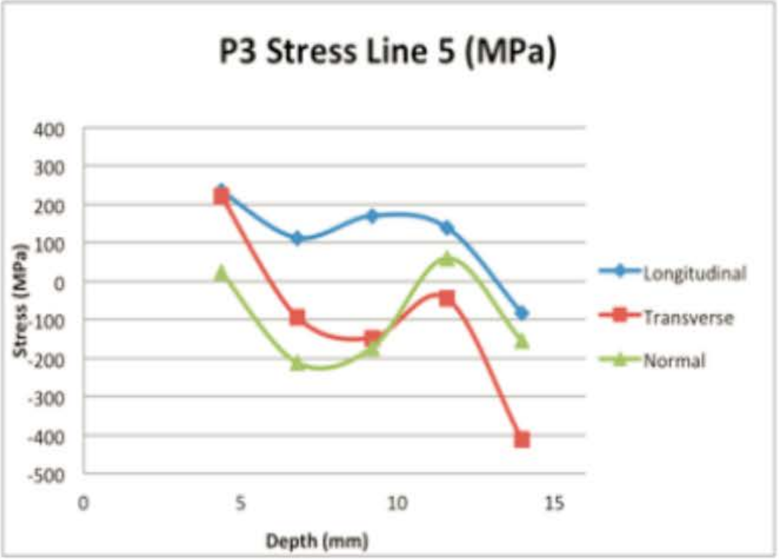
Plate Specimen – Contour Method

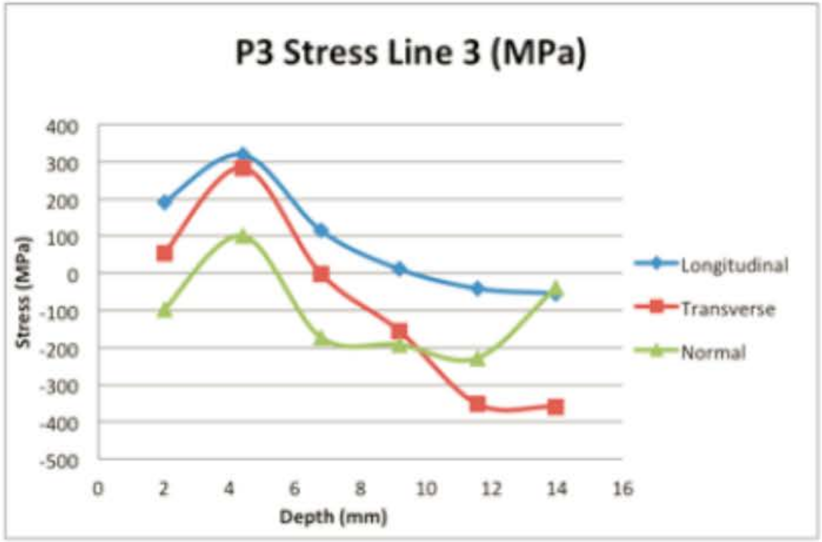


Source: MRP-316, EPRI, 2011

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

Phase 1 Bulk WRS Measurements





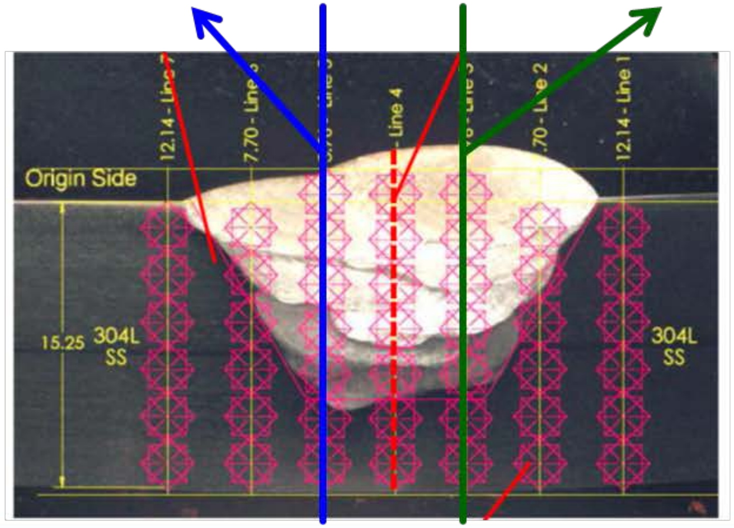


Plate Specimen – Neutron Diffraction Reactor Neutron Source

Source: MRP-316, EPRI, 2011

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

Phase 1 Model-Measurement Comparison

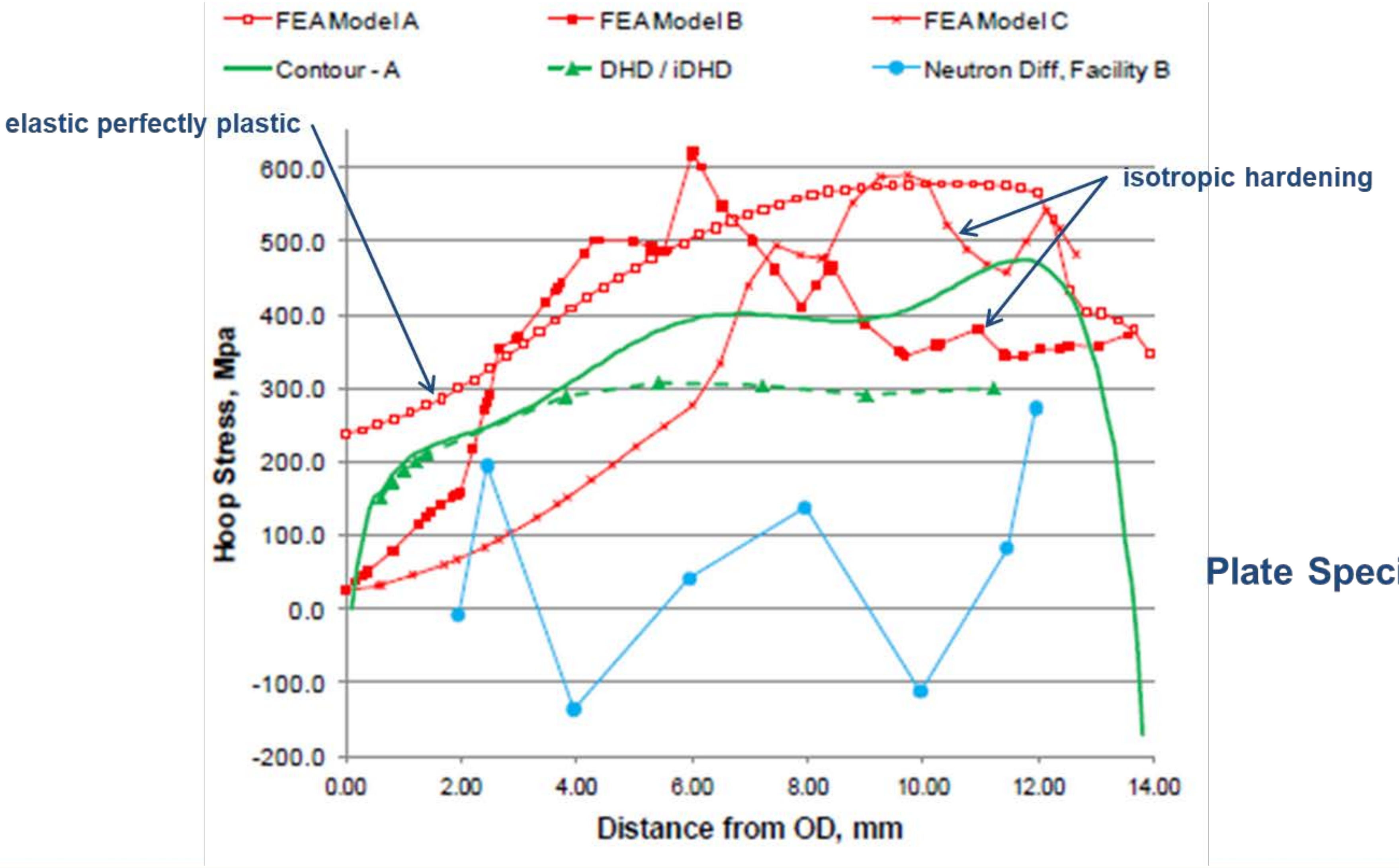


Plate Specimen

Source: MRP-316, EPRI, 2011

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

Phase 1 Summary and Conclusions

- Simple weld geometries in order to develop measurement and modeling techniques
- Near-surface stress measurement is uncertain
- In general, mechanical strain relief techniques seemed most reliable
- Agreement between models and experiment seems feasible

Phase 2: Fabricated Prototype Nozzles

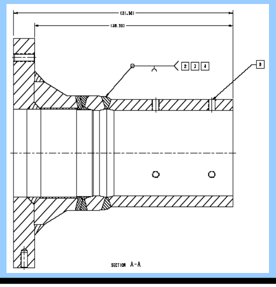
- Full-scale mockups
  - Two mockups: Phase 2a and Phase 2b
  - Fabricated under controlled conditions
- Finite Element Round Robin
  - Double-blind: i.e., modelers did not have access to the measurement data and vice-versa
  - Obtain modeling results from a community of independent modelers
- Objectives
  - To validate WRS modeling with experiment
  - To assess WRS modeling uncertainty

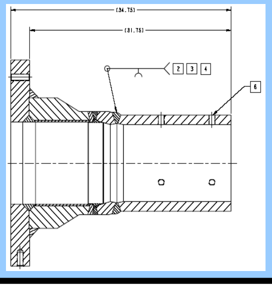
Phase 2 - NRC

•Fabricated Prototypic Nozzles

•Type 8 Surge Nozzles (QTY 2)

•Purpose: Prototypic scale under controlled conditions. Validate FE models.

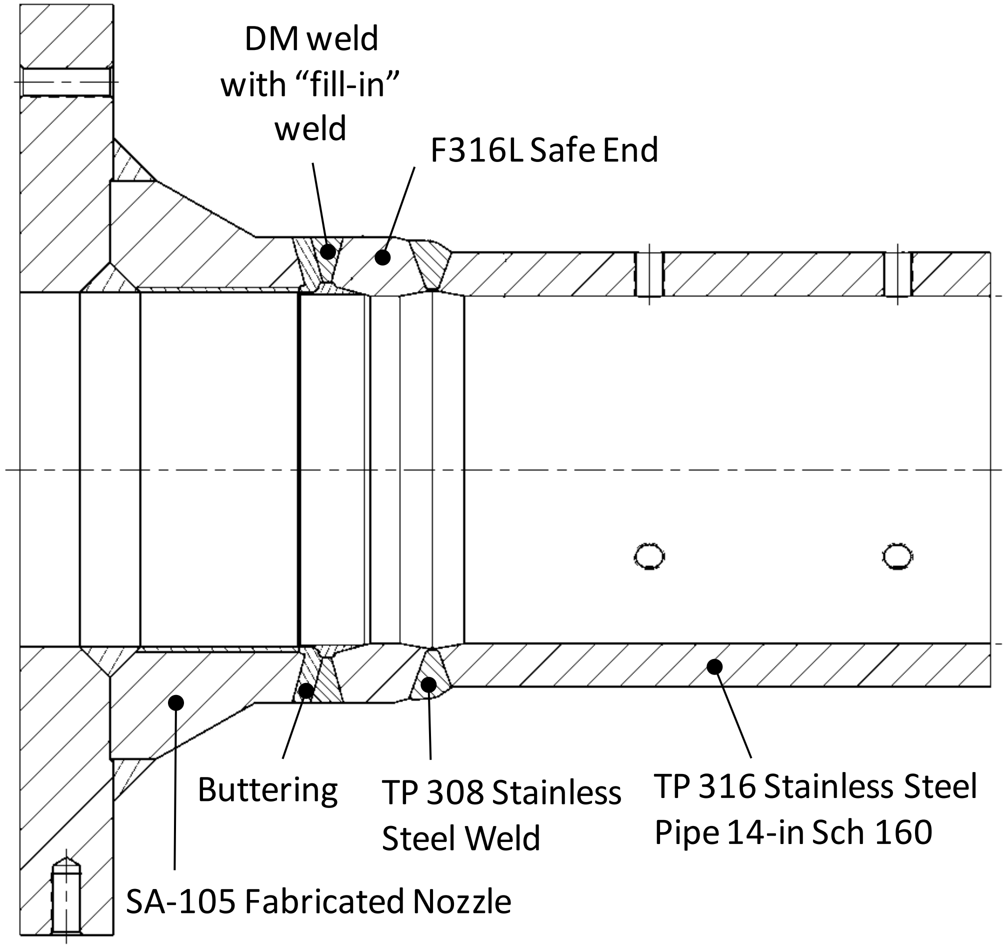




U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Phase 2a Mockup Fabrication

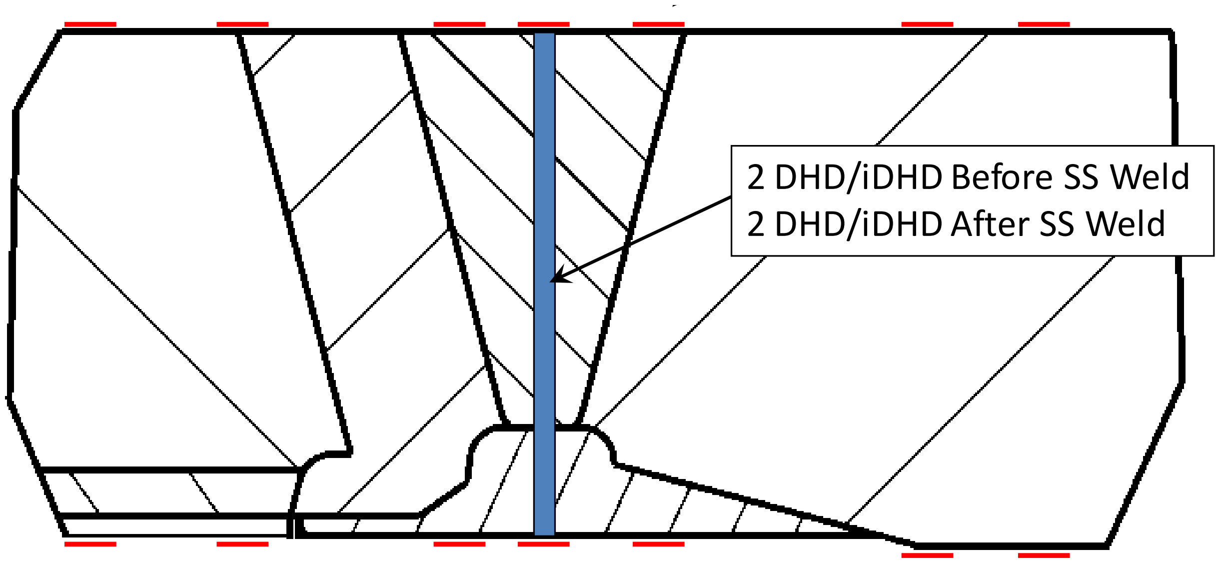
- Pressurizer surge nozzle
- Welding performed by automated gas tungsten arc welding
- Thermocouple and laser profilometry readings
- Rough dimensions: 31” overall length, 11” inner diameter



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

Phase 2a WRS Measurement

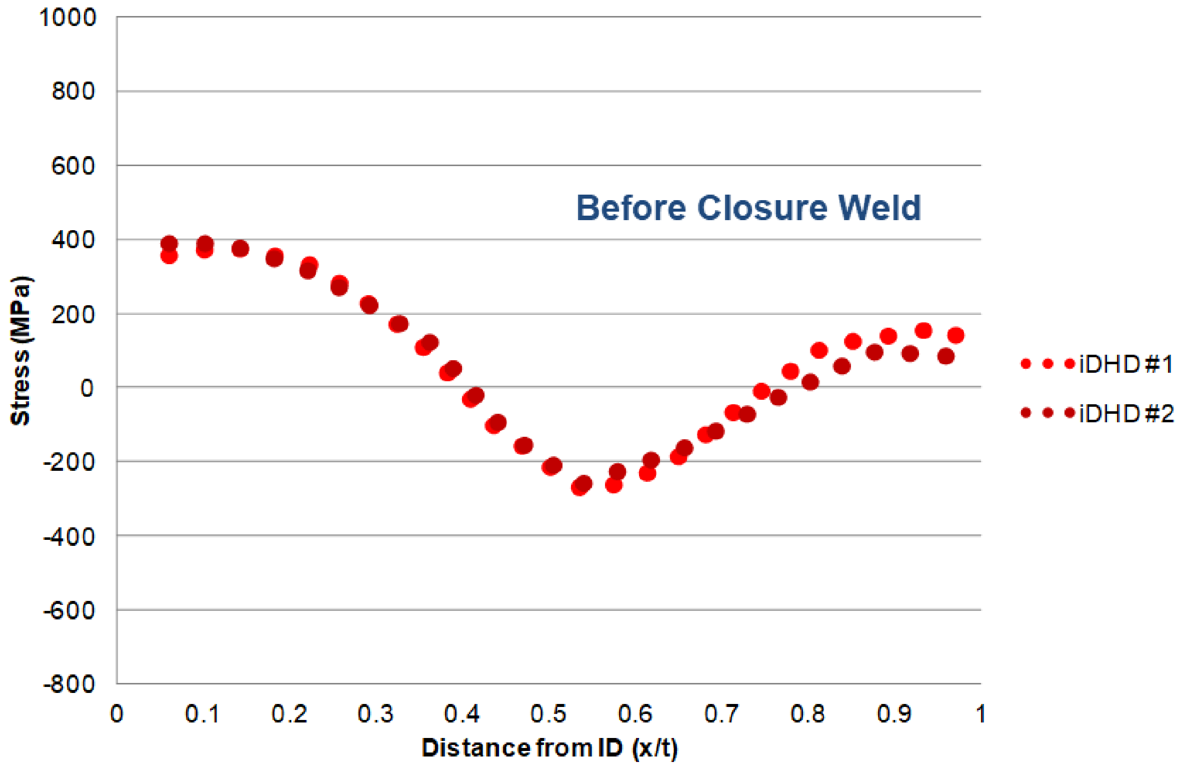
- Incremental deep hole and deep hole drilling - bulk
- Measurements taken before and after safe end to pipe weld was complete
  - Safe end to pipe weld can affect the stress field at the dissimilar metal weld

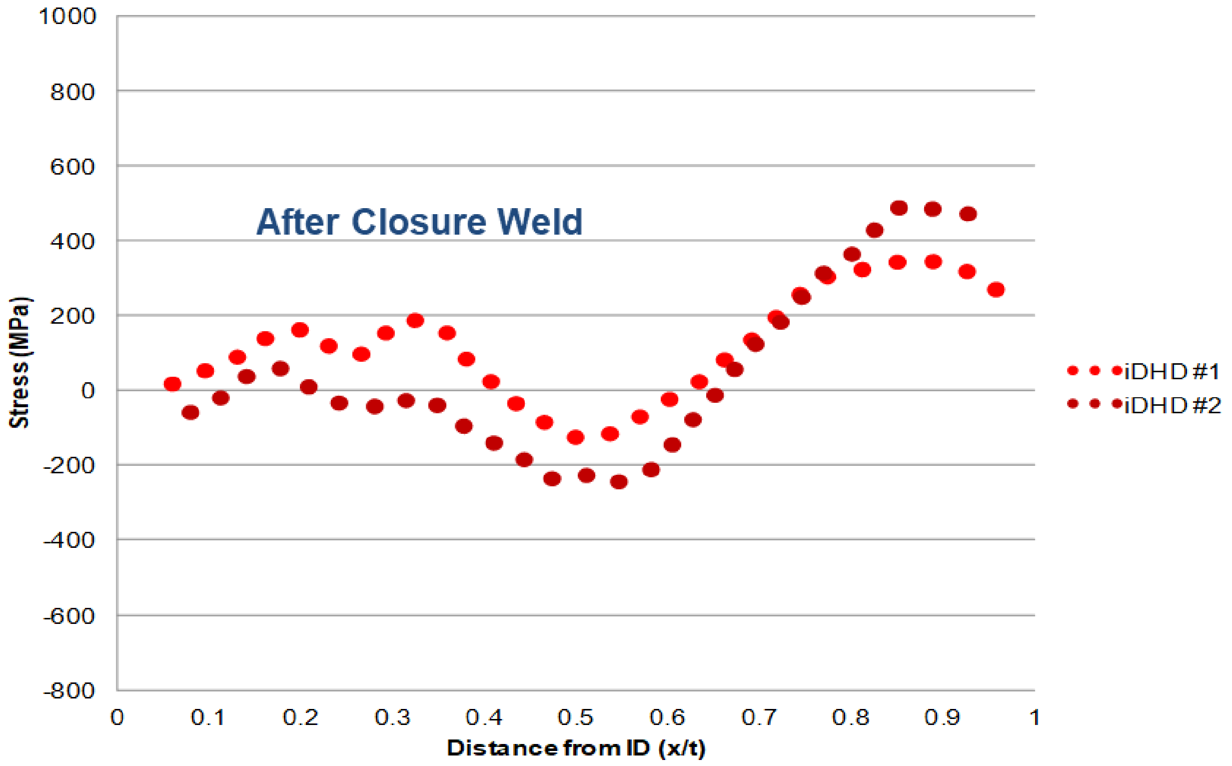


U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Phase 2a Deep Hole Drilling

- Axial stresses shown here
- Safe end to pipe weld can potentially have a beneficial affect on inner diameter stress
- Safe end length can be an important parameter

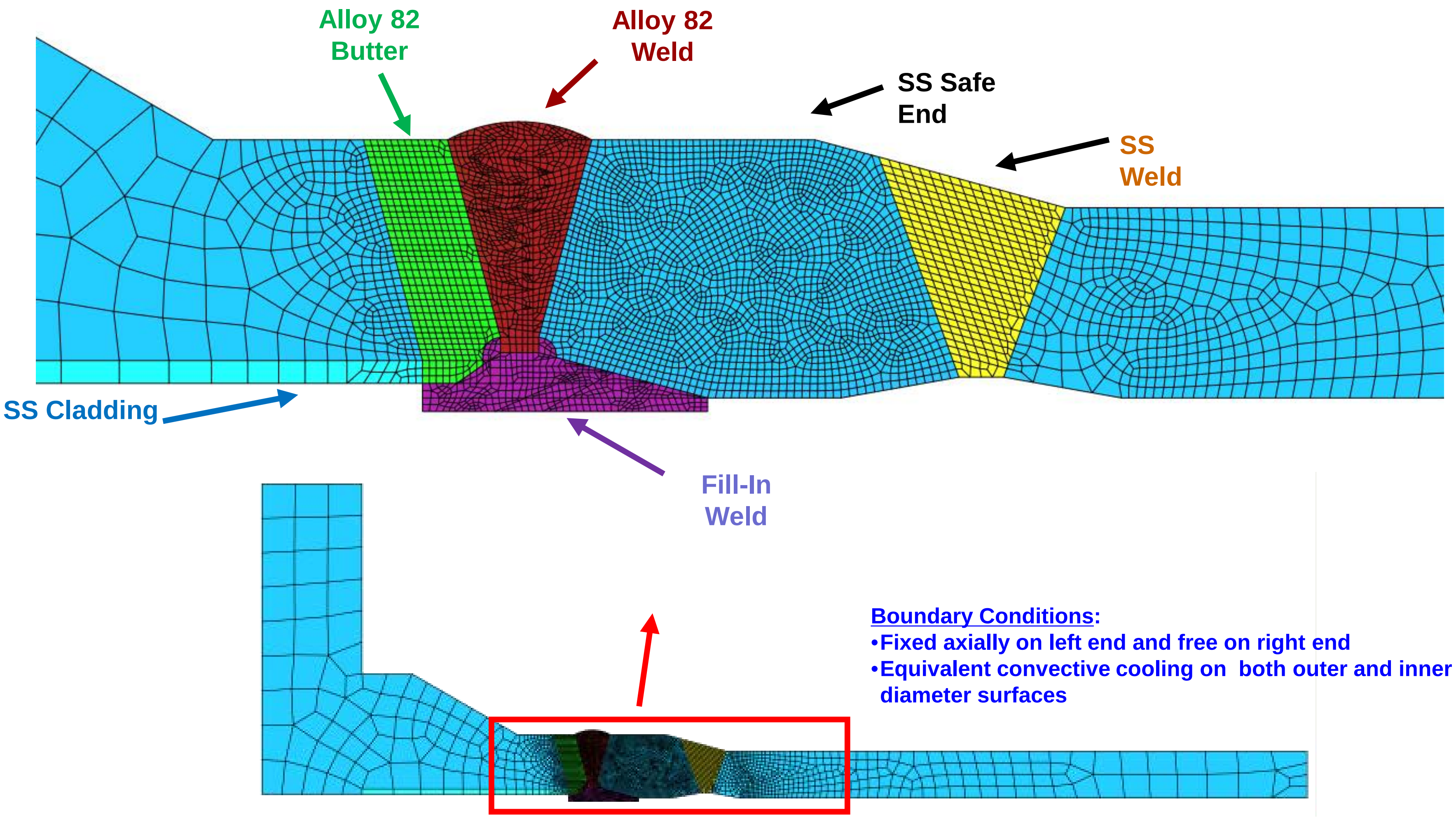




Phase 2a Finite Element Round Robin Study

- ANSTO (Australia)
- AREVA (USA and EU)
- Battelle (USA)
- Dominion Engineering (USA)
- Goldak Technologies (Canada)
- ESI Group (USA)
- EMC2 (USA)
- Inspecta Technology (EU)
- Institute of Nuclear Safety System (Japan)
- Osaka University (Japan)
- Rolls Royce (UK)
- Structural Integrity Associates (USA)
- Westinghouse Electric Company (USA)

Phase 2a Example Model

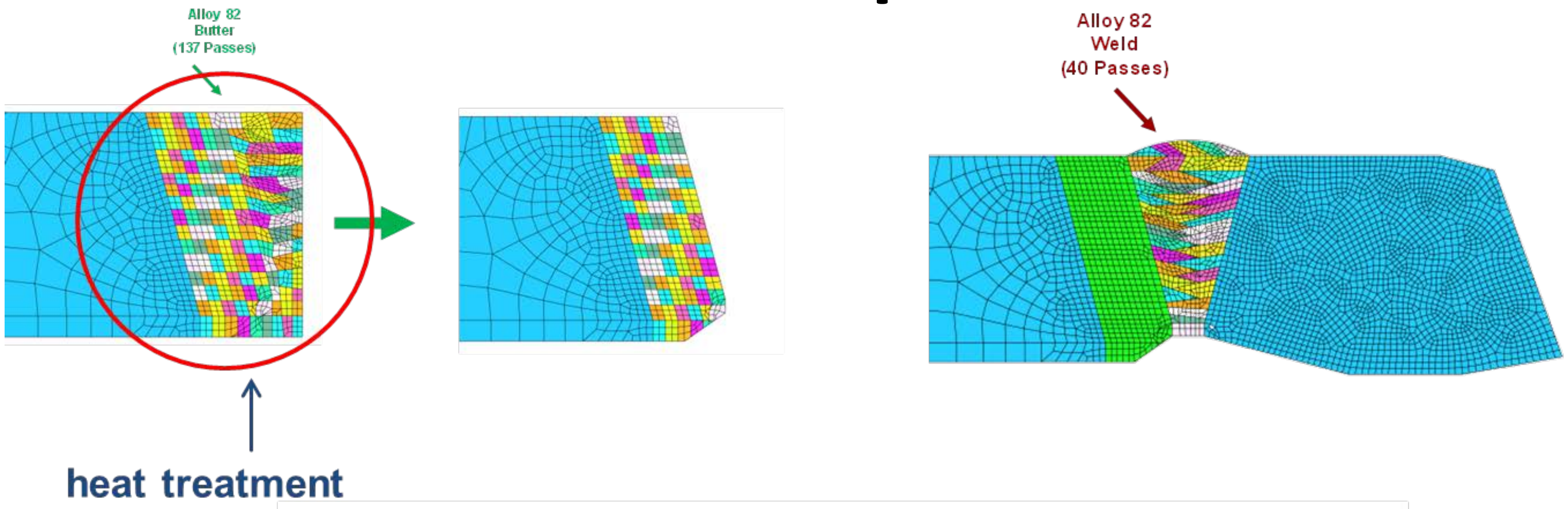


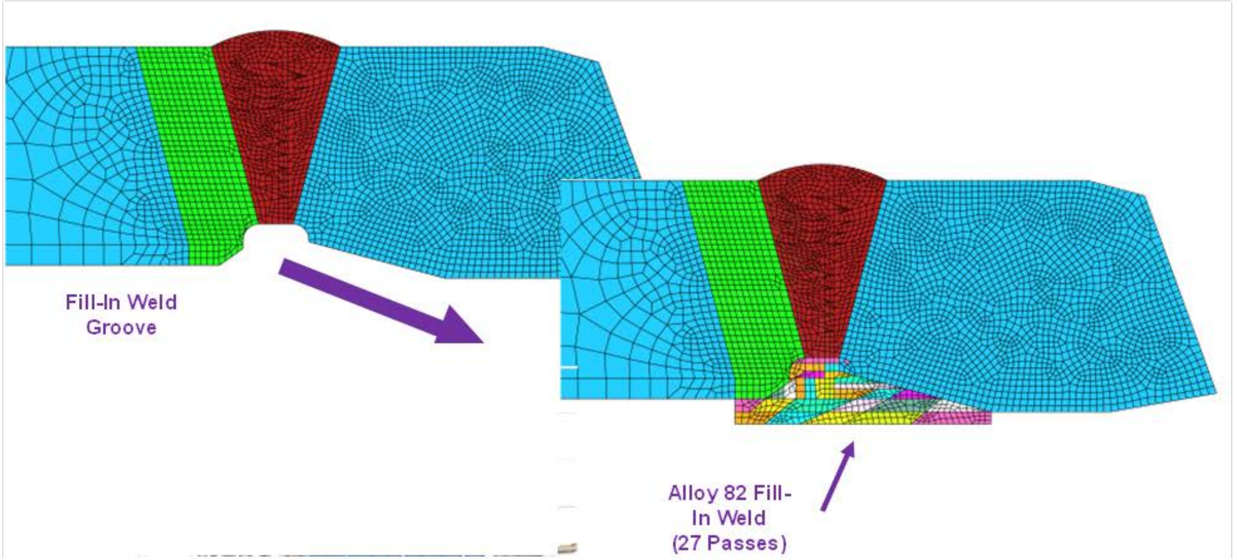
Boundary Conditions:

- Fixed axially on left end and free on right end
- Equivalent convective cooling on both outer and inner diameter surfaces

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

Phase 2a Example Model

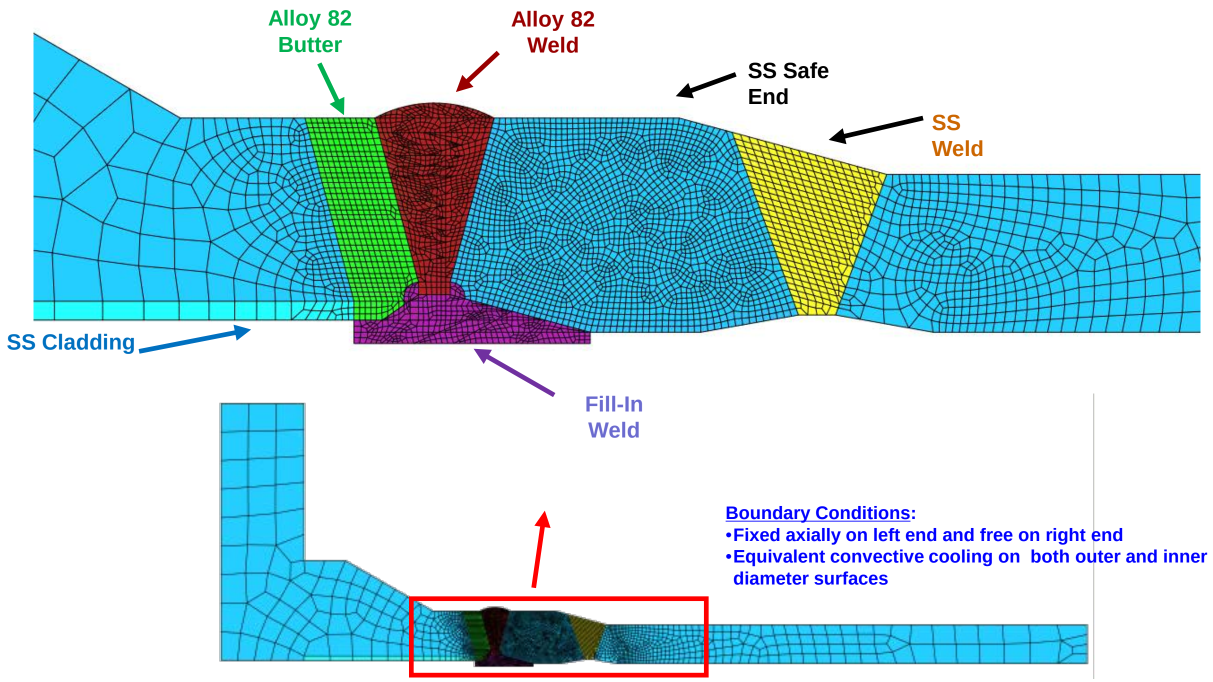




U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Phase 2a Round Robin Study Philosophy

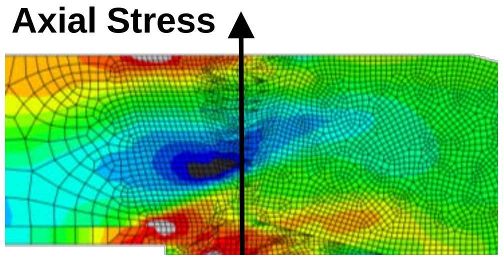
- Postulated sources of uncertainty: welding heat input and material properties
- Three analysis stages
  - No thermocouple data or material property data supplied
  - Thermocouple data only supplied
  - Thermocouple and material property data supplied
- Models completed before and after the stainless-steel closure weld



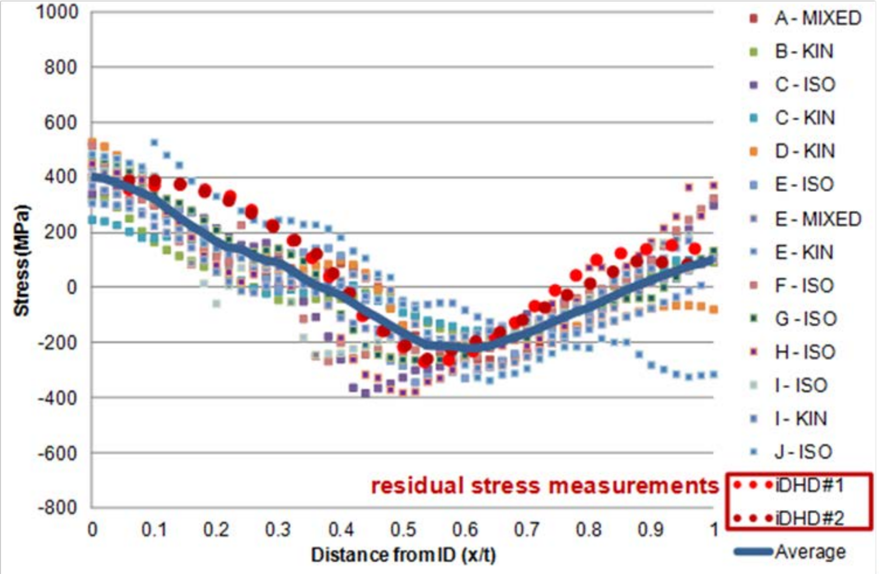
U.S.NRC United States Nuclear Regulatory Commission Protecting People and the Environment

Phase II: Fabricated Prototype Nozzles

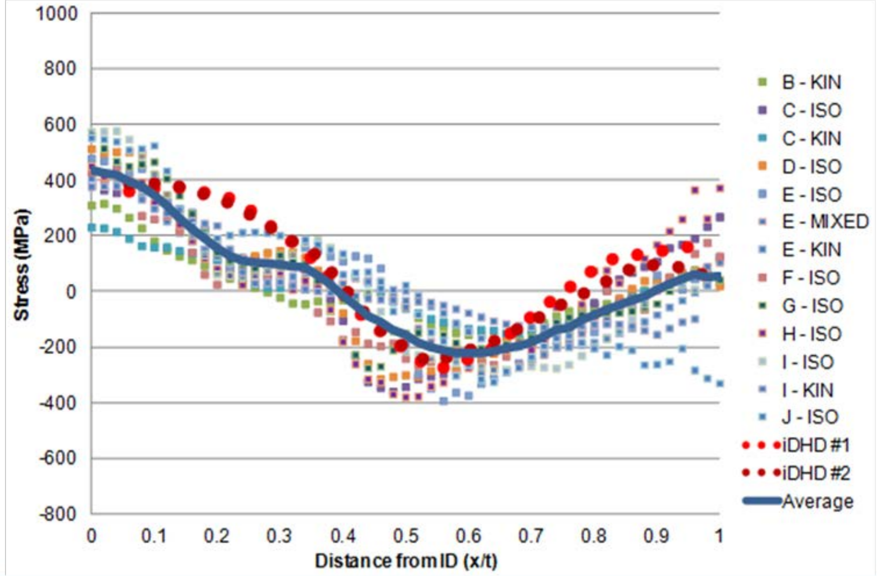
- Axial stresses shown here
- Variety of hardening laws employed
- Modeling uncertainty is the same



Pre-stainless-steel weld
No material properties
No thermal couple data



Pre-stainless-steel weld
Supplied material properties
Supplied thermal couple data



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

Observations from Phase 2a

- While modeling and measurement results show reasonable agreement in magnitude and profile shape, there is significant model-to-model variability

- Providing thermocouple data and material property data did not decrease modeling uncertainty

- Hardening law is a significant modeling parameter

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

Phases 3 and 4

- Nozzles from a canceled plant
- Phase 4 nozzle had a weld overlay
- Double-Blind Finite Element Round Robin

Phase 3 - EPRI

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

Phase 4 - EPRI

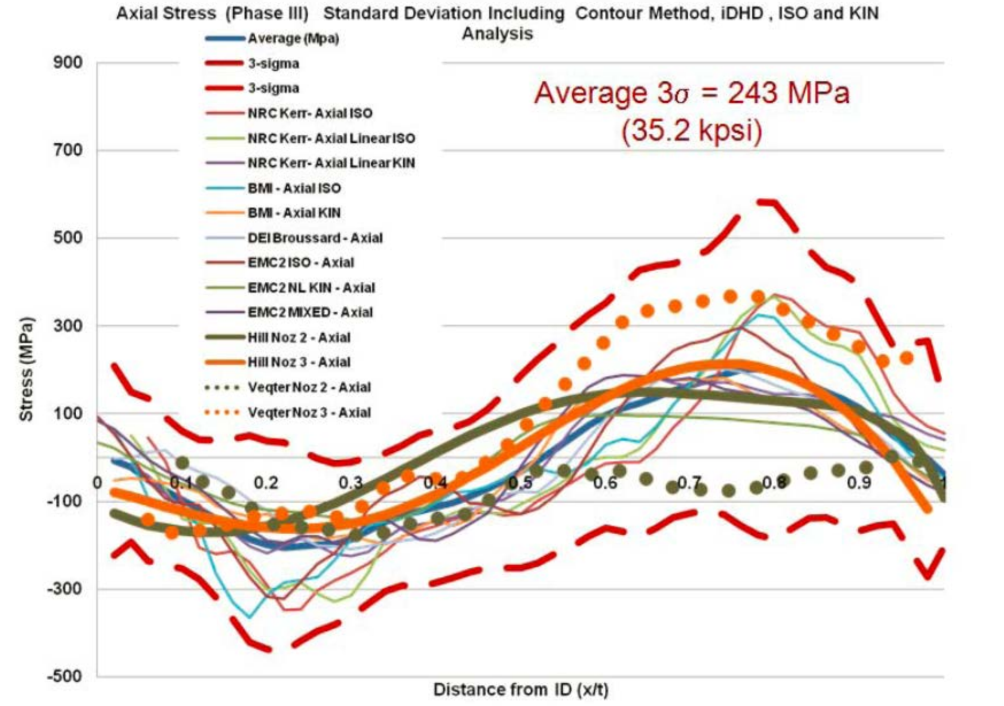
- **Plant Components**
- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.

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

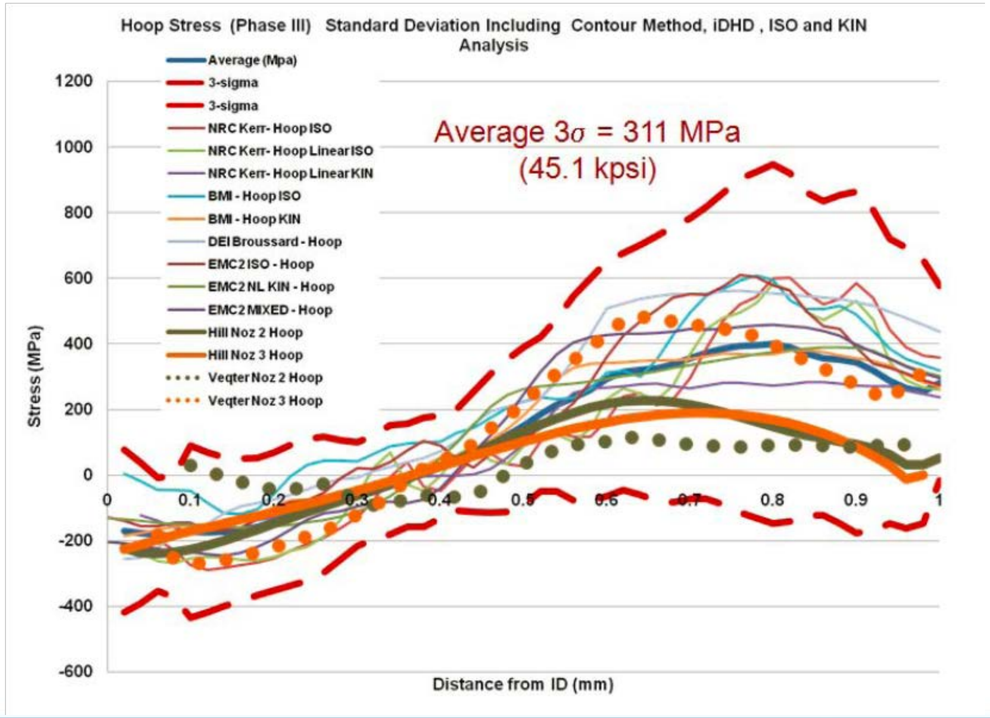
Phase 3 Results

- Spread in modeling results evident in the Phase III results
- Phase 3 average 3s = 243 MPa, Phase 2a average 3s = 278 MPa

Axial Stress
Post safe end weld



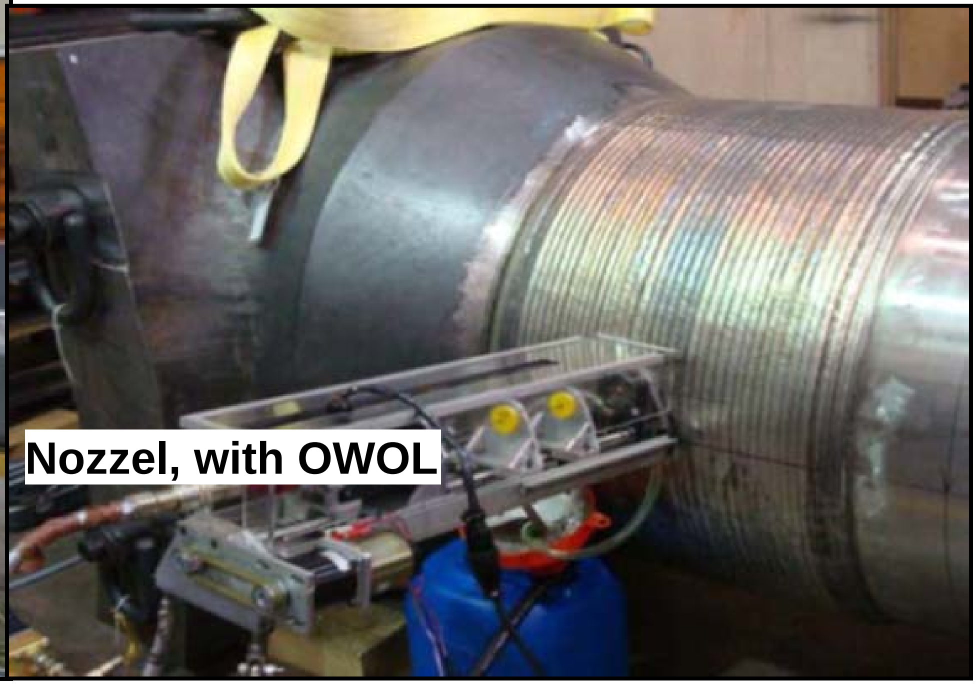
Hoop Stress
Post safe end weld



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

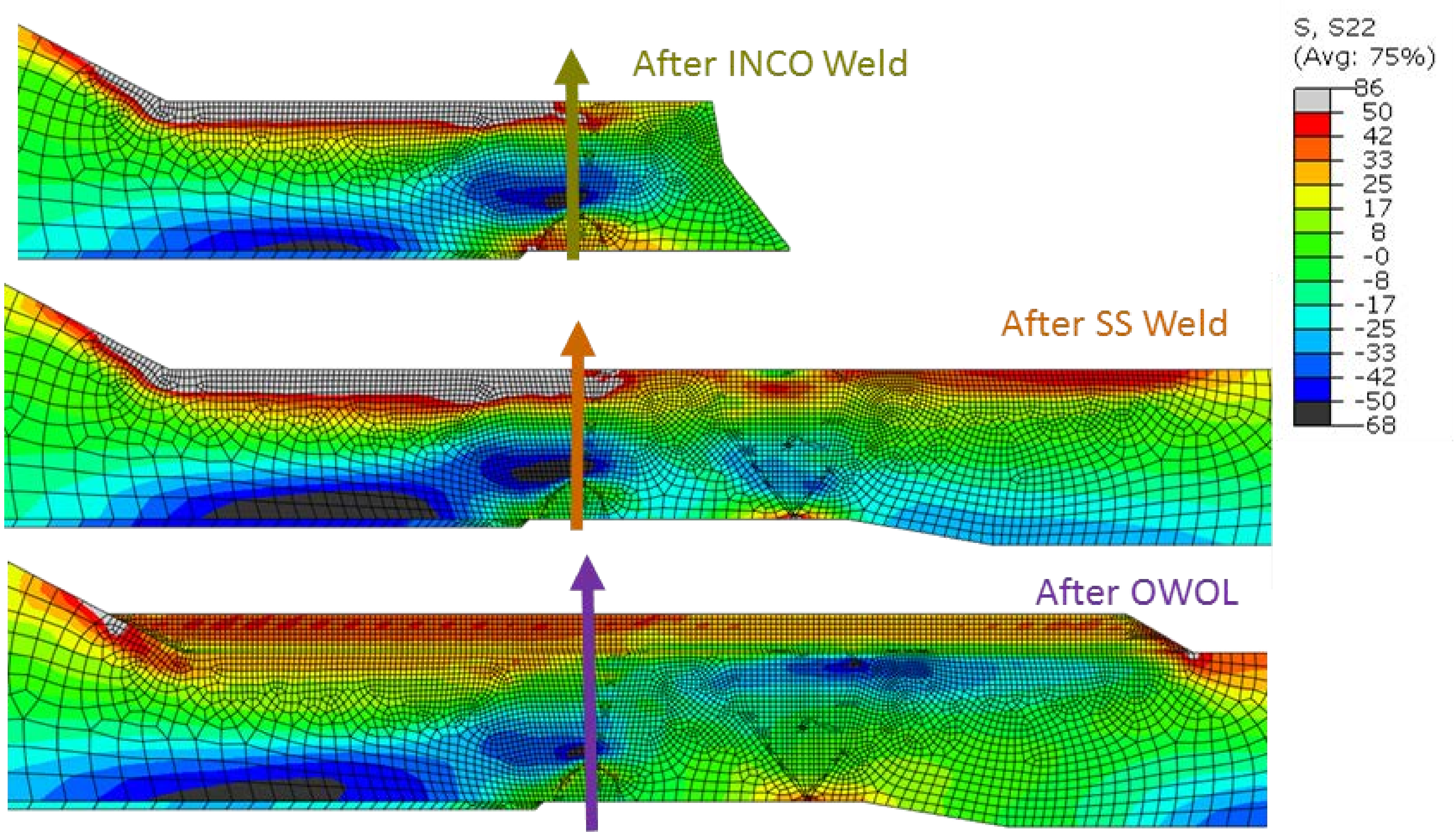
Phase 4 Weld Overlay Study

- Investigation of a mitigation technique: Optimized Weld Overlay (OWOL)



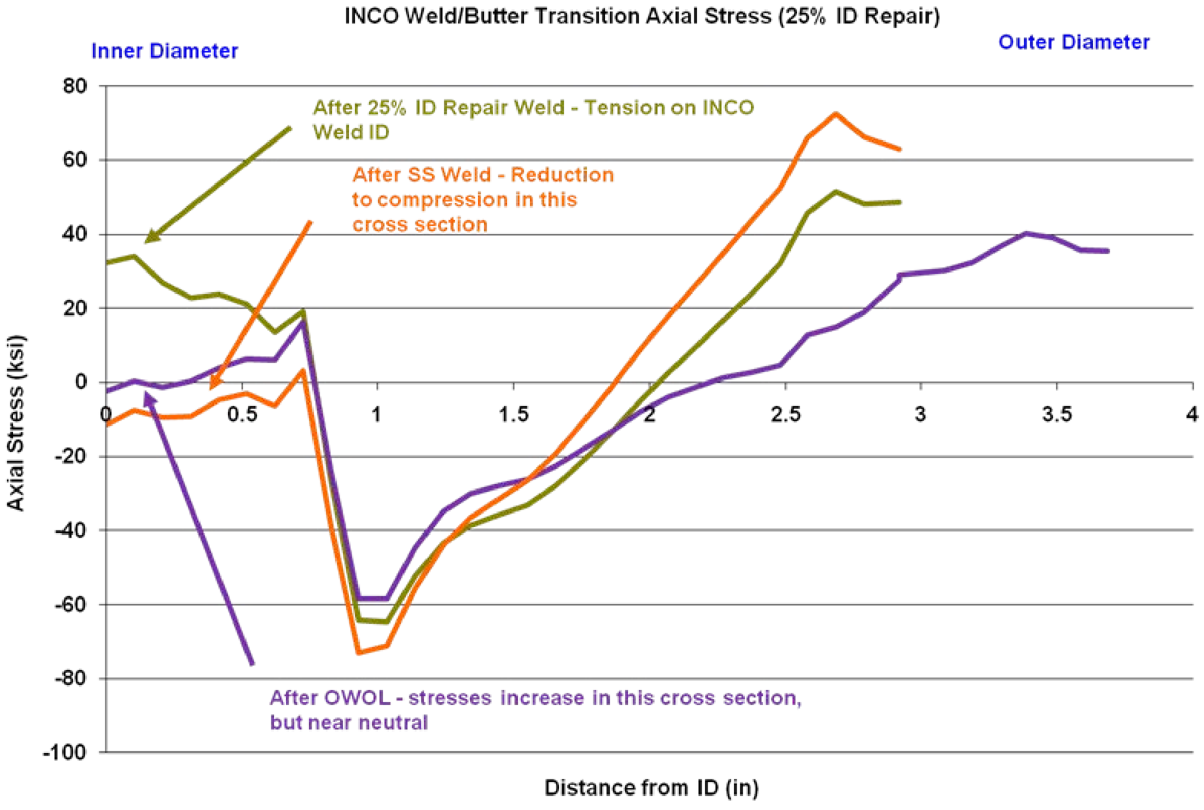
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

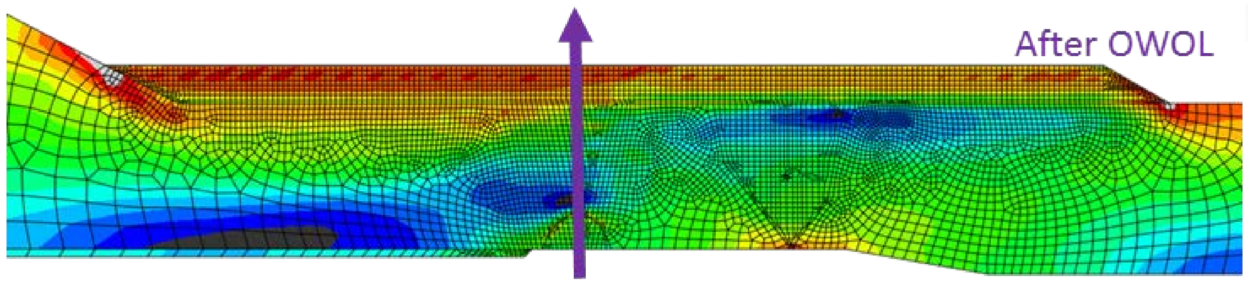
Phase 4 Example Model



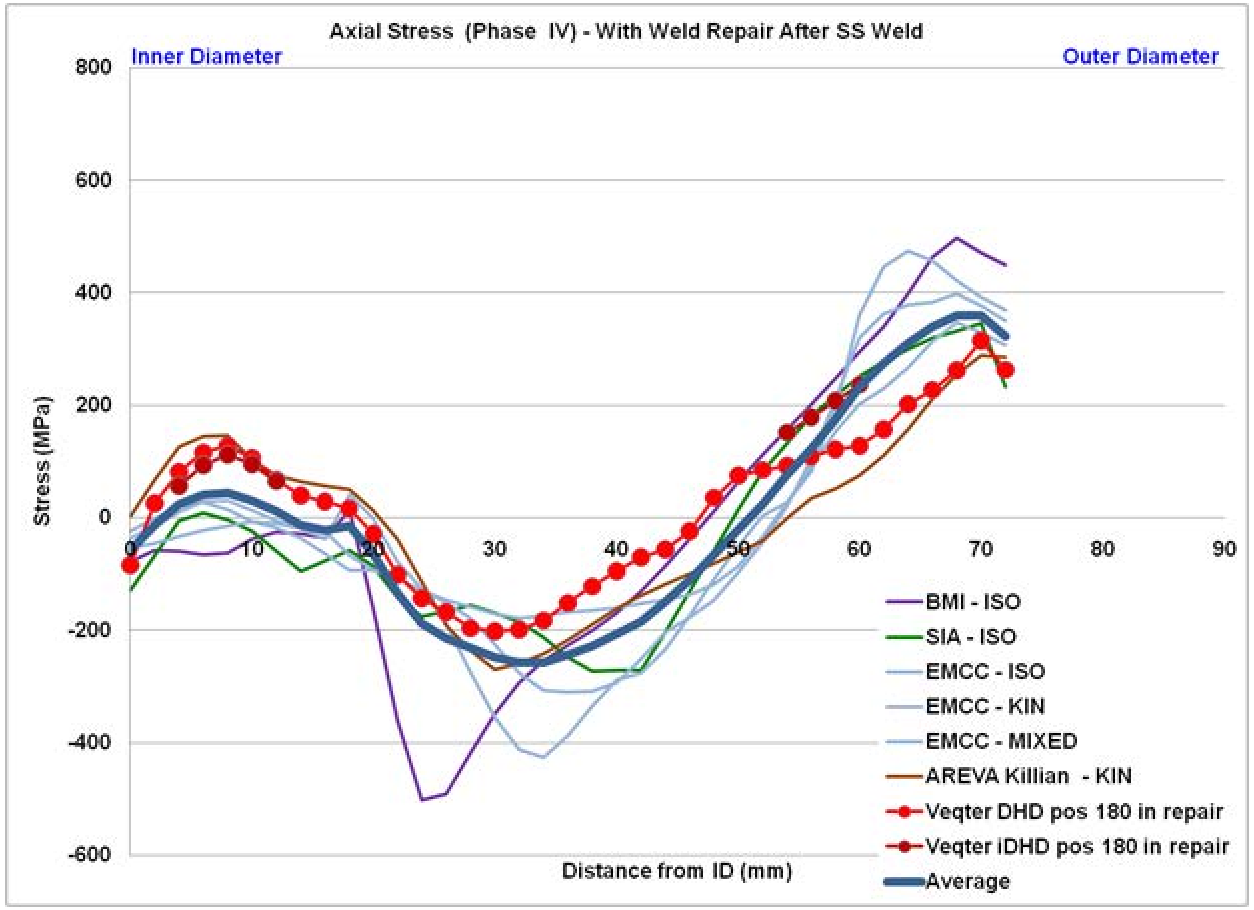
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Phase 4 Example Model





Phase 4 Round Robin Study



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

Observations from Phases 3 and 4

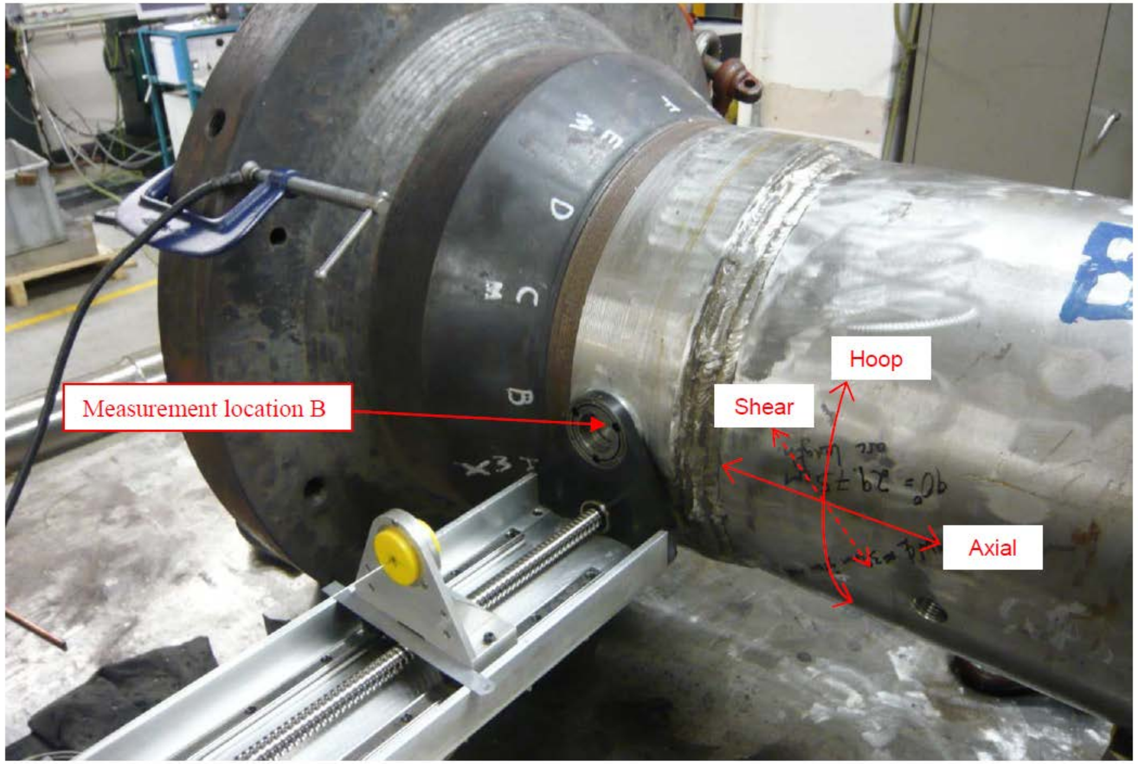
- The modeling and measurement results showed improvement of the residual stresses at the ID location after OWOL was applied

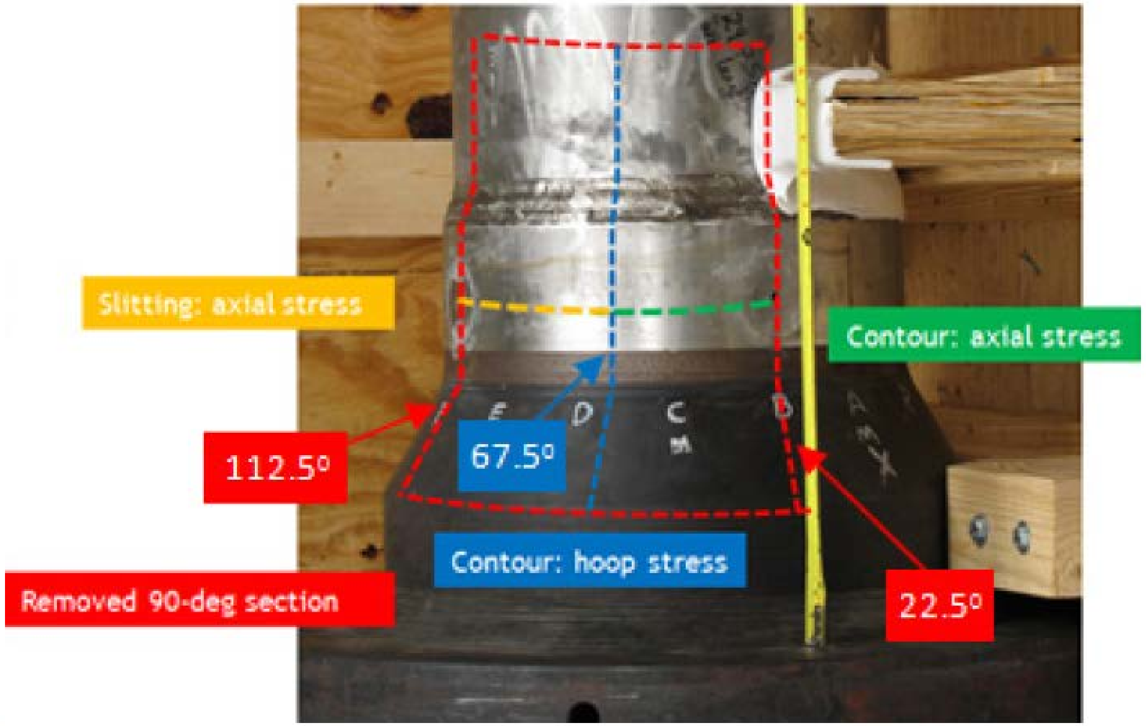
- Modeling uncertainty still exists, but general agreement between models and measurements

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

Phase 2b Mockup

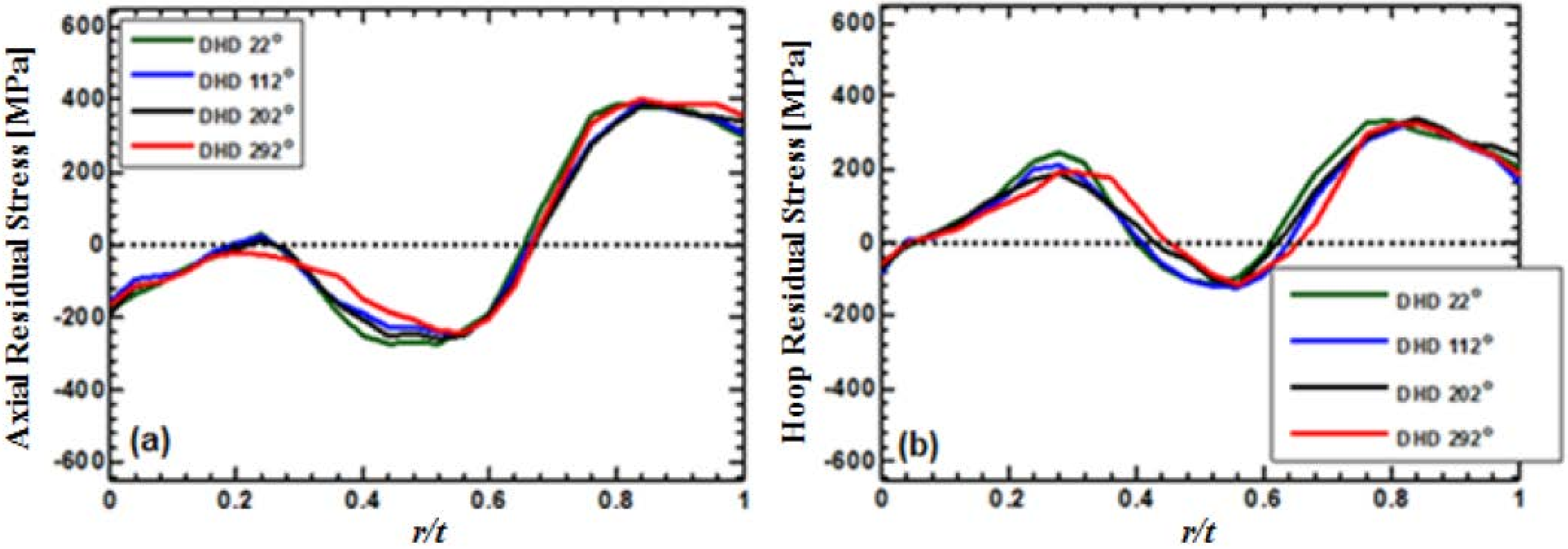
- Final mockup chronologically in the EPRI/NRC WRS program
- Last data collection effort before developing modeling and validation recommendations
- Deep hole drilling measurements, contour measurements, finite element round robin





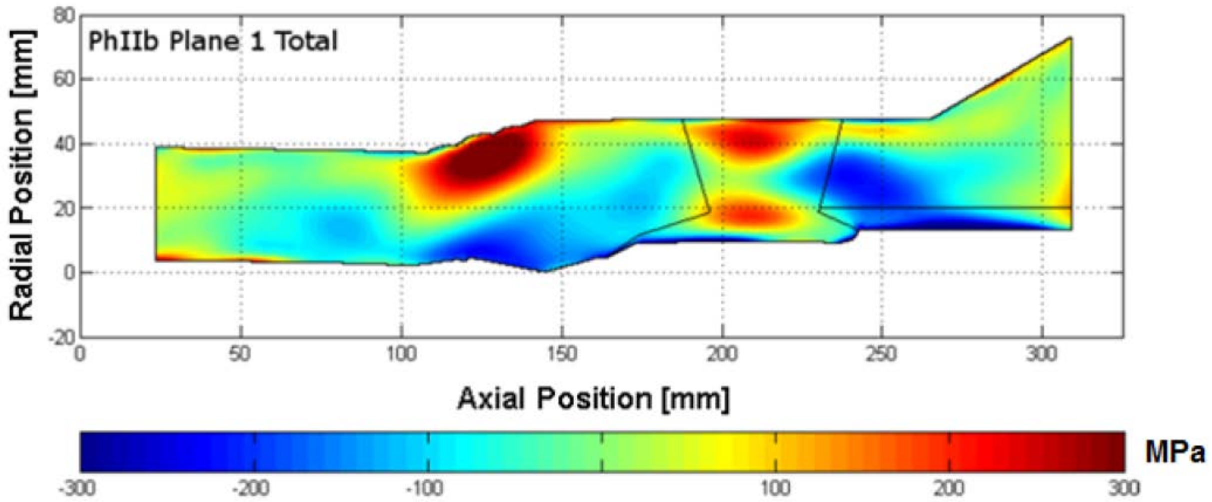
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

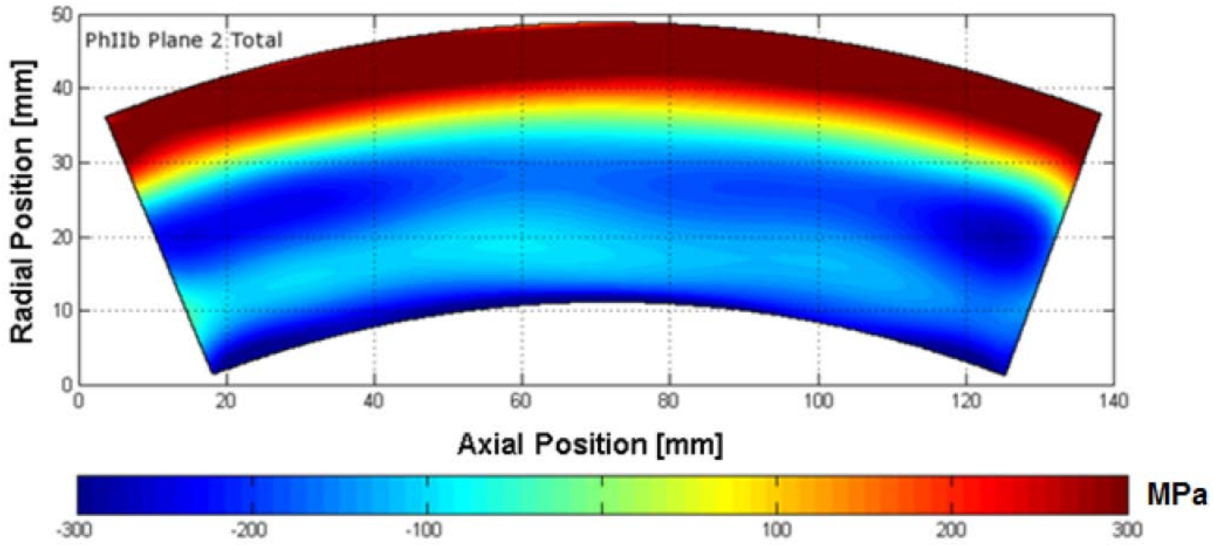
Phase 2b Measurement Results – Deep Hole Drilling



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

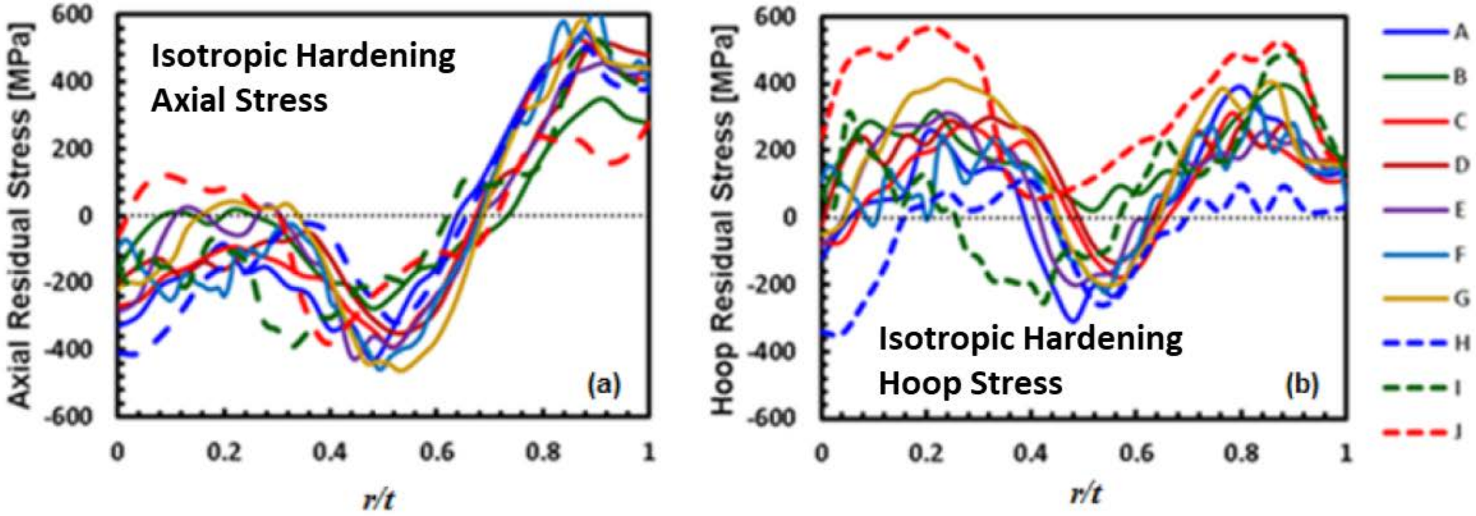
Phase 2b Measurement Results – Contour Method

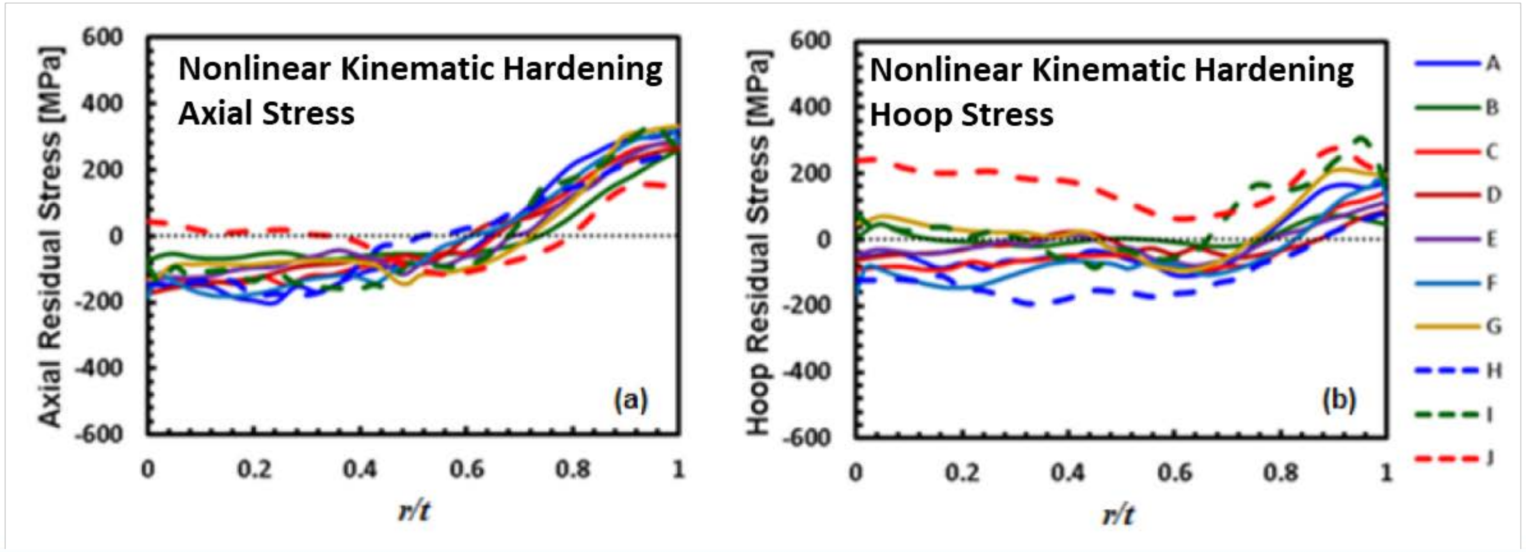




United States Nuclear Regulatory Commission
Protecting People and the Environment

Phase 2b Round Robin Results

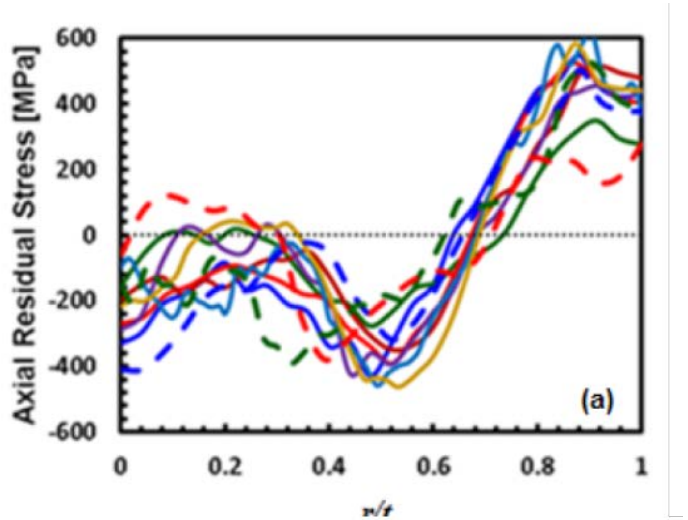


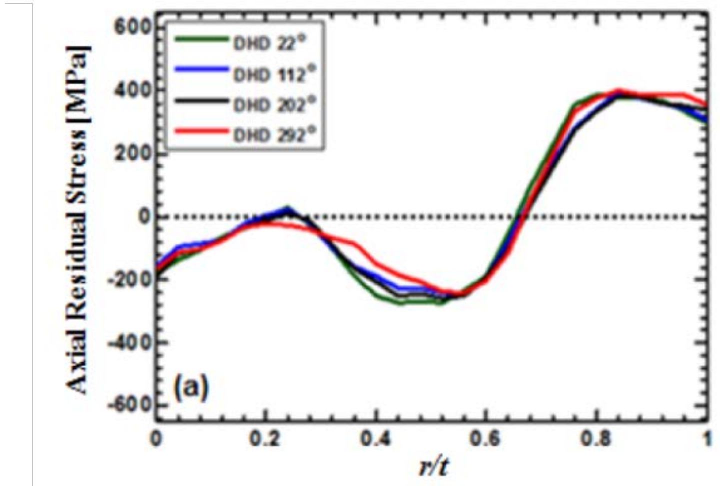


Dominion Engineering, Inc.
Oak Ridge National Laboratory
Inspecta
AREVA
KEPCO
ansto
Structural Integrity Associates, Inc.
Battelle The Business of Innovation
UC DAVIS UNIVERSITY OF CALIFORNIA
EPRI ELECTRIC POWER RESEARCH INSTITUTE
U.S.NRC United States Nuclear Regulatory Commission Protecting People and the Environment
Emc²

Phase 2b Uncertainty Quantification Project

- Uncertain models and uncertain measurements
- How do we make meaningful comparisons between the two?
- Uncertainty quantification work at Sandia National Laboratory
  - Final Report at NRC ADAMS Accession Number ML16301A055
  - Pressure Vessels and Piping Conference Proceedings Paper PVP2017-65552
  - Chapters 3 and 5 of NUREG-2228

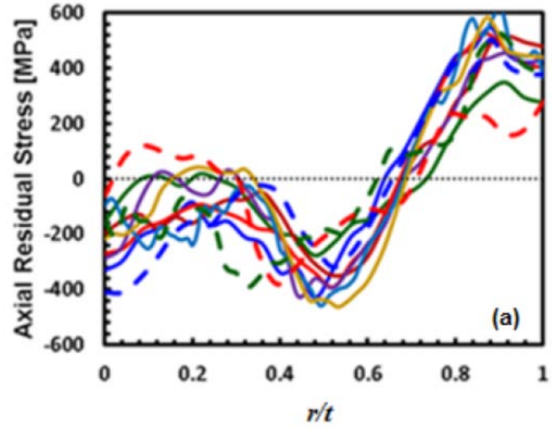




U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

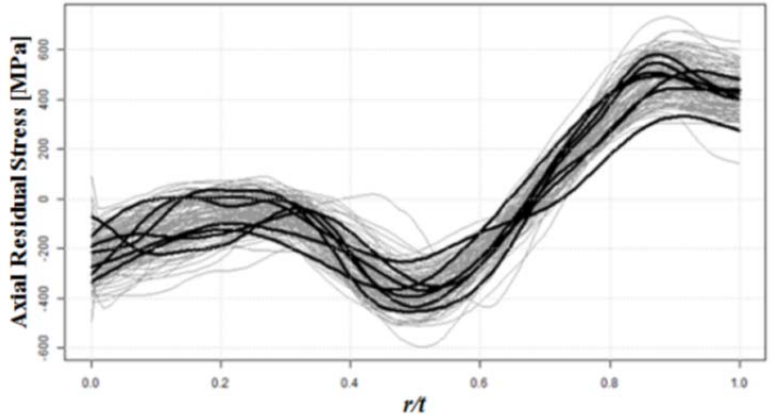
Phase 2b Uncertainty Quantification Project

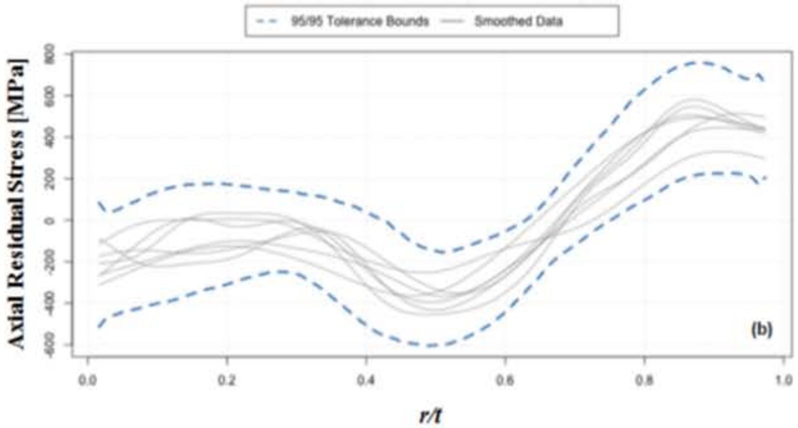
Raw Data



Statistical Modeling
Bootstrapping

Bootstrapped Samples





End result: statistical description of the data

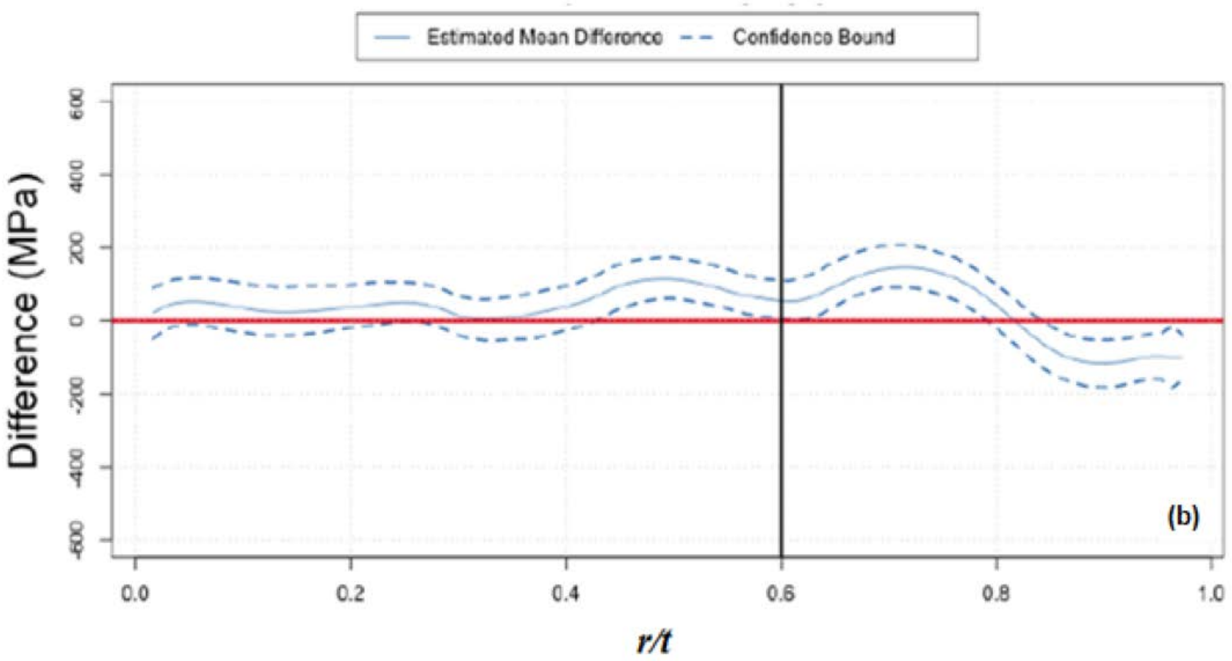
e.g., tolerance bounds and confidence bounds

Repeat for all the data, including measurements

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

Phase 2b Uncertainty Quantification Project

- With a similar bootstrapping approach, we can construct a difference in means function (i.e., mean of the measurements – mean of the models)
- Confidence bounds on the difference function
- Judgment on when a difference between the models and measurements is statistically significant



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

Recommended Modeling Guidelines

- The round robin data and subsequent statistical analysis was used to justify modeling recommendations
- Much of the guidance is based upon MRP-317, Revision 1, published by the Electric Power Research Institute, e.g.:
  - Weld bead geometry
  - Bead and process sequence
  - Element birth and death methodology for welding process modeling
  - Heat input model tuning
  - Structural and thermal boundary conditions
  - Element selection and mesh
- The NRC developed guidance on hardening law, based upon the statistical analysis (NUREG-2228)
  - Average of the isotropic and nonlinear kinematic results
  - An engineering approach to hardening law, rather than physics-based
  - The analysis indicated that the averaging approach provided improved predictions over isotropic or nonlinear kinematic alone

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

NUREG-2228 Proposal on WRS Validation Criteria

- Proposed Quality Metrics
  - Root mean square error on WRS: $RMSE_{WRS}$
  - Average difference up to the initial crack depth of interest: $diff_{avg}$
  - Developed based upon flaw growth studies

$$RMSE_{WRS} = \sqrt{\frac{1}{L}\sum_{k=1}^{L}\left(WRS_k - WRS_k^{mean}\right)^2}$$

$$diff_{avg} = \frac{1}{L_{0.1}}\sum_{k=1}^{L_{0.1}}\left(WRS_k - WRS_k^{mean}\right)$$

- Axial WRS criteria in WRS NUREG

Quality Metric	Acceptance Criteria
$RMSE_{WRS}$	≤ 55 MPa
$diff_{avg}$	≥ -15 MPa ≤ 15 MPa

- Hoop WRS criteria in WRS NUREG

Quality Metric	Acceptance Criteria
$RMSE_{WRS}$	≤ 70 MPa
$diff_{avg}$	≥ 0 MPa ≤ 65 MPa

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

Other Metrics Investigated

- D1
  - Looking at first derivative as a test for slope
  - Did not improve differentiation between 'good' and 'bad' predictions
- D2
  - Looking at second derivative as a test for concavity/convexity
  - Did not improve differentiation between 'good' and 'bad' predictions
- Truncated RMSEs
  - Calculate RMSE up to x/t = T, with 0.01<T<0.99
  - Calculation performed for T=0.1, 0.2, … , 0.9
  - No improvement
- Weighted RMSEs
  - Apply a weight function on the error to give more importance to low x/t values
  - Calculation performed for W=1, 2, 5, 10
  - No improvement

$$RMSE_{D1} = \sqrt{\frac{1}{K-2}\sum_{k=2}^{K-1}\left(D1_k - D1_k^{mean}\right)} \qquad D1_k = \left.\frac{dWRS}{dx_{norm}}\right|_k \approx \frac{1}{2h}\left(-WRS_{k-1} + WRS_{k+1}\right)$$

$$RMSE_{D2} = \sqrt{\frac{1}{K-4}\sum_{k=3}^{K-2}\left(D2_k - D2_k^{mean}\right)} \qquad D2_k = \left.\frac{dD1}{dx_{norm}}\right|_k \approx \frac{1}{4h^2}\left(WRS_{k+2} - 2WRS_k + WRS_{k-2}\right)$$

$$RMSE_{WRS}^{T} = \sqrt{\frac{1}{K_T}\sum_{k=1}^{K_T}\left(WRS_k - WRS_k^{mean}\right)}$$

$$RMSE_{D1}^{T} = \sqrt{\frac{1}{K_T-1}\sum_{k=2}^{K_T}\left(D1_k - D1_k^{mean}\right)} \qquad RMSE_{D2}^{T} = \sqrt{\frac{1}{K_T-2}\sum_{k=3}^{K_T}\left(D2_k - D2_k^{mean}\right)}$$

$$RMSE_{WRS}^{W} = \sqrt{\frac{1}{K}\sum_{k=1}^{K}\left(1-\frac{x}{t}\right)^{W}\left(WRS_k - WRS_k^{mean}\right)}$$

$$RMSE_{D1}^{W} = \sqrt{\frac{1}{K-2}\sum_{k=2}^{K-1}\left(1-\frac{x}{t}\right)^{W}\left(D1_k - D1_k^{mean}\right)} \qquad RMSE_{D2}^{W} = \sqrt{\frac{1}{K-4}\sum_{k=3}^{K-2}\left(1-\frac{x}{t}\right)^{W}\left(D2_k - D2_k^{mean}\right)}$$

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

Thoughts on a Flaw Growth Validation Approach (1/2)

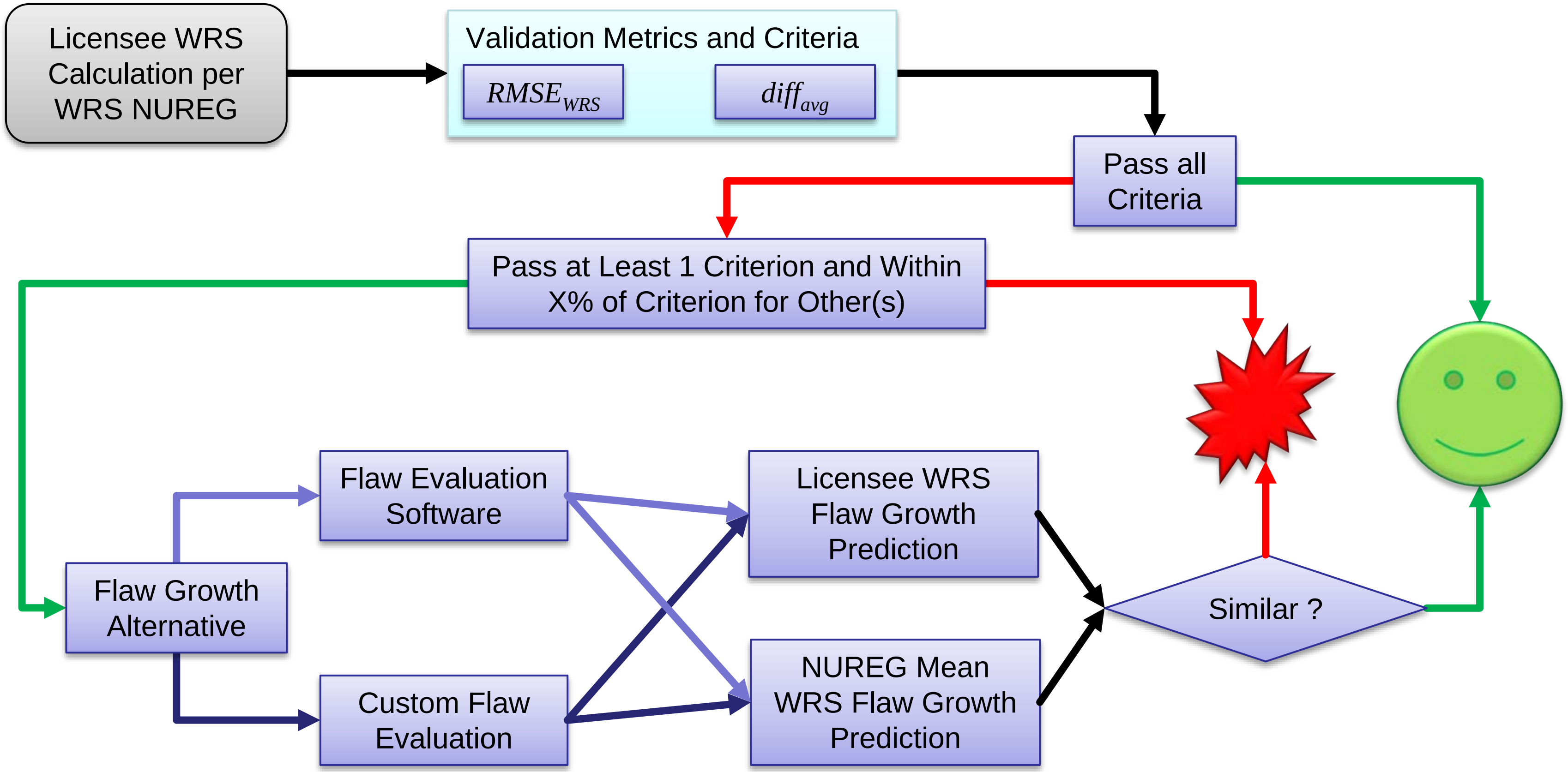
- Current proposed approach:
  - Metrics are based on WRS predictions
  - Acceptance criteria are based on results of flaw growth calculations performed by RES with FES
  - Could there be predictions that do not pass all WRS acceptance criteria but do result in adequate prediction of flaw growth?
  - Could there be predictions that do pass all WRS acceptance criteria but do not result in adequate prediction of flaw growth?

- Flaw growth behavior is ultimately what matters, and is strongly influenced by WRS
  - Could potentially use flaw growth predictions as a metric and define acceptance criteria
  - BUT
  - Flaw growth calculations can be performed in many ways, which introduces source of variability

- Flaw growth analysis could be offered as option when WRS acceptance criteria cannot all be met, but licensee's WRS predictions looks 'close' to the correct result (example: within 10% or 25% or proposed acceptance limits, TBD)
  - Let licensee use their preferred flaw growth method on both the mean prediction in the NUREG and their prediction, for equal comparison
    - Harder to validate licensee calculations, potential disagreements with methods or constants employed
  - OR
  - Impose that licensee use FES to perform flaw growth calculation based on their predicted WRS
    - Easy to validate, less potential variation, can fix loads and other crack growth constants

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

Thoughts on a Flaw Growth Validation Approach (2/2)



WRS Modeling in Nuclear Applications: NRC Evaluation Tools

Flaw Evaluation Software (FES)

- Deterministic code that analyzes time to leak or rupture for SCC piping flaws
- WRS added to operating stresses
- Internal NRC Code

Extremely Low Probability of Rupture (xLPR)

- PFM piping code that assesses leakage and rupture probabilities for SCC and fatigue cracks
- WRS distributions used in analysis
- More information: NUREG-2247

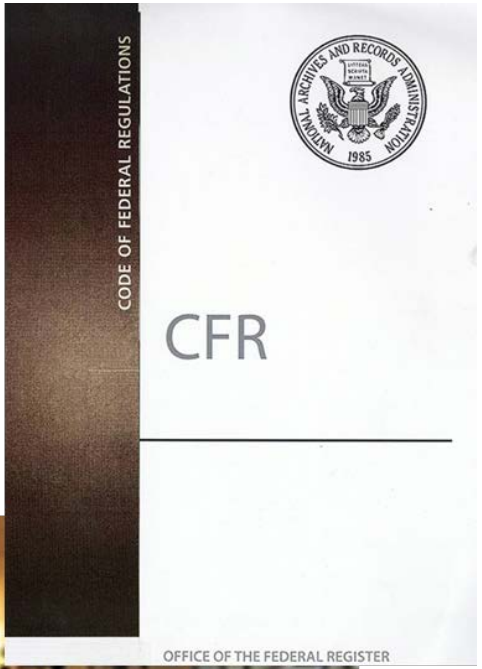
Fracture Analysis of Vessels, Oak Ridge (FAVOR)

- PFM RPV code that assesses crack initiation and through wall cracking frequencies
- Residual stresses from RPV cladding incorporated deterministically
- More information: Theory and User manuals

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

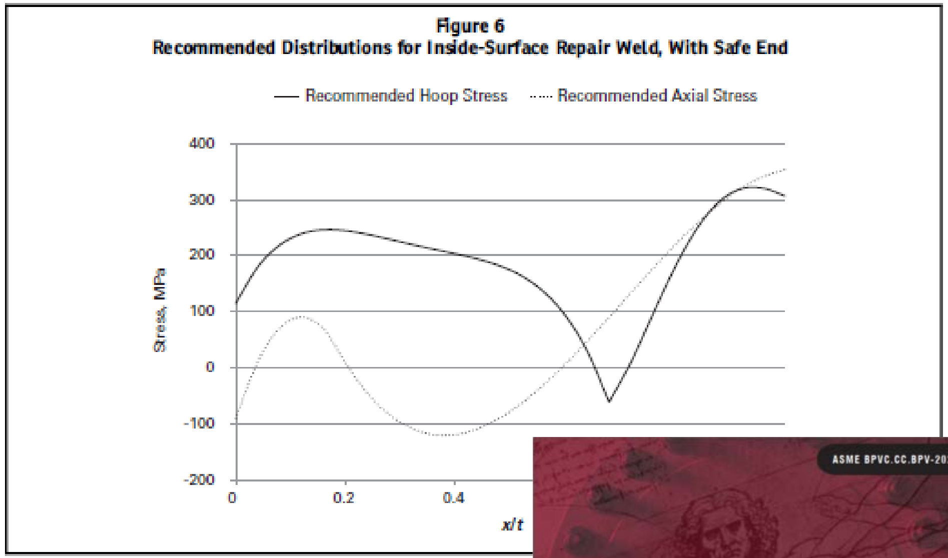
WRS Modeling in Nuclear Applications: NRC's Regulatory Evaluations

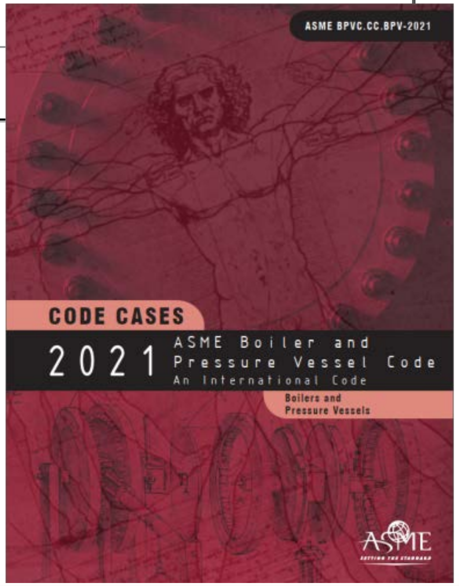
- Evaluate acceptability of proposed ASME Code modifications related to repair, inspection, and other mitigation techniques for safety significant systems, structures, and components.
  - Use NUREG-2228 acceptance criteria proposed as a condition to accepting ASME CC N-847, Evacuate and Weld Repair Technique for SCC Mitigation.
    - Confirm appropriateness of requests for regulatory relief of existing requirements (e.g., inspection periodicity, coverage, or acceptance criteria).
    - Evaluate significance of emergent issues, usually related to service-induced degradation found during required inspections.
  - NUREG-2228 incorporated by reference in 10 CFR 50.55a



WRS Modeling in Nuclear Applications: ASME Code

- Code Case (CC) N-899: WRS for Ni-based Alloy Butt Welds
  - Scope
    - Full penetration, single-V dissimilar metal welds (DMWs)
    - Weld thickness between 32 and 102 mm
    - No outside surface weld repairs
  - Level I: Yield level, constant through-wall hoop and axial stresses
  - Level II: Predetermined WRS distributions for applicable welds (with and without safe ends)
    - Machined surface
    - Back gouged and rewelded
    - Inside surface repair
  - Level III: WRS calculation using FEA
    - Methodology used to calculate WRS distribution should be verified and validated
    - NUREG-2228 methodology could be considered for V&V acceptance criteria
- Examples of other relevant CCs (not inclusive)
  - N-694-2: Evaluation procedure and acceptance criteria for PWR RPV penetration nozzles
  - N-770: Alternate examination requirements for DM butt weld
  - N-881: Exempting SA-508 Grade 1A from PWHT based on WRS measurement
  - N-897: Analytical evaluation procedures for axial flaws in partial penetration nozzle welds

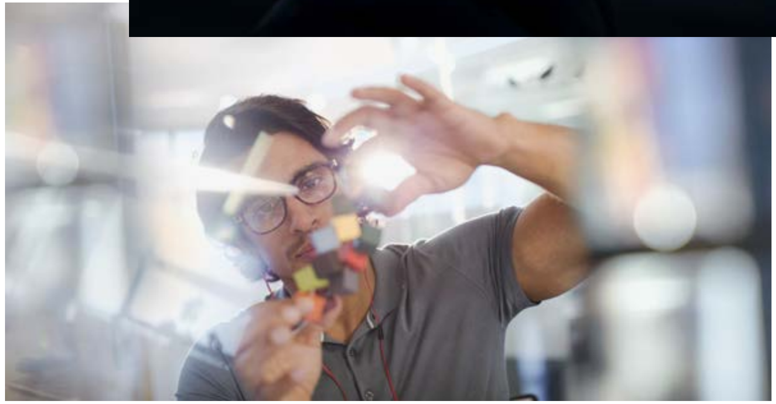




WRS Modeling in Nuclear Applications: Possible Future Directions

- Continue to monitor and evaluate best practices in other industries and throughout relevant codes and standards
- Implement and refine acceptance criteria in relevant applications
  - Consider incorporating best practices
  - Gather stakeholder feedback
  - Pilot guidance in hypothetical or actual nuclear applications
  - Continue sensitivity analyses to examine significance of deviations on crack growth rate
- Expand technical basis beyond initial DMW scope
  - Evaluate different weld joint configurations
  - Consider other safety-significant nuclear piping systems
  - Expand to other common weld and base materials (e.g., carbon, LAS, stainless steel)


Photo by Drew Beamer on Unsplash



Conclusions

- NRC, in conjunction with nuclear industry and other partners, conducted extensive, ≈ decade-long WRS measurement and modeling program
  - Representative nuclear-specific dissimilar metal weld joint configurations
  - Phase I: Experimental measurement
  - Phase 2: Validate modeling approaches and assess modeling uncertainties
  - Phases 3 & 4: Validate using plant components and assess mitigation effects
- Modeling guidance developed based on results from WRS program
  - Modeling best practices for inputs, boundary conditions, mesh refinement and weld bead geometry
  - Guidance for material properties, specifically material hardening law
- Proposed guidance for verification and validation of weld-specific WRS models
  - Three unique acceptance criteria or quality metrics
  - Considering coupling with flow growth evaluations to assess sensitivity of metrics for specific applications
- Implement and refine proposed guidance as experience is gained and additional best practices are evaluated