ELECTRIC POWER RESEARCH INSTITUTE

EPRI Welding Residual Stress Measurement and Model Validation Project

US NRC Workshop on LBB in PWSCC Systems
Rockville, Maryland
Thursday, January 10, 2008

Glenn White
John Broussard
Dominion Engineering, Inc.

Paul Crooker
EPRI

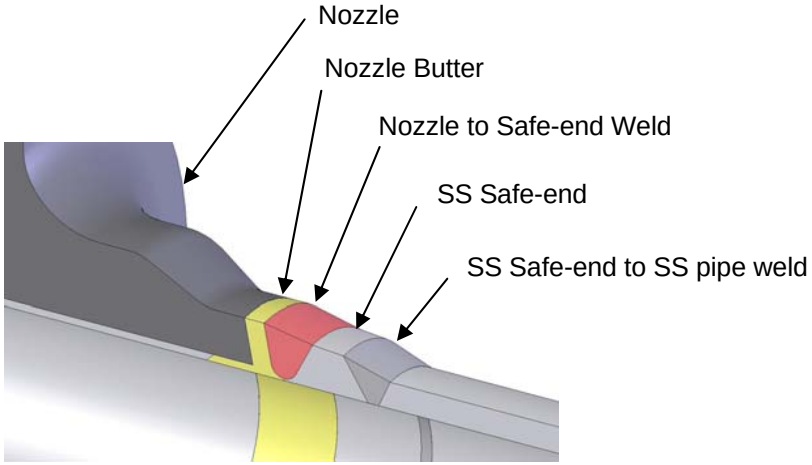
Topics

- Background
- Project Objectives
- Project Plan
  - Background Investigations
  - Fabrication and Test Matrix
  - WRS Modeling Development
  - Prototypical Mockup Development
- Project Deliverables
- WRS Benchmarking Example—NESC III Study
- Project Status

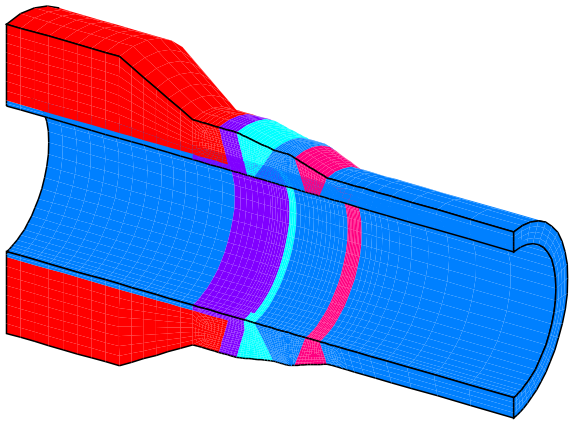
© 2008 Electric Power Research Institute, Inc. All rights reserved.

Background
Technical Perspective

- Welding residual stress (WRS) predictions in combination with fracture mechanics calculations are used extensively in evaluations of PWR pressure boundary components
- Knowledge gaps exist in current WRS prediction methods
  - Measured stresses from BWR piping
  - FEA models not fully validated
- Recent flaw evaluations for pressurizers demonstrated sensitivity of predicted crack growth to WRS
- Data needed to confirm modeling assumptions



Nozzle Dissimilar Metal Butt Weld



FEA Model of DM Butt Weld

© 2008 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Background
Industry Perspective

- Intense efforts to refine fracture mechanics analyses of DM welds recently performed in response to the PZR nozzle inspection findings at Wolf Creek
  - Included initial efforts to validate DM weld models
- Industry MRP-139 examination schedules are being implemented for additional sets of piping DM butt welds beyond the PZR nozzles
- Refined FEA methods and WRS validation are part of the industry's proactive approach to address materials degradation

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Background
Industry Perspective (cont'd)

- Better understanding of uncertainties needed to avoid unnecessary overconservatism in modeling assumptions
  - Through-wall stress distributions
  - Extent of axisymmetry of welding residual stress patterns

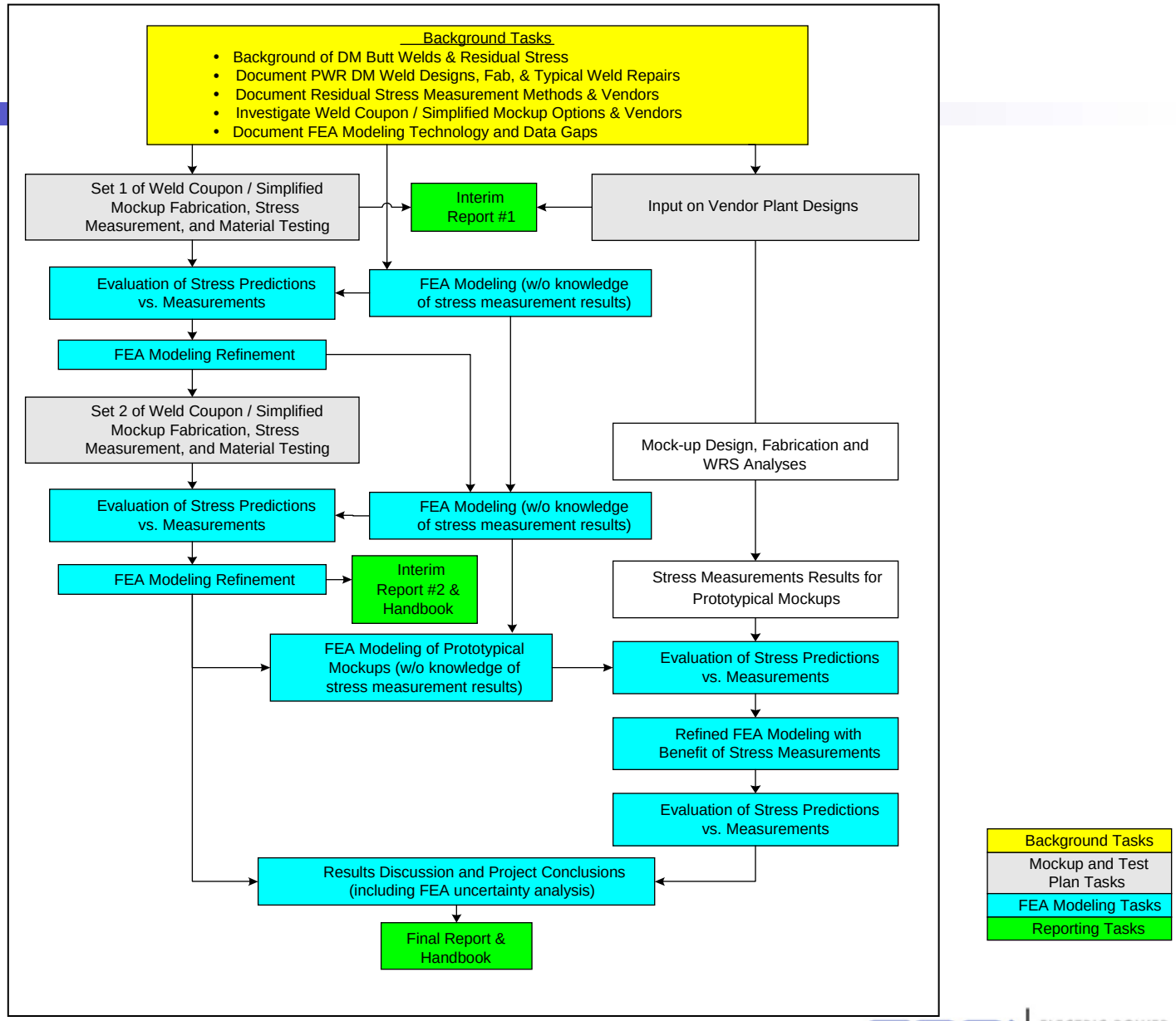
© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Objectives

- Provide validated FEA methods for future use
- Use prototypic dissimilar metal welds and components
- Maximize measurement accuracy through multiple measurements at the surface, slightly sub-surface, and through-wall thickness
- Reduce uncertainty in the FEA calculations by validating models against measured residual stresses
- Establish agreement that WRS FEA analytical methods are:
  - Validated
  - Scaleable
  - Transferable to different plant geometries

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Flow Chart and Plan



© 2008 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Project Plan
Research on Welding Fabrication and Residual Stress

- Document typical PWR DM weld design and fabrication
  - Build on work done for pressurizers in 2007
- Investigate residual stress measurement methods and vendors
  - Identify expertise in various measurement techniques for project guidance
- Investigate weld coupon / simplified mockup fabrication
  - Initial focus on simpler mockups to provide cost-effective samples for measurement and modeling
- Document FEA methodology knowledge gaps
  - Initial areas of focus when comparing measured residual stresses to predicted

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Plan
Develop and Implement Fabrication and Test Matrix

- Results of background research will be used to develop initial Phase 1 test matrix
  - Weld samples fabricated and evaluated for residual stress as well as material properties
  - Initial matrix will be about half of total planned number of samples
  - Measured stresses will be compared across methods and compared to analytical model predictions
- Second round of Phase 1 testing will be planned using knowledge developed from initial test matrix

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Plan
WRS Analytical Model Areas of Focus

- Material hardening parameters
  - Elastic-perfectly plastic hardening for weld material
    - Avoids unrealistic stress predictions from isotropic hardening observed in ANSYS
    - Predicted strains are not realistic
  - Researchers have investigated a variety of hardening behaviors
    - Isotropic hardening with annealing parameters
    - Kinematic hardening
  - Other thermophysical and mechanical properties are reasonably well characterized

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Plan
WRS Analytical Model Areas of Focus (cont'd)

- Weld deposition methodology
  - Physical simulation of weld deposition is complicated by needing to define entire model prior to analysis
    - Element birth/death used to "activate" successive weld passes
  - Three dimensional weld deposition as opposed to 2-D planar or axisymmetric modeling
  - Lumping of individual passes into layers or blocks of weld material treated as a single weld pass
  - Geometry of "weld pass" cross section
    - Squared geometries less realistic but simplify complex operations such as repairs

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Plan
WRS Analytical Model Areas of Focus (cont'd)

- Thermal analysis methodology
  - Idealized temperature model uses arbitrary heat inputs to reach reasonable weld bead and HAZ temperatures
    - Simplification generally produces reasonably accurate stress values
    - Cannot capture effect of varying weld process parameters
  - Other models use weld process specifications as inputs to determine heat generation and duration in thermal model

© 2008 Electric Power Research Institute, Inc. All rights reserved.

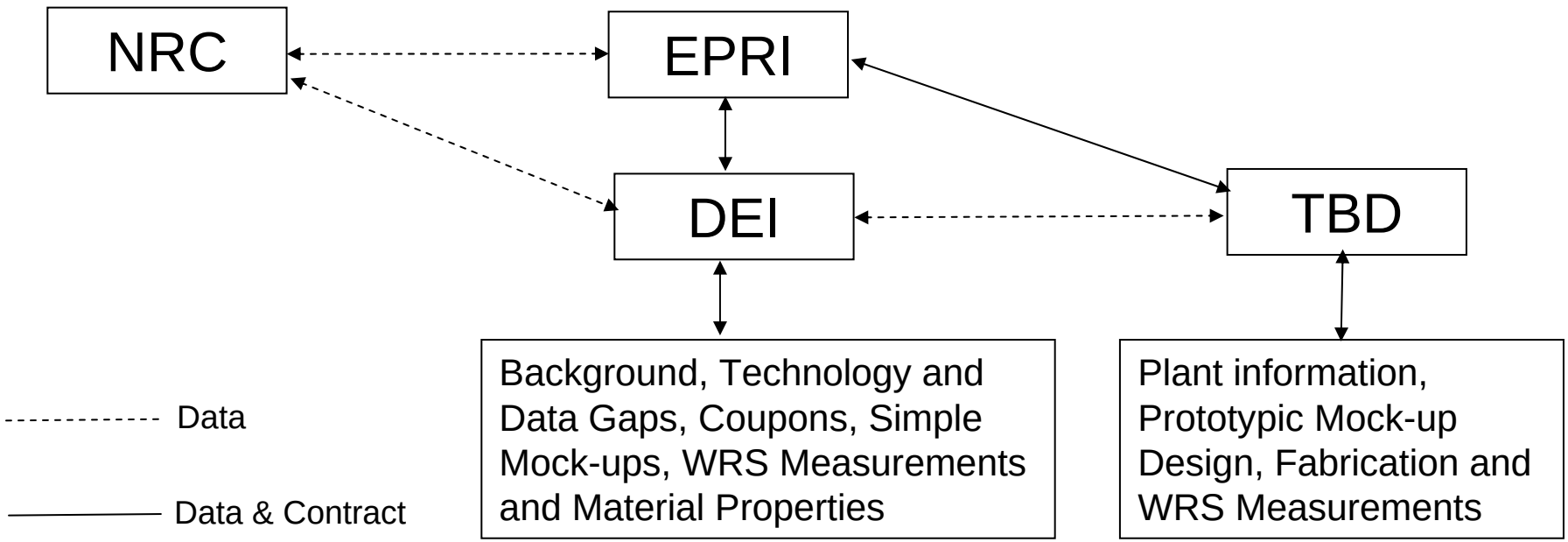
Project Plan
Prototypical Mockup Development

- A prototypical mockup of a plant nozzle DM weld geometry will be evaluated in Phase 2
  - Fabrication process and materials will be representative of actual plant fabrication
- Measured residual stresses will be compared to predicted values as final validation of analytical predictions

© 2008 Electric Power Research Institute, Inc. All rights reserved.

Project Structure

Sharing of Data with US NRC Research Program



Structure to share (where possible) data, coupons, mock-ups, methods, expand parameter range, provide data checks, etc., while allowing focus on independent needs.

© 2008 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Project Deliverables

- **Interim and Final Reports**

  Project methodology, inputs, results, and conclusions

- **WRS FEA Modeling Handbook**

  An Industry guide to the use of FEA methods in calculation of WRS for PWR components. This handbook will including descriptions of representative models, specific examples and data packages, and material on model benchmarking activities.

© 2008 Electric Power Research Institute, Inc. All rights reserved.

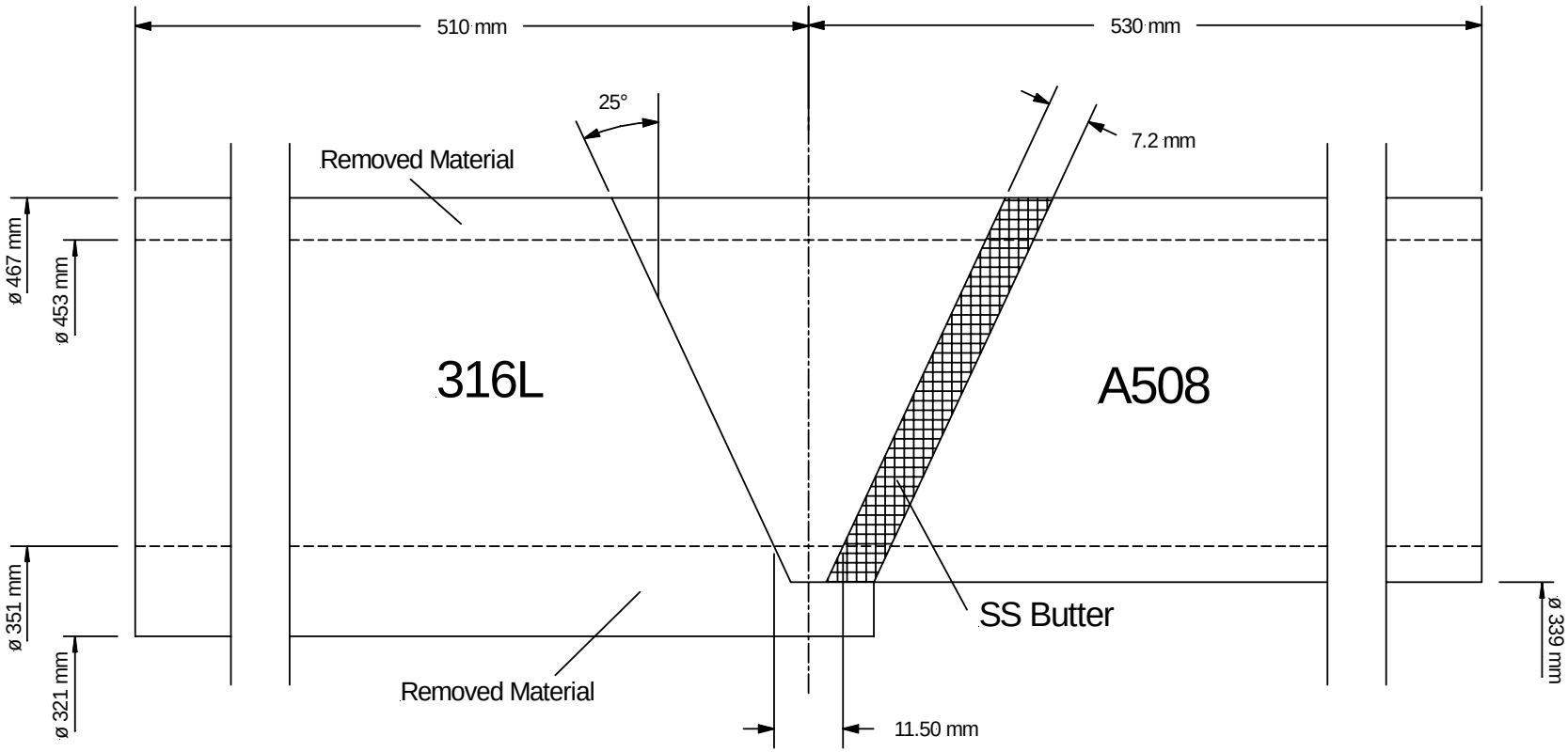
WRS Validation and Benchmarking Example
NESC III Round Robin Study

- Welding residual stress model was validated using results of NESC III round robin study
  - EU study with measured residual stresses compared to vendor FEA results
  - Stainless steel DMW joining stainless to low-alloy steel
- DEI validation performed using same materials and methods as pressurizer work
  - Butter weld deposition not simulated
  - Weld passes lumped into about 20 layers

© 2008 Electric Power Research Institute, Inc. All rights reserved.

WRS Validation and Benchmarking Example

NESC III Mockup Sketch

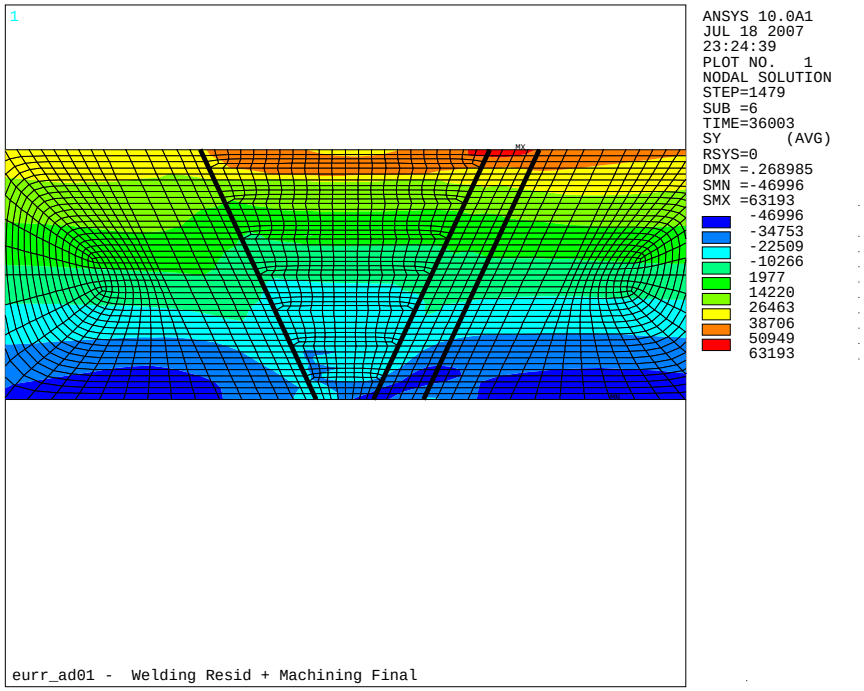


© 2008 Electric Power Research Institute, Inc. All rights reserved.

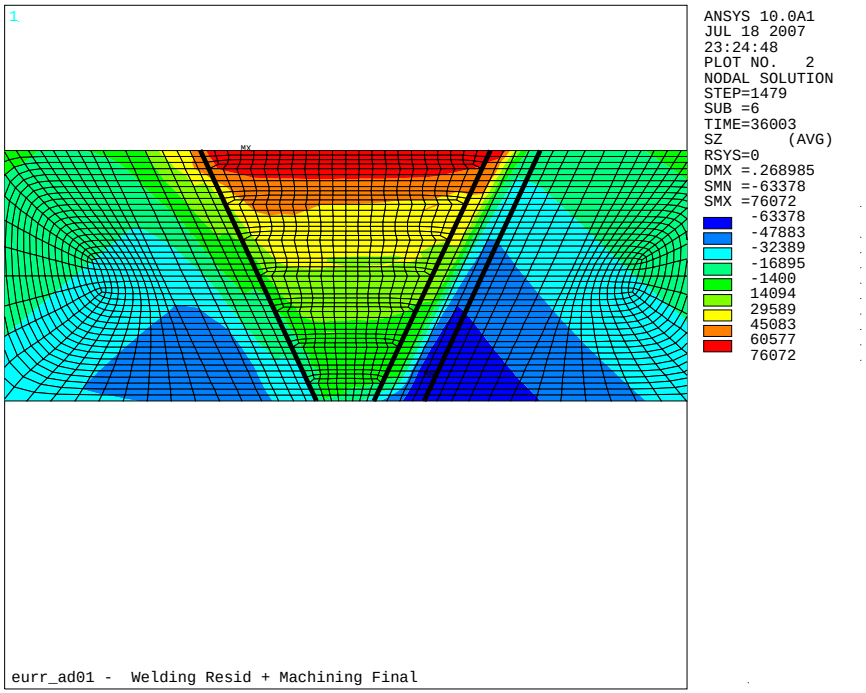
ELECTRIC POWER RESEARCH INSTITUTE

WRS Validation and Benchmarking Example

Final Machining Residual Stresses



Axial Stress



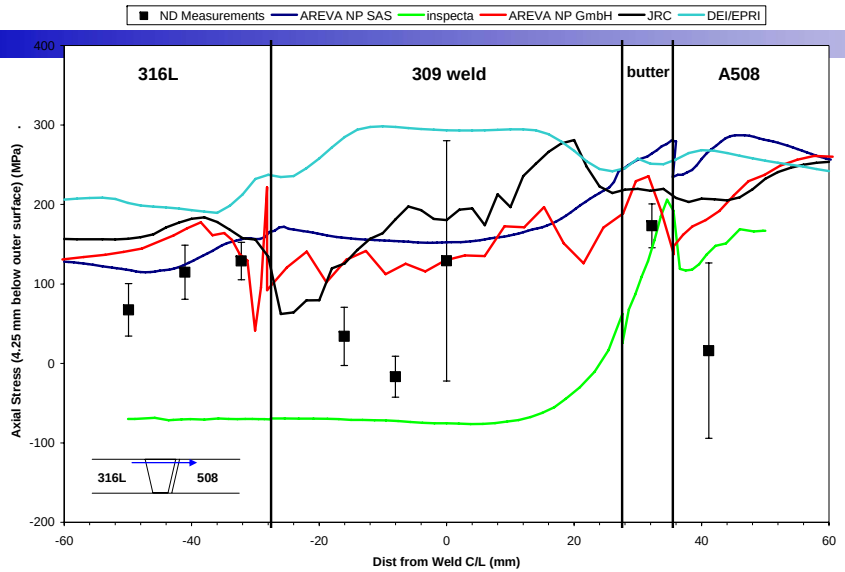
Hoop Stress

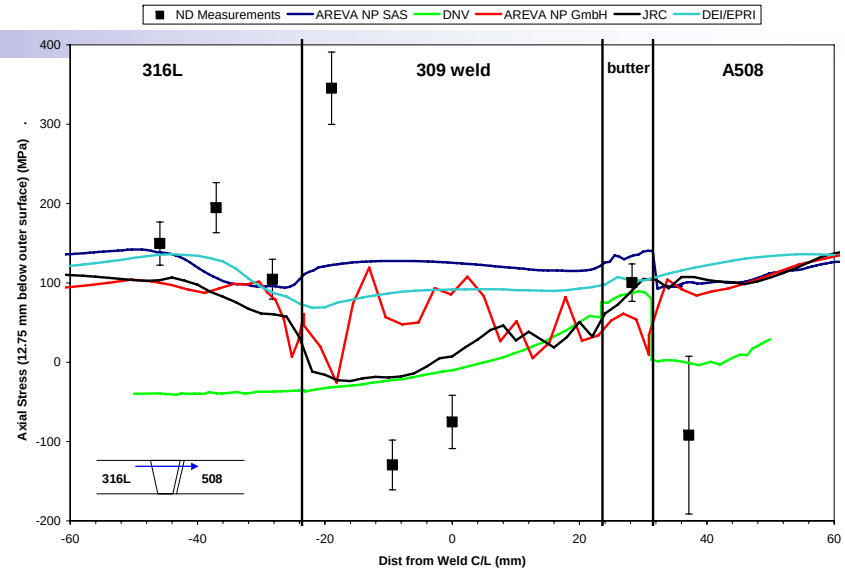
© 2008 Electric Power Research Institute, Inc. All rights reserved.

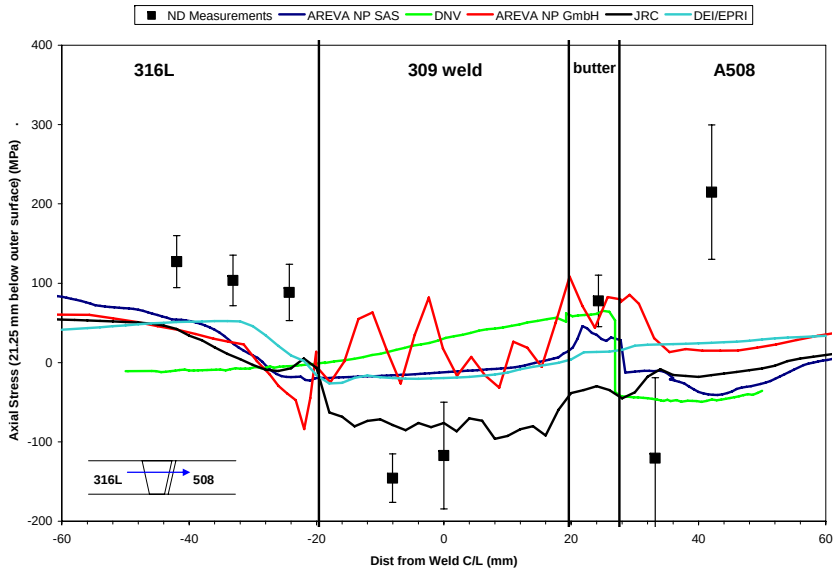
ELECTRIC POWER RESEARCH INSTITUTE

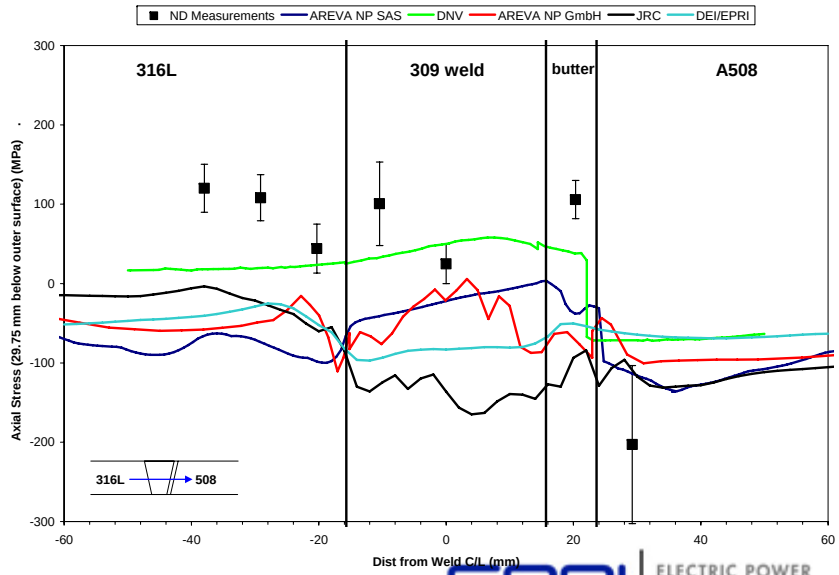
WRS Validation and Benchmarking Example

NESC III and DEI Axial Stress Results at Horizontal Cuts







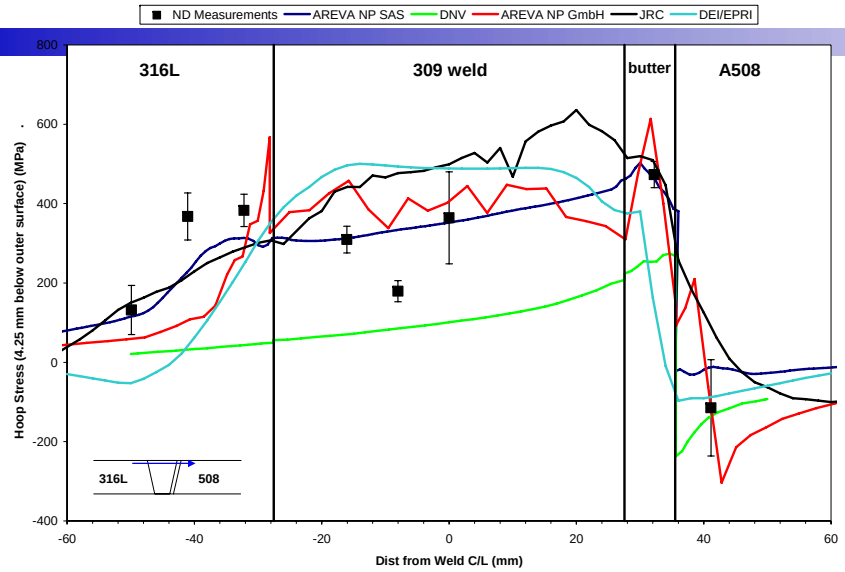


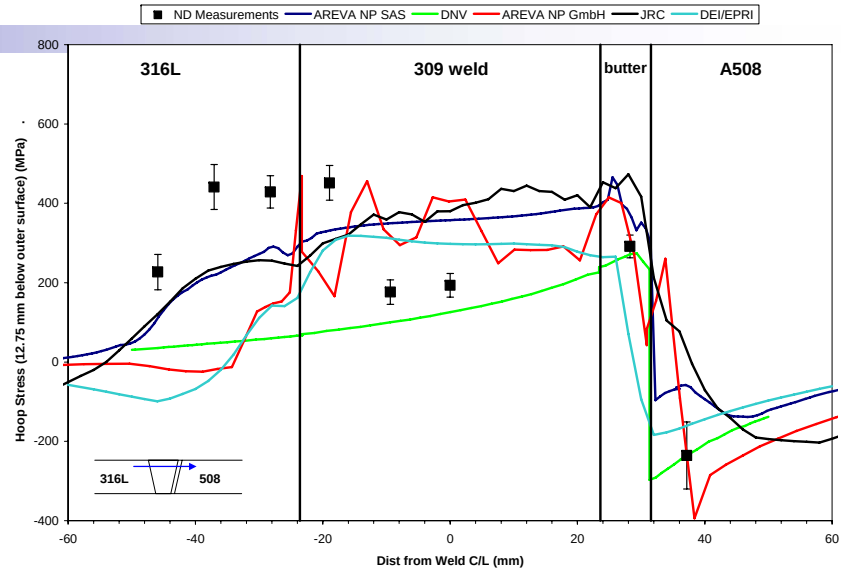
© 2008 Electric Power Research Institute, Inc. All rights reserved.

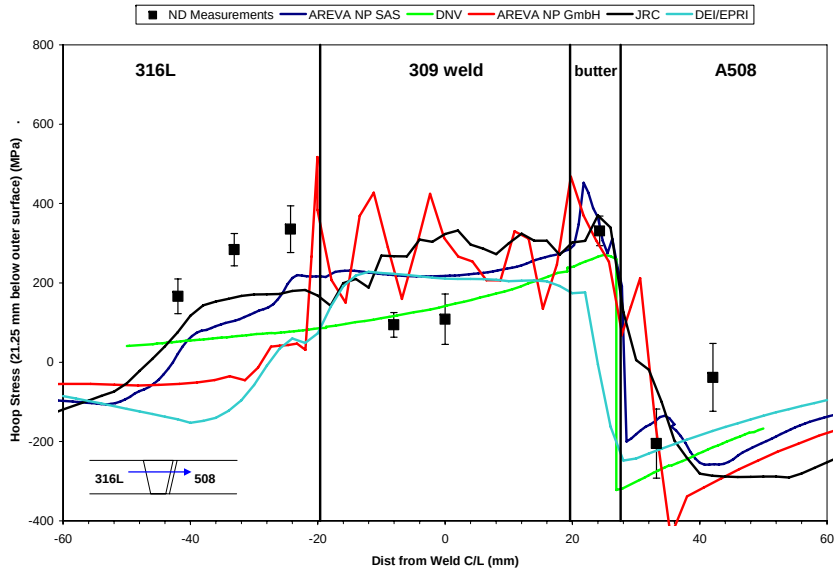
ELECTRIC POWER RESEARCH INSTITUTE

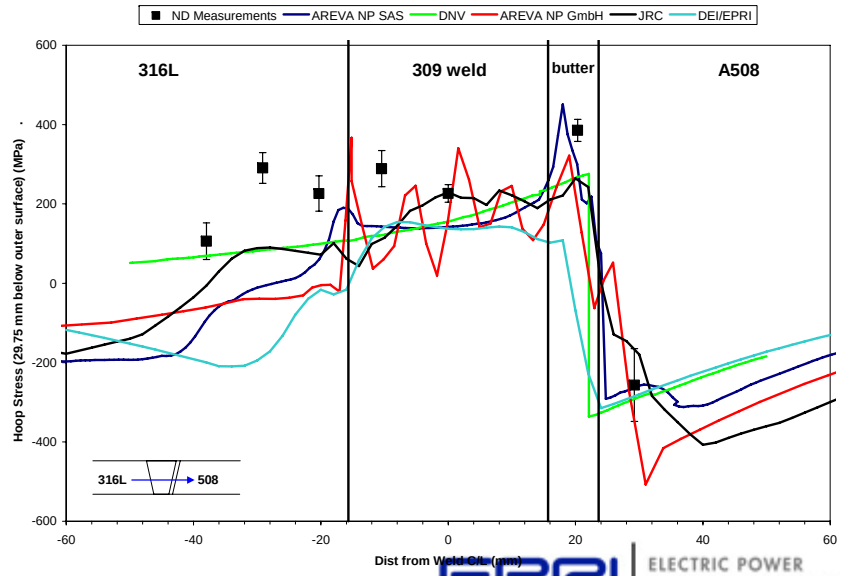
WRS Validation and Benchmarking Example

NESC III and DEI Hoop Stress Results at Horizontal Cuts







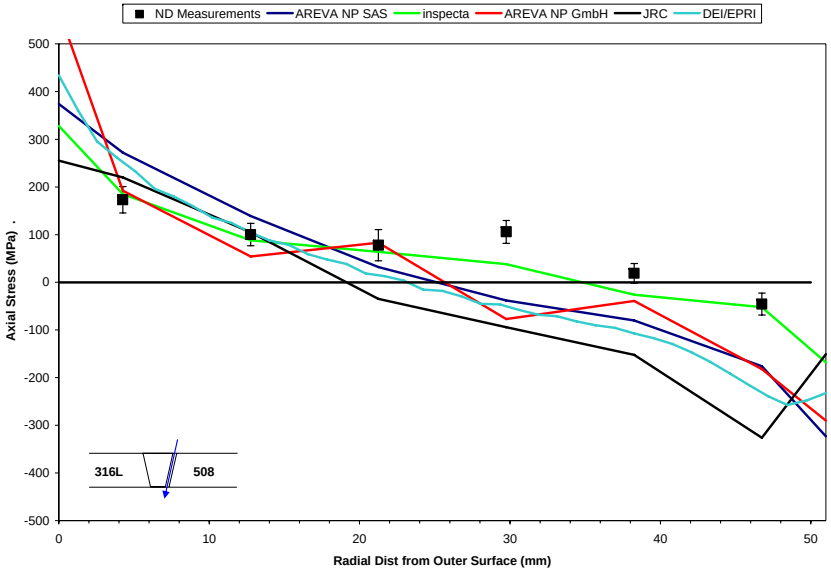


© 2008 Electric Power Research Institute, Inc. All rights reserved.

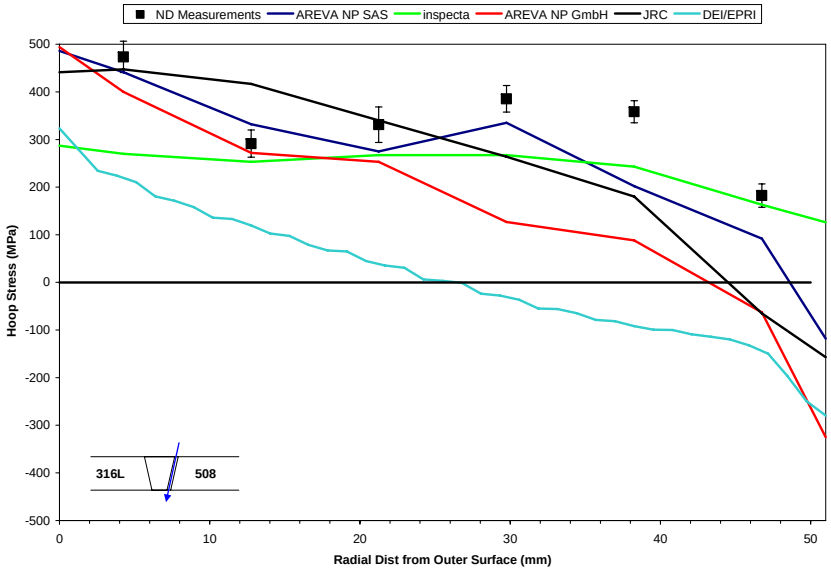
ELECTRIC POWER RESEARCH INSTITUTE

WRS Validation and Benchmarking Example

NESC III and DEI Butter Stress (Through-Wall Section at Butter Layer Center)



Axial Stress



Hoop Stress

© 2008 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Project Status

- Project formally initiated on January 1, 2008
- Phase 1 scheduled for completion end of 2008
- Phase 2 scheduled for completion September 2009

© 2008 Electric Power Research Institute, Inc. All rights reserved.