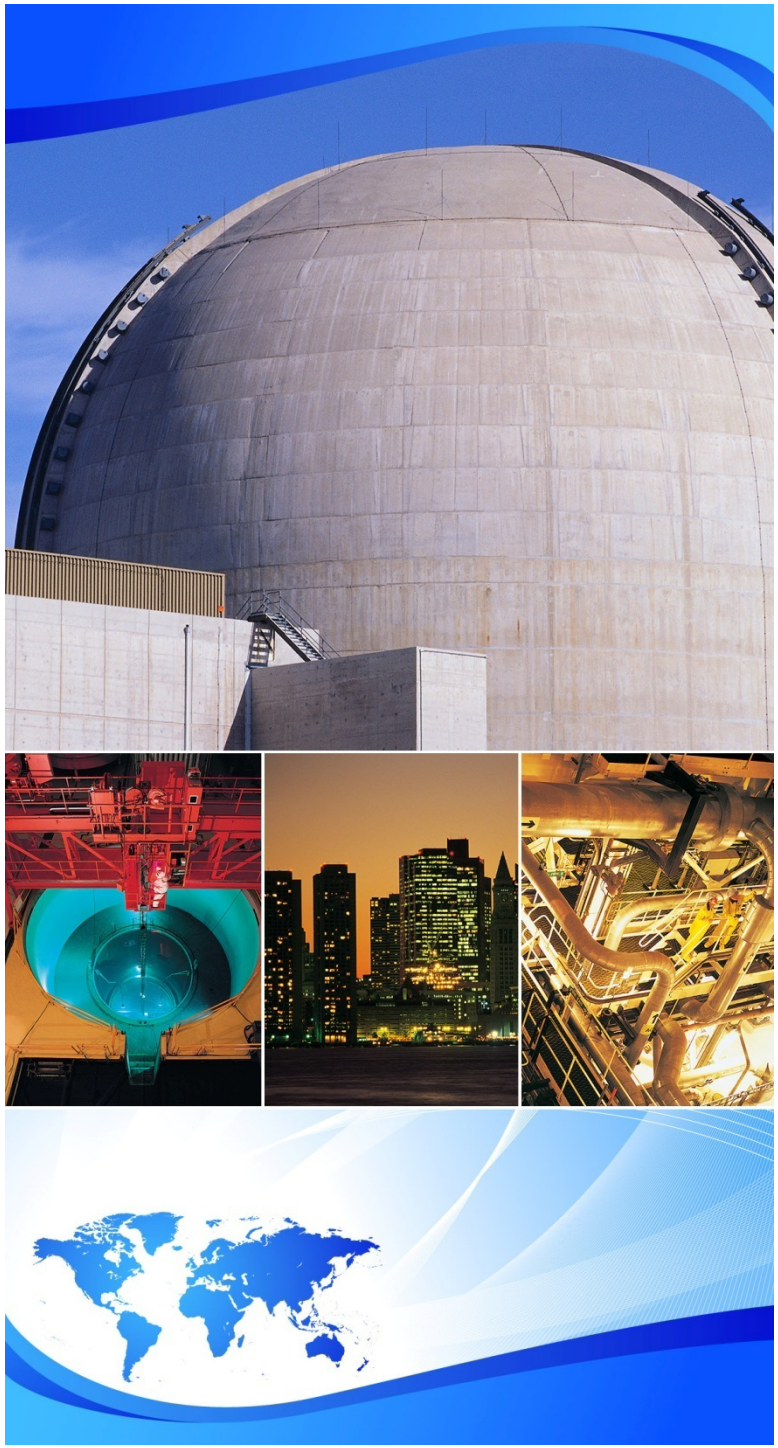

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EPRI MRP Welding Residual Stress Measurement and Validation Program for PWR Piping Dissimilar Metal Butt Welds

PWSCC Flaw Evaluation Meeting

November 20, 2009

Paul Crooker – EPRI

John Broussard – Dominion Engineering, Inc

Topics

- Background & Objectives
- Project Plan
- Project Schedule and Status Summary
- Phase 1 Overview
- Finite Element Analysis Overview
- Neutron Diffraction Technical Issues
- Residual Stress Results Comparison
- Future Efforts

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Project Background & Objectives

Background:

- Analyses of MRP-216 identified that fracture mechanics models are sensitive to through-thickness welding residual stresses (WRS)
  - Need to fill knowledge gap by experimentally validating finite element WRS models
- Need to better understand uncertainties to avoid overconservatism in modeling assumptions for
  - Through-wall WRS stress distributions
  - Extent of axisymmetry of WRS patterns

Objectives:

1. Provide validated FEA method for future use (produce modeling handbook)
2. Use prototypic dissimilar metal welds and components
3. Reduce uncertainty in FEA calculations by validating models against measured residual stresses

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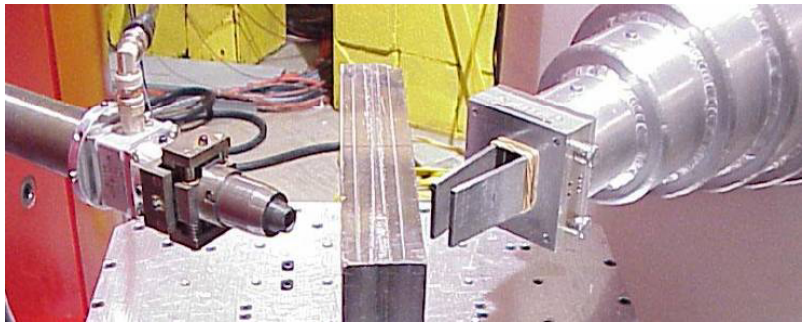
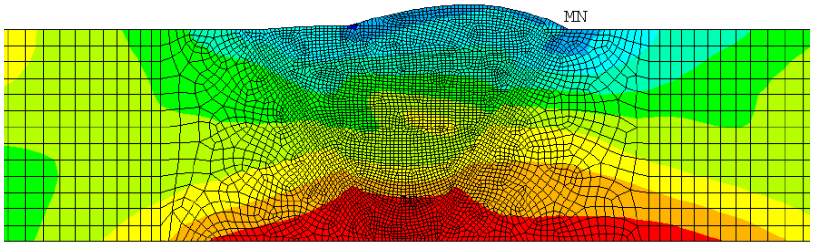
Approach to Validation

- 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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Project Plan

Scope Adjustment with NRC Collaboration

Original Plan (Jan 2008)

- Self-contained EPRI project
- **Phase 1:** Investigate RS in weld specimens of simple geometries in order to develop FE models
  - **Phase 1A:** Plates
  - **Phase 1B:** Cylinders
- **Phase 2:** validate FE models on prototypic DM welds
  - Fabricated large nozzle using prototypic geometry, materials, fabrication methods

Current Plan

- **EPRI/NRC** Collaboration
  - NRC use Phase 1 for their validation work
  - Phase 2 prototypic nozzle fabricated by NRC
  - NRC provide funds for additional RS measurements on specimens
- Two additional phases expand scope of investigation
  - **Phase 3:** Pressurizer nozzles from WNP-3 (true prototypic)
  - **Phase 4:** Large (RPV cold leg) nozzle from WNP-3 (true prototypic)

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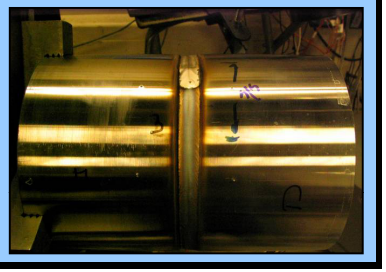
Project Plan

Specimens and Mockups by Project Phase

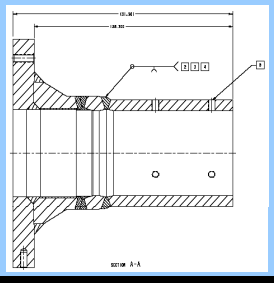
Phase 1 - EPRI

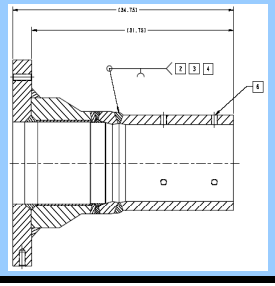
- **Scientific Weld Specimens**
- **Phase 1A:** Restrained Plates (QTY 4)
- **Phase 1B:** Small Cylinders (QTY 4)
- Purpose: Develop FE models.



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.

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Project Plan

Residual Stress Measurement

- **Measurement techniques chosen:**
  - Industry accepted technologies/methods
  - Commercially available
  - Applicable to specimen materials
- **Different principles allow cross-validation:**
  - Diffraction (non-destructive)
  - Mechanical relaxation (semi- & destructive)
- **Different depth penetrations allow assembly of a complete through-wall stress profile for comparison with FEA**
- **Plan moves from non-destructive to destructive techniques**
- **Requires investigation of material properties:**
  - Grain Size [MSi, EWI]
  - Diffraction Elastic Constants (DEC) [ORNL]
  - Bulk Elastic Constants [ORNL, Battelle]
  - Orientation of principal directions [ORNL]

	Through-Wall	Surface/ Sub-Surface
Non-Destructive	Neutron Diffraction [ORNL]	X-ray Diffraction [TEC, EPRI]
Semi-Destructive	Incremental Deep Hole Drilling/Deep Hole Drilling [VEQTER]	Hole Drilling [Lambda Tech] Ring-Core [Lambda Tech]
Destructive	Contour Method [Hill Eng]	

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Project Status Summary

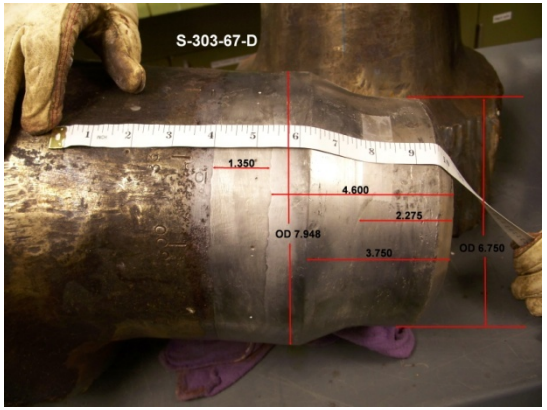
Phase 1

- Weld specimen fabrication complete
- Ongoing development FE models and refinement as RS data becomes available
- Neutron Diffraction technique difficulties required additional measurements to develop accurate RS data (indicated by "ND (d_0)" below).
  - Need to fabricate strain-free reference sample (comb) from each specimen
- **Residual Stress Measurements Completed 2009:**

	Phase 1A	Phase 1B	Phase 3
ND	✓	✓	2010
ND (d_0)	✓	✓	2010
XRD	✓	✓	✓
HD/RC	✓	2010	2010
DHD	✓	✓	✓
Contour	2010		

Phase 3 – Nozzle #1

- 2 DHD
- Laser scans and dimensional layout
- XRD on ID
- Sectioned for:
  - Metallography
  - Weld Geometry
  - Mechanical properties coupons
- 2 slabs removed for ND reference-free samples (combs)



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Schedule Summary

Year by Year

2008	2009	2010	2011
• Background tasks • Phase 1 specimen design and fabrication • FEA support for specimen design • Phase 1 ND WRS measurements	• Finish Phase 1 fab • Phase 1 FE model dev • Phase 1 ND technical issues resolution • Phase 1 surface RS measurements • Phase I DHD	• Finish Phase 1 ND • Phase 1 Contour Method	**PROPOSED** • Hardening law testing • FEA add'l plant nozzles • 3-D FE modeling • Sensitivity studies • FE modeling for xLPR, long-term operation, and relicensing
	• **Interim Report**	• Finish Phase 1 FEA • Phase 2 FEA results comparison • Phase 3 FEA results comparison	
	• Phase 3 –DHD and met exam of nozzle 1 • Phase 4 surface and TW RS measurements	• Phase 3 RS meas (ND, DHD, HD and XRD)	
		• **Final Report** **(Conclusion of Current Project Scope)**	

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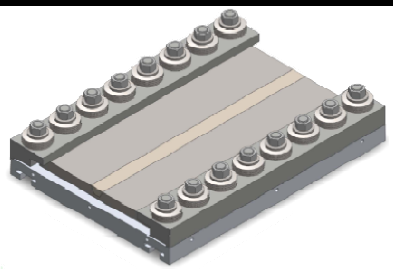
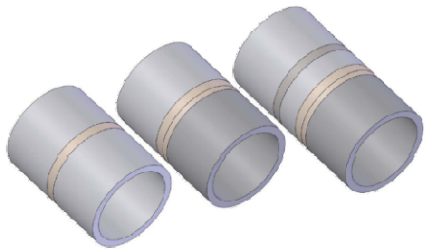
Phase 1

Weld Specimen Design

- **Fabricate and measure RS in simple experimental specimens in order to develop and refine FE models**
- **Scientific Design Approach:**
  - Investigate how weld parameters and geometry affect RS distribution
  - Representative weld configurations
  - Controlled fabrication
  - Maximize region of fully-developed stress
  - Facilitate multiple RS measurements
- **Investigate influence on RS state of:**
  - **Phase 1A:** weld parameter variation
    - Current and wire feed rate
    - Torch speed
  - **Phase 1B:** weld configuration
    - Buttering
    - Post-Weld Heat Treatment (PWHT)
    - Safe-End and SS weld
    - Repair Weld

	Phase 1A	Phase 1B
Geometry	Restrained Plates	Cylinders
	0.6" Thk, 0.4" Groove, 14" Long	6.51" OD x 0.47" Thick
	Simplest Geometry	Increasing Specimen Complexity
Material	Base Metal: 304L SS	Base Metal: 304L SS, CS
	Weld Metal: Alloy 82	Weld Metal: Alloy 82
		Buttering: Alloy 82
Variables	Fix Geometry	Fix Weld Parameters
	Vary Weld Parameters	Vary Configuration
Specimens	P-3: Base Case - 11 passes	C-1: SS to SS
	P-4: Incr. Heat Input - 7 passes	C-3: Buttered CS to SS w/ PWHT
	P-5: Incr. Heat Input - 7 passes	C-4: Buttered CS to SS w/o PWHT
	P-6: Decr. Heat Input - 23 passes	C-5: Add SE and Repair to C-4
Allow ND	Aluminum backing plate is fairly transparent to neutrons	Machine beam windows allow measurement of hoop strain
Misc.	Fixture design preserves original stress state.	C-6 has manual 90° 75% TW ID Repair Weld. Groove machined.
		

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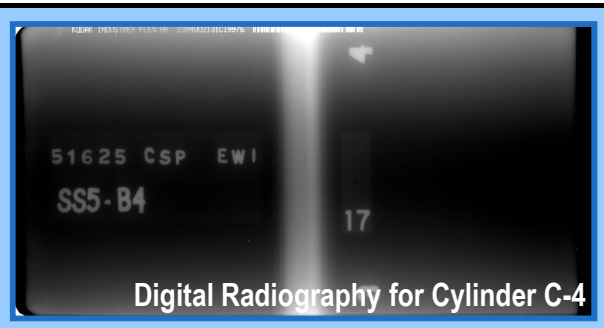
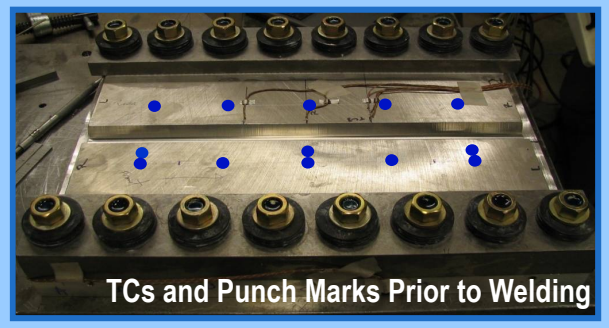
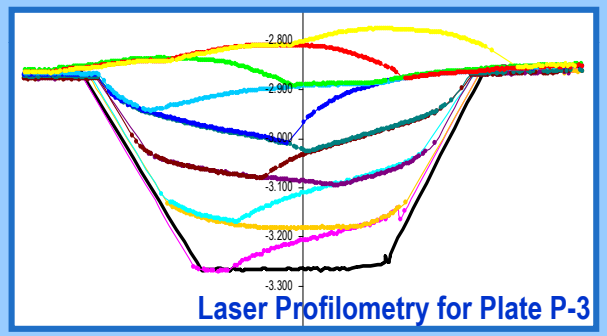
Phase 1
Specimen Fabrication

- **Controlled fabrication**
  - Test welds to test weld parameters
  - Materials from same heats
  - Automated GTAW welding for maximum control and precision
  - Visual inspection and NDE
    - **Phase 1A**: Phased Array UT
    - **Phase 1B**: Digital Radiography
- **Welding procedures developed by Edison Welding Institute (EWI)**
- **Welding Measurements:**
  - Thermocouples for temperature history
  - Punch marks for lateral shrinkage
  - Laser profilometry for bead geometry
  - Videotape welding
  - Written records for weld parameters
- **Record measurements after each weld pass**
- **Phase 1B:** Machined beam windows and measured relaxation with strain gauges



Digital Radiography for Cylinder C-4


TCs and Punch Marks Prior to Welding



Laser Profilometry for Plate P-3

Beam Window and Strain Gauges

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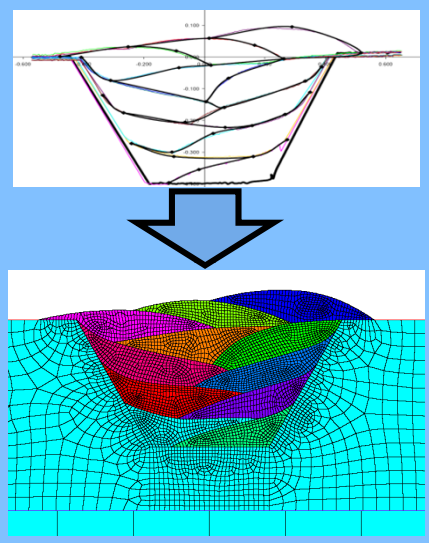
Phase 1

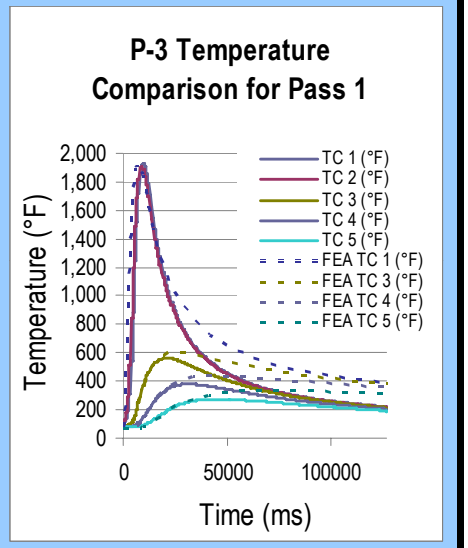
Finite Element Model Development

- **Develop most accurate model based upon known inputs**
- **Structural Model**
  - Weld specimen geometry (dimensions, etc.)
  - Assembly inputs (bolt pre-load force, etc.)
  - Bead geometry based on laser profilometry and/or metallography samples
- **Heat Generation and Thermal Model**
  - Develop heat inputs from weld parameters
  - Check simulated temperatures against thermocouple data
  - Check against shrinkage measurements
- **Simulate effect of different hardening laws**
  - Elastic-Perfectly Plastic
  - Isotropic
  - Kinematic
  - Mixed Mode

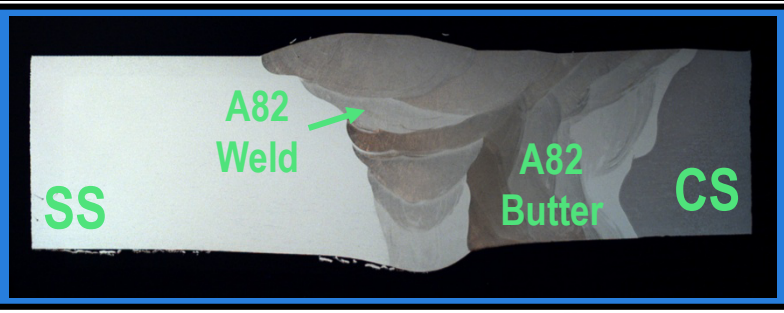
Laser Profilometry Data for P-3



Themocouple Data for P-3



C-2 Test Weld



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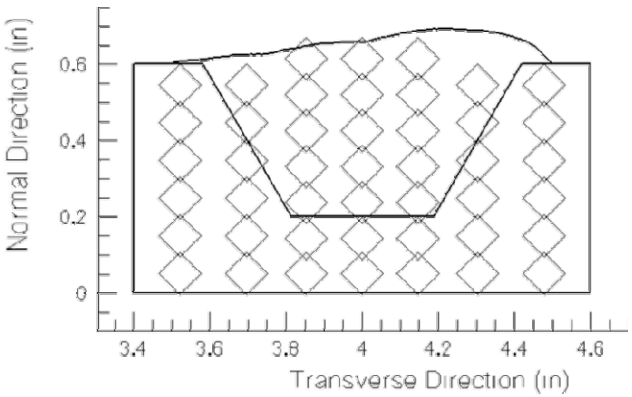
Neutron Diffraction Technical Issues

- ND is a preferred through-wall technique since all stress components at an entire plane can be measured
  - Deep hole drilling measures a single TW line
  - Contour method measures an entire plane, but only one stress component



- Initial ND results did not match trends in literature nor intuition
- After research and comparison, additional measurements identified as necessary to provide accurate results
- Proposed investigations will help identify main contributors to issues:
  - Energy Dispersive X-ray Spectroscopy: measure chemical composition
  - Electron Backscatter Diffraction (if EDS is not conclusive): indicate level of plastic deformation in WM

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Summary of Current Efforts

- Most extensive welding residual stress investigation program to date
  - European and UK researchers interested in US results
- Initial issues with ND have been studied and remedied
  - Updated ND results look promising
- Phase 1 RS measurements will be nearly complete by end of 2009
  - Model comparisons performed as results available
- Phase 2 RS measurements and comparisons complete in 2010
- Phase 3 RS measurements will be performed in 2010

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Future Efforts

- Continue to reduce uncertainty and improve WRS FE predictions for field dissimilar metal welds
  - Acquire data to validate material strain hardening laws
  - Develop 3-D models to improve 2-D models
  - Perform sensitivity analyses
- Keep pace with NRC's WRS efforts for 2011 and beyond
- Support xLPR by further exploring welding residual stresses

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