Pre-emptive Weld Overlays (PWOLs) for Alloy-82/182 Butt Welds in PWRs

Topical Report Kickoff Meeting w/NRC
Presented by:
Structural Integrity Associates
EPRI / MRP

March 16, 2005

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Meeting Agenda

1. INTRODUCTION
2. PURPOSE / OBJECTIVES
3. DESIGN REQUIREMENTS
4. VERIFICATION OF WELD OVERLAY EFFECTIVENESS
5. MATERIALS AND WELDING CONSIDERATIONS
6. INSPECTION REQUIREMENTS
7. EXAMPLE ANALYSES AND RESULTS
8. CONCLUSIONS
9. SCHEDULE
10. NRC FEES for REVIEW

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1. Introduction

- **Utilities interested in applying WOLs preemptively if some assurance received that current inspection and LBB requirements will remain valid**
- **Preemptively WOLs justify:**
  - ASME Code Inspection Intervals
  - Inspection coverage consistent with current WOL requirements
  - Support LBB
- **Topical Report**
  - Technical Report by Structural Integrity Associates, Inc. for MRP/EPRI
  - Provide a technical basis for PWOL as an effective long term mitigation of PWSCC
  - Provide information to aid the NRC in establishing suitable inspection and LBB requirements for uncracked and PWOL mitigated dissimilar metal welds susceptible to PWSCC

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2. Technical Report Objectives

- **Provide information to establish design basis for pre-emptive WOLs on PWSCC susceptible butt welds in PWRs that permanently retains ASME Code margins:**
  - Mitigates against future cracking/crack growth by producing favorable residual stress reversal
  - Provides additional margin against leakage and pipe rupture by structural reinforcement with a PWSCC resistant material
  - Pre-emptive WOLs are additional reinforcement of piping
    - not a repair but analyzed as such
    - *no defects in Piping*
- **Provide information to establish inspection requirements:**
  - Change inspection coverage based on additional reinforcement (WOL material plus a percentage of the original pipe wall per Code Case N-504-2)
  - Provide technical basis to maintain current Section XI inspection interval (ten years)
- **Provide information to maintain Leak Before Break status of the mitigated welds**
- **Obtain NRC approval of Topical Report in time-frame consistent with Spring 2006 implementation schedule**

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3. Weld Overlay Design Requirements

- Weld Overlay Structural Sizing
- Residual Stress Improvement
- Inspectability Considerations
- Fatigue Considerations
- Leak Before Break

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WOL Design Requirements: Structural Sizing

- Two types of design basis flaws assumed for PWOLs:
  - 100% thru original nozzle wall and 360° around circumference (full structural overlay)
  - 75% thru original nozzle wall and 360° around circumference (reduced thickness overlay)

  Thus, both are structural overlays, in addition to providing residual stress benefits
- WOL must satisfy ASME XI margins (IWB-3640) in presence of above flaw assumptions
- Minimum WOL length is $1.5\sqrt{Rt}$ plus length of susceptible material on OD of original DMW
- WOL thickness & length must also be checked against residual stress & inspectability criteria

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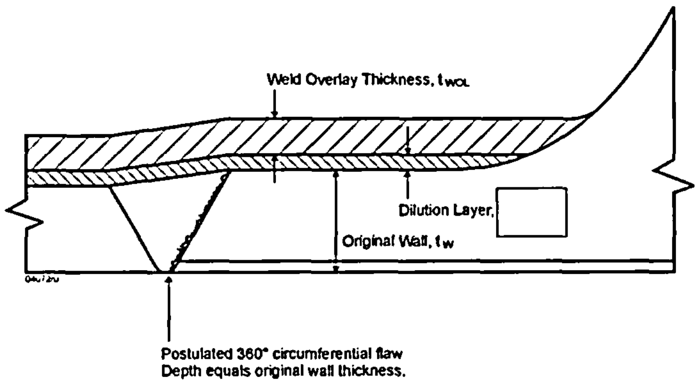
Full Structural Overlay Concept (per CC N-504-2)



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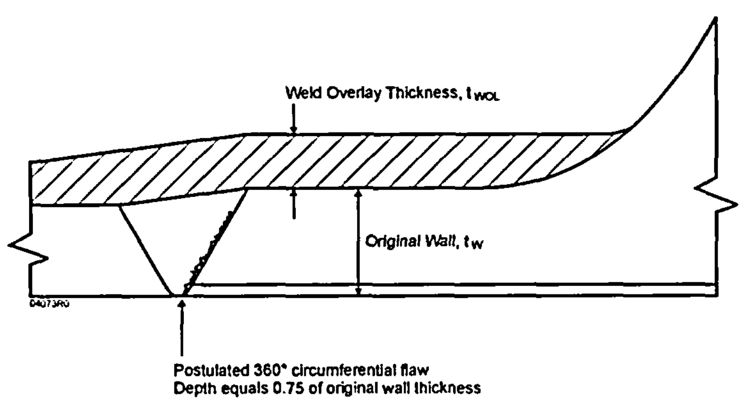
Reduced Thickness Overlay Concept



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WOL Design Requirements: Residual Stress Improvement

- **Weld overlay improves residual stress condition**
  - Initial unfavorable residual stress state assumed to exist due to original weld ID repair during plant construction
  - Nozzle-specific analyses performed to demonstrate that PWOL reverses residual stress field producing compressive residual stresses (both axial and hoop) in original pipe wall
  - Prior experimental work has verified residual stress analysis techniques (EPRI Reports NP-7103-D and NP-7085-D)
- **Current MRP project underway to confirm residual stress improvement (and inspectability) on typical PWR nozzle geometry**

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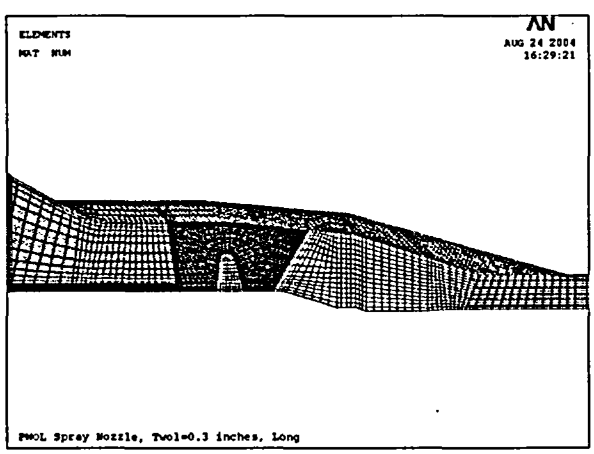
Residual Stress Model: Pressurizer Spray Nozzle



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WOL Design Requirements: Inspectability Considerations

- **WOL length and other design details often need to be modified to accommodate inspection requirements**
  - WOL plus outer 25% or 50% of original nozzle thickness, encompassing PWSCC material + ½" on either side of weld
  - Inspectability of adjacent welds also needs to be considered

WOL Design Requirements: Fatigue Considerations

- **Fatigue Crack Growth**
  - Assume initial flaw that could be missed by pre-WOL inspection (10% thru wall)
  - Apply residual stresses plus all design basis loading conditions, including flow stratification concerns where applicable (e.g.. NRC Bulletin 88-01 for surge nozzles)
  - Demonstrate that flaw doesn't grow to design basis flaw for PWOL in remaining design life (plus license renewal period where applicable)
  - For geometries that are uninspectable pre-WOL, start with flaw depth = post-WOL inspection depth.
- **Fatigue Usage**
  - Demonstrate acceptable fatigue usage for overlay geometry in accordance with ASME Section III requirements

WOL Design Requirements: Leak Before Break

- Guidelines for LBB Evaluation provided in NUREG-1061, Vol. 3 and Draft SRP 3.6.3
- Design basis loads considered:
  - Normal (pressure + deadweight + thermal) used to determine leakage from a crack no larger than 1/2 critical flaw size
  - Normal + SSE used to determine critical flaw size (or other
  - Alternately, leakage flaw size may be determined using factor of 1.4 on loads
- Leakage rate determined from thru-wall crack with required margin to critical flaw size (factor of 2 on flaw size or 1.4 on load)
- To qualify for consideration, there must be no potential for degradation by erosion, erosion/corrosion, erosion/cavitation, water hammer, thermal fatigue, or other mechanisms that could lead to cracking
- Factor of 10 required between predicted leakage rate and detection capability of plant leakage detection systems (previously ~1 GPM, but improving w/current technology)

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4. Verification of Weld Overlay Effectiveness

- Prior Experimental Programs (in support of BWR WOLs)
  - 28-Inch Notched Pipe Test [Ref. 1]
  - EPRI/GE Degraded Pipe Program [Ref. 2]
  - EPRI Weld Overlay Large Diameter Pipe Test Program [Ref. 1]
  - Battelle/NRC Degraded Pipe Tests [Ref. 3]
- Current EPRI-MRP Program
- Field Experience [Refs. 4, 5]

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WOL Verification References

1. EPRI NP-7103-D, "Justification for Extended Weld-Overlay Design Life", January 1991
2. EPRI NP-5881-LD, "Assessment of Remedies for Degraded Piping," June 1988
3. "Assessment of Design Basis for Load Carrying Capacity of Weld Overlay Repair" Topical Report, NUREG/CR-4877, Paul Scott, Battelle Columbus Division, February, 1987
4. BWR Vessel and Internals Project: Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75), EPRI, Palo Alto, CA, and BWRVIP: 1999. TR-113932
5. "Technical Justification for Extension of the Interval Between Inspections of Weld Overlay Repairs," EPRI TR-110172, Charlotte, NC, February 1999

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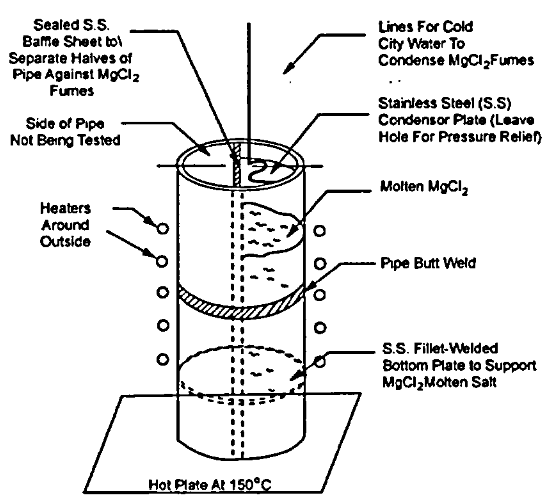
28-Inch Notched Pipe Test



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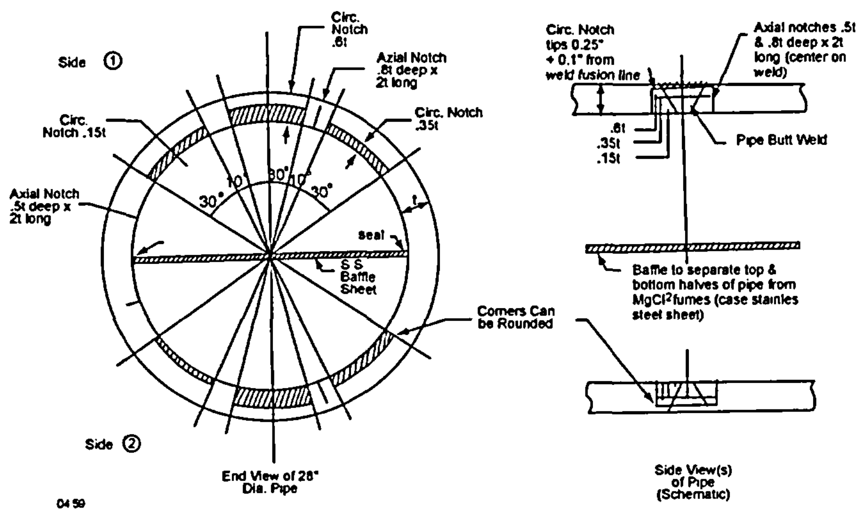
28-Inch Notched Pipe Test



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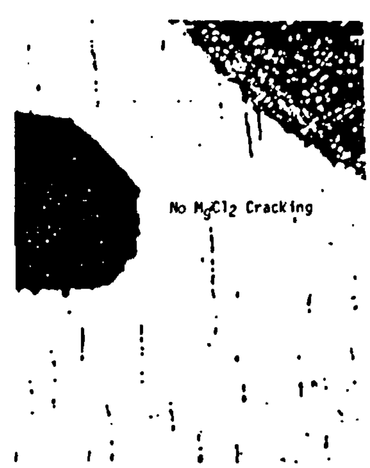
28-Inch Notched Pipe Test



a) Notch Tested Before Weld Overlay **b) Notch Tested After Weld Overlay**

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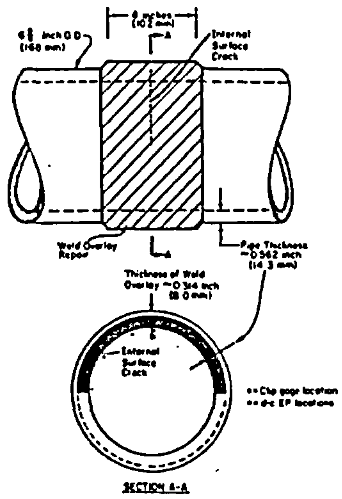
Battelle/NRC Degraded Pipe Tests



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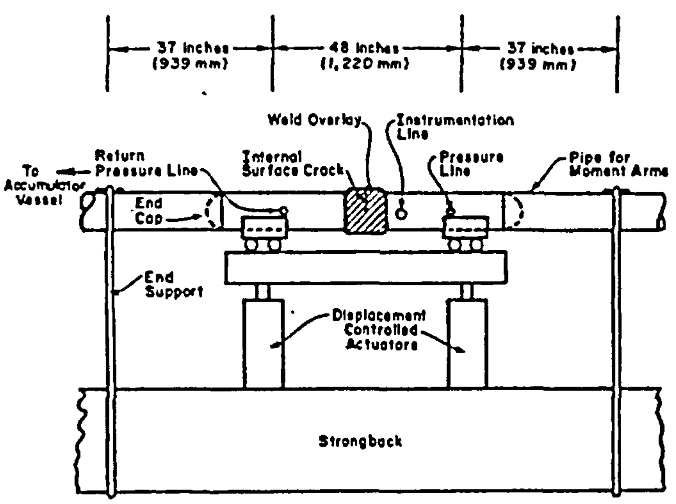
Battelle/NRC Degraded Pipe Tests



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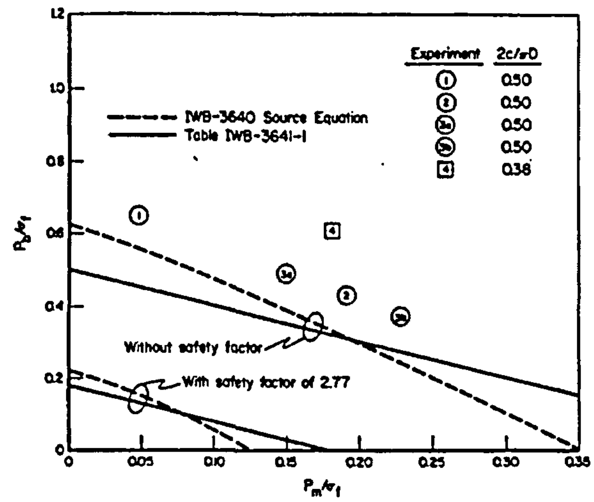
Battelle/NRC Degraded Pipe Tests



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Current EPRI/MRP PWOL Demonstration Program

- **Task Descriptions - Development And Testing Of Preemptive Weld Overlay Mitigation Techniques For PWSCC**
  - Finite Element Analysis
    - Perform weld overlay sizing calculations plus finite element analyses (FEA) in accordance with the mockup design specification to optimize/guide experimental results
    - Provide a PWOL design drawing for mockup based on the analyses
    - Results from the FEA of the mockup will be compared with those from a prior FEA of a generic surge nozzle
  - Mockup Fabrication
    - Welding Services, Inc. (WSI) contracted through SI, with the support of SI and input from EPRI, will fabricate the mockup and weld overlay
    - Preliminary mockup drawing is seen in the following figure

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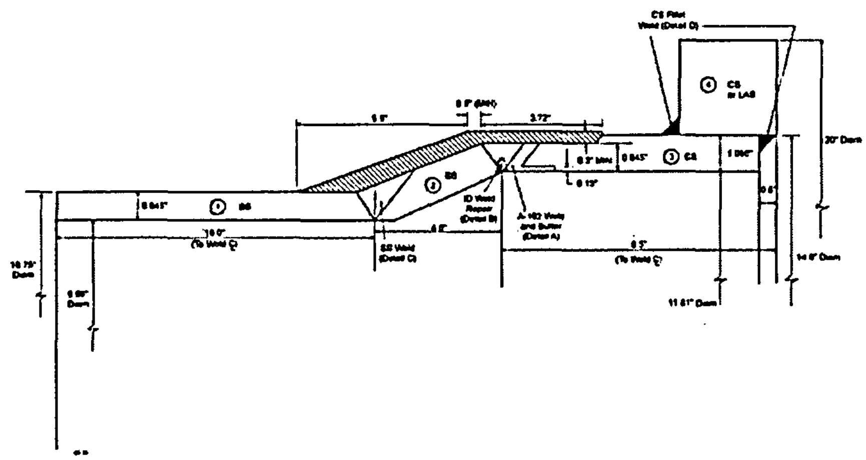
Preliminary Mockup Drawing



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Current EPRI/MRP PWOL Demonstration Program (Con't)

- Application of PWOL
  - Provide the design drawing and FEA results to EPRI to assist in application of the PWOL and to compare with the diametrical displacement measurements to be taken by EPRI at 4 azimuths, with spacing at approximately ¼-inch from the edge of the overlay and at two additional locations
- Residual Stress Measurements and Metallography
  - XRD residual stress analysis and strain gage testing, to provide measurements to compare with the FEA results
  - Metallography of mockup sections
- Inspection
  - Examine mockup using an inspection protocol that satisfies the requirements of the Performance Demonstration Initiative (PDI)
  - Inspection procedures, personnel and equipment (including instrumentation and ultrasonic probes) used to conduct these inspections will satisfy the requirements of the PDI

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Current EPRI/MRP PWOL Demonstration Program (Con't)

- Reporting and Documentation
  - final report on demonstration program will include:
    - details of the mockup fabrication, FEA, PWOL, and surface conditioning
    - results from XRD stress measurements, metallography, hardness profile, and corrosion testing.
- Topical Report
  - EPRI/MRP topical report will be prepared documenting overall PWOL technical basis
  - will include residual stress, fatigue, LBB and other work that SI has performed at its own expense
  - Will also summarize the experimental and analytical work performed under the demonstration program

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Weld Overlay Field Experience

- **Used extensively in BWRs**
  - Code Case N-504-2
  - Code Case N-638 (ambient temperature temperbead)
  - NUREG-0313
  - EPRI Reports (NP-7103-D and NP-7085-D)
  - Vermont Yankee Core Spray Nozzle to Safe-End Repair
    - In Service ~20 years
    - Multiple UT Inspection results demonstrated no flaw growth
  - Repairs Greater than 100 square inches approved by NRC
- **Initial PWR butt weld WOL applied in Dec. 2003 (TMI surge line to hot leg nozzle)**
  - Repair over 100 square inches
  - Approved by NRC

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BWRVIP-75 Review of BWR WOL Experience

- Weld overlays applied to BWR SS and DM welds since 1981
- Initially considered temporary repair
- Total applied: more than 800
- BWRVIP-75 survey of overlays still in service (issued 1999):
  - 262 in service, in 33 responding plants
  - More applied since that survey

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BWR Weld Overlay Inspection Requirements

- GL 88-01/NUREG-0313 Rev. 2 Category E:
  - 100% every two refueling cycles
- BWRVIP-75 Category E:
  - Normal water chemistry: 25%/10 years
  - Hydrogen water chemistry: 10%/10 years
- Weld overlays now considered permanent repair

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Experience with Weld Overlays for Dissimilar Metal Welds

Date	Plant	Component
March 2005	Calvert Cliffs	RCL drains (2)
December 2004	Hope Creek	Recirc. Inlet Nozzle
April 2004	Susquehanna Unit 1	Recirc. inlet nozzle Recirc. outlet nozzle
November 2003	TMI Unit 1	Surge line nozzle
October 2003	Pilgrim	Core spray nozzle CRD return nozzle
October 2002	Peach Bottom Units 2 & 3	Core spray nozzle Recirc. outlet nozzle CRD return nozzle
October 2002	Oyster Creek	Recirc. outlet nozzle
December 1999	Duane Arnold	Recirc. inlet nozzle
June 1999	Perry	Feedwater nozzle
June 1998	Nine Mile Point Unit 2	Feedwater nozzle
March 1996	Brunswick Units 1 & 2	Feedwater nozzle
February 1996	Hatch Unit 1	Recirc. inlet nozzle
January 1991	River Bend	Feedwater nozzle
March 1986	Vermont Yankee	Core spray nozzle

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5. Metallurgical and Welding Considerations

- **Metallurgical Considerations on Service Performance**
  - Micro-Structure/Cooling Rate
  - Tempering
  - Hydrogen Cracking
- **Welding Considerations**
  - ASME Code Cases
    - N-XXX - Dissimilar Weld Overlays
      - CR Content of First layer
  - N-638-3 -Ambient Temp. Temper Bead Welding
    - 100 square inch imitation

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Metallurgical and Welding Considerations (Con't)

- **Metallurgical Considerations on Service Performance**
  - ♦ Micro-Structure/Cooling Rate
    - ° High Cooling Rate for Weld from Water or Large Heat Sink from Nozzle
    - ° Heat Affected Zone (HAZ) Fully Martensitic
  - ♦ Tempering
    - ° Second and Third Weld Layers Temper HAZ
    - ° Final Structure of HAZ – Tempered Martensite
    - ° Base Materials with lower fracture toughness most improved
  - ♦ Hydrogen Cracking
    - ° Auto GTAW Process
    - ° Bare Filler Wire/Dry Shielding Gas
    - ° High Permeability Ferritic Base Materials
    - ° 48 Hour Hold Time Prior to NDE

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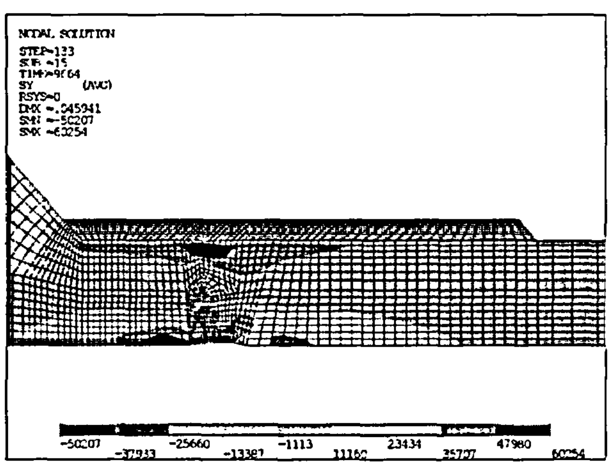
Metallurgical and Welding Considerations (Con't)



Pre-PWOL Axial Stress Contour, 70 F

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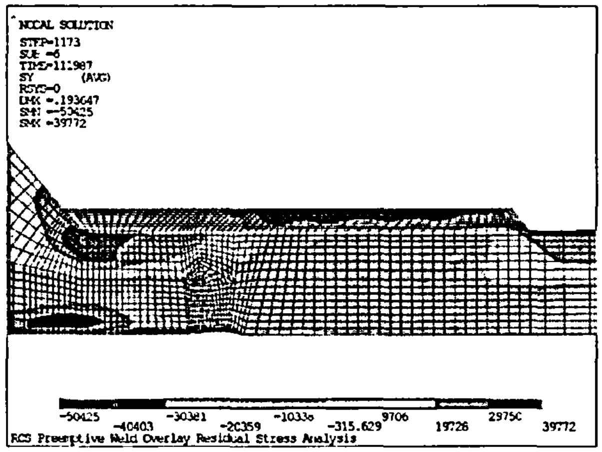
Metallurgical and Welding Considerations (Con't)



Post PWOL Axial Stress Contour, 650 F

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Metallurgical and Welding Considerations (Con't)

- **Welding Considerations**
  - ASME Code Cases
    - N-XXX - "Alternative Rules for Repair of Class 1, 2, and 3 Dissimilar Metal Welds by Weld Overlay"
      - ASME White Paper-CR Content of First Layer
      - At WG Welding & SG RR&A Next Section XI Meeting
      - Design and Inspection Consistent with N-504 and Non-Mandatory Appendix
  - N-638-3 -Ambient Temp. Temper Bead Welding
    - ASME White Paper-100 square inch imitation
      - Analyses and Experimental Work Show Residual Stresses for Repairs to 500 Square Inches Equivalent or better than Cavity and Overlay Repairs 100 Square Inches or Less
      - All Repairs meet ASME Section III or Construction Code and Owner's Requirements
      - Service History for Repairs (Dissimilar Weld Overlays, Cavity and Weld Pads) made with Ambient Temperature Temper Bead Welding has been Excellent
      - Many of the Repairs are Greater than 100 Square Inches and have been approved by the NRC
  - New Alloy 52 MS Filler Wire has been Shown to have Much Improved Weldability

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6. PWOL Inspection Requirements

- **Inspection requirements for structural weld overlays defined in Code Case N-504-2**
  - Initial Inspection – WOL material for welding defects + outer 25% of original weld (±0.25")
  - Subsequent ISIs – WOL directly over original weld (±0.25") + outer 25% of original weld (±0.25")
- **Proposed Inspection requirements for reduced thickness PWOLs**
  - Initial Inspection – WOL material for welding defects + outer 50% of original weld (±0.25")
  - Subsequent ISIs – WOL directly over original weld (±0.25") + outer 50% of original weld (±0.25")
- **Easier exam than inspection of entire original bi-metallic weld**
  - PDI Qualification Process available
- **Favorable residual stresses plus structural reinforcement justify ASME Section XI ISI intervals (10 years)**

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7. Example Analyses and Results

- **Example Nozzles**
  - pressurizer upper head spray nozzle (OD=6", t=0.875")
  - pressurizer lower head surge nozzle (OD=15", t=1.28")
  - a typical main RCS hot leg nozzle (OD=33", t=2.33")
- **Analyses Performed**
  - WOL Sizing and Residual Stress (all nozzles)
  - Fatigue Crack Growth (surge nozzle)
  - Leak Before Break (surge and hot leg nozzles)

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PWOL Examples: Structural Sizing Results

Nozzle	WOL Thickness (in.)		Minimum Length (in.)
	Reduced Thickness	Full Structural	
Pressurizer Spray	0.210	0.292	4.28
Pressurizer Surge	0.210	0.427	6.27
RCS Hot Leg	0.481	1.045	11.30

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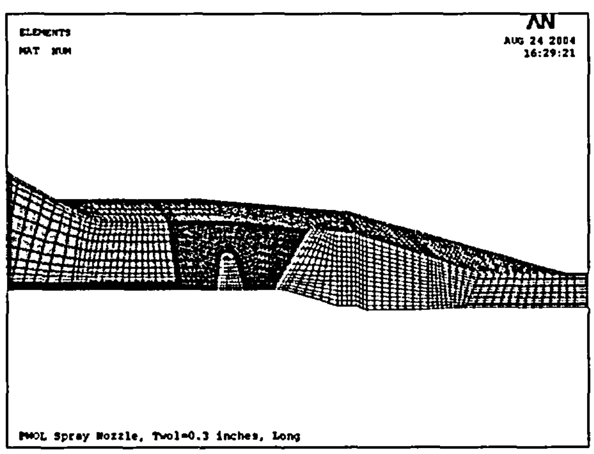
Residual Stress Model: Pressurizer Spray Nozzle



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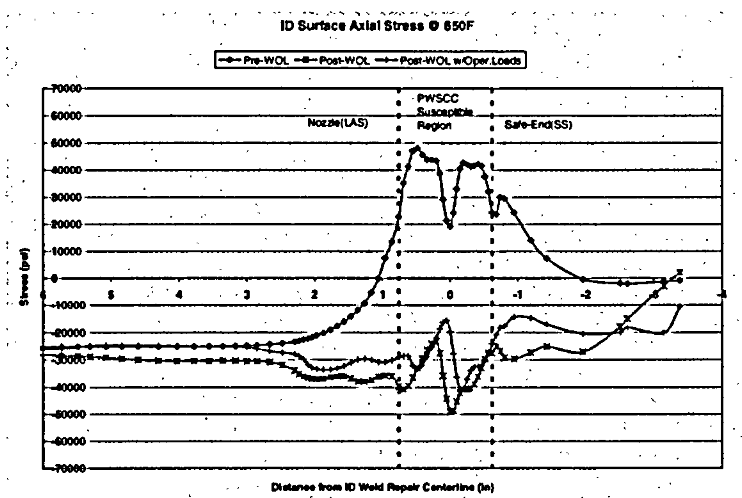
Residual Stress Results: Pressurizer Spray Nozzle



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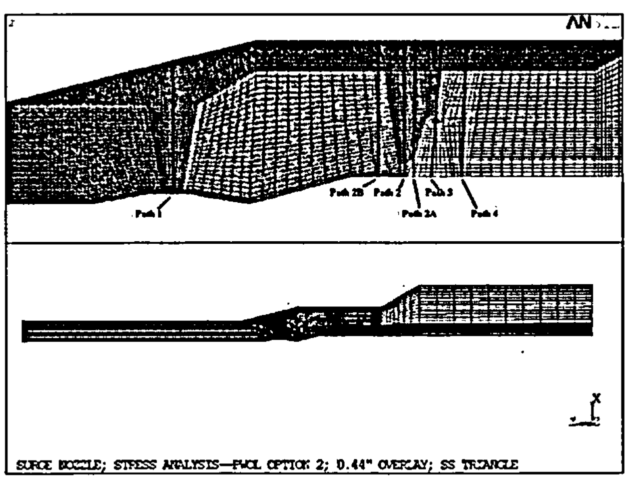
Residual Stress Model: Pressurizer Surge Nozzle



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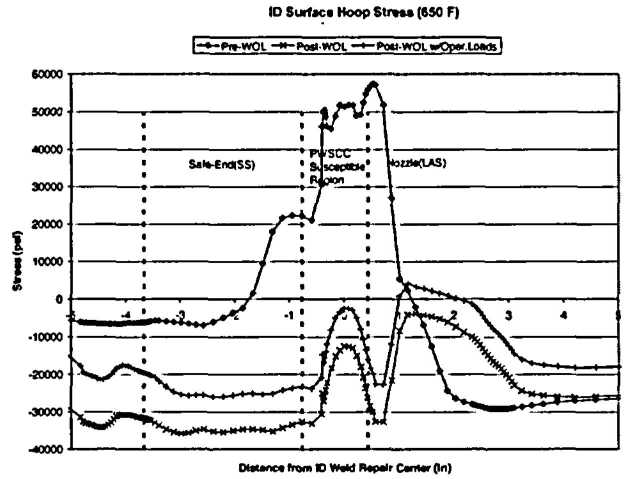
Residual Stress Results: Pressurizer Surge Nozzle



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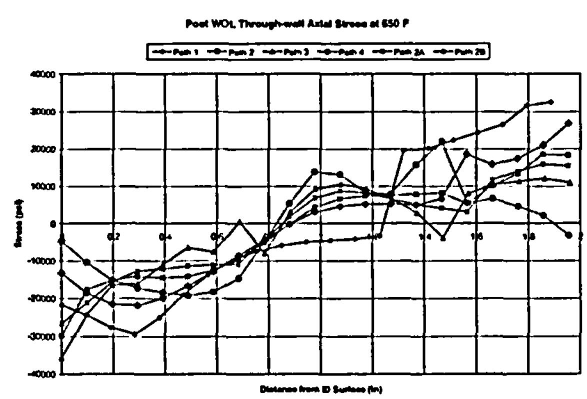
Residual Stress Results: Pressurizer Surge Nozzle



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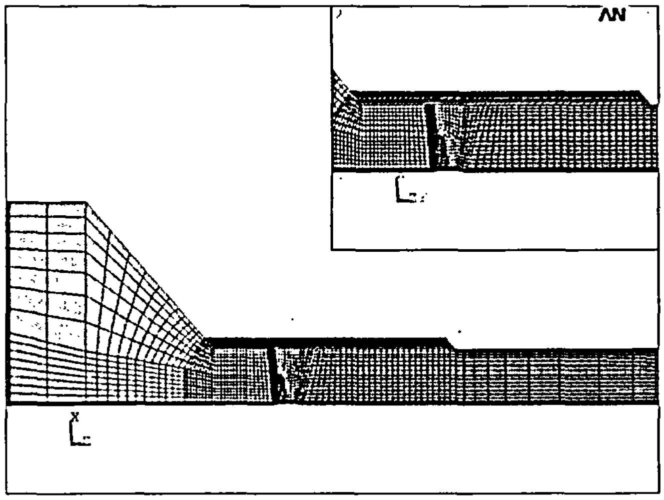
Residual Stress Model: RCS Hot Leg Nozzle



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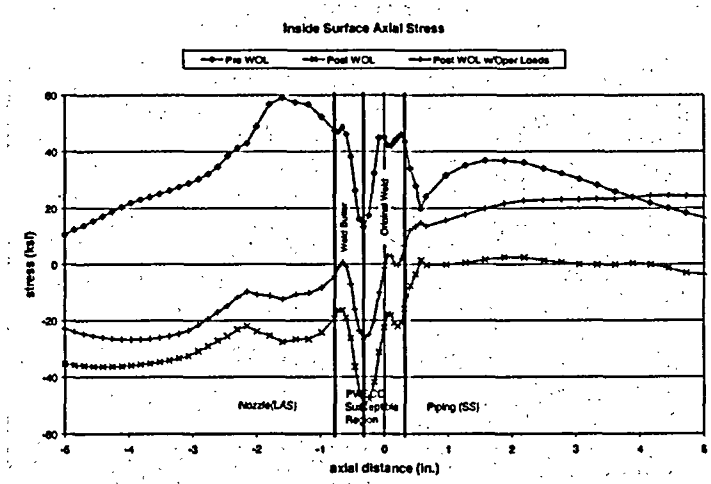
Residual Stress Results: RCS Hot Leg Nozzle



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Final PWOL Designs
(Reflecting Resid. Stress & Inspectability)

Nozzle	WOL Thickness (in.)	WOL Length (in.)
Pressurizer Spray	0.30	7.19
Pressurizer Surge	0.44	9.81
RCS Hot Leg	0.48	11.60

Vs. Structural Sizing

Nozzle	WOL Thickness (in.)		Minimum Length (in.)
	Reduced Thickness	Full Structural	
Pressurizer Spray	0.210	0.292	4.28
Pressurizer Surge	0.210	0.427	6.27
RCS Hot Leg	0.481	1.045	11.30

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Example Fatigue Evaluation: Surge Nozzle

- **Plant transients defined for 500 HU/CD Transients, including:**
  - Pressure stresses
  - Dead weight stresses
  - *Residual stresses (from prior analyses)*
  - Bending stresses due to thermal stratification (from NRC Bulletin 88-11 evaluation)
  - Surge line thermal expansion stresses (scaled proportionally to surge line mean temperature)
  - Hot leg thermal anchor movement stresses (scaled proportionally to the hot leg temperature)
- **Initial Flaw Assumptions**
  - Circ crack; 10% through wall, 10 to 1 aspect ratio
  - Axial crack: 10% through-wall; 2 to 1 aspect ratio (length limited by adjacent LAS and SS)

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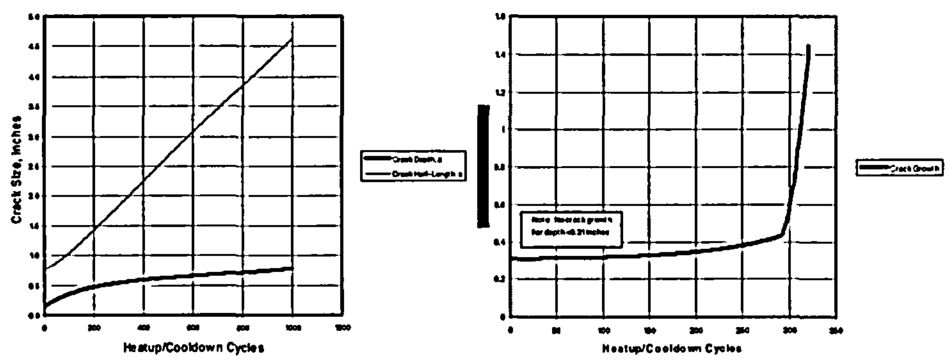
Surge Line Fatigue Crack Growth Analysis Results



Circumferential Cracks

Axial Cracks

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Results of LBB Evaluation of Surge Nozzle

Case	Crack Morphology	Critical Flaw Size, inches	Leakage Flaw Size, inches	Leakage Rate, GPM
w/o Overlay	SCC	19.33	9.67	15.64
w/o Overlay	Fatigue	19.33	9.67	94.76
w/ Overlay	Fatigue	22.77	11.38	61.83
w/ Overlay	SCC	22.77	11.38	8.63

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Results of LBB Evaluation of Hot Leg Nozzle

Case	Crack Morphology	Critical Flaw Size, inches	Leakage Flaw Size, inches	Leakage Rate, GPM
w/o Overlay	Fatigue	20.93	9.57	250
w/o Overlay	SCC	20.93	9.57	76.78
w/ Overlay	Fatigue	25.53	12.77	260
w/ Overlay	SCC	25.53	12.77	86.2

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8. Conclusions

- **Significant technical bases and field experience exist in support of WOLs as a long term repair of SCC susceptible welds**
- **Technical bases and field experience equally applicable to WOLs applied preemptively to uncracked welds (PWOLs)**
- **When used preemptively on welds that are inspected and found clean, PWOLs justify:**
  - ASME Code Inspection Intervals
  - Reduced inspection coverage
  - Preservation of LBB
- **Several utilities interested in applying if some assurance received that current inspection and LBB requirements will remain valid**

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9. Schedule

- **Design basis established and sample analyses completed**
- **Additional mockup/experimental program underway**
- **Topical Report submittal July 1, 2005**
  - Technical report on new mockup program by Sept. 2005
- **SER desired to support Fall 2005 outage schedule**

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10. NRC Fees for Review

- **Request is made to 10CFR170.11(a)(1)(iii) which states: As a means of exchanging information between industry organizations and the NRC for the specific purpose of supporting the NRC's generic regulatory improvements or efforts**
- **Technical report when approved by the NRC could be used to establish a generic position for inspection credit for the use of a Preventive Weld Overlay for mitigating PWSCC and for establishing that the criteria for mitigating the active degradation mechanism of PWSCC for LBB are satisfied**
- **Fee exemption applies since the document would aid NRC in establishing generic guidance as a part of a NUREG or Regulatory Guide. Similar type to example in 10CFR170.11(a)(1)(iii)(B). NRC has established generic positions for addressing acceptable ways to mitigate cracking caused by Inter-Granular Stress Corrosion Cracking in BWRs in NUREG-313, Rev. 1.**

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