ELECTRIC POWER RESEARCH INSTITUTE

MRP Meeting with NRC

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Mitigation of Primary Water Stress Corrosion Cracking in Alloy 600 and its Weld Metals

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Mitigation of PWSCC in Alloys 600/182/82: Background

- PWSCC of components fabricated from Alloy 600 and its weld metals (Alloys 182/82) is an important degradation mechanism in PWRs worldwide
- Replacement of key components using resistant materials (e.g. Alloys 690/152/52) has been widely carried out
- Need remains to identify appropriate mitigation methods to deal with remaining Alloy 600 locations by
  - Avoiding initiation of new cracks at susceptible locations
  - Slowing down the rate of growth of existing cracks (particularly of incipient cracks below the NDE threshold)
- Extensive experience of IGSCC in BWRs suggests that both “chemical” and “mechanical” methods are beneficial
- MRP is also studying “novel” approaches

Mitigation of PWSCC in Alloys 600/182/82: Material susceptibility

- Both laboratory data and plant experience suggest that PWSCC susceptibility of Alloy 600 is governed primarily by
  - heat of material (including thermomechanical processing)
  - stress level (applied and residual)
  - temperature
  - primary water chemistry is a secondary factor

Mitigation of PWSCC in Alloys 600/182/82: Industry Approach to mitigation

- Industry approach is to use one or more of the following:
- "Chemical" methods to alter environment
- "Mechanical" methods to alter stress
- Replacement of susceptible materials

PWSCC Mitigation Strategy

- Develop and demonstrate both chemical and mechanical mitigation technologies
- Submit technical reports for NRC review
- Mitigation credit for
  - Flaw evaluation for continued operation
  - Reduced weld inspection frequency
- Follow BWRVIP Methodology

PWSCC Mitigation Technologies

- Chemical Mitigation
  - Elevated Hydrogen
  - Zinc Addition
- Mechanical Mitigation
  - Preemptive Weld Overlay (PWOL)
  - Cavitation Peening
  - Mechanical Stress Improvement (MSIP)

BWR Mitigation Methodology

- Reduced Weld Inspection Frequencies
  - BWR Vessel and Internals Project Technical Basis for Revisions to Generic Letter 88-01 Inspection Schedules (BWRVIP-75)
  - Specifies reduced inspection frequencies for recirculation piping welds based upon effective mechanical or chemical mitigation
    - MSIP
    - Hydrogen Water Chemistry

BWR Methodology (continued)

- Crack growth rates, including reduced crack growth rates for mitigation
  - "BWR Vessel and Internals Project, Evaluation of Crack Growth in BWR Stainless Steel RPV Internals (BWRVIP-14)", March 1996
  - "BWR Vessel and Internals Project, Evaluation of Crack Growth in BWR Nickel Base Austenitic Alloys in RPV Internals (BWRVIP-59)", December 1998
- Crack Initiation Studies
  - "BWR Vessel and Internals Project, Stress Corrosion Cracking Initiation in BWRs in Nickel-Base Alloys 600 and 690, and Their Weld Alloys 182, 82 and 72 (BWRVIP-71)", June 1999

BWR Methodology (continued)

- NRC approval of technical reports that define effective mitigation requirements
  - "BWR Vessel and Internals Project, Technical Basis for Inspection Relief for BWR Internal Components with Hydrogen Injection" (BWRVIP-62), December 1998
  - Weld Overlay and MSIP accepted by NRC in GL 88-01

PWR Industry Status

- Crack Growth Rate Reports do not include benefits of chemical mitigation
  - MRP-55, “Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials”
  - MRP-115, “Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182 and 132 Welds”
- MRP-78, “Effect of Zinc Addition on Mitigation of Primary Water Stress Corrosion Cracking of Alloy 600”
  - Presents laboratory results on crack initiation and crack growth rate.

PWR Mitigation Plan

- Qualification of PWSCC mitigation technologies
- Submit technical reports that define requirements for effective application of mitigation technologies
  - Qualification program results and any applicable field experience
  - Factors of Improvement for delaying crack initiation and for crack growth rate reductions
- Acceptable mechanical mitigation techniques, i.e. stress improvement, addressed in MRP-139
- Acceptable chemical mitigation techniques would be addressed in revision to MRP-139

Chemical Mitigation Specifics

- Elevated hydrogen
- Zinc addition

Mitigation of PWSCC in Alloys 600/182/82 by "Chemical" methods: MRP Program

Objective: Demonstrate by testing chemical methods to mitigate SCC susceptibility of Alloy 600/182/82.

- MRP program is focused on:
  - Optimization of H_2 fugacity to avoid peak in growth rates
  - Zn additions to mitigate SCC initiation
- All published test data (including, e.g. work carried out in NR program and further international results) will be considered in final evaluation

Mitigation of PWSCC in Alloys 600/182/82 by "Chemical" methods: MRP Program Schedule

- Testing to study effect of hydrogen and zinc began in 2003. This phase will conclude in 2006.
- Parallel evaluations in progress to determine and address any negative "side effects" of chemical mitigation
- Technical basis for extending inspection intervals based on test data (MRP, EDF, other) and relevant field experience will be developed in 2007
- Water chemistry guidelines will address "chemical" mitigation benefits in its 2008 revision

Mitigation of PWSCC in Alloys 600/182/82 by "Chemical" methods: Test Methods

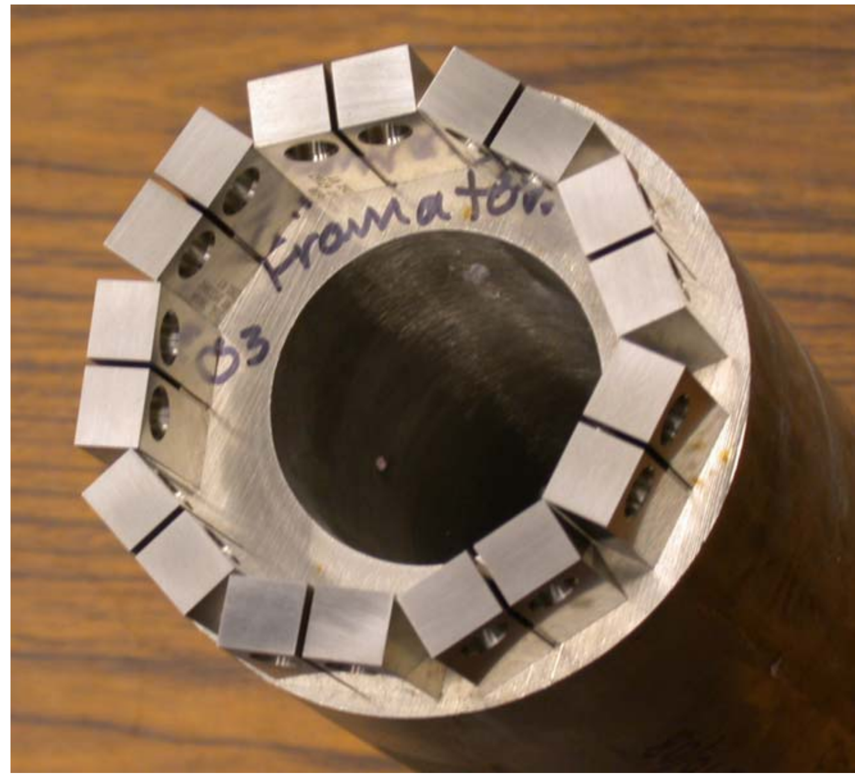
- Employ sophisticated crack growth rate measurement techniques with thorough transition from fatigue to SCC
- Use susceptible heat of A600 from CRDM housing
- Fabricate 0.5" CT specimens for tandem testing
- Test at moderate stress intensity factor of $K = 25$ ksi$\sqrt{in}$
- Test in 325C water with a range of Zn, B/Li & H_2
- Use B/Li-equilibrated demineralizer for high water purity
- Use ZrO_2 / CuO and Pt reference electrodes

Mitigation of PWSCC in Alloys 600/182/82 by "Chemical" methods: Test System

Fully instrumented high temp. water SCC systems, incorporating water supply, autoclave, digital load control, digital temp. control, data acquisition…

Mitigation of PWSCC in Alloys 600/182/82 by “Chemical” methods: Test Specimens

Considered various orientations; chose orientation at right, designated C-L



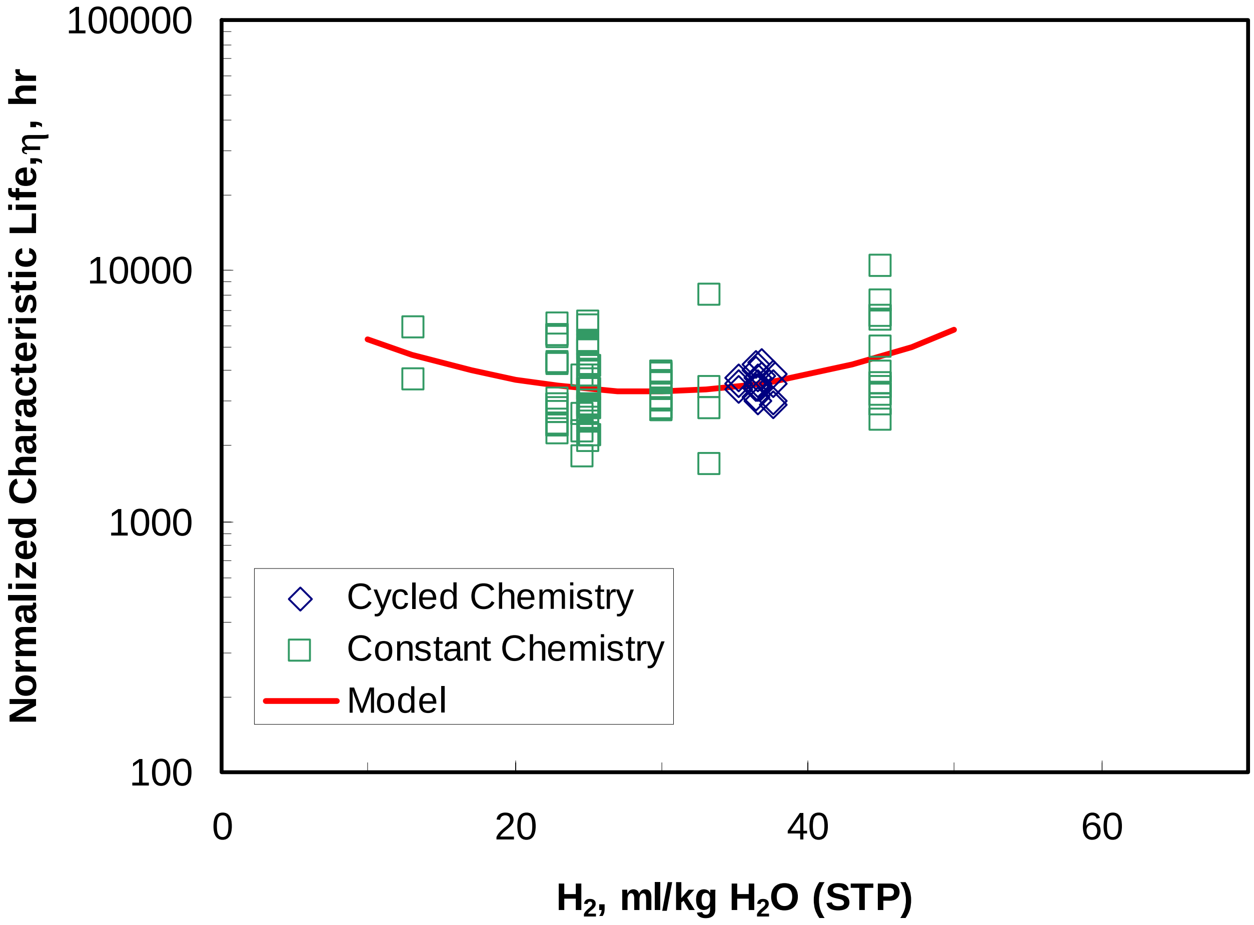
Approximate representation of specimen removal at mid-wall position

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Elevated hydrogen

- Optimizing hydrogen levels may provide a modest benefit on crack initiation
- Test data on this point goes back nearly 40 years and is sometimes difficult to interpret and/or contradictory
- Short-term tests on highly susceptible Alloy 600 heats (with characteristic Weibull failure times < 1000 h) have been found to be unsuitable for evaluating chemistry effects
- MRP has recently completed re-evaluation of an empirical model based on statistical analysis of relevant datasets obtained by testing Reverse U-Bend (RUB) specimens of Alloy 600 steam generator tubing in simulated primary water over a limited range (320-300 ^{o}C) of autoclave temperatures
- Preliminary results are shown in the next slide

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Elevated hydrogen

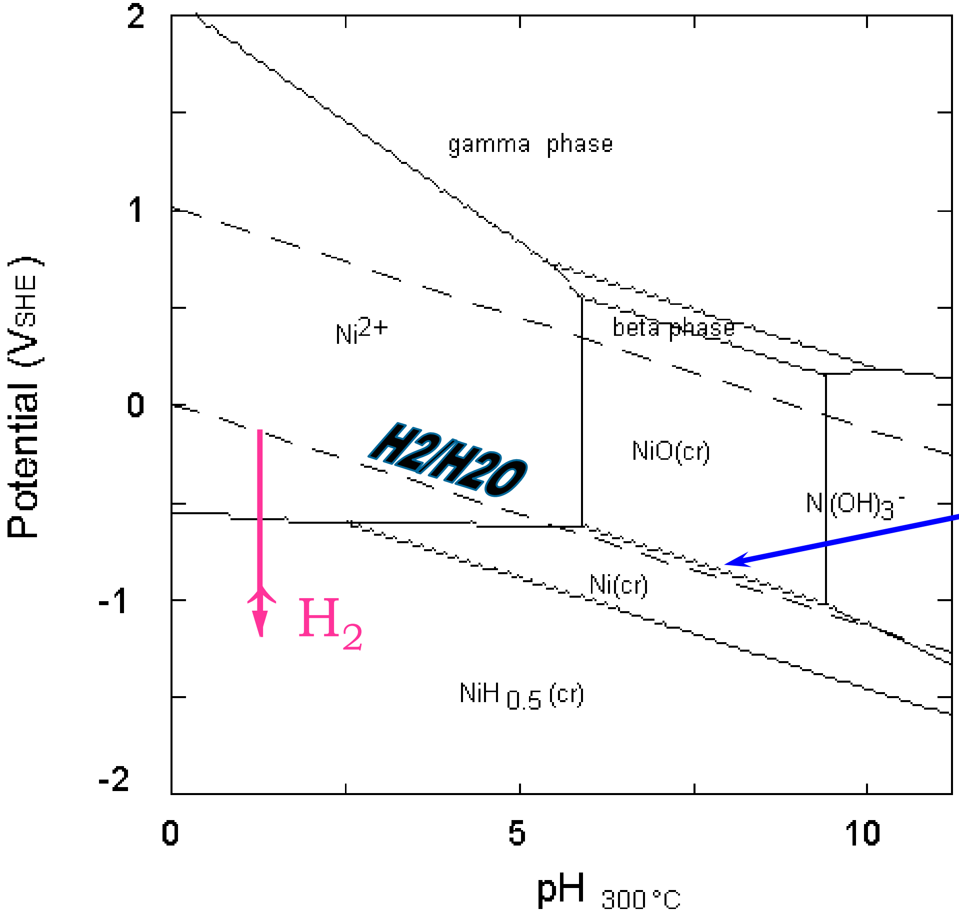
PRELIMINARY RESULTS



Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Elevated hydrogen

- Optimizing hydrogen levels in primary coolant offers valuable mitigation benefit with existing shallow cracks
- Evidence from numerous laboratory investigations shows existence of a crack growth rate (CGR) maximum near the ECP value corresponding to the Ni/NiO transition
- Mechanistically related to the role of oxide film instability in SCC, as seen for crack growth in numerous systems
- Ongoing MRP program is designed to confirm and quantify the effects of moving to higher H_2 levels via a different experimental approach, namely on-line monitoring of CGR as primary water chemistry is changed
- Preliminary results are promising

Mitigation of PWSCC in Alloys 600/182/82: “Chemical” methods: Elevated hydrogen

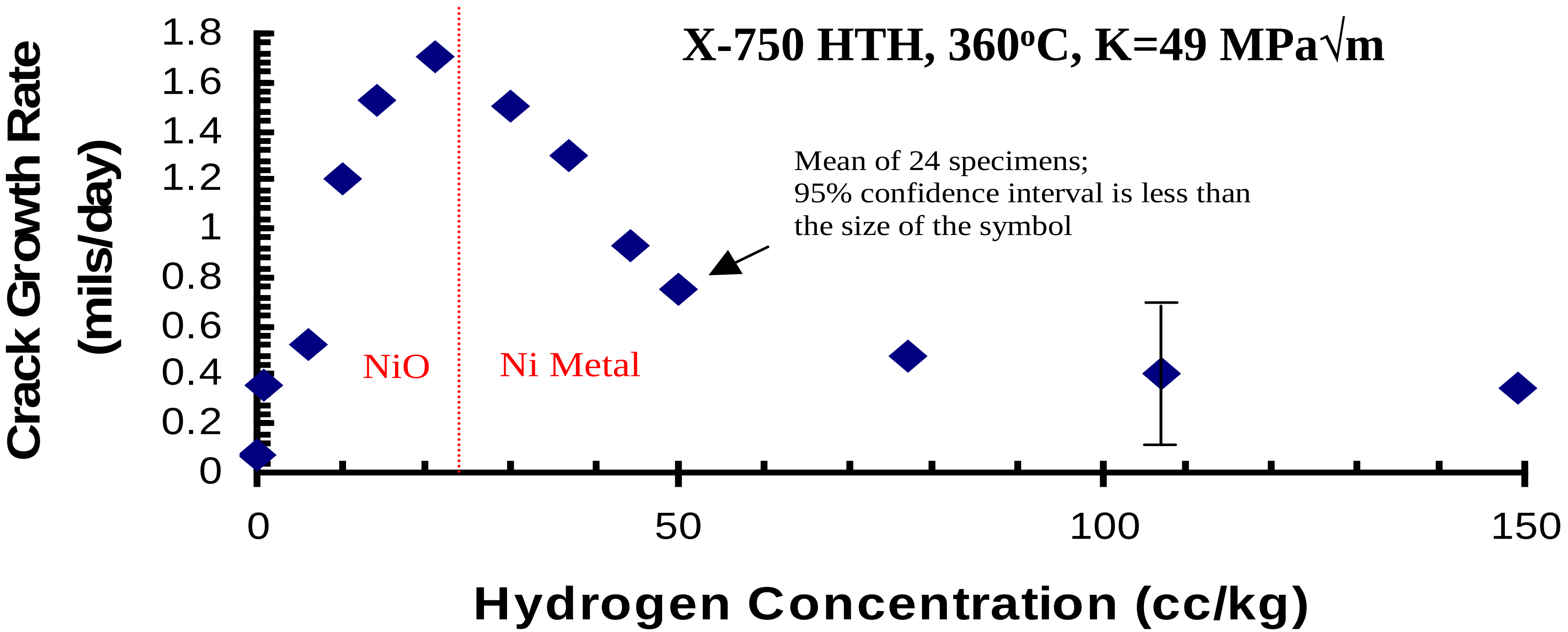


Proximity of Ni/NiO and H_2/H_2O is very important for Ni alloys

Proximity depends on H_2 & temperature but not on pH

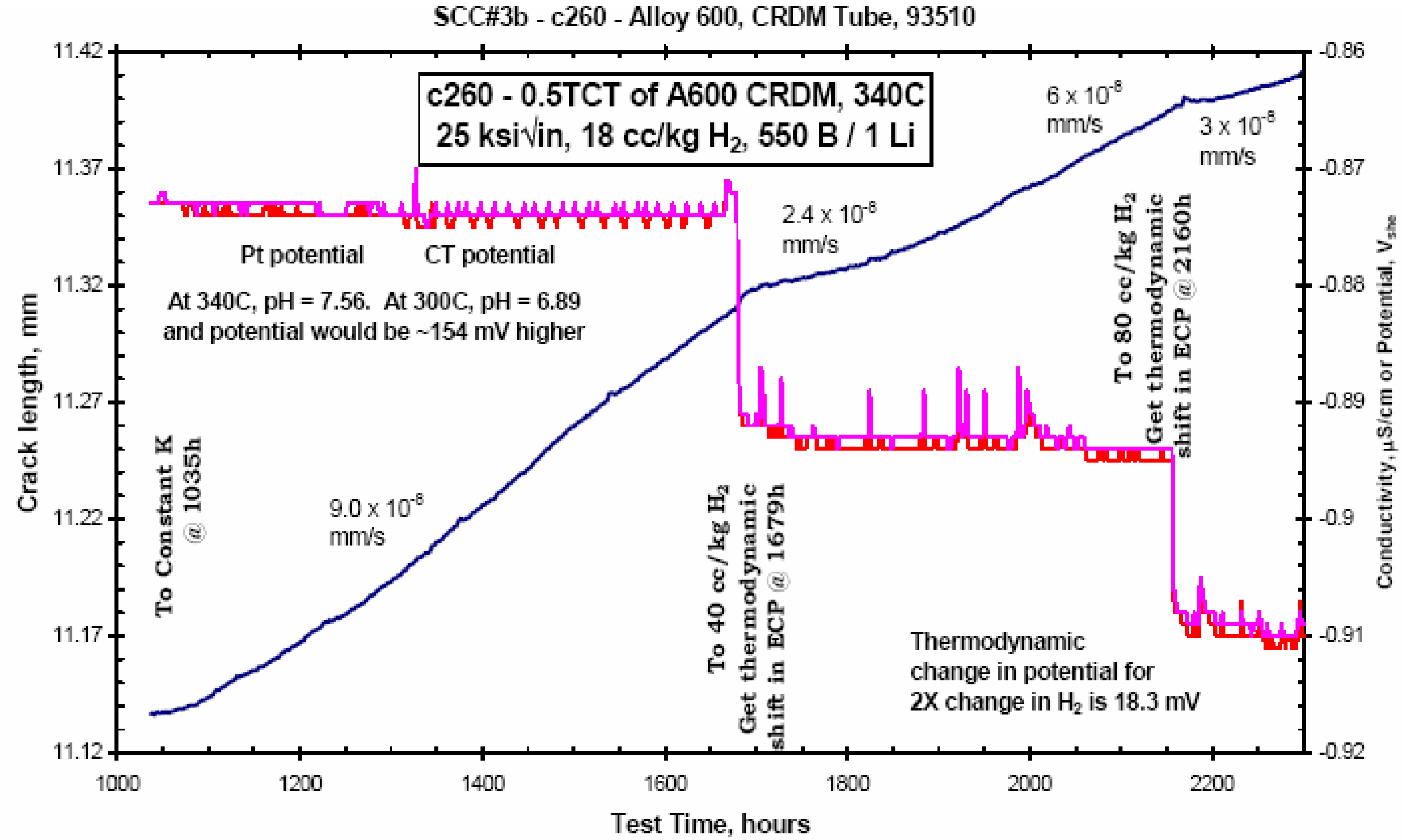
Low H_2 unwise because of radiolysis in core

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Elevated hydrogen



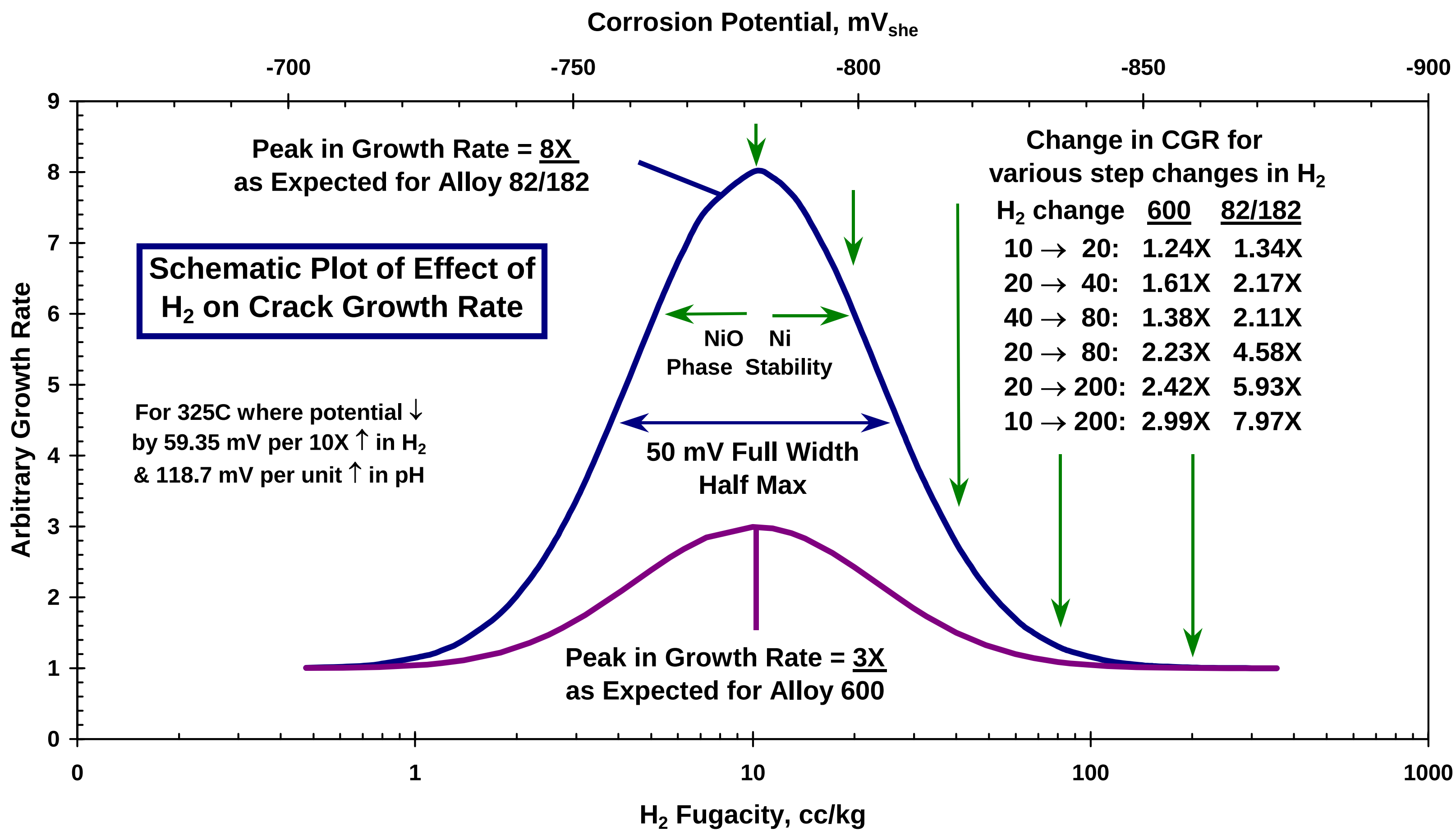
Example of recently published data from the Naval Reactor program

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Elevated hydrogen



Preliminary Alloy 600 CGR data from MRP program

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Elevated hydrogen

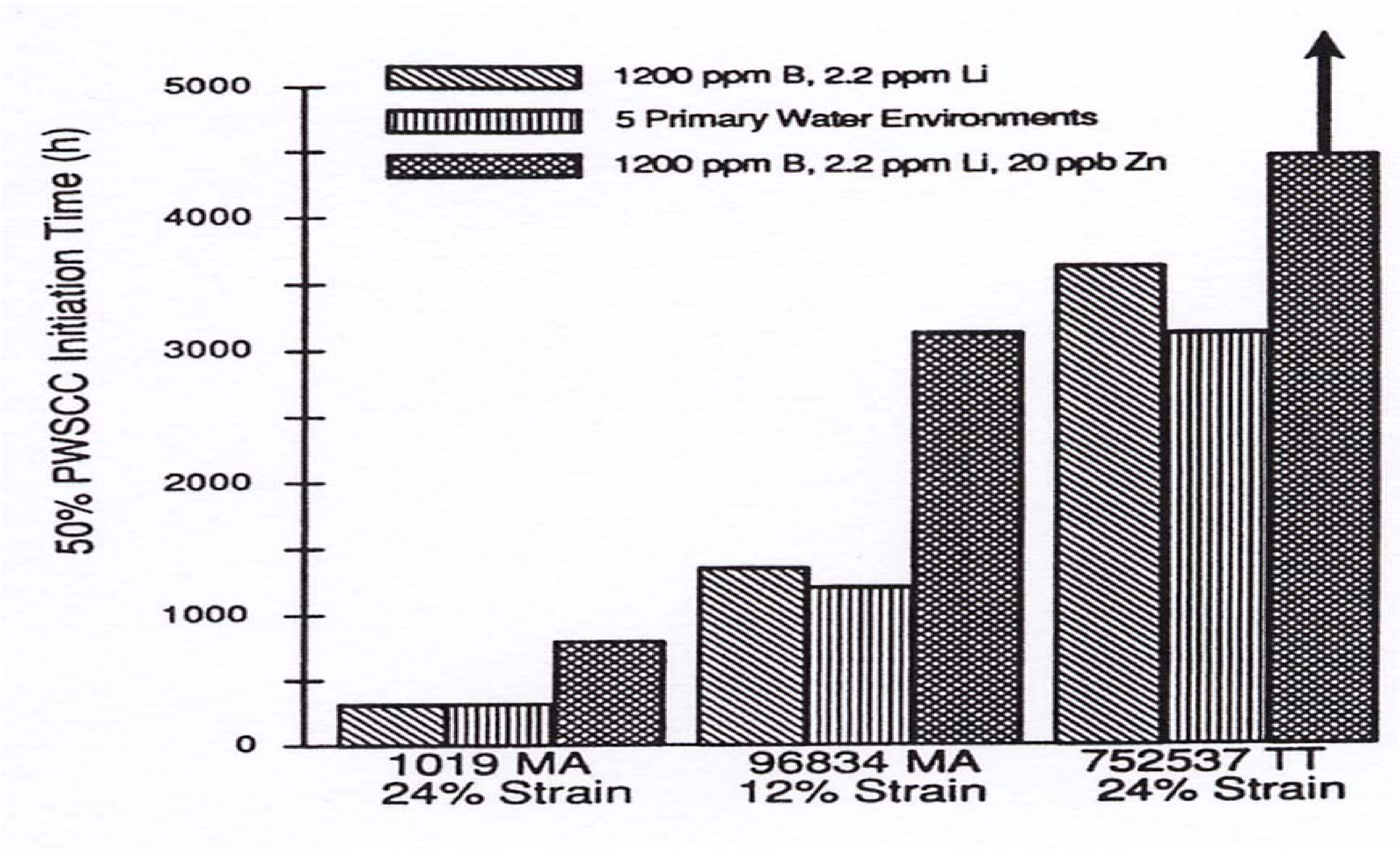


Schematic for the likely effects of hydrogen level on PWSCC

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Zinc addition

- Zinc injection has potentially significant mitigation benefit on crack initiation
- Zn is already being added to primary water in ~ 20 US plants
- Mechanism is understood: Zn displaces Co, Ni and other cations from the normal inner spinel oxides on SS and Ni-base alloys because of its higher site preference energy
- Lab data has consistently shown a reduction in PWSCC initiation by adding Zn at ~ 20 ppb level (see following slide)
- Possible that cumulative Zn exposure is more important than actual level
- Some field evidence for likely role of Zn in mitigating crack initiation is available (Diablo Canyon SGs, Farley RPV head), but more analysis is required to confirm this

Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Zinc addition



Mitigation of PWSCC in Alloys 600/182/82: "Chemical" methods: Zinc addition

- Laboratory evidence as to whether zinc additions may effectively inhibit PWSCC ***propagation*** is inconclusive, but they clearly are not detrimental
- Ongoing MRP testing program is intended to resolve this issue by following CGR on-line during dosing of Zn
- Recent high-resolution ATEM studies indicate that crack tip oxides in Ni-based alloys are complex and may vary both according to the environment and the CGR
- Possible that effective introduction of Zn into the crack tip films requires more time than is often allowed in testing
- Would be consistent with theoretical considerations (see next slide) and the work of Andresen on factors affecting Zn incorporation into Alloy 600 cracks in BWR water

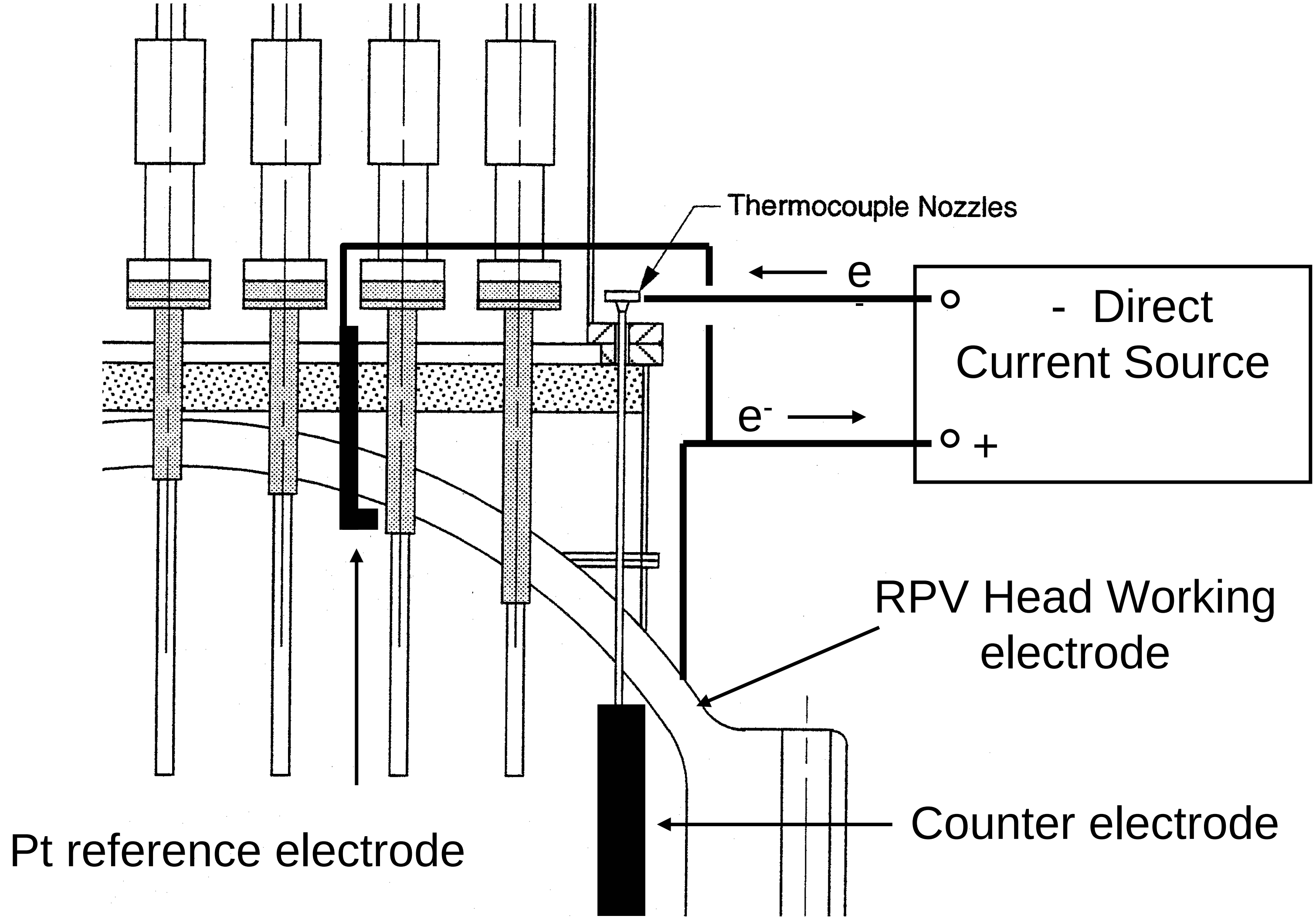
Mitigation of PWSCC in Alloys 600/182/82: Chemical Methods: Summary

- Industry is conducting work to demonstrate beneficial effect of realistic changes in existing water chemistry (e.g. H_2) on the growth of existing PWSCC cracks, and to establish the degree of mitigation which could be achieved by using modifications to water chemistry (e.g. Zn additions).
- "Chemical" methods of mitigating PWSCC offer the fundamental possibility of both delaying the initiation of cracking, and slowing down the growth of pre-existing cracks, <u>irrespective</u> of component location in the system, mechanical stresses, etc. As such the potential benefits are very large, both in terms of minimizing inspection burdens and avoiding component repair or replacement.

Mitigation of PWSCC in Alloys 600/182/82: Novel Methods

- Experimental work on the feasibility of using impressed current (anodic protection) to mitigate PWSCC in process at the Colorado School of Mines (CSM)
- Work at EDF on proof-of-concept testing of an EPRI patented process for PWSCC mitigation using Cr surface enrichment is near conclusion

Mitigation of PWSCC in Alloys 600/182/82: Novel Methods: Anodic Protection Schematic



Mitigation of PWSCC in Alloys 600/182/82: Novel Methods: Stabilized Chromium Process

- The three-step EPRI "Stabilized Chromium Process (SCrP)" results in a thin Cr enriched layer (to ~ 90 weight %) from a depth of about 3 – 40 A
- SCrP has been successfully applied to various replacement components, and the virtues of this process have been demonstrated in a number of field applications
- MRP has recently concluded testing using RUB specimens exposed to simulated PWR primary coolant conditions to evaluate the technology for potential mitigation of PWSCC. Preliminary results appear favorable.

Mechanical Mitigation

- Preemptive Weld Overlay (PWOL)
- Cavitation Peening
- Mechanical Stress Improvement (MSIP)

Problem Statement

- Cracking/Leakage observed domestically and internationally in several plants
- Inspection Issues
  - Inspection of dissimilar metal butt welds a challenging task
  - Some design details render welds virtually un-inspectable
  - MRP-139 recently issued – requires augmented inspections

PWOLs - Applied Preemptively to Uncracked Welds

- Mitigate potential future PWSCC in susceptible locations by two means:
  - Residual Stress Reversal (ID stresses either neutral or compressive)
  - Structural Reinforcement with Resistant Material
- Extend inspection intervals and improve inspectability
  - PWSCC Mitigation permits return to ASME Section XI (or RI-ISI) inspection intervals
  - Overlaid weld inspection easier to qualify for and perform than original DMW

PWOL Design Requirements

- Weld Overlay Structural Sizing
- Residual Stress Improvement
- Inspectability Considerations
- Fatigue Considerations

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]**

Current EPRI/MRP PWOL Demonstration Program

- Development And Testing Of Preemptive Weld Overlay Mitigation Techniques For PWSCC - Tasks
  - Finite Element Analysis
  - Mockup Fabrication
  - Application of Preemptive Weld Overlay (PWOL)
  - Residual Stress Measurements and Metallography
  - Examination and Inspection

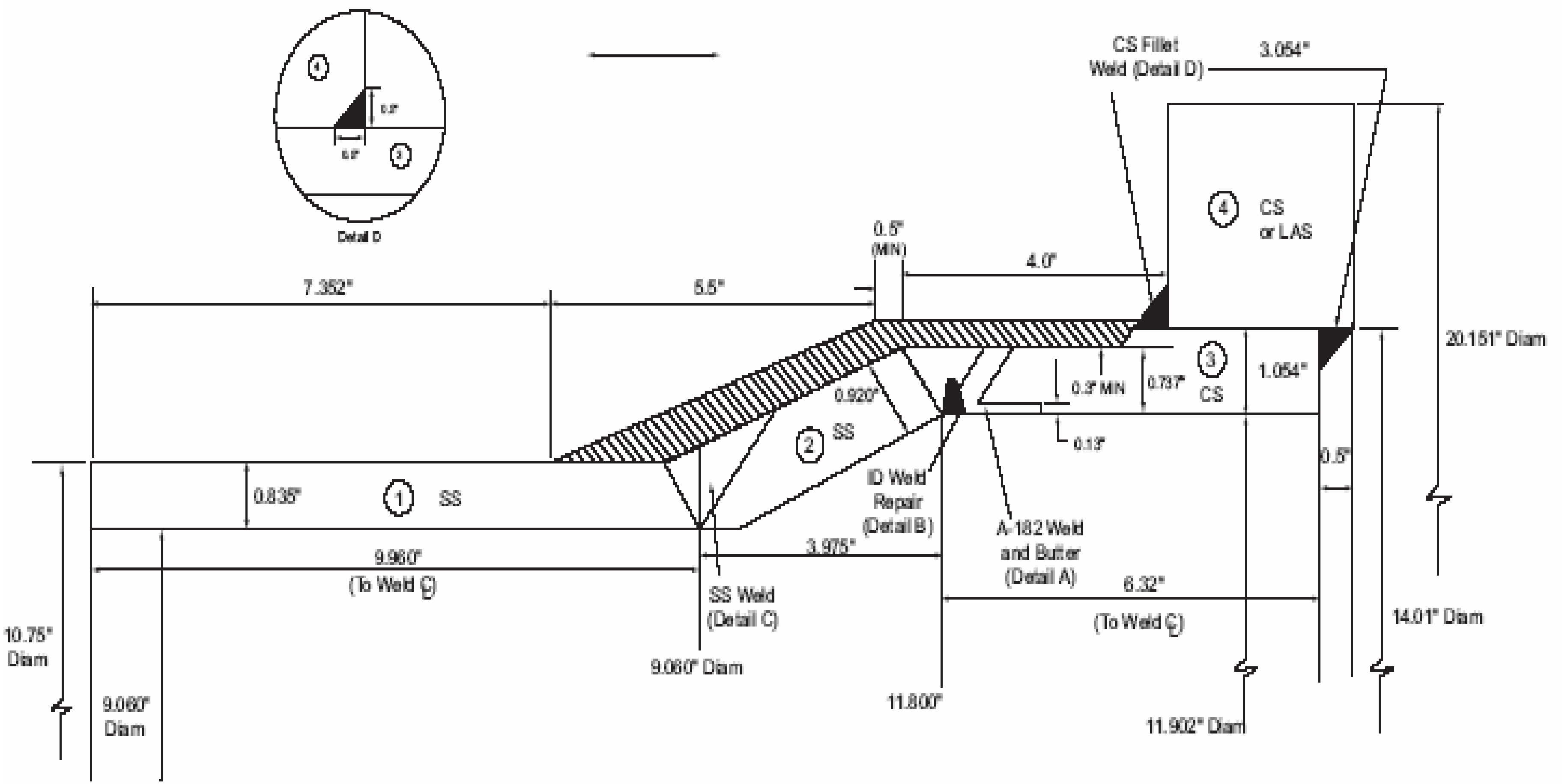
WOL Verification References

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

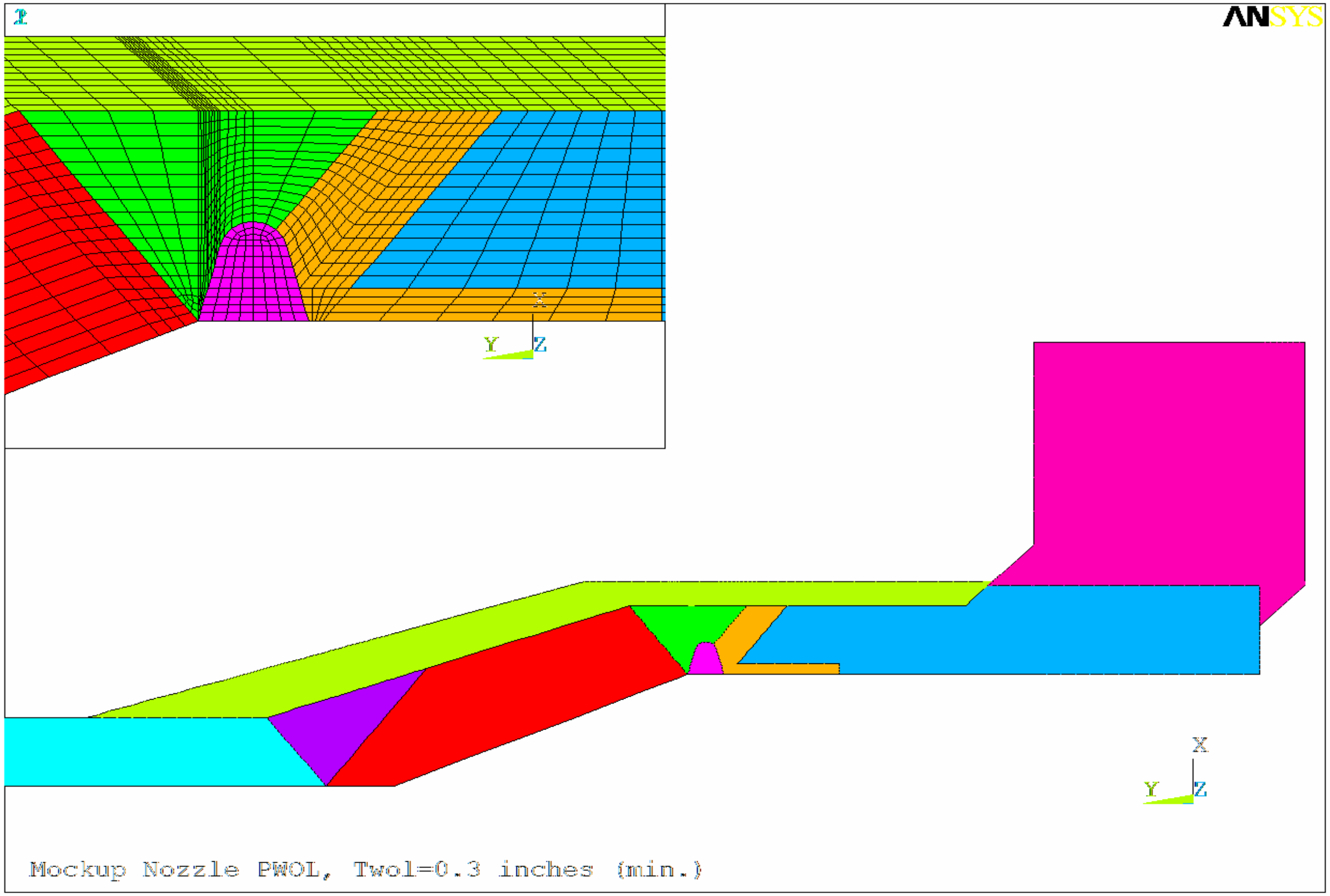
Experience with Weld Overlays for DM Welds

Date	Plant	Component
Spring 2005	DC Cook Unit 1	Pressurizer Safety Nozzle
February 2005	Calverts Cliff Unit 2	Hot Leg Drain and Cold Leg Letdown Nozzles
April 2004	Susquehanna Unit 1	Recirculation inlet and outlet nozzles
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, Recirculation outlet, and CRD return nozzles
October 2002	Oyster Creek	Recirculation outlet nozzle
December 1999	Duane Arnold	Recirculation inlet nozzle
June 1999	Perry	Feedwater nozzle
June 1998	Nine Mile Point Unit 2	Feedwater nozzle
October 1997	Hope Creek	Core spray nozzle
March 1996	Brunswick Units 1 &2	Feedwater nozzle
February 1996	Hatch Unit 1	Recirculation inlet nozzle
January 1991	River Bend	Feedwater nozzle
March 1986	Vermont Yankee	Core spray nozzle

PWOL Mockup Drawing

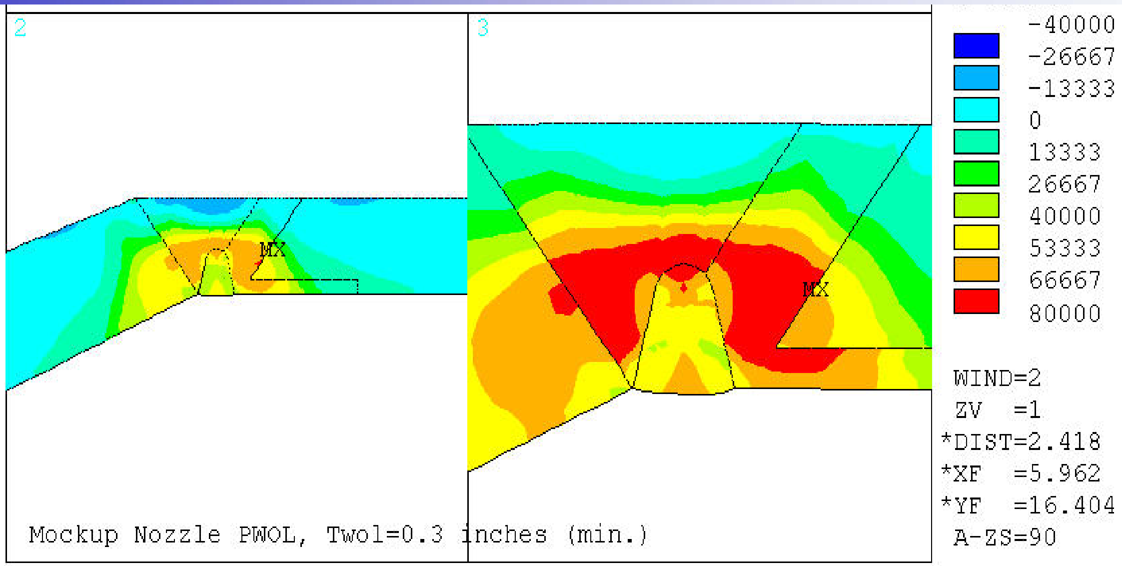


PWOL Mockup
Finite Element Model

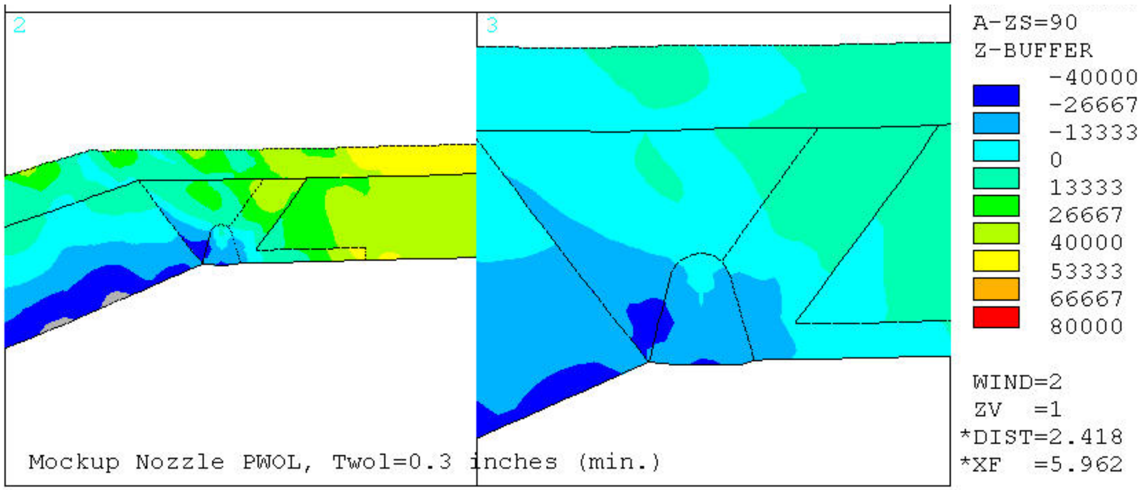


PWOL Mockup Residual Stress Results
Hoop Stresses (Preliminary)

Pre-PWOL

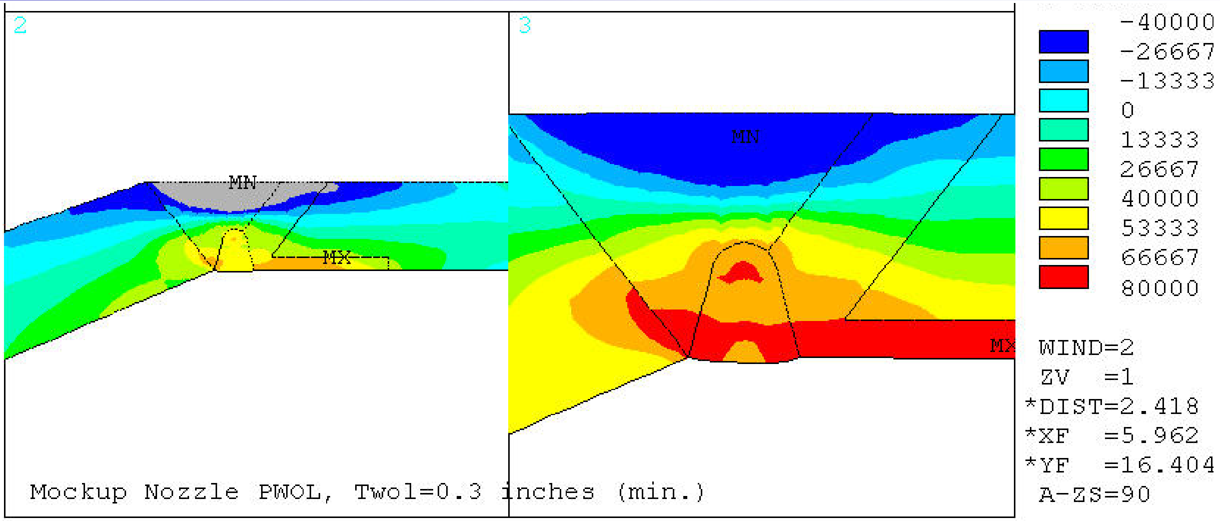


Post-PWOL

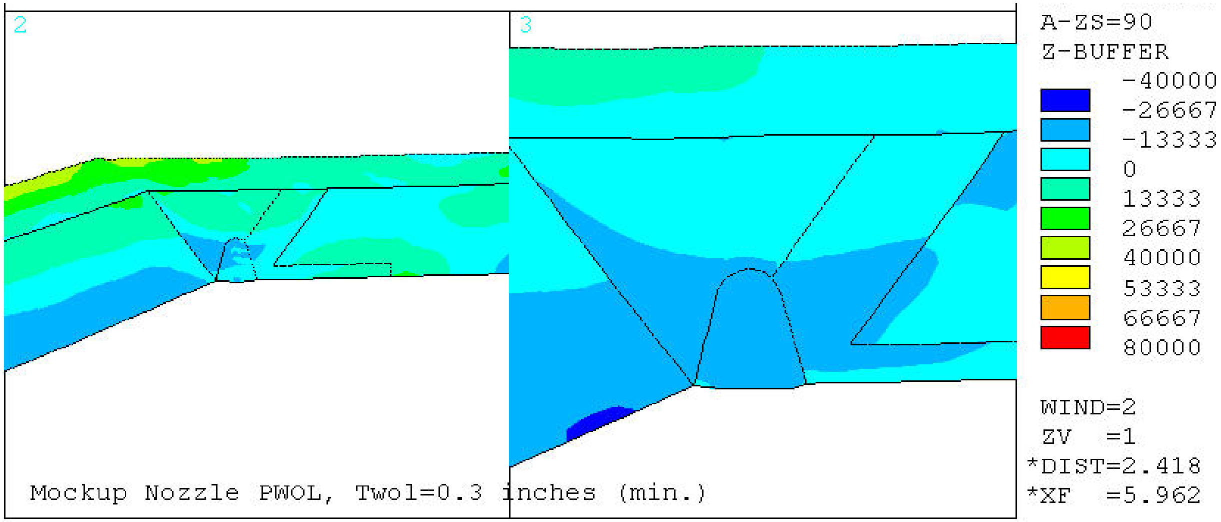


Mockup Residual Stress Results Axial Stresses (Preliminary)

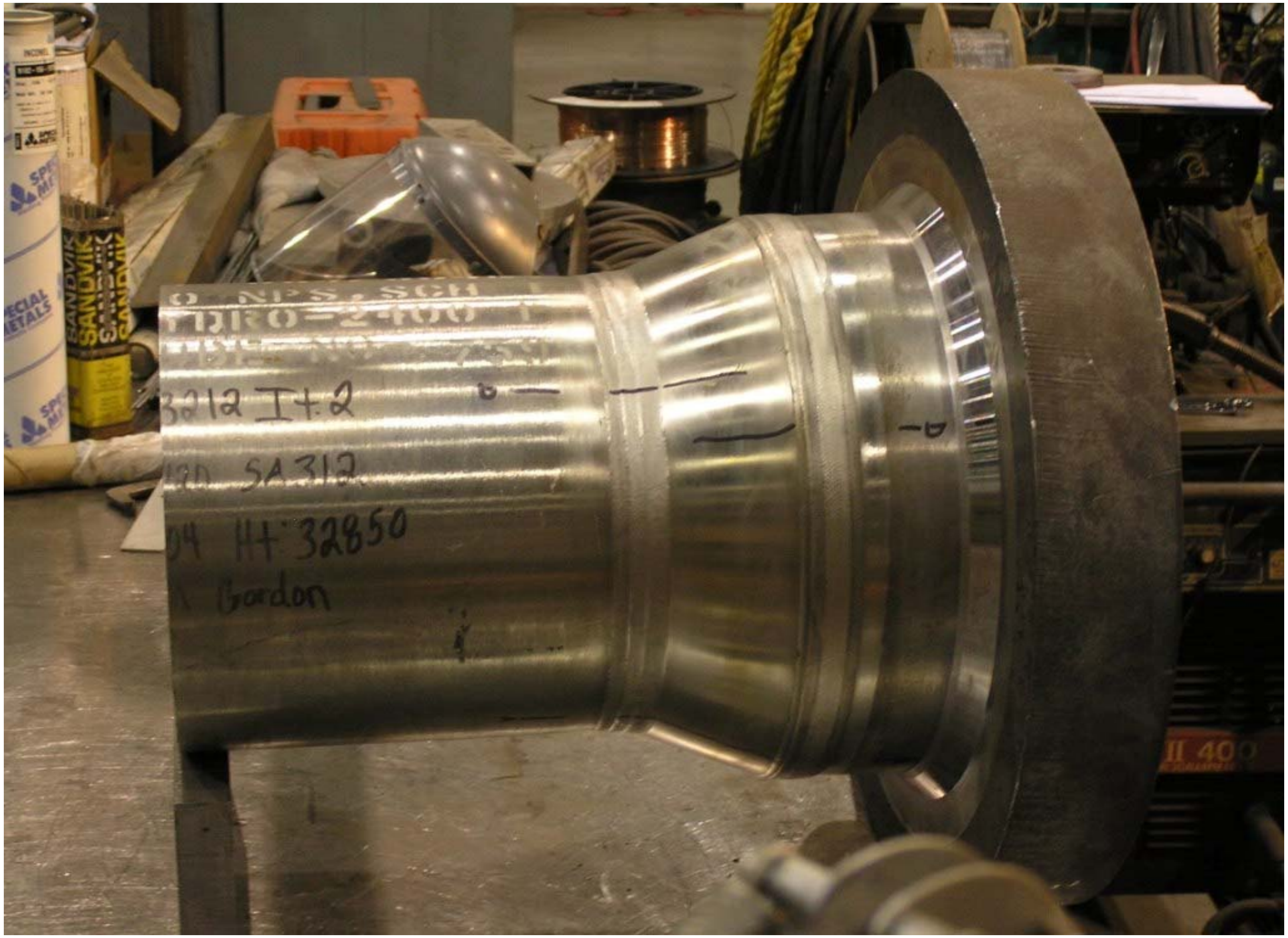
Pre-PWOL



Post-PWOL



PWOL Mockup
(Before Application of Overlay)



Mockup Inside Surface
(Showing Simulated Construction Repair)

PWOL Mockup
with Partial Weld Overlay in Place

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)
- Preemptive WOLs justify:
  - ASME Code Inspection Intervals
  - Inspection coverage consistent with current WOL requirements
- Current EPRI/MRP PWOL Mockup Program Underway
  - Validate residual stress analysis
  - Provide metallurgical and chemical data
  - Provide mockup for NDE demonstration

Cavitation Peening

- EPRI MRP is pursuing studies to evaluate the effectiveness of cavitation peening for PWSCC mitigation
- Other peening processes (laser and water jet) are available and have been used in the field (both international and domestic) – these processes will be discussed in our final evaluation.

Cavitation Peening – General Info.

- Cavitation Peening - Method of Inducing Residual Compressive Stresses in Metal Components
- Process -
  - Manipulation of Ultra High-pressure Water Jets
  - Promote Cavitation Bubble Formation and Collapse on the Surface
- Benefits -
  - Shock of the Collapsing Bubbles Results in Residual Compressive Stresses
  - Measurements have shown No Weight Loss or Change in Surface Finish
  - Enhance Fatigue Life, Improve Damage Tolerance and Provide Resistance to SCC
- Equipment –
  - Commercially Available Ultra-high Pressure (UHP) Water Pumps
  - Custom Cavitation Peening Nozzle and delivery systems to Move the Jet Over the Surface to Be Peened.

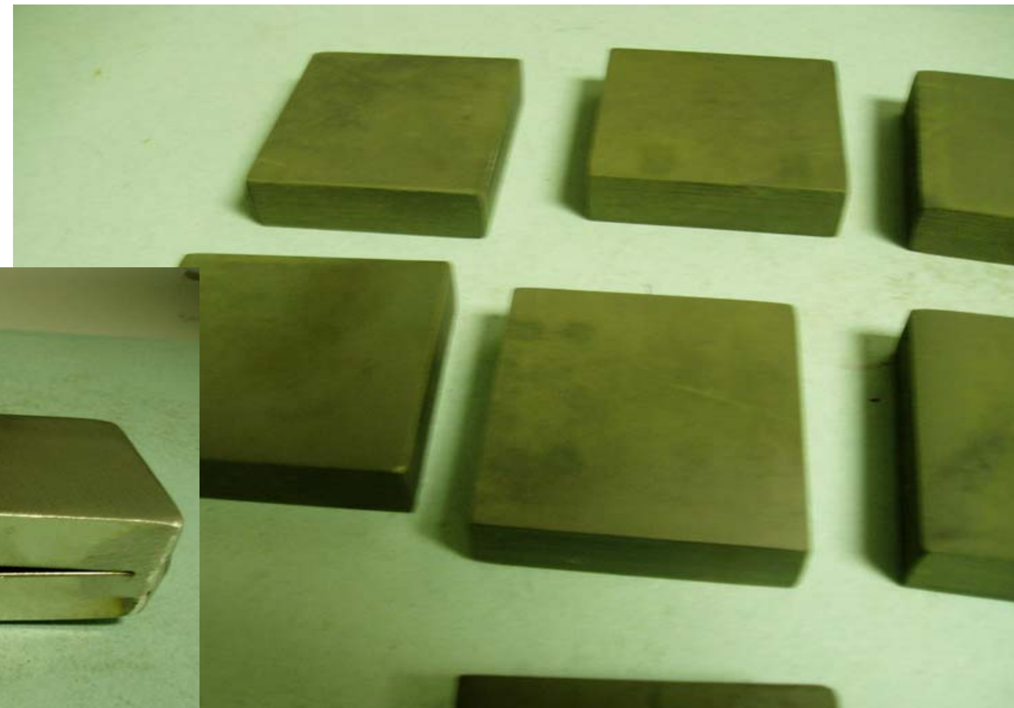
Cavitation Peening – General Info.

- Cavitation Peening is a New Technology That Shows Promise as a Mitigation Technology
- Test Results have shown Compressive Residual Stresses can be Imparted to about 0.040” in SS
- Technology is Mature (Used in Aerospace Industry)
- Process is as “energetic” as Abrasive Water Jet Conditioning and other similar processes
- Can be Used in RCS Both for Lower Head and Main Coolant Loop Dissimilar Metal Welds
- Evaluating use for J-groove Weld Wetted Areas

Cavitation Peening ~ Scope of Work

- Process Validation
  - Sample Fabrication, Surface Treatment, Stress analyses and profile, Metallurgical Evaluations
- Test Program to Demonstrate Results for:
  - Alloy 600 Plate
  - Butt Welds
    - 82/182/Alloy 600 Weldments
  - J-groove Welds
    - Low Alloy Steel/52/152/Alloy 690 Weldments
- Development of Tooling
  - Basic tooling and technology appears available for Butt welds and flat plate.
  - Establish tooling to address limited access locations, such as BMN or CRDM inside surfaces.

Plate and Weld Specimens



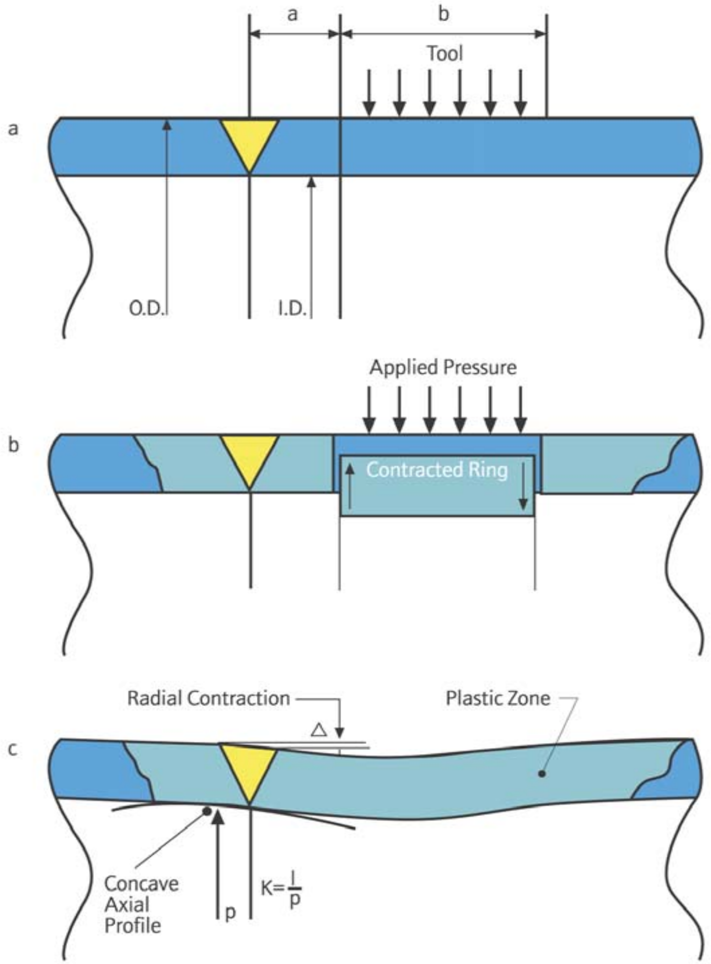
Mechanical Stress Improvement Process

MSIP

- What is it?
  - Mechanical Stress Improvement Process involving a hydraulic "squeeze" of a pipe weldment region to remove tensile stress and generate compressive stress
- Benefits:
  - Prevents stress corrosion crack (SCC) initiation
  - Arrests existing SCC growth
  - Cost effective means of mitigation
  - Minimal outage schedule impact
  - Accepted by NRC as mitigation technique for SCC
- Disadvantage:
  - Requires a qualified inspection. Can not be applied in the presence of flaws >= 30% through-wall

MSIP is a patented mechanical process that prevents or mitigates SCC in piping...

- MSIP
  - Mechanically contracts the pipe on one side of weldment
  - Replaces residual tensile stresses with compressive stresses
- MSIP mitigates SCC in:
  - RV nozzles / SG nozzles
  - Pressurizer attachments
  - Safety Injection nozzles

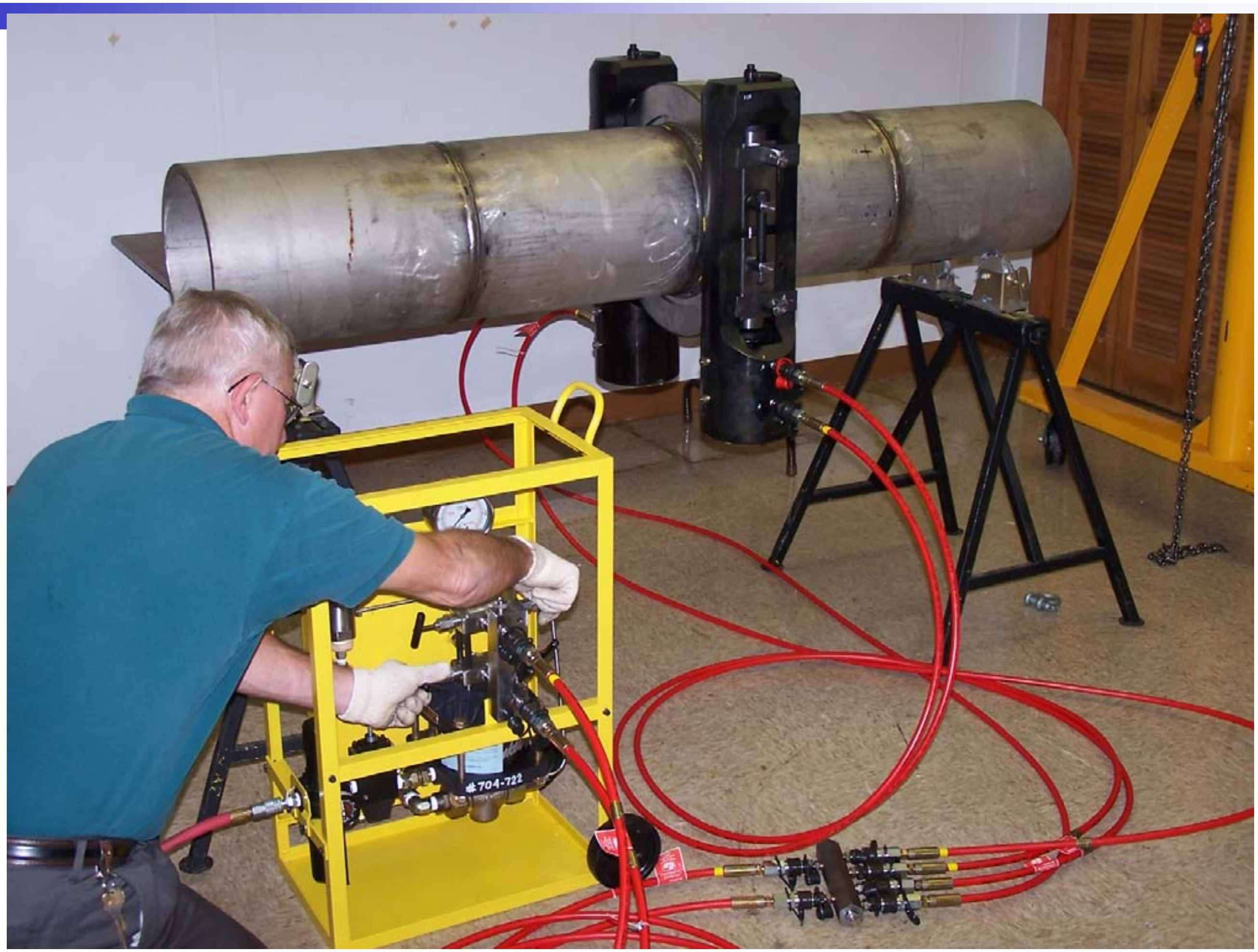


…and has been accepted by the NRC

- Verified by Argonne National Laboratory & EPRI
- Accepted by the NRC (NUREG 0313, Rev. 2)

- MSIP has been used since 1986 on over 1300 welds
  - More than 500 nozzle safe-ends
  - Over 30 BWRs & 2 PWRs (V.C. Summer & Palisades)
- Applied to welds *without* and *with* SCC
- No new indications found in MSIP-treated welds
  - Pre-existing cracks arrested
  - No crack growth after MSIP

Typical MSIP Equipment



WOG Phase 1
MSIP FTE & Accessibility Evaluation for Pressurizers

- Complete FEA stress analysis for
  - Safety/relief, spray & surge nozzles for WE & CE pressurizers
  - RCS surge, shutdown cooling & drain line nozzles for CE
- Preliminary MSIP tool & installation equipment design
- A number of plant walk downs
- Completed June 2004
- Results of analysis
  - Post-MSIP stresses will be in compression at the ID of the weld region

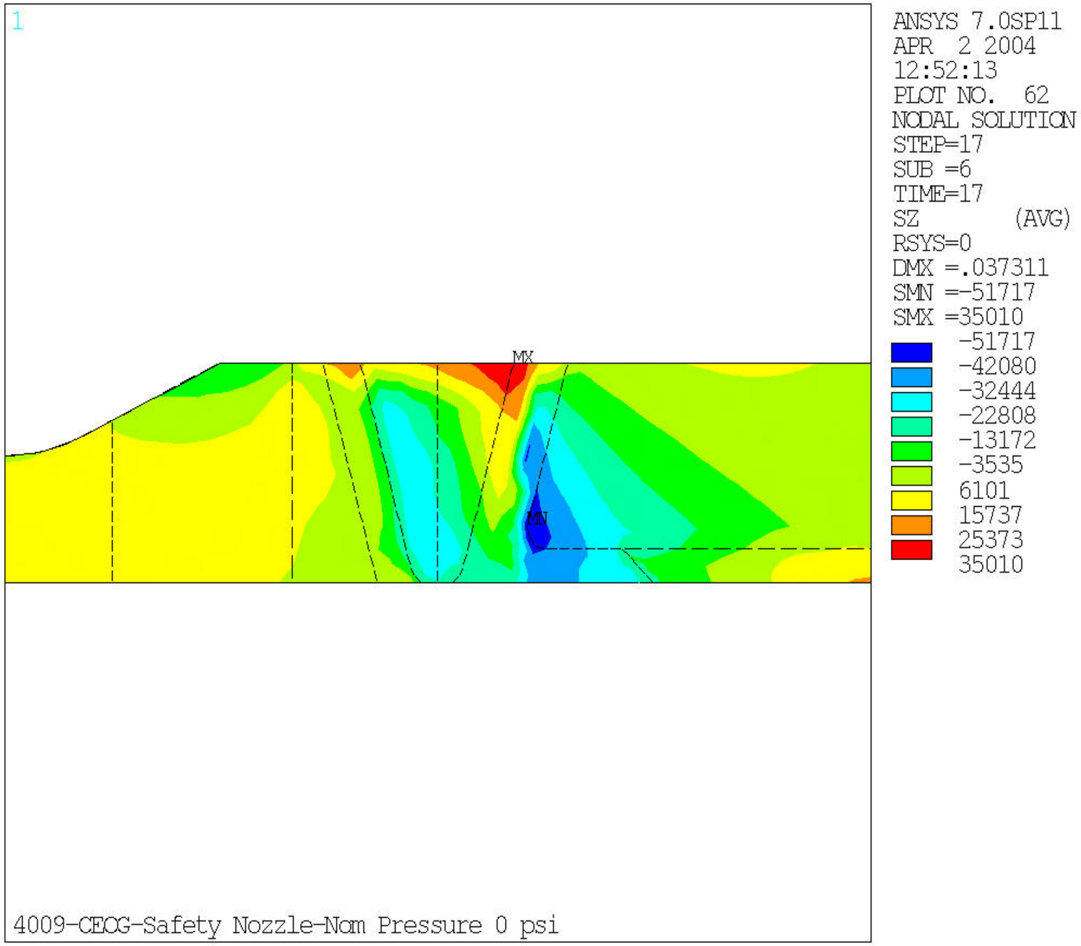
WOG Phase 2
MSIP - Engineering & Qualification for Pressurizers

- Engineering & licensing evaluations
  - Structural, flow, fatigue, LOCA, & generic 50.59a
- Detailed design & fabrication of MSIP tooling, lifting & handling equipment
- Qualification & testing of MSIP tooling, lifting & handling equipment
  - Representative safe end mockups
  - Functional and load tests
  - Strain gage tests

WOG Phase 2 (continued)
MSIP - Engineering & Qualification for Pressurizers

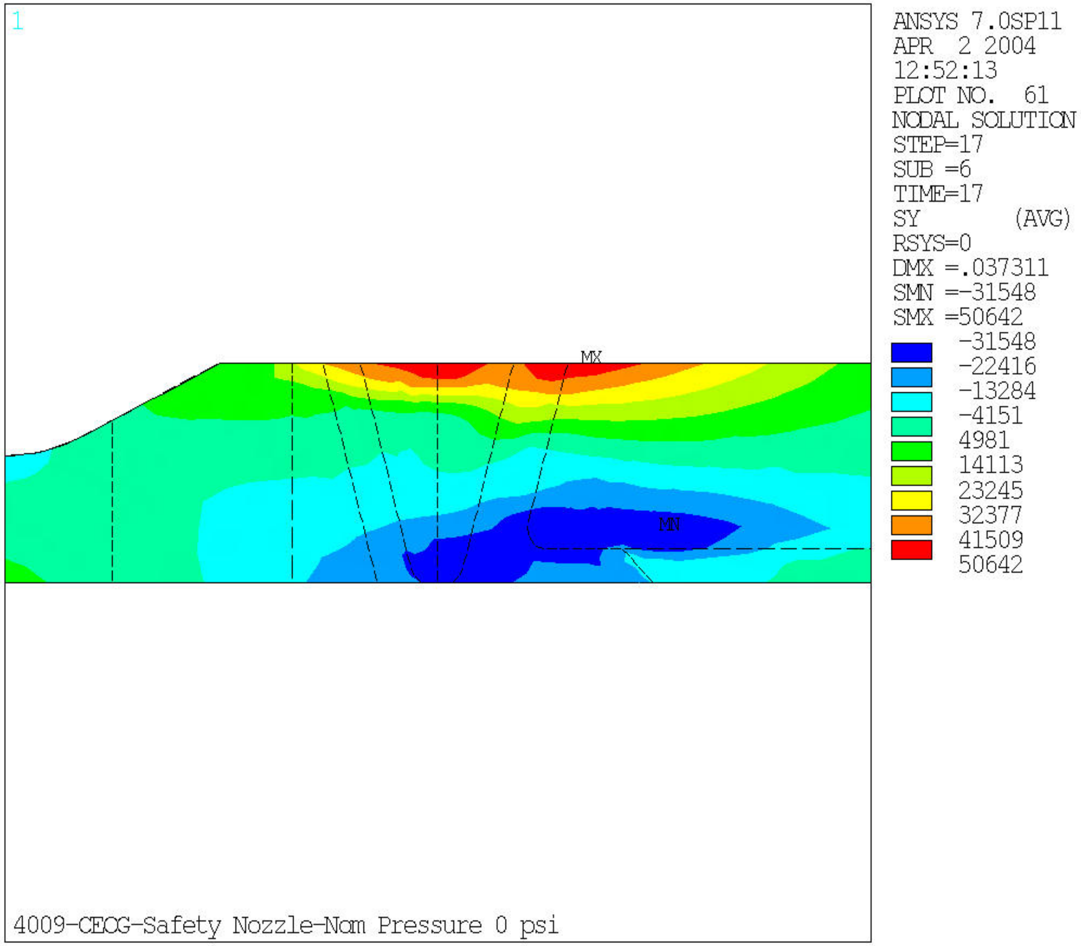
- Generic procedures and implementation parameters
  - Training procedure
  - Application parameters
  - Engineering & qualification report
- Results
  - Qualification tests confirm we have compression at the ID of the weld region
  - Tooling and handling equipment has been qualified for use
  - Report to be completed June 2005

Typical Safety Nozzle Post-MSIP
Hoop Stress – N/SE Weld



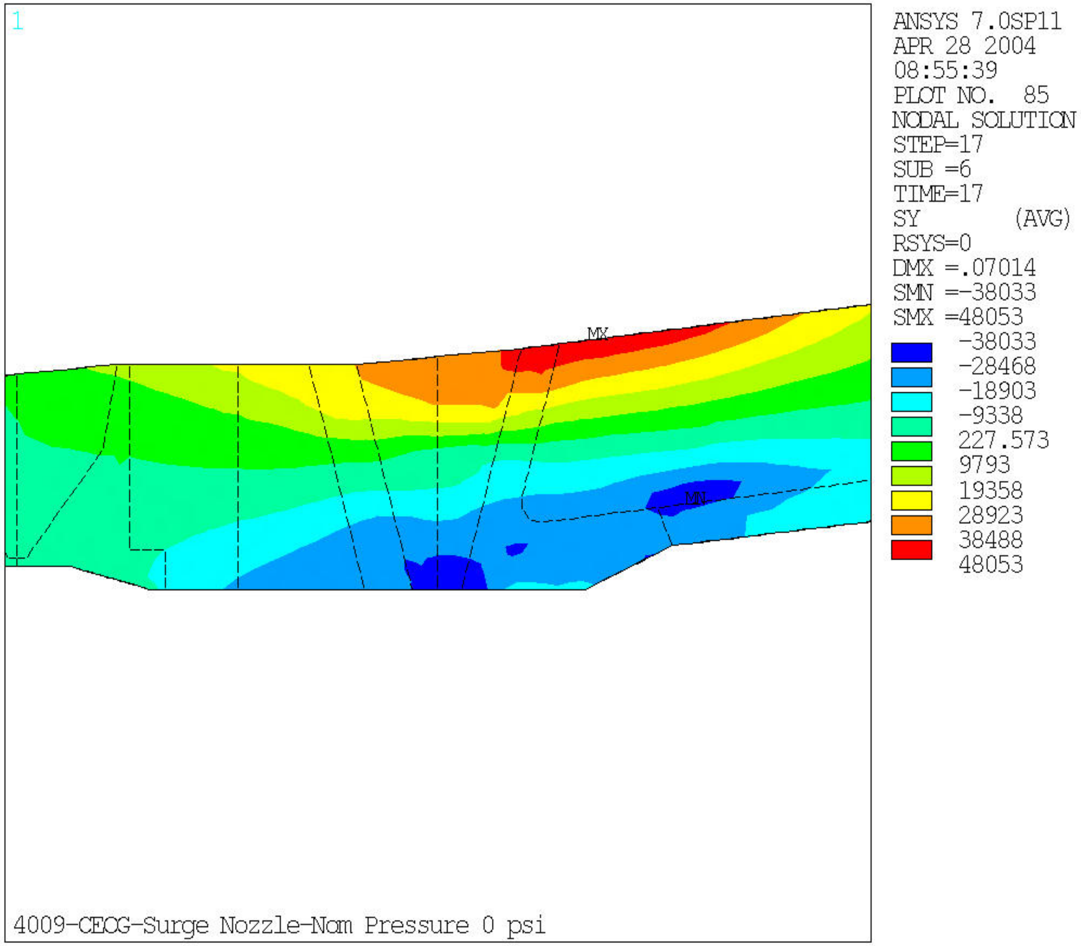
Typical Safety Nozzle Post-MSIP

Axial Stress – N/SE Weld



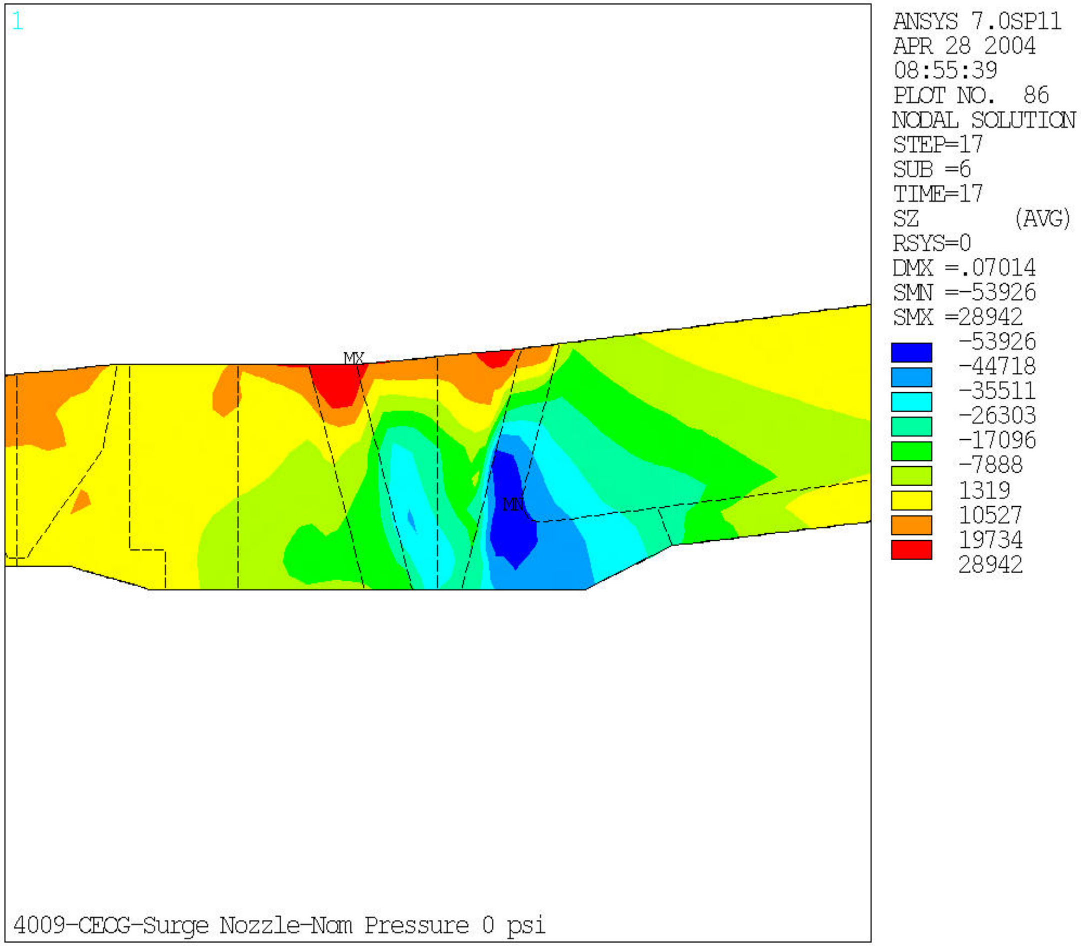
Typical Surge Nozzle Post-MSIP

Axial Stress – N/SE Weld



Typical Surge Nozzle Post-MSIP

Hoop Stress – N/SE Weld



Summary

- The NRC accepted this technology in NUREG-0313, Revision 2 as a stress improvement process for mitigation of SCC in BWR’s. Operating experience demonstrates mitigation via MSIP is successful.
- The WOG program provides data which qualifies MSIP for PWR applications.
- The WOG will consider submitting the results from these studies to the NRC for information. There are no current plants to request additional NRC approvals on this technology.