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Materials Reliability Program: Mechanical Stress Improvement Process (MSIP) Implementation and Performance Experience for PWR Applications (MRP-121)

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Technical Report

Materials Reliability Program: Mechanical Stress Improvement Process (MSIP) Implementation and Performance Experience for PWR Applications (MRP-121)

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Final Report, June 2004

EPRI Project Manager
S. Findlan

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Structural Integrity Associates, Inc.

AEA Technology Engineering Services, Inc.

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CITATIONS

This report was prepared by

Structural Integrity Associates, Inc.
3315 Almaden Expressway, Suite 24
San Jose, CA 95118

Principal Investigator
R. Smith

AEA Technology Engineering Services, Inc.
241 Curry Hollow Road
Pittsburgh, PA 15236

Principal Investigators
M. Badnani
T. Damico

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PRODUCT DESCRIPTION

The EPRI pressurized water reactor (PWR) Materials Reliability Program (MRP), the Mitigation Working Group of the Alloy 600 Issue Task Group (ITG), has initiated this effort to evaluate the potential of emerging and available mitigation techniques as remedial measures for primary water stress corrosion cracking (PWSCC). Among the measures to be identified are the mechanical, non-environmental methods that have been developed previously as mitigation measures for intergranular stress corrosion cracking (IGSCC) in boiling water reactors (BWRs). This effort is focused on the stress remedies (such as heat-sink welding or mechanical stress improvement, corrosion-resistant cladding weld overlay, and induction heating stress improvement) as well as on potential emerging technologies that can be applied to existing installed components.

This task evaluated the capabilities and limitations of existing remedial mechanical technologies that address PWSCC of nickel-based alloys. The Mechanical Stress Improvement Process (MSIP[1]) technology was evaluated.

Results and Findings

This report contains:

- A detailed review of MSIP field applications and related performance data, including nondestructive evaluation (NDE) reports, field lessons learned, and presentation of relevant data in MSIP experience tables for pressurized water reactors (PWRs)
- A compilation post-MSIP of residual stress contour plots from finite element analyses
- A detailed review of MSIP qualifications/demonstrations completed for PWRs to provide a description of MSIP tooling developed, MSIP application results, and strain gage test data

Challenges and Objectives

This report is of value to technical and management personnel tasked with finding solutions and evaluating costs for mitigating components susceptible to PWSCC. There are no apparent challenges to the application of this process.

Applications, Values, and Use

The report provides information to aid an owner in evaluating mitigation in lieu of costly repair and replacement of components subject to PWSCC.

Based on the materials and configuration of PWR nozzle weldments, the analysis, inspection, and testing results demonstrate that MSIP can generate high-axial and hoop-residual compressive

[1] MSIP is a trademark of AEA Technology Engineering Services, Inc.

stresses in the inner region of the Inconel weld and nozzle butter. Generation of such a compressive stress field will protect the weldment against crack initiation and will arrest any shallow pre-existing cracks.

EPRI Perspective

The report contains technical information for EPRI members that would not be available to the general public given its proprietary nature from an economic perspective.

Approach

The goals of this report were to review new technologies and define a test program to qualify the MSIP process and to make it available for PWR applications for mitigating PWSCC. Those goals were met and are represented by the results and information included in the report.

Keywords

Mechanical stress improvement process (MSIP)
Mitigation
Primary water stress corrosion cracking (PWSCC)
Pressurized water reactor (PWR)

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1
INTRODUCTION

The Mechanical Stress Improvement Process (MSIP[1]) is a mechanical process developed by AEA Technology Engineering Services, Inc. and protected by U.S. Patent Nos. 4,683,014 and 4,612,071 for mitigating stress corrosion cracking (SCC). MSIP is accepted by the United States Nuclear Regulatory Commission (NRC) [1] as a stress-improvement (SI) process for mitigation of intergranular stress corrosion cracking (IGSCC) in boiling water reactor (BWR) plants.

The application of MSIP has been extended to pressurized water reactors (PWRs) where it was used to mitigate SCC in some Inconel welds at Palisades Nuclear Plant, and more recently at VC Summer Nuclear Station. An MSIP program has recently been completed to qualify the process for application to the pressurizer surge nozzle-to-safe-end weld at Tihange 2-TSP.

[1] MSIP is a trademark of AEA Technology Engineering Services, Inc.

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SCOPE OF WORK

The scope of work for this study included the following tasks:

- Contact utilities to obtain approval for release of relevant plant-specific information.
- Conduct a detailed review of MSIP field applications and related performance data, including nondestructive evaluation (NDE) reports, field lessons learned, and presentation of relevant data in MSIP experience tables for PWRs.
- Compile post-MSIP residual stress contour plots from finite element analyses.
- Conduct a detailed review of MSIP qualifications or demonstrations completed for PWRs to provide descriptions of MSIP tooling developed, MSIP application results, and strain gage test data.

3

DESCRIPTION OF THE PROCESS

MSIP removes residual tension occurring in weldments due to the welding process, and generates axial and hoop compressive stresses in the weld and heat-affected zones (HAZs) at the inner region of the piping wall. MSIP application involves the use of simple hydraulically actuated tools that provide a slight permanent contraction of the pipe on only one side of the weld. Only a lightweight, portable air-operated pump is used as an energy source. The ease of application, low labor cost, low radiation exposure, and lack of interference with other activities are typical advantages of MSIP.

The basic concept of MSIP is illustrated in Figure 3-1. The pipe is contracted locally in the direct vicinity of the circumferential weld, as shown in Figure 3-1(A). Contraction of the pipe and the position of the tool are such that the plastic zone generated during application of the process extends throughout the susceptible region of the weldment. Compatibility of the deformation along the pipe, illustrated in Figure 3-1(B), then requires the axial profile of the pipe in the weld root region to become concave. The resulting negative axial curvature and corresponding reduction of the pipe radius in the vicinity of the weld location generates residual compressive stresses at the inner region of the piping in both the axial and hoop directions.

The process can be applied to pipes, elbows, safe ends, or nozzles with or without the presence of contained water. Performance can easily be verified by physically measuring the pipe circumference. Unlike thermal processes, MSIP imposes only compressive strains and does not include severe thermal gradients. Hence, the use of MSIP is particularly advisable for weldments that include geometrical material discontinuities, such as nozzle-to-safe-ends, and for weldments with shallow (that is, less than about 30% through-wall) pre-existing cracks.

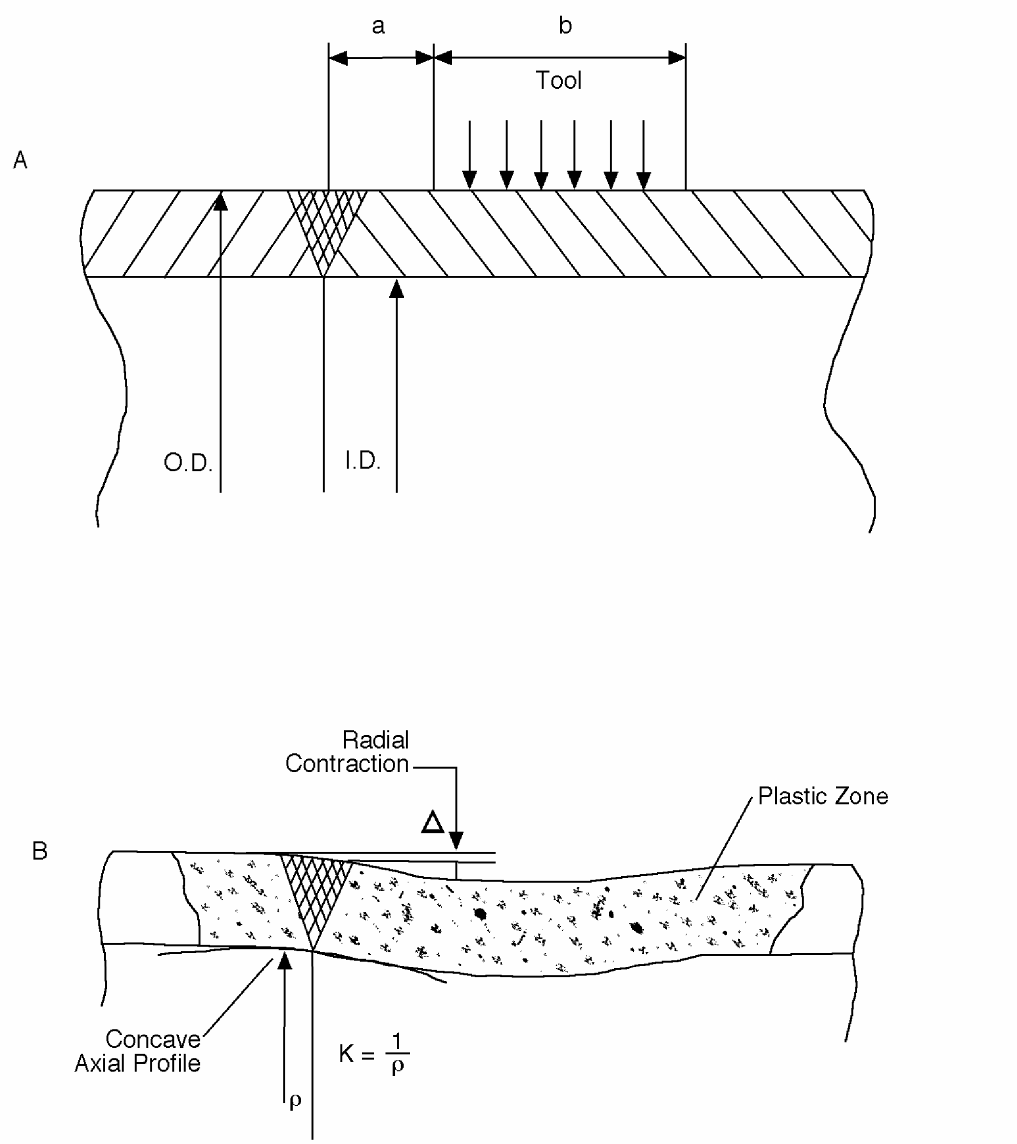

Figure 3-1
Basic Concept of MSIP

4

TOOLS DEVELOPED AND PROCESS APPLICATION

Four basic types of tools have been used for applying the process as shown in Figures 4-1, 4-2, 4-3, and 4-4. The stud tensioner tool shown in Figures 4-2 and 4-3 is typically used for standard weldments such as pipe-to-pipe or pipe-to-elbow joints for sizes up to 14 in. (356 mm) in diameter.

In the second type of tool shown in Figure 4-1, a specially designed hydraulic box press is used to bring the clamp halves together. This type of box press is typically used to squeeze heavy-wall nozzles and large-diameter pipes. For BWR nozzles, the tool and presses are assembled outside the bioshield and are then moved into position using an upper rail-type delivery system.

Figure 4-2 illustrates the typical design for contour, insert, and filler rings that are available for the aforementioned MSIP tools. These rings are used to match the MSIP tool inner surface with the piping component outer surface contour.

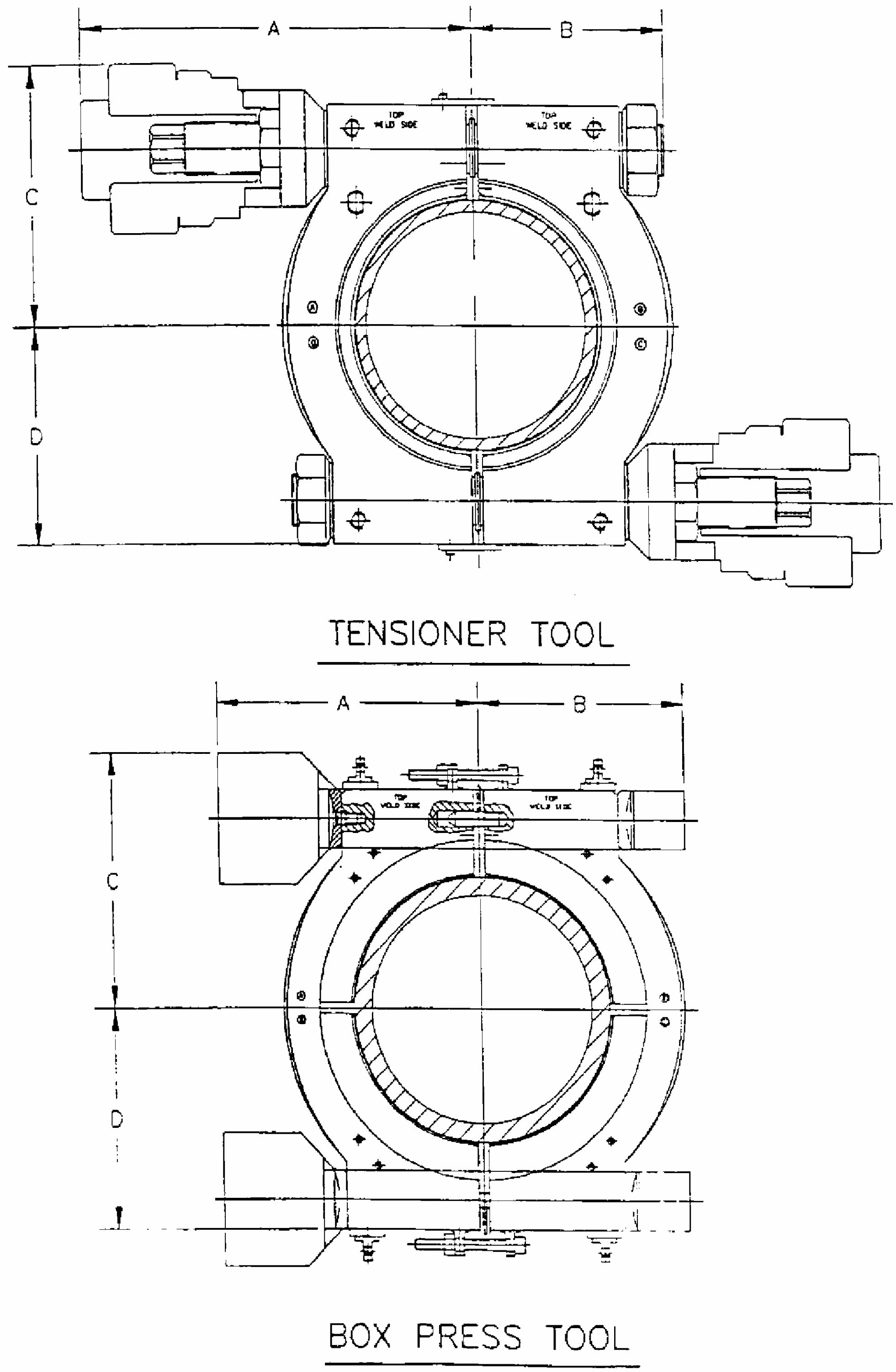

Figure 4-1
MSIP Tools

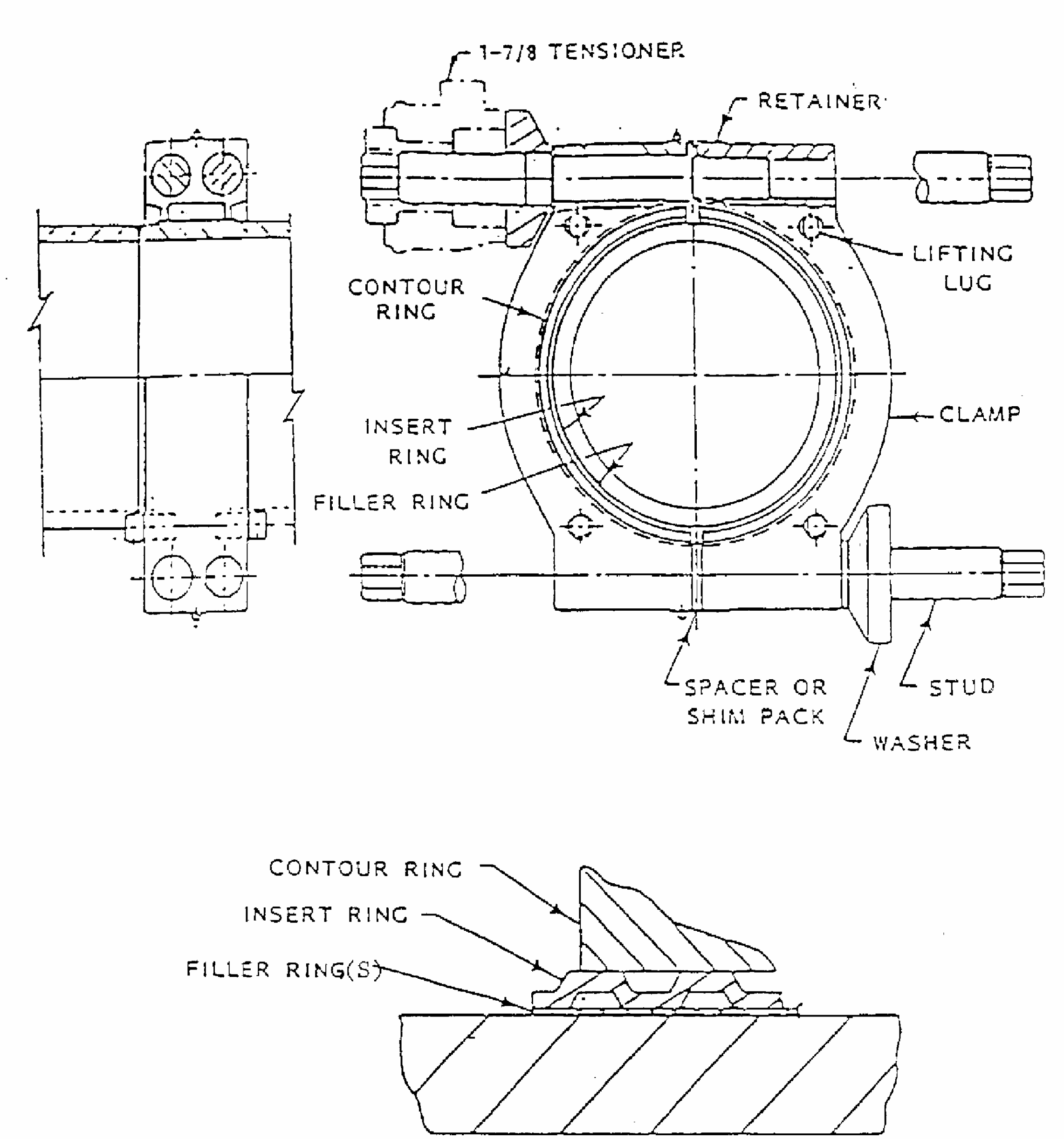

Figure 4-2
Typical Design of MSIP Tool

Assembly drawings of the 12-in.-(305-mm-) MSIP Collet and 6-in.-(153-mm-) Multi-Cylinder Tools are shown in Figures 4-3 and 4-4, respectively. These tools have a smaller overall space envelope than the other types and are used to avoid structural interferences. Pressure is applied to the piping component by way of hydraulically powered multiple segments rather than by two clamp halves.

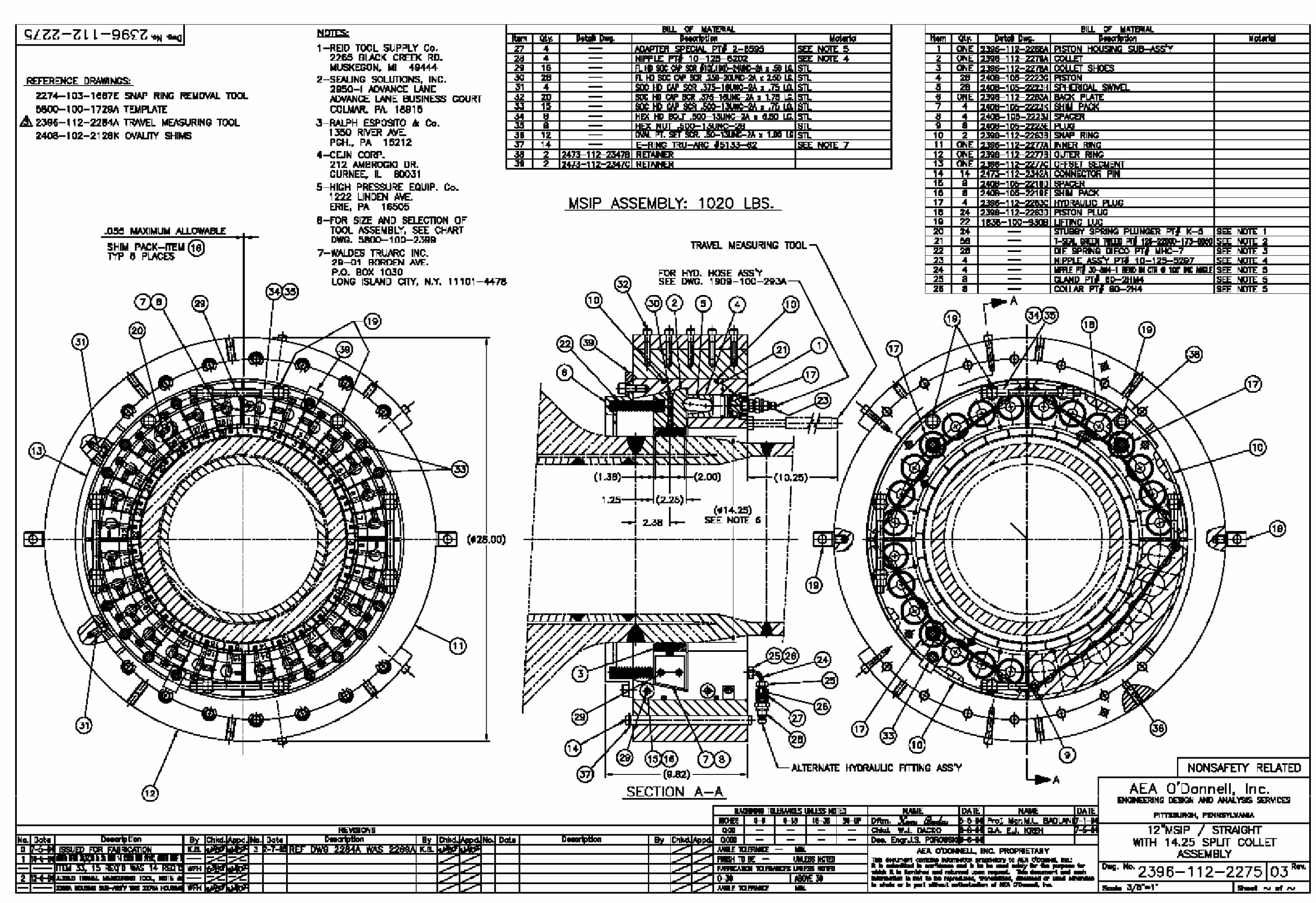

Figure 4-3
MSIP Collet Tool

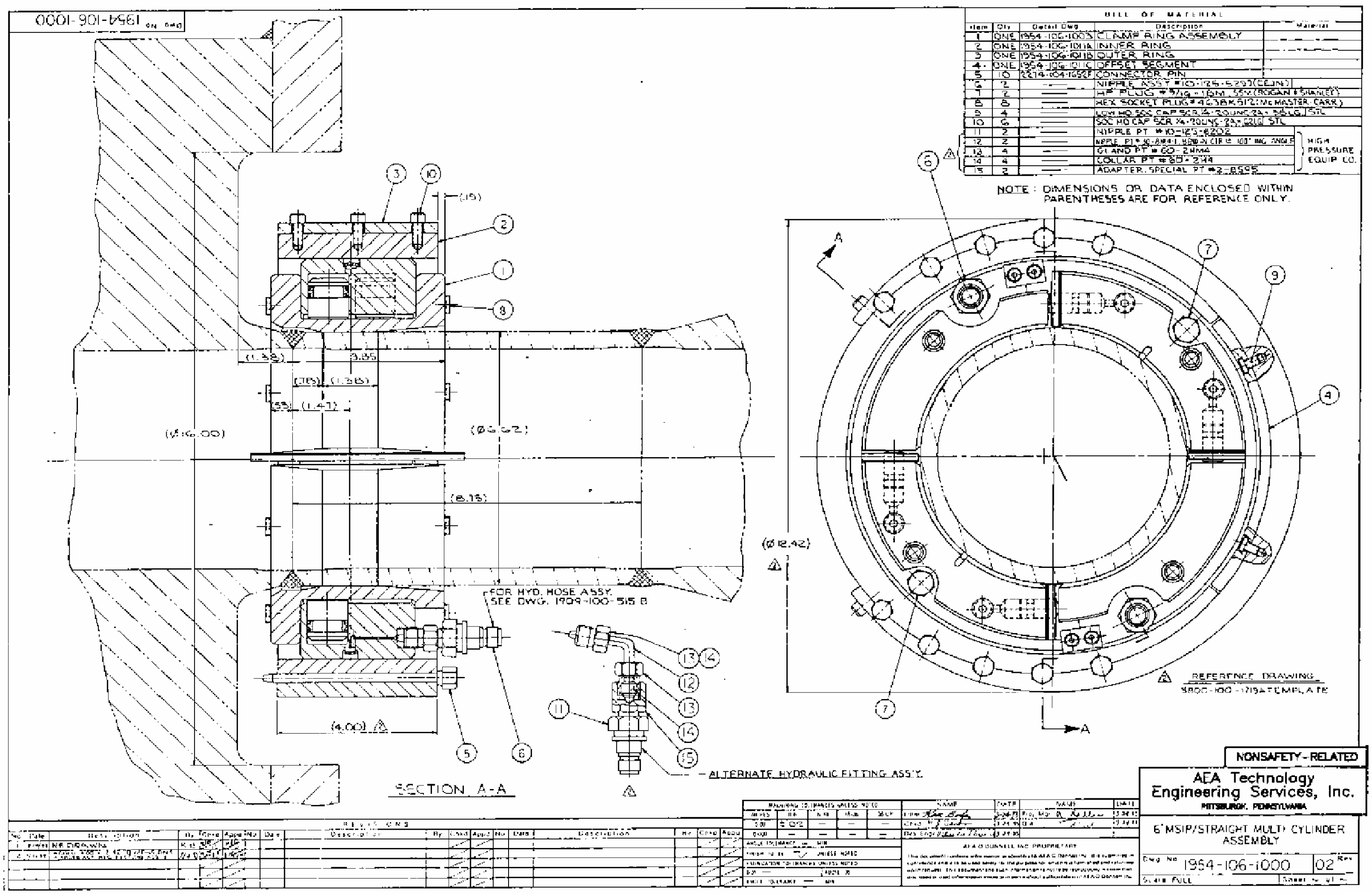

Figure 4-4
MSIP Multi-Cylinder Tool

Tools have been designed and fabricated for most applications in BWR plants and some applications in PWR plants. Although modifications such as new contour rings to match the safe-end configuration and dimensions are sometimes necessary, these modified tools can typically be provided in a short time. The overall dimensions of the various size tools are given in Table 4-1. While these tools are currently available in inventory, new tooling can be designed to meet special space requirements as necessary.

MSIP tooling developed for the PWR plant applications is described in this report. The MSIP 14-in. (356-mm) box press tool made for BWR plant piping, along with a new contour ring, was used to apply the process to the three Inconel 600 safe-end-to-elbow weldments at the Palisades Nuclear Plant. A new 34-in. (864-mm) box press tool was designed and fabricated to apply MSIP to the two hot leg pipe-to-reactor-vessel nozzle weldments at the VC Summer Nuclear Station.

For Tihange Unit 2-TSP, a new MSIP tool assembly was developed and qualified for application to the pressurizer surge nozzle-to-tapered safe-end weldment. An existing 26-in. (660-mm) high-strength clamp ring, AEA Technology's highest capacity 28-in. (711-mm) box presses, and a specially designed contour ring were included in the assembly. The contour ring was designed to span the safe end and surge line to address two requirements. First, pressure applied to the pipe must create frictional forces that restrain the tool from sliding along the tapered safe end away from its required position. Second, the MSIP clamp ring and box presses should then be positioned so they do not interfere with any pressurizer heater assemblies. Dimensions for these MSIP tools are shown in Table 4-1.

The process is applied using approved engineering and field service procedures. Weld travelers with performance and verification records are used to document application results and to record measurements and verification. Verification is provided by measuring pipe contraction between circumference or diameter measurements before and after MSIP. The outline of the basic steps in applying the process is provided in Table 4-2.

Table 4-1
MSIP Tool Dimensions

Size	Overall Tool Width			Overall Tool Height		
	A*	B*	Total	C*	D*	Total
4-in. Tensioner	9.12	4.00	13.12	6.25	4.38	10.63
4-in. Box Press	8.31	6.44	14.75	5.56	4.38	9.94
6-in. Tensioner	9.96	5.38	15.34	7.38	5.50	12.88
6-in. Box Press	8.44	6.31	14.75	6.56	5.38	11.94
6-in. Multi-cylinder	6.21	6.21	12.42	6.21	6.21	12.42
8-in. Tensioner	17.04	7.45	24.52	10.00	8.00	18.00
8-in. Box Press	14.50	10.25	24.75	9.94	7.68	17.62
10-in. Tensioner	17.82	8.20	26.02	11.19	9.44	20.63
10-in. Box Press	16.98	12.90	29.88	12.00	10.25	22.25
12-in. Tensioner	18.32	8.70	27.02	12.06	10.18	22.25
12-in. Box Press	15.02	9.73	24.75	11.75	9.50	21.25
12-in. Collet	14.00	14.00	28.00	14.00	14.00	28.00
14-in. Tensioner	18.28	10.12	28.40	12.75	10.62	23.37
14-in. Box Press	17.10	12.78	29.88	14.12	12.38	26.50
16-in. Tensioner	19.53	11.88	31.41	14.50	12.38	26.88
16-in. Box Press	17.10	12.78	29.88	14.12	12.38	26.88
18-in. Box Press	19.03	14.35	33.38	17.44	14.94	32.38
20-in. Box Press	16.98	16.40	33.38	17.38	14.87	32.25
22-in. Box Press	19.03	14.35	33.38	19.62	17.12	36.75
24-in. Box Press	19.03	14.35	33.38	19.62	17.12	36.75
26-in. Box Press	19.03	14.35	33.38	19.28	17.12	36.40
28-in. Box Press	21.40	17.35	38.75	22.38	19.75	42.13
34-in. Box Press	33.69	29.81	63.50	30.75	25.13	55.88

Note: 1 in. = 25.4 mm
* See Figure 4-2

Table 4-2
Process Application

1. Mark the weld centerline, tool edge, and tool-measuring plane.
2. Measure the outer diameter (OD) to check for ovality (if required).
3. Measure the pipe circumference or diameters at tool-measuring plane.
4. Install the tool on the pipe and align with reference marks.
5. Connect the hoses.
6. Apply preload.
7. Measure the gaps between tool halves.
8. Select the appropriate shims per application procedure and insert into gaps.
9. Pressurize the tool to close gaps.
10. Remove the tool and measure the new circumference or diameters at the tool-measuring plane.

5 MSIP EXPERIENCE AND RELATED PERFORMANCE DATA

MSIP was first used to improve weldments in 1986. Since then, 1332 welds (including 534 nozzle and safe-end weldments) have been treated in plants worldwide. All of the MSIP application records for PWR plant welds treated to date have been collected and reviewed. An MSIP experience table for PWRs has been prepared that tabulates the following information for each weldment:

- Plant name/reactor type
- Date of application and years of service/service life schedule
- Base materials and weld materials
- Weldment configuration
- OD and wall thickness of piping component at MSIP tool location

The table of data, "MSIP Experience for PWRs," is provided in Appendix A.

An overall summary of the total number of nozzle and safe-end weldments and other weldments treated to date is given in Table 5-1. As indicated in Table 5-1, MSIP has also been applied to replacement piping weldments constructed with SCC-resistant materials at several BWR plants to ensure that SCC is prevented. The utility names shown in Table 5-1 were the names in existence at the time MSIP was applied.

MSIP has also been used to treat some welds with pre-existing indications. In no case has MSIP extended existing flaws. Available information for these applications is summarized in Table 5-2. All of these plants have now gone through several cycles of operation except for the single PWR, VC Summer. In all cases, subsequent ultrasonic testing (UT) inspections have confirmed no change in flaw size, thus verifying that the cracks have been arrested.

MSIP field implementations at Palisades and VC Summer easily met schedule requirements and resulted in few significant lessons learned. At Palisades, a small amount of concrete had to be chipped away on the floor under the shutdown cooling outlet nozzle to provide clearance for the MSIP tool. This was not a planned outage activity. The lesson here is that, rather than relying solely on the accuracy/tolerances of construction drawings, early walkdowns should be performed when feasible.

At VC Summer, a portable gantry system was developed to provide hoisting and rigging for installation of the MSIP tool into the hot leg nozzle compartments. When moving the gantry from loop C to loop B, hot leg nozzle interference was encountered with appurtenances extending from the reactor cavity wall. Some time was lost before it was realized that the gantry had to be disassembled before the move. As a result, the requirements for walkdowns and plant drawings in such applications now include reactor cavity wall appurtenances as part of the checklist.

Table 5-1
MSIP Experience

Utility	Plant	Year	Pipe and Fittings	Nozzles and Safe Ends	Total	Notes
CECo	Dresden 3	1986	50	2	52	
CECo	LaSalle 2	1987	25	29	54	3
CECo	Quad Cities 1	1987	36	2	38	
CP&L	Brunswick 2	1988	0	15	15	1, 3
CECo	Quad Cities 2	1988	43	4	47	
Nuclenor	Santa Maria de Garona	1988	24	0	24	
OKG Aktiebolag	Oskarshamn 2	1988	1	0	1	1
CP&L	Brunswick 1	1988	0	10	10	3
CECo	LaSalle 1	1988	15	15	30	
CECo	LaSalle 2	1988	8	0	8	
CECo	Dresden 2	1988	82	22	104	
PECo	Limerick 2	1989	2	16	18	
Northeast	Millstone 1	1989	0	22	22	3
Detroit Edison	Fermi 2	1989	6	21	27	3
CECo	Quad Cities 1	1989	28	12	40	
CP&L	Brunswick 2	1989/90	16	20	36	2
CECo	Quad Cities 2	1990	30	14	44	2
Teollisuuden Voima Oy	TVO	1990	5	0	5	
Niagara Mohawk	Nine Mile Pt 2	1990	0	1	1	1, 3
Taiwan Power	Kuosheng 2	1990	2	0	2	1
CP&L	Brunswick 1	1990/91	10	24	34	2
Northeast	Millstone 1	1991	34	9	43	
Iberdrola	Cofrentes	l991	0	42	42	3
Boston Edison	Pilgrim 1	1991	16	0	16	2

Table 5-1 (cont.)
MSIP Experience

Utility	Plant	Year	Pipe and Fittings	Nozzles and Safe Ends	Total	Notes
PECo	Peach Bottom 3	1991	10	0	10	
PECo	Limerick 1	1992	0	7	7	1
Cleveland Elec	Perry 1	1992	0	27	27	1, 3
TVA	Browns Ferry 3	1992	71	29	100	2
GPU	Oyster Creek	1992	70	0	70	2
Georgia Power	Hatch 1	1993	18	11	29	3
TVA	Browns Ferry 2	1993	12	0	12	2
PP&L	Susquehanna 1	1993	8	6	14	
PECo	Limerick 1	1994	4	14	18	
Georgia Power	Hatch 2	1994	0	18	18	3
PP&L	Susquehanna 2	1994	7	5	12	
GSU	River Bend	1994	0	28	28	3
WPPSS	WNP-2	1994	6	38	44	3
GPU	Oyster Creek	1994	39	16	55	
PP&L	Susquehanna 1	1995	5	15	20	
Consumers Pr.	Palisades	1995	0	3	3	3, 4
PP&L	Susquehanna 2	1995	5	16	21	
Northeast Util.	Millstone 1	1995	13	0	13	
Northeast Util.	Millstone 1	1996/97	71	0	71	
PSE&G	Hope Creek	1999	0	17	17	
Exelon	Quad Cities 1	2000	5	0	5	
Amergen	Oyster Creek	2000	17	0	17	
Exelon	Quad Cities 2	2002	4	0	4	
SCE&G	VC Summer	2002	0	2	2	1, 4
PSE&G	Hope Creek	2003	0	2	2	
Electrabel	Tihange 2-TSP	2003	0	0	0	1, 4, 5
TOTALS			798	534	1,332	

Notes: 1. Some weldments with pre-existing cracks.
2. Weldments for replacement piping made of SCC-resistant materials.
3. Treated weldments include Inconel 600 safe ends.
4. Application to PWRs.
5. Tihange 2-TSP may be rescheduled for spring of 2005.

Table 5-2
MSIP-Treated Weldments with Pre-Existing Cracks

Plant	Date of Application	Nominal Pipe Size	Type of Joint	Direction of Crack	Depth of Crack	Length of Crack	Contact Name Phone	Results
Brunswick 2	February 1988 February 1988	28 in. 28 in.	Nozzle-SE Nozzle-SE	Axial Axial	0.25 in. 0.25 in.	0.3 in 0.3 in	Ed Black 1.910.495.3319	Can see cracks after MSIP - cracks stable
Oskarshamn 2	August 1988	9 in.	Pipe-elbow	Circumferential	16%	23%		Crack stable
Nine Mile Point 2	November 1990	10 in.	SE-extension	Circumferential	41%	11%	S. Dhar 1.315.349.4732	Can see crack after MSIP - crack stable
Kuosheng 2	December 1990 December 1990	19 in. 20 in.	Pipe-elbow Pipe-valve	Circumferential Circumferential	15% 20%	2% 4%	No information	No information
Limerick 1	April 1992	12 in.	Nozzle-SE	Circumferential	29%	23%	Dave Schmidt 1.610.718.3777	Can see crack after MSIP - crack stable
Perry 1	April 1992 April 1992 April 1992	12 in. 12 in. 12 in.	Nozzle-SE Nozzle-SE Nozzle-SE	Circumferential Circumferential Circumferential	15% 13% 10%	5% 7% 2%	Chuck Wirtz 1.440.280.7665	Can see cracks after MSIP - cracks stable
VC Summer	May 2002 May 2002	34 in. 34 in.	Nozzle-SE-pipe Nozzle-SE-pipe	Circumferential and axial - four total flaws UT detected	All <14%	All ~ 0.3 in.	Gary Moffitt 1.770.644.8870	After MSIP, one flaw was not visible using automated ID UT

Note: 1 in. = 25.4 mm

6
RESIDUAL STRESS DISTRIBUTIONS FOR BOILING WATER REACTORS

During the application of MSIP, the inside wall is subjected to monotonically increasing compressive strains. It is important to note that MSIP does not impose tensile strains at the inner surface. Hence, it does not extend pre-existing shallow cracks. Application of MSIP is, therefore, also appropriate for older piping systems that may contain undetected shallow flaws.

MSIP generates residual compressive stresses at the inner region of the weldment in both axial and hoop directions. The residual compressive hoop stresses extend to over 50% of the wall thickness while the residual compressive stresses in the axial direction extend about halfway through the wall. The axial stress distribution is approximately linear, with the maximum compression on the ID and maximum tension on the OD.

While the actual residual stress distribution for a given geometry and materials can be determined by inelastic finite element analysis for radial contractions typically in the range of 0.8–1.8%, the residual axial and hoop compressive stresses generally range from -20 to -40 ksi (-137.8 to -275.6 MPa) at the inner surface in the weldment. The inelastic finite element analysis is used for establishing the process parameters for a specific geometry and includes simulation of as-welded residual stress and application of MSIP followed by unloading.

The generation of residual compressive stresses has been verified and confirmed by independent tests. These tests included:

- Residual stress measurements on 12-in. (305-mm) and 28-in. (711-mm) mockup weldments by Argonne National Laboratory (ANL) for US NRC
- A 28-in. (711-mm) pipe-to-elbow mockup weldment with cracks by EPRI for BWR Owners Group
- Several actual 12-in. (305-mm) nozzle-to-safe-end weldments performed taken from discontinued plants by EPRI

Results of these successful qualification tests are described in more detail in the Task C section of the overall report [2] for this initiative and in additional sources [3, 4, 5].

PWR nozzle-to-safe-end-to-piping weldments have materials of construction either the same as or very similar to those found in BWRs including Inconel weld materials. Also, the nozzle and safe-end designs for some BWR nozzle weldments are nearly as thick as those found in PWRs for the same nominal diameters. Hence, some of the generic verification work done for BWRs is directly applicable for PWRs including the nozzle-to-safe-end weldments treated by MSIP and tested by EPRI. Hence, similar magnitudes of stress improvement experienced in BWRs can be expected for PWRs.

7 QUALIFICATIONS AND DEMONSTRATIONS FOR PRESSURIZED WATER REACTORS

MSIP has been successfully applied at the VC Summer Nuclear Station on two reactor pressure vessel (RPV) hot leg nozzle-to-pipe weldments and at the Palisades Nuclear Plant on the pressurizer system (PZR) surge nozzle safe end-to-elbow, hot leg surge nozzle safe end-to-elbow, and shutdown cooling outlet nozzle safe end-to-elbow weldments. Due to similarity of designs, only one analytical verification was required for each of the above plants. For illustration purposes, the finite element model and the post-MSIP stress plots for a 1.5% radial contraction for the VC Summer hot leg nozzle-to-safe-end weld are shown in Figures 7-1 through 7-4. Materials and the properties used are shown in Table 7-1. For Palisades, the finite element model and post-MSIP stress plots for a 1.16% radial contraction are shown in Figures 7-5 through 7-9, and the materials and properties are shown in Table 7-2. These plots clearly demonstrate the generation of high compressive stresses due to MSIP that extend at least halfway through the wall in both axial and hoop directions. The MSIP tool and a cutaway view of the full-scale mockup used for training for VC Summer are shown in Figures 7-10 and 7-11.

For potential application of MSIP to the Electrabel Tihange Unit 2-TSP PZR surge nozzle-to-safe-end weldment, both analytical and laboratory verifications were performed. The generation of compressive residual stresses was demonstrated by applying MSIP to a full-scale carbon steel mockup of the subject weldment. At the request of the utility and the Belgian regulating authorities, active strain gages were used to monitor compression generated during process application and after removal of the MSIP tooling. Post-MSIP OD profiles were also measured to verify in-service inspection (ISI) acceptability.

Relevant data from the analytical verification and the active strain gage testing are presented in this report section.

The Tihange 2 pressurizer surge nozzle mockup is shown in Figure 7-12. Strain gages were installed on the ID, 45 degrees apart, near the weld region. Figure 7-13 illustrates the strain gage positions schematically. Measured axial strain and analytical hoop stress results of the MSIP squeezes are illustrated in Figures 7-14 and 7-15. The strain gage results confirmed that MSIP generated the desired compression at the inner weld region and that the compression was maintained throughout the MSIP application. The test validated the analysis and demonstrated the effectiveness of MSIP for thick-walled PWR applications. It also demonstrated that the post-MSIP OD profiles were sufficiently smooth to be acceptable for ISI.

Table 7-1
Material Properties at Room Temperature—Analytical Verification of MSIP for PWR RPV Hot Leg Nozzle Weld for VC Summer Loop B/C

Component Description	Material Region in Model	Material Designation	E (10^6psi)	Sγ (psi)	α (1/°F x 10^6)	ν
Nozzle	1	SA-508 Class 2	27.8	50,000	6.41	0.3
SS cladding	2	SS 308 Cladding	28.3	30,000	8.46	0.3
Safe end	3	Inconel (182)	31.0	55,000	7.51	0.3
Weld (root)	4	Inconel (82)	30.0	53,000	7.43	0.3
Weld (filler) and nozzle butter	5	Inconel (182)	31.0	55,000	7.51	0.3
Piping	6	SA-376 304N	28.3	49,700	8.46	0.3

Note: 1 psi = 0.069 MPa
°C = (°F – 32) x 5/9

Table 7-2
Material Properties at Room Temperature—Analytical Verification of MSIP for PWR 12-in. (305-mm) Safe-End-to-Elbow Weld for Palisades

No.	Component	Material	Property
1	Pipe	SA-376 TP 316	E = 28.3 Sγ = 30.0
2	Safe end	Inc 600	E = 31.0 Sγ = 51.2
3	Safe end/pipe weld	Inc 182	E = 31.0 Sγ = 55.3
4	Nozzle	508 CL 1	E = 29.3 Sγ = 36.0
5	Nozzle/safe-end weld	Inc 182	E = 31.0 Sγ = 55.3
6	Nozzle butter	Inc 182	E = 31.0 Sγ = 55.3
7	Nozzle cladding	304 SS	E = 28.3 Sγ = 30.0

KEY: E = Elastic Modulus ($x10^6$ psi)
Sγ = Yield Strength (ksi)

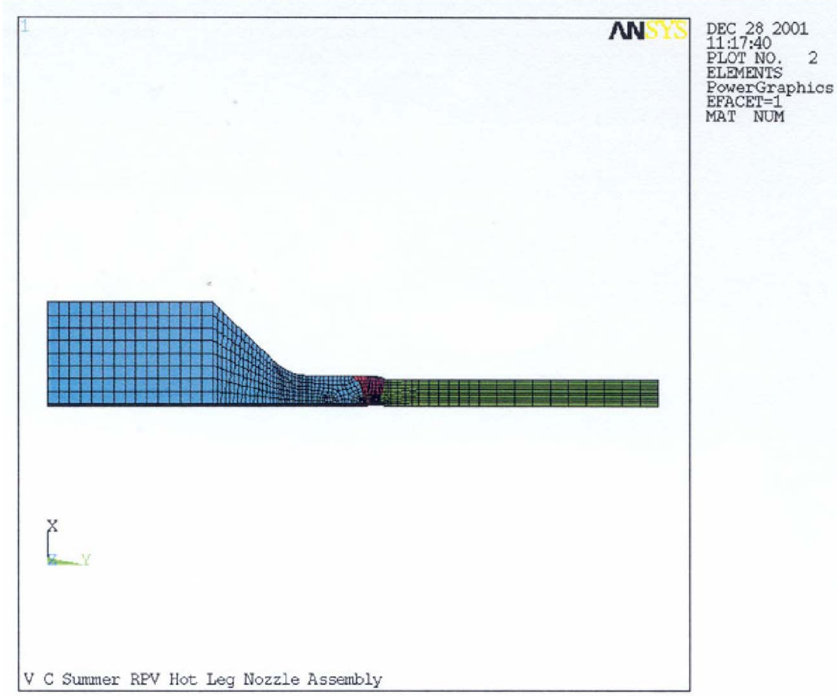

Figure 7-1
Finite Element Model

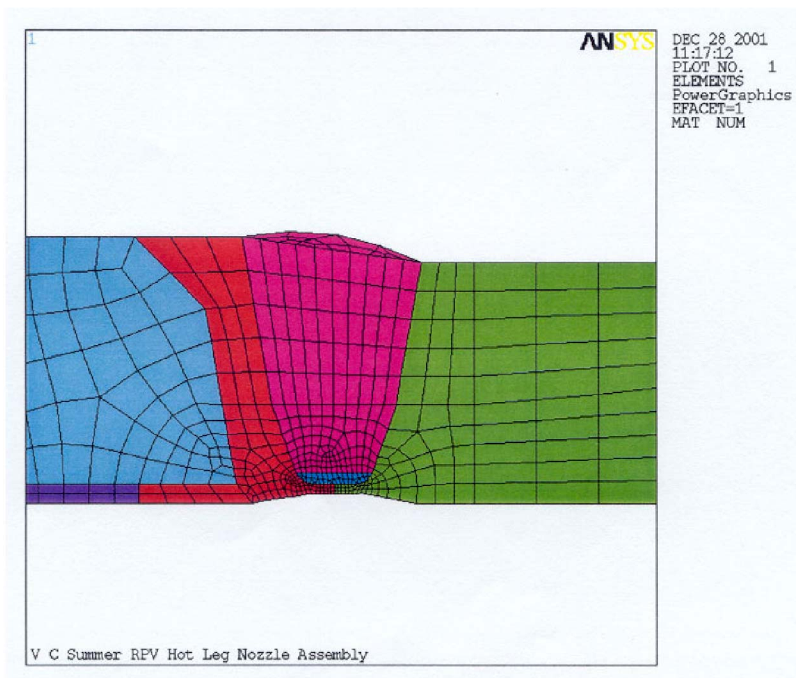

Figure 7-2
Finite Element Model (Weld Region)

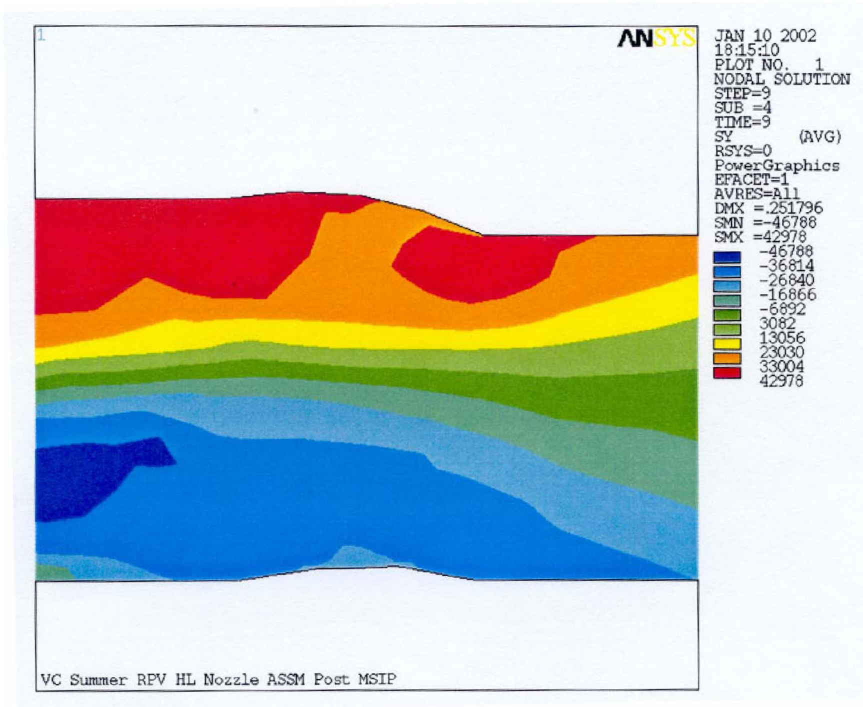

Figure 7-3
Axial Stress Distribution Post-MSIP (1.5% Radial Contraction)

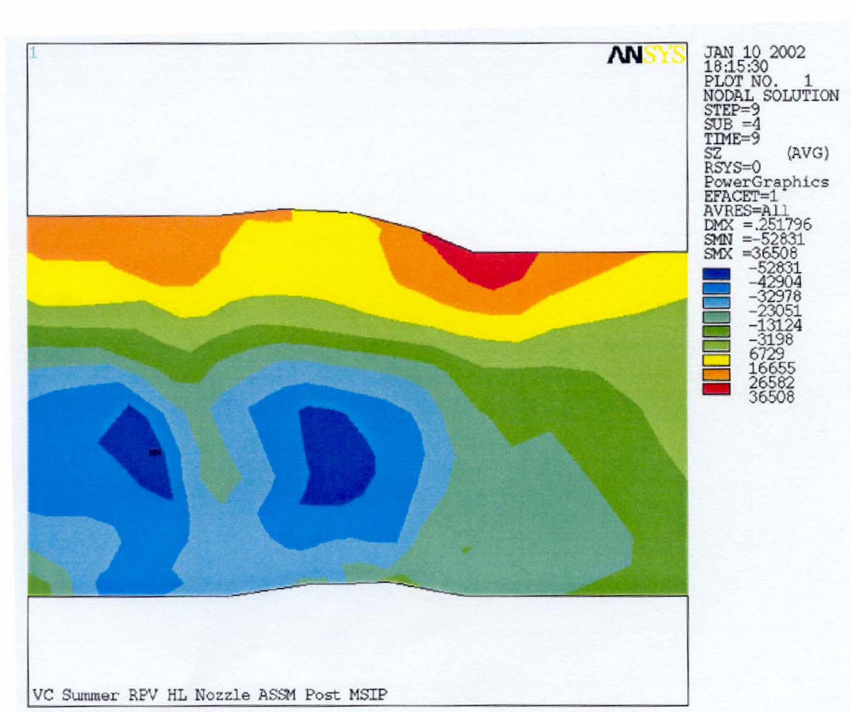

Figure 7-4
Hoop Stress Distribution Post-MSIP (1.5% Radial Contraction)

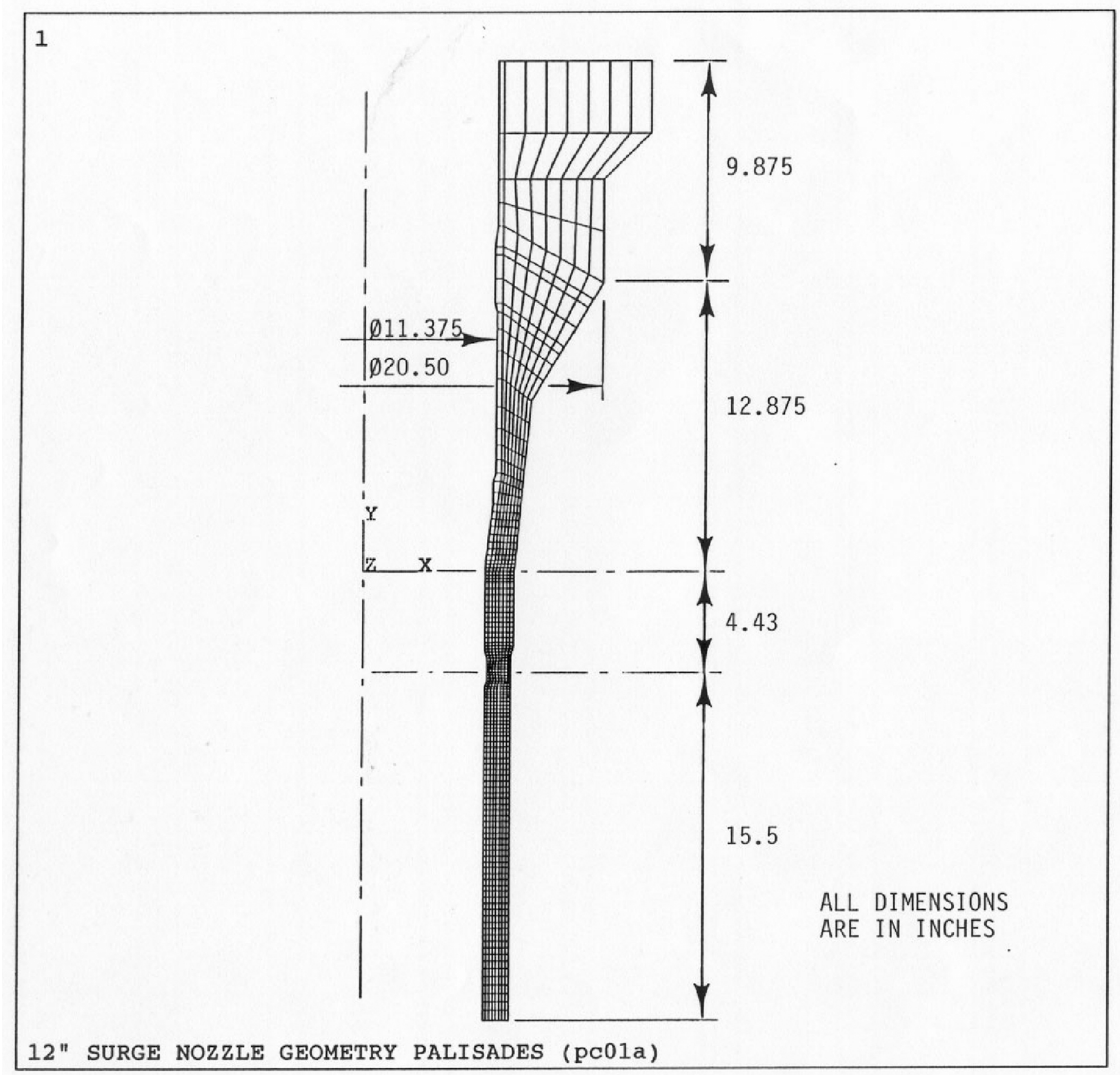

Figure 7-5
Overall View of the Finite Element Model

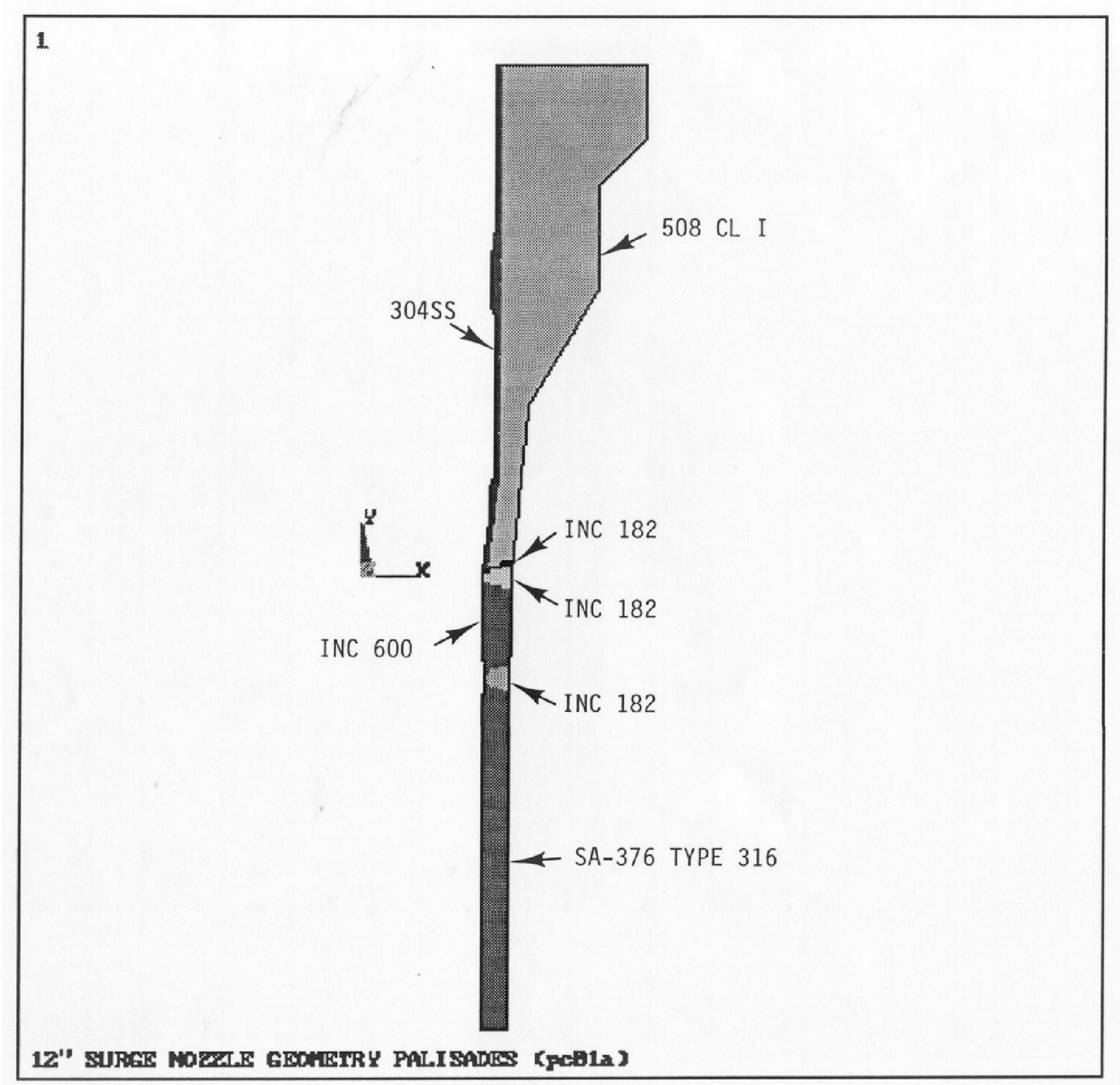

Figure 7-6
Material Regions of the Model

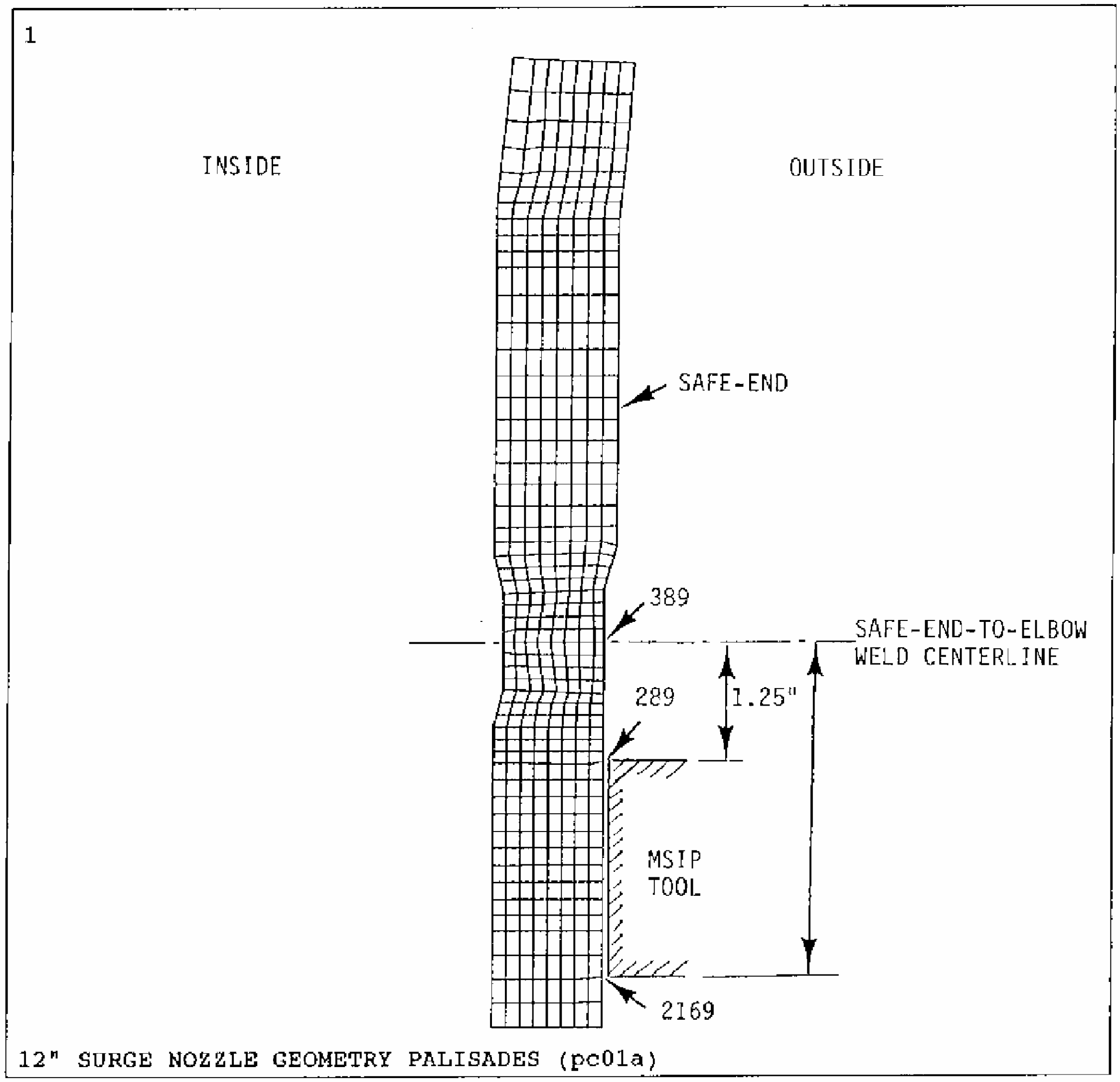

Figure 7-7
Finite Element Model Showing Tool Location

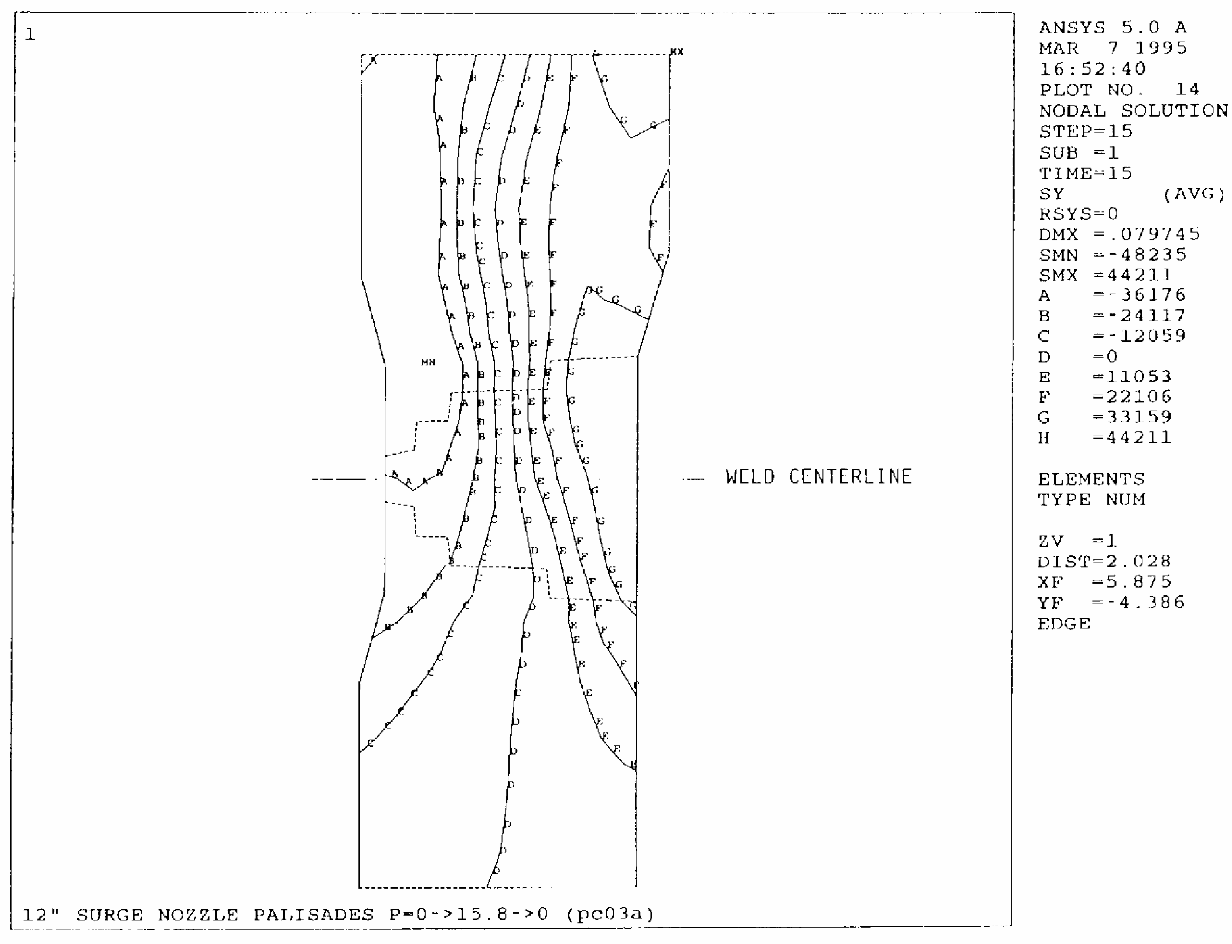

Figure 7-8
Post-MSIP Stresses in the Axial Direction with Permanent Contraction of 1.16%

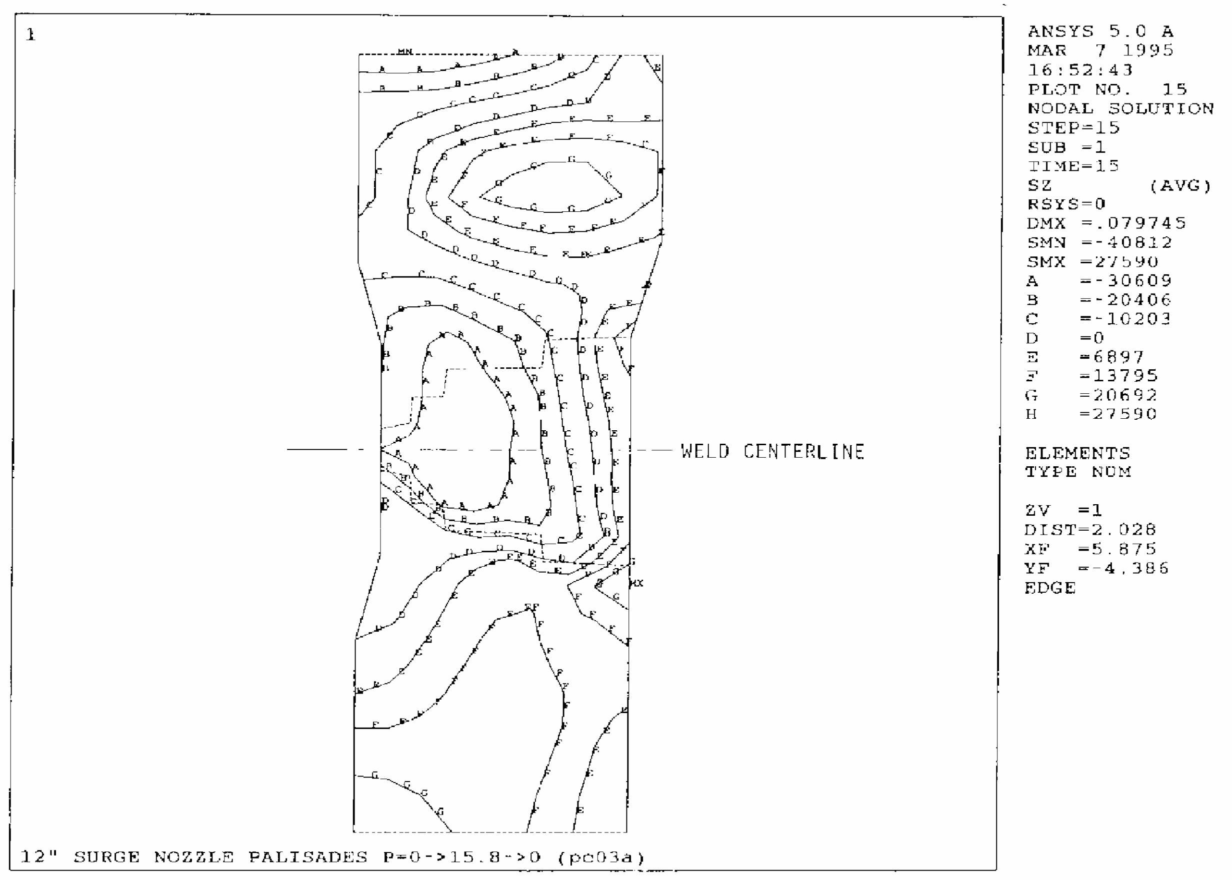

Figure 7-9
Post-MSIP Stresses in the Hoop Direction with Permanent Contraction of 1.16%

Figure 7-10
VC Summer Hot Leg Nozzle MSIP Tool Details

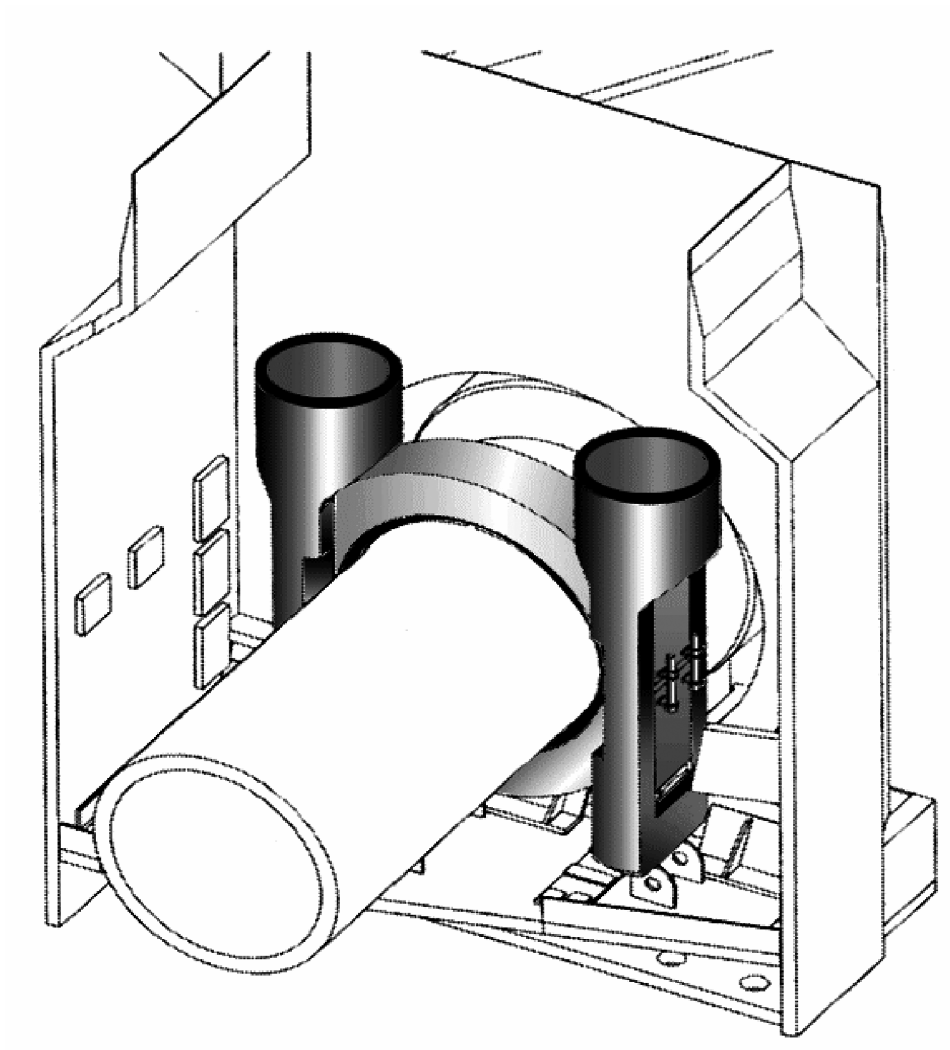

Figure 7-11
VC Summer Hot Leg Nozzle MSIP Tool Setup

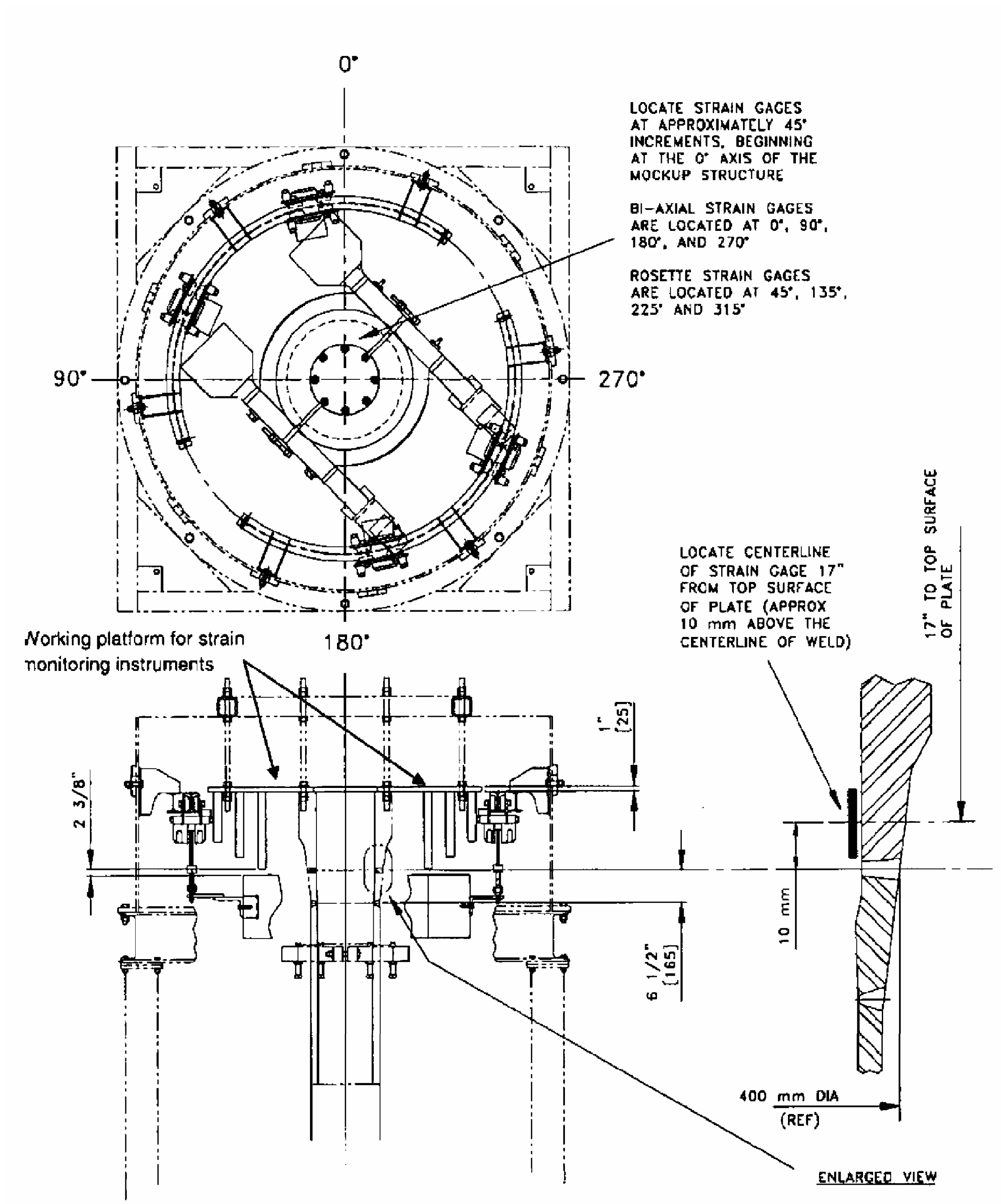

Figure 7-12
Schematic Illustration of Tihange 2 Nozzle-to-Pipe Assembly—Mockup in Position Showing the Location of Strain Gages

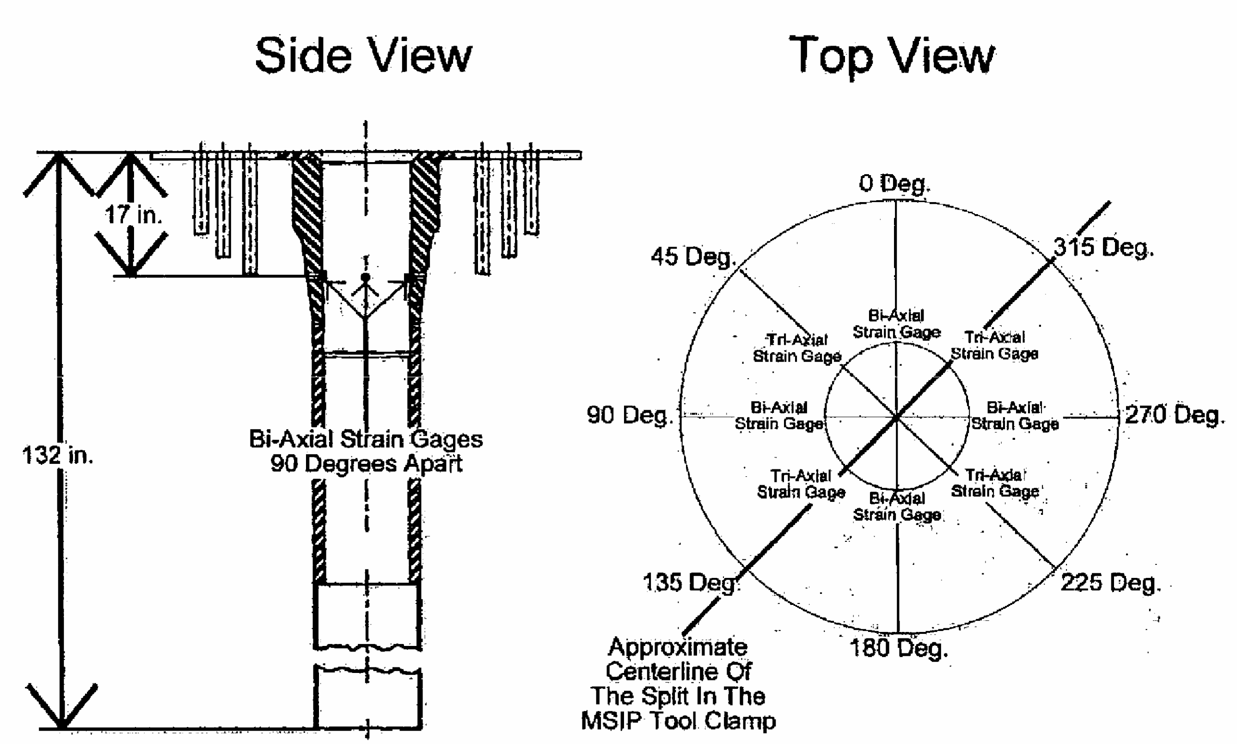

Figure 7-13
Schematic Illustration of the Positions of Biaxial and Triaxial (Rosette) Strain Gauges Near the Weld Region at the ID Surface

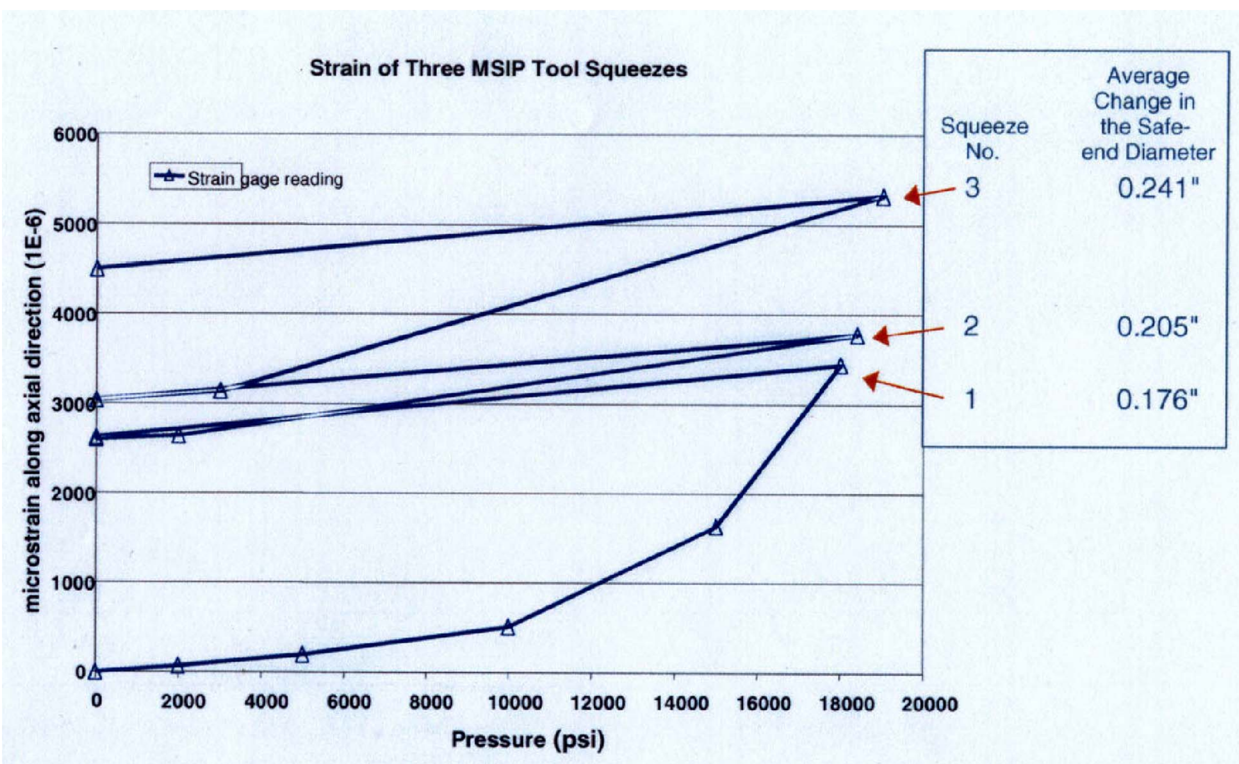

Figure 7-14
Axial Strain and Safe-End Diameter Changes Associated with the Three MSIP Squeezes

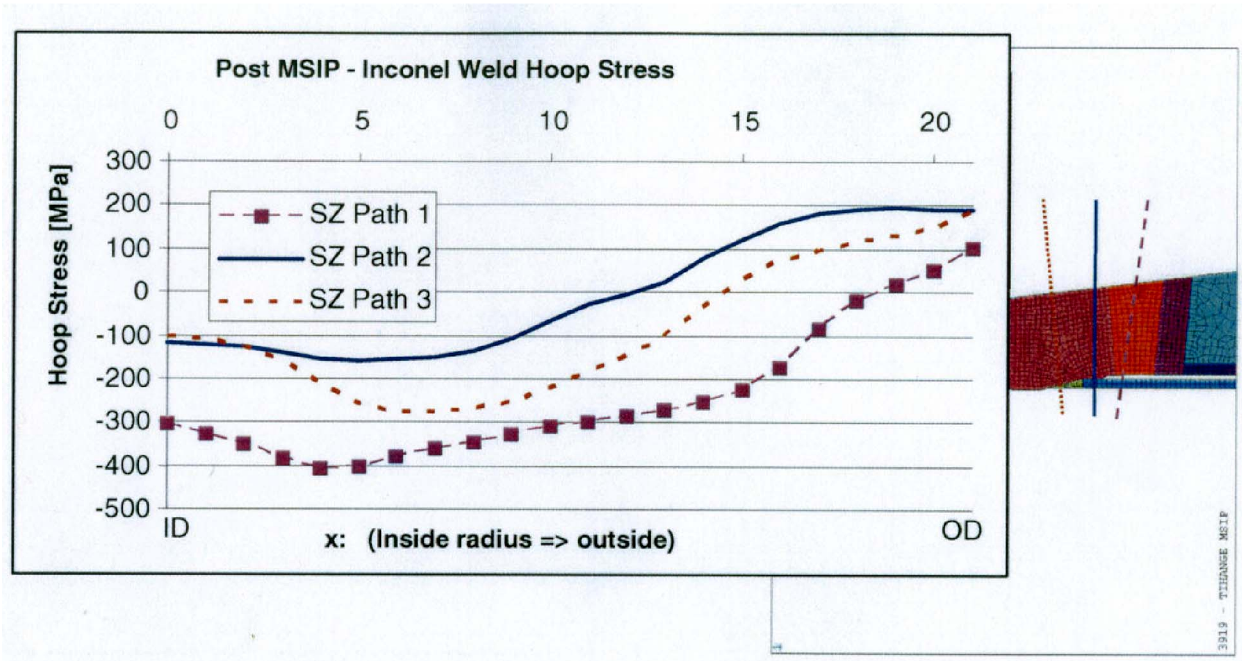

Figure 7-15
Predicted Distribution of Through-Wall Hoop Stress at the Weld Joint

8 CONCLUSIONS

The applicability of MSIP to PWR nozzle weldments is evaluated in this study. A table of prior MSIP experience for PWRs is included as part of the study. A discussion on the process, tooling, materials, and residual stress distribution including test results is also presented.

Based on the materials and configuration of PWR nozzle weldments, it is concluded that MSIP can generate high axial and hoop residual compressive stresses in the inner region of the Inconel weld and nozzle butter. Generation of such a compressive stress field will protect the weldment against crack initiation and arrest any shallow pre-existing cracks.

9
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A

MSIP EXPERIENCE FOR PRESSURIZED WATER REACTORS

Table A-1
MSIP Experience for PWRs

AEA Technology Engineering Services, Inc. - MSIP Experience for PWRs

				Materials					Tool Location	
Date Applied	Reactor Name	Reactor Type	Years of Operation/ Scheduled Service Life	Base 1	Base 2	Weld	Nozzle Weld Butter	Weldment Configuration	Outer Diam.	Component
6/16/1995	Palisades	PWR	33/40	SS	I-600	I-182		Elbow-Safe End (1.25" thk)	12.77	Elbow - Sch.140
6/15/1995	Palisades	PWR	33/40	SS	I-600	I-182		Elbow-Safe End (1.25" thk)	12.8	Elbow - Sch.140
6/20/1995	Palisades	PWR	33/40	SS	I-600	I-182		Elbow-Safe End (1.66" thk)	12.8	Elbow - Sch.140
5/3/2002	V.C. Summer	PWR	21/40	SS	LAS	I-182	I-182	Pipe - Nozzle (2.72" thk)	33.96	Pipe - 2.40" thk.
5/3/2002	V.C. Summer	PWR	21/40	SS	LAS	I-182	I-182	Pipe - Nozzle (2.72" thk)	34.00	Pipe - 2.40" thk.

Material Abbreviations

LAS - Low Alloy Steel CS - Carbon Steel SS - Stainless Steel Inc - Inconel I-82 - Inconel 82 I-182 - Inconel 182 I-600 - Inconel 600

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