Advanced FEA Crack Growth Calculations for Evaluation of PWR Pressurizer Nozzle Dissimilar Metal Weld Circumferential PWSCC

Sponsored by: EPRI Materials Reliability Program

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Presented To:

Expert Review Panel for Advanced FEA Crack Growth Calculations

Presented By:

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John Broussard
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Tuesday, May 1, 2007
Meeting on Treatment of Welding Residual Stress
DEI Offices
Reston, Virginia

Topics

- Nozzle and weld geometry cases for subject welds
- Collected weld repair information for subject welds
- Application of WRS FEA models
  - Previous FEA results by DEI (MRP-106)
  - FEA work by Battelle and EMC2 (presentation by Dave Rudland, EMC2)
  - Discussion of approach to new FEA for selected subject weld cases
- WRS data for piping butt welds in open literature
- Candidate WRS profiles
  - Axisymmetric profiles
  - Non-axisymmetric profiles
- Validation of WRS inputs
- Meeting wrap-up

Principal Meeting Participants

- EPRI Project Management / Support
  - Craig Harrington, EPRI
  - Tim Gilman, Structural Integrity Associates
- Project Team
  - Glenn White, Dominion Engineering, Inc.
  - John Broussard, Dominion Engineering, Inc.
- Expert Review Panel
  - Warren Bamford, Westinghouse (via phone)
  - Pete Riccardella, Structural Integrity Associates (via phone)
  - Doug Killian, AREVA
  - Ken Yoon, AREVA
- NRC Participants
  - Al Csontos, NRC Research
  - Ted Sullivan, NRC NRR
  - Simon Sheng, NRC NRR
  - Dave Rudland, EMC2

Nozzle Geometry for Subject Plants
Summary

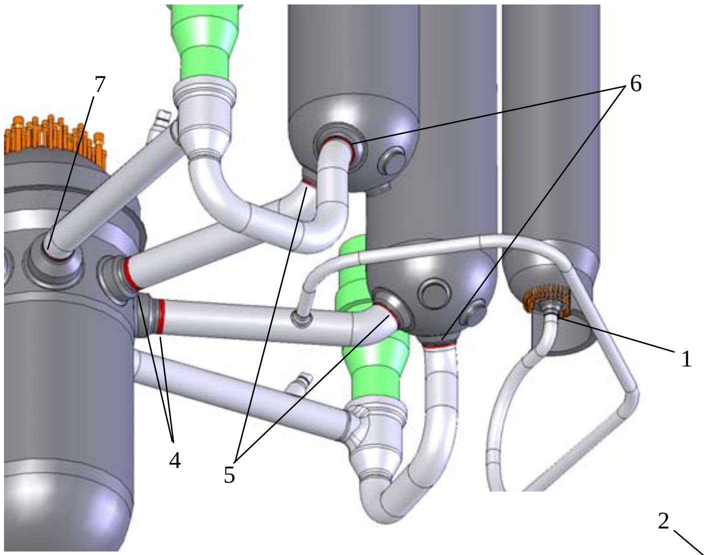
- There are a total of 51 pressurizer DM welds of concern in the group of nine plants:
  - 35 safety and relief (S&R) nozzles (1 plant has only three S&R nozzles)
  - 8 surge nozzles (+1 already overlayed)
  - 8 spray nozzles (+1 examined by PDI process in 2005)

Nozzle Geometry for Subject Plants
Geometry Cases

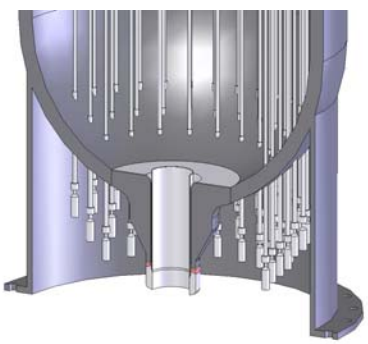
- A review of design drawings for the nine plants indicates the following nozzle geometry cases:
  - S&R nozzles
    - Types 1a and 1b: W design without liner, connected to 6″ pipe
    - Types 2a and 2b: W design with liner directly covering DM weld, connected to 6″ pipe
    - Type 3: CE design (no liner), connected to 6″ pipe
  - Spray nozzles
    - Type 4: W design with liner (does not extend to most of DM weld), connected to 4″ pipe
    - Type 5: W design with liner directly covering DM weld, connected to 4″ pipe
    - Type 6: W design without liner, connected to 6″ pipe
    - Type 7: CE design (no liner, sleeve not extending to DM weld), connected to 4″ pipe
  - Surge nozzles
    - Type 8: W design (sleeve directly covers fill-in weld under nozzle-to-safe-end weld), connected to 14″ pipe
    - Type 9: CE design (sleeve not extending to DM weld), connected to 12″ pipe

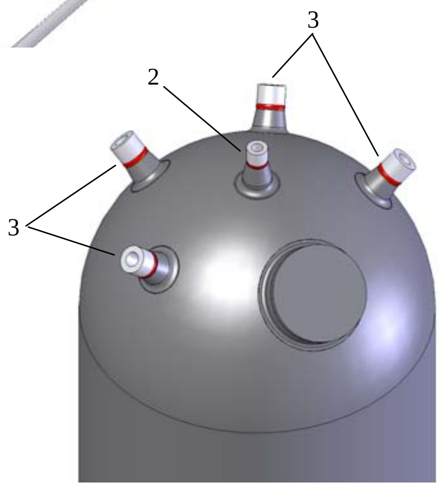
Nozzle Geometry for Subject Plants

PWR Pressurizers

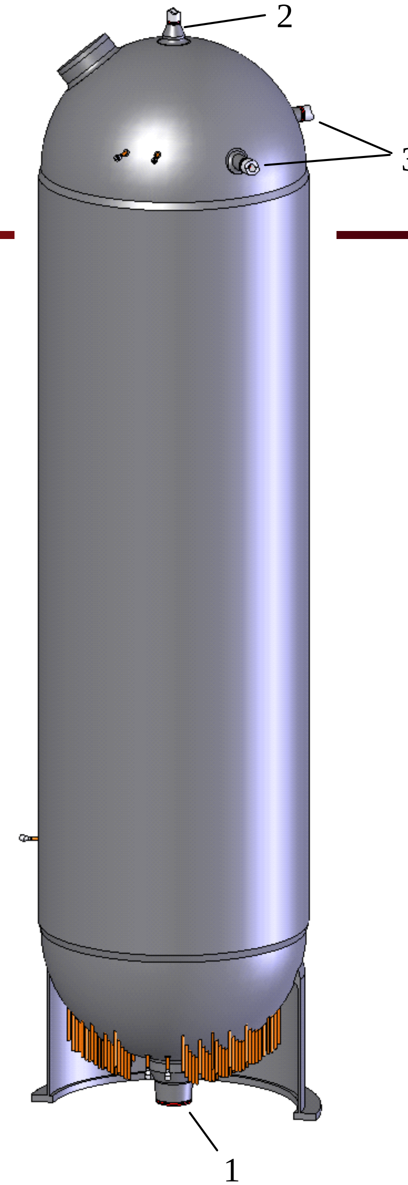


1. Surge Nozzle
2. Spray Nozzle
3. Safety/Relief Nozzle





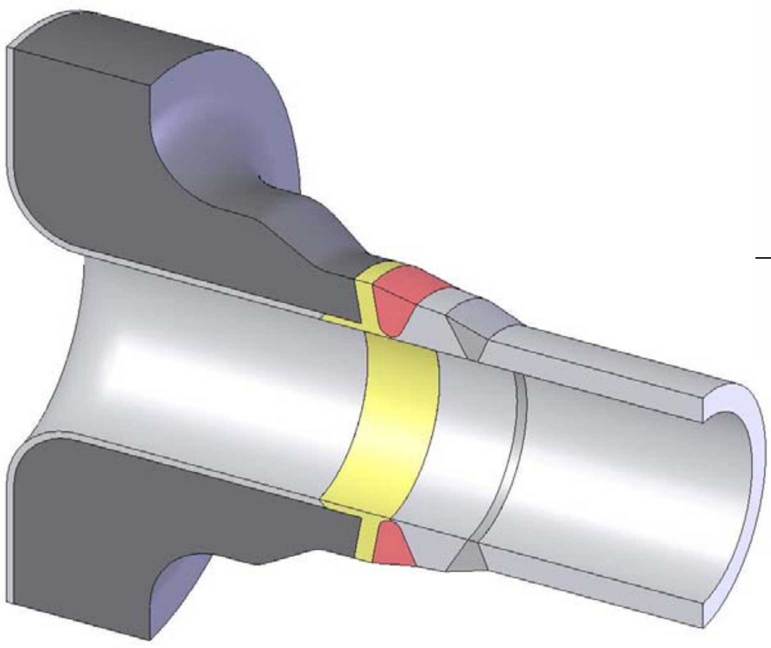
Example Westinghouse Design Pressurizer

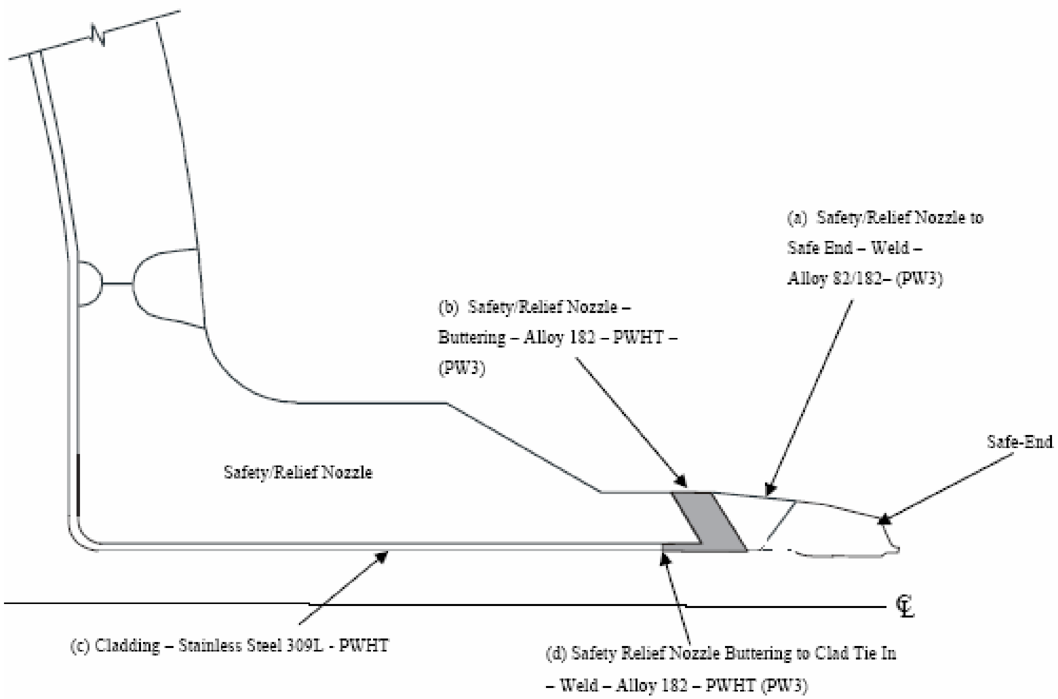


Example CE Design Pressurizer

Nozzle Geometry for Subject Plants
S&R Types 1a and 1b: W design without liner

Source: *MRP 2007-003 Attachment 1 (White Paper).*

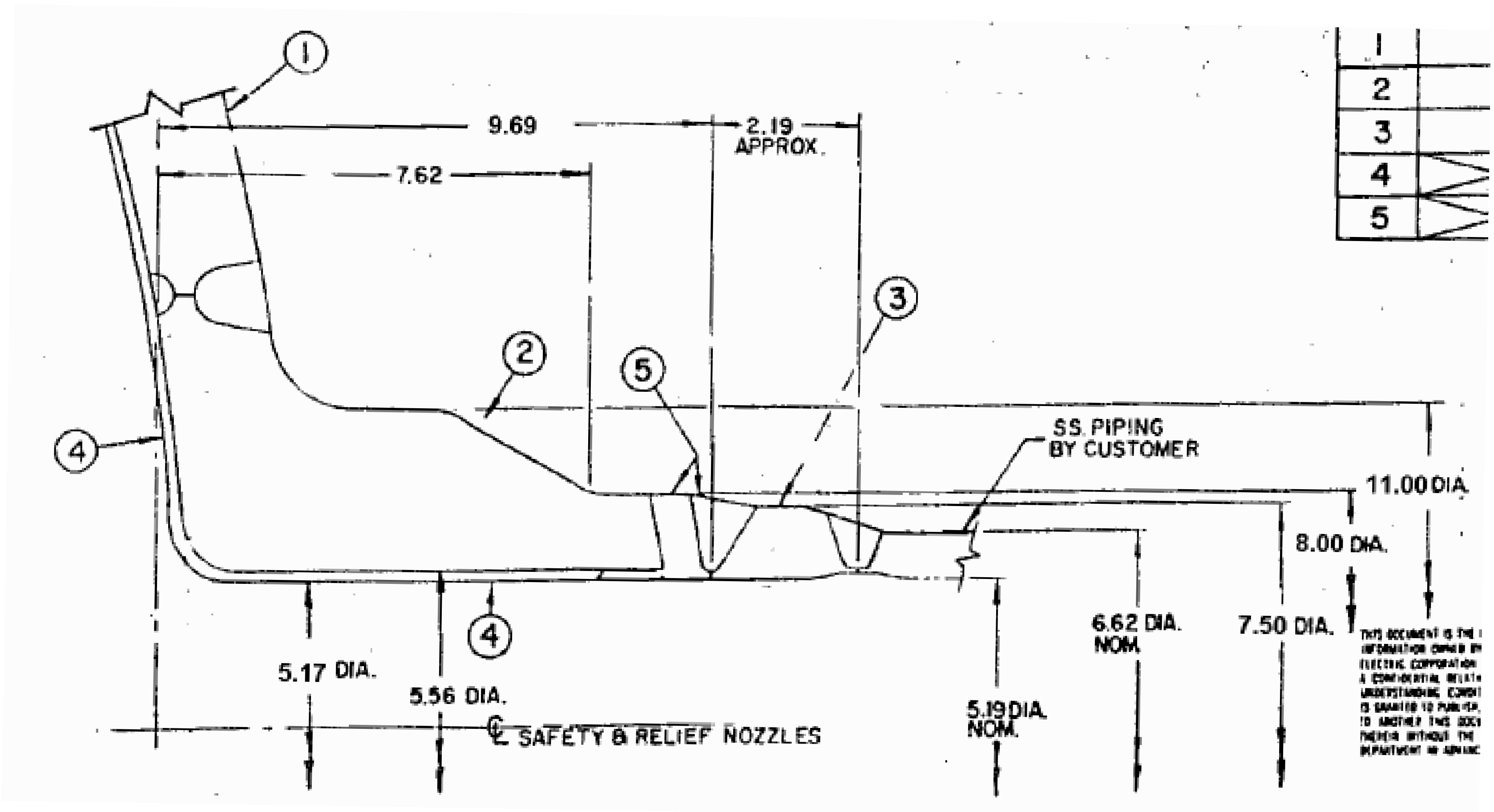




Wolf Creek Surge Nozzle Materials

Nozzle Geometry for Subject Plants

S&R Type 1a: W design without liner (6″ pipe)



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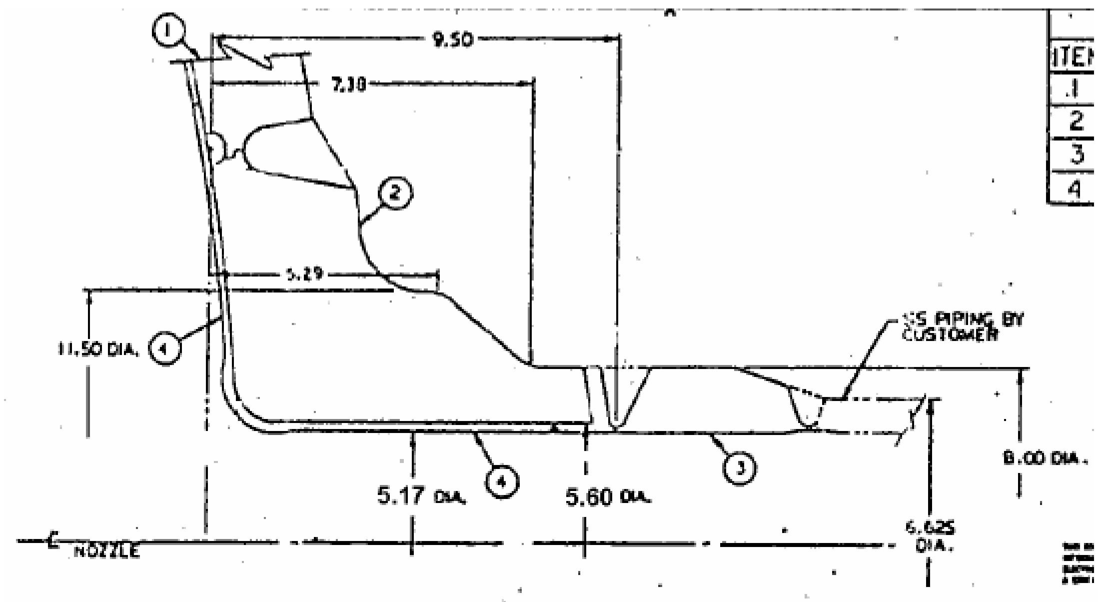
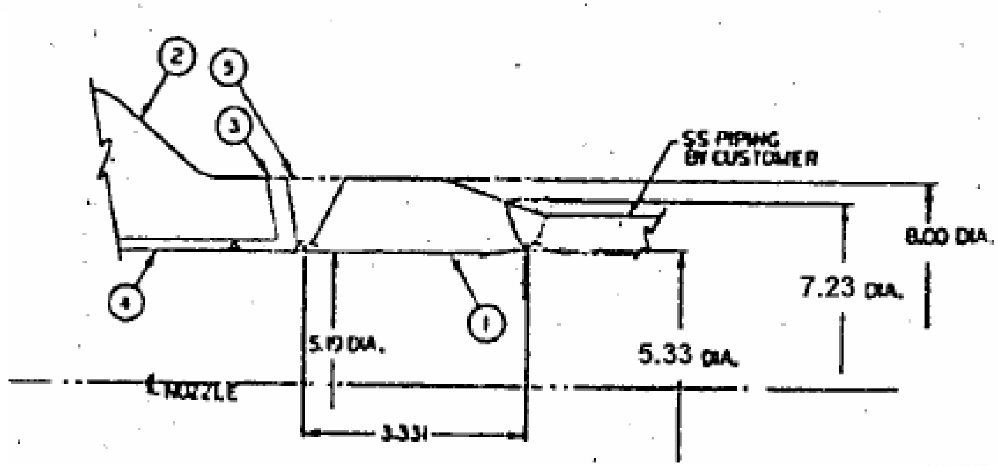
Nozzle Geometry for Subject Plants

S&R Type 1b: W design without liner (6″ pipe)





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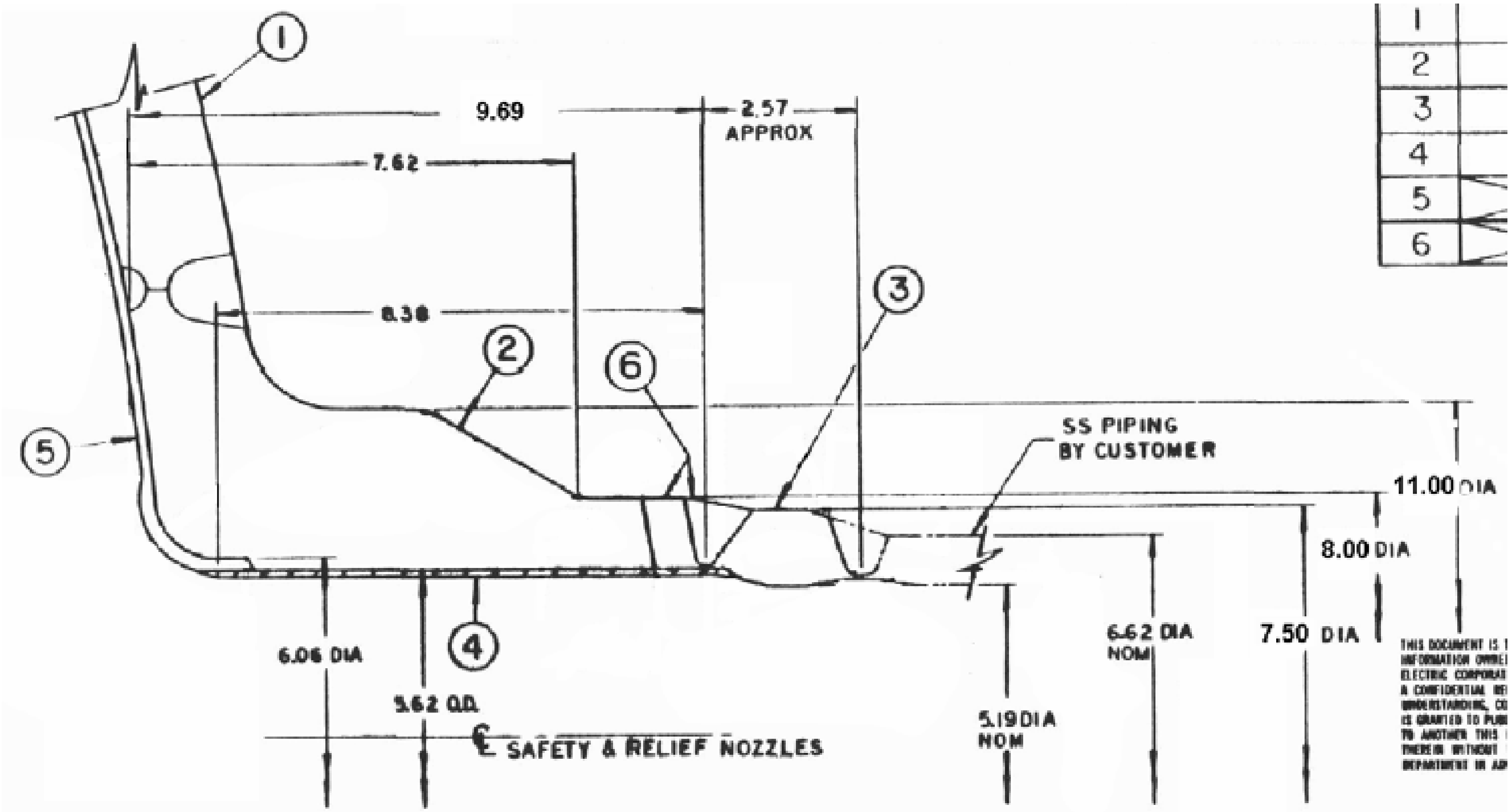
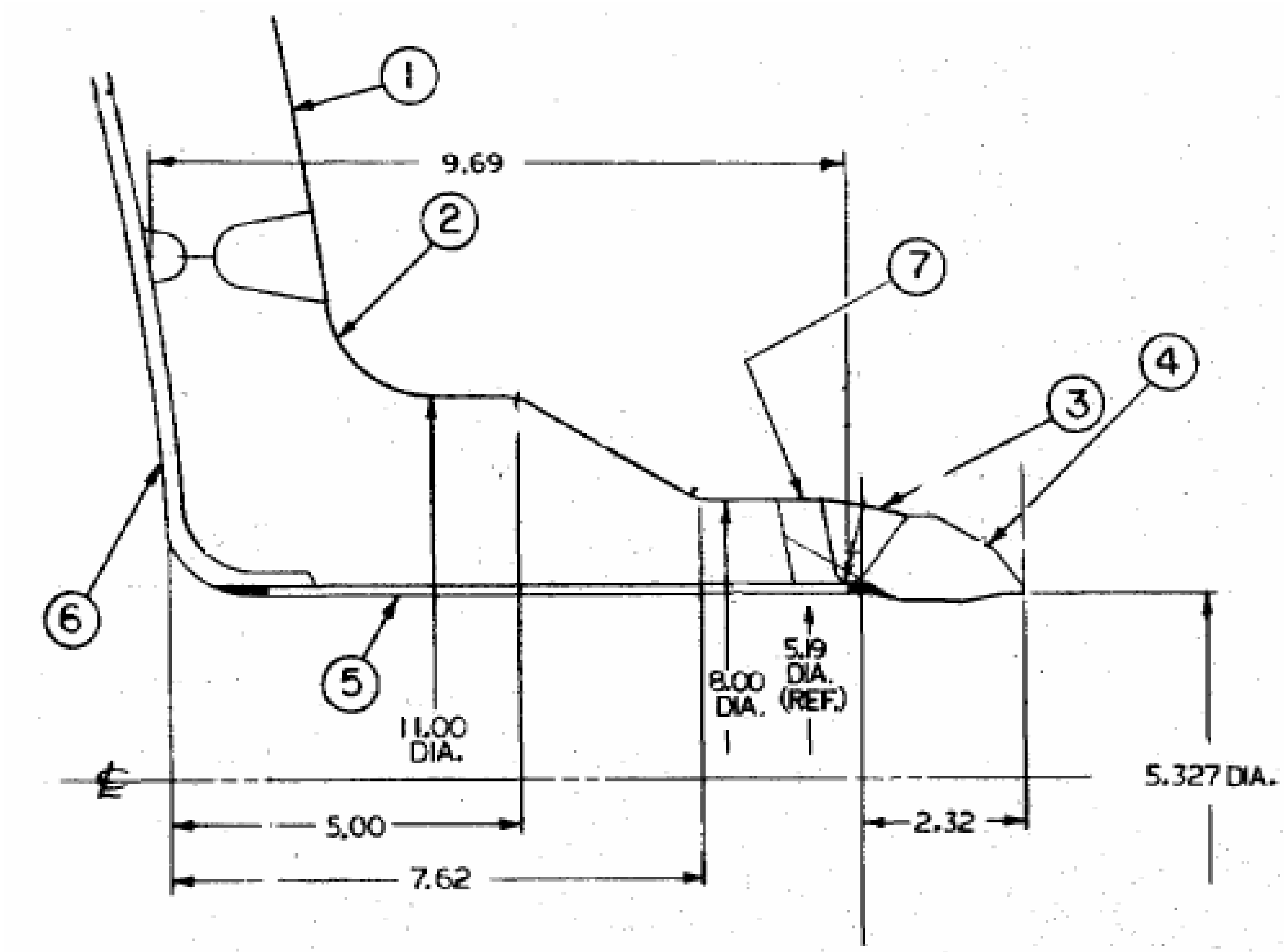
Nozzle Geometry for Subject Plants
S&R Type 2a: W design with liner (6″ pipe)

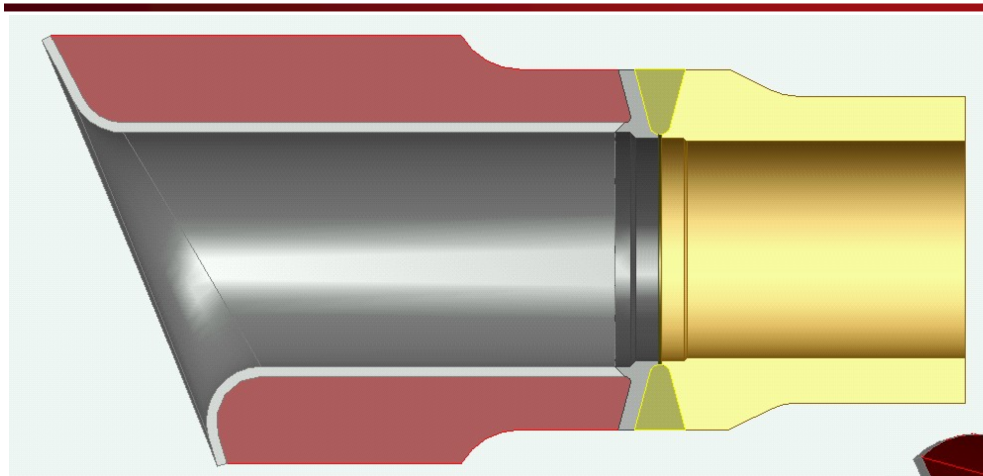


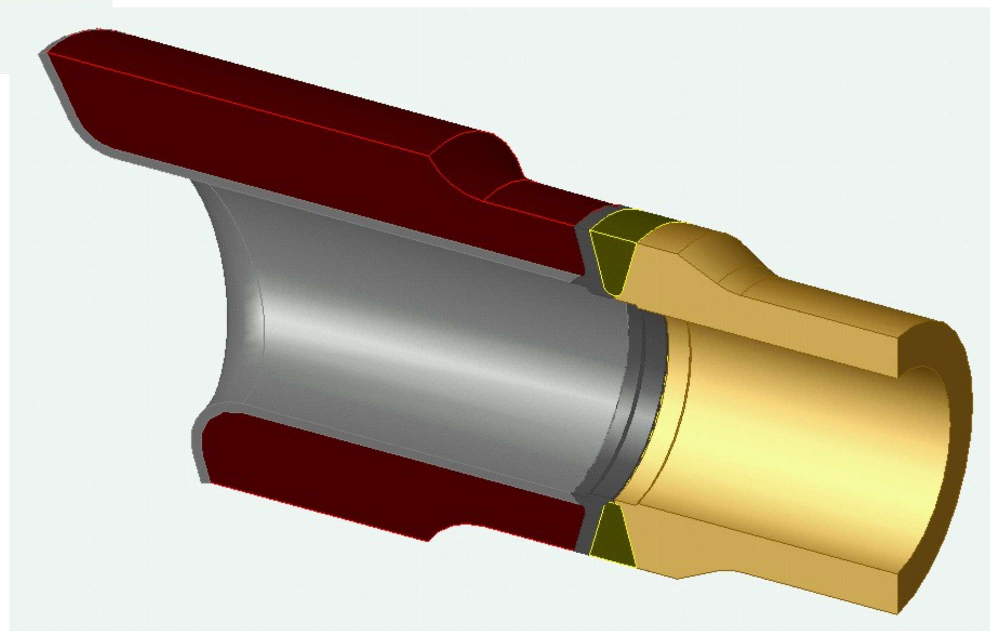
Nozzle Geometry for Subject Plants

S&R Type 2b: W design with liner (6″ pipe)

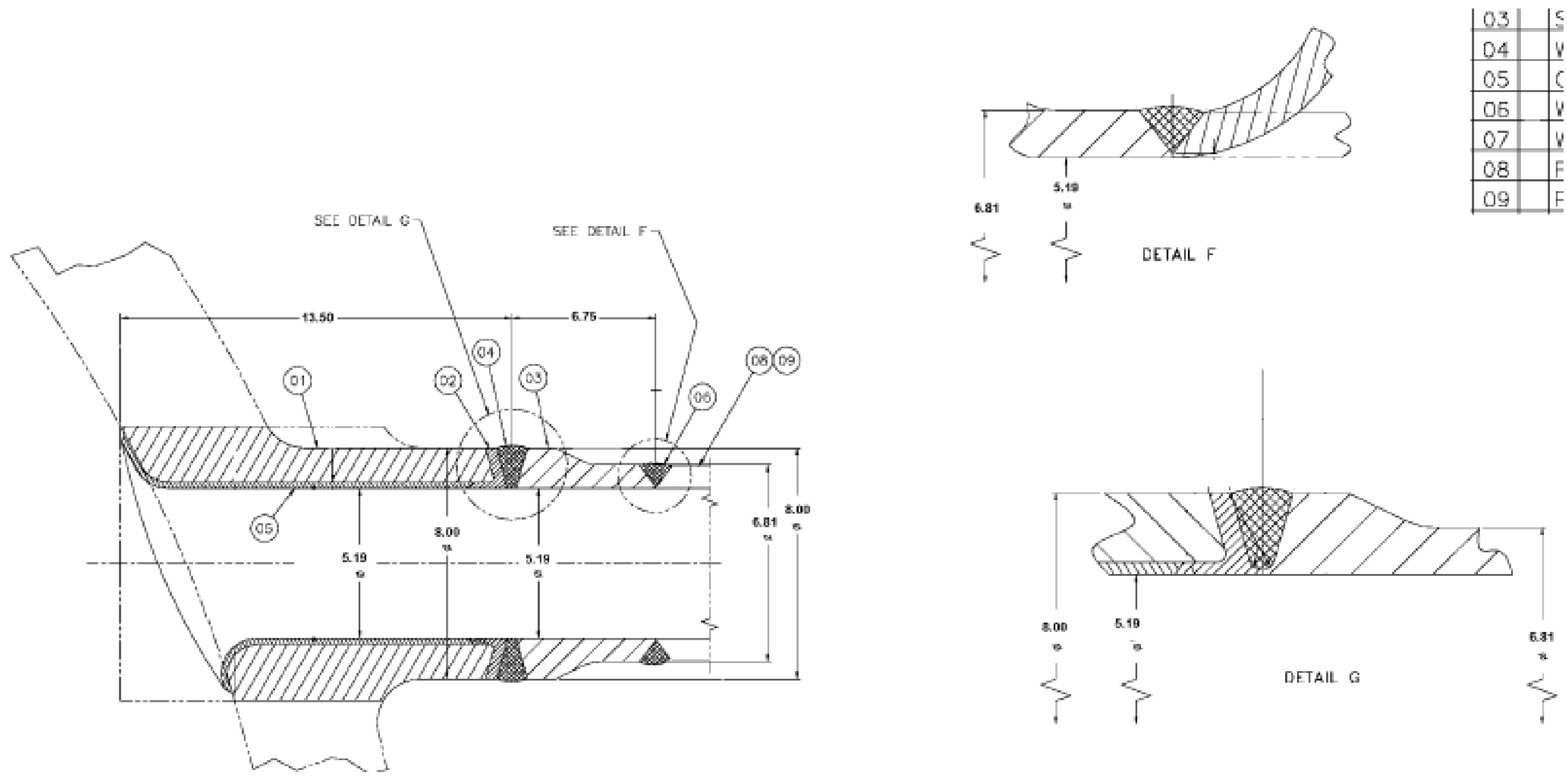


Nozzle Geometry for Subject Plants
S&R Type 3: CE design





Nozzle Geometry for Subject Plants
S&R Type 3: CE design (no liner) (6″ pipe)



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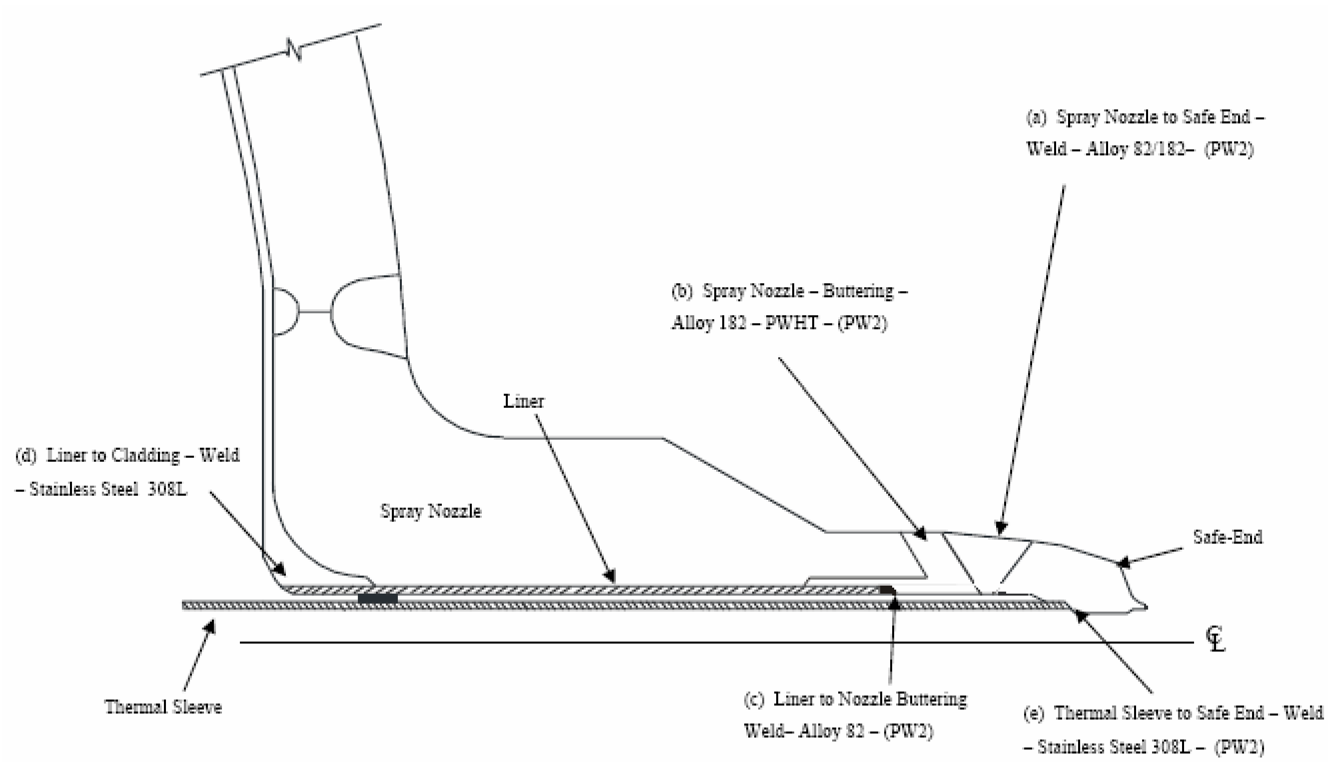
Nozzle Geometry for Subject Plants

Spray Type 4: W w/liner (not extend to most DM) (4″ pipe)



Wolf Creek Surge Nozzle Materials

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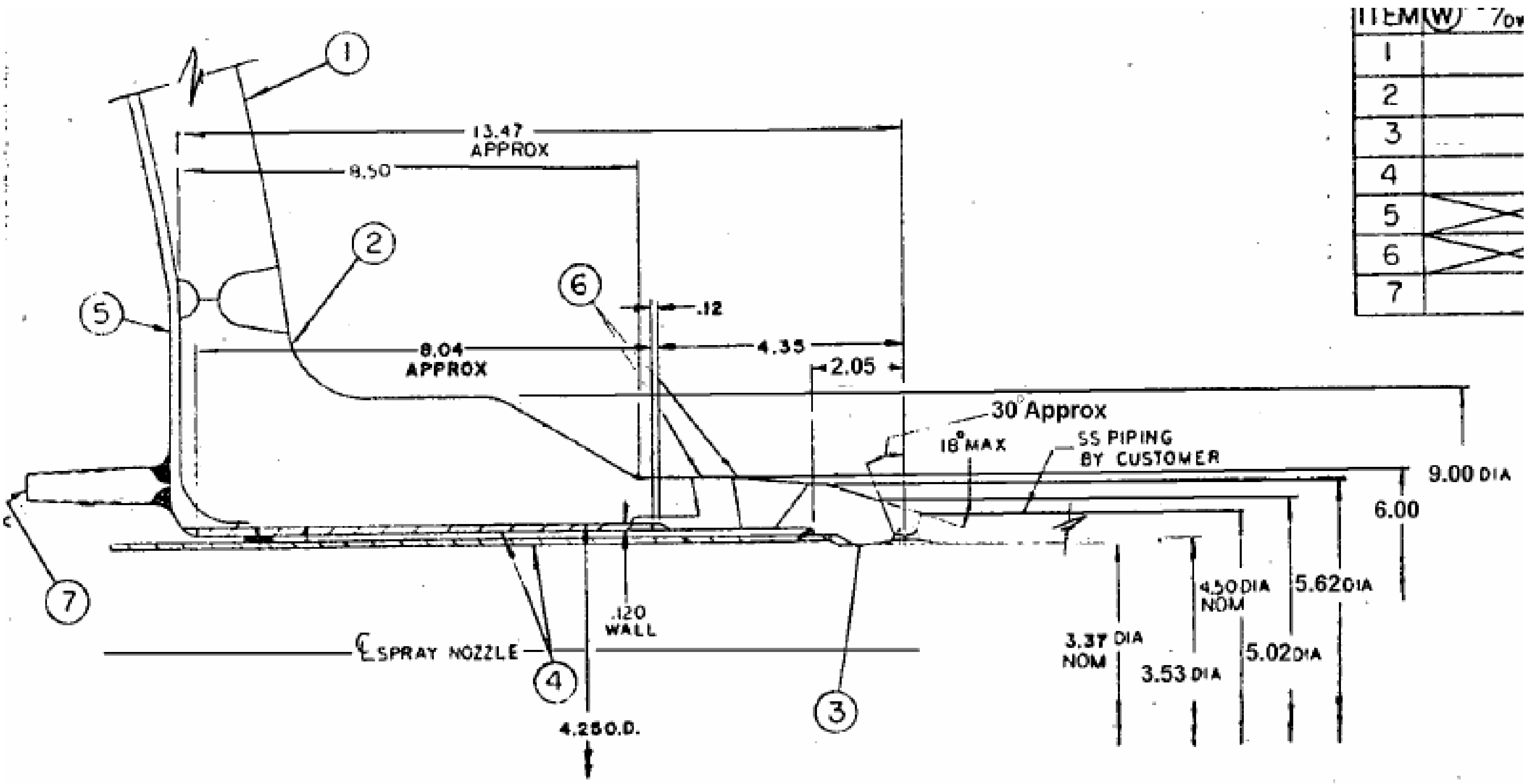
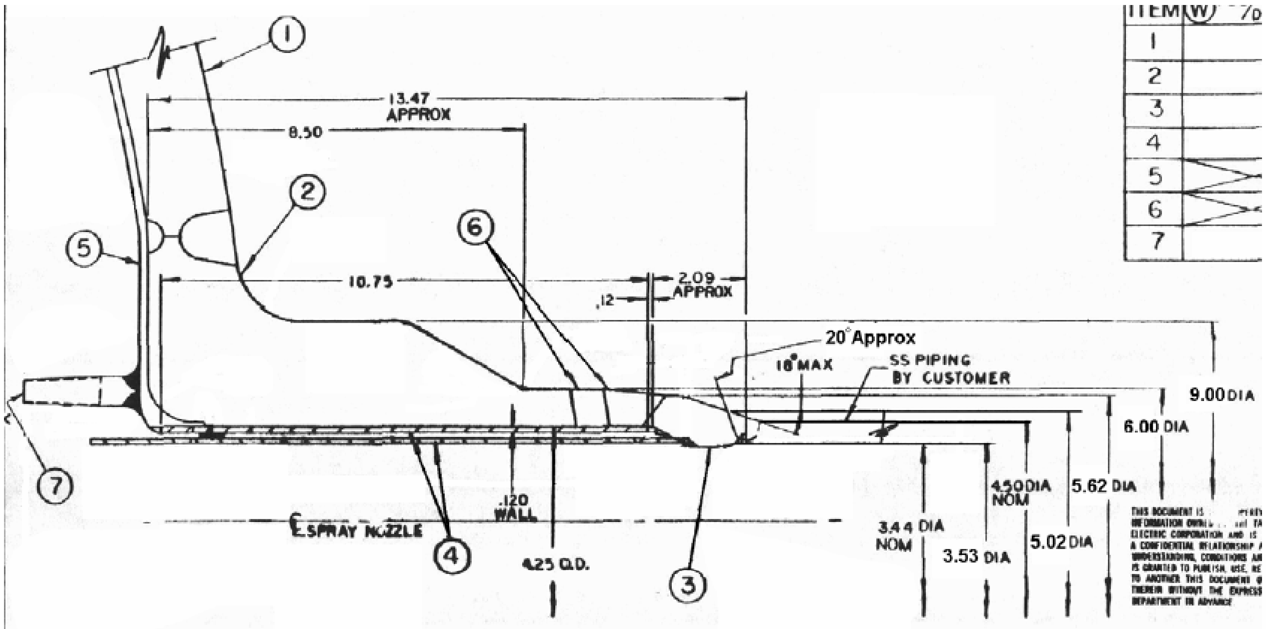
Nozzle Geometry for Subject Plants

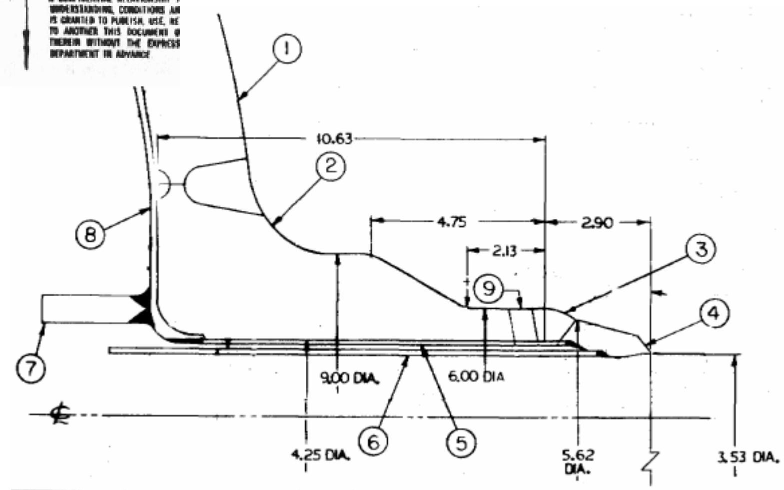
Spray Type 4: W w/liner (not extend to most DM) (4″ pipe)



Nozzle Geometry for Subject Plants

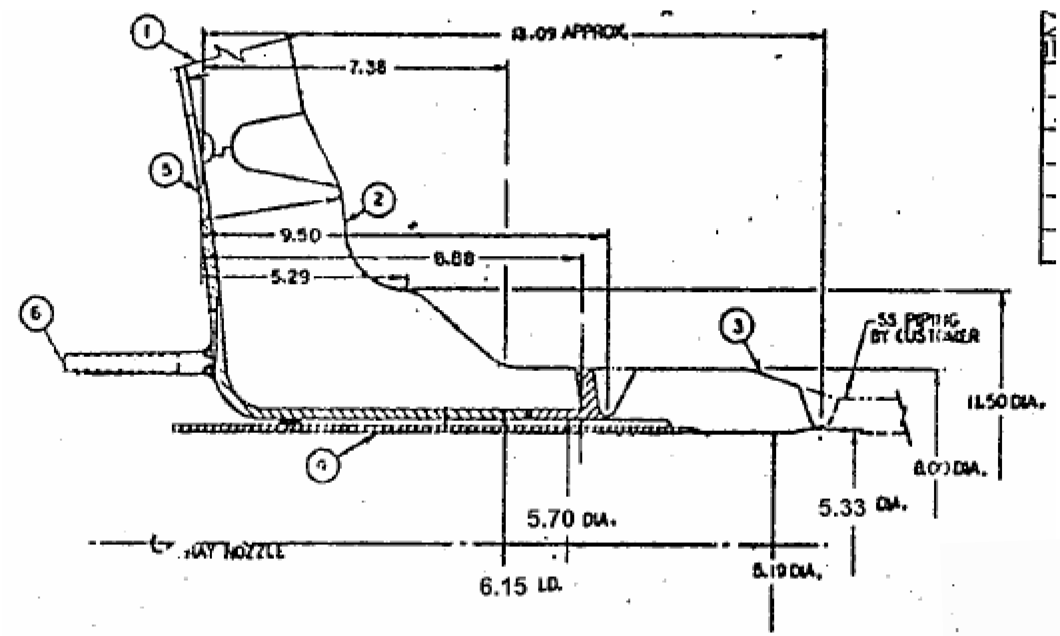
Spray Type 5: W with liner directly covering DM (4″ pipe)

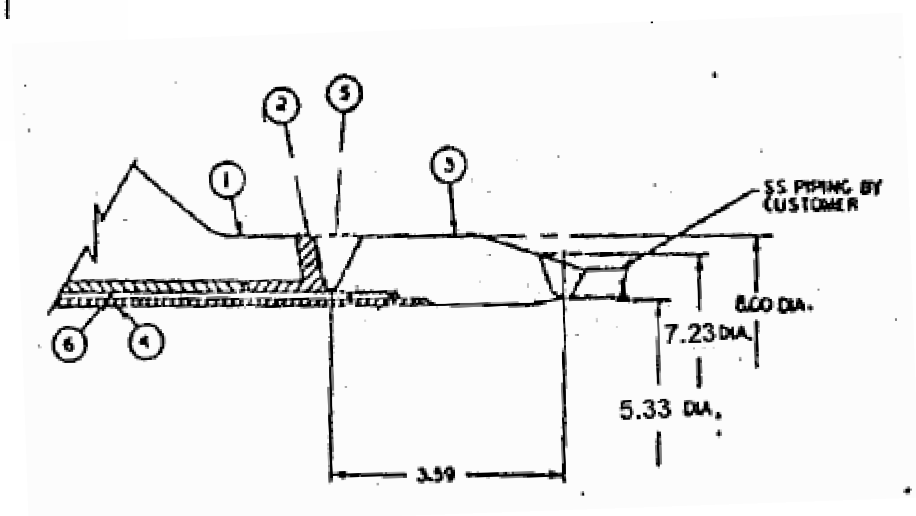




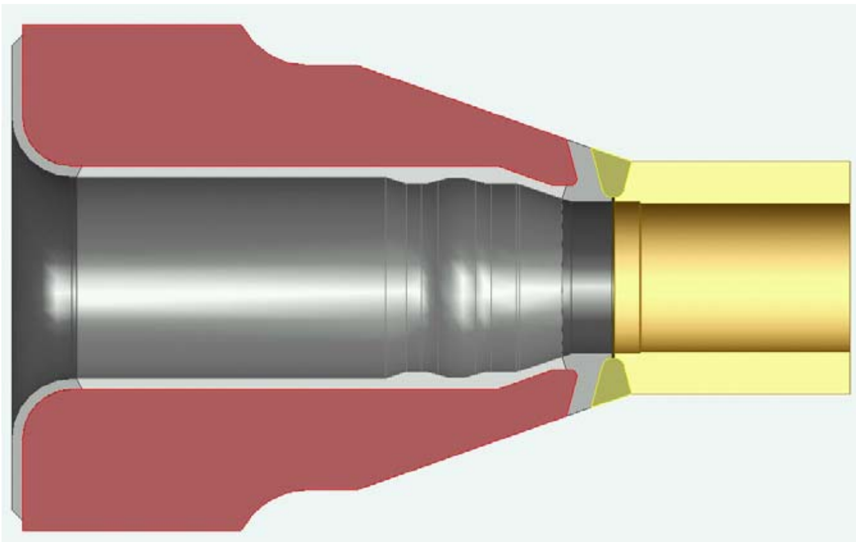
Nozzle Geometry for Subject Plants

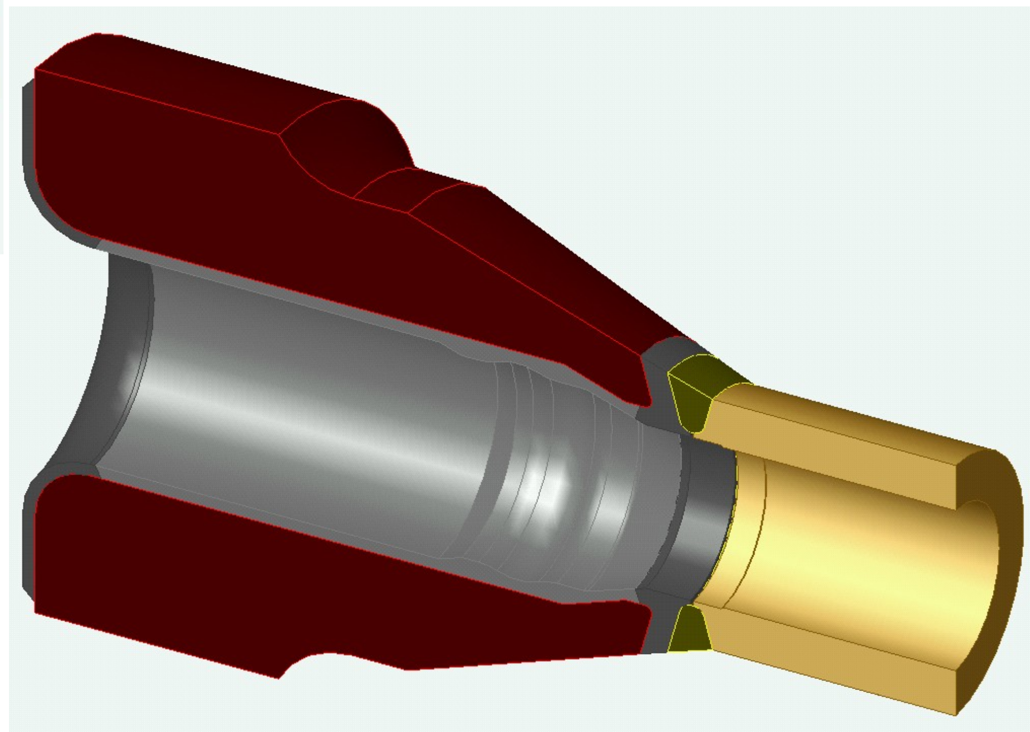
Spray Type 6: W design without liner (6″ pipe)





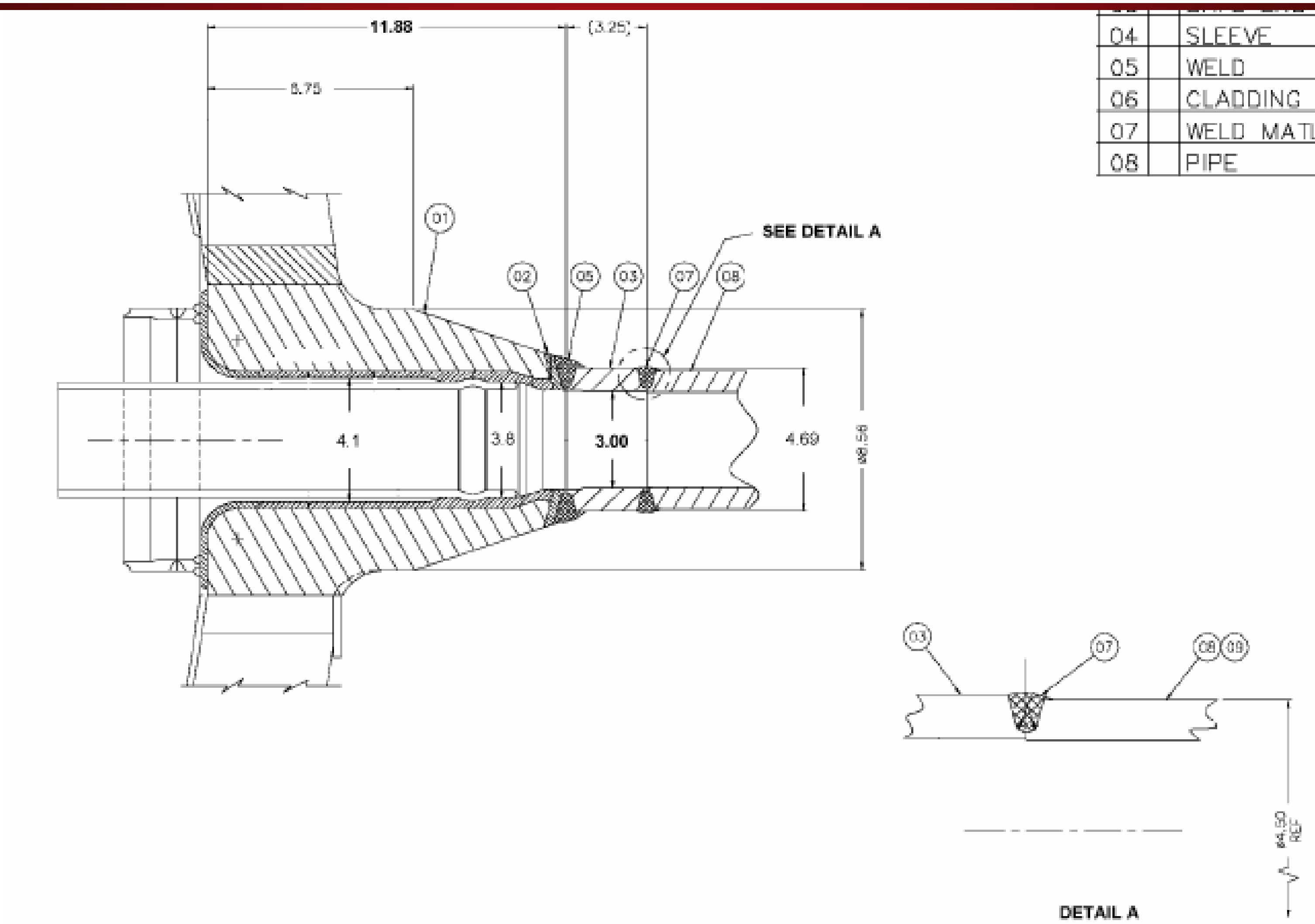
Nozzle Geometry for Subject Plants
Spray Type 7: CE design





Nozzle Geometry for Subject Plants

Spray Type 7: CE (no liner, sleeve not extend) (4″ pipe)



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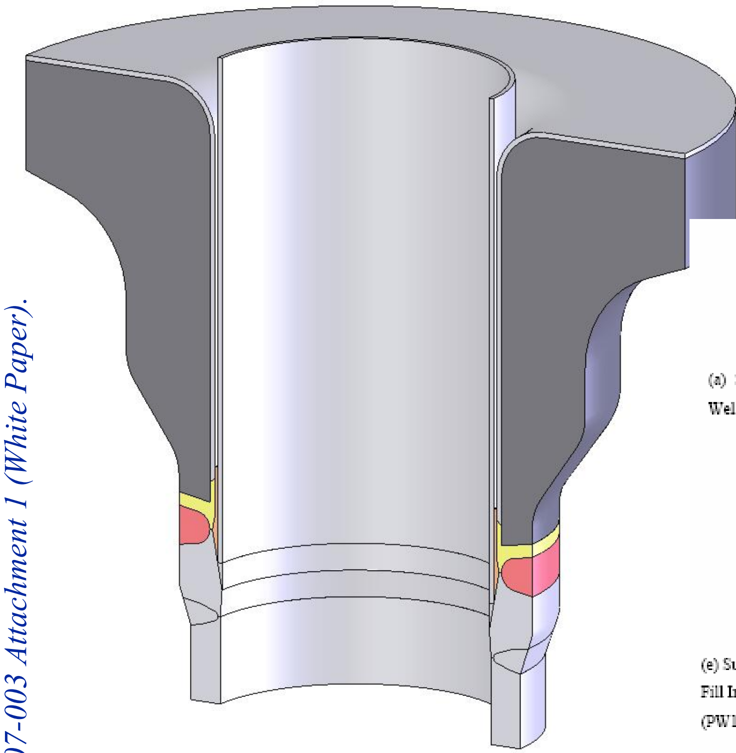
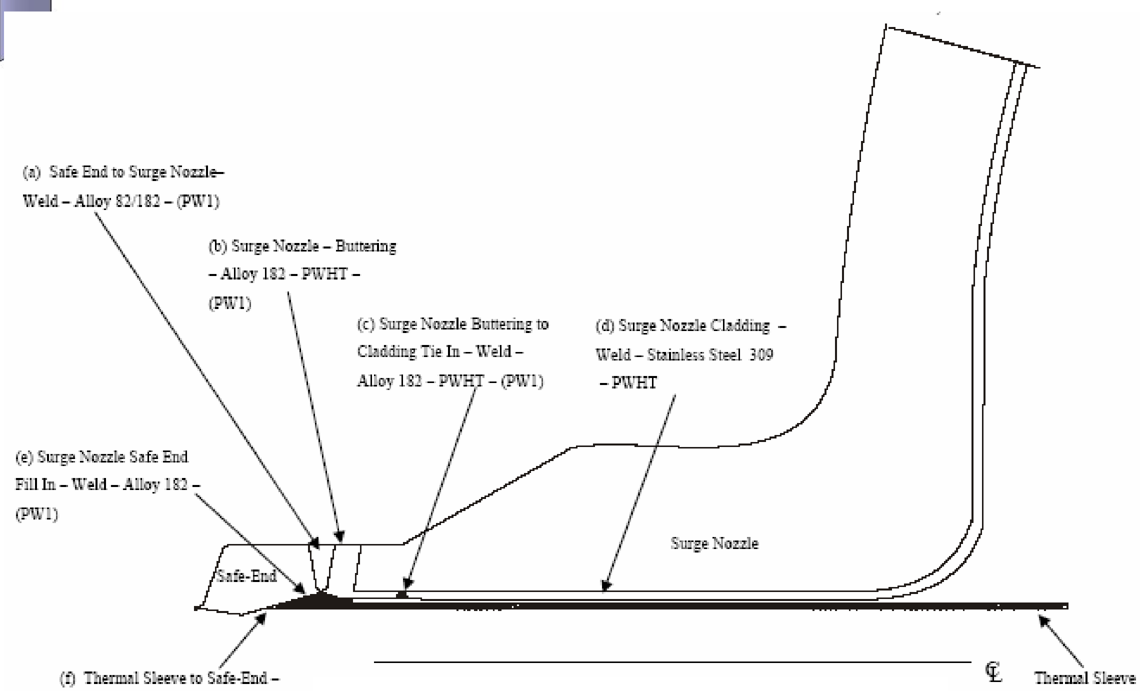
Nozzle Geometry for Subject Plants

Surge Type 8: W design (sleeve under fill-in weld)



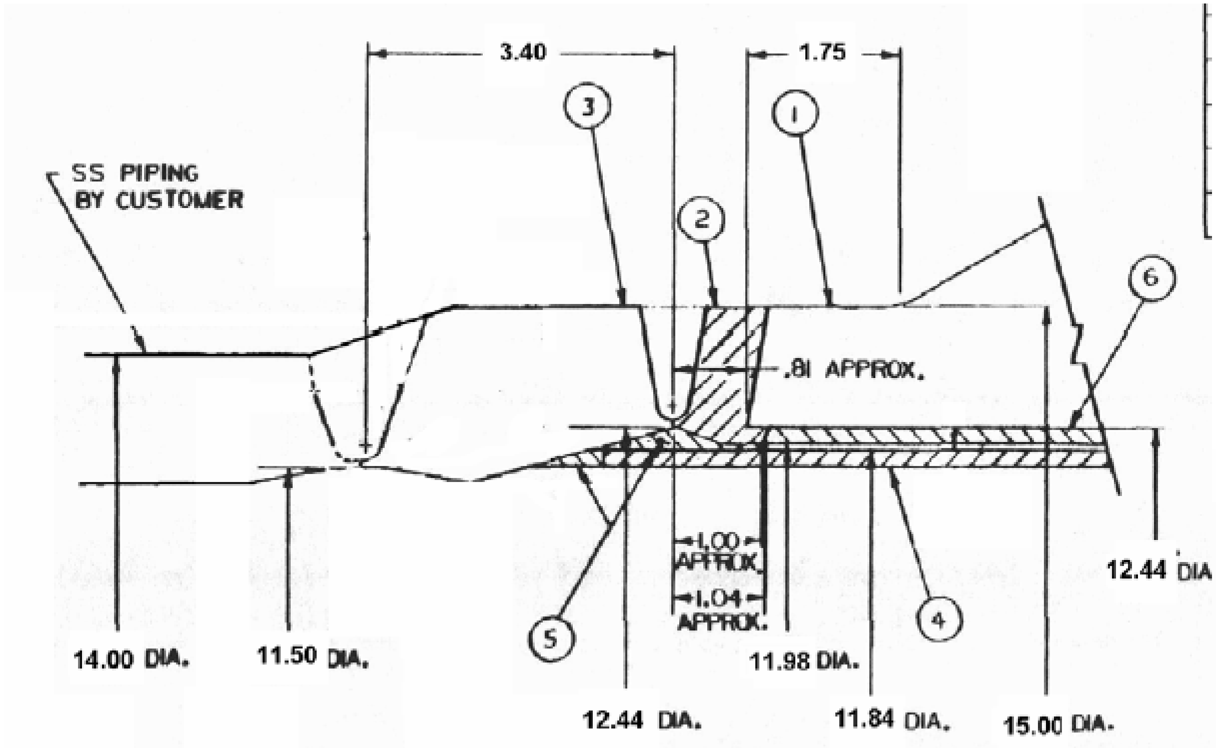


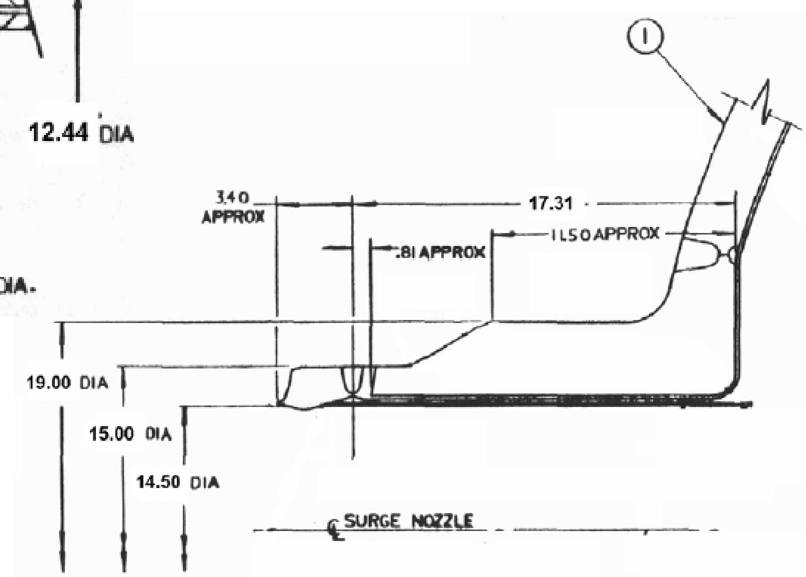
Wolf Creek Surge Nozzle Materials

Source: MRP 2007-003 Attachment 1 (White Paper).

Nozzle Geometry for Subject Plants

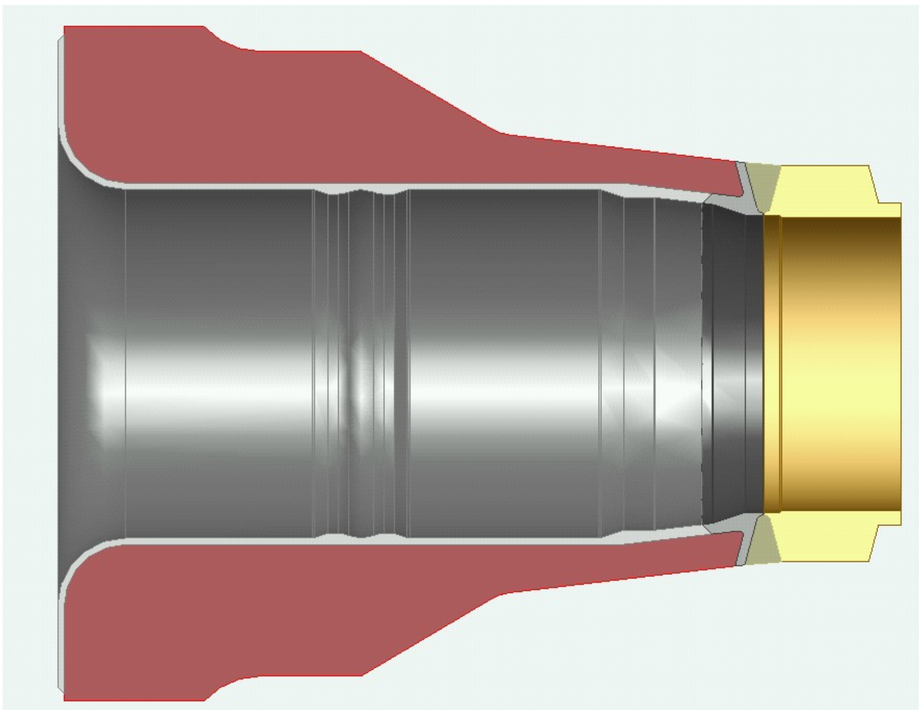
Surge Type 8: W design (sleeve under fill-in weld) (14″ pipe)

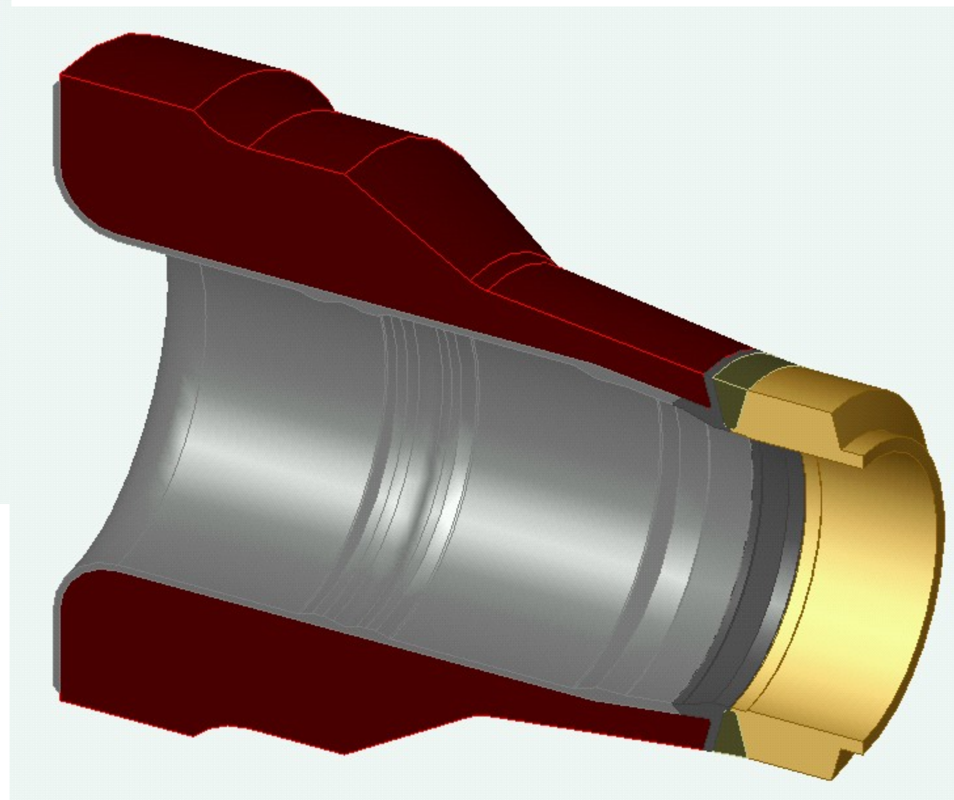




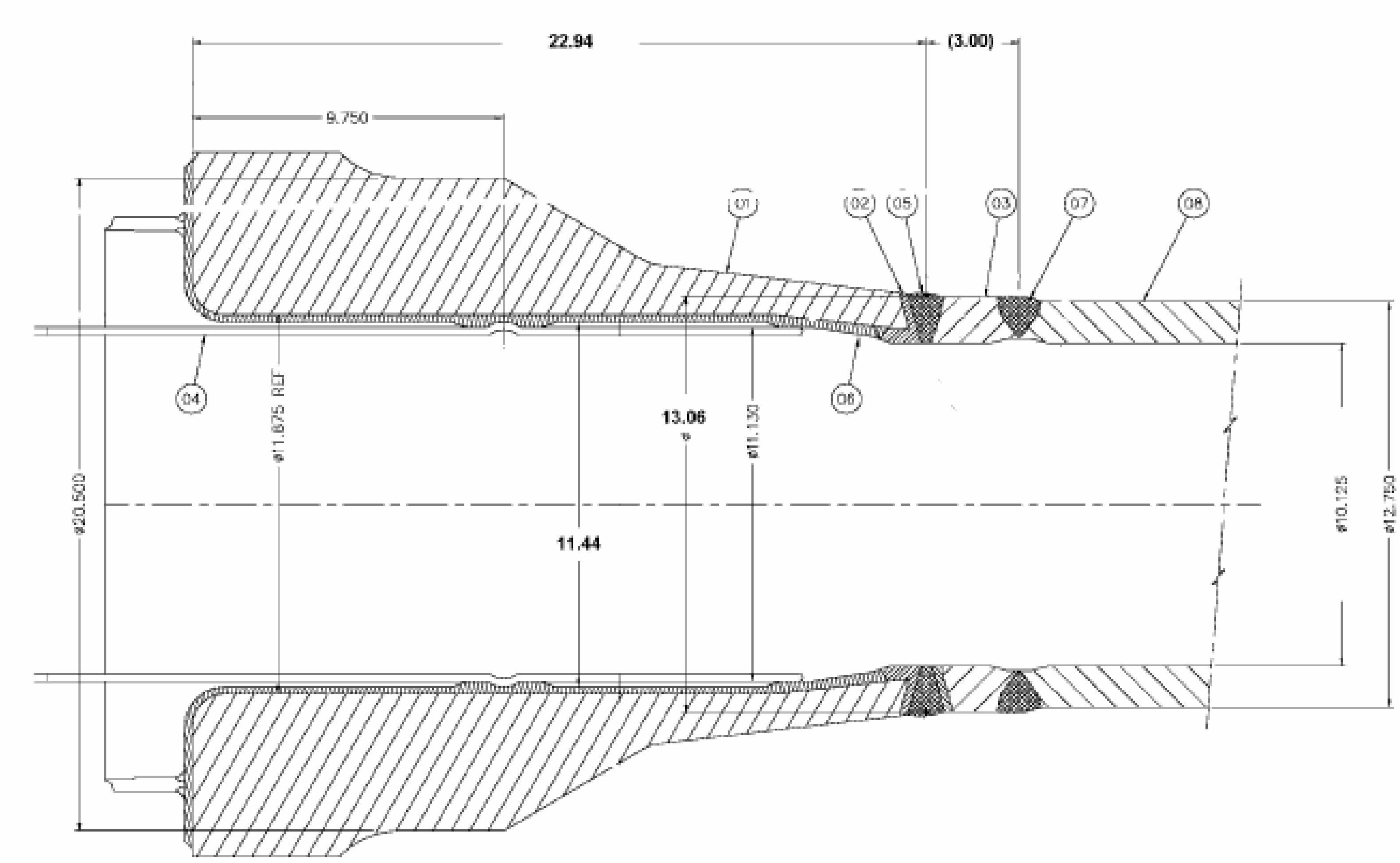
Nozzle Geometry for Subject Plants

Surge Type 9: CE design



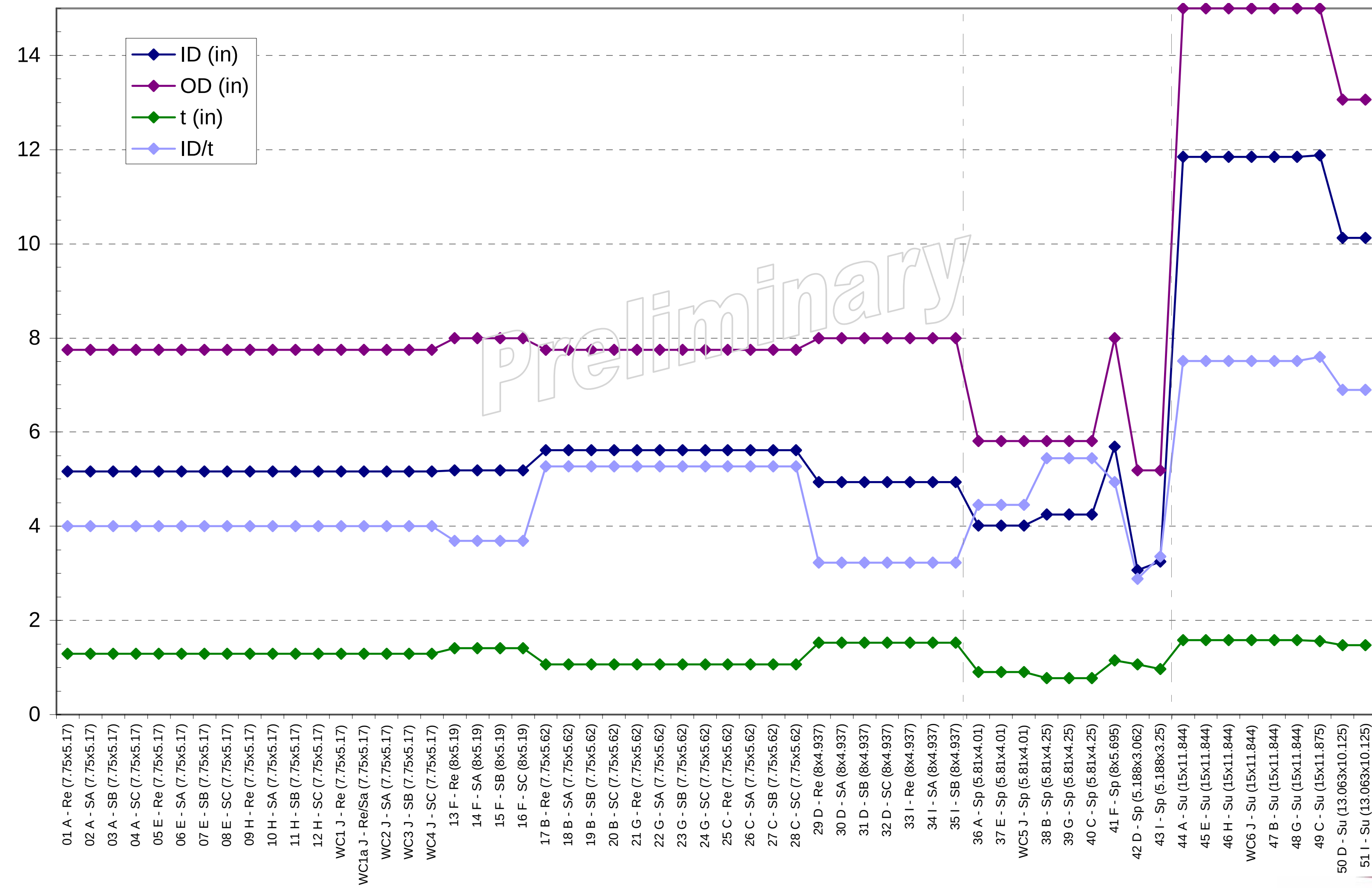


Nozzle Geometry for Subject Plants
Surge Type 9: CE design (sleeve not extend) (12″ pipe)



Nozzle Geometry for Subject Plants

Basic Weld Dimensions



Nozzle Geometry and Repair History
PRELIMINARY Summary Table

Plant Code	Relief									Safety A								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs
Plant A	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	R4
Plant E	1a	6"	N	1.29	2.0	2.2	NR	NR	R	1a	6"	N	1.29	2.0	2.2	NR	NR	NR
Plant H	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	R	R
Plant B	2a	6"	Y	1.07	2.6	2.6	NR	NR	R1	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant G	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant C	2b	6"	Y	1.07	2.6	2.3	NR	NR	NR	2b	6"	Y	1.07	2.6	2.3	R		
Plant F	1b	6"	N	1.41	1.8	3.3	NR	NR	NR	1b	6"	N	1.41	1.8	3.3	R		
Plant D	3	6"	N	1.41	1.8	6.8	NR	NR	NR	3	6"	N	1.41	1.8	6.8	R	NR	NR
Plant I	3	6"	N	1.41	1.8	6.8	N/A	N/A	N/A	3	6"	N	1.41	1.8	6.8	N/A	N/A	N/A
Plant J	1a	6"	N	1.29	2.0	2.2	Rx5	R1	R1	1a	6"	N	1.29	2.0	2.2	R	R2	NR

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. For Designs #7 and #9, sleeve does not extend to DM weld.
6. NR = No weld repairs reported
7. Rn = Repairs reported (n indicates number of defect or repaired areas if reported; "x" indicates repeat weld repair operations)
8. N/A = Results for fabrication records review not available
9. Weld repair entries for Plants C and F are preliminary.
10. All pressurizer nozzle DM welds in Plant H are reported to be Alloy 82, not Alloy 82/182.

Nozzle Geometry and Repair History

PRELIMINARY Summary Table (cont'd)

Plant Code	Safety B									Safety C								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs
Plant A	1a	6"	N	1.29	2.0	2.2	NR	R1	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	NR
Plant E	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	R	NR
Plant H	1a	6"	N	1.29	2.0	2.2	NR	NR	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	NR
Plant B	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant G	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR	2a	6"	Y	1.07	2.6	2.6	NR	NR	NR
Plant C	2b	6"	Y	1.07	2.6	2.3	R			2b	6"	Y	1.07	2.6	2.3	R		
Plant F	1b	6"	N	1.41	1.8	3.3	NR	NR	NR	1b	6"	N	1.41	1.8	3.3	NR	NR	NR
Plant D	3	6"	N	1.41	1.8	6.8	NR	NR	NR	3	6"	N	1.41	1.8	6.8	NR	NR	NR
Plant I	3	6"	N	1.41	1.8	6.8	N/A	N/A	N/A	No Safety C								
Plant J	1a	6"	N	1.29	2.0	2.2	NR	R6x2	NR	1a	6"	N	1.29	2.0	2.2	NR	NR	NR

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. For Designs #7 and #9, sleeve does not extend to DM weld.
6. NR = No weld repairs reported
7. Rn = Repairs reported (n indicates number of defect or repaired areas if reported; "x" indicates repeat weld repair operations)
8. N/A = Results for fabrication records review not available
9. Weld repair entries for Plants C and F are preliminary.
10. All pressurizer nozzle DM welds in Plant H are reported to be Alloy 82, not Alloy 82/182.

Nozzle Geometry and Repair History

PRELIMINARY Summary Table (cont'd)

Plant Code	Spray (all have thermal sleeve)									Surge (all have thermal sleeve)								
	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs	Design #	Piping NPS	Liner?	DM Weld t (in.)	DM Weld R_i/t	Weld Sep. (in.)	Butter Weld Repairs	ID Weld Repairs	OD Weld Repairs
Plant A	4	4"	Y	0.90	2.2	~2.3	NR	NR	NR	8	14"	N	1.58	3.8	3.4	NR	R5	R3
Plant E	4	4"	Y	0.90	2.2	~2.3	R	NR	R	8	14"	N	1.58	3.8	3.4	NR	R3	NR
Plant H	Already PDI examined									8	14"	N	1.58	3.8	3.4	NR	NR	NR
Plant B	5	4"	Y	0.78	2.7	2.2	NR	NR	NR	8	14"	N	1.58	3.8	3.4	R1	R1x2	R2
Plant G	5	4"	Y	0.78	2.7	2.2	NR	NR	NR	8	14"	N	1.58	3.8	3.4	NR	NR	NR
Plant C	5	4"	Y	0.78	2.7	~2.2	R			8	14"	N	1.56	3.8	3.5	NR	NR	NR
Plant F	6	6"	N	1.15	2.5	3.6	NR	NR	NR	Already structural overlayed								
Plant D	7	4"	N	1.06	1.4	3.3	NR	NR	NR	9	12"	N	1.47	3.4	3.0	NR	NR	NR
Plant I	7	4"	N	1.06	1.4	3.3	N/A	N/A	N/A	9	12"	N	1.47	3.4	3.0	N/A	N/A	N/A
Plant J	4	4"	Y	0.90	2.2	~2.3	R	NR	NR	8	14"	N	1.58	3.8	3.4	R2	R1	NR

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. For Designs #7 and #9, sleeve does not extend to DM weld.
6. NR = No weld repairs reported
7. Rn = Repairs reported (n indicates number of defect or repaired areas if reported; "x" indicates repeat weld repair operations)
8. N/A = Results for fabrication records review not available
9. Weld repair entries for Plants C and F are preliminary.
10. All pressurizer nozzle DM welds in Plant H are reported to be Alloy 82, not Alloy 82/182.

Nozzle Geometry and Repair History

PRELIMINARY Weld Repair Summary Table

Table Line	Plant Code	Nozzle Type	Nozzle Count	Design #	Buttering or Weld	ID/OD (% circ.)	Alloy 82 or 182	PWHT after Repair?	# Defect or Repair Areas	Defect/Repair Area #1		Defect/Repair Area #2		Defect/Repair Area #3		Defect/Repair Area #4		Defect/Repair Area #5		Defect/Repair Area #6	
										Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)
1	A	Safety A	1	1a	weld	OD	N/A	N/A	4	N/A	~1/2	N/A	~1/2	N/A	~1/2	N/A	~1/2				
2	A	Safety B	2	1a	weld	ID	N/A	N/A	1	1/2	5/8										
3	E	Relief	3	1a	weld	OD	N/A	N	N/A	N/A	N/A										
4	E	Safety C	4	1a	weld	ID<22%	N/A	N	N/A	N/A	N/A										
5	H	Safety A	5	1a	weld	ID	82	Y	N/A	N/A	N/A										
6						OD	82	Y	N/A	N/A	N/A										
7	F	Safety A	6	1b	NR	NR	NR	NR	NR	NR	NR										
8	B	Relief	7	2a	weld	OD	182	N/A	1	0.5	0.375										
9	C	Safety A	8	2b	NR	NR	NR	NR	NR	NR	NR										
10	C	Safety B	9	2b	NR	NR	NR	NR	NR	NR	NR										
11	C	Safety C	10	2b	NR	NR	NR	NR	NR	NR	NR										
12	D	Safety A	11	3	butter	N/A	N/A	Y	N/A	N/A	N/A										
13	E	Spray	12	4	butter	ID	82	Y	N/A	N/A	~0.3										
14					weld	OD	N/A	N	N/A	N/A	N/A										
15	C	Spray	13	5	NR	NR	NR	NR	NR	NR	NR										
16	A	Surge	14	8	weld	ID	N/A	N/A	5	1.5	5/16	3.75	0.5	2	3/16	2.5	5/16	2	5/16		
17						OD	N/A	N/A	3	2.5	0.5	2	0.5	1	3/16						
18	E	Surge	15	8	weld	ID<10%	82	N	3	N/A	N/A	N/A	N/A	N/A	N/A						
19	B	Surge	16	8	butter	N/A	82	Y	1	N/A	N/A										
20					weld	OD	182	N/A	2	1.75	0.875	1.5	1								
21						ID	182	N/A	1	1.0	0.625										
22						ID	182	N/A	1	4	0.75										

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. NR = Information not yet reported (or may not be available)
6. N/A = Information not available
7. Weld repair entries for Plants C and F are preliminary.

Nozzle Geometry and Repair History

PRELIMINARY Weld Repair Summary Table (cont'd)

Table Line	Plant Code	Nozzle Type	Nozzle Count	Design #	Buttering or Weld	ID/OD (% circ.)	Alloy 82 or 182	PWHT after Repair?	# Defect or Repair Areas	Defect/Repair Area #1		Defect/Repair Area #2		Defect/Repair Area #3		Defect/Repair Area #4		Defect/Repair Area #5		Defect/Repair Area #6	
										Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)	Length (in.)	Depth (in.)
WC1	J	Relief	WC1	1a	butter	N/A	82/182	Y	N/A	N/A	N/A										
WC2						ID+OD	82	Y	2	1/2	7/16ID	1	7/16OD								
WC3						OD	182	Y	1	1	3/4										
WC4						ID	82	Y	3	3/4	3/4	2-1/4	3/4	1/2	3/4						
WC5						OD	182	Y	3	1	3/4	2-1/4	3/4	1/2	3/4						
WC6					weld	OD	82	N/A	1	1-1/4	1/2										
WC7						ID	82	N/A	1	1/2	1/2										
WC8	J	Safety A	WC2	1a	butter	N/A	182	Y	N/A	N/A	1/8										
WC9					weld	ID	82	N/A	2	1-1/4	11/32	7/8	11/32								
WC10	J	Safety B	WC3	1a	weld	ID	82	N/A	6	2-1/2	3/4	1	1/2	1-1/2	1/2	1	1/2	2-1/2	3/4	2-1/2	3/4
WC11							82	N/A	6	1-1/2	1/2	1-1/4	1	3/4	7/8	1-1/2	3/8	1	1-1/16	1/2	1/2
WC12	J	Spray	WC4	4	butter	lip/bondline	82	Y	N/A	N/A	N/A										
WC13	J	Surge	WC5	8	butter	OD	182	Y	2	7/8	9/16	1-1/8	1								
WC14					weld	ID	82	Y	1	1	7/16										

Notes:

1. For Designs #2a, #2b, and #5, liner directly covers DM weld.
2. For Design #4, liner does not extend to most of DM weld.
3. For Designs #4, #5, and #6, sleeve covers but does not contact DM weld.
4. For Design #8, sleeve directly covers DM weld.
5. NR = Information not yet reported (or may not be available)
6. N/A = Information not available
7. Weld repair entries for Plants C and F are preliminary.

Nozzle Geometry and Repair History

Wolf Creek Repair History Summary

Defect Location and Description	Repair Description
Surge Nozzle Welds	
1. Not enough weld build-up on buttering	A182 added
2. During Repair #1 RT found (2) OD indications	Indications removed, repaired with A182, PT
3. Safe end RT showed (1) ID flaw 0.20/0.44	Indication removed, repaired with A82, PT/RT
4. Cuts made in surge nozzle SS clad to check thickness	Cuts repaired with 308L and inspected
5. With completed PZR on rail car it was discovered that Repair #4 had not been PT inspected after PWHT	Unpacked PZR, thermal sleeve removed by grinding, Repair #4 weld removed/inspected/rewelded with 308L & 309L, local PWHT, PT of repair, and thermal sleeve reinstalled by A82 weld
Spray Nozzle Welds	
6. PT indications found on build-up prior to PWHT	Indications removed, repaired with A82, PT
Safety Nozzle "A"	
7. Butter grind outs to 1/8" needed to clear PT	Repaired with A182, PWHT, PT
8. Safe end RT showed (2) ID flaws 0.34/1.25, 0.34/0.875	Indications removed, repaired with A82, PT/RT
Safety Nozzle "B"	
9. Safe end RT showed (6) ID flaws 0.5/1.0 to 0.75/2.5	Indications removed, repaired with A82, PT/RT
10. Repair #9 did not include proper cleaning step	Repairs #9 removed, repaired with A82, PT/RT
11. SS safe end ID too large	Added 308L to ID, machined, PT
Relief Nozzle	
12. Butter grind outs needed to clear PT	Repaired with A82/182, PWHT, PT
13. Butter and clad RT showed (1) ID flaw 0.44/0.5 and (1) OD flaw 0.44/1.0	Indications removed, repaired with A82, PWHT, PT/RT
14. Additional butter OD flaw (1) 0.75/1.0	Indication removed, failed RT, additional material removed, repaired with A182, PT/RT, PWHT
15. Additional butter ID flaws (3) 0.75/0.75 to 0.75/2.25	Indications removed, repaired with A82
16. Additional butter OD flaws after PWHT 0.75/0.5 to 0.75/2.25	Indications removed, repaired with A82, PT
17. ID of butter and cladding damaged during Repair #16. PT of damaged area showed ID indications	Clad weld repaired with A82, ground to clean up surface, PT
18. Safe end RT showed (1) OD flaw 0.5/1.25	Indication removed, weld repaired with A82,PT/RT
19. Safe end RT showed (1) ID flaw 0.5/0.5	Indication removed, weld repaired with A82, PT/RT
20. Safe end ID exceeded drawing maximum	Applied 308L buildup, machined, PT
21. PT after PWHT and hydro showed ID indications 1.88" long, 2.38" wide and 0.50" deep	Indication removed, weld repaired with A82,PT

Notes:
(1) Sequence numbers agree with Reference Repair Numbers in Westinghouse evaluation.
(2) See complete Westinghouse evaluation for further details.
(3) Code for flaws is Depth / Length.

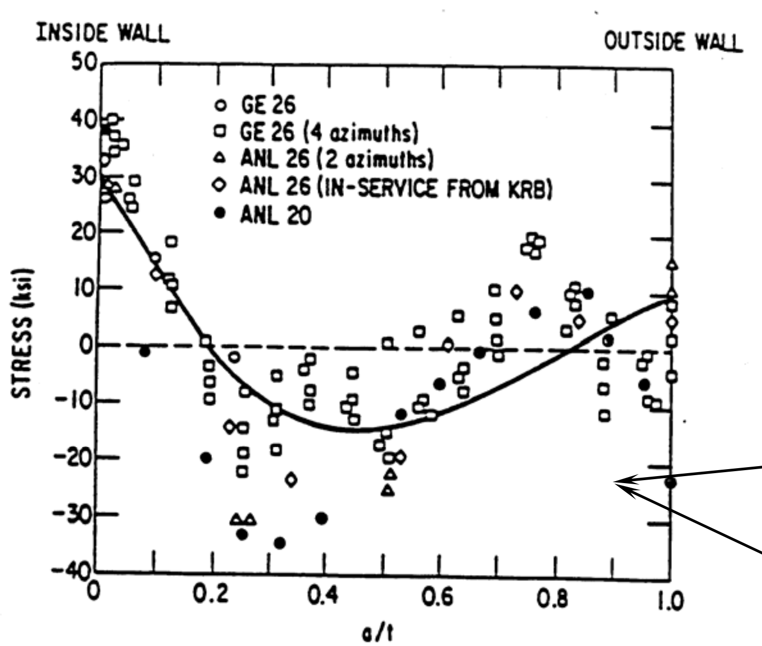
Source: MRP 2007-003 Attachment 1 (White Paper).

Nozzle Geometry for Subject Plants
As-Built Dimensional Information

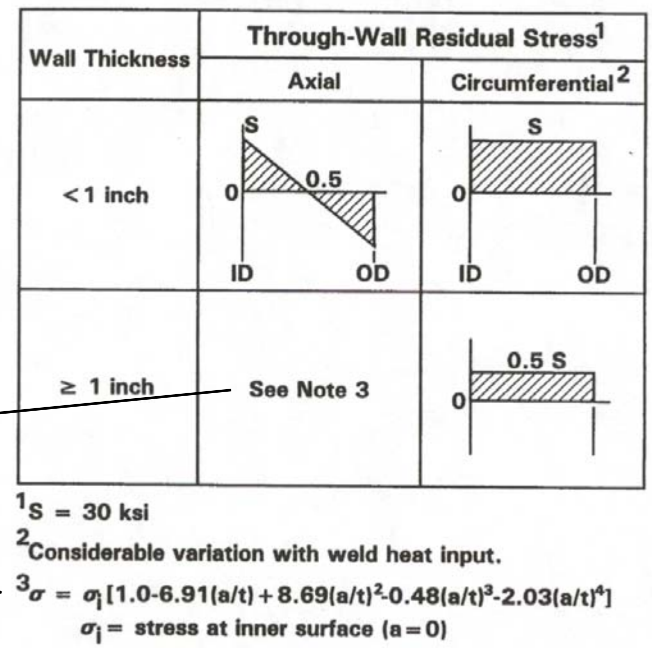
- Available as-built dimensions are being collected for the subject welds
- This information is being used to investigate as-built DM weld OD and thickness versus design dimensions
- Sensitivity cases for the crack growth calculations are planned to check sensitivity to as-built dimensions

Welding Residual Stress
ASME Distributions

- Generic residual stress models established by testing
  - Most results were for thinner wall BWR piping
  - Generic models based on nominal fit of test data



NUREG-0313, *Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping: Final Report*



Wall Thickness	Through-Wall Residual Stress[1]	
	Axial	Circumferential[2]
< 1 inch	S, 0, 0.5, ID, OD	S, 0, ID, OD
≥ 1 inch	See Note 3	0.5 S, 0

[1] $S = 30$ ksi

[2] Considerable variation with weld heat input.

[3] $\sigma = \sigma_i[1.0-6.91(a/t)+8.69(a/t)^2-0.48(a/t)^3-2.03(a/t)^4]$

$\sigma_i =$ stress at inner surface $(a=0)$

"Evaluations of Flaws in Austenitic Piping," *Transactions of ASME, J. of Pressure Vessel Technology*, v. 108, Aug. 1986, pp. 352-366.

DEI Welding Residual Stress FEA

Previous FEA Results for Butt Welds

- Weld stresses originally not explicitly considered in DEI nozzle penetration analyses
- Initial use of DEI finite element analysis techniques for weld metal residual stresses in BWRVIP-14 (1995)
  - Stainless steel BWR shroud horizontal welds
  - Vertical shroud welds considered in later work
- Initial use of DEI FEA model for Ni-alloy butt weld stresses in BWRVIP-59 (1998)
  - Welds joined low-alloy steel RPV and stainless steel shroud to Alloy 600 shroud support components
  - Extensive comparisons made to measured residual stresses in samples taken from fabricated RPVs

DEI Welding Residual Stress FEA

Previous FEA Results for Butt Welds

- Analysis models were then used to investigate PWSCC cracking observed in PWR butt weldments
- PWR Ni-alloy butt weld stress analyses are summarized in two MRP reports
  - *Elastic-Plastic Finite Element Analysis: Single and Double-V Hot Leg Nozzle-to-Pipe Welds (MRP-33): Welding Residual and Operating Stresses*, EPRI, Palo Alto, CA. TR-1001501
  - *Materials Reliability Program – Welding Residual and Operating Stresses in PWR Plant Alloy 182 Butt Welds (MRP-106)*, EPRI, Palo Alto, CA, 1009378
    - MRP-106 considers MRP-33 cases plus multiple additional nozzle geometries

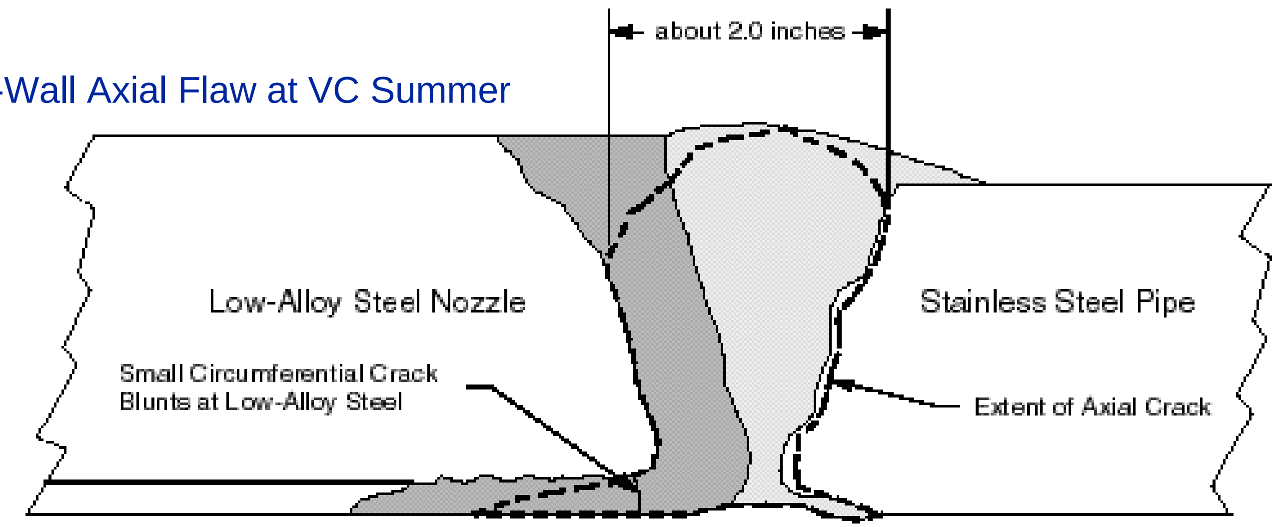
DEI Welding Residual Stress FEA
Analysis Methodology

- Welding analysis model is a combined thermal transient plus structural analysis
  - Temperatures generated during welding simulated using thermal transient analysis
  - Structural model analyzed with a series of static load steps by inputting temperatures from the thermal transient analysis
- Weld beads are simulated using layers of weld material
  - Number of weld layers used depends on age (i.e., available computing power) and complexity of analysis model
  - Heat generation rate and time for each layer varied to obtain idealized temperatures at the center and at the fusion line of the weld
- Models have been developed for
  - 2-D (axisymmetric) and 3-D models
  - Single-V and Double-V groove butt welds
  - Single V groove butt welds with ID repair, both axisymmetric and partial-arc

VC Summer – 2000

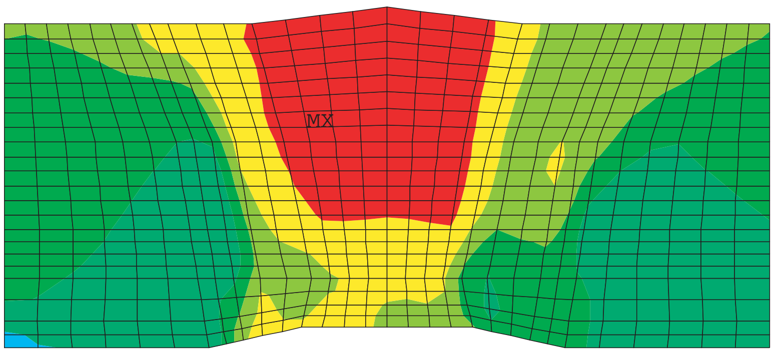
- PWSCC cracks have been discovered in RPV inlet and outlet nozzle to primary coolant pipe butt welds at VC Summer and Ringhals
  - Axial cracks in inlet and outlet nozzle butt welds at VC Summer, including one through-wall crack in an outlet nozzle butt weld that led to a leak
  - Part-depth axial cracks in outlet nozzle welds at Ringhals 3 and 4
  - A shallow circumferential crack in outlet nozzle cladding at VC Summer that arrested once the crack penetrated to the low-alloy steel nozzle

Through-Wall Axial Flaw at VC Summer

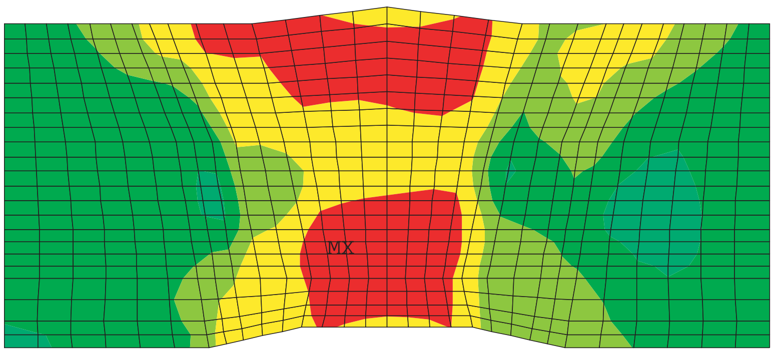


VC Summer – 2000
MRP-33

- The outlet nozzle butt weld at VC Summer had been repaired from the inside surface
- Weld repair on the inside of a nozzle has been shown to produce high residual tensile stresses



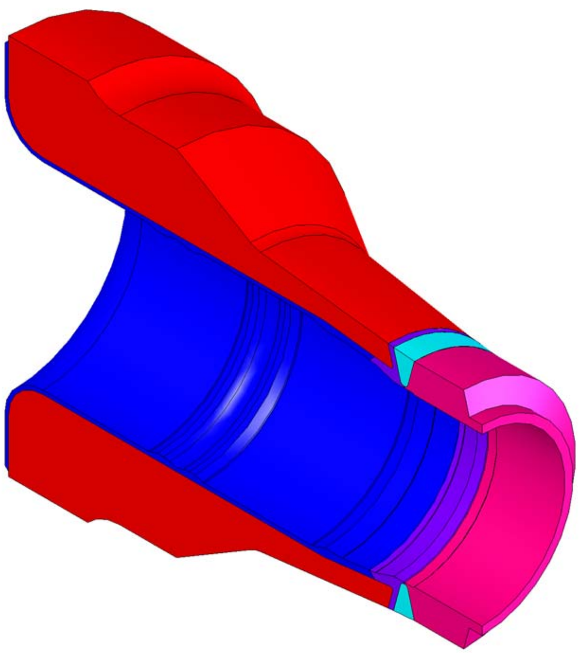
Operating Hoop Stress – As Designed

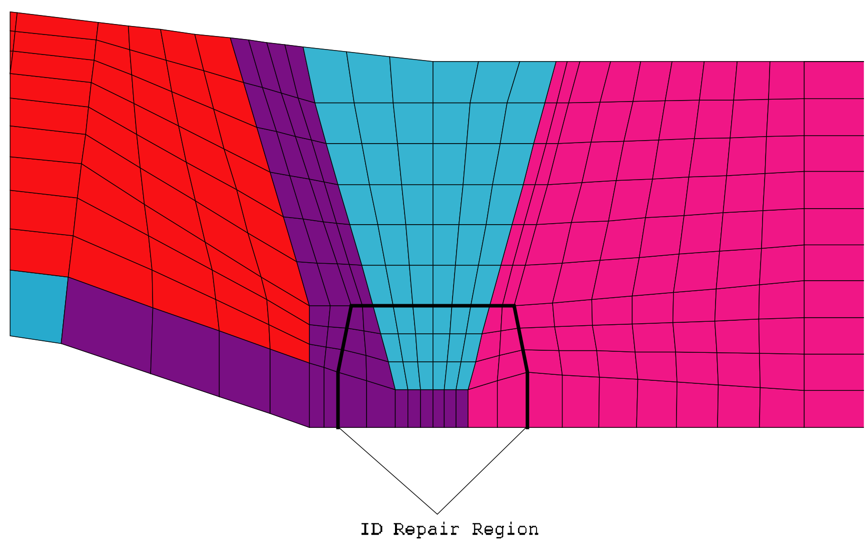


Operating Hoop Stress – With ID Repair

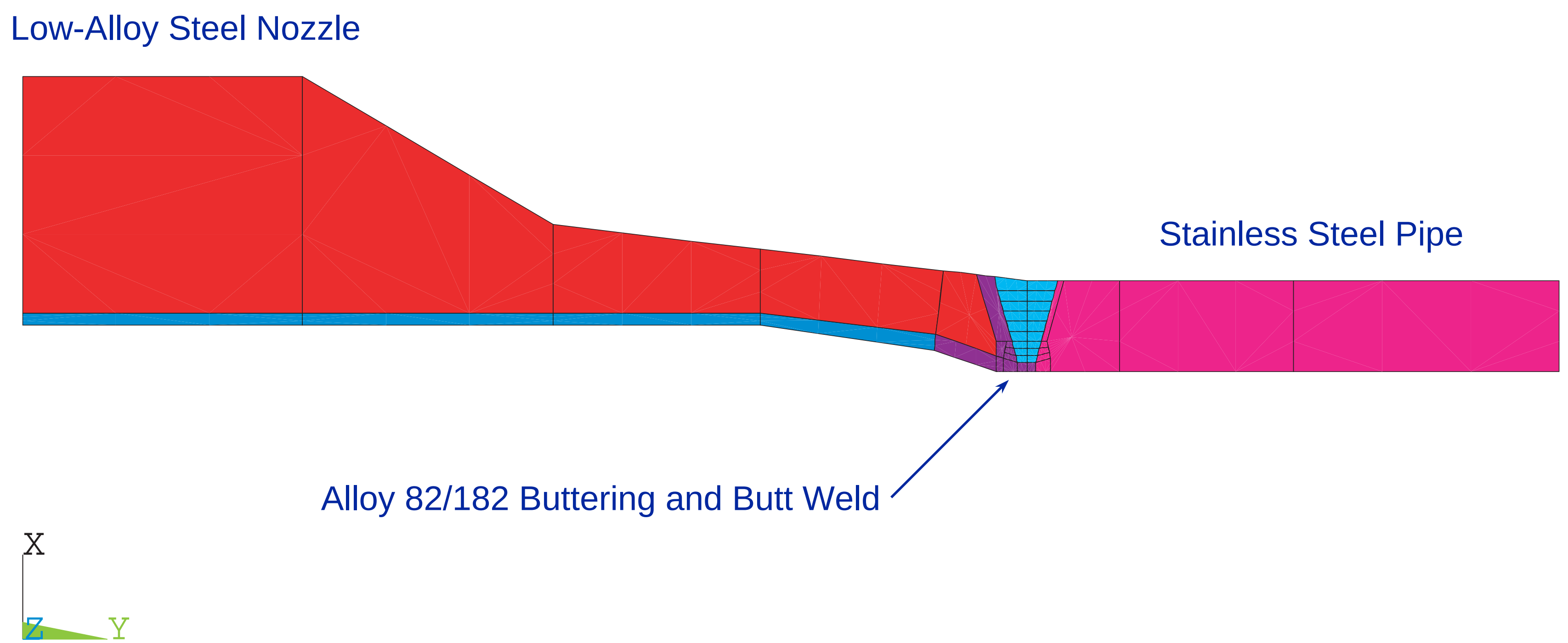
FEA Methodology
Pressurizer surge nozzle with ID repair

- About 10 weld pass layers for original weld
- Weld backgouged from the inside surface approximately 1/3 wall thickness
- Backgouged area weld repaired from the inside surface using 4 passes

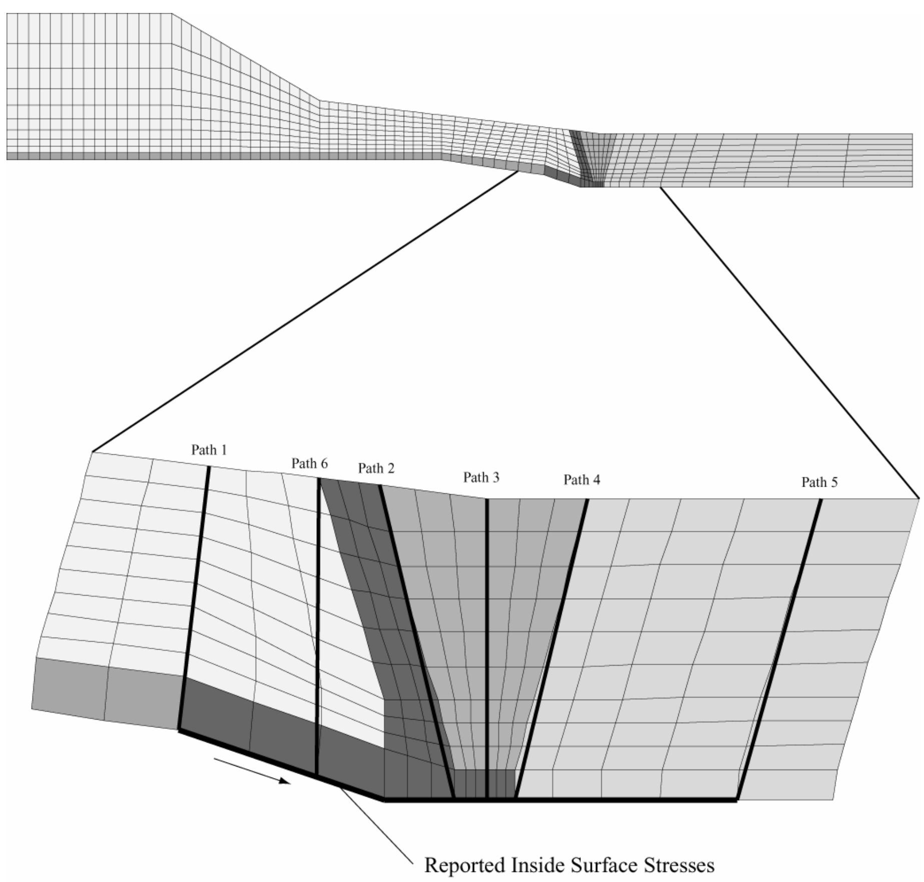


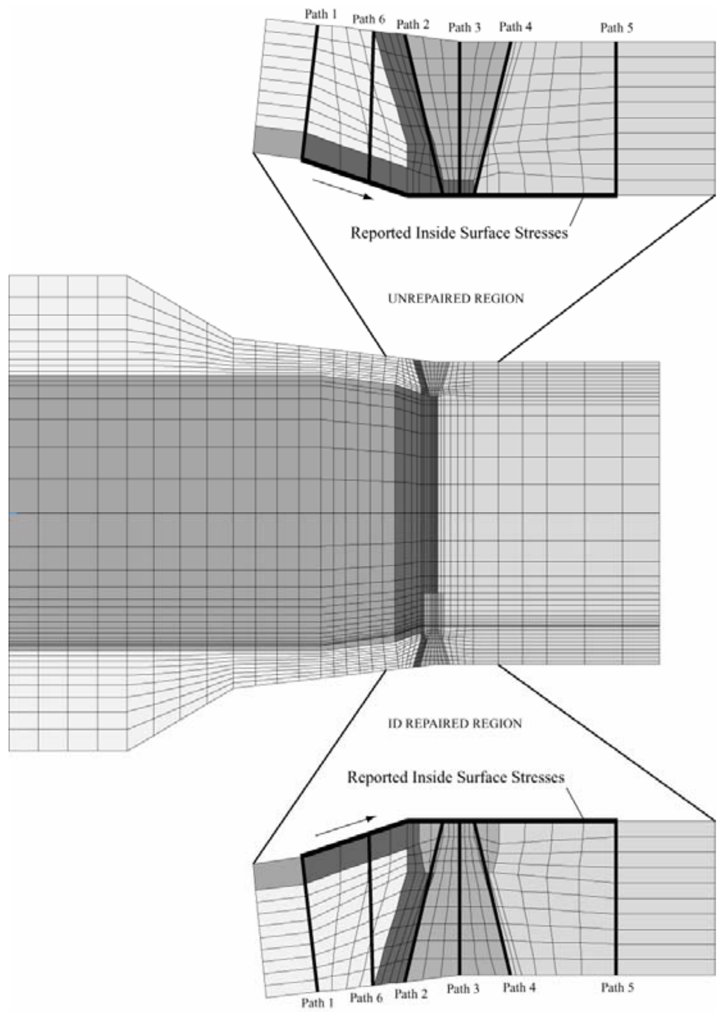


FEA Methodology
Example Finite Element Model



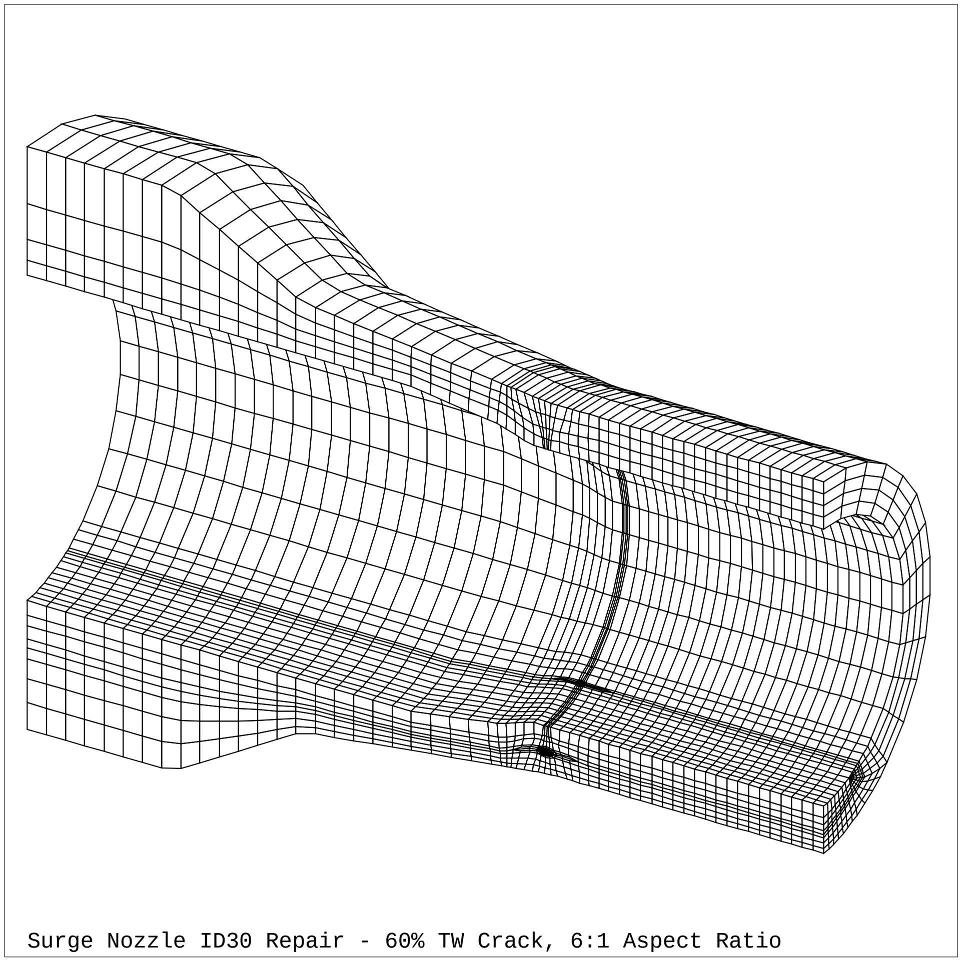
FEA Methodology
Example Finite Element Model (cont'd)

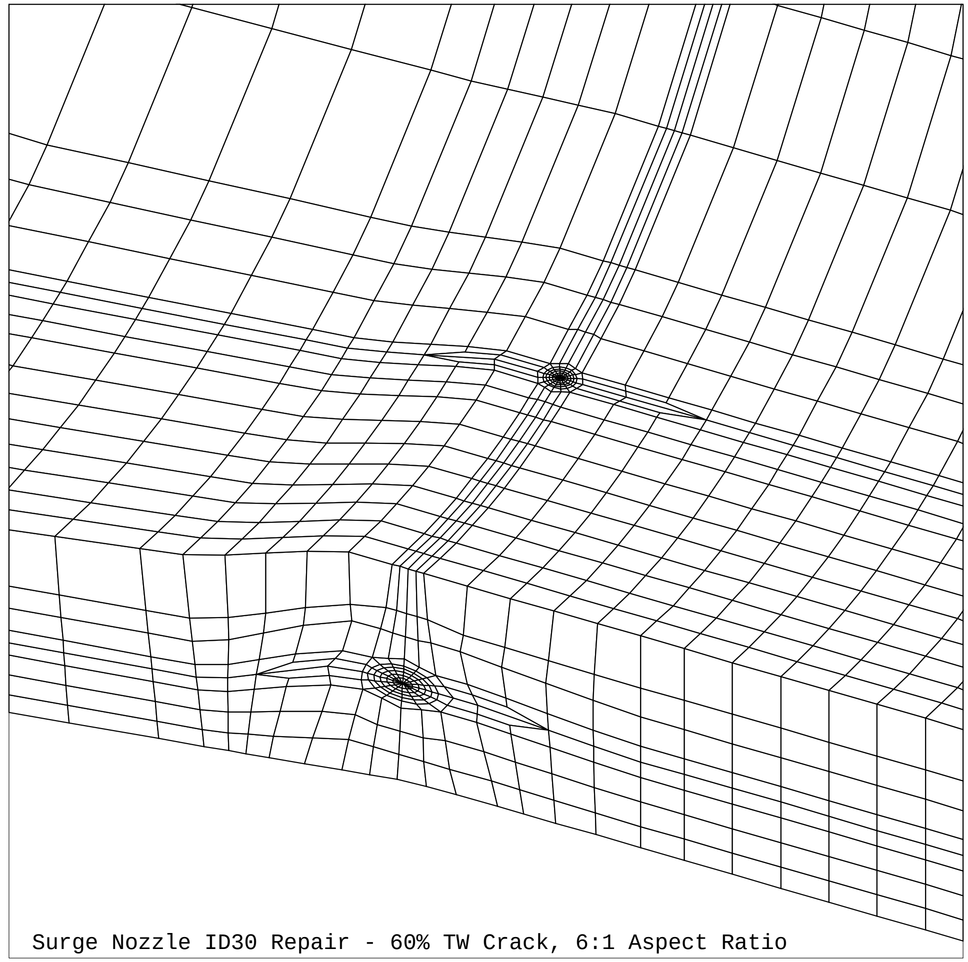




FEA Methodology

Example 3D Finite Element Model

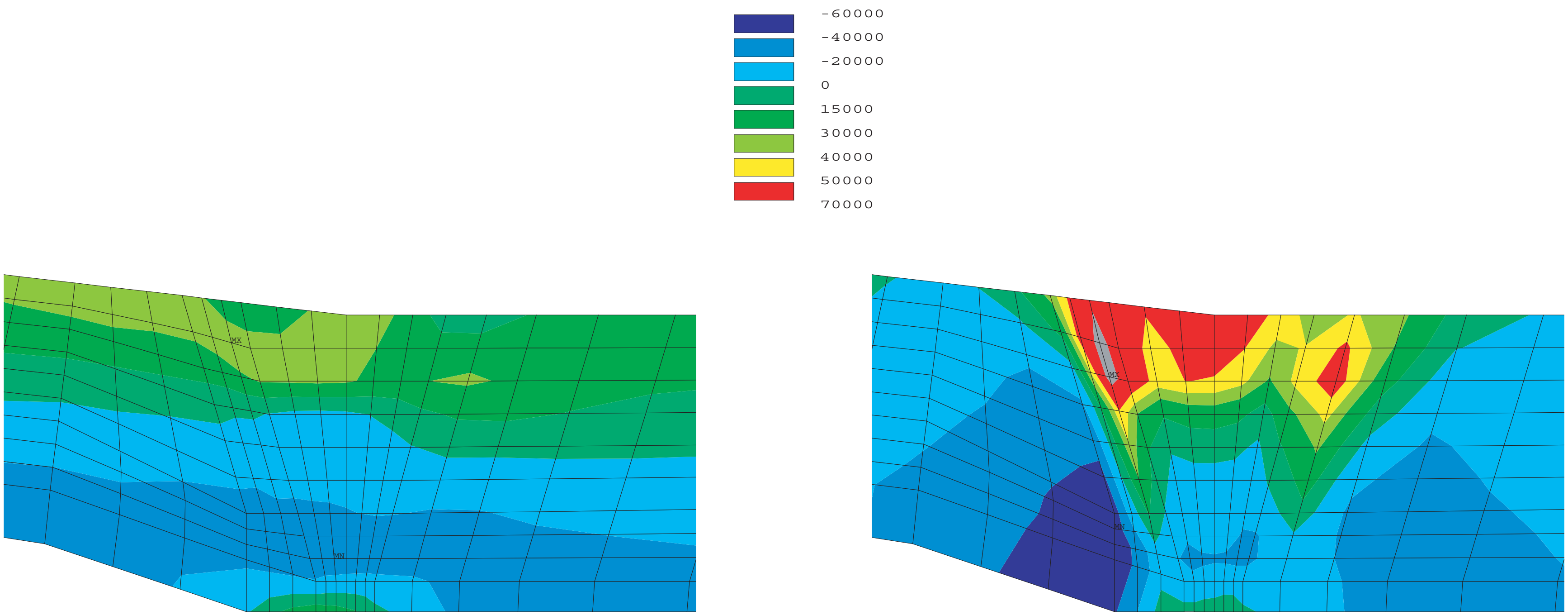




DEI Welding Residual Stress FEA

Analysis Results – Surge Nozzle

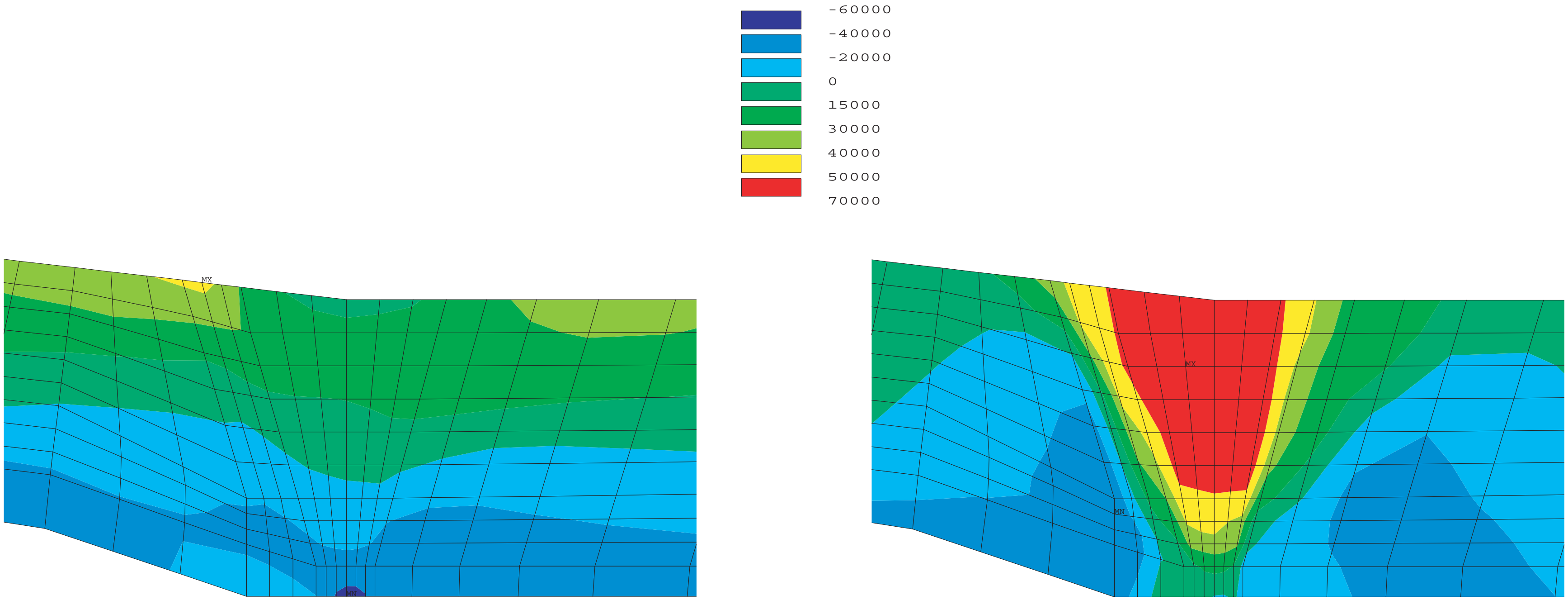
- Welding Residual Stress (as designed)



Axial Stress Hoop Stress

DEI Welding Residual Stress FEA
Analysis Results – Surge Nozzle

- Operating Stress (as designed)



Axial Stress

Hoop Stress

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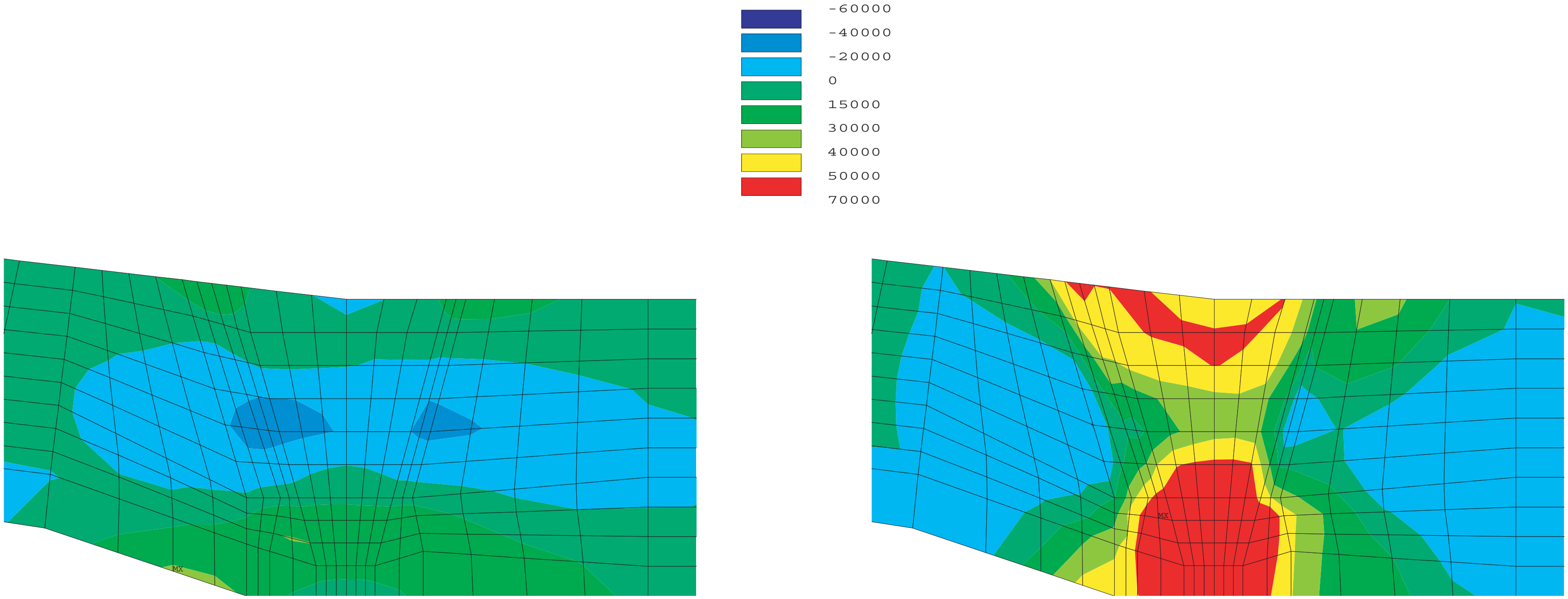
DEI Welding Residual Stress FEA
Analysis Results – Surge Nozzle

- Operating Stress (with ID 360° weld repair)

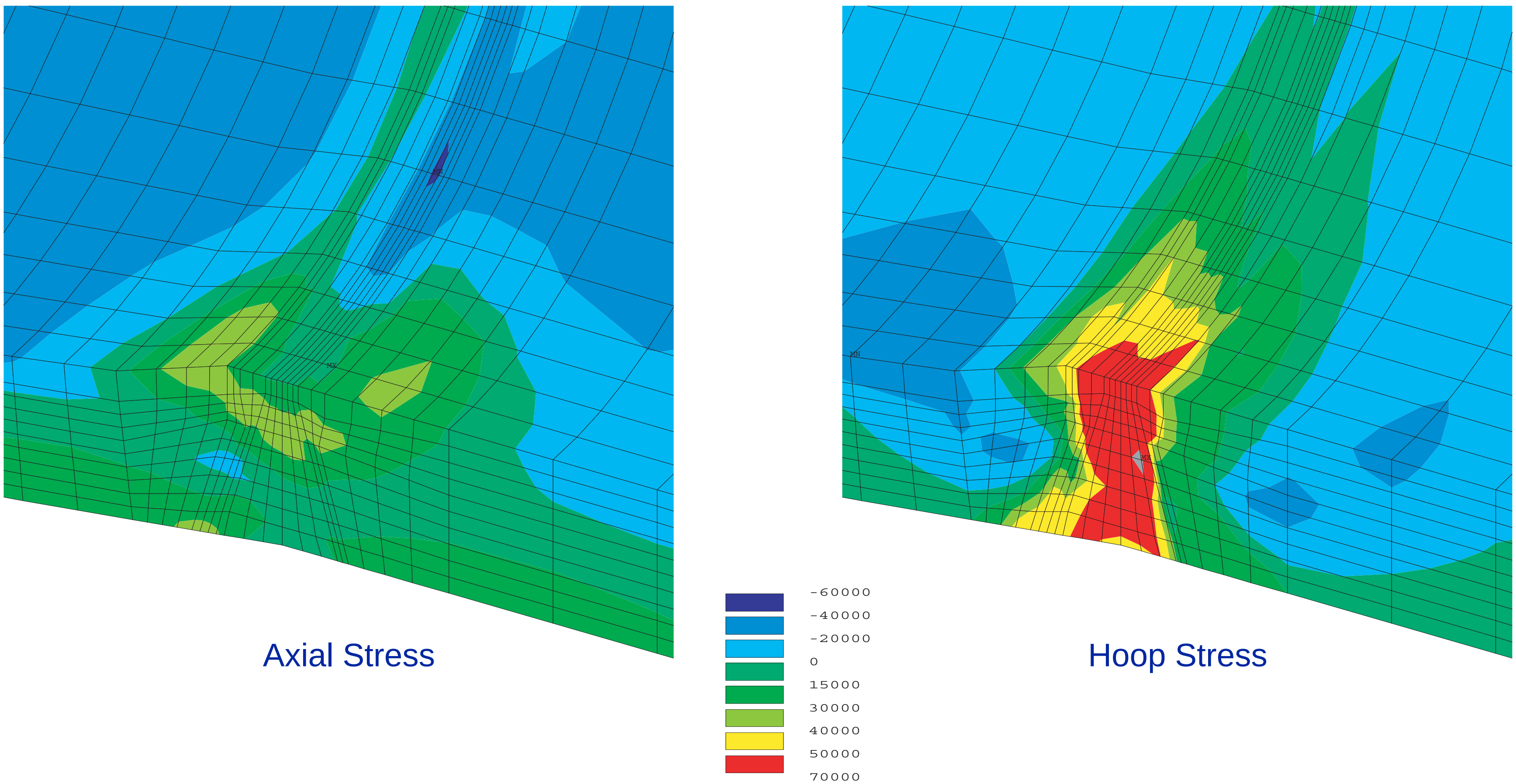


Axial Stress

Hoop Stress

DEI Welding Residual Stress FEA
Analysis Results – Surge Nozzle

- Operating Stress (with ID 30° weld repair)



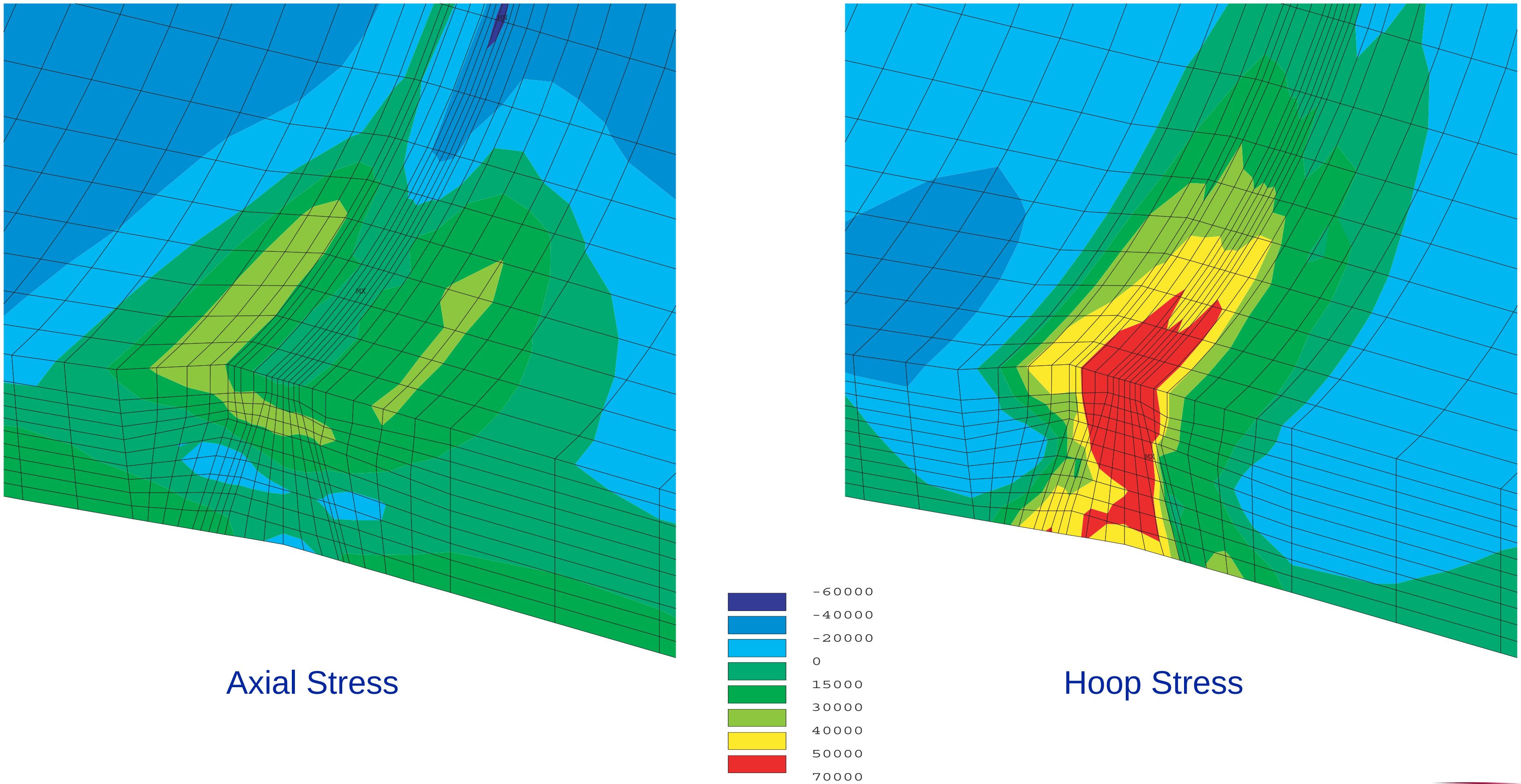
Axial Stress

Hoop Stress

DEI Welding Residual Stress FEA

Analysis Results – Surge Nozzle

- Operating Stress (with ID 60° weld repair)



Axial Stress

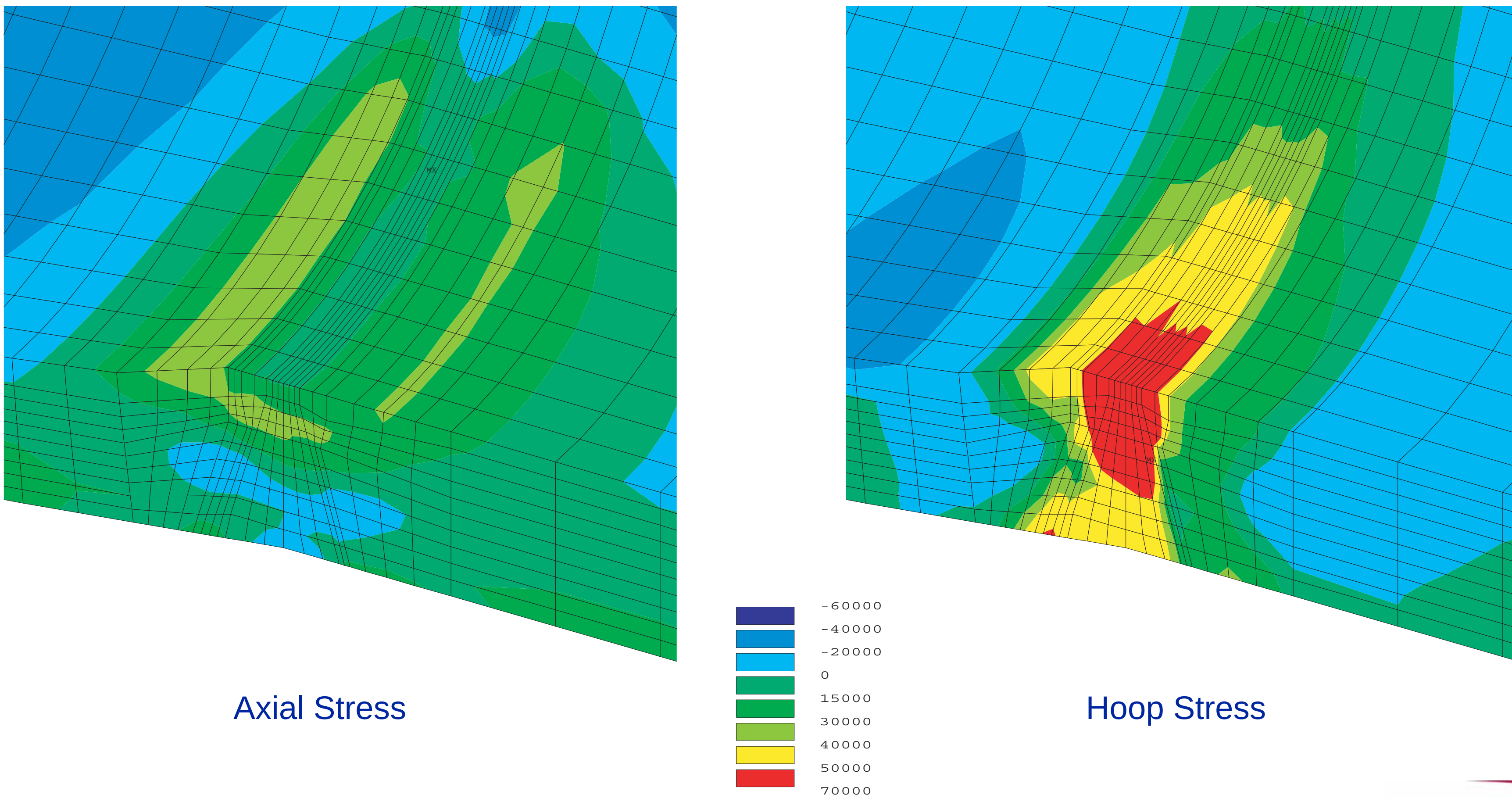
Hoop Stress

Dominion Engineering, Inc.

DEI Welding Residual Stress FEA

Analysis Results – Surge Nozzle

- Operating Stress (with ID 90° weld repair)

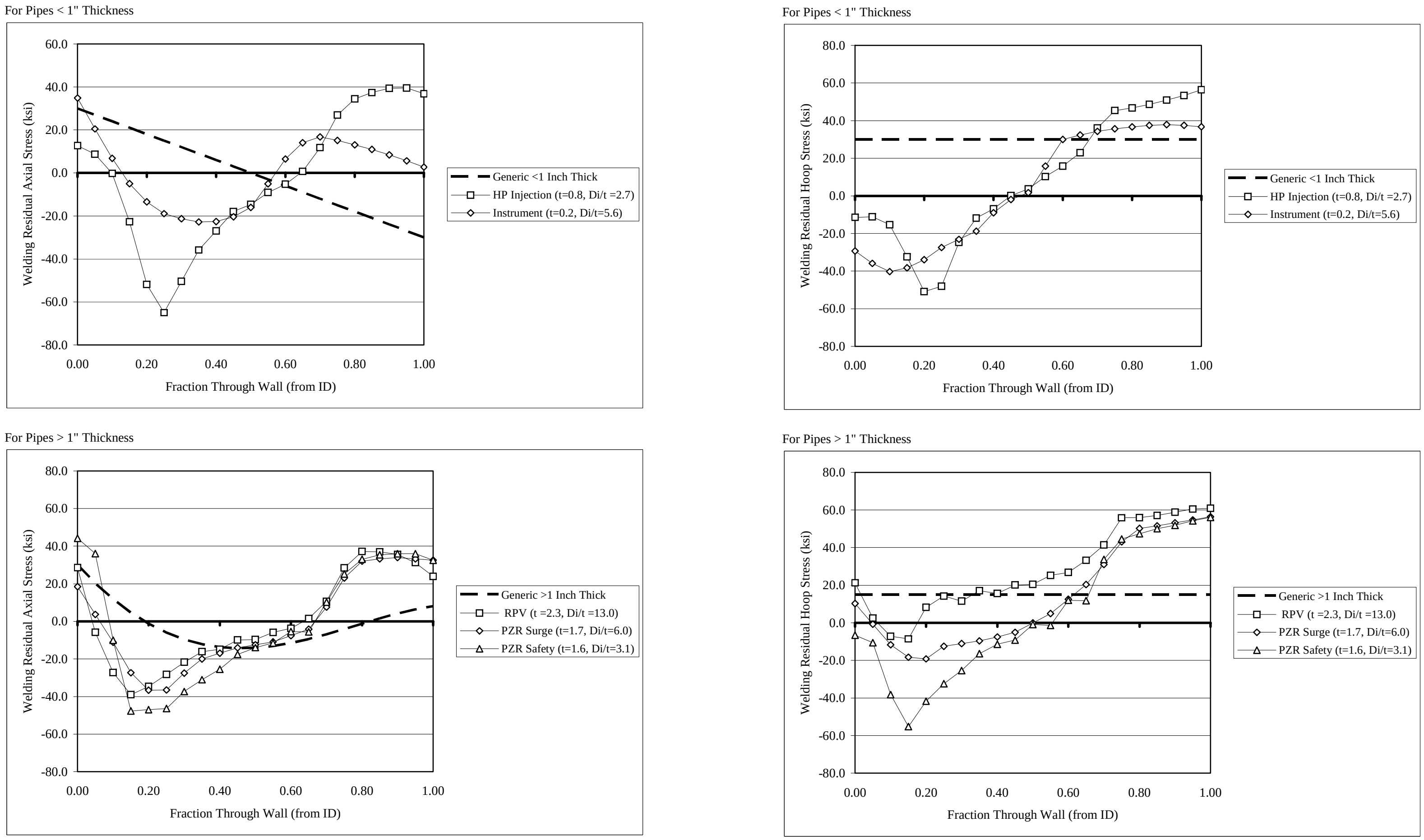


Axial Stress

Hoop Stress

Dominion Engineering, Inc.

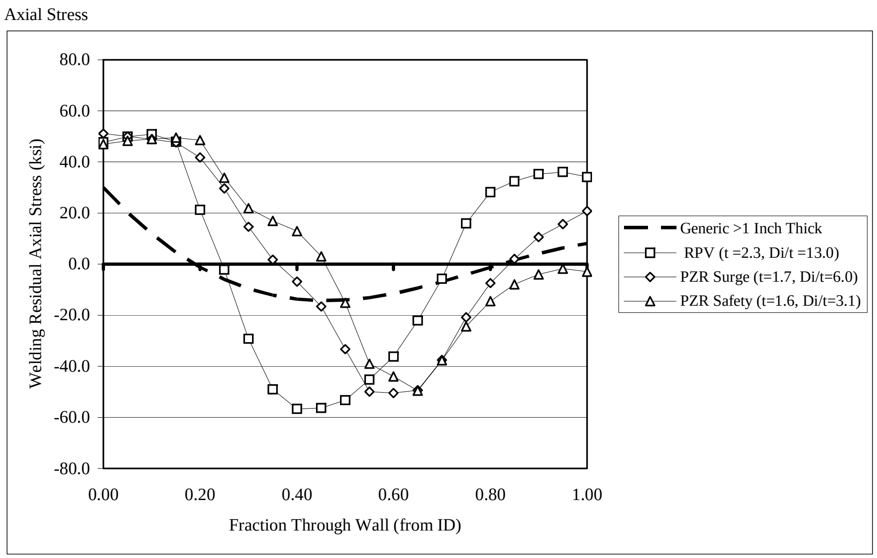
Welding Residual Stresses
FEA vs. Standard Generic Model (Without Weld Repairs)

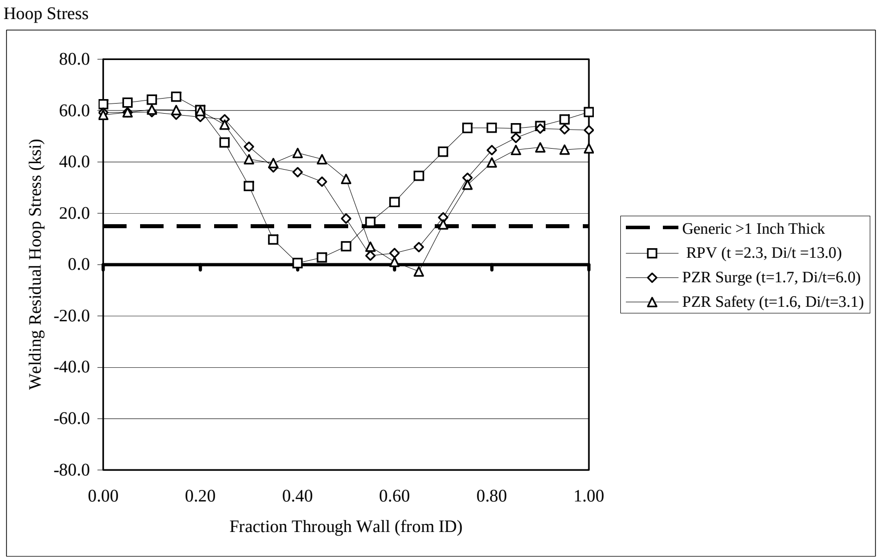


Generic results generally <u>conservative</u> through mid-wall

Welding Residual Stresses

FEA vs. Standard Generic Model (with Weld Repair from ID Surface)

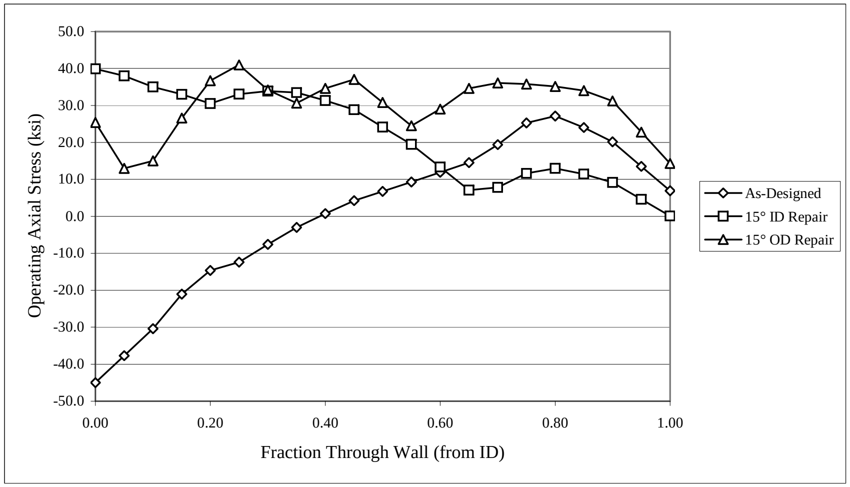


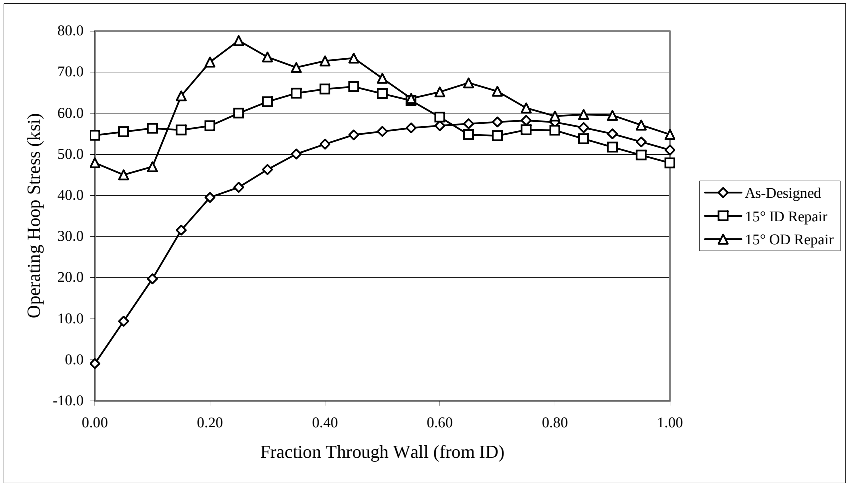


Generic results do not bound FEA results for areas with ID repairs

Welding Residual & Operating Stresses

With Partial-Arc Weld Repair from ID & OD Surface (FEA vs. FEA)





Partial-arc weld repairs from ID and OD produce high restraint and result in through-wall stresses much higher than without weld repairs

Welding Residual Stress

Conclusions of Previous DEI Work for EPRI (MRP-106, etc.)

- Welding residual stresses are high and a significant contributor to butt weld PWSCC
- The generic welding residual stress model is conservative for the as-designed case without repairs
- Weld repairs from the ID surface (360° or partial-arc) significantly increase ID surface stresses
  - Generic welding residual stress model does not bound FEA results for cases involving repairs from the ID surface
- <u>Deep partial-arc</u> weld repairs from the OD surface have high restraint and may produce similar through-wall stress distributions as for cases of ID repairs depending on depth of repair
  - Generic welding residual stress model does not bound FEA results for some cases involving partial-arc repairs from the OD surface
- High stresses for cases involving partial-arc repairs are limited to the repaired area
  - Expected to produce cracks limited to the repaired area, not 360°

Piping Butt Weld WRS – Literature Review
P. Dong, J. Zhang, and P.J. Bouchard

- P. Dong, J. Zhang, and P.J. Bouchard, "Effects of Repair Weld Length on Residual Stress Distribution," *Journal of Pressure Vessel Technology*, vol. 124, February 2002.
  - 3D shell element model with 21.3″ OD × 0.75″ thickness, 75% depth repairs
  - Short repairs → highest peak OD axial stress in repair zone
  - Model shows OD repair start-stop region characterized by sharp transition from compressive to tensile axial stresses (as high as 70 ksi change in stress within about 20°)

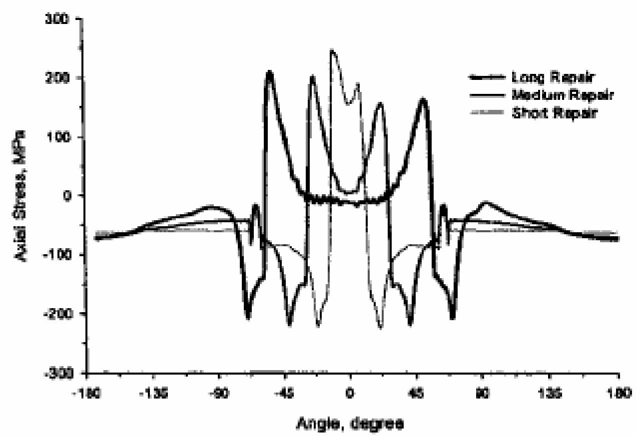


Fig. 7 Circumferential variations in axial residual stresses

  - Generally good agreement between 3D shell model and deep hole residual stress measurements

Piping Butt Weld WRS – Literature Review
A. Scaramangas et al.

- A. Scaramangas et al., "Residual Stresses in Cylinder Girth Butt Welds," *Offshore Technology Conference*, OTC 5024, pp. 25-28.
  - Developed model for predicting surface axial residual stresses as a function of net linear heat input, and validated it with experimental measurements and literature review
  - At higher net linear heat input and lower R/t, the through-thickness axial stress profile adopts a pure bending shape with yield occurring at the outer and inner fibers (tourniquet effect)
  - At lower net linear heat input, profile is more complex and axial stress at weld root is reduced

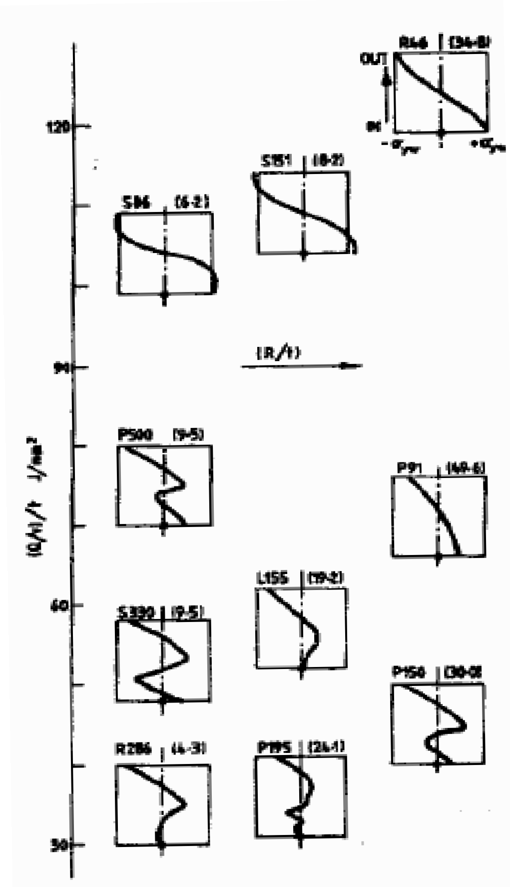


Fig. 4—Axial residual stress at weld center-line.

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Piping Butt Weld WRS – Literature Review
T. McGaughy and L. Boyles

- T. McGaughy and L. Boyles, "Significance of Changes in Residual Stresses and Fracture Toughness due to SMAW Repair of Girth Welds in Line Pipe," *Pipeline Technology Conference*, Ooostende, Belgium, vol. 2., pp. 16.29-16.36, 1990.
  - Experimental study with three different repair types (single pass part-depth, two-pass part-depth, and through-wall)
  - Pipe thickness = 0.257″, Pipe outside diameter = 20″
  - 8″ repair length (between 5 and 7 o'clock positions)
  - Through-wall repair produced highest axial residual stress distributions – yield magnitude tensile axial stresses at weld centerline on ID
  - Highest residual axial stresses found on the inner pipe surface of repaired and non-repaired weld samples
  - OD residual stresses significantly lower than those on ID

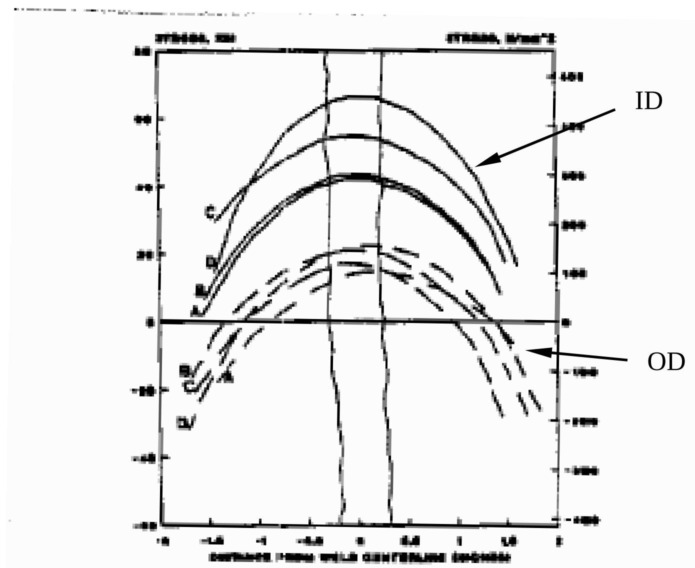


Fig.5- Comparison of axial residual stresses
A - no repair
B - single part wall repair
C - multiple part wall repair
D - full wall repair

Piping Butt Weld WRS – Literature Review
CANDU Feeder Pipe Studies

- AECL and National Research Council Canada have studied welding residual stresses in CANDU reactor feeder pipe butt welds
  - Detailed studies are proprietary
  - CANDU feeder pipes are about 2″ to 3½″ NPS diameter
  - Neutron diffraction technique has been applied to measure through-wall welding residual stress distributions
  - Studies examined WRS field with and without presence of repairs
  - Work demonstrates that weld start/stops and presence of repairs lead to asymmetries in WRS
  - Work demonstrates that weld repairs generally increase the magnitude of maximum tensile axial residual stress

Piping Butt Weld WRS – Literature Review
Other References

- W. J. Shack, “Measurement of Through-Wall Residual Stresses in Large-Diameter Piping Butt Weldments using Strain-Gauge Techniques,” *Proceedings: Second Seminar on Countermeasures for Pipe Cracking in BWRs*, EPRI, vol. 2, pp. 8-1 to 8-22, 1983.
- K. Satoh and T. Terasaki, “Effect of Weld Heat-Input Parameters on Residual Stress Distribution in Butt Joint,” *International Institute of Welding Annual Assembly*, ASM, 1978.
- A. Stacey, J.-Y. Barthelemy, R. H. Leggatt, and R. A. Ainsworth, “Incorporation of Residual Stresses into the SINTAP Defect Assessment Procedure,” *Engineering Fracture Mechanics*, 67 (200), pp. 573-611.
- R. H. Leggatt,”Residual Stresses at Circumferential Welds in Pipes,” *Welding Institute Research Bulletin*, 23/6, pp. 181-188, 06/1982.

Piping Butt Weld WRS – Literature Review
Preliminary Conclusions

- Piping Butt Welds Without Repairs:
  - Stress measurements show that welding start/stops can produce variations in axial and hoop stress on the order of or greater than the material yield strength over circumferential arc lengths of 15° to 20°
- Piping Butt Welds With Repairs:
  - Weld repairs generally increase the magnitude of maximum tensile axial residual stress
  - Location of maximum axial tensile stresses can be in the repair zone or possibly opposite the repair zone depending on the location of the repair relative to the original weld start/stop location
  - Weld cap removal provides little benefit in reducing welding residual stresses, particularly on the weld ID
  - Short, deep repairs generally result in greater increases in axial tensile residual stresses

Development of WRS Cases
Approach

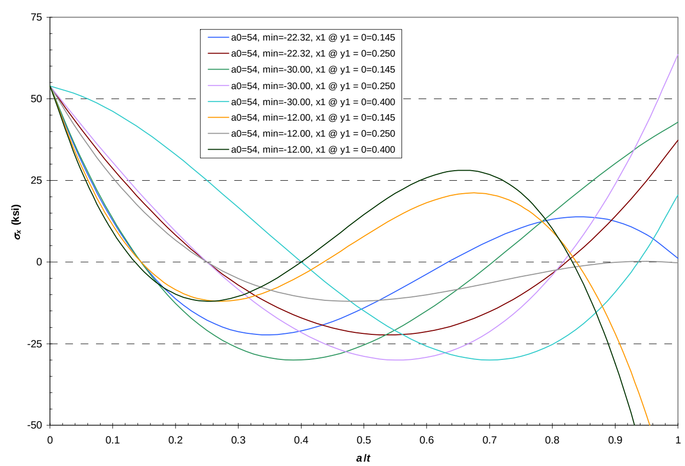
- Because of the uncertainty in the true residual stress field in each of the 51 subject welds, a matrix of sensitivity cases will be considered covering a wide range of WRS patterns
- Range of welding residual stress profiles
  - Axisymmetric (self balance at every circumferential position)
  - Non-axisymmetric (self balance over entire cross section)
  - Weld fabrication and repair data compiled as input to selection of WRS profiles for analysis
- As previously planned, the following sources will be applied to develop the WRS cases considered:
  - Weld fabrication and repair data from construction for the 51 subject welds
  - Previous WRS calculations by DEI and others for PWR piping butt welds
  - Limited number of DEI WRS FEA model runs for the specific geometry of some of the 51 subject welds considering the weld fabrication information
  - WRS data in the open literature including BWR mockup data used to develop the ASME standard WRS distributions

Development of WRS Cases

Potential Axisymmetric WRS Profiles

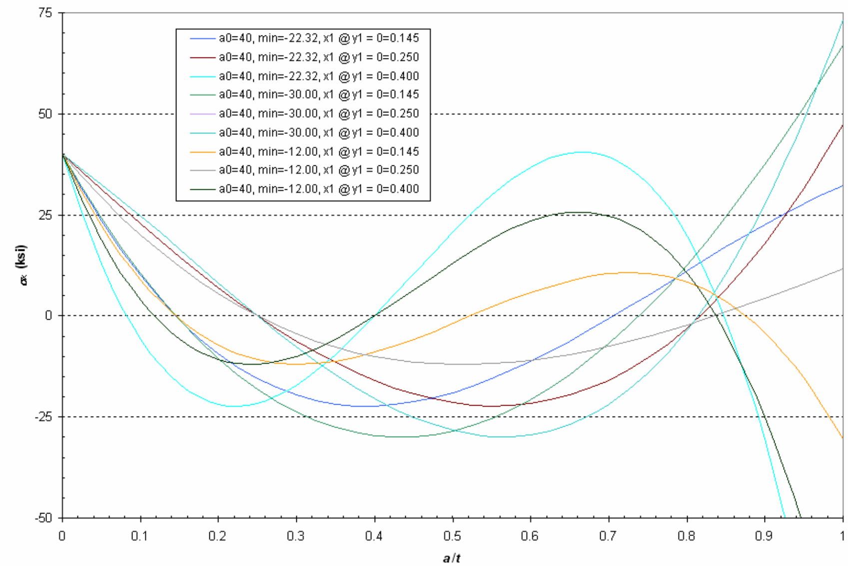
- Axisymmetric WRS profile must be self balancing
  - Definite integral from ID to OD weighted by radius *r* must be zero
  - If a cubic profile is assumed, then 3 of the 4 coefficients may be specified
  - On a preliminary basis, 26 possible profiles have been developed using the following constraints:
    - Stress on ID: $\sigma_{x,ID}$ = 54, 40, 20 ksi
    - Depth at which tensile stress becomes compressive: a/t = 0.145, 0.25, 0.40
    - Maximum compressive stress: $\sigma_{x,min}$ = -12, -22.32, -30 ksi

Plot for $\sigma_{x,ID}$ = 54 ksi cases



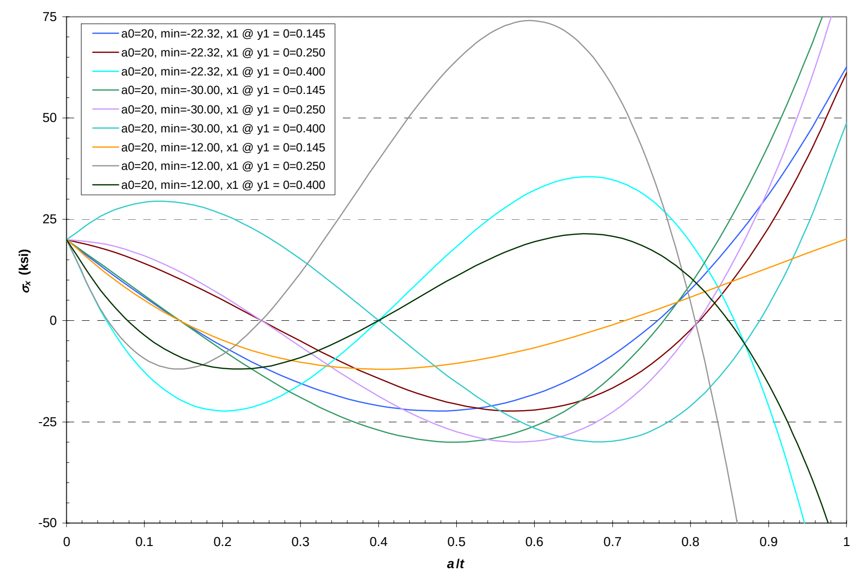
Development of WRS Cases

Potential Axisymmetric WRS Profiles (cont'd)



Plot for $\sigma_{x,ID}$ = 40 ksi cases

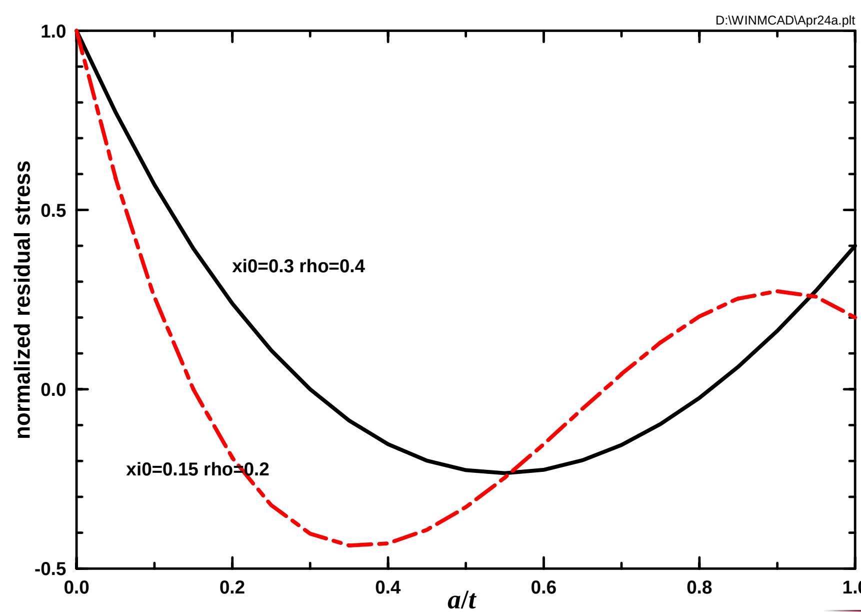
Plot for $\sigma_{x,ID}$ = 20 ksi cases



Development of WRS Cases
Alternative Method to Build Distributions

- An alternative method was suggested by David Harris
  - Definite integral from ID to OD weighted by radius *r* must be zero
  - Normalize with respect to stress at inside surface
  - If a cubic profile is assumed, then 2 additional constraints are needed for cubic shape:
    - Specify the value of *a*/*t* at which the residual stress passes through zero
    - Specify the ratio of the stress at the OD to that at the ID (ρ)
  - Could specify ρ so that there would not be a peak in the curve close to the OD

Example distributions for 2 selected cases



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Validation of WRS Inputs

- A two-step process to model validation is envisioned:
  - Validation of residual stress assumptions based on available stress measurements, model predictions, and the general WRS literature
  - Validation of the overall crack growth model based on available destructive examinations results for weld metal applications and other information
- Various sources of WRS information will be sorted and organized to support range of WRS cases considered in the calculations:
  - Mockup stress measurements
  - Stress measurements on removed plant components
  - Various FEA models including DEI, SI, EMC2, etc.
  - General WRS literature

Validation of WRS Inputs (cont'd)

- The results of the DEI WRS model have shown reasonable agreement versus measured WRS:
  - Measured CRDM nozzle mockup stress
  - Measured BWR shroud support weld stress
  - Measured CRDM nozzle ovality
- Discussion of sources of data for validation of WRS assumptions

Welding Residual Stress Model Validation
General Model Background

- Independent welding residual stress models have been developed by many industry and regulatory consultants
- DEI model originally developed in 1990 to simulate J-groove attachment welds of pressurizer heater sleeves
  - Expanded to include other nozzle penetrations with J-groove welds since 1991
  - Expanded to butt welds in 1995 (stainless steel) and 1997 (Ni base alloys)
  - Expanded to various nozzle repair methodologies since 2002
- Consistent analysis methodology has been used since initial development of welding residual stress model
  - Thermal model simulates weld heating and cooling using idealized target temperatures for weld center and HAZ
  - Structural model uses temperatures from thermal model to simulate thermal expansion followed by weld strengthening with cooling

Welding Residual Stress Model Validation
Model Background

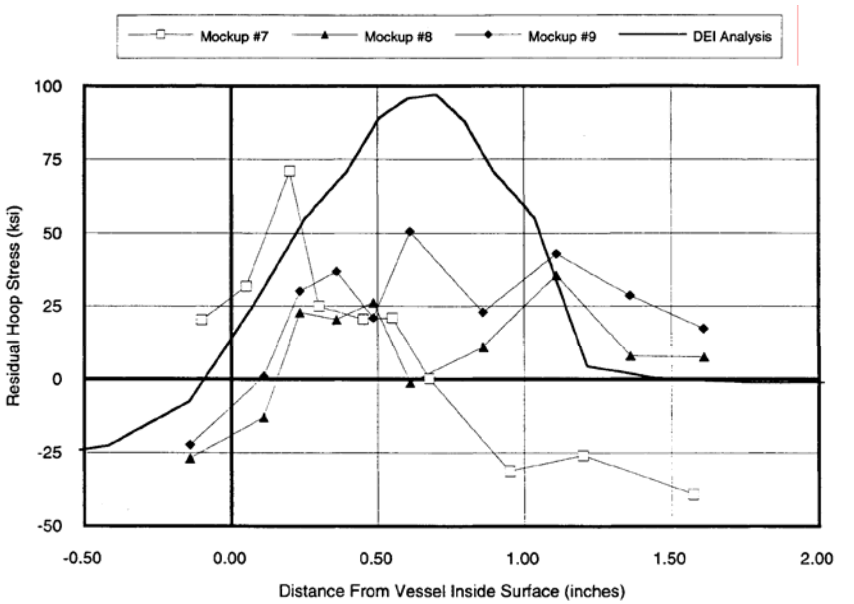
- Welding residual stress calculations have been performed for a variety of Ni base alloy welds
- J-groove welds for a wide range of nozzle penetration types (e.g., CRDM, heater sleeve, etc.)
- Piping butt welds for sizes ranging from RPV outlet to 1-inch diameter nozzles
- All major nozzle repair types
  - Nozzle left in place (ID inlay, J-groove weld overlay)
  - Nozzle partially removed (internally or externally)
    - ID temper-bead half nozzle weld repair
    - Outer surface weld pad buildup with new J-groove weld attachment

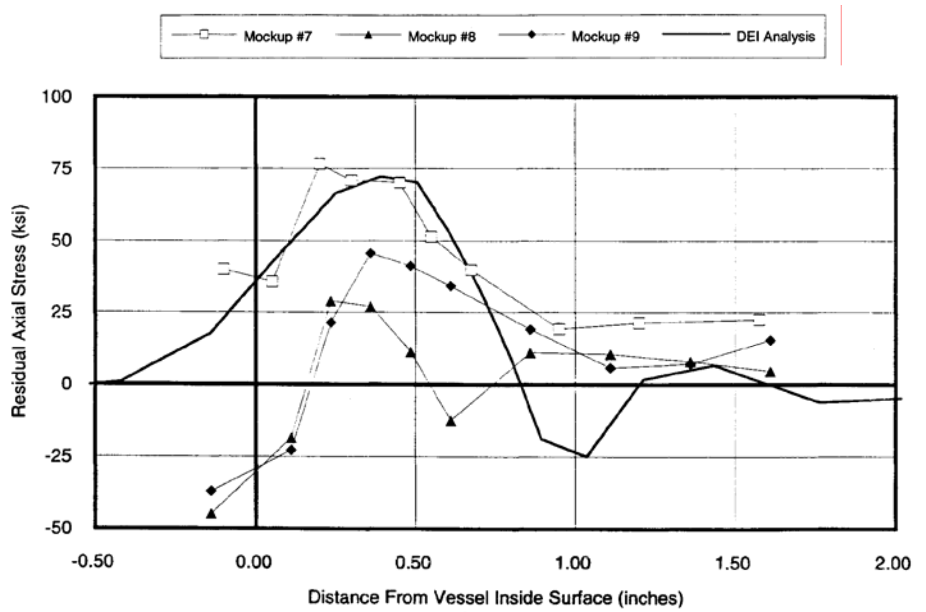
Welding Residual Stress Model Validation
Key Reports

- *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*, EPRI TR-103696, July 1994.
  - Describes development of welding residual stress model properties
  - Compares model results to measured residual stresses from mockups
- *Evaluation of Crack Growth in BWR Nickel Base Austenitic Alloys in RPV Internals (BWRVIP-59),* EPRI TR-108710.
  - Shroud support welds examined (butt weld type geometries)
  - Model results compared to measured residual stresses from actual welds
- *Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs*. December 1993. EPRI TR-103345.
  - Overview of industry at a time when many models were being developed

Welding Residual Stress Model Validation
EPRI TR-103696

- Comparison with Combustion Engineering XRD residual stress measurements for pressurizer heater sleeve mockups at inside surface





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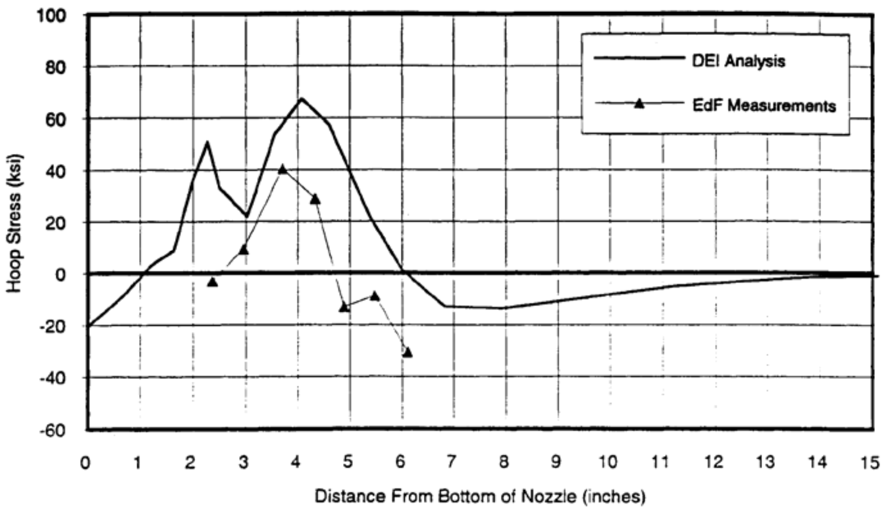
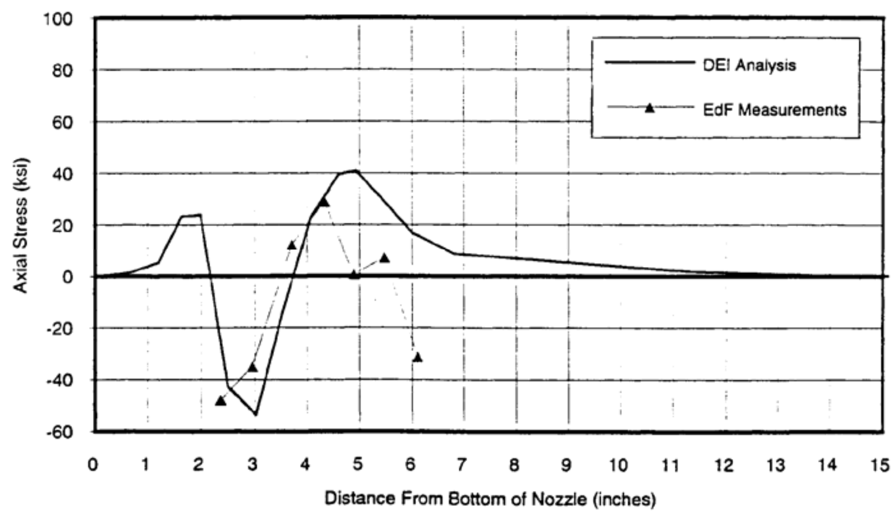
Welding Residual Stress Model Validation
EPRI TR-103696

- Comparison with EdF hole-drilling strain gauge residual stress measurements for CRDM nozzle mockups at inside surface (39° nozzle, downhill side shown)





Welding Residual Stress Model Validation
Measured Ovality

- TR-103696 reported two sets of ovality measurements taken from mockups compared to DEI analyses
  - 47° EdF CRDM: 0.064 inch measured vs 0.052 inch calculated
  - Ringhals outer row CRDM: 0.045 inch measured vs 0.049 inch calculated
- BMN analyses for South Texas compared against measured ovality for EdF plants
  - Measured ovality (average outer penetrations): 0.020 inch vs 0.0122 inch calculated

Meeting Wrap-Up

- Summary
- Action items