Materials Reliability Program: Welding Residual and Operating Stresses in PWR Alloy 182 Butt Welds (MRP-106NP)

1009378-NP

Final Report, February 2004

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REPORT SUMMARY

EPRI Materials Reliability Program report MRP-33 (1001501), documented elastic-plastic finite element analyses to determine the welding residual and operating condition stresses in idealized single-V and double-V weld joints similar to those at V.C. Summer and Ringhals plants. This report – an extension of MRP-33 work – describes elastic-plastic stress analyses of Alloy 182 butt welds for a range of nozzle geometries, sizes, weld repairs, and external pipe loading conditions. These stress distributions provide insight regarding the potential for primary water stress corrosion cracking (PWSCC) and possible PWSCC crack growth rates in Alloy 182 butt welds.

Background

PWSCC of Alloy 600 nozzles and penetrations in pressurized water reactor (PWR) plant primary system pressure boundaries has been a recurring problem since the mid-1980s. During the second half of 2000, cracks were discovered in Alloy 182 welds joining low alloy steel reactor vessel hot leg nozzles to stainless steel pipes at Ringhals 3 and 4 and V.C. Summer plants. Both cases involved axial cracks in the weld metal. In the case of V.C. Summer, one of the axial cracks appears to have initiated at a weld repair location and then developed into a leak that resulted in over 200 pounds of boric acid crystals being deposited outside the pipe near the weld. A short circumferential crack was also discovered on the inside diameter (ID) region of the Alloy 182 weld clad at V.C. Summer. This circumferential crack arrested when it reached the low alloy steel base material. The root cause analyses performed by utilities and contractors attributed the cracking to PWSCC of the Alloy 182 weld metal.

In 2002, axial indications were discovered in the Alloy 182 butt weld between the pressurizer surge nozzle and safe end at Tihange 2 plant. This weld had been stress-relieved with the pressurizer vessel. The weld was inspected again after six months of operation in 2003, with no evidence of crack growth. The utility is evaluating the source of the indications, which might not represent PWSCC. In addition to these indications at Tihange, a leak was discovered from a pressurizer safety relief line butt weld at Tsuruga 2 in 2003.

Interest in the potential for PWSCC of Alloy 182 butt welds between low alloy steel and stainless steel components has increased due to the discovery of PWSCC cracks in some Alloy 182 J-groove welds between the low alloy steel RPV heads and Alloy 600 control rod drive mechanism (CRDM) nozzles.

Objective

- To extend the work in MRP-33 to cover a wider range of Alloy 182 butt weld geometries and sizes.
- To determine the stresses induced by partial-arc inside surface weld repairs.
- To assess the potential beneficial effect of applying weld overlay cladding to the outside surface of the weld joints.

Approach

Elastic-plastic finite element analyses were performed to determine the welding residual and operating condition stresses in idealized Alloy 182 butt welds of several common designs and sizes. Analyses were first performed to determine the temperature distributions in the weld metal and base metal as a function of time after depositing the weld metal. The results of the thermal analysis were then used in a structural calculation to determine the stresses generated in the nozzle, weld, and pipe as the weld cools. Following completion of the weld passes, the nozzle and pipe were subjected to hydrostatic pressure test conditions that act to reduce the peak stresses after release of the test pressure. Finally, work was performed to demonstrate that live piping loads can be added by elastic superposition with little error.

Results

For the as-designed case, without weld repairs to the inside surface, the analyses show that hoop and axial stresses on the wetted Alloy 600/82/182 materials tend to be low and that hoop stresses exceed axial stresses at highest stress locations. ID weld surface repairs are clearly detrimental in that they create high residual axial and hoop tensile stresses. However, some of the subject joints appear to be too small to be weld repaired from the inside surface. Addition of a weld overlay clad on the nozzle and weld has the effect of reducing the ID surface stresses and, therefore, is expected to reduce the potential for PWSCC initiation and crack growth rates. Finally, analyses show that elastic addition of stresses produced by live pipe loads provides somewhat conservative results relative to including the live stresses in the elastic-plastic analysis.

EPRI Perspective

This extension of MRP-33 work was performed to provide insight into both the state of stresses on the inside surface of butt welds of Alloy 182 material that affect crack initiation as well as through-thickness distributions that affect crack growth.

Keywords

Weld Stresses
Butt Welds
Primary Water Stress Corrosion Cracking
Elastic-Plastic Analysis
Alloy 182 Material
Materials Reliability Program

ABSTRACT

Primary Water Stress Corrosion Cracking (PWSCC) in reactor pressure vessel nozzle to pipe welds was observed at VC Summer and at Ringhals 3 & 4 during the second half of 2000. During 2002 indications were discovered in a pressurizer surge nozzle butt weld at Tihange 2, although this has not been confirmed to be PWSCC. A leak was discovered from a pressurizer safety relief line butt weld at Tsuruga 2 in 2003. This report describes elastic-plastic stress analyses of Alloy 182 butt welds in a range of nozzle geometries, sizes, repair conditions and external pipe loading. These stress distributions provide insight regarding the potential for PWSCC and possible PWSCC crack growth rates in these welds.

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1
INTRODUCTION

Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 600 nozzles and penetrations in PWR plant primary system pressure boundaries has been a recurring problem since the mid-1980s. During the second half of 2000, cracks were discovered in Alloy 182 welds joining low-alloy steel reactor vessel hot leg nozzles (≈30 inches ID) to stainless steel pipes at Ringhals 3 and 4 and VC Summer. All of these cases involved axial cracks in the Alloy 182 weld metal. In the case of VC Summer, one of the axial cracks developed into a leak that resulted in over 200 pounds of boric acid crystals being deposited outside the pipe near the weld. At VC Summer, a short circumferential crack was also discovered on the ID region of the Alloy 182 weld. The circumferential crack arrested when it reached the low alloy steel base material. The root cause analyses performed by the utilities and contractors attributed the cracking to PWSCC of the Alloy 182 weld metal. Weld repairs, including repairs performed on the ID surface, were identified as a potential contributing factor at VC Summer.

In 2003 a leak was discovered from a pressurizer safety relief nozzle butt weld at Tsuruga 2.

Elastic-plastic finite element analyses to determine the welding residual and operating condition stresses in idealized single-V and double-V weld joints similar to those at VC Summer and Ringhals, including the effect of reported weld repairs at VC Summer, were provided in EPRI report MRP-33, *Elastic-Plastic Finite Analysis: Single and Double-J Hot Leg Nozzle-to-Pipe Welds – Welding Residual and Operating Stresses* [1].

The purpose of this document is to provide results of finite element stress analyses of a wider range of Alloy 82/182 butt weld geometries and sizes in PWR plants. The results will be used to 1) provide a better understanding of the reason for the low incidence of PWSCC in these welds to date, 2) assist in predicting the potential for PWSCC in the future, 3) provide information that can be used to assess the potential for circumferential cracks, and 4) provide input to fracture mechanics analyses to assess potential for crack growth. The work also covers the use of weld overlays on the outside of the pipe at the weld to reduce the potential for PWSCC and slow the rate of crack growth.

The methodology used for the analyses is essentially the same as used for analyses of the VC Summer RPV outlet nozzle to hot leg pipe welds as reported in MRP-33 [1].

2
MATRIX OF CASES ANALYZED

The purpose of this work is to establish welding residual and operating stress levels in typical Alloy 82/182 PWR butt welds. Accordingly, a series of models was created, as shown in Figure 2-1, to span the range of applications from large (30") reactor vessel outlet nozzles to the butt welds between 1 inch diameter Alloy 600 instrument nozzles and attached stainless steel pipe.

2.1 Geometries Analyzed

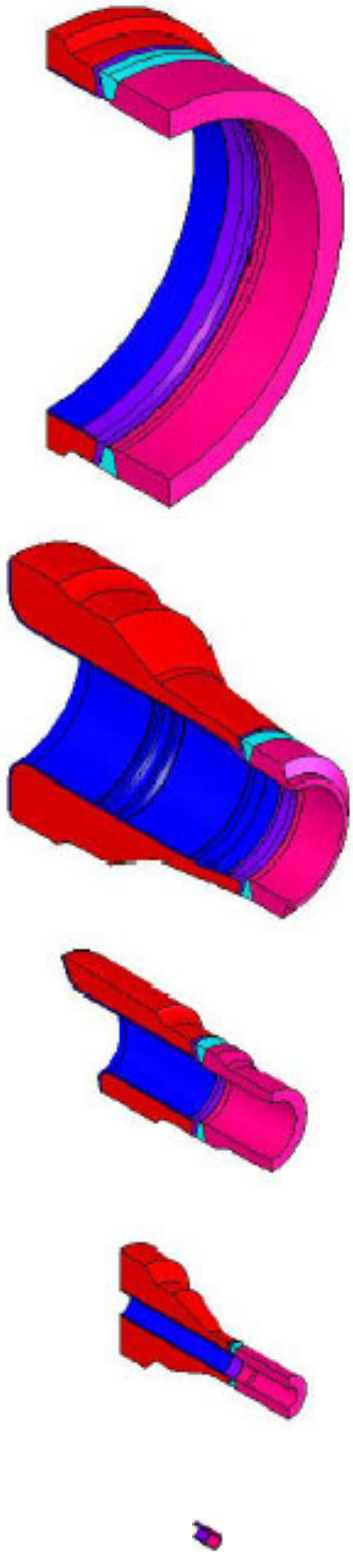
Figures 2-2 through 2-6 show details of the geometries analyzed. The joints typically included a low-alloy steel or Alloy 600 nozzle, stainless steel pipe, Alloy 82/182 buttering and weld, and stainless steel cladding on the inside surface of larger diameter low-alloy steel nozzles. The weld joints were analyzed in the as-designed condition (with welds built up from the outside with no ID repairs), in a repaired condition with ID repairs over 30°, 60°, 90° or 360°, and with overlay weld deposits intended to increase the compressive stress on the inside of the weld and thereby reduce tensile hoop and axial stresses at the weld inside surface. The depths of ID repairs are relatively shallow to illustrate the potentially detrimental effect, even for shallow repairs. Dimensions for the nozzles analyzed are provided in Table 9-1 which summarizes the analysis cases and results.

2.2 Operating Conditions

The operating condition analyses include internal operating pressure of 2250 psi and a temperature of 615°F. The 615°F temperature is between the reported 610°F and 619°F hot leg temperatures for VC Summer and Ringhals 3/4 respectively. While some of the nozzles operate at pressurizer temperatures of 650°F, sensitivity studies show that stresses are slightly lower at 650ºF due to the lower material yield strength at higher temperature.

The analysis cases did not include piping reaction forces such as axial, shear, torsion and moment loads applied to the joints as a result of thermal expansion of the piping loops. These loads were not included since they vary significantly from plant-to-plant, and within a single plant if there are several joints of the same design. The stresses produced in the pipe by these piping loads should be determined by superposition as discussed in Section 6.

The weld overlays were selected to be nominally 0.25" thick, but the actual thickness was reduced somewhat for smaller size nozzles to limit the overlay thickness to about 20% of the nozzle wall thickness. The overlay lengths were selected to ensure that high axial tensile stresses were not created at locations of nickel-chromium-iron materials. The purpose of including the weld overlay cases was to highlight the potential benefit of a weld overlay, not to recommend a specific overlay thickness or length. The length of the overlay assumed for each case is given in Table 9-1.



RPV Nozzle
30" ID, 2.3" Wall

Pressurizer Surge Nozzle
10" ID, 1.66" Wall

Pressurizer Safety Relief Nozzle
5" ID, 1.59" Wall

HP Injection Nozzle
2" ID, 0.75" Wall

Instrument Nozzle
1" ID, 0.179" Wall

Figure 2-1
Matrix of Butt Welds Analyzed (Shown to Scale)

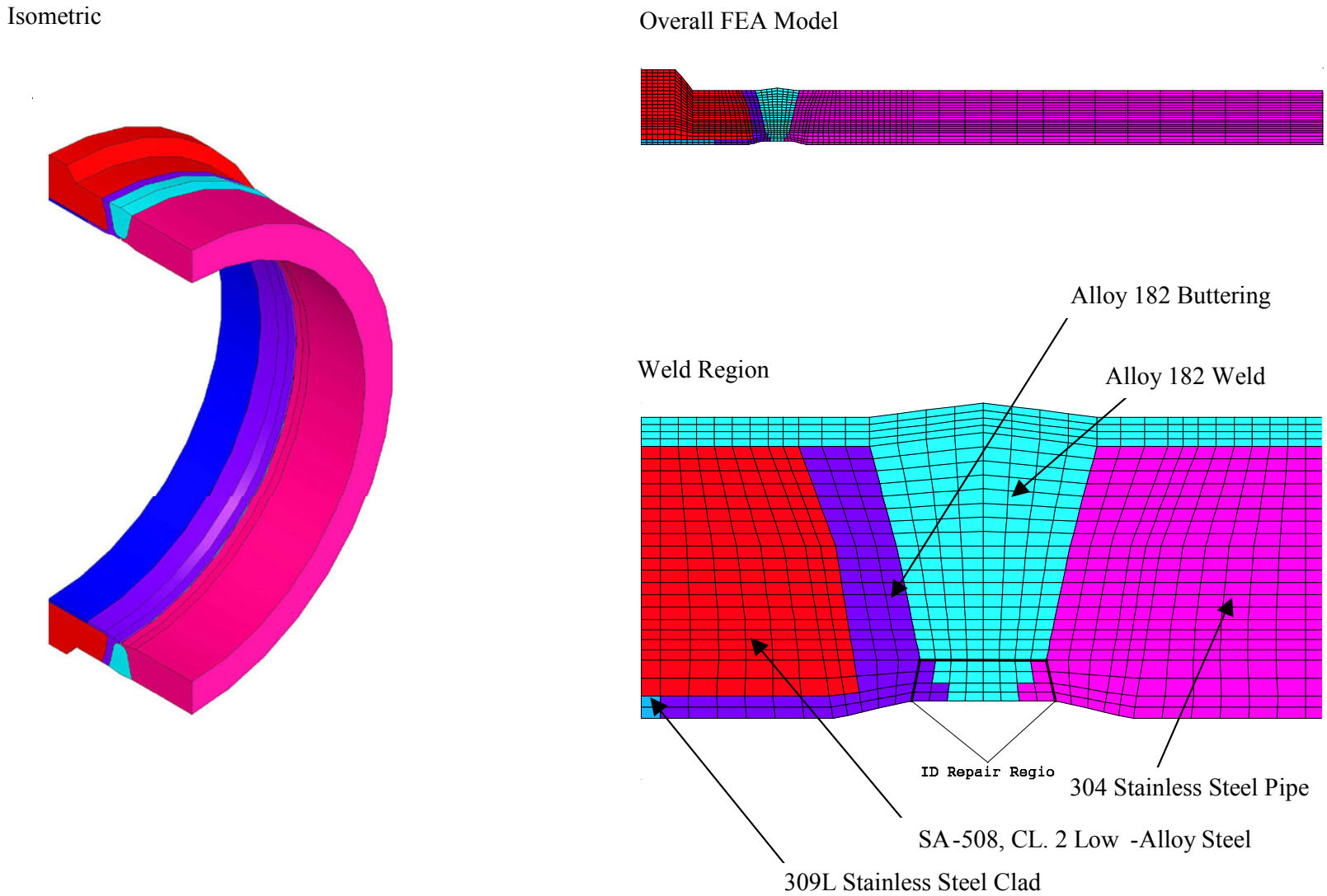
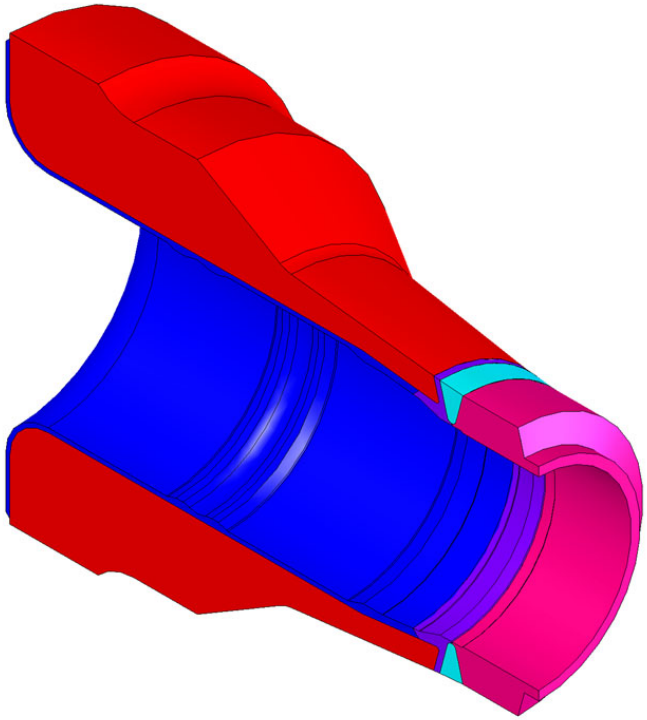
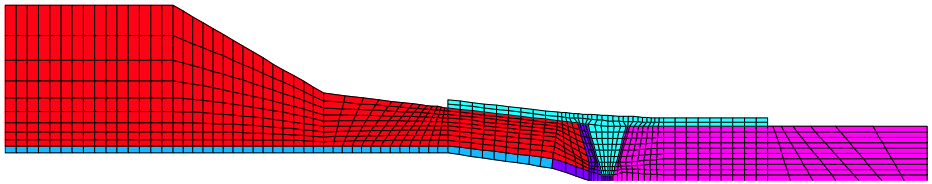


Figure 2-2
Finite Element Model of Single V RPV Outlet Nozzle (30" ID)

Isometric



Overall FEA Model



Weld Region

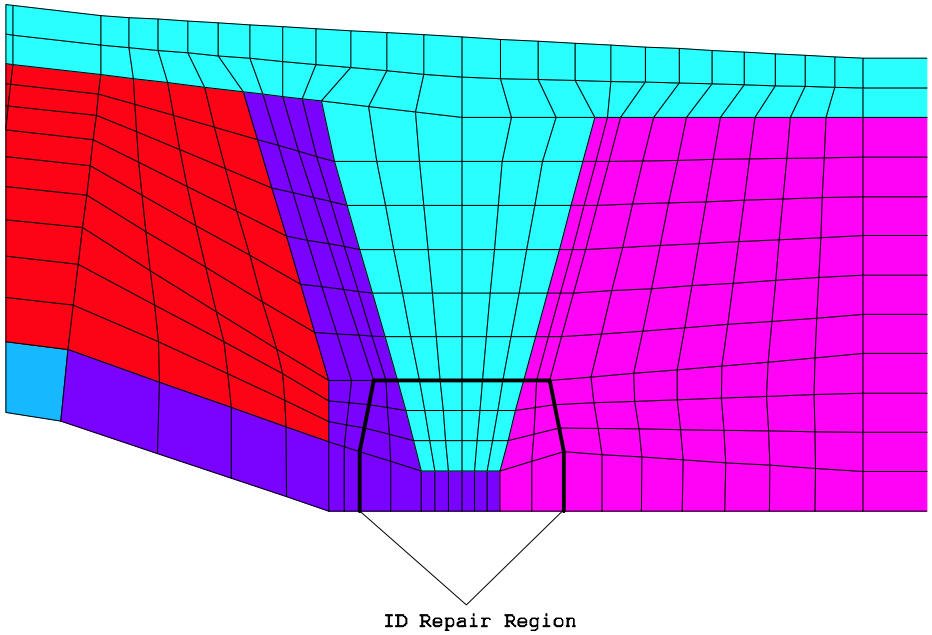
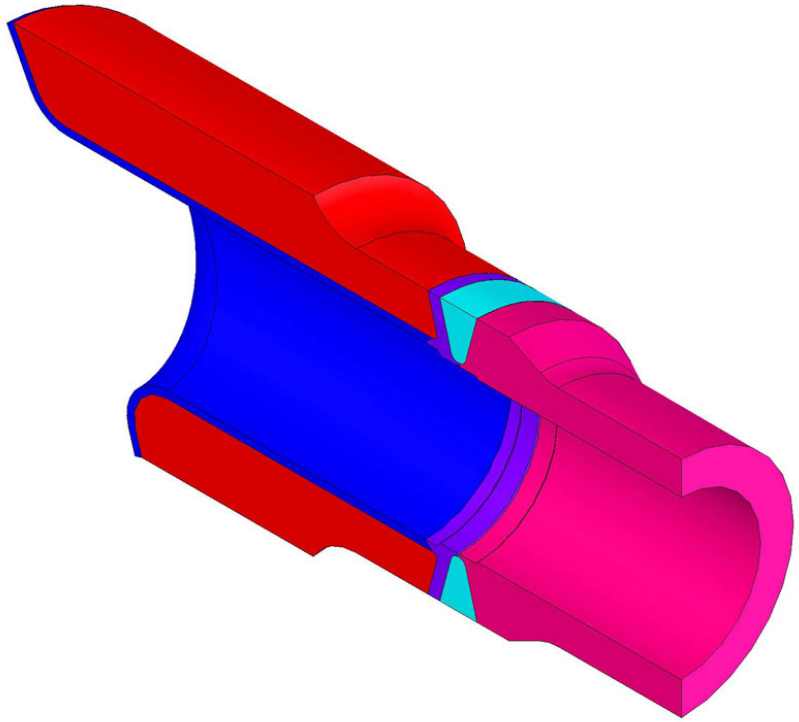
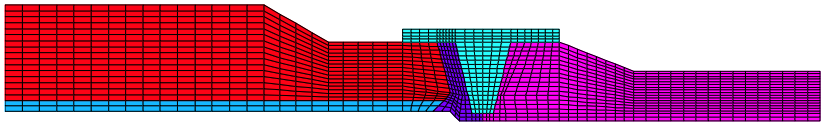


Figure 2-3
Finite Element Model of Pressurizer Surge Nozzle (10" ID)

Isometric



Overall FEA Model



Weld Region

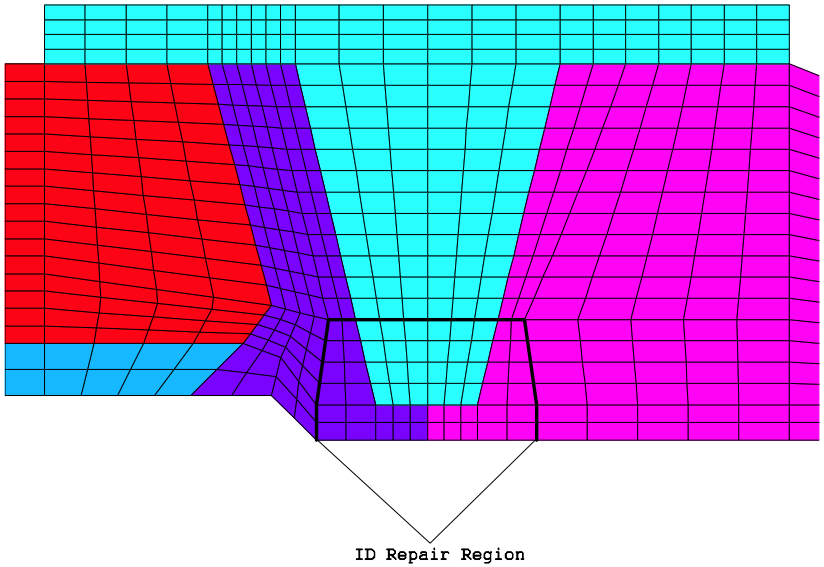
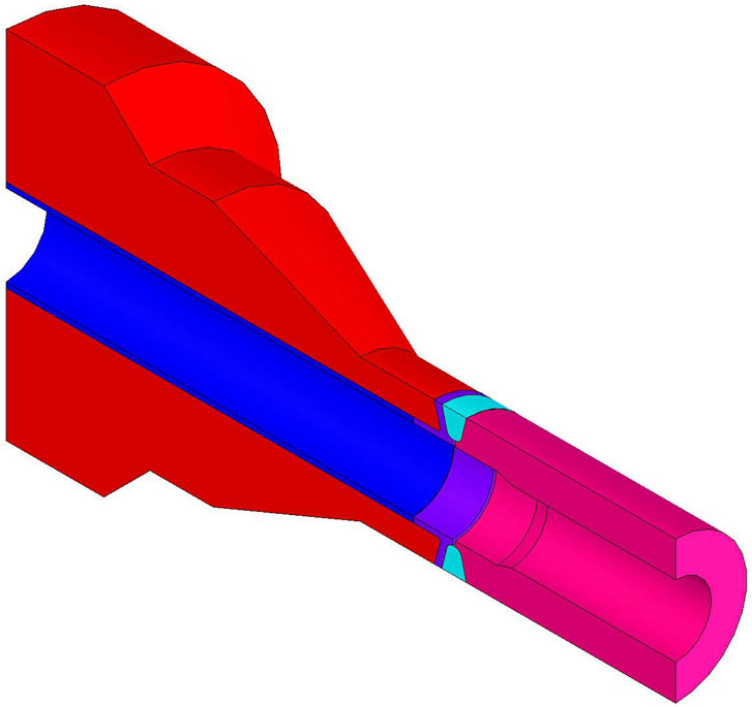
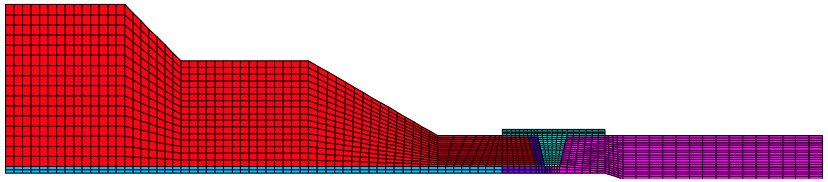


Figure 2-4
Finite Element Model of Pressurizer Safety Relief Nozzle (5" ID)

Isometric



Overall FEA Model



Weld Region

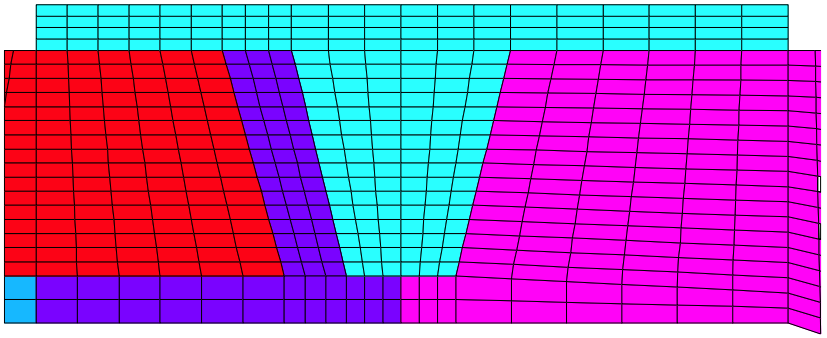
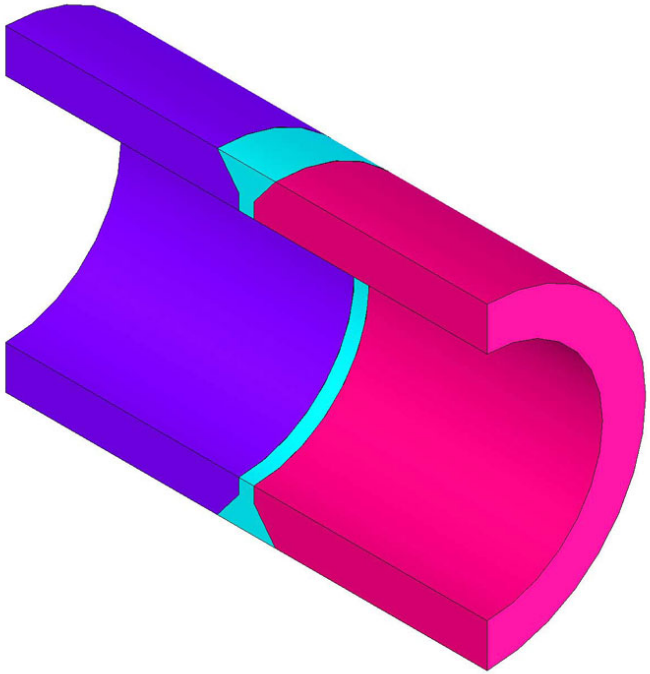
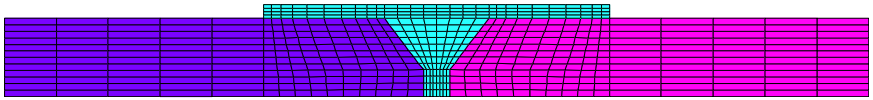


Figure 2-5
Finite Element Model of High Pressure Injection Nozzle (2.5" ID)

Isometric



Overall FEA Model



Weld Region

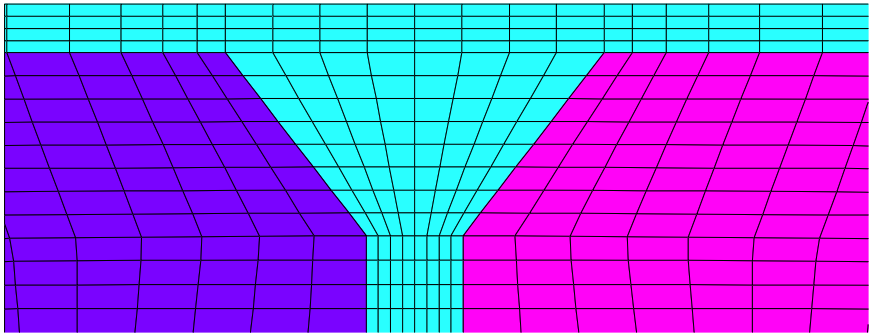


Figure 2-6
Finite Element Model of Instrument Nozzle (1" ID)

3
ANALYSIS METHODS

The following is a brief description of the method used for the nozzle analyses.

3.1 Finite Element Program

Finite element analyses were performed using Revision 5.7 of the ANSYS general-purpose finite element computer program.

3.2 Geometric Models

All nozzle configurations/cases, except for the cases of partial-arc inside diameter repairs, were analyzed using axisymmetric models.

All axisymmetric models used four-node quadrilateral elements. A large number of four-node elements was used to achieve accuracy rather than a smaller number of higher order elements.

Alloy 182 weld passes were simulated by rings of weld metal that are deposited sequentially in layers two elements thick across the entire weld length.

3.3 Analysis Approach

The models consist of a short length of nozzle, cladding on the inside of the nozzle, Alloy 182 buttering, stainless steel pipe, and the Alloy 182 weld.

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Additional information regarding the load steps is provided in the next section.

3.4 Loading Steps

The models were loaded in a series of steps as follows:

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All stress plots in Sections 4 through 6 use the color coding in Figure 3-1.

3.5 Live Piping Loads

In addition to the welding residual stresses and operating pressure stresses, the nozzle butt weld regions are also subjected to live piping loads due to pipe thermal expansion and dead weight. Because these stresses vary significantly from plant to plant, and can include different combinations of bending and axial loads, it is not possible to create a single representative ANSYS model incorporating the live loads. Instead, it was proposed that live piping loads might be linearly superposed on the welding residual and operating stresses in the nozzles. This would

allow the crack propagation analyses to assess the plant-specific effects of the live piping loads without requiring separate ANSYS analysis of each individual plant or load case.

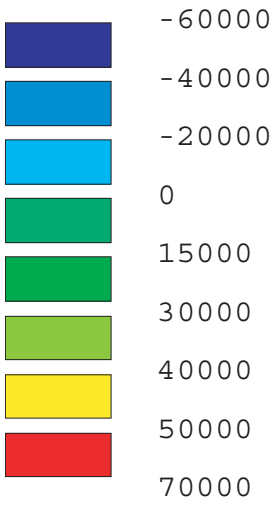

Figure 3-1
Color Code for All Stress Plots

To test the viability of the proposed superposition method, diagnostic cases were run on the reactor vessel outlet nozzle (single V) as-designed, 360° ID repair, and 30° partial arc ID repair cases. In each of these cases, uniform axial tensile loads (similar to an endcap pressure load) of 5, 10, and 15 ksi were applied to the model in addition to the normal operating pressure loads. The results of the ANSYS analyses for these additional loads are provided in Section 6.

4
ANALYSIS RESULTS FOR AS DESIGNED CASE (NO WELD REPAIRS)

This section provides stress plots for the as-designed case without weld repairs to the ID surface. The data for each of the five cases consist of plots of axial and hoop stresses near the weld for operating conditions (including welding residual stresses) and plots of the hoop and axial stresses through the centerline of the weld and along the Alloy 182 weld inside surface.

It is clear from this data that for the as-designed condition, all nozzles exhibit similar behavior:

- High tensile hoop stresses at the outside of the weld.
- Lower hoop stresses on the inside of the weld caused by the outer weld layers pulling the ID of the nozzle inward.
- Compressive, or very low tensile, axial stresses on the ID of the weld.

These findings are consistent with the fact that there have been few reports of PWSCC or leaks from Alloy 182 butt welds and that in the two main cases of interest (VC Summer and Ringhals 3/4), the cracks have been predominantly axial.

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Figure 4-1
30" RPV Nozzle: As-Designed (Case 1.a)

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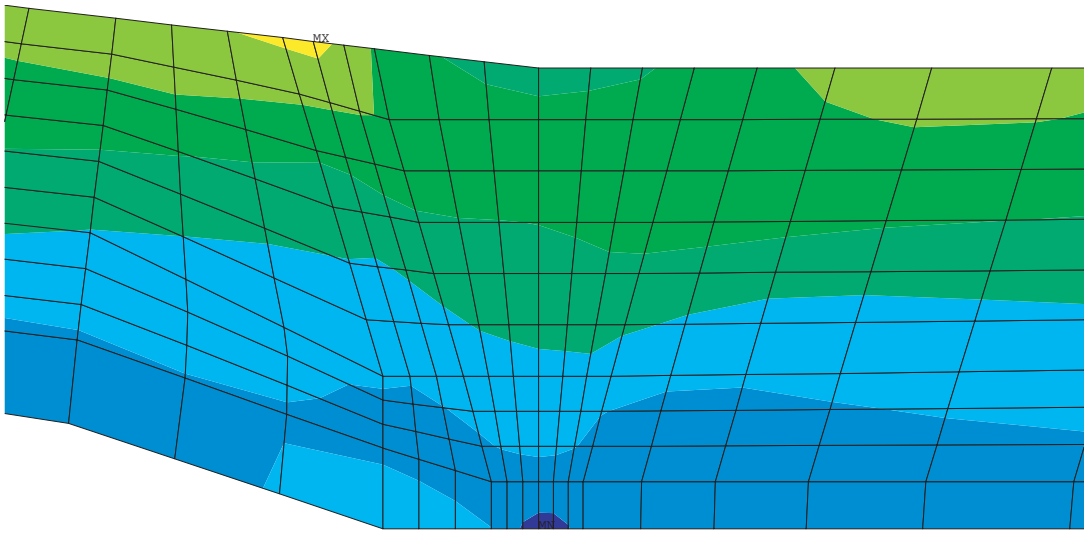
Figure 4-1
30" RPV Nozzle: As-Designed (Case 1.a) (Continued)

Axial Stress



Hoop Stress

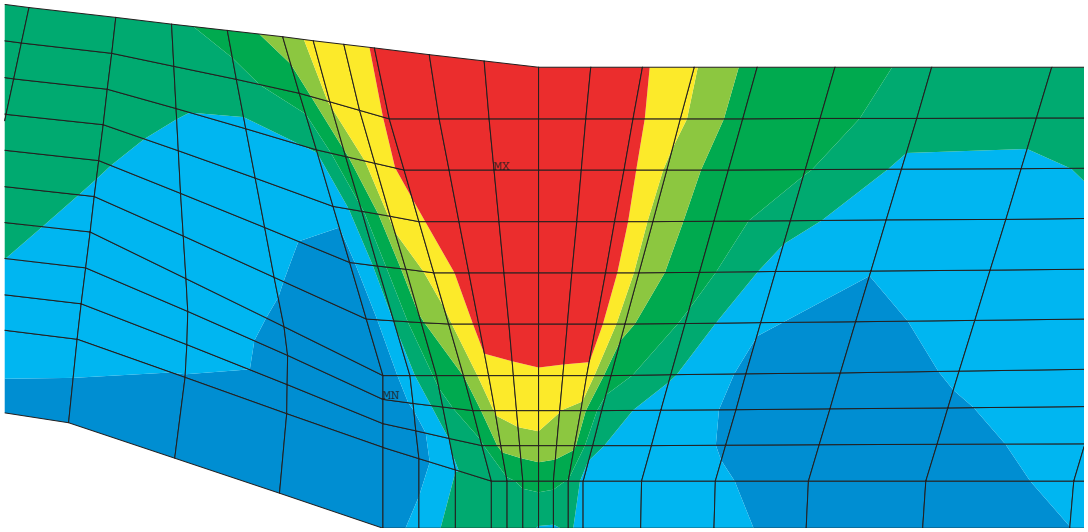


Figure 4-2
10" Pressurizer Surge Nozzle: As-Designed (Case 2.a)

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Figure 4-2
10" Pressurizer Surge Nozzle: As-Designed (Case 2.a) (Continued)

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Figure 4-3
5" Pressurizer Safety Relief Nozzle: As-Designed (Case 3.a)

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Figure 4-3
5" Pressurizer Safety Relief Nozzle: As-Designed (Case 3.a) (Continued)

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Figure 4-4
2.5" HP Injection Nozzle: As-Designed (Case 4.a)

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Figure 4-4
2.5" HP Injection Nozzle: As-Designed (Case 4.a) (Continued)

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Figure 4-5
1" Instrument Nozzle: As-Designed (Case 5.a)

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Figure 4-5
1" Instrument Nozzle: As-Designed (Case 5.a) (Continued)

5
ANALYSIS RESULTS FOR LARGER SIZE NOZZLES REPAIRED FROM ID SURFACE

This section provides selected stress plots for the cases of larger diameter nozzles that could be repaired from the inside surface. For the 30" RPV outlet nozzle, there is physical access to the inside to the nozzle, and it is known that weld repairs were carried out at this location at VC Summer. The 5" and 10" pressurizer nozzles could have been weld repaired in the shop prior to welding the nozzle into the pressurizer vessel. The data for the three larger diameter nozzles consists of plots of axial and hoop stresses near the weld for operating conditions (including welding residual stresses), and plots of the hoop and axial stresses through the centerline of the weld and along the Alloy 182 weld inside surface for the case of 360° repairs and 30°, 60° and 90° partial arc repairs.

It is clear from these data that weld repairs on the ID of the weld have the potential for creating higher PWSCC susceptibility. In particular:

- In every case, the calculations show high tensile hoop stresses at the ID of the weld.
- In every case the calculations show higher tensile axial stresses than the as-designed case.
- In most cases, the maximum hoop stress on the ID of the nozzle is greater than the maximum axial stress. However, two of the models (RPV outlet nozzle and pressurizer safety relief nozzle) show maximum axial tensile stresses essentially the same as the maximum hoop stresses, thereby suggesting the potential for circumferential cracks. It is particularly interesting to note that the high axial tensile stress for the RPV outlet nozzle is at the location where the short shallow circumferential crack was reported at VC Summer. In the case of the 5" pressurizer spray nozzle, the high axial stress location is right at the diameter transition (stress concentration).

All stresses are plotted using the color code shown in Figure 3-1.

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Figure 5-1
30" RPV Outlet Nozzle: 360° ID Weld Repair (Case 1.d)

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Figure 5-1
30" RPV Outlet Nozzle: 360° ID Weld Repair (Case 1.d) (Continued)

Axial Stress

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Hoop Stress

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Figure 5-2
30" RPV Outlet Nozzle: 90° ID Weld Repair (Case 1.g)

Axial Stress

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Hoop Stress

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Figure 5-3
30" RPV Outlet Nozzle: 60° ID Weld Repair (Case 1.h)

Axial Stress

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Hoop Stress

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Figure 5-4
30" RPV Outlet Nozzle: 30° ID Weld Repair (Case 1.i)

90° ID Weld Repair

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30° ID Weld Repair

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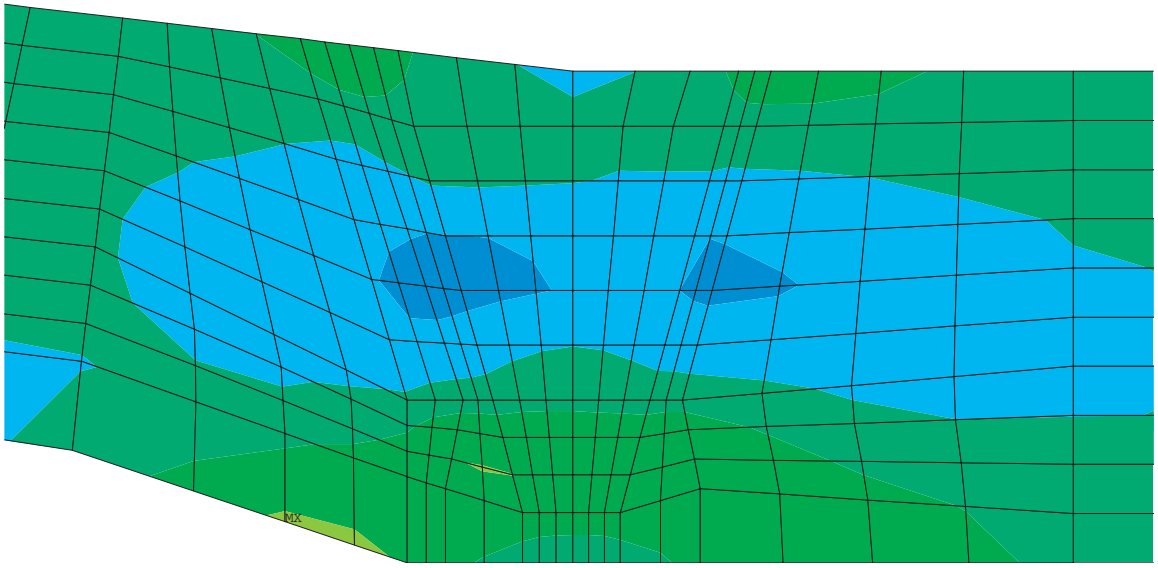
Figure 5-5
30" RPV Outlet Nozzle: 30° and 90° ID Weld Repair (Case 1g and 1.i)

Axial Stress



Hoop Stress

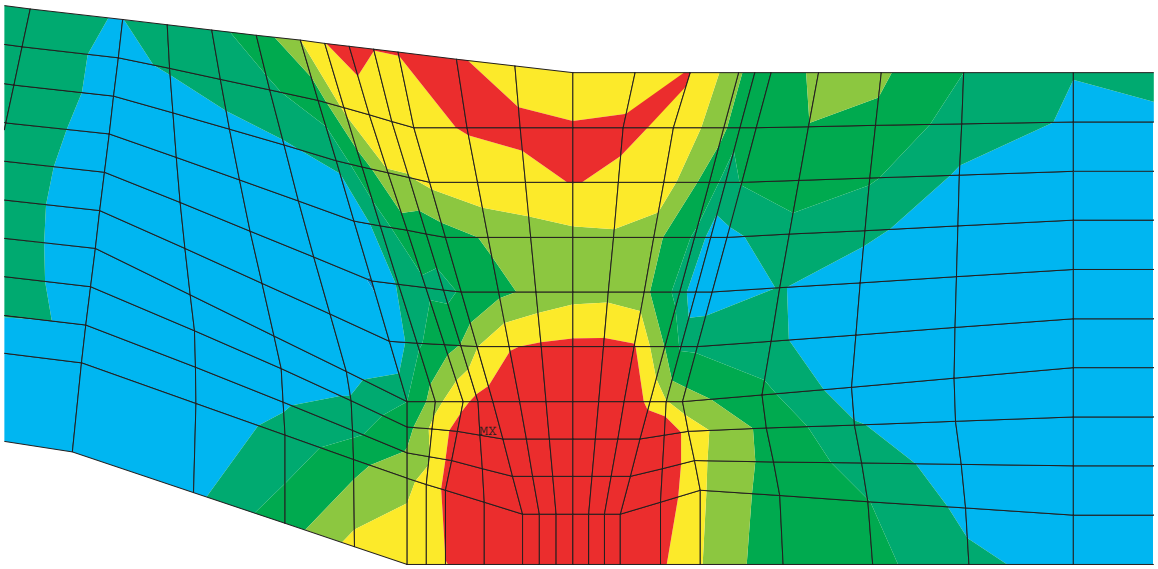


Figure 5-6
10" Pressurizer Surge Nozzle: 360° ID Weld Repair (Case 2.d)

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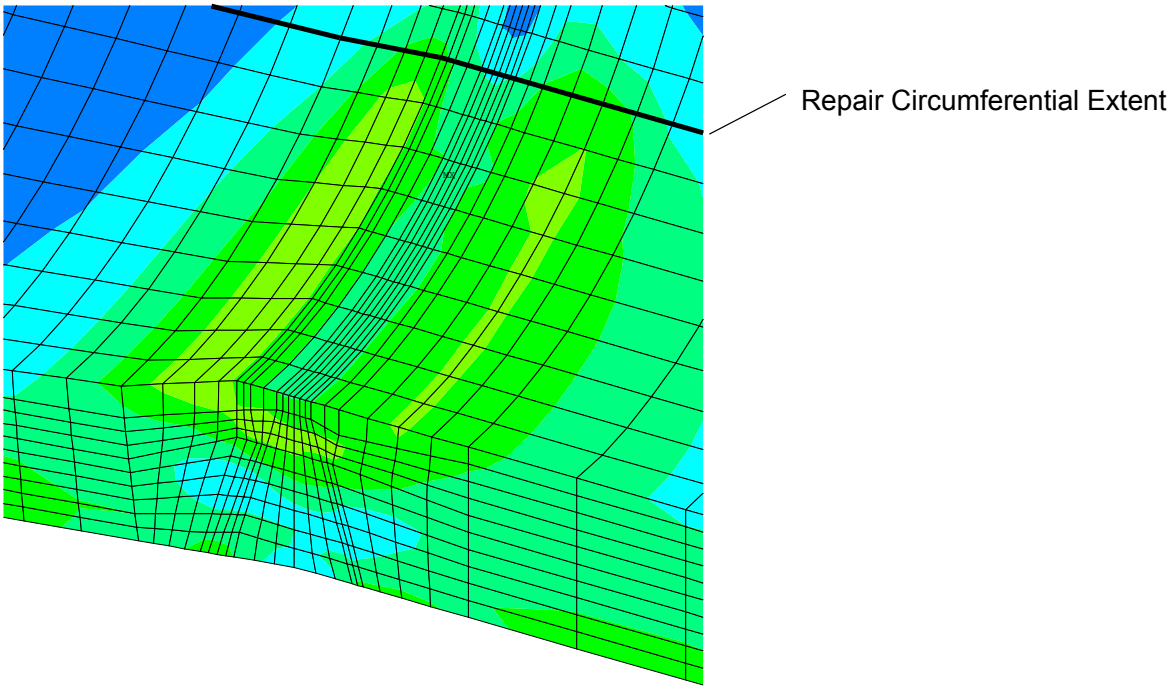
Figure 5-6
10" Pressurizer Surge Nozzle: 360° ID Weld Repair (Case 2.d) (Continued)

Axial Stress



Hoop Stress

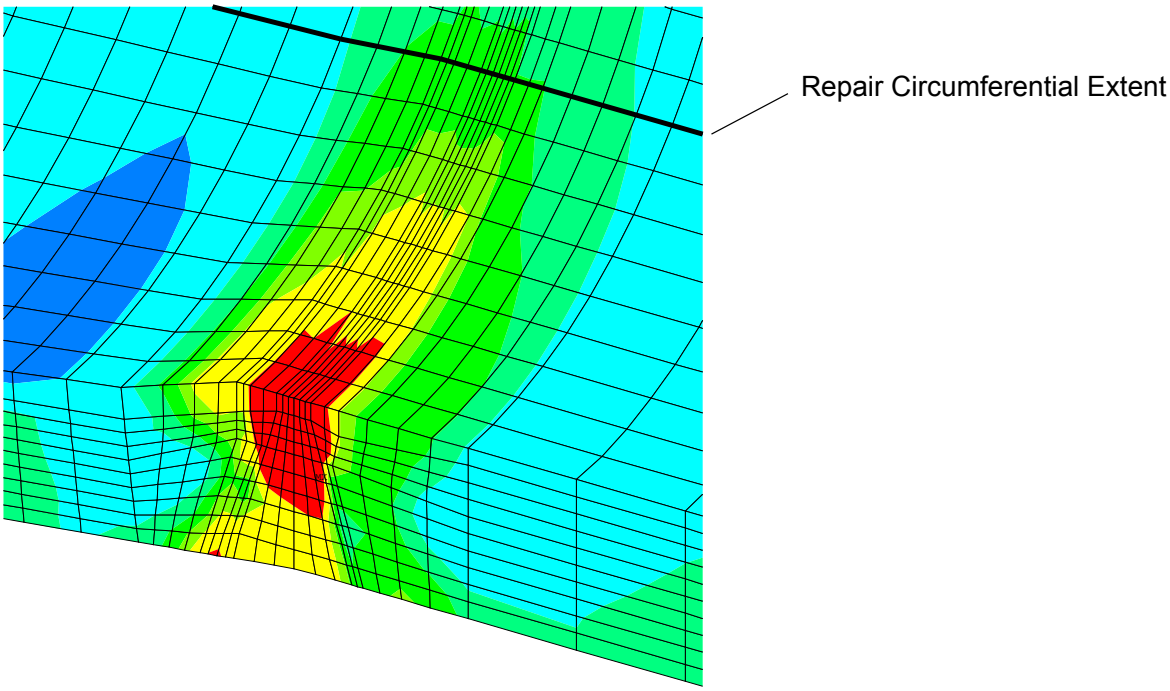
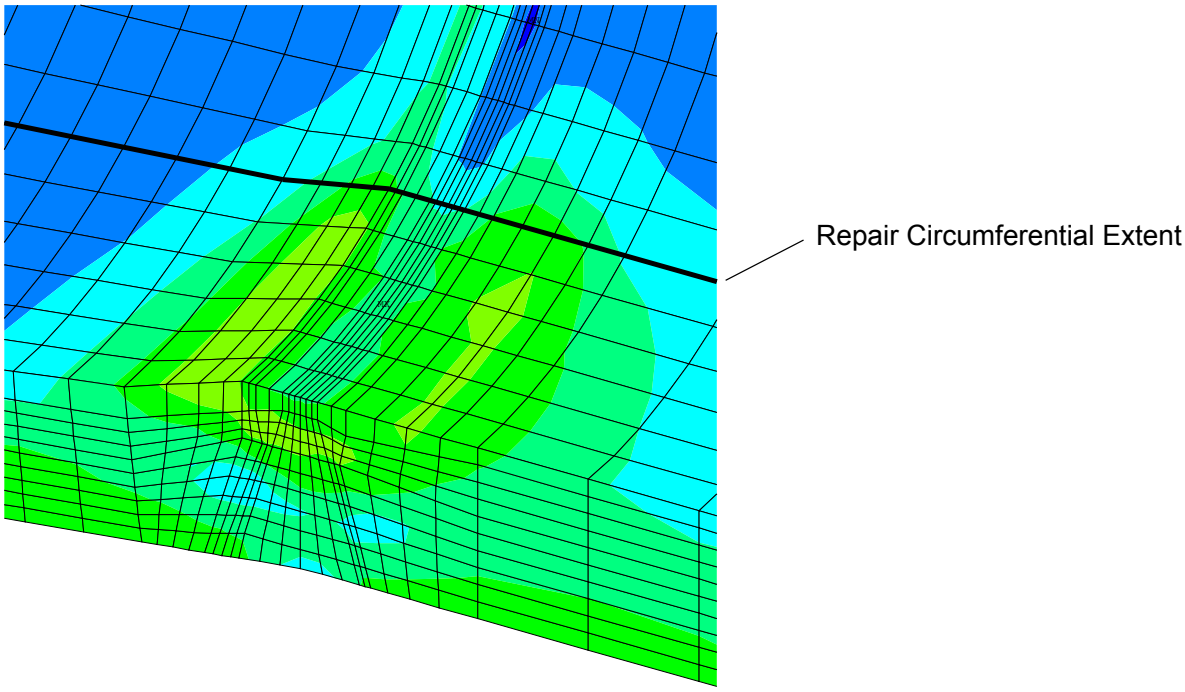


Figure 5-7
10" Pressurizer Surge Nozzle: 90° ID Weld Repair (Case 2.g)

Axial Stress



Hoop Stress

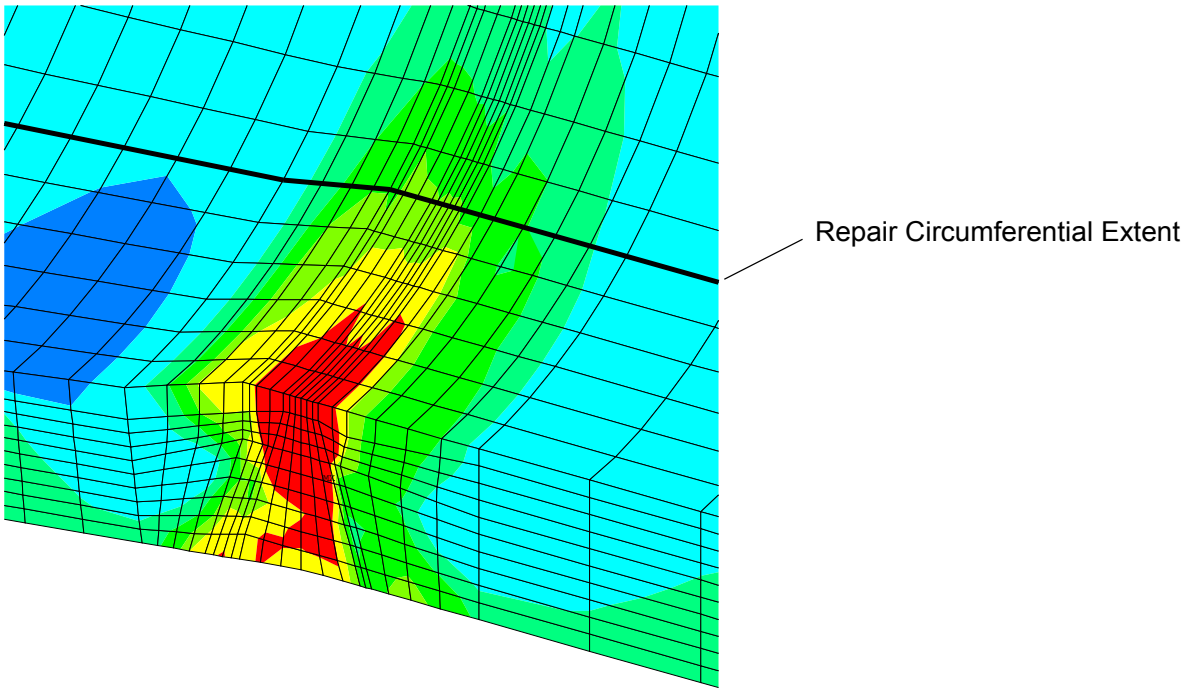
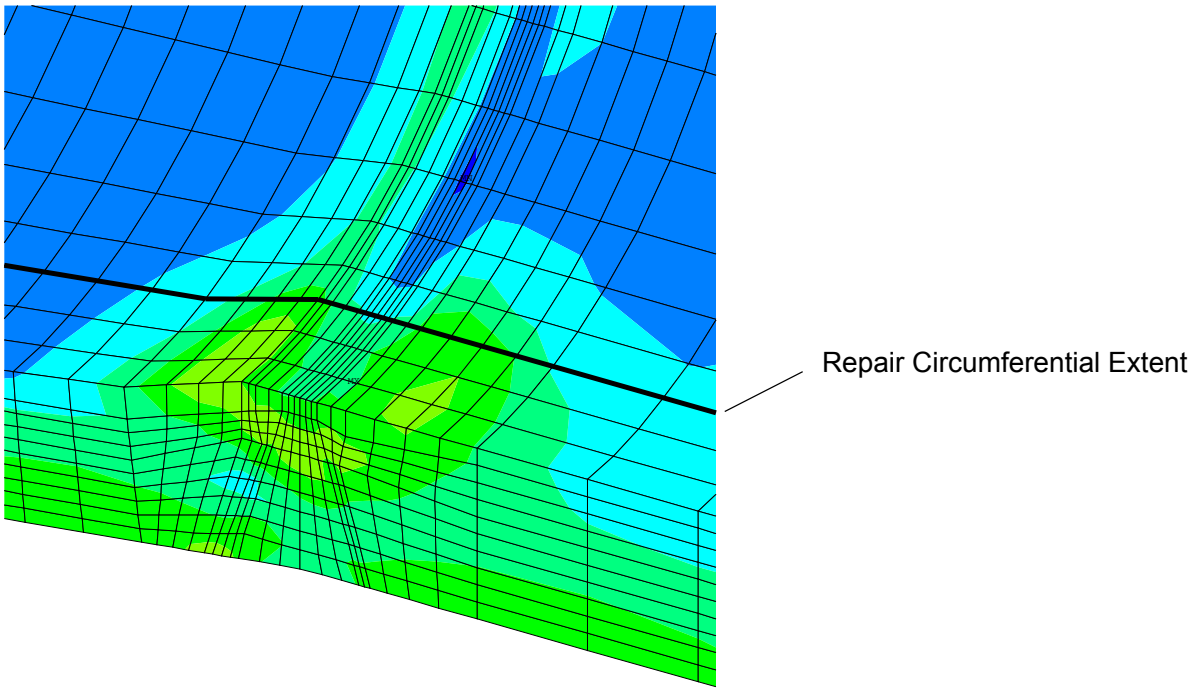


Figure 5-8
10" Pressurizer Surge Nozzle: 60° ID Weld Repair (Case 2.h)

Axial Stress



Hoop Stress

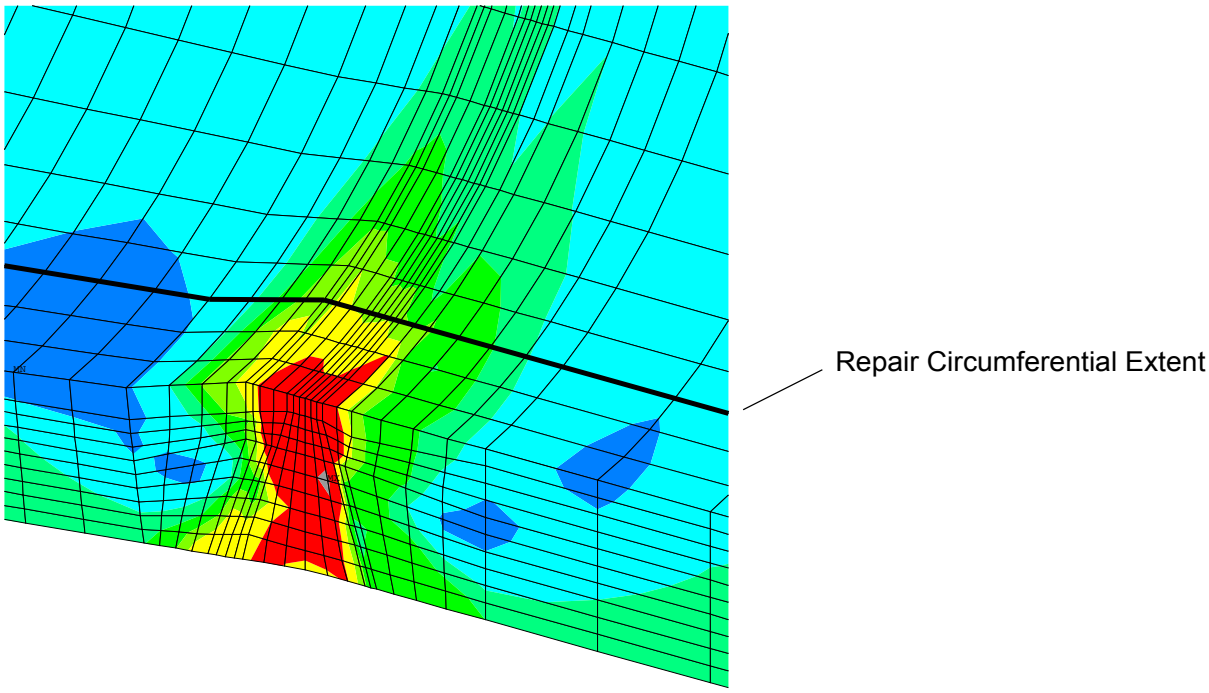


Figure 5-9
10" Pressurizer Surge Nozzle: 30° ID Weld Repair (Case 2.i)

90° ID Weld Repair

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30° ID Weld Repair

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Figure 5-10
10" Pressurizer Surge Nozzle: 30° and 90° ID Weld Repair (Cases 2.g and 2.i)

Axial Stress

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Hoop Stress

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Figure 5-11
5" Pressurizer Safety Relief Nozzle: 360° ID Weld Repair (Case 3.d)

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Figure 5-11
5" Pressurizer Safety Relief Nozzle: 360° ID Weld Repair (Case 3.d) (Continued)

Axial Stress

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Hoop Stress

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Figure 5-12
5" Pressurizer Safety Relief Nozzle: 90° ID Weld Repair (Case 3.e)

Axial Stress

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Hoop Stress

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Figure 5-13
5" Pressurizer Safety Relief Nozzle: 60° ID Weld Repair (Case 3.f)

Axial Stress

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Hoop Stress

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Figure 5-14
5" Pressurizer Safety Relief Nozzle: 30° ID Weld Repair (Case 3.g)

90° ID Weld Repair

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30° ID Weld Repair

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Figure 5-15
5" Pressurizer Safety Relief Nozzle: 30°and 90° ID Weld Repair (Case 3.e & 3.g)

6
EFFECT OF EXTERNAL PIPING LOADS ON COMBINED RESIDUAL PLUS OPERATING STRESSES

Figures 6-1 through 6-3 show the effects of the live piping loads discussed in Section 3.4. Figure 6-1 shows the effects of the additional loads on the as-designed single V RPV nozzle. Figure 6-2 gives the results for the 360° ID repair case, and Figure 6-3 gives the results for the 30° partial arc ID repair case. Also shown in these figures are the results that would be calculated using the proposed superposition method for a 15 ksi axial tensile stress, labeled as "Operating Shifted +15ksi".

The plots show that the results predicted by the superposition method approximate the ANSYS-generated results relatively closely. Since the diagnostic cases support the use of superposition to calculate additional, live-load induced stresses, the nozzle operating stresses listed in this report do not include any live piping loads.

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Figure 6-1
30" RPV Nozzle: As-Designed (Case 1.a)

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Figure 6-2
30" RPV Nozzle: 360° ID Weld Repair (Case 1.d)

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Figure 6-3
30" RPV Nozzle: 30° ID Weld Repair (Case 1.i)

7
EFFECT OF WELD OVERLAY ON ID STRESSES

A weld overlay applied to the outside surface of a butt weld will reduce the tensile stresses on the inside surface of the weld. Specifically weld shrinkage causes a reduction in diameter at the weld and a resultant reduction in tensile stress. Reducing tensile stresses will delay the time to PWSCC crack initiation and the growth rate of any preexisting cracks. While weld overlays can also be used to provide a redundant load path around a cracked weld, the subject work was not focused upon creating a redundant load path.

Figure 7-1 shows a typical pressurizer surge nozzle assumed for this evaluation and Figure 7-2 shows a weld overlay applied over the weld to reduce ID surface stresses. The overlay assumed for this study had a thickness of 15% of the nominal pipe wall thickness and a length 5.8 times the nominal pipe wall thickness.

Figure 7-3 shows the effect of applying weld overlay for both the as-designed case and the case with a 360° ID weld repair. In both cases the axial and hoop stresses are significantly reduced from the cases without weld repair. This should have a beneficial effect on both crack initiation and growth.

The conclusions of the analysis are as follows:

- Repairing the ID surface of a butt weld after completing the through-wall weld increases both the axial and hoop stresses on the ID surface.
- Partial-arc ID repairs also produce higher hoop and axial stresses on the ID surface.
- Weld overlay applied to the outside surface of the butt weld reduces the hoop and axial stresses on the ID surface and should therefore reduce the susceptibility to PWSCC initiation and growth.
- Weld overlay dimensions (thickness and length) can be selected to produce the desired stress reduction over the area of potentially high ID stresses.
- The axial length of the overlay deposits must be selected such that any increase in axial ID stress due to bending occurs at a location where the material is not susceptible to PWSCC.

Finally, it should be noted that the subject analysis is not intended to represent an actual weld overlay design. The purpose of the work is to demonstrate the beneficial effect of weld overlays.

Results for weld overlay deposits on other butt welds are reported in Table 7-1.

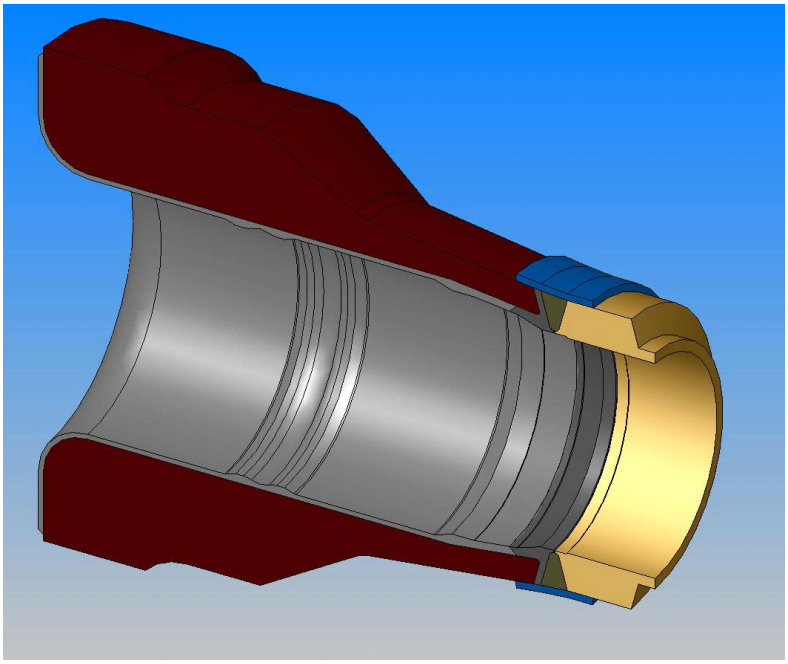


Figure 7-1
Weld Overlay Applied to Pressurizer Surge Nozzle
(Figure Shows Shorter Overlay Length than used for Analysis)

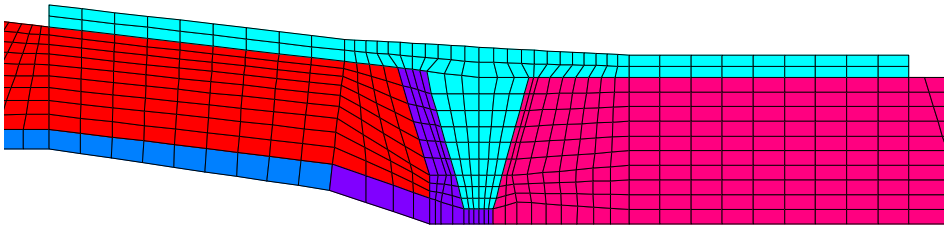


Figure 7-2
Finite Element Mesh for Pressurizer Surge Nozzle Analysis

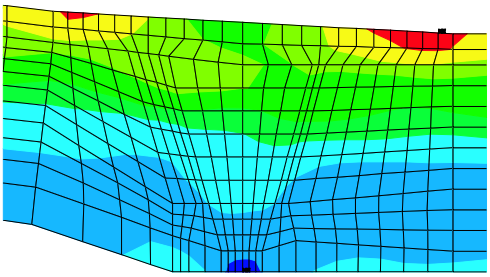
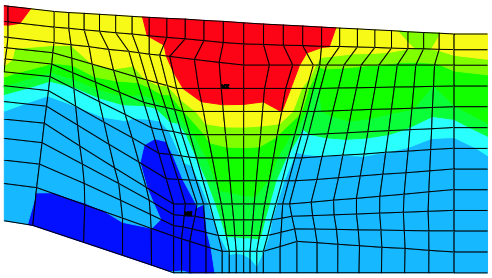
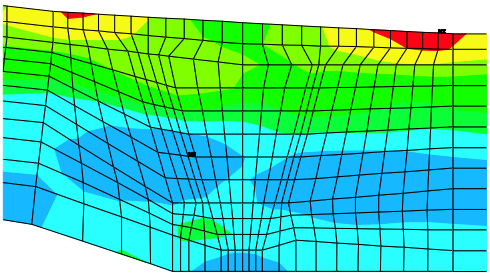
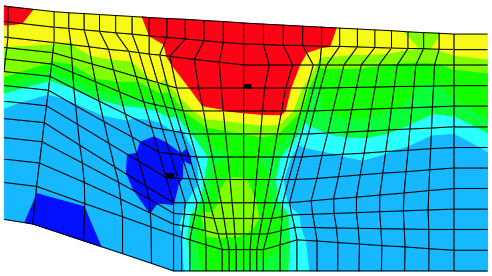
Condition	Axial Stress	Hoop Stress
Welding Residual and Operating Stresses With Overlay – As Designed	 -8.6 ksi Max ID Stress	 -23.2 ksi Max ID Stress
Welding Residual and Operating Stresses With Overlay-360° ID Weld Repair	 1.7 ksi Max ID Stress	 19.9 ksi Max ID Stress

Figure 7-3
ID Surface Stresses with Overlay for Typical Pressurizer Surge Nozzles

Table 7-1
Effect of Weld Overlay on ID Surface Stresses for Typical Pressurizer Surge Nozzle

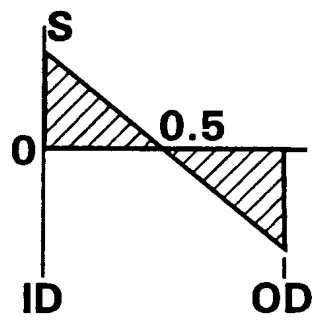
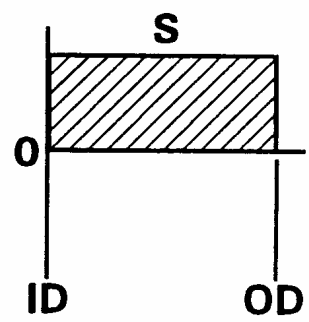
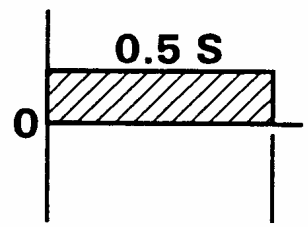
As-Designed (no weld repair)		
Direction	**No Overlay**	**Overlay**
Hoop	9.0 ksi	-23.2 ksi
Axial	-2.7 ksi	-8.6 ksi
With 360° ID Weld Repair		
Direction	**No Overlay**	**Overlay**
Hoop	52.8 ksi	19.9 ksi
Axial	32.5 ksi	1.7 ksi

8
COMPARISON OF CALCULATED RESIDUAL STRESSES TO TYPICALLY ASSUMED INDUSTRY VALUES

In the absence of finite element welding residual stress analyses, flaw evaluations are typically performed using residual stresses obtained from empirical models based on analysis and testing of butt welds in austenitic steel piping [7, 8]. Figure 8-1 shows the empirical model. The purpose of this section is to compare the welding residual stresses calculated for PWR butt welds to the residual stresses determined using the empirical models in references 7 and 8.

Figure 8-2 gives hoop stresses and Figure 8-3 gives axial stresses for as-designed welds which are built up from the ID to the OD without repairs being made to the ID surface. In each figure the upper plot is for welds less than 1 inch thickness and the lower plot is for welds greater than 1 inch thickness. This breakdown is consistent with the wall thicknesses in references 7 and 8. The main conclusion from Figures 8-2 and 8-3 is that the stresses predicted by the empirical model tend to be higher than the finite element analysis results over the inside half of the nozzle wall. This will lead to the empirical model predicting higher stress intensities over the inside half of the pipe wall. This will dominate the crack growth and lead to conservative crack growth predictions of time to a leak.

Figure 8-4 shows the hoop and axial stresses for the case of ID repairs for welds greater than 1 inch thickness. ID repair calculations were not performed for thicknesses less than 1 inch since the inside diameters of these welds are not likely to be accessible for repairs. These results for the ID repair cases are quite different from results for the as-designed cases. In particular, the welding residual stresses over the inside half of the wall thickness are much higher than the values obtained using the empirical model. This will lead to the empirical model under predicting the crack tip stress intensity and growth rates for cases involving repairs to the inside surface.

Wall Thickness	Through-Wall Residual Stress[1]	
	Axial	Circumferential[2]
< 1 inch		
≥ 1 inch	See Note 3	

[1] S = 30 ksi

[2] Considerable variation with weld heat input.

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

σ_i = stress at inner surface (a = 0)

Figure 8-1
Empirical Model for Welding Residual Stresses [7, 8]

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Figure 8-2
Through-Wall Hoop Residual Stresses (As-Designed)

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Figure 8-3
Through-Wall Axial Residual Stresses (As-Designed)

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Figure 8-4
Through-Wall Residual Hoop and Axial Stresses (With ID Repairs)

9
SUMMARY OF ANALYSIS RESULTS

Table 9-1 is a summary of the analysis results. The main conclusions from these results are as follows:

- For the as-design case with no repairs, hoop and axial stresses on the wetted Alloy 600/82/182 materials are low. The highest tensile stresses for these cases are hoop stresses nearer the OD on the weld. The relatively low ID hoop and axial tensile stresses may have contributed to the small number of reports of PWSCC or leaks to date for these joints.
- Weld repairs to the inside surface of the nozzle/pipe are clearly detrimental, creating high tensile hoop stresses and axial tensile stresses of similar magnitude. These results are consistent with the axial and shallow circumferential PWSCC cracks at VC Summer.
- While weld repairs to the ID surface are clearly detrimental from the standpoint of PWSCC susceptibility, many butt weld joints are believed to be too small diameter for weld repairs to have been performed.
- Adding an appropriately sized weld deposit to the outside of the nozzle/weld can significantly reduce the stresses, thereby mitigating the potential for PWSCC.

More complete analysis output data is available on CD ROM.

Table 9-1
Summary of Stress Analysis Results

Analysis Parameters			Maximum Stresses on Alloy 600 ID Surface (ksi)	
Nozzle	Condition	Ref.	Hoop	Axial
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10
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3. ASM Materials Handbook, Ninth Edition.

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5. E.F. Rybicki and R.B. Stonesifer, "Computation of Residual Stresses due to Multipass Welds in Piping Systems," Journal of Pressure Vessel Technology, Volume 101, May 1979, pp. 149-154.

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7. *Evaluation of Flaws in Austenitic Steel Piping*, EPRI NP-4690-SR, July, 1986.

8. *Evaluation of Flaws in Austenitic Stainless Steel Piping*, Trans ASME, Journal of Pressure Vessel Technology, Vol. 108, August 1986, pp. 352-366.