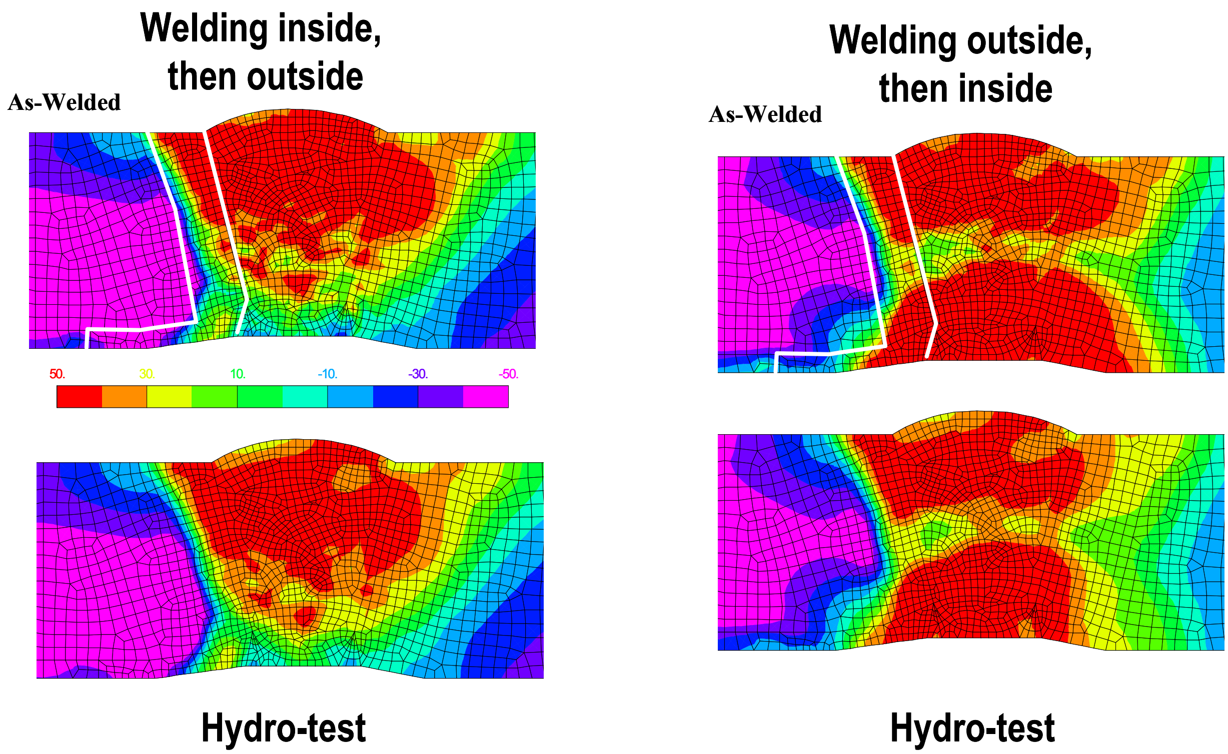


Figure G.37 Effect of hydro-test – hoop stresses (pressure = 3.125 ksi, then unload at room temperature)

The thermal loading was applied to the model of Figure G.24. It was assumed that the entire hot leg was heated (and expands) to 324°C (615°F). The vessel and steam generator were assumed to be massive, providing the fixity constraints illustrated in Figure G.24. Hence, the hot leg expands while the vessels provide constraint. Figure G.38 compares the axial residual stress states before and after heat up to 324°C (615°F). The axial stresses decrease due to the hot leg expansion and vessel constraint. Figure G.39 shows the corresponding hoop residual stresses at 324°C (615°F). The small reduction in hoop stress is mainly due to the heat up (and corresponding reduction in material properties at high temperature). The constraint has little effect on the hoop stresses.

The detailed fine mesh required for the weld analysis is not required for the service load (moment and bending) case analyses. A fine mesh is also not required for the subsequent fracture analyses to be discussed next. As discussed in connection with Figure G.23, the residual stresses are mapped from the fine weld (2D axis-symmetric) analysis model to a coarser (2D axis-symmetric) model. Figure G.40 (a) and (b) provide axial and hoop residual stresses as mapped from the fine to coarse model. Figure G.41 (a) and (b) provide the same mapping comparison for the outside first weld. It is seen that the mapping procedure is quite accurate.

Figure G.42 shows a similar mapping between the coarse two-dimensional mesh to a full three-dimensional mesh. Again, the comparison is quite good (compare to Figure G.41) illustrating that the mapping procedure is adequate. Figures G.43 and G.44 show similar comparisons between the 2D stresses and mapped 3D stresses. Finally, Figure G.45 shows the plastic strains mapping from the coarse 2D mesh to the 3D mesh. This is explicitly shown to illustrate that stresses and strains are mapped to the three dimensional model. As such, the service load cases (moment, tension, and pressure) include the effects of plasticity.

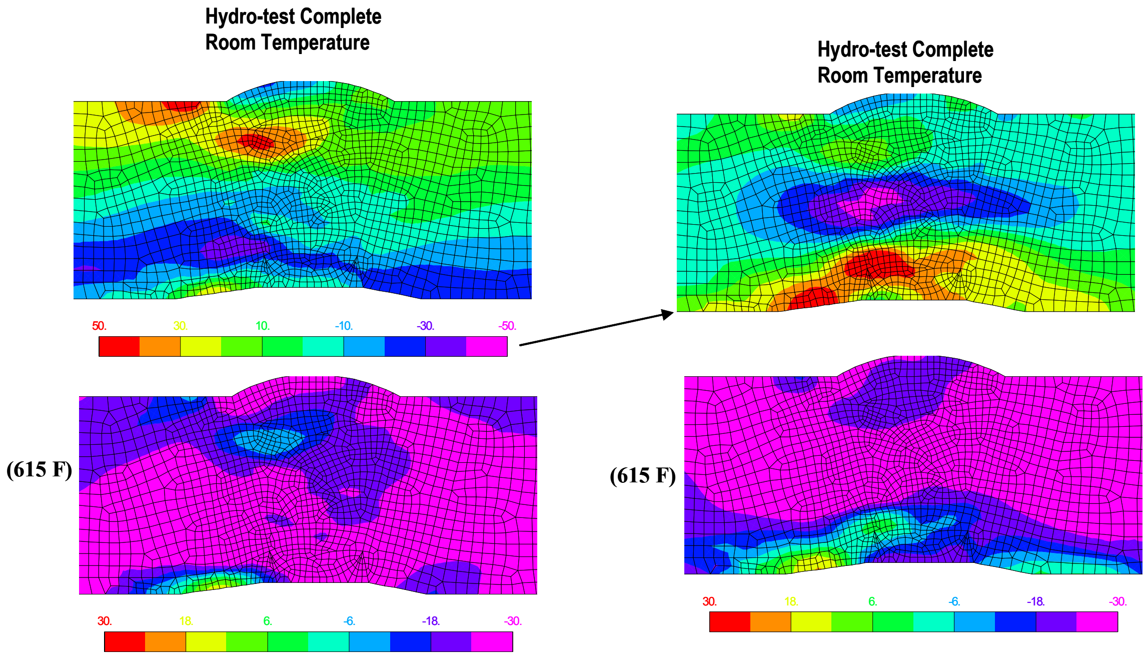


Figure G.38 Axial residual stresses at operating temperature (after all welding and hydro-test) Top: room temperature before heat up to 324°C (615°F); Bottom: after heat up; left is for welding inside then outside, right is for welding outside then inside

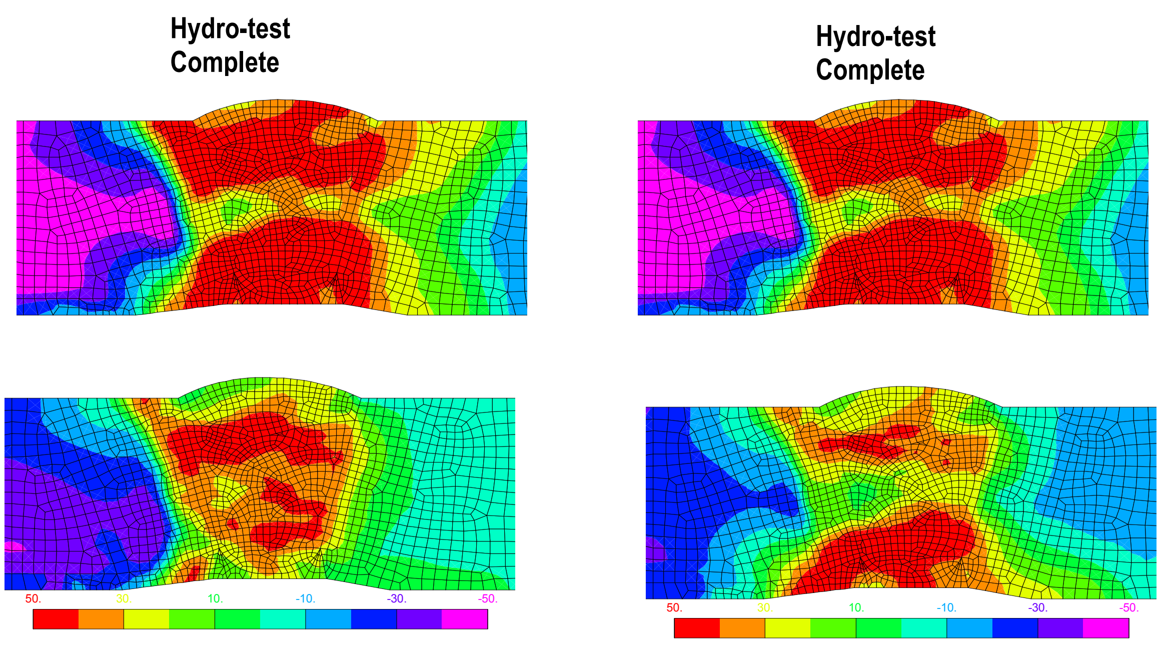


Figure G.39 Hoop residual stresses at operating temperature (after all welding and hydro-test) Top: room temperature before heat up to 324°C (615°F); Bottom: after heat up; left is for welding inside then outside; right is for welding outside then inside

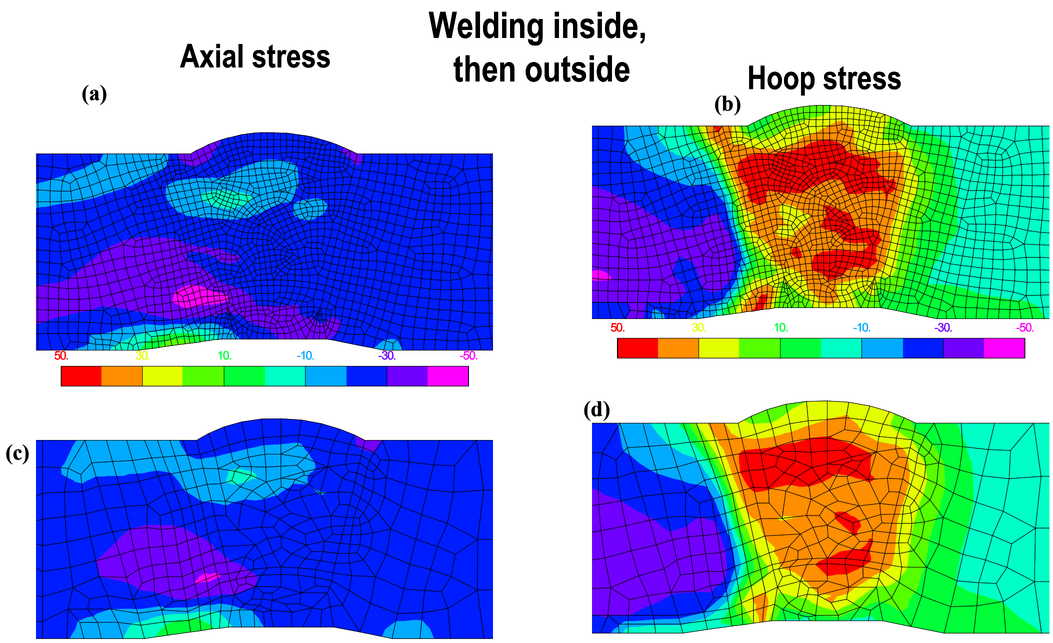


Figure G.40 Operation residual stresses (324°C (615°F) – no loading) for inside first weld (a) and (b). (c) and (d) mapped residual stresses at operating temperature from fine to coarse mesh. These stresses are then mapped to a three dimensional mesh (inside weld first, then outside weld)

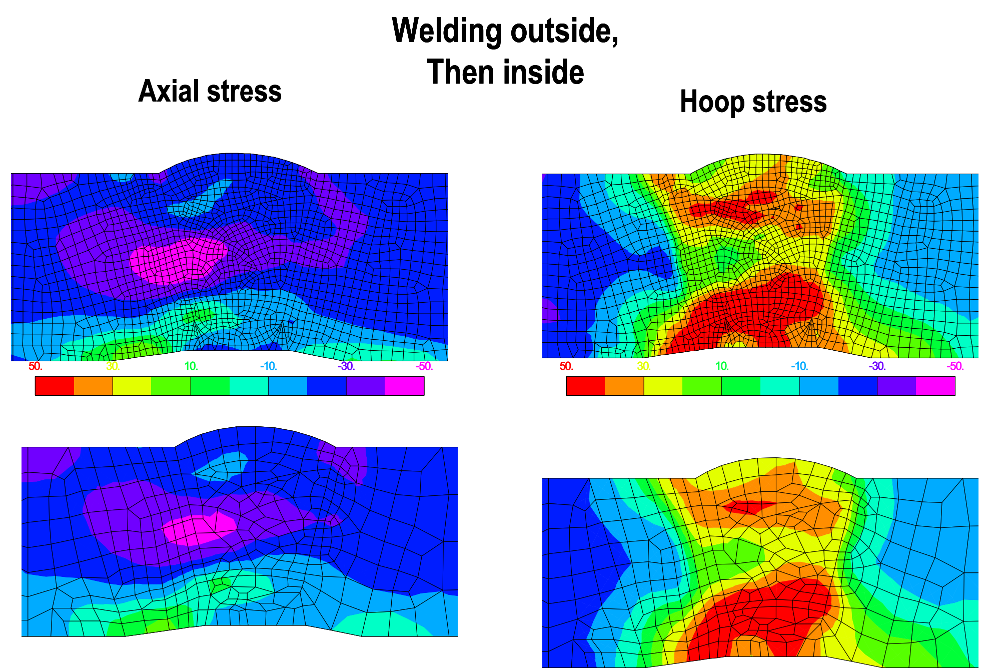


Figure G.41 Operation residual stresses (324°C (615°F) – no loading) for outside first weld (a) and (b). (c) and (d) mapped residual stresses at operating temperature from fine to coarse mesh. These stresses are then mapped to a three dimensional mesh (outside weld first, then inside weld)

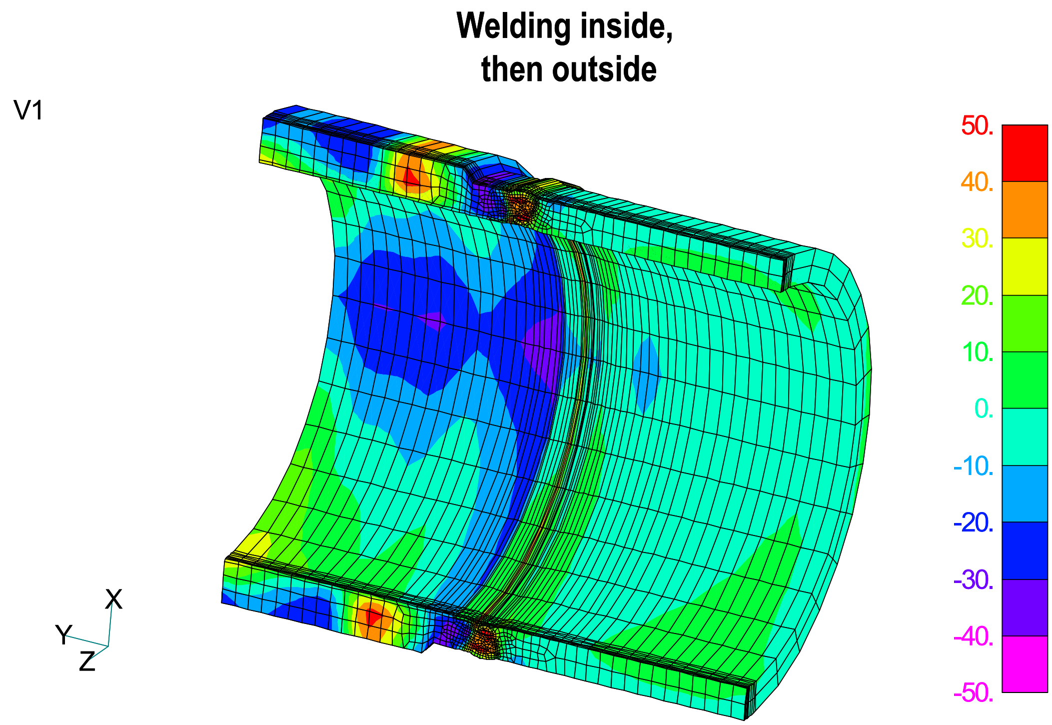


Figure G.42 Mapped hoop residual stresses at operating temperature from coarse axis-symmetric mesh to 3D mesh (inside weld first, then outside weld). (This 3D model is then used to obtain stress intensity factors via the finite element alternating method)

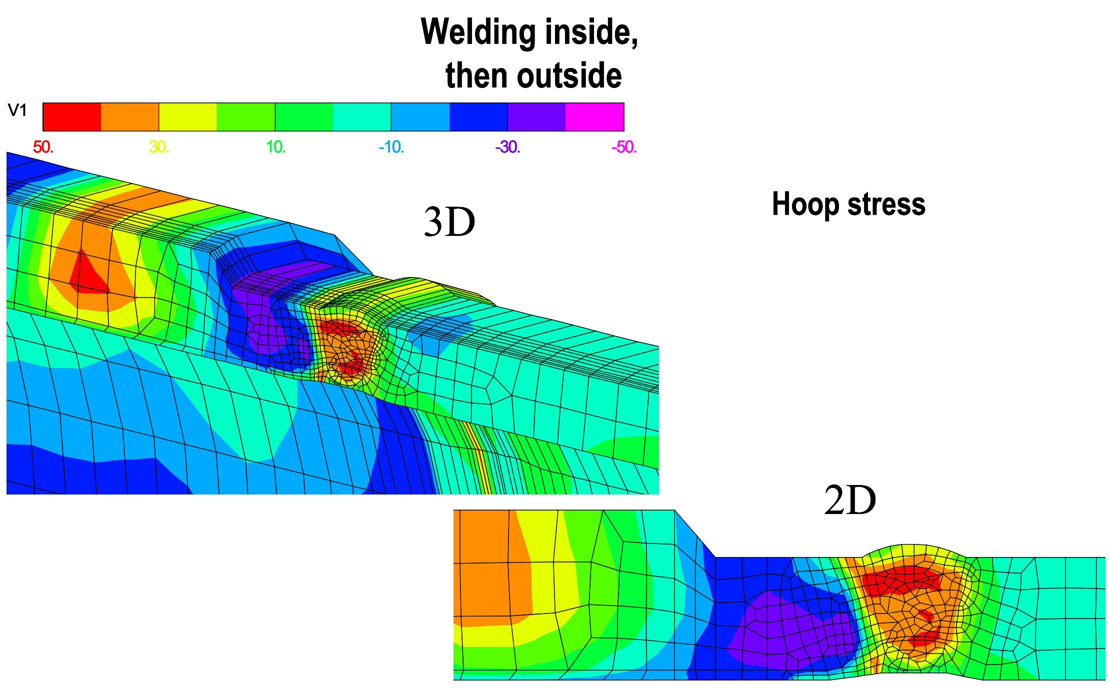


Figure G.43 Comparison of mapped hoop residual stresses at operating temperature from coarse axis-symmetric mesh to 3D mesh (inside weld first, then outside weld)

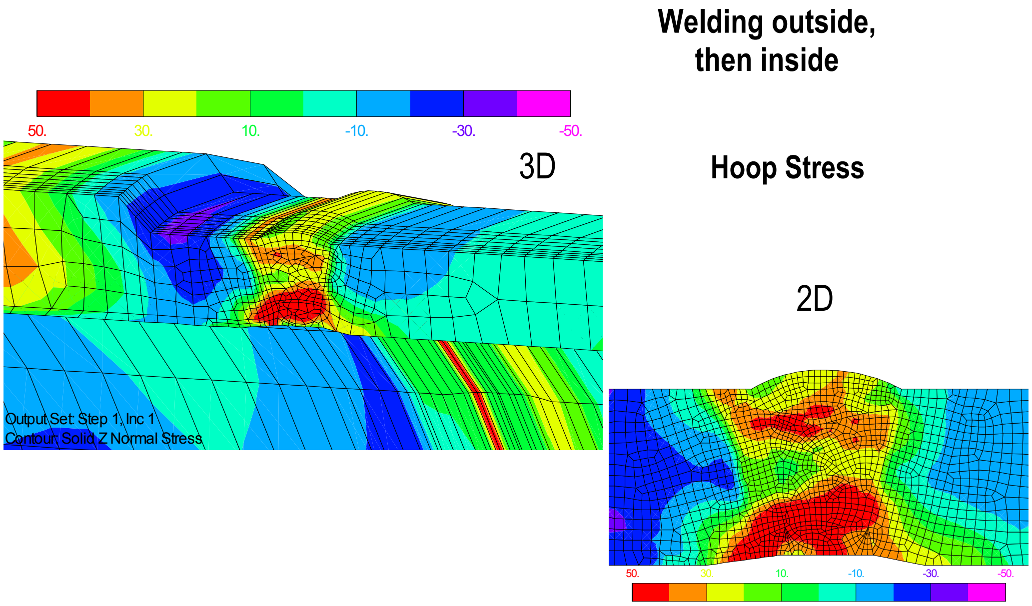


Figure G.44 Comparison of mapped hoop residual stresses at operating temperature from coarse axis-symmetric mesh to 3D mesh (outside weld first, then inside weld)

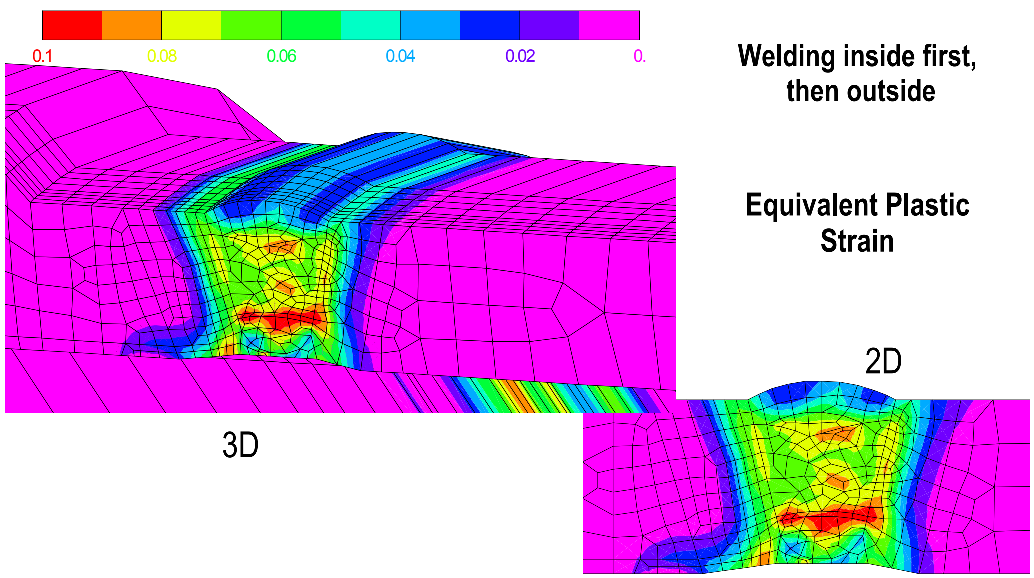


Figure G.45 Comparison of mapped equivalent plastic strains at operating temperature from coarse axis-symmetric mesh to 3D mesh (inside weld first, then outside weld)

G.7 PRIMARY WATER STRESS CORROSION CRACKING AND FRACTURE ASSESSMENT OF HOT LEG/RPV BIMETAL WELD

The finite element alternating method (FEAM) was used to obtain stress intensity factors to perform the PWSCC analyses. FEAM is very convenient for obtaining mixed mode stress intensity factors in complex structures. Stress intensity factors were obtained for numerous crack sizes and shapes for cases of:

- Inside weld first, then outside weld repairs
- Outside weld first, then inside weld repairs
- Residual stress only
- Residual stress plus normal operating loads
- Circumferential cracks
- Axial cracks

Typically it required about two minutes for a new solution on a high-end personal computer once the stiffness matrix was reduced once. Typical 3D meshes consisted of about 20,000 elements. In all, about sixty K solutions were obtained and used to model crack growth via SCC equations (discussed later). Although mode I stress intensity factors dominated, there were some cases where mode II was about 20 percent of the mode I value. However, mixed mode effects were not considered here.

The FEAM method properly accounts for stress redistribution as the cracks grow. As such, cracks that grow through a residual stress field that reach a compressive residual stress field (after stress re-distribution) can stop growing. Weight function methods often have problems accounting for stress redistributions properly.

The results of the stress corrosion cracking assessment are provided here. For the SCC analyses, crack growth was predicted for the case of residual stress alone (at operating temperature of 324°C [615°F]), and for normal operating loads. The normal operating loads were obtained from Reference G.11 and are included in Figure G.46. The residual stress states that serve as input to the FEAM analysis are illustrated in Figures G.47 to G.50 for both the inside weld first case (Figures G.47 and G.48) and outside weld first case (Figures G.49 and G.50). The top illustrations in Figures G.47 to G.50 consist of only the residual stress state at the operating temperature of 324°C (615°F). The bottom illustrations consist of residual stresses including operating loads. Plasticity (if any) was included in the analysis where loading was applied to the weld residual stress results.

Stress Intensity Factors. Figure G.51 provides a few of the stress intensity factor plots used for the PWSCC assessment. This case is for an axial elliptic crack positioned with aspect ratio as shown in Figure G.51. Both the 'residual stress only' and 'residual stress plus normal operating load' conditions were considered for all cases. In all K was calculated for cracks of many different sizes and shapes (a total of 60 cracks for both axial and circumferential locations).

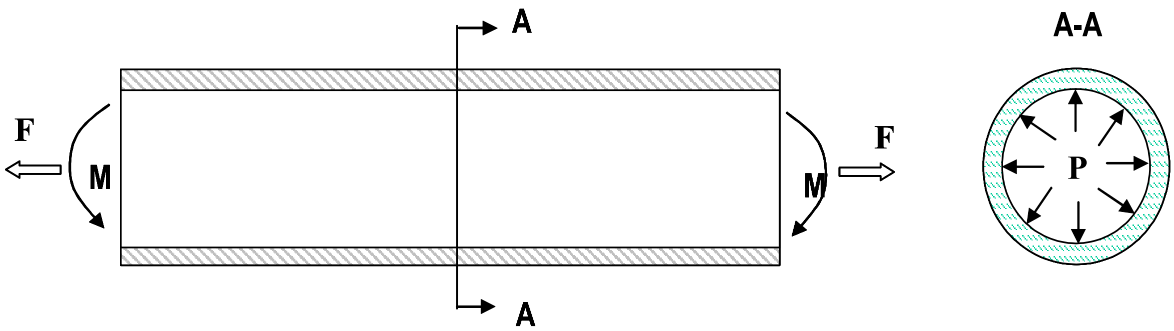
The crack growth rate equation, taken from Reference G.13, is:

$$\frac{da}{dt} = 1.4 \times 10^{-11} (K_I - 9)^{1.16} (m/\sec) \qquad \text{(G.1)}$$

Here K_I has units of MPa $m^{1/2}$ and the range for the data is for K values between 20 and 45. The K values calculated in this study are both lower and higher than this range. Moreover, this equation represents the Scott model based on the application of a factor of 5. Hence, while this equation may need improvement for future analyses, it is used for the crack growth and life predictions shown in the following. Moreover, for this study, this was the only available data for the PWSCC crack growth analyses, i.e., no other PWSCC laws were used here.

G.7.1 The 3 Dimensional Growth of Axial Cracks Through the Hot Leg Weld

The growth of a 3 Dimensional (3D) crack through a thick pipe must account for both the residual stress field left from the welding process as well as the stress imposed from the applied loadings. Because the residual stresses can change from compressive to tensile (or vice



P-pressure: 2.25 (ksi)
F-force: 1476 kips (including the force due to the pressure)
M-bending moment: 22052 in-kips

Figure G.46 Normal operating loads applied on hot leg

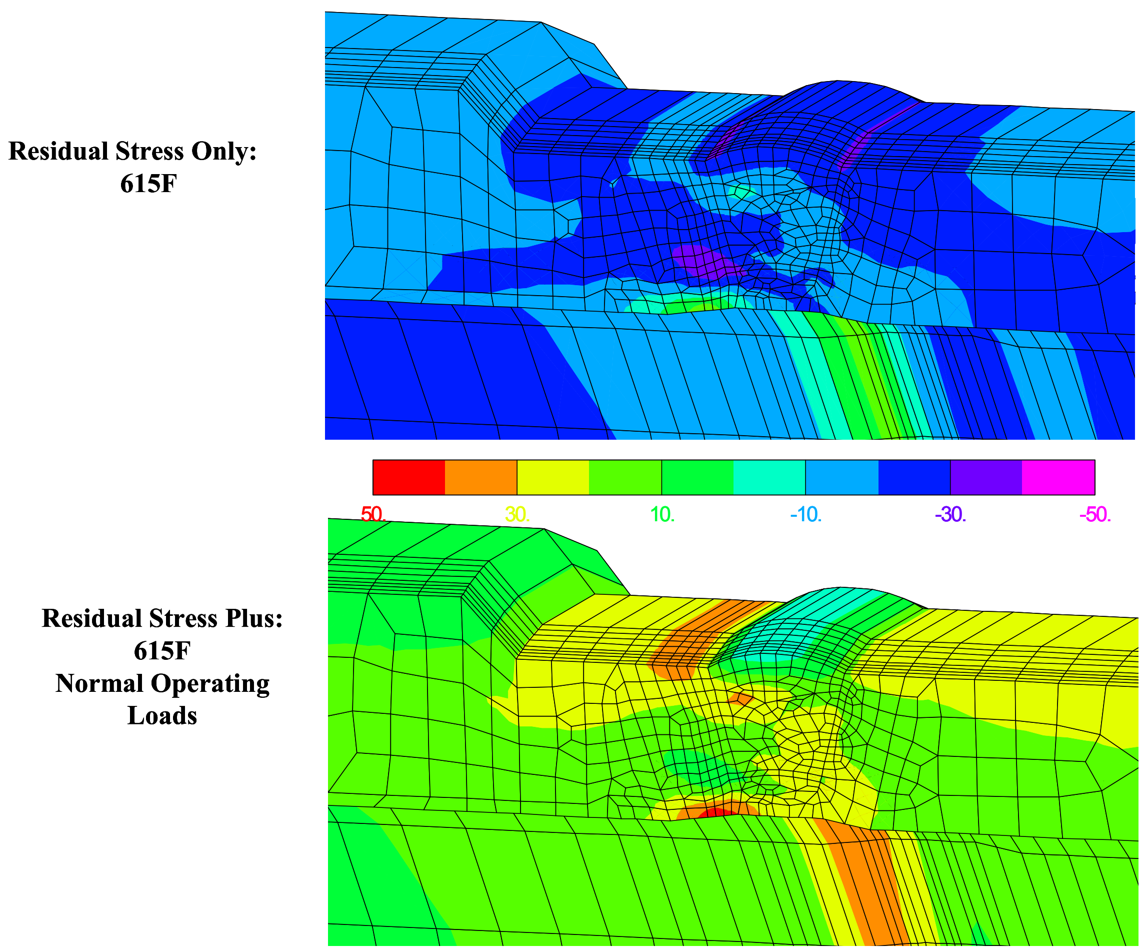
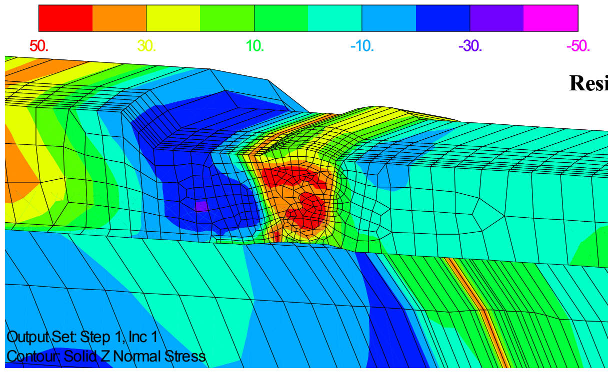
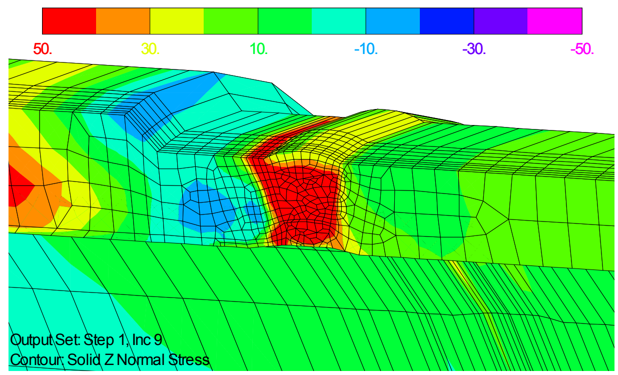


Figure G.47Axial stresses – used for FEAM analyses: inside weld first then outside weld



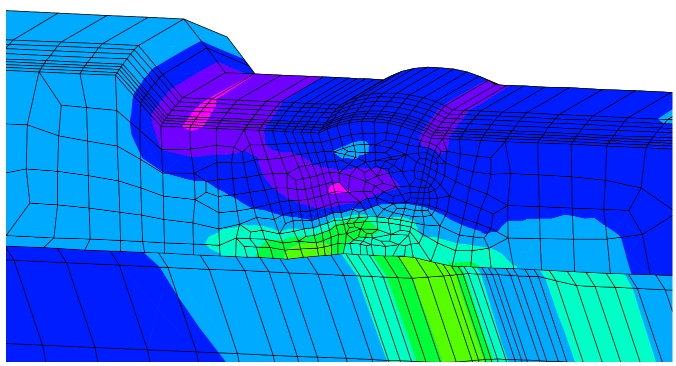
Residual Stress Only:
615F



Residual Stress Plus:
615F
Normal Operating
Loads

Figure G.48 Hoop stresses – used for FEAM analyses: inside weld first then outside weld

Residual Stress Only:
615F



Residual Stress Plus:
615F
Normal Operating
Loads

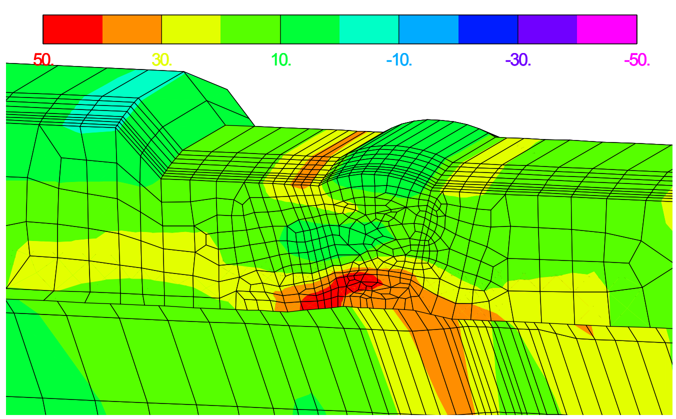


Figure G.49 Axial stresses – used for FEAM analyses: outside weld first then inside weld