Justification for Extension of Temper Bead Limit to 1000 Square Inches for WOL of P1 and P3 Materials

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PRODUCT DESCRIPTION

As nuclear plants age, there is an increasing need to perform repairs to provide life extension of existing components. One of the commonly used techniques is temperbead welding, which is included in the ASME Boiler and Pressure Vessel Code. However, this Code has traditionally restricted the use of temperbead welding to a surface area of not larger than 100 square inches. The study described in this report demonstrates that larger repairs could be conducted without deleterious effects on the repaired component.

Results and Findings

The results of the analysis work described in this report show that larger scale temperbead weld repairs could be performed on low-alloy steel components. Specifically, repairs that included weld overlays on vessel nozzles and similar components could be expanded to an area of 1000 square inches without creating deleterious residual stress levels and still maintain the structural integrity of the component.

Challenges and Objectives

The development of new or revised Code rules for repair of nuclear plants requires significant effort in establishing the technical basis and demonstrated safety of any proposed modification. The purpose of this report, developed by the Electric Power Research Institute (EPRI) Welding & Repair Technology Center, is to support a Code revision that would allow for the performance of larger temperbead weld repairs.

Applications, Value, and Use

The technical information included in this report is intended to support large-scale temperbead welding repair applications at nuclear facilities. Temperbead welding technology developed by EPRI Welding & Repair Technology Center and other researchers has become a proven method that has provided significant savings to the industry. This expansion of the temperbead technique to larger scale repairs will assist utilities in meeting the challenges of difficult repairs on large-bore nozzles and vessel components.

EPRI Perspective

The technology described in this report will lead to broader use of the valuable temperbead welding technique, providing substantial savings to utilities.

Approach

Support of technical revisions of the ASME Code for repair of nuclear vessel components is a goal that this report achieves by providing the necessary technical basis for expansion of the current temperbead area limitations to a surface area of 1000 square inches.

Keywords
Repair
Temperbead
Welding

ABSTRACT

This report presents the results of analyses supporting the technical justification of increasing the amount of temperbead welding that can be performed on carbon and low-alloy steel (LAS) dissimilar metal welds for weld overlay repair application (WOL). The analyses provided in this report are specific to WOLs and are not applicable to extending the cavity repair limits that were developed in an earlier EPRI study and described in the 2005 EPRI technical update 1011898, *RRAC Code Justification for the Removal of the 100 Square Inch Temper Bead Weld Repair Limitation.* The results of this work provide a basis justifying the increase of the 500 in^2 temperbead welding limit developed in the earlier Electric Power Research Institute (EPRI) program (EPRI report 1011898) to as much as 1000 in^2. The need to expand the application area limitations has increased again for ambient temperature gas tungsten arc weld temperbead weld overlay repairs on LAS components as a result of significant numbers of repairs required for large-diameter, thicker PWR primary coolant piping and nozzles.

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1 OBJECTIVE AND BACKGROUND

This report presents the results of analyses supporting the technical justification of increasing the amount of temper bead welding that can be performed on carbon and low alloy steel (LAS) dissimilar metal welds (DMWs) for weld overlay repair application (WOL). The analyses provided herein are specific to WOLs and are not applicable to extending the cavity repair limits that were developed in an earlier EPRI study [1]. The results of this work provide a basis justifying the increase of the 500 in^2 temperbead welding limit developed in the earlier EPRI program [1] to as much as 1000 in^2. The need to expand the application area limitations has increased again for ambient temperature Gas Tungsten Arc Weld (GTAW) temperbead weld overlay repairs on LAS components as a result of significant numbers of repairs required for large diameter, thicker pressurized water reactor (PWR) primary coolant piping and nozzles. These components are often greater than 30-inches in diameter, and more than 3-inches thick. These repairs have been necessitated by the observation of primary water stress corrosion cracking (PWSCC) in nickel alloy components (Alloys 600, 82 and 182) in the PWRs. It is anticipated further, that as plants age and as inspection techniques continue to improve increasing the area limit continues to be important. Existing evaluations have indicated that the ASME Code limitation of 500 in^2 imposed in the Code for temper bead welding and in Code Cases N-638-5 and in N-740-2 for ambient temperature temper bead welding may be overly conservative. In fact the weld overlays or repairs applied to most component geometries, increasing the temperbead area produces improved residual stresses on the inside surface of the component and improved stress distributions well into the component thickness.

The approach taken for this investigation has been to perform a series of finite element based residual stress evaluations to support increasing the area of temper bead weld overlay repairs over ferritic materials (carbon and low alloy steels). This increase in temper bead area is necessary to support weld overlay repairs of increasingly large bore, thick wall piping and nozzle components in PWRs.

The temper bead area for a weld overlay repair of a ferritic component is currently limited to 500 in^2, which was qualified in an earlier EPRI program [1]. Therefore, a comparison will be performed between the currently allowed 500 in^2 repair and increased WOL repairs for 750 and 1000 in^2 piping to ascertain the impact of the increased overlay sizes on large bore ferritic piping components.

Two sets of three separate analyses (one for each repair size) are performed. These analyses serve as sensitivity studies for justifying the increase of the temper bead weld overlay repair area of large bore ferritic piping components up to a repair area of 1000 in^2. The analyses provide the weld residual stress condition on the inside surface at the centerline of the DMW, that area susceptible to PWSCC, and on the inside surface at the toe of the overlay on the ferritic side of the overlay and on the stainless steel side of the overlay for the three different temper bead weld overlay areas evaluated, as well as the radial displacements associated with the weld overlay repair applications on the inside surface of the components beneath the overlay.

These analyses are relevant only to nozzles, pipes and similar cylindrical component welds. It should be noted that the stainless steel pipe is not susceptible to PWSCC so the residual stress and shrinkage information associated with the stainless steel component is only provided for completeness.

The first set of analyses compare the temper bead WOL repair for the three different area repairs using as the initial boundary condition the same conditions as were used in the prior EPRI study [1]. This results in the material properties for the DMW modeled in the analysis but no residual stresses due to the fabrication of that weld are included nor is any inside surface (ID) weld repair that is current practice for analyses of PWR components requiring WOL repair.

The second set of analyses compare the temper bead WOL repair for the three different area repairs utilizing the material properties described above, but also including the initial DMW weld including the residual stresses produced by that weld as well as an ID repair applied following the original DMW butt weld application. The detailed approaches used and the results of these analyses are described in the following sections of this report.

In addition, a separate report performed as part of another EPRI project is included as Attachment 1 to this document. This report describes an evaluation of the effect of a temperbead weld overlay on the structural integrity of the elbow, including radial shrinkage and distortion. For this mockup, the temper bead area over the P1 elbow was approximately 670 in^2, consistent with the sizes of overlay repairs evaluated in the body of this report.

It should be noted that these analyses are not intended to support any increase in the size of vessel shell cavity repairs, which was also previously evaluated in Reference 1. Nor are these evaluations intended to specifically address residual stress and its impact on Primary Water Stress Corrosion Cracking (PWSCC).

2 APPROACH

As was reported in the Introduction and Objective section of this document, two separate sets of three analyses were performed in order to evaluate extending the temperbead limit developed in an earlier EPRI program [1] from 500 to 1000 in^2 over ferritic carbon and low alloy steel materials. The initial analyses set presents the results of analyses to extend the temper bead surface area from 500 in^2 to 750 in^2 and to 1000 in^2 using a similar approach to that used in the referenced EPRI study [1]. The current analysis set replicates the initial EPRI study while adding the effects of modeling the effects of the initial DMW weld out on the residual stress followed by the modeling of a 50% through-wall ID weld repair on the residual stress. Finally the weld overlay repair is applied to determine the final state of ID and through thickness residual stress.

The studies are reported separately in this section of the report (Sections 2.1 and Section 2.2 respectively) and discussed jointly in the Conclusion section of the report (Section 3). Additionally, a separate investigation developed in another EPRI program describing the results of temper bead welding on a 36-inch nominal diameter clad carbon steel elbow, with a temper bead area of approximately 670 in^2 is presented in Attachment 1 to this report and the results are compared to the modeling results presented herein.

2.1 Initial Temper Bead WOL Surface Area Sensitivity Study

In this study, the temper bead area for an overlay repair of a ferritic component is compared between the currently allowed 500 in^2 repair and repairs increased to 750 in^2 and 1000 in^2 to ascertain the impact of the increased temper bead overlay area on large bore ferritic piping components and on the DMW. The approach taken in these analyses are similar to that taken in the Reference 1 WOL analyses, for consistency.

Three separate analyses (one for each repair size) are performed. These analyses serve as sensitivity studies for justifying the increase of the temper bead weld overlay repair area of large bore ferritic piping components up to a repair area of 1000 in^2. The analyses will provide the weld residual stress condition on the inside surface at the centerline of the DMW, that area susceptible to PWSCC, and on the inside surface at the toe of the overlay on the ferritic side of the overlay and on the stainless steel side of the overlay for the three different temper bead weld overlay areas evaluated, as well as the radial displacements associated with the weld overlay repair applications on the inside surface of the components beneath the overlay. These analyses are relevant only to nozzles, pipes and similar cylindrical component welds. It should be noted that the stainless steel pipe is not susceptible to PWSCC so the residual stress and shrinkage information associated with the stainless steel component is only provided for completeness. In this manner, the effect of increasing the temperbead area overy the ferritic material can be evaluated as regards the ID weld residual stress and radial shrinkage for three different temper bead areas over the ferritic component.

The same residual stress analysis methods are applied to the 500, 750 and 1000 in^2 weld overlay repairs. The three configurations are identical, except for the axial length of the weld overlay repair, which is increased to achieve the desired coverage area over the ferritic component. The finite element model meshing characteristics are also essentially identical for all three configurations.

2.1.1 Configuration Summary, Assumptions and Design Inputs

The configuration for this study is based on a large bore stainless steel to ferritic steel DMW configuration. The base inside diameter is 28 inches and the base stainless wall thickness is 3.25 inches. The axial DMW length at the outside surface, including the ferritic steel weld butter, is 3.75 inches. The weld overlay repair area parameter is determined by the base ferritic component outside diameter and the axial length measured from the edge of the butter.

The configuration and geometry for a representative large bore weld overlay repair is shown in Figure 2-1. The base configuration consists of a SA-351 Grade CF8M stainless steel pipe welded to a SA-516 Grade 70 carbon steel pipe, which is clad with 304L stainless material. The total configuration therefore comprised of the stainless pipe, the Alloy 82/182 DMW, the Alloy 82/182 butter on the carbon steel pipe, the carbon steel pipe (with stainless cladding) and the weld overlay repair, which is comprised of Alloy 52M, with a stainless steel buffer layer over the cast stainless pipe. The weld overlay repair covers the DMW and extends in both directions. The area measurement of the weld overlay is one side only and is measured from the edge of the butter to the end of the weld overlay repair on the carbon steel pipe side, as that is the side requiring a temper bead weld overlay repair. The overlay thickness roughly conforms to 1/3 of the thickness of the DMW (overlay thickness over the DMW is 1.083 inches and the thickness of the susceptible material is if 3.18 inches). It is noted that the overlay thickness is not the result of a specific sizing evaluation and is not applicable to a specific WOL evaluation.

The dimensions and materials are typical for PWR large bore pipes used on the cold leg and hot leg sides of the reactor coolant system. An example of the finite element model, for the 500 in^2 weld overlay repair case is shown in Figure 2-2.

Material properties used for the residual analysis are temperature dependent and use the Multilinear Isotropic Hardening formulation as defined in the ANSYS software [6].

The residual stresses due to welding are controlled by various welding parameters, thermal transients due to application of the welding process, temperature dependent material properties, and elastic-plastic stress reversals. The analytical technique uses finite element analysis to simulate the multi-pass weld overlay processes as described in the following sections of this report.

2.1.2 Weld Bead Simulation

In order to reduce computational time, individual weld beads or passes are lumped together into weld nuggets. This methodology is based on the approach presented in References 2, 3, 4 and 5.

The number of equivalent bead passes is estimated by dividing each nugget area by the area of an individual bead. The resulting number of equivalent bead passes per nugget is used as a multiplier to the heat generation rate. The welding direction is defined to be from the ferritic pipe to the stainless steel pipe. A plot of nuggets for the weld overlays are shown in Figures 2-3, 2-4 and 2-5.

All three weld overlay repairs are performed using 10 layers, each of which is approximately 0.1 inches thick. The number of nuggets increases for each configuration due to the added length of the overlay. Therefore, the 500 in^2 repair has 301 nuggets, the 750 in^2 repair has 422 nuggets and the 1000 in^2 repair has 524 nuggets.

2.1.3 Welding Simulation

The welding simulation is basically a two step process within the ANSYS finite element software package [6]. In the first step, time dependent thermal loads are applied and temperature gradients are solved for many points in time for the welding process. This sequence of temperature history is then used in the stress analysis step to calculate residual stresses resulting from the welding process.

The stainless buffer layer is applied first, after which it is cooled to an ambient temperature of 70°F. The remainder of the weld overlay repair simulation is then performed. After the weld overlay is completed, the entire structure is again allowed to cool to a uniform ambient temperature of 70°F. The final result is the predicted state of stress with path dependent effects based on representative thermal and mechanical load history.

Note that no simulation of the DMW welding process was considered. This evaluation is only intended to compare the effects of the increased overlay size on the ferritic component and not consider the overlay residual stress, and its effects on PWSCC or other cracking concerns.

2.1.4 Finite Element Analysis

The finite element analysis was run using axisymmetric PLANE55 elements in the thermal analysis, while axisymmetric PLANE182 elements are used in the stress analysis. The weld bead depositions are simulated using the element "birth and death" feature in ANSYS. The element "birth and death" feature in ANSYS allows for the deactivation (death) and reactivation (birth) of the elements' stiffness contribution when necessary. It is used such that elements that have no contribution to a particular phase of the weld simulation process are deactivated (via EKILL command) because they have not been deposited. The deactivated elements have near-zero conductivity and stiffness contribution to the structure. When those elements are required in a later phase, they are then reactivated (via EALIVE command). The analyses consist of a thermal pass to determine the temperature distribution due to the welding process, and an elastic-plastic stress pass to calculate the residual stresses through the thermal history. Appropriate weld heat efficiency along with sufficient cooling time are utilized in the thermal pass to ensure that the temperature between weld layer nuggets meets the required interpass temperature of 350°F for a temper bead weld overlay repair [7] as well as obtain acceptable overall temperature distribution within the finite element model (i.e., peak temperature, sufficient resolution of results, etc.).

During all welding processes, a convection heat transfer coefficient of 5.0 Btu/hr-ft^2-°F at 70°F bulk ambient temperature is applied to simulate an air backed condition at the inside and outside surfaces of the structure.

2.1.5 Residual Stress Results and Radial Displacements

The resulting axial and hoop residual stresses, following the completion of the overlay and cooling to 70°F ambient, for each of the configurations is shown in Figure 2-6 through 2-11. Figures 2-12 and 2-13 are ID surface stress plots for the axial and hoop directions, for each configuration, as a function of distance from the DMW centerline, respectively. Finally, Figure 14 shows the resulting inside surface radial displacement, for each configuration, as a function of distance from the DMW centerline, respectively.

Tables 2-1 through 2-3 tabulate the inside surface residual axial stress, the inside surface residual hoop stress, and the inside surface residual radial displacements at the centerline of the DMW, at the toe of the overlay over the ferritic component and at the toe of the overlay over the stainless component.

Table 2-1
Inside Surface Residual Axial Stress, Post Weld Overlay Repair

WOL Area, in^2	Residual Axial Stress, psi		
	Inside Surface At Toe of Overlay Over Ferritic Component(1)	Inside Surface At Centerline of DMW	Inside Surface At Toe of Overlay Over Stainless Component
500	-22,915	22,146	-17,448
750	-26,232	12,409	-18,212
1000	-27,059	6,061	-18,553

Note:
1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Table 2-2
Inside Surface Residual Hoop Stress, Post Weld Overlay Repair

WOL Area, in²	Residual Hoop Stress, psi		
	Inside Surface At Toe of Overlay Over Ferritic Component(1)	Inside Surface At Centerline of DMW	Inside Surface At Toe of Overlay Over Stainless Component
500	-33,022	-40,201	-30,718
750	-31,426	-47,590	-29,561
1000	-30,100	-51,627	-29,534

Note:
1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Table 2-3
Inside Surface Residual Radial Displacement, Post Weld Overlay Repair

WOL Area, in²	Residual Radial Displacement, inches		
	Inside Surface At Toe of Overlay Over Ferritic Component(1)	Inside Surface At Centerline of DMW	Inside Surface At Toe of Overlay Over Stainless Component
500	-0.013	-0.031	-0.013
750	-0.011	-0.034	-0.012
1000	-0.011	-0.035	-0.012

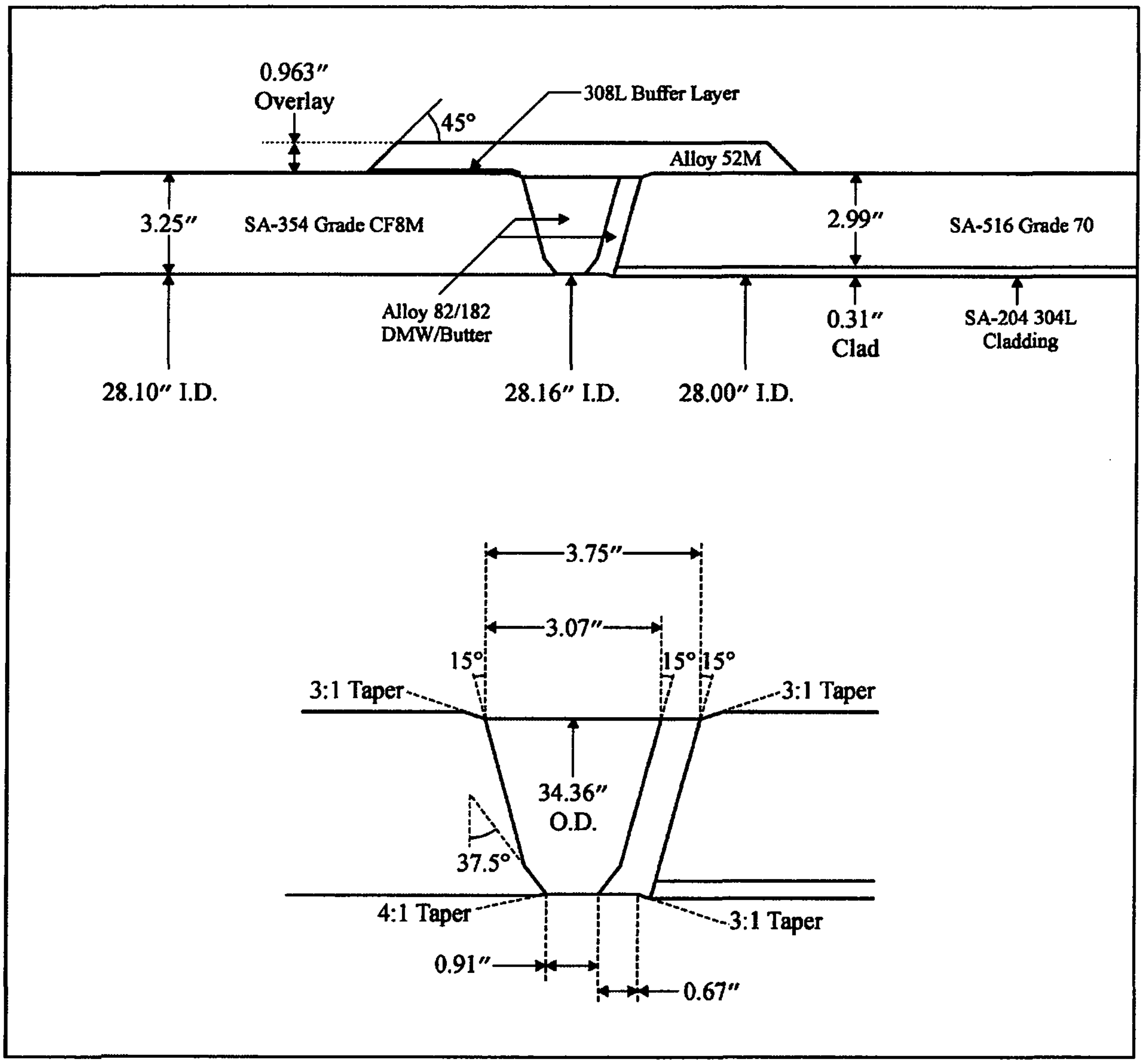
Note:
1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

2.1.6 Conclusions from Initial Temper Bead Surface Area Sensitivity Study

The results provided in Tables 2-1 and 2-2 and in Figures 2-6 through 2-13 show that for each incremental increase in weld overlay size there is a reduction in tensile stress on the inside surface in the region of the DMW, the region susceptible to PWSCC, in both the axial and hoop directions. The same trend is observed for inside surface locations at the axial locations of the WOL toes. However, the hoop stress shows a slightly different trend than the axial stress. The hoop stress on inside surface at the axial location of the WOL toe on the ferritic side shows increasing compressive stress with increasing WOL area. The hoop stress on the inside surface at the axial location of the WOL toes on the stainless side shows approximately the same compressive stress for all three WOL areas. Again, it is noted that the stainless steel information is provided herein for completeness, as stainless steel is not susceptible to PWSCC in the PWR environment.

As expected, the residual radial displacement does increase slightly with weld overlay area increase. However, Table 2-3 and Figure 2-14 indicate that the displacements change is minimal; 0.031 inches at the DMW centerline for the 500 in² configuration to 0.034 inches for the 1000 in² configuration. The variation in residual radial displacement is even less at the toes of the overlay, with the 750 in^2 configuration having essentially identical displacement as the 1000 in^2 configuration.

It is noted that while the indicated results may imply an inadequate residual stress in the region of the DMW at the pipe ID for the axial residual stress, the overlay configurations were not specifically designed to produce a favorable ID residual stress, but only to compare the impact of increased overlay temper bead area on the ferritic component. In the case of an actual repair design, the overlay configuration will be designed to generate the desired residual stresses by modification of the overlay length, thickness or both.



Overlay Shape is for 500 Square In Configuration

Figure 2-1
Weld Overlay Repair Configuration Schematic

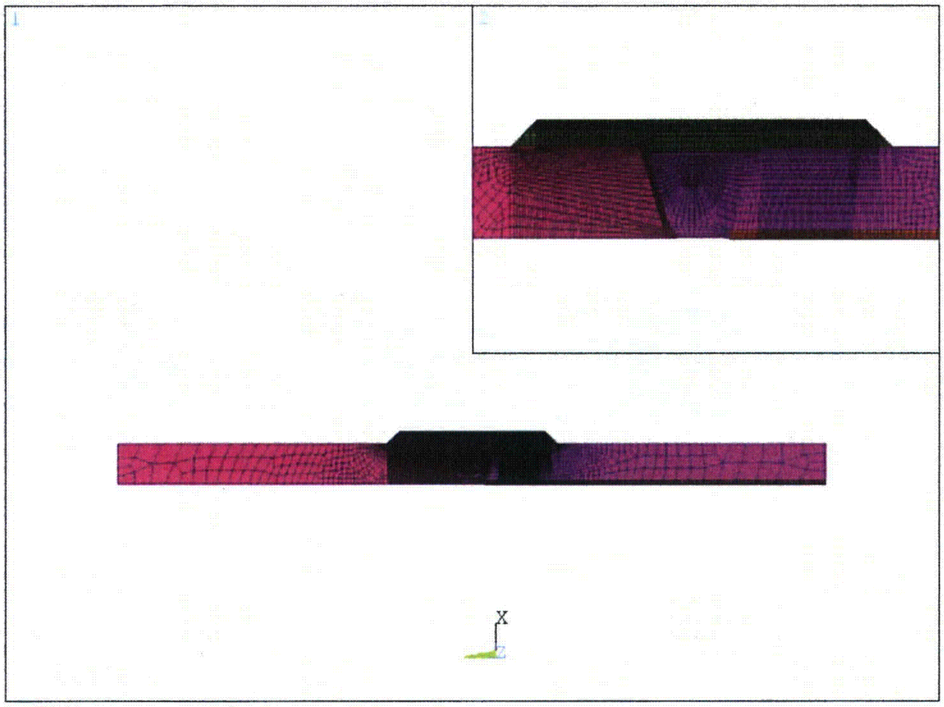


Figure 2-2
Finite Element Model Example (500 in²)

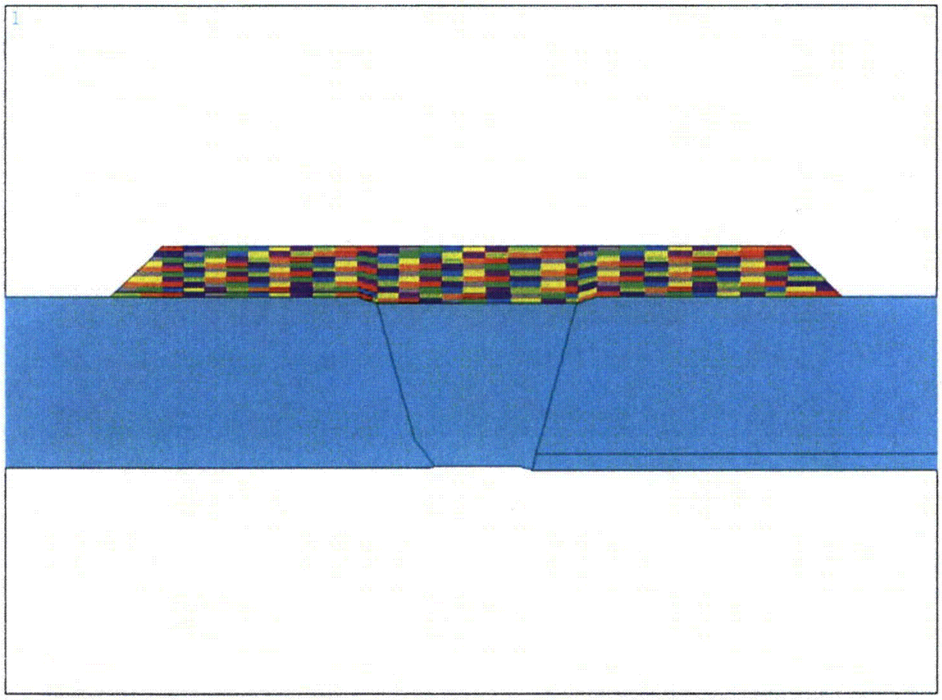


Figure 2-3
Nugget Area Plot for 500 in² Size Weld Overlay Repair (301 Nuggets)

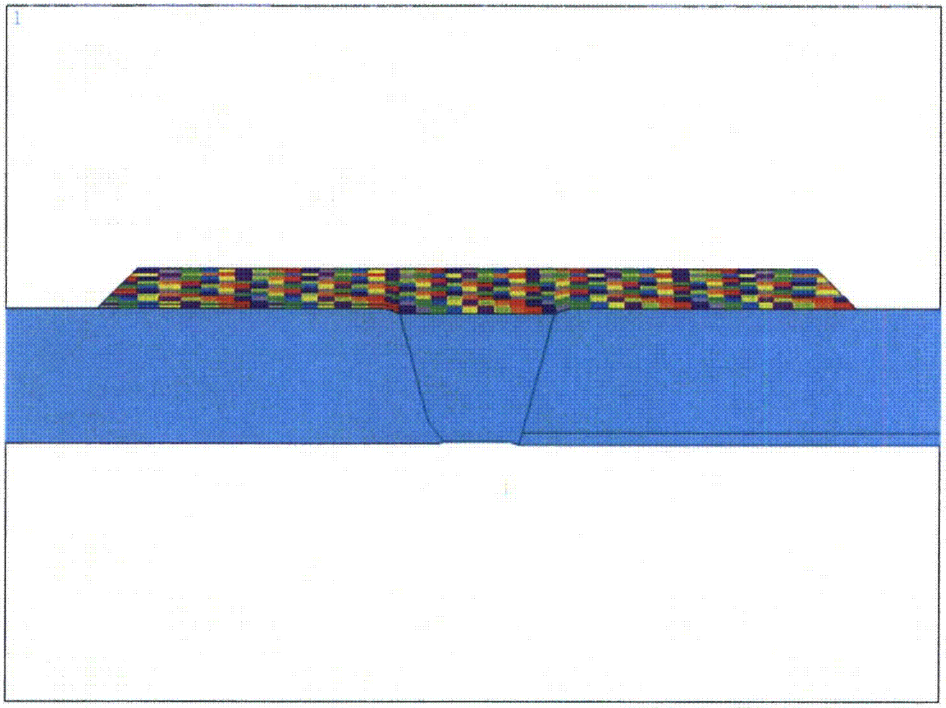


Figure 2-4
Nugget Area Plot for 750 in^2 Size Weld Overlay Repair (422 Nuggets)

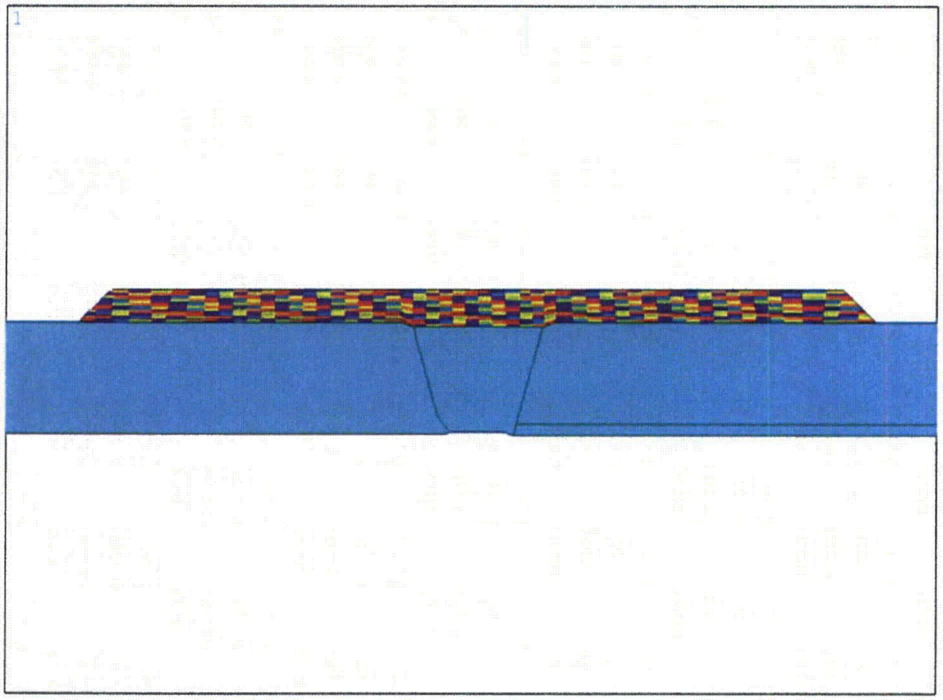


Figure 2-5
Nugget Area Plot for 1000 in^2 Size Weld Overlay Repair (524 Nuggets)

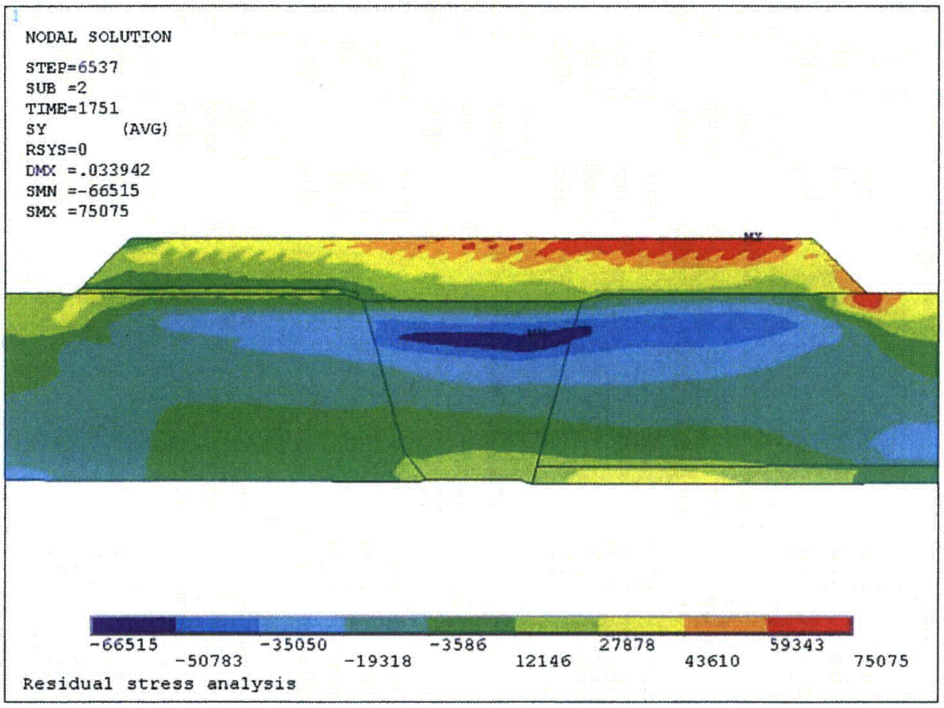


Figure 2-6
Post Weld Overlay Axial Stress at 70°F for 500 in²

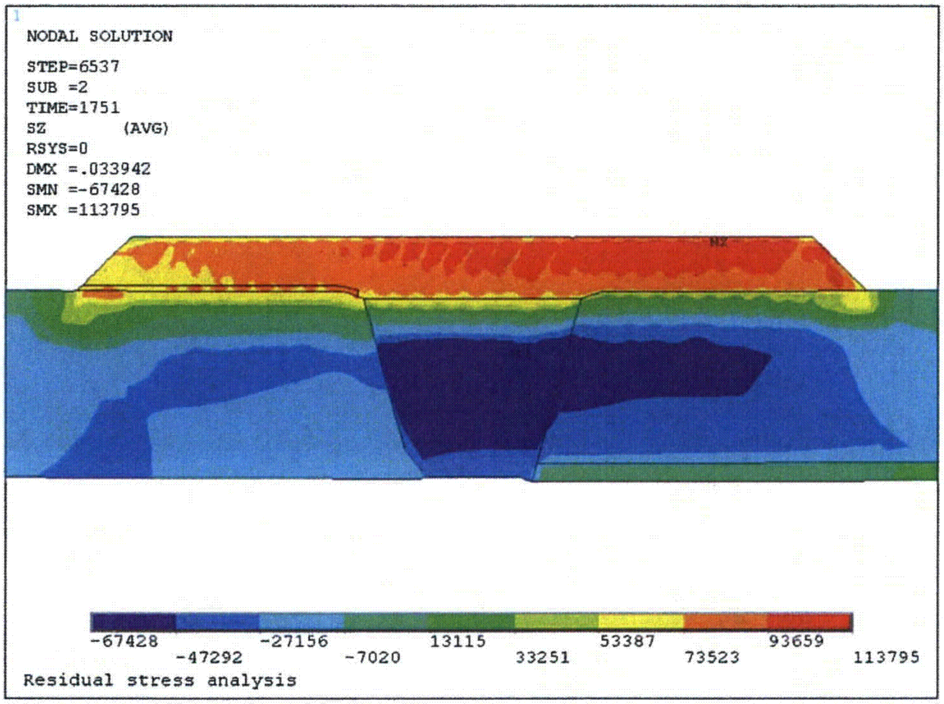


Figure 2-7
Post Weld Overlay Hoop Stress at 70°F for 500 in²

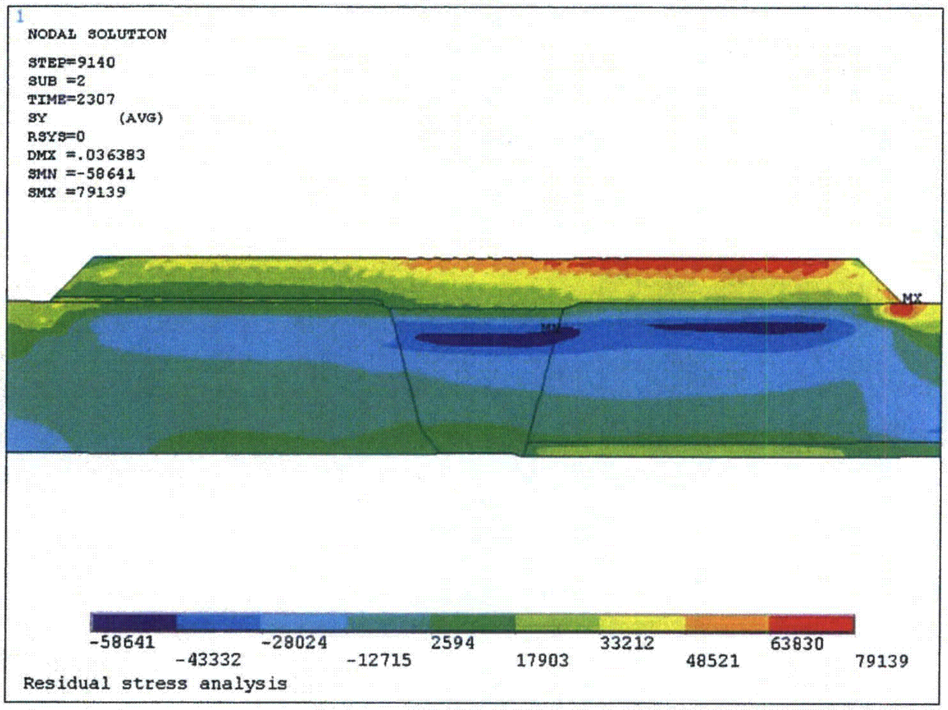


Figure 2-8
Post Weld Overlay Axial Stress at 70°F for 750 in^2

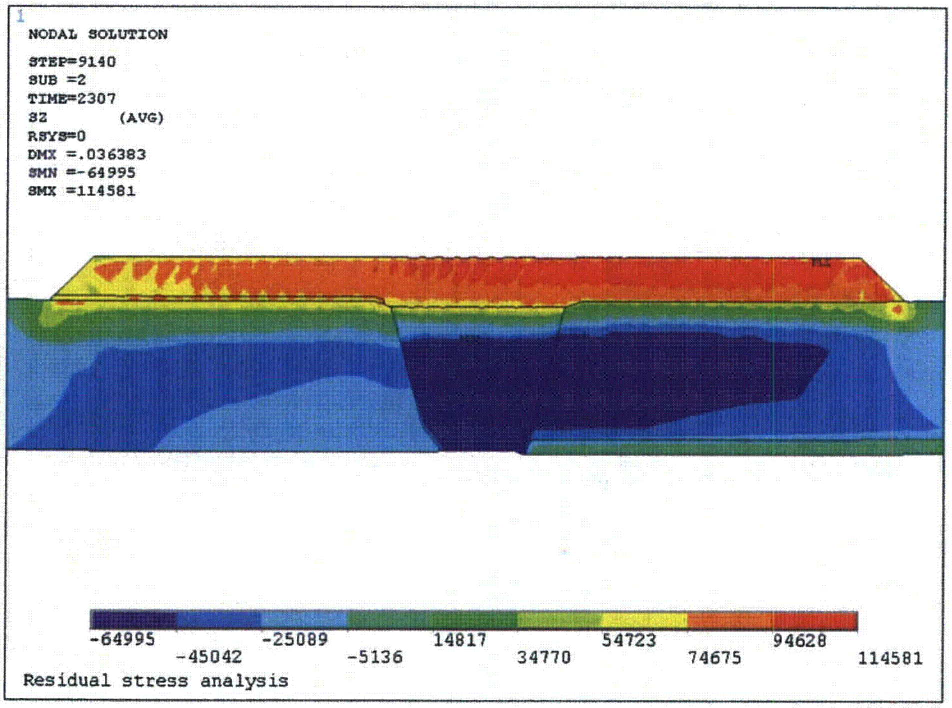


Figure 2-9
Post Weld Overlay Hoop Stress at 70°F for 750 in^2

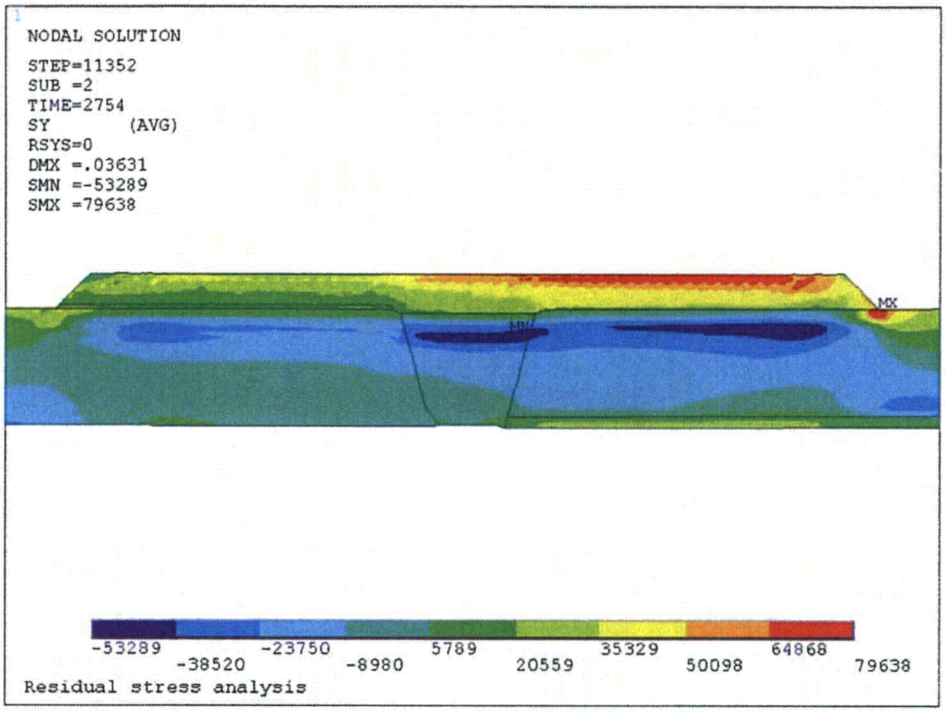


Figure 2-10
Post Weld Overlay Axial Stress at 70°F for 1000 in^2

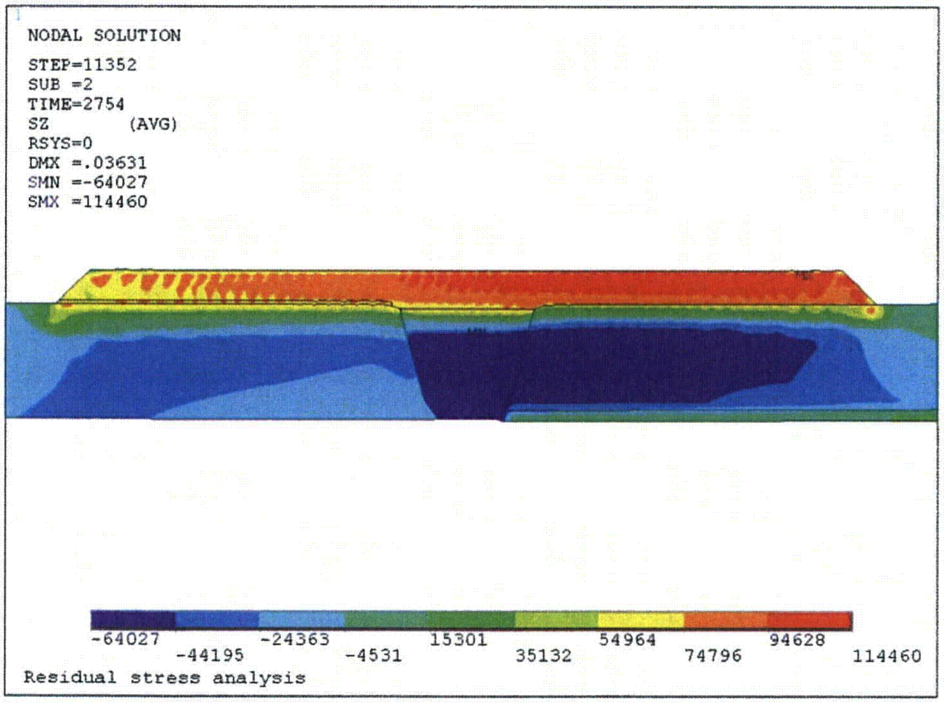
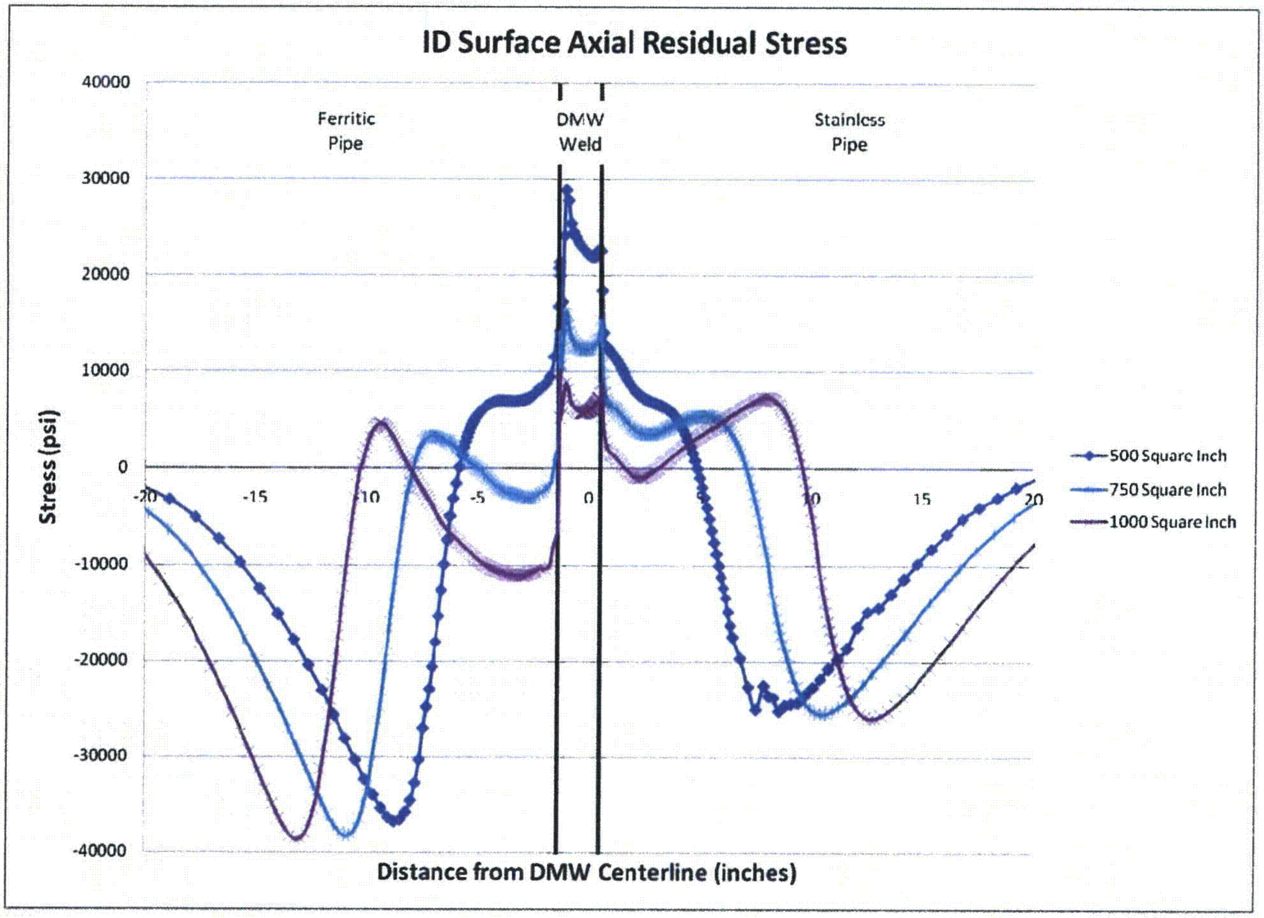
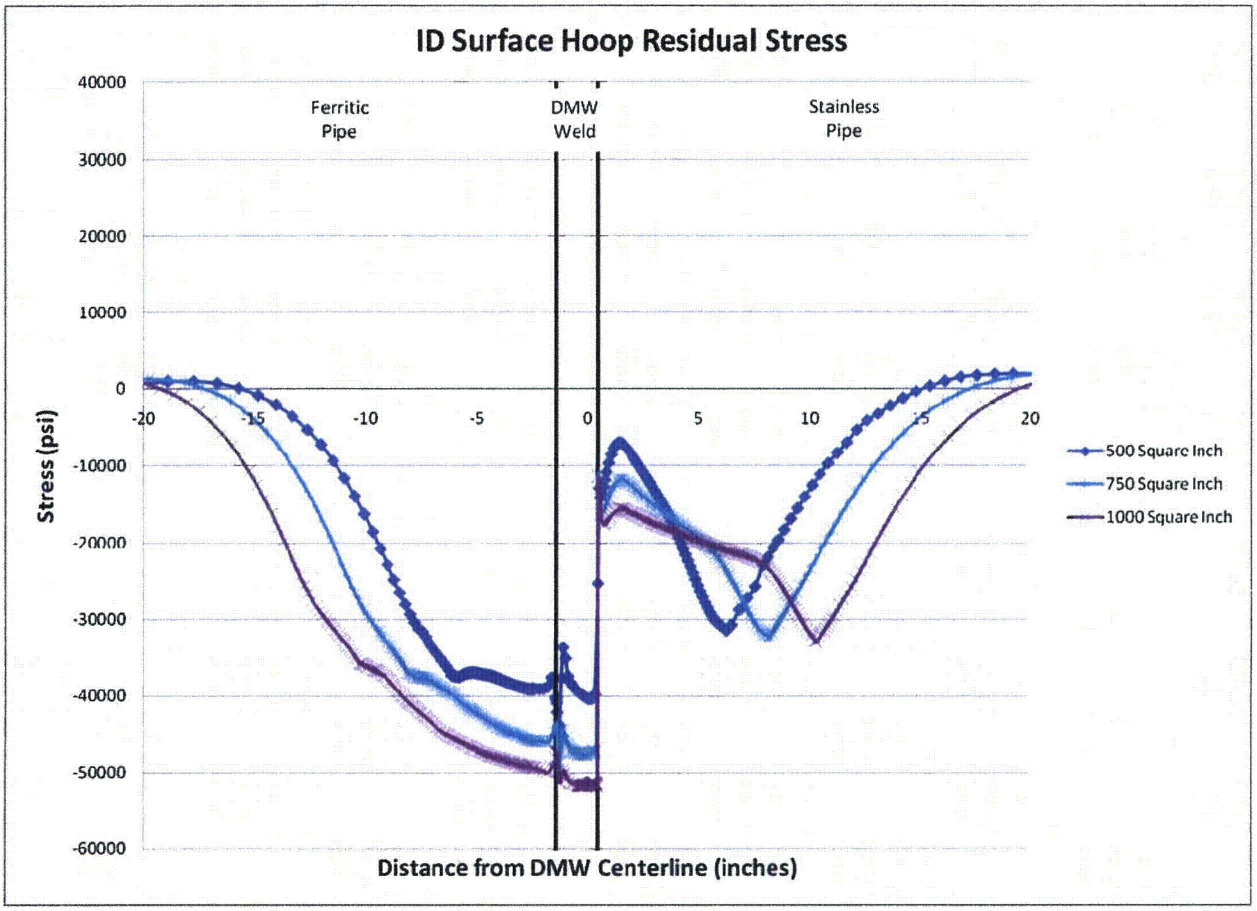


Figure 2-11
Post Weld Overlay Hoop Stress at 70°F for 1000 in^2



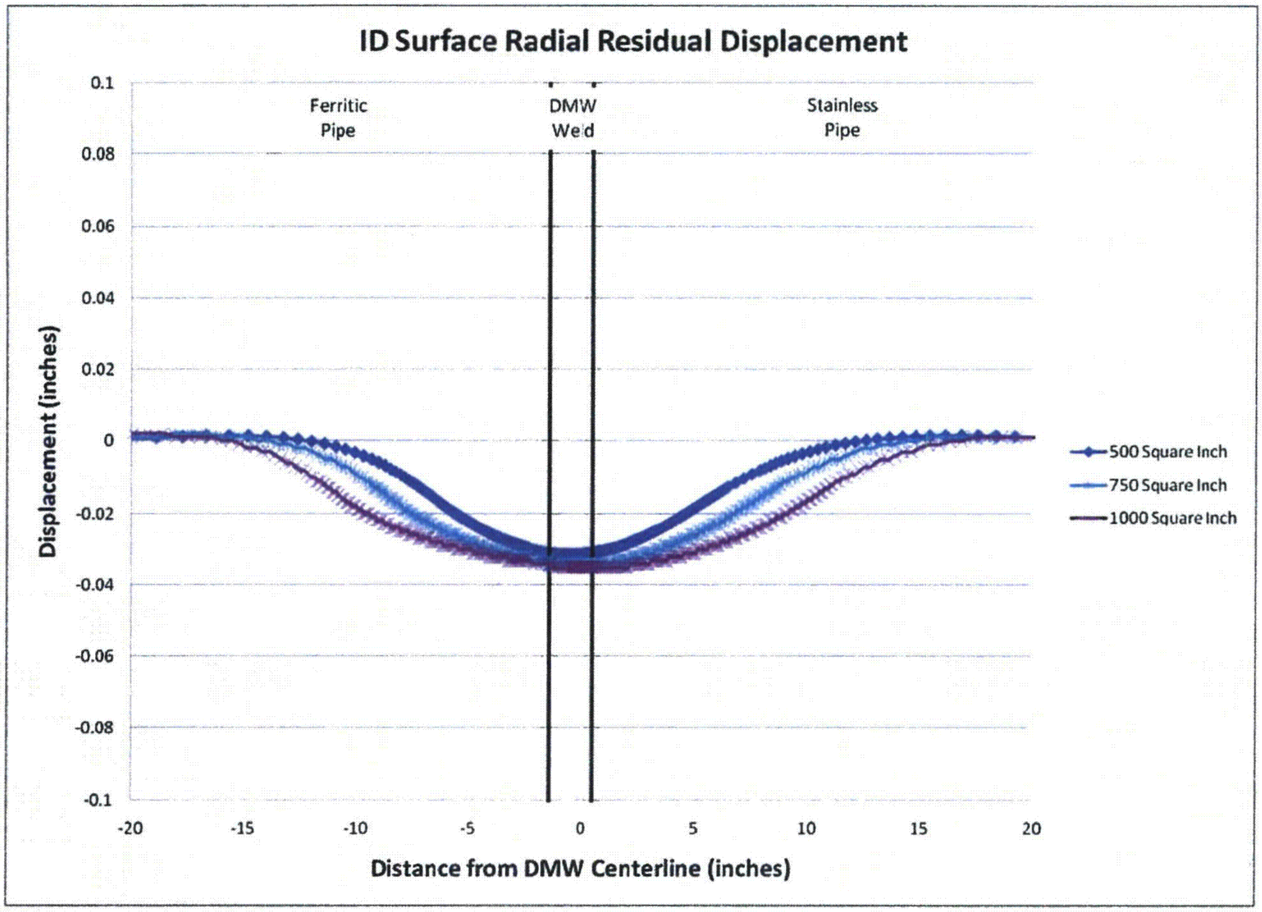
The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding

Figure 2-12
ID Surface Axial Residual Stress



The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding

Figure 2-13
ID Surface Hoop Residual Stress



The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-14
ID Surface Radial Residual Displacement

2.2 Current Temper Bead Surface Area Sensitivity Study

In the current study, the temper bead area for an overlay repair of a ferritic component is compared between the currently allowed 500 in^2 repair and repairs increased to 750 in^2 and 1000 in^2 to ascertain the impact of the increased temper bead overlay area on large bore ferritic piping components and on the DMW, as was the case in the initial study (Section 2.1). However, the approach taken in these analyses are to weld out the DMW first, and allow the component to cool to ambient temperature so as to produce the as-welded residual stresses in the weld. Then an ID weld repair is introduced, in conformance with the guidelines established by the Materials Reliability Program (MRP). The ID repair is a 50% though wall semi-elliptical repair located within the DMW. Details regarding the welding of the original DMW and the introduction of the weld repair are included in Section 2.2.5.

As is the case for the initial temper bead surface area sensitivity study reported in Section 2.1, three separate analyses (one for each repair size) were performed. These analyses serve as sensitivity studies for justifying the increase of the temper bead weld overlay repair area of large bore ferritic piping components up to a repair area of 1000 in^2. The analyses provide the weld residual stress condition on the inside surface at the centerline of an assumed ID weld repair of the DMW, which is the area susceptible to PWSCC. In addition, the residual stress distribution on the inside surface at the toe of the overlay on the ferritic and stainless steel sides of the overlay for the three different temper bead weld overlay areas are evaluated. Furthermore, the radial and axial displacements associated with the weld overlay repair applications on the inside surface of the components beneath the overlay are presented.

As noted in Section 2.1 above, these analyses are relevant only to nozzles, pipes and similar cylindrical component welds. Further, the stainless steel pipe is not susceptible to PWSCC. Consequently, the residual stress and shrinkage information associated with the stainless steel component is only provided for completeness.

The same residual stress analysis methods are applied to the 500, 750 and 1000 in^2 weld overlay repairs. The three configurations are identical, except for the axial length of the weld overlay repair, which is increased to achieve the desired coverage area over the ferritic component. The finite element model meshing characteristics are also essentially identical for all three configurations.

2.2.1 Configuration Summary, Assumptions and Design Inputs

The configuration, assumptions and design inputs for these analyses are as were used in the initial study, described in Section 2.1.1 except for the modeling of the welding out of the DMW and the introduction of an ID repair, following the DMW welding and prior to the application of the WOL. As a result of the introduction of the ID repair, the configuration and geometry for a this weld overlay repair differs from that in Figure 2-1, and is shown in Figure 2-15.

The DMW weld-out is simulated with approximately 20 layers, resulting in approximately 120 nuggets. The ID weld repair, included in the evaluations to conform with the guidelines established by the Materials Reliability Program (MRP), is modeled as a 50% though wall semi-elliptical repair whose dimensions are assumed to be 1.55 inches through the thickness (50% through wall repair) and 1.04 inches wide at the ID surface. The repair is located within the DMW. The ID weld repair simulation is performed using 10 layers, each of which is approximately 0.15 inches thick, resulting in approximately 19 nuggets. The ID weld repair size and shape are identical for all three weld overlay repairs.

The dimensions and materials are typical for PWR large bore pipes used on the cold leg and hot leg sides of the reactor coolant system. An example of the finite element model, for the 750 in^2 weld overlay repair case including the welding of the DMW and including the ID repair is presented in Figure 2-16.

2.2.2 Weld Bead Simulation

In order to reduce computational time, individual weld beads or passes are lumped together into weld nuggets. This methodology is based on the approach presented in References 4, 5, 6 and 7.

The number of equivalent bead passes is estimated by dividing each nugget area by the area of an individual bead. The resulting number of equivalent bead passes per nugget is used as a multiplier to the heat generation rate. The welding direction for the overlay repair is defined to be from the ferritic pipe to the stainless pipe. A plot of nuggets for the weld overlay, DMW, and ID repairs are shown in Figures 2-17, 2-18 and 2-19. The DMW and ID repair welds are modeled as described in Section 2.2.1.

The ID weld repair size and shape are identical for all three weld overlay repairs. All three weld overlay repairs (including the stainless buffer layer) are performed using 10 layers, each of which is approximately 0.1 inches thick. The number of nuggets increases for each configuration due to the added length of the overlay. As a result, the 500 in^2 repair contains 292 nuggets, the 750 in^2 repair contains 422 nuggets and the 1000 in^2 repair contains 521 nuggets.

2.2.3 Welding Simulation

The welding simulation process was performed as described in Section 2.1.4. However, since the process for this evaluation program involved the effects of the original DMW weld out and the modeling of the ID repair, the process is repeated here.

The welding simulation is basically a two step process within the ANSYS finite element software package [8]. In the first step, time dependent thermal loads are applied and temperature gradients are solved for many points in time for the welding process. This sequence of temperature history is then used in the stress analysis step to calculate residual stresses resulting from the welding process.

The DMW weld out is performed first, after which the structure is allowed to cool to an ambient temperature of 70°F. A steady state evaluation is then performed with the ID repair material removed in order to simulate the revised residual stress condition following the grind process to remove the repair region material.

The ID weld repair is then performed, after which the structure is allowed to cool to an ambient temperature of 70°F. The stainless steel buffer layer is then applied, and the structure again allowed to cool to an ambient temperature of 70°F. The remainder of the weld overlay repair simulation is then performed. After the weld overlay is completed, the entire structure is again allowed to cool to a uniform ambient temperature of 70°F. Finally, an operating stress condition is evaluated at 2,235 psig operating pressure and 543°F steady state temperature, which are representative operating pressure and temperature loads for large bore piping in PWR reactor coolant systems.

Note, that this evaluation activity has been only designed to compare the effects of the increasing sizes of the overlay on the ferritic component for the temper bead application. This evaluation has not been specifically designed to optimize the effect of the overlay on residual stress, and its effects on PWSCC or other cracking concerns, as would be the case for plant specific WOL designs.

2.2.4 Finite Element Analysis

The finite element analysis was performed using axisymmetric PLANE55 elements in the thermal analysis, while axisymmetric PLANE182 elements are used in the stress analysis. The weld bead depositions are simulated using the element "birth and death" feature in ANSYS. The element "birth and death" feature in ANSYS allows for the deactivation (death) and reactivation (birth) of the elements' stiffness contribution when necessary. It is used such that elements that have no contribution to a particular phase of the weld simulation process are deactivated (via EKILL command) because they have not been deposited. The deactivated elements have near-zero conductivity and stiffness contribution to the structure. When those elements are required in a later phase, they are then reactivated (via EALIVE command). The analyses consist of a thermal pass to determine the temperature distribution due to the welding process, and an elastic-plastic stress pass to calculate the residual stresses through the thermal history. Appropriate weld heat efficiency along with sufficient cooling time are utilized in the thermal pass to ensure that the temperature between weld layer nuggets meets the required interpass temperature of 350°F for a temper bead weld overlay repair [9] as well as obtain acceptable overall temperature distribution within the finite element model (i.e., peak temperature, sufficient resolution of results, etc.).

During all welding processes, a convection heat transfer coefficient of 5.0 Btu/hr-ft^2-°F at 70°F bulk ambient temperature is applied to simulate an air backed condition at the inside and outside surfaces of the structure.

2.2.5 Internal Pressure Loading

A representative operating pressure of 2235 psig is applied to the interior surfaces of the model. An end-cap load is applied to the free end of the attached carbon steel piping in the form of tensile axial pressure, and the value is calculated below. See Figure 2-20 for applied pressure loading example. Axial boundary conditions are applied at the free end of the stainless steel piping and the free end of the attached carbon steel piping is coupled in the axial direction as shown in Figure 2-20, to simulate a long pipe.

$$P_{end\text{-}cap} = \frac{P \cdot r_{inside}^2}{\left(r_{outside}^2 - r_{inside}^2\right)} = \frac{2235 \cdot 14.05^2}{\left(17.3^2 - 14.05^2\right)} = 4330 \text{ psig}$$

where,

$P_{end\text{-}cap}$ = End cap pressure on attached carbon steel piping and cladding (psig)

P = Internal pressure (psig)

r_{inside} = Inside radius of attached carbon steel pipe cladding (in)

$r_{outside}$ = Outside radius of attached carbon steel pipe (in)

2.2.6 Residual Stress Results and Radial Displacements

The resulting axial and hoop residual stresses, following the completion of the overlay and cooling to 70°F ambient, for each of the configurations is shown in Figure 2-21 through 2-26.

The resulting axial and hoop residual stresses, following the completion of the overlay, at a nominal operating pressure of 2235 psig and nominal operating temperature of 543°F, for each of the configurations is shown in Figure 2-27 through 2-32.

Figures 2-33 and 2-34 present ID surface stress plots for the axial and hoop directions, for each configuration at 70°F following the overlay process, as a function of distance from the DMW centerline, respectively. Figure 2-35 shows the correspond inside surface radial displacements for each configuration, as a function of distance from the DMW centerline.

Figures 2-36 and 2-37 are ID surface stress plots for the axial and hoop directions, for each configuration at nominal operating pressure (2235 psig) and temperature (543°F) following the overlay process, as a function of distance from the DMW centerline, respectively. Figure 2-38 shows the corresponding inside surface radial displacements for each configuration, as a function of distance from the DMW centerline.

Tables 2-4 through 2-6 tabulate the inside surface residual axial stress, the inside surface residual hoop stress, and the inside surface residual radial displacements at the centerline of the ID weld repair of the DMW at the 70°F condition following the application of the weld overlay. In addition, the same inside surface results are documented for the toe of the overlay over the ferritic component and for the toe of the overlay over the stainless component.

Tables 2-7 through 2-9 tabulate the same results for the same locations, but do so at nominal operating pressure (2235 psi) and temperature (543°F) following the application of the weld overlay repair

Table 2-4
Inside Surface Residual Axial Stress, Post-WOL at 70°F

WOL Area, in²	Residual Axial Stress, psi		
	Inside Surface At Toe of Overlay Over Ferritic Component(1)	Inside Surface At Centerline of ID Repair	Inside Surface At Toe of Overlay Over Stainless Component
500	-12,005	-8,072	-17,597
750	-14,473	-17,980	-22,712
1000	-13,952	-25,040	-24,363

Note:
1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Table 2-5
Inside Surface Residual Hoop Stress, Post-WOL at 70°F

WOL Area, in²	Residual Hoop Stress, psi		
	Inside Surface At Toe of Overlay Over Ferritic Component(1)	Inside Surface At Centerline of ID Repair	Inside Surface At Toe of Overlay Over Stainless Component
500	-17,060	-16,991	-31,246
750	-13,050	-29,703	-30,813
1000	-10,876	-36,513	-31,024

Note:
1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Table 2-6
Inside Surface Residual Radial Displacement, Post-WOL at 70°F

WOL Area, in²	Residual Radial Displacement, inches		
	Inside Surface At Toe of Overlay Over Ferritic Component(1)	Inside Surface At Centerline of ID Repair	Inside Surface At Toe of Overlay Over Stainless Component
500	-0.022	-0.117	-0.028
750	-0.016	-0.119	-0.022
1000	-0.012	-0.124	-0.019

Note:
1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Table 2-7
Inside Surface Residual Axial Stress, Post-WOL at Operating Conditions

WOL Area, in²	Residual Axial Stress, psi		
	Inside Surface At Toe of Overlay Over Ferritic Component[(1)]	Inside Surface At Centerline of ID Repair	Inside Surface At Toe of Overlay Over Stainless Component
500	-18,789	-18,841	-21,417
750	-22,297	-29,259	-26,977
1000	-22,644	-36,419	-28,147

Notes:

1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.
2. Nominal operating conditions are 2,235 psig and 543°F.

Table 2-8
Inside Surface Residual Hoop Stress, Post-WOL at Operating Conditions

WOL Area, in²	Residual Hoop Stress, psi		
	Inside Surface At Toe of Overlay Over Ferritic Component[(1)]	Inside Surface At Centerline of ID Repair	Inside Surface At Toe of Overlay Over Stainless Component
500	-20,492	558	-26,380
750	-17,777	-12,021	-23,840
1000	-16,303	-18,460	-22,396

Notes:

1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.
2. Nominal operating conditions are 2,235 psig and 543°F.

Table 2-9
Inside Surface Residual Radial Displacement, Post-WOL at Operating Conditions

WOL Area, in²	Residual Radial Displacement, inches		
	Inside Surface At Toe of Overlay Over Ferritic Component[(1)]	Inside Surface At Centerline of ID Repair	Inside Surface At Toe of Overlay Over Stainless Component
500	0.035	-0.056	0.040
750	0.041	-0.059	0.046
1000	0.044	-0.064	0.051

Notes:

1. The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.
2. Nominal operating conditions are 2,235 psig and 543°F.

2.2.7 Conclusions from Current Temper Bead Surface Area Sensitivity Study

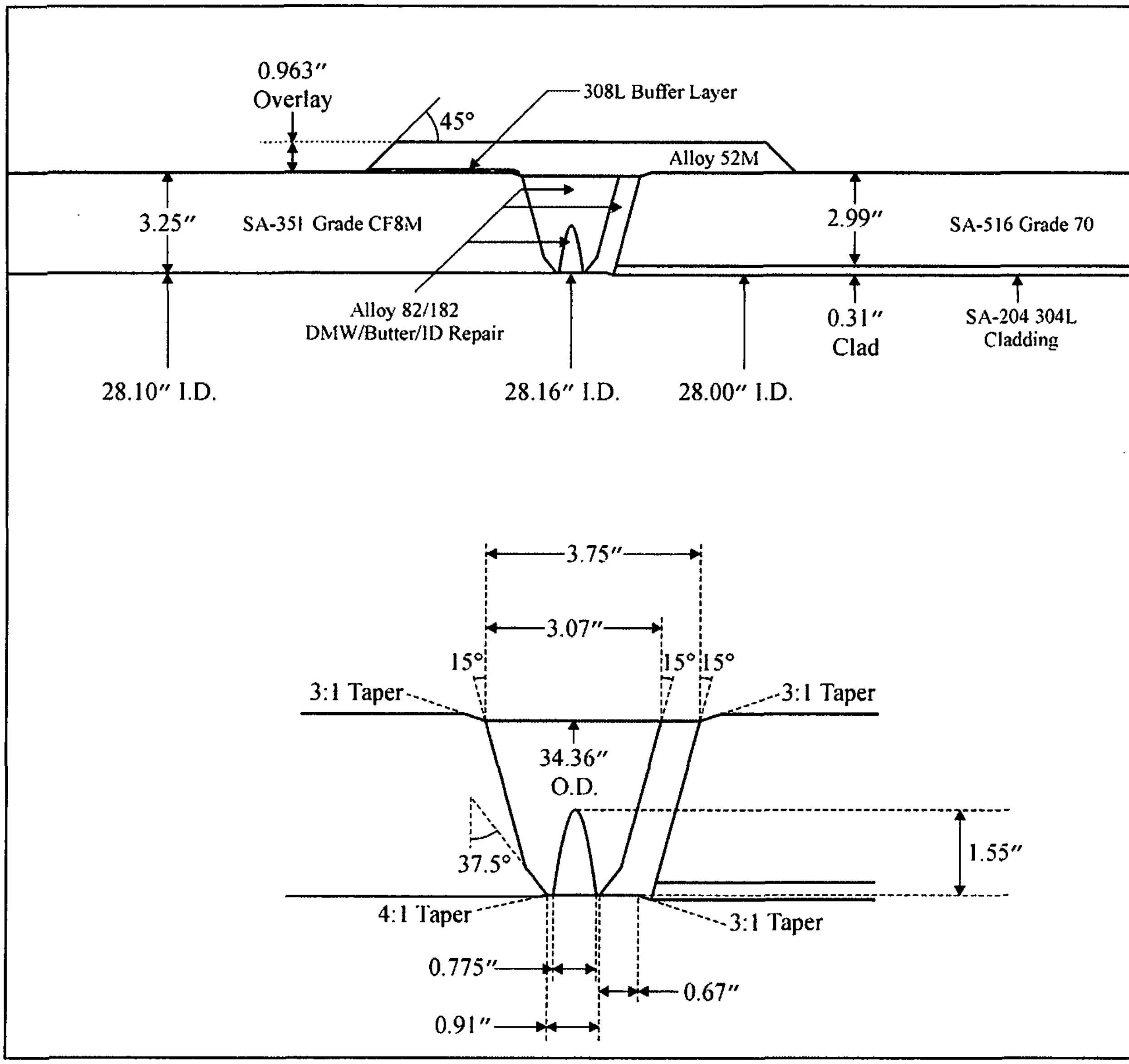
The results of the analyses provided in Tables 2-4, 2-5, 2-7 and 2.8 (see Figures 2-33, 2-34, 2-36 and 2-37) show that for each incremental increase in weld overlay size there is a reduction in tensile stress on the inside surface in the region of the DMW/ID repair in both the axial and hoop directions.

The axial and hoop stresses at the ID surface at the toes of the weld overlay repair vary with weld overlay size. However, this variation is not consistent. The axial stress at the ferritic location remains relatively constant, where as the stainless side becomes more compressive. The hoop stress at the ferritic location becomes less compressive, where as the stainless side remains relatively constant. These variations are not unexpected nor are they particularly significant given that the magnitudes do not vary significantly. Again, it is noted that the stainless steel information is provided herein for completeness, as stainless steel is not susceptible to PWSCC in the PWR environment and does not require the temper bead weld process.

As expected, the residual radial displacement does increase with weld overlay area increase. However, Tables 2.6 and 2.9 (see Figures 2-35 and 2-38) indicate that the displacements changes are minimal; -0.117 inches at the DMW/ID repair centerline for the 500 in² configuration to -0.124 inches for the 1000 in² configuration at 70°F. The variation in residual radial displacement is equally small at the toes of the overlay, though the variation is in the opposite direction (-0.022 inches at the ferritic toe for the 500 in² temper bead area, compared to -0.012 inches for the 1000 in² temper bead area at 70°F).

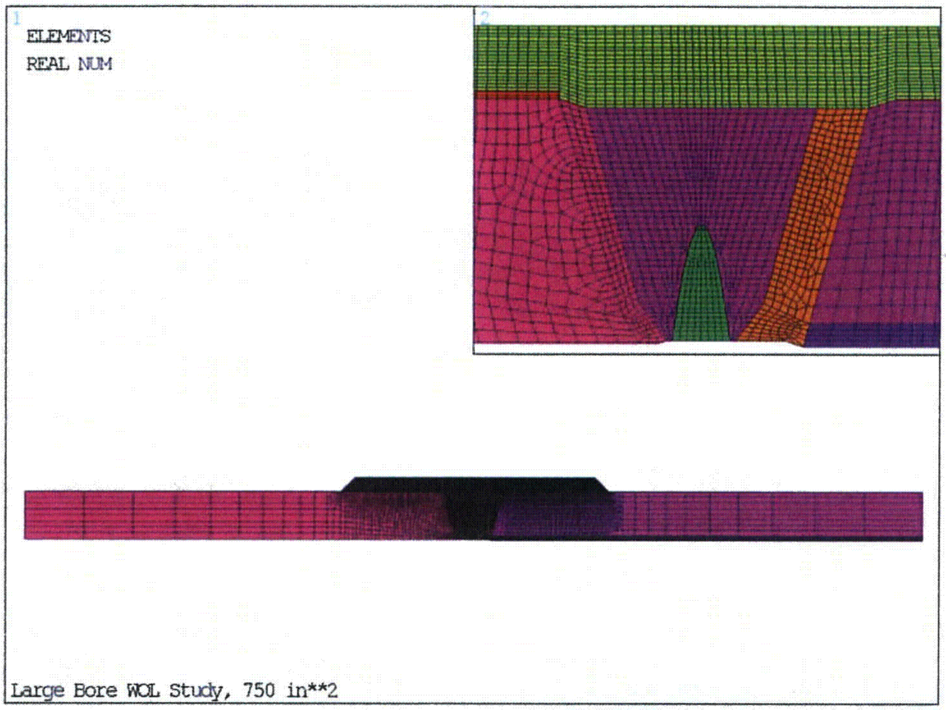
It should be noted again that these analyses are not intended to specifically address residual stress and its impact on Primary Water Stress Corrosion Cracking (PWSCC). While the results presented herein may imply an inadequate residual stress in the region of the DMW, the overlay configurations were not specifically designed to produce a favorable ID residual stress, but only to compare the impact of increased overlay temper bead area on the ferritic component. In the case of an actual repair design, the overlay configuration would be designed to generate the desired residual stresses.

In conclusion, the results of this investigation demonstrate that increasing the area of the temper bead WOL area over the ferritic material does indeed improve the ID residual stresses in the DMW and reduce the likelihood for new PWSCC initiation following the application of the overlay. The residual stresses that developed and radial variations that resulted between the 500 in², 750 in² and 1000 in² temper bead repairs were consistent with expectations and produced no unexpected or unacceptable results that would preclude the use of the temper bead process for weld overlays up to and beyond 1000 in². In fact, the residual stress results illustrate that at the DMW, on the inside surface of the component, the axial and hoop residual stresses are improved as the weld overlay area is increased over the ferritic component.



500 in² Configuration is shown

Figure 2-15
Weld Overlay Repair Configuration Schematic



750 in² Configuration is Shown

Figure 2-16
Finite Element Model Example

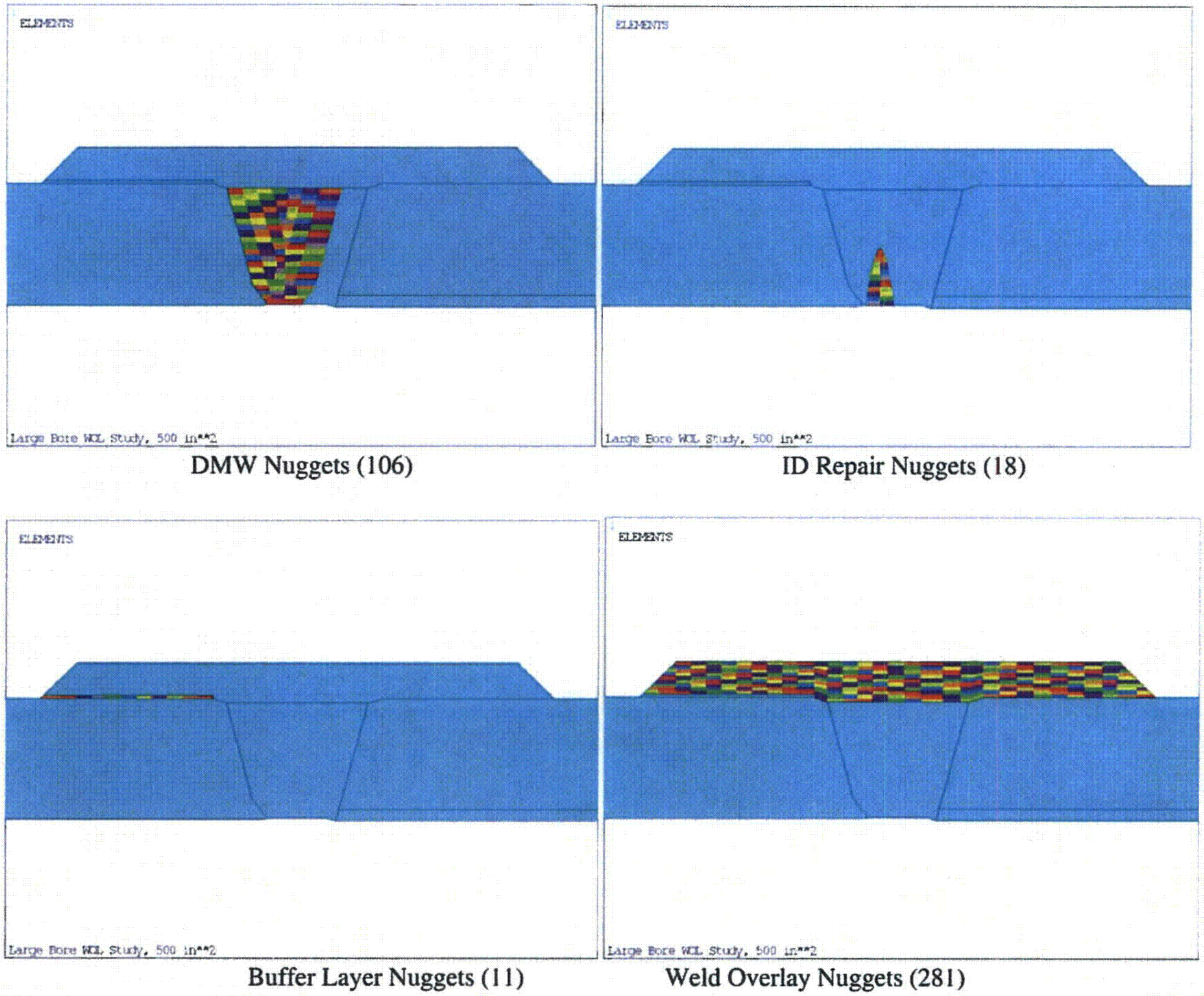


Figure 2-17
Nugget Definitions for 500 in² Size Weld Overlay

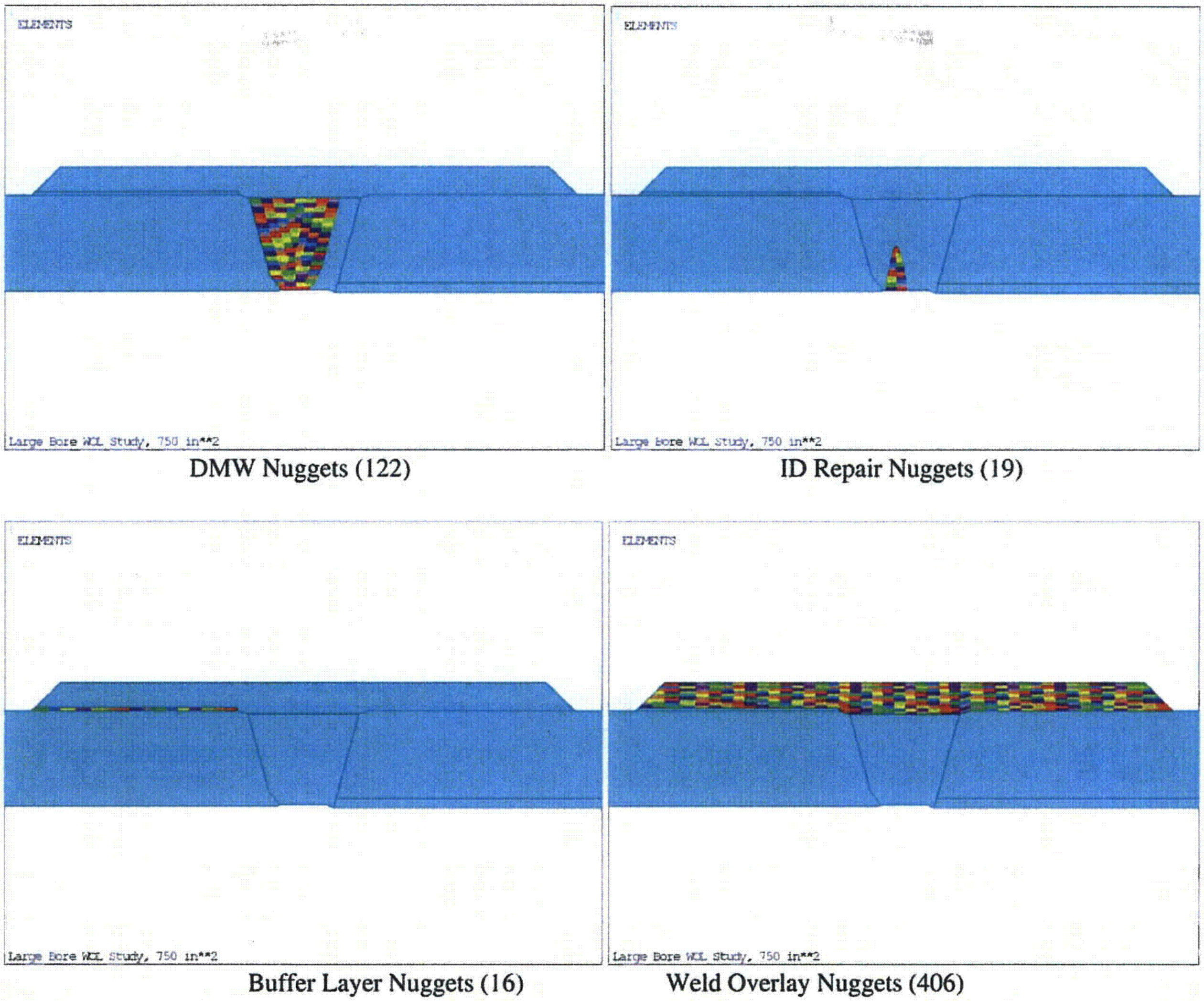
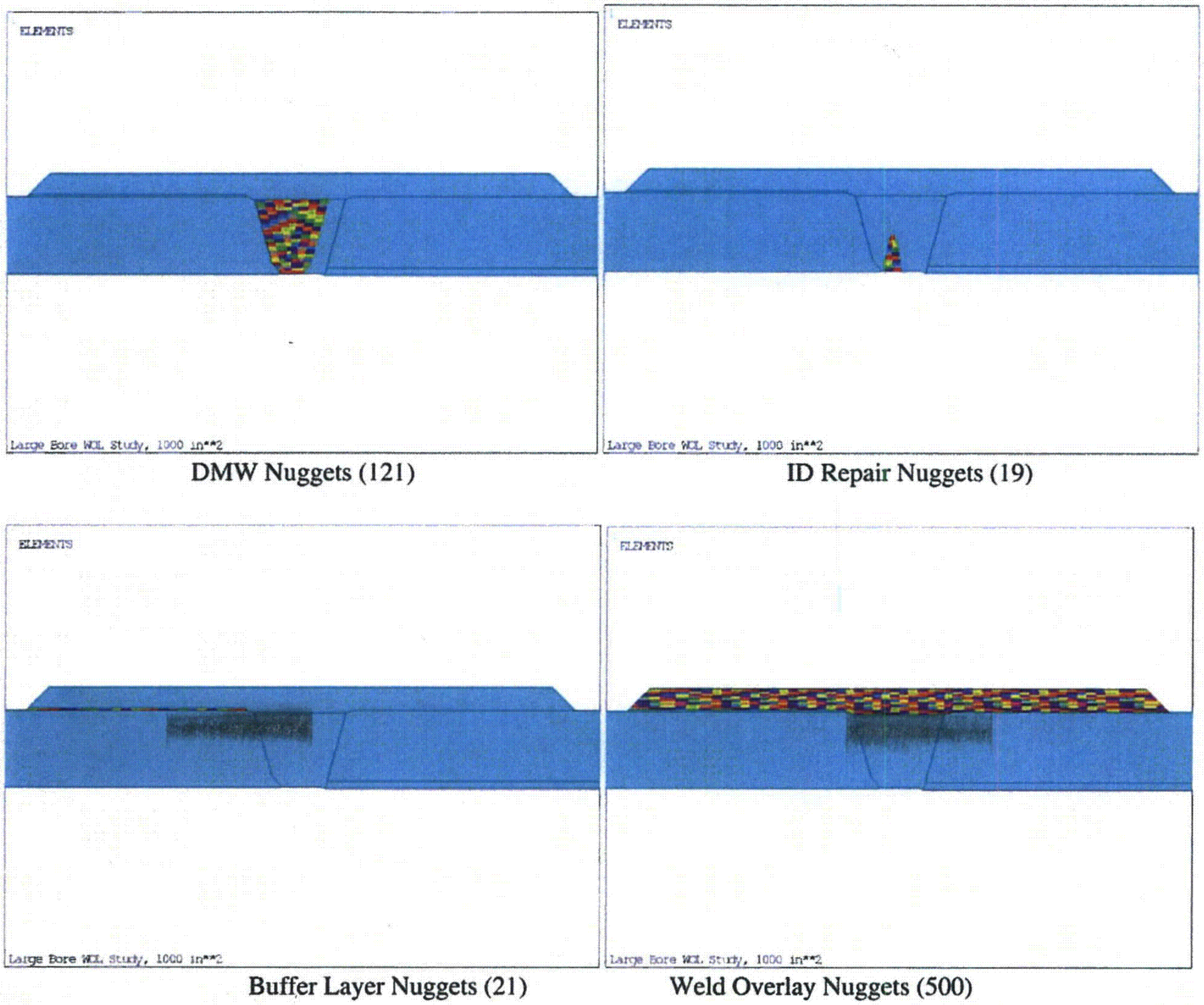


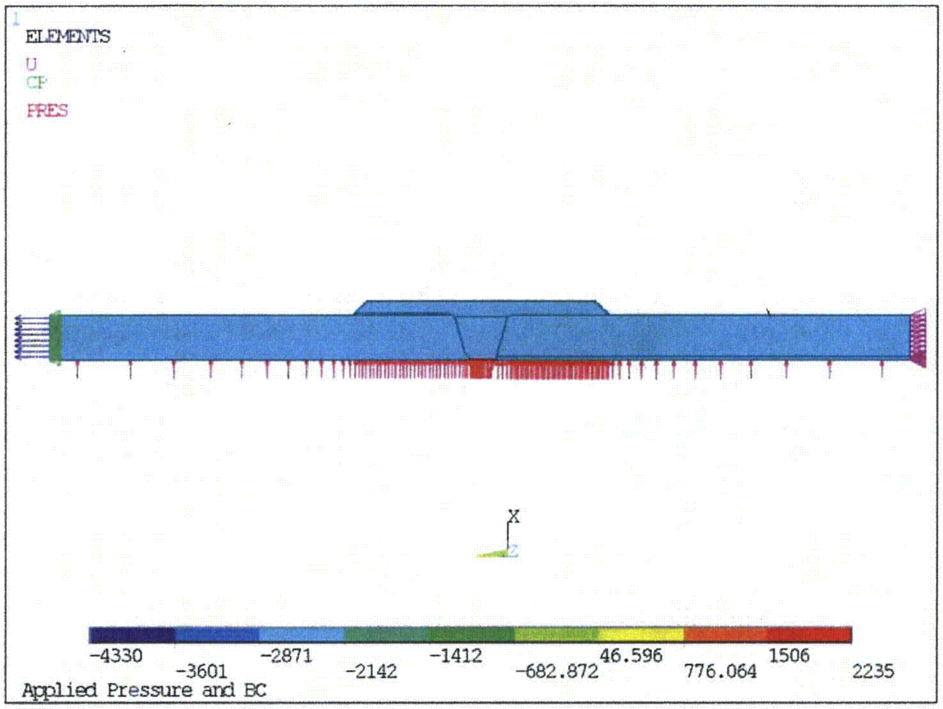
Figure 2-18
Nugget Definitions for 750 in² Size Weld Overlay



DMW Nuggets (121) ID Repair Nuggets (19)

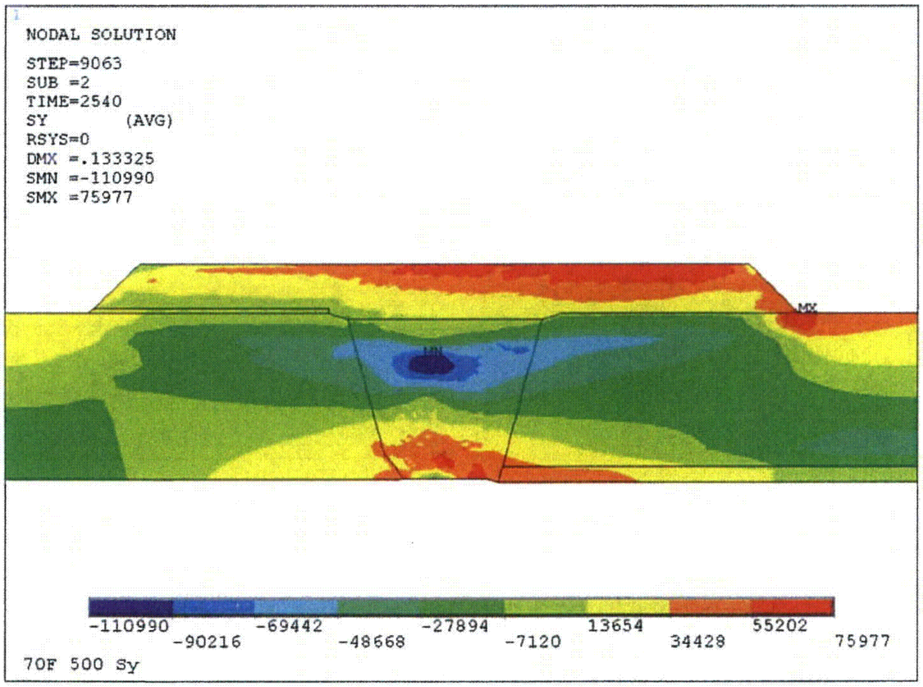
Buffer Layer Nuggets (21) Weld Overlay Nuggets (500)

Figure 2-19
Nugget Definitions for 1000 in² Size Weld Overlay



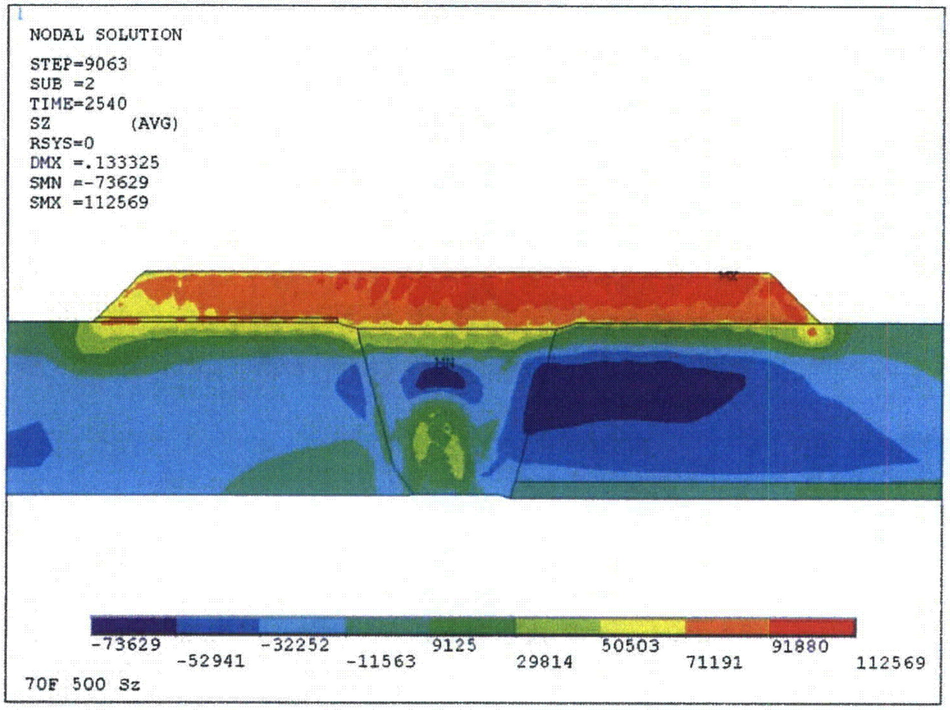
750 in² Configuration is Shown

Figure 2-20
Internal Pressure Loading Example



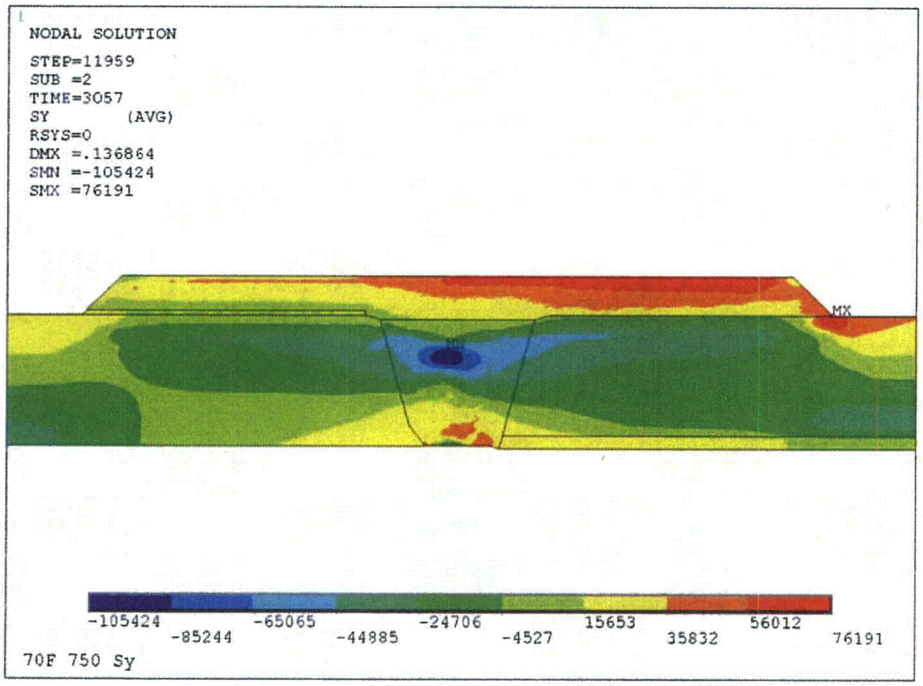
Stress results are in units of psi.

Figure 2-21
Post Weld Overlay Axial Stress at 70°F for 500 in² Configuration



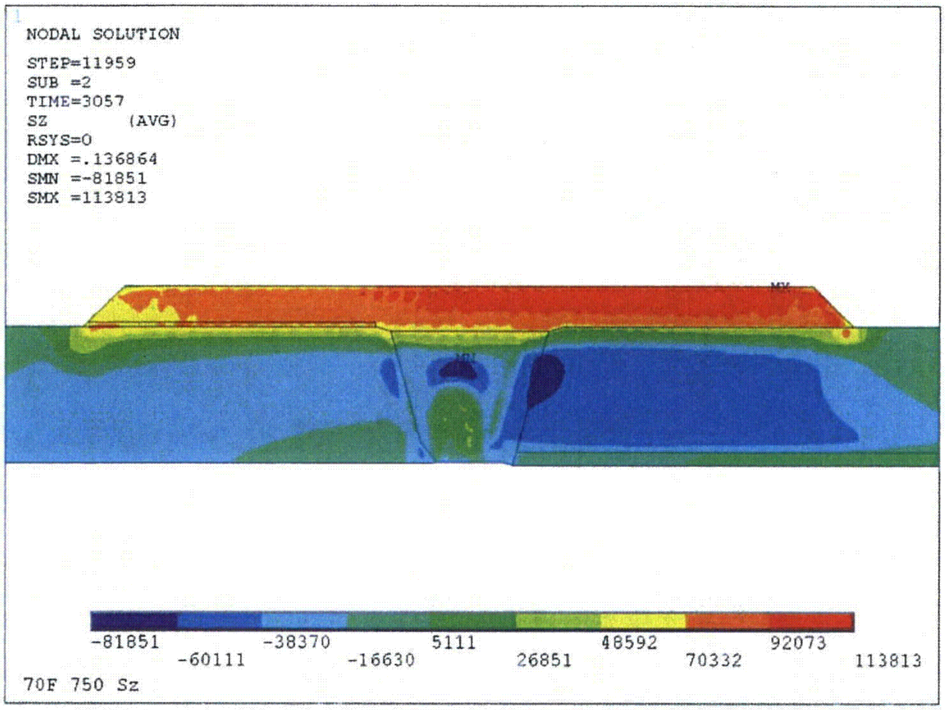
Stress results are in units of psi.

Figure 2-22
Post Weld Overlay Hoop Stress at 70°F for 500 in² Configuration



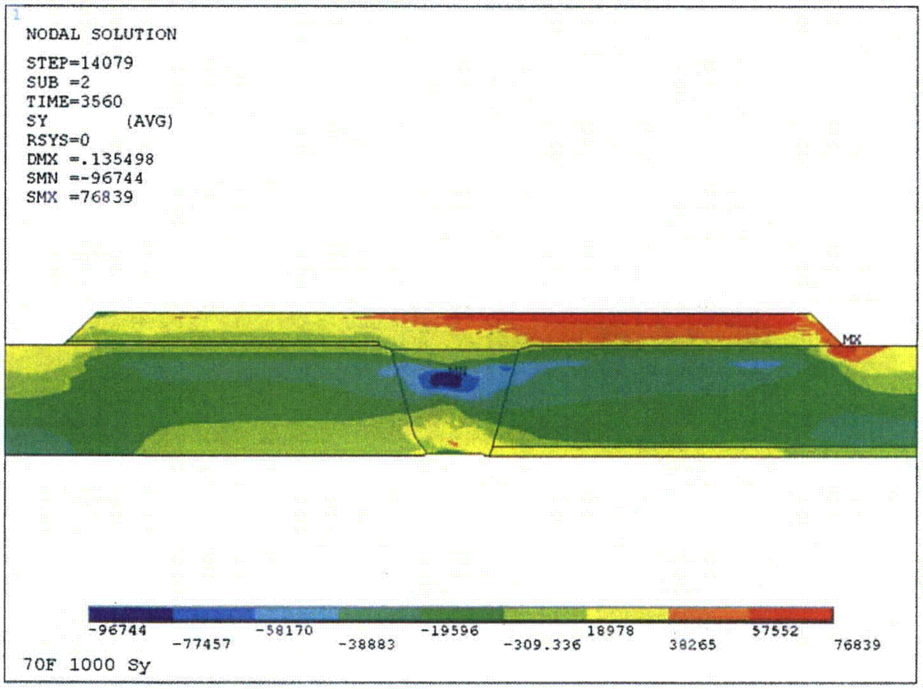
Stress results are in units of psi.

Figure 2-23
Post Weld Overlay Axial Stress at 70°F for 750 in² Configuration



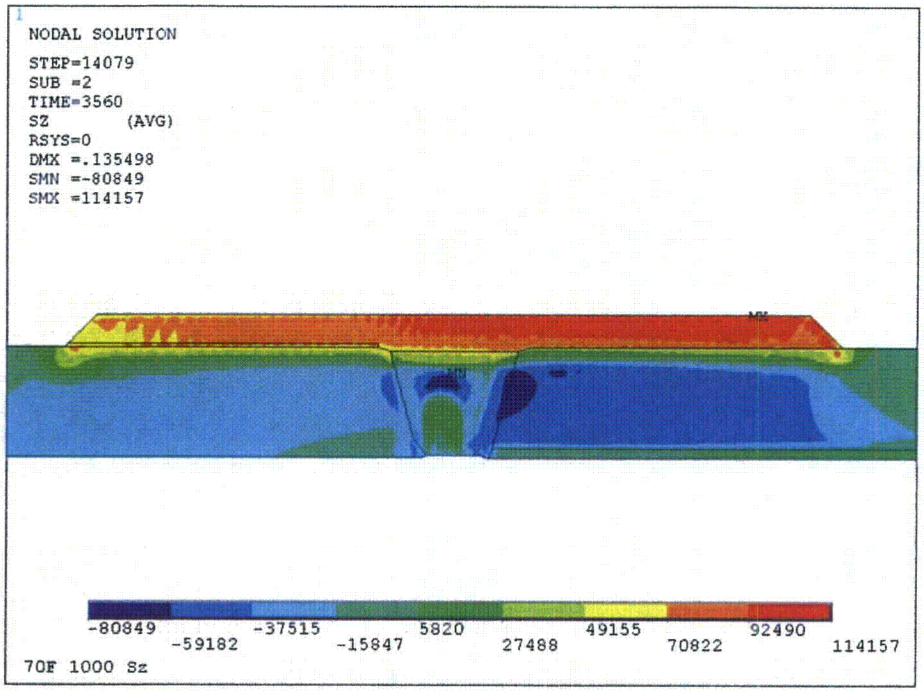
Stress results are in units of psi.

Figure 2-24
Post Weld Overlay Hoop Stress at 70°F for 750 in² Configuration



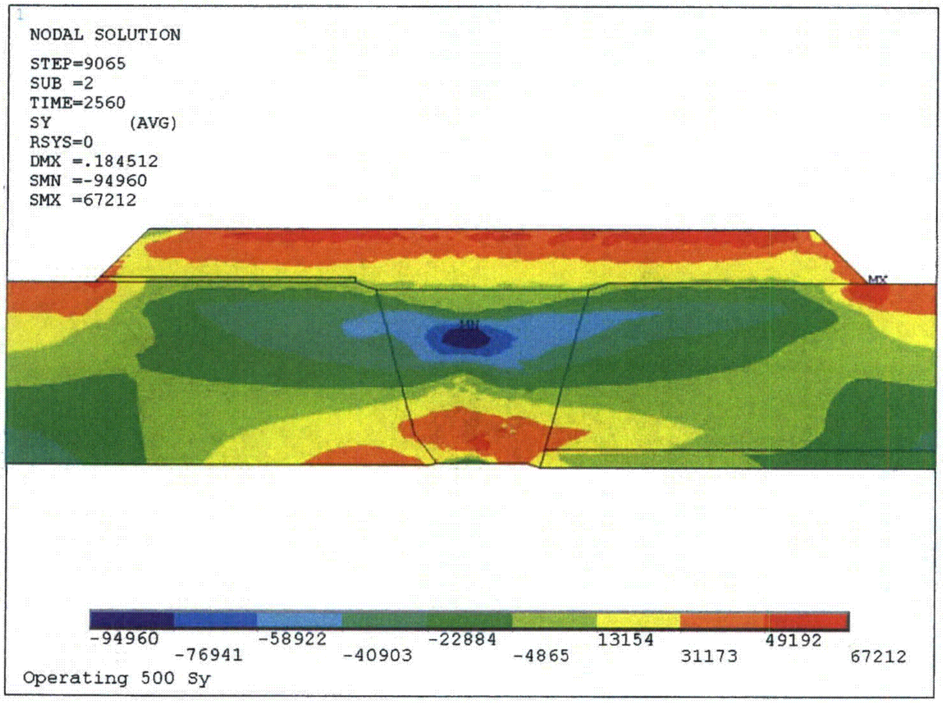
Stress results are in units of psi.

Figure 2-25
Post Weld Overlay Axial Stress at 70°F for 1000 in² Configuration



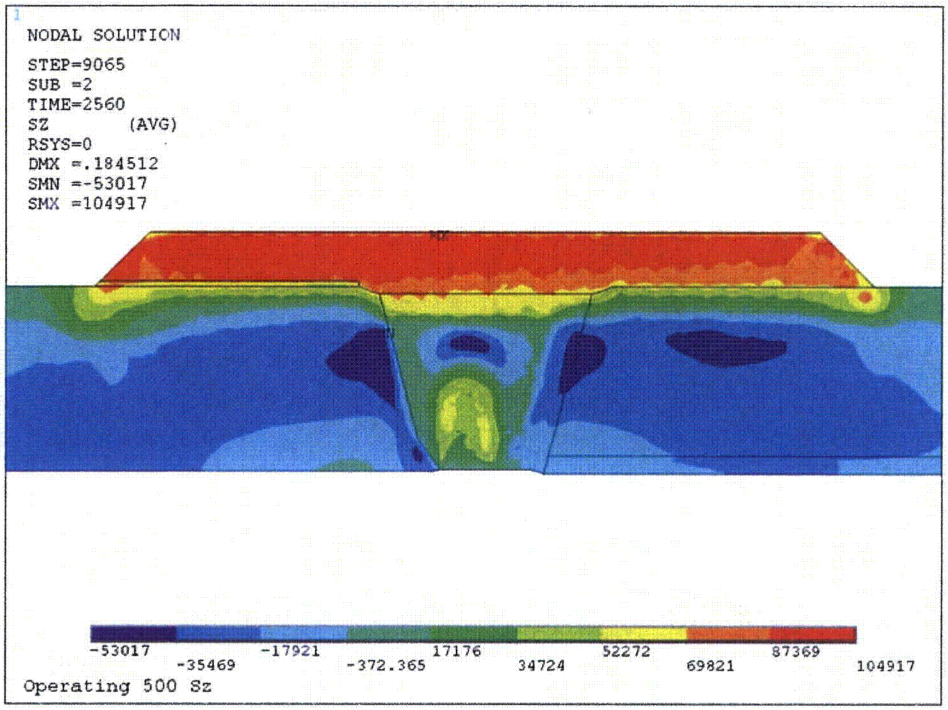
Stress results are in units of psi.

Figure 2-26
Post Weld Overlay Hoop Stress at 70°F for 1000 in² Configuration



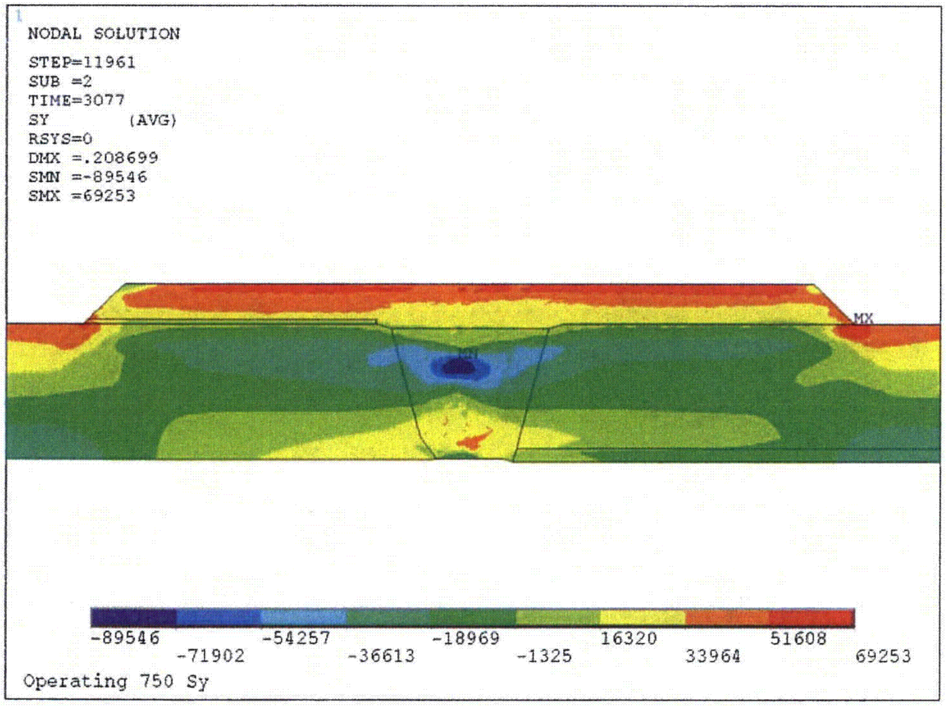
Stress results are in units of psi.

Figure 2-27
Post Weld Overlay Axial Stress at Operating Conditions for 500 in² Configuration



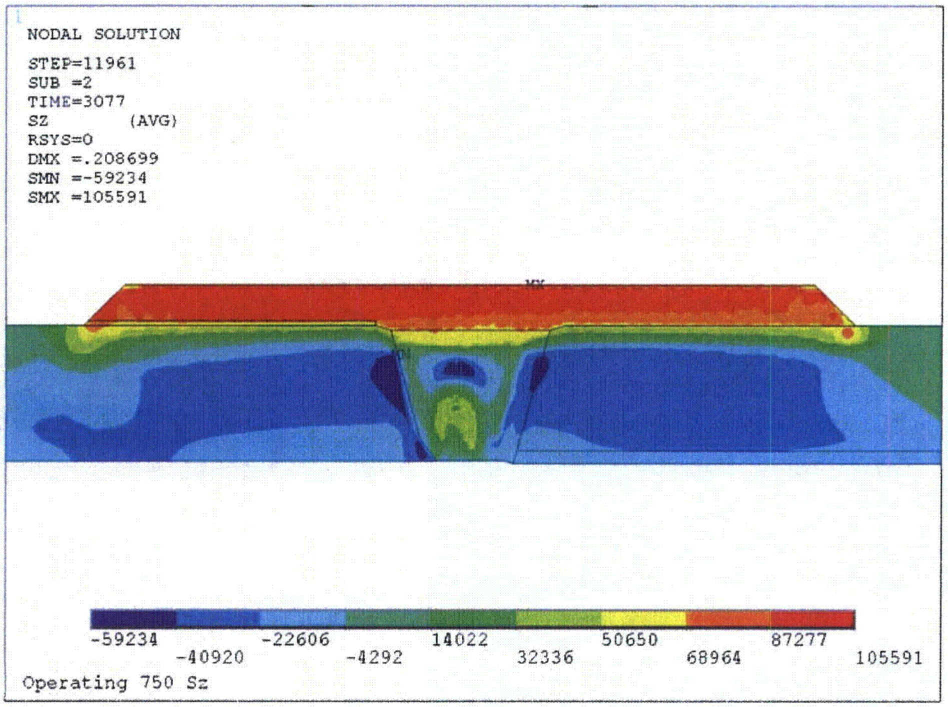
Stress results are in units of psi.

Figure 2-28
Post Weld Overlay Hoop Stress at Operating Conditions for 500 in² Configuration



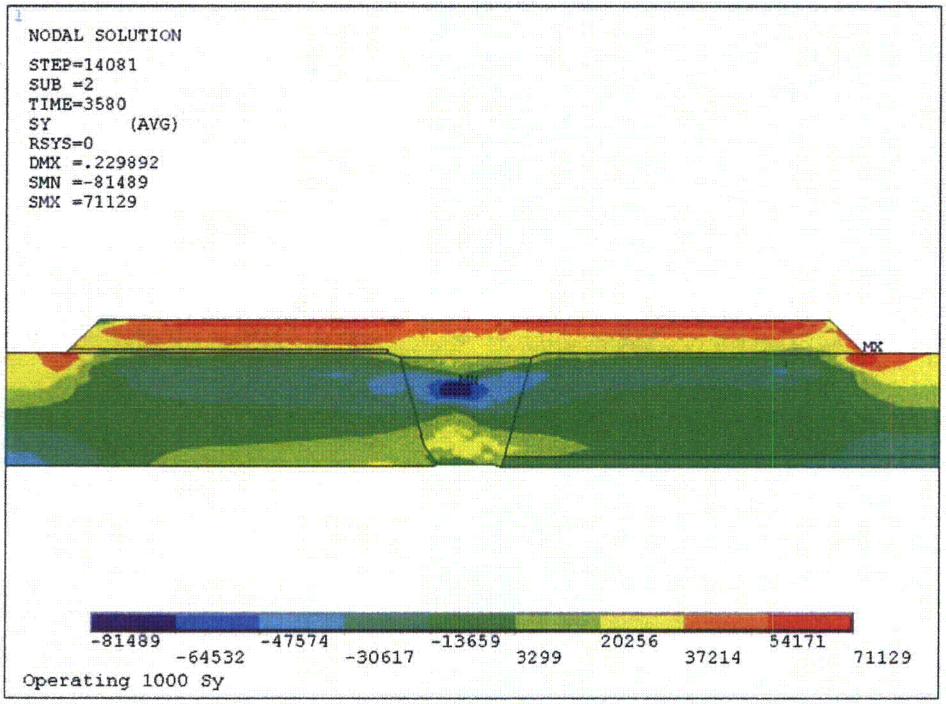
Stress results are in units of psi.

Figure 2-29
Post Weld Overlay Axial Stress at Operating Conditions for 750 in² Configuration



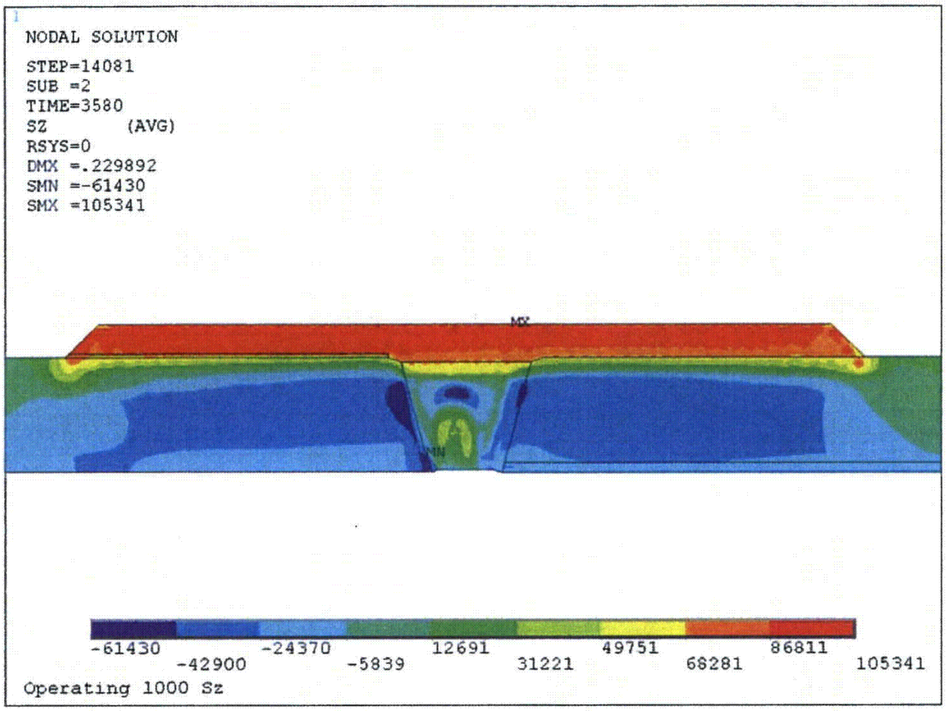
Stress results are in units of psi.

Figure 2-30
Post Weld Overlay Hoop Stress at Operating Conditions for 750 in² Configuration



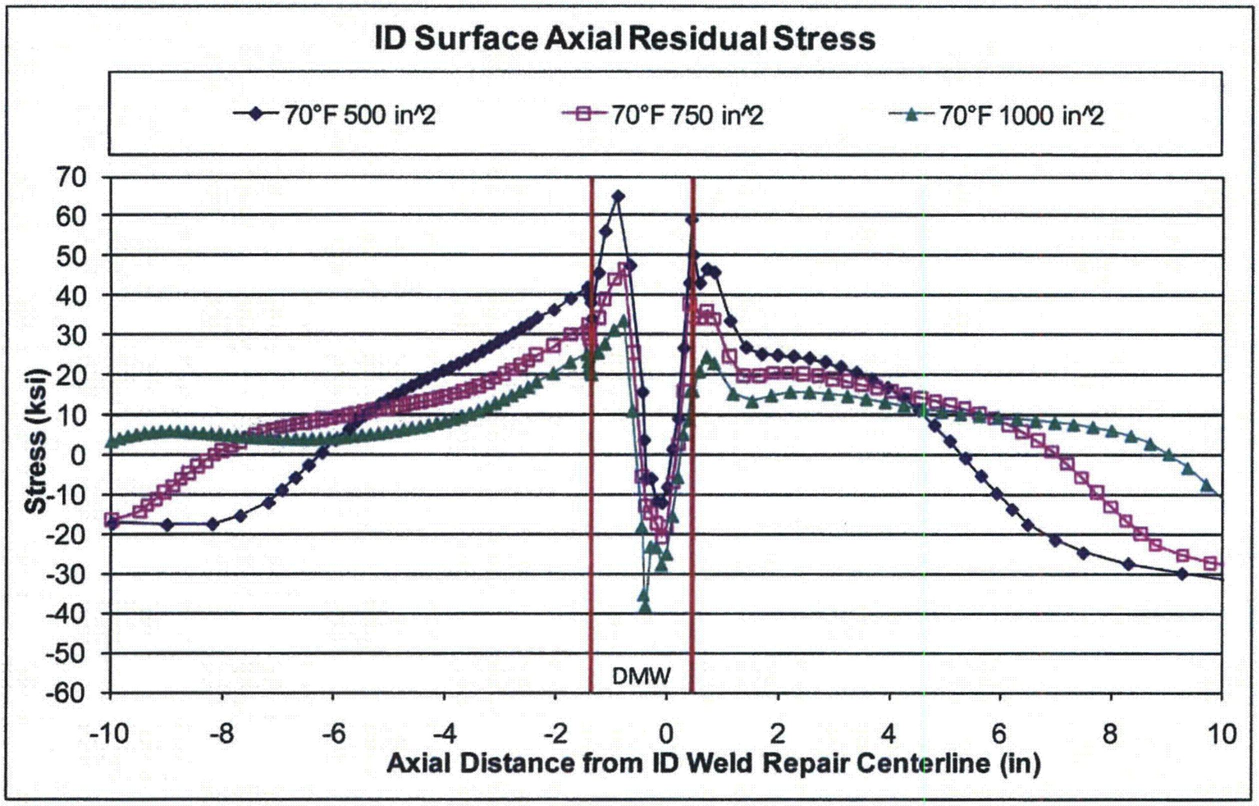
Stress results are in units of psi.

Figure 2-31
Post Weld Overlay Axial Stress at Operating Conditions for 1000 in² Configuration



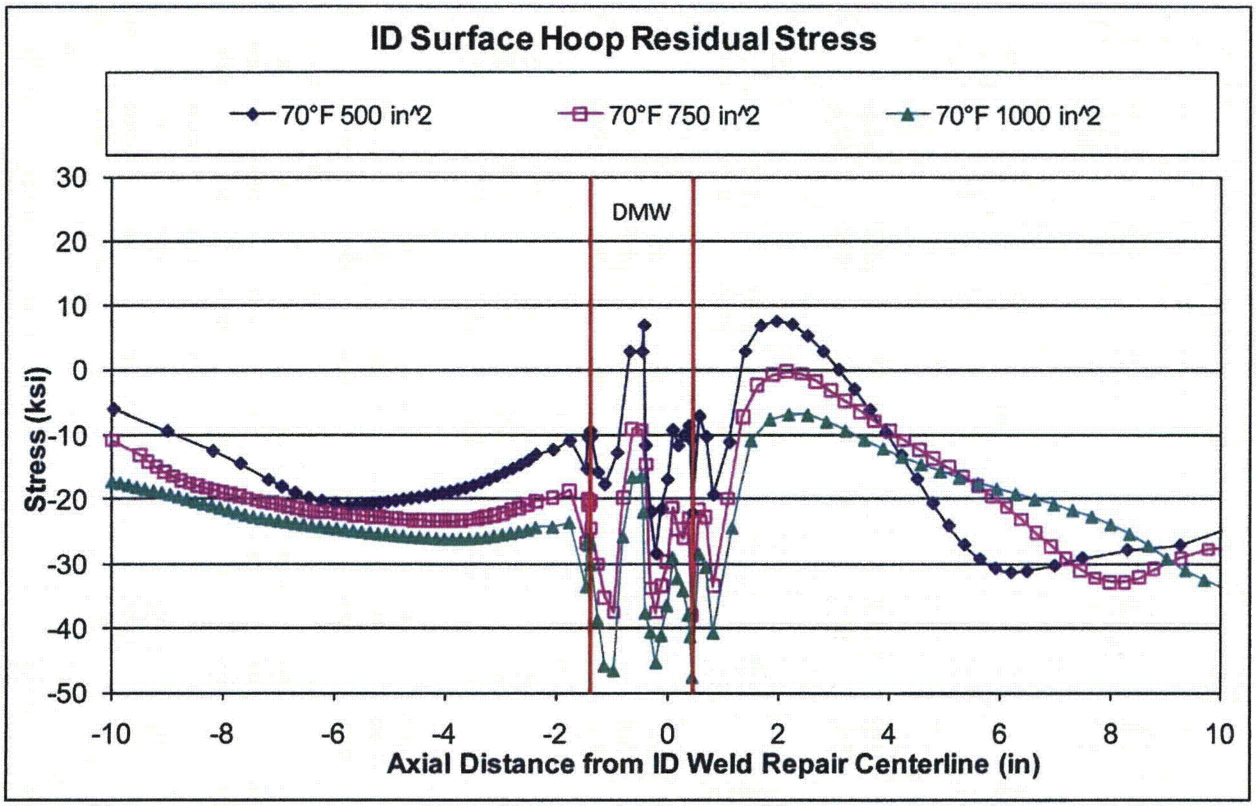
Stress results are in units of psi.

Figure 2-32
Post Weld Overlay Hoop Stress at Operating Conditions for 1000 in² Configuration



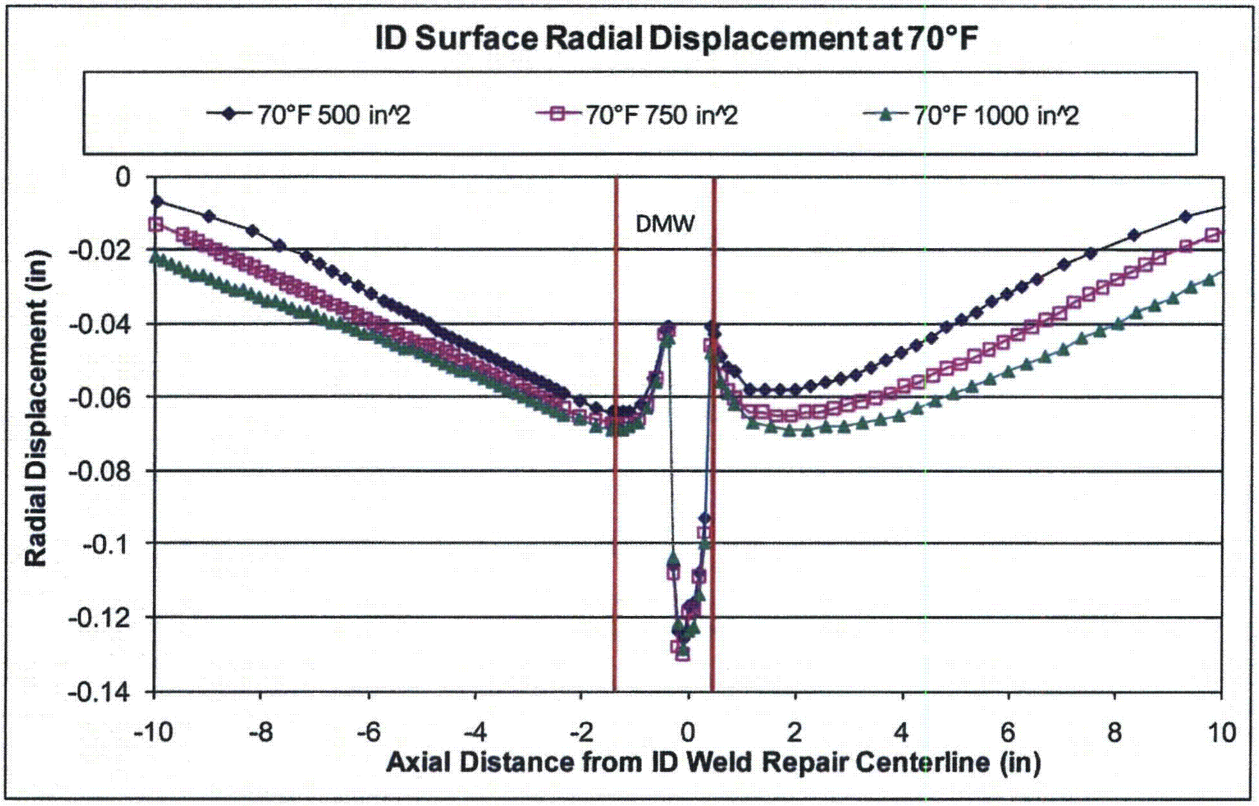
The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-33
ID Surface Axial Residual Stresses at 70°F



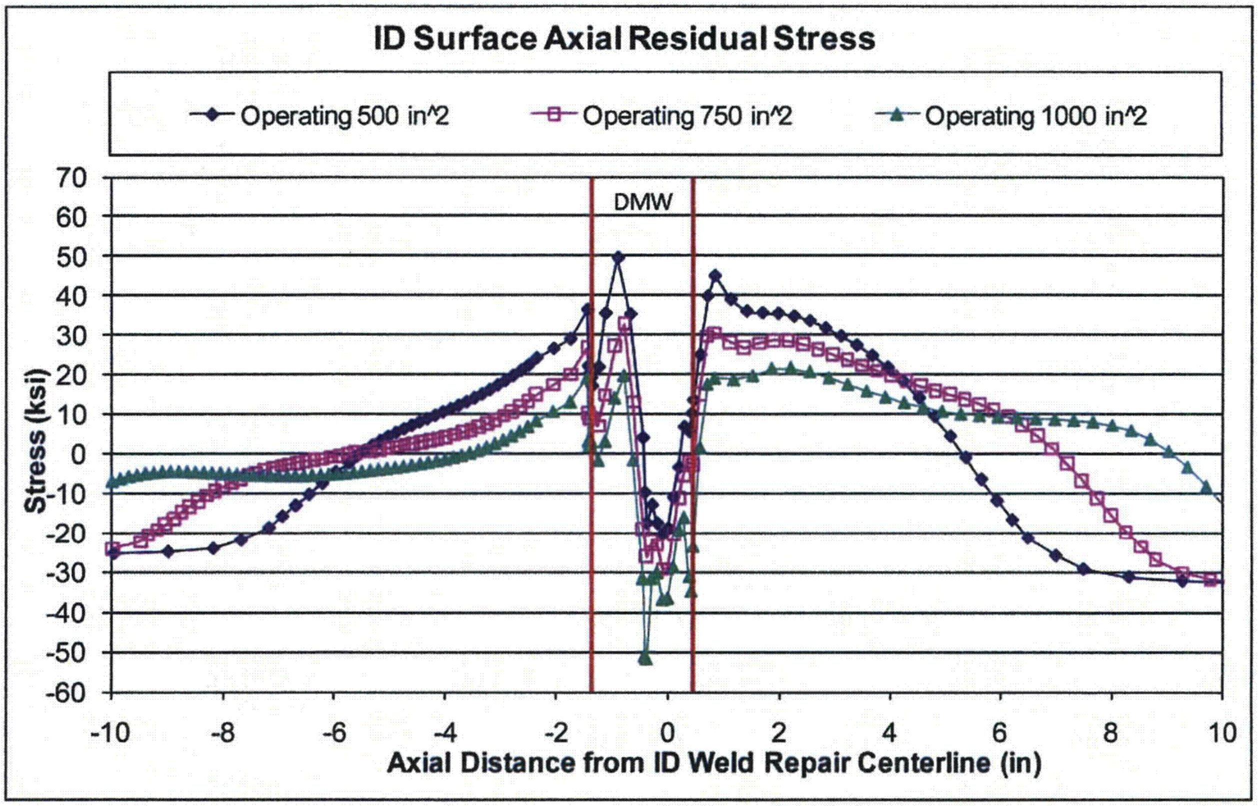
The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-34
ID Surface Hoop Residual Stresses at 70°F



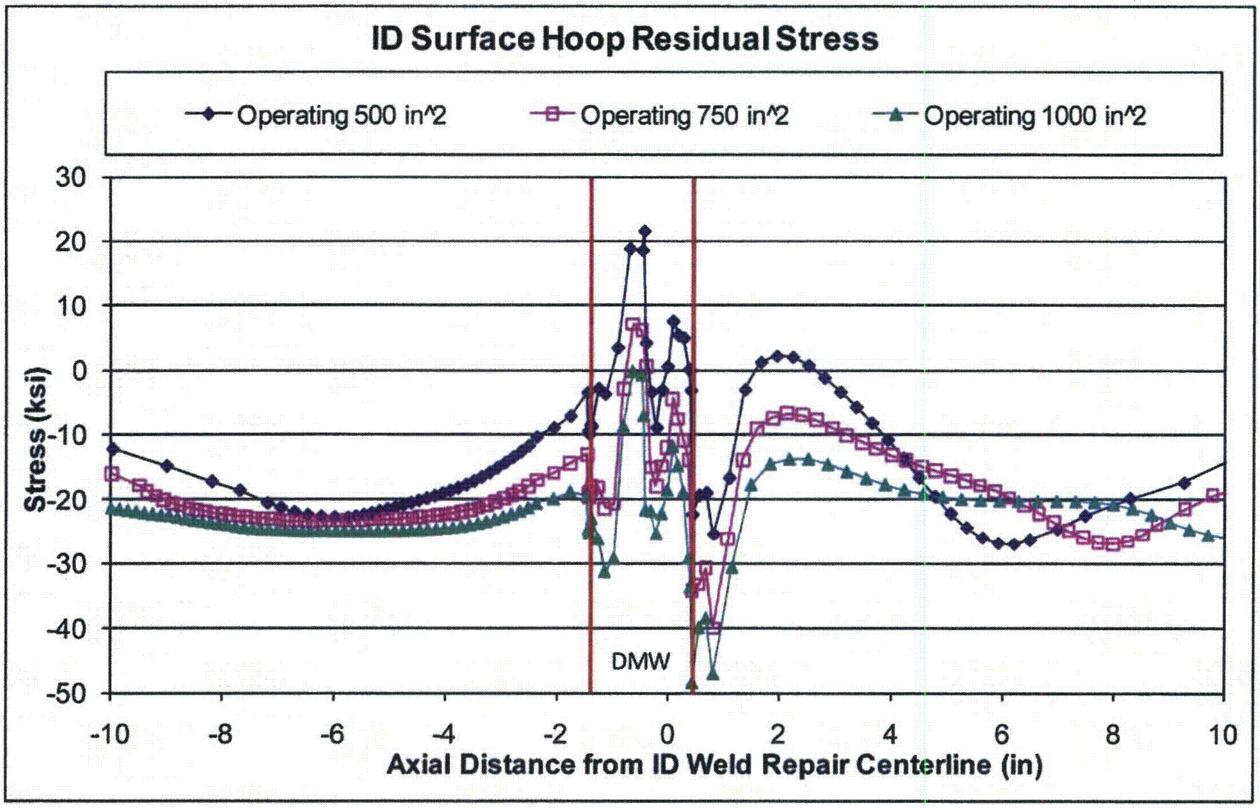
The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-35
ID Surface Radial Residual Displacement at 70°F



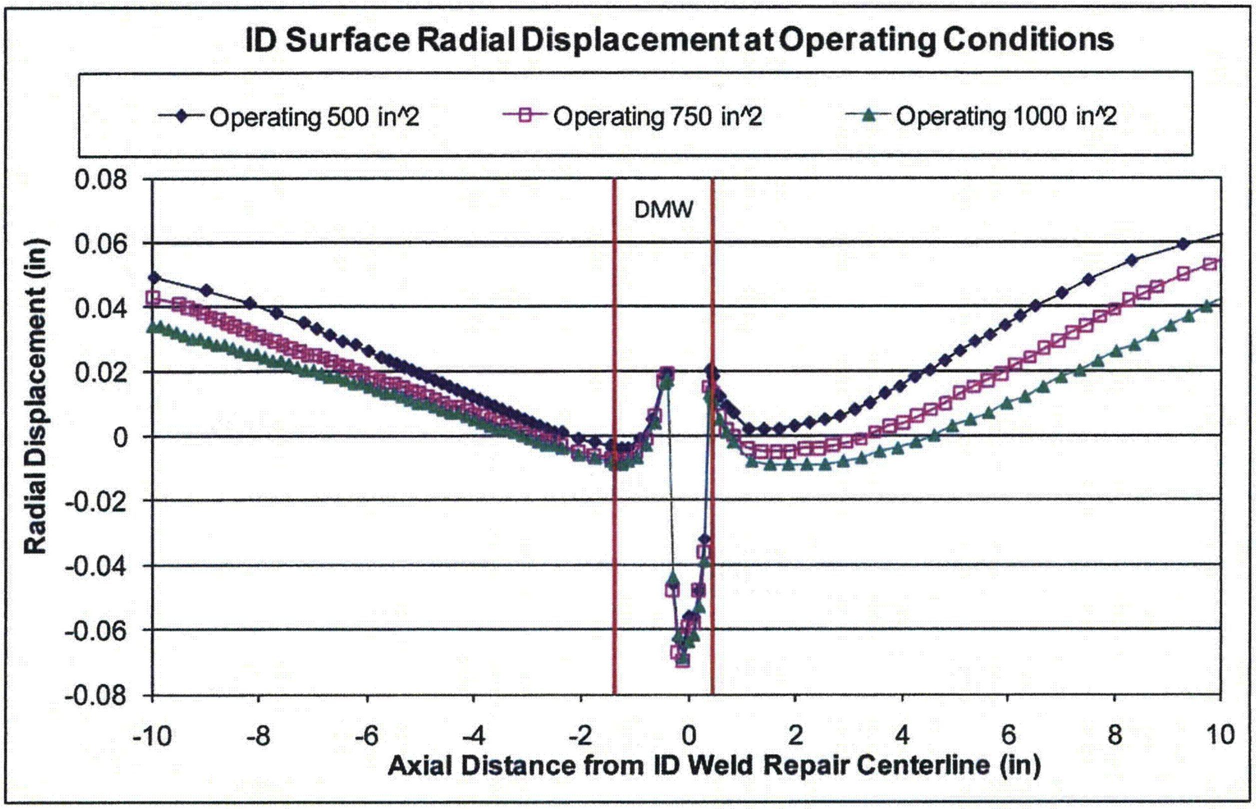
The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-36
ID Surface Axial Residual Stresses at Operating Conditions



The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-37
ID Surface Hoop Residual Stresses at Operating Conditions



The results for the ferritic component are taken at the ID of the ferritic material and not the stainless cladding.

Figure 2-38
ID Surface Radial Residual Displacement at Operating Conditions

3 CONCLUSIONS

A series of finite element modeling activities were performed presenting the results of two different analyses supporting the technical justification for increasing the amount of temper bead welding that can be performed on carbon and LAS components involving dissimilar metal welds DMWs for WOL application. The analyses provided herein were compared to temper bead repair limits that were developed in an earlier EPRI study [1]. The results of this work provide a basis for justifying the increase of the 500 in^2 temperbead welding limit developed in the earlier EPRI program to as much as 1000 in^2 as was developed in this study. The need to expand the application area limitations has been increased again for ambient temperature Gas Tungsten Arc Weld (GTAW) temperbead weld overlay repairs on LAS components as a result of significant numbers of repairs required for large diameter, thicker pressurized water reactor (PWR) primary coolant piping and nozzles. Since these components are often greater than 30-inches in diameter, and more than 3-inches thick, these repairs are required as a repair option by the utility industry to mitigate the effects of PWSCC on nickel alloy DMWs in the PWR primary water coolant environment.

The approach that was taken for this investigation was to perform a series of finite element based residual stress evaluations to support increasing the area of temper bead weld overlay repairs over ferritic materials (carbon and low alloy steels). Two sets of three separate analyses (one for each repair size) were performed. These analyses served as sensitivity studies for justifying the increase of the temper bead weld overlay repair area of large bore ferritic piping components up to a repair area of 1000 in^2. The analyses have been designed to provide the weld residual stress condition on the inside surface at the centerline of the DMW, that area susceptible to PWSCC, and on the inside surface at the toe of the overlay on the ferritic side of the overlay and on the stainless steel side of the overlay for the three different temper bead weld overlay areas evaluated, as well as the radial displacements associated with the weld overlay repair applications on the inside surface of the components beneath the overlay.

The two sets of analyses were similar to each other and similar to the original EPRI study [1] as noted above. The distinction between the two sets of analyses was that the second set of analyses compared the temper bead WOL repair for the three different area repairs utilizing the material properties described for the EPRI analyses [1] and the initial extension of that analyses to 1000 in^2, but also modeled the initial DMW weld including the residual stresses produced by that weld as well as an ID repair applied following the original DMW butt weld application.

In addition to the work documented in this report, a separate report performed as part of another EPRI project is included as Attachment 1 to this document. This report describes an evaluation of the effect of a temperbead weld overlay on the structural integrity of the elbow, including radial shrinkage and distortion For this mockup, the temper bead area over the P1 elbow was approximately 670 in^2, consistent with the sizes of overlay repairs evaluated in the body of this report.

The results of the analyses described in this document provide the following conclusions:

- The restriction on surface area for temper bead welding of WOLs in general has been arbitrary, and has been justified herein to be able to be extended, without restriction, to at least 1000 in^2.
- There has been no direct correlation of residual stresses with surface area of the repair either for overlay repairs done using temper bead welding. The cases analyzed in this report for up to 1000 in^2, and the supporting mockup results that are documented in Attachment 1, verify that residual stresses associated with weld overlay repairs can be designed to remain compressive in the weld region for larger area repairs as well a for smaller area repairs provided that allowances in temper bead surface area can be increased.
- The implementing of ASME Code and Code Case requirements for repairs assure that code stress limits and safety factors are maintained for overlay repairs regardless of size.
- Results from previous programs show that metallurgical, mechanical, and hardness testing results demonstrate that adequate tempering is achieved and that adequate fracture toughness and strength is maintained in the weld and heat affected zone. These results are further validated by the mockup results presented in Attachment 1.
- The restriction on surface area of repairs should be increased to 1000 in^2 based on the results of analyses and testing performed to date. The Code and the industry should provide an option to users to justify repairs beyond 1000 in^2 by additional analysis and evaluation of the type presented in this report, if required.

4
REFERENCES

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A
EVALUATION OF OVERLAY COVERAGE APPROACHING 700 SQUARE INCHES BASED ON EPRI 36-INCH DIAMETER OPTIMIZED WELD OVERLAY MOCKUP

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A.1 Introduction

EPRI (MRP/WRTC) has produced a series of NDE mockups containing flaws that span the exam volume requirement for optimized weld overlays (OWOLs). One of these mockups, a 36" nominal diameter simulated nozzle-to-pipe weld, was also instrumented to determine shrinkage effects due to the overlay welding process and to confirm the residual stress benefits of the OWOL. The area coverage on the carbon steel side of the overlay approached 700 square inches. The mockup was produced using weld processes typical of reactor coolant loop nozzle fabrication practices. NDE targets were installed, and an inside surface weld repair during construction was simulated. A weld overlay was applied to the mockup, with dimensions that approximate those of an optimized weld overlay (OWOL) for this size pipe.

Shrinkage measurements were performed for the OWOL using the standard field approach of installing punch marks at four azimuthal locations on either side of the overlay location and accurately measuring the axial length between the punchmarks before and after weld overlay application.

Strain gauge measurements of inside surface residual stresses were also performed using the incremental hole-drilling approach. The residual stress measurements were performed before and after the overlay was applied to the mockup to determine the benefits of the OWOL. A second form of residual stress measurement, X-ray diffraction (XRD) was also performed for a limited number of confirmatory measurements, after application of the OWOL.

This paper presents a description of the mockup and summarizes the shrinkage and residual stress measurements performed on it.

A.2 Description of Mockup

The overall layout and dimensions of the mockup are illustrated in Figures A-1 and A-2. The mockup consisted of a cast stainless steel pipe segment, welded to a 45° clad carbon steel elbow, via an Alloy 82/182 DMW. The two pipe segments had 37.4 inch outside diameters, with a 3.37 inch wall thickness. After completing the DMW, a 30° partial arc, inside surface repair was performed, to a depth of 0.65 inches, to simulate construction repairs that were not uncommon in this vintage of nuclear plants (Figure A-2). Finally the inside surface counterbore was filled in with Alloy-182 weld metal, as indicated in Figure A-2.

A weld overlay was applied to the mockup, with dimensions that approximate those of an optimized weld overlay (OWOL) for this size pipe, although no actual OWOL sizing calculations were performed. The dimensions of the overlay are indicated in Figure A-2. In-process photographs of the weld overlay application are shown in Figure A-4.

Materials for the various components in the mockup are listed in Table A-1.

Table A-1
EPRI 36 in. OWOL Mockup Materials

Component	Material
Elbow	Carbon Steel (SA-106 Grade B)
Pipe	Type 304 Stainless Steel
Cladding	Type 316L Stainless Steel
Butt Weld	Alloy 82/182
ID Weld Repair	Alloy 82/182
Buffer Layer	Type 309L
WOL	Alloy 52M

Of interest in this paper is the coverage area of weld overlay over the carbon steel side of the weld. Utilizing the dimensions in Figures A-1 and A-2, this area can be computed as follows:

$$\text{CS Area Overlaid} = \pi D(L1 + L2 - L3)$$

Where,

L1 = 6.128 in. (Length of WOL on CS side of DMW, Fig. 2-2)

L2 = 0.7 in. (Additional length due to 45° taper, Fig. 2-2)

L3 = 0.532 in. + 3.37 Tan (10°) (OD length of DMW + butter, Fig. 2-1)

D = 37.4 in. (OD of Pipe)

The resulting Carbon Steel coverage area is ~670 sq. in.

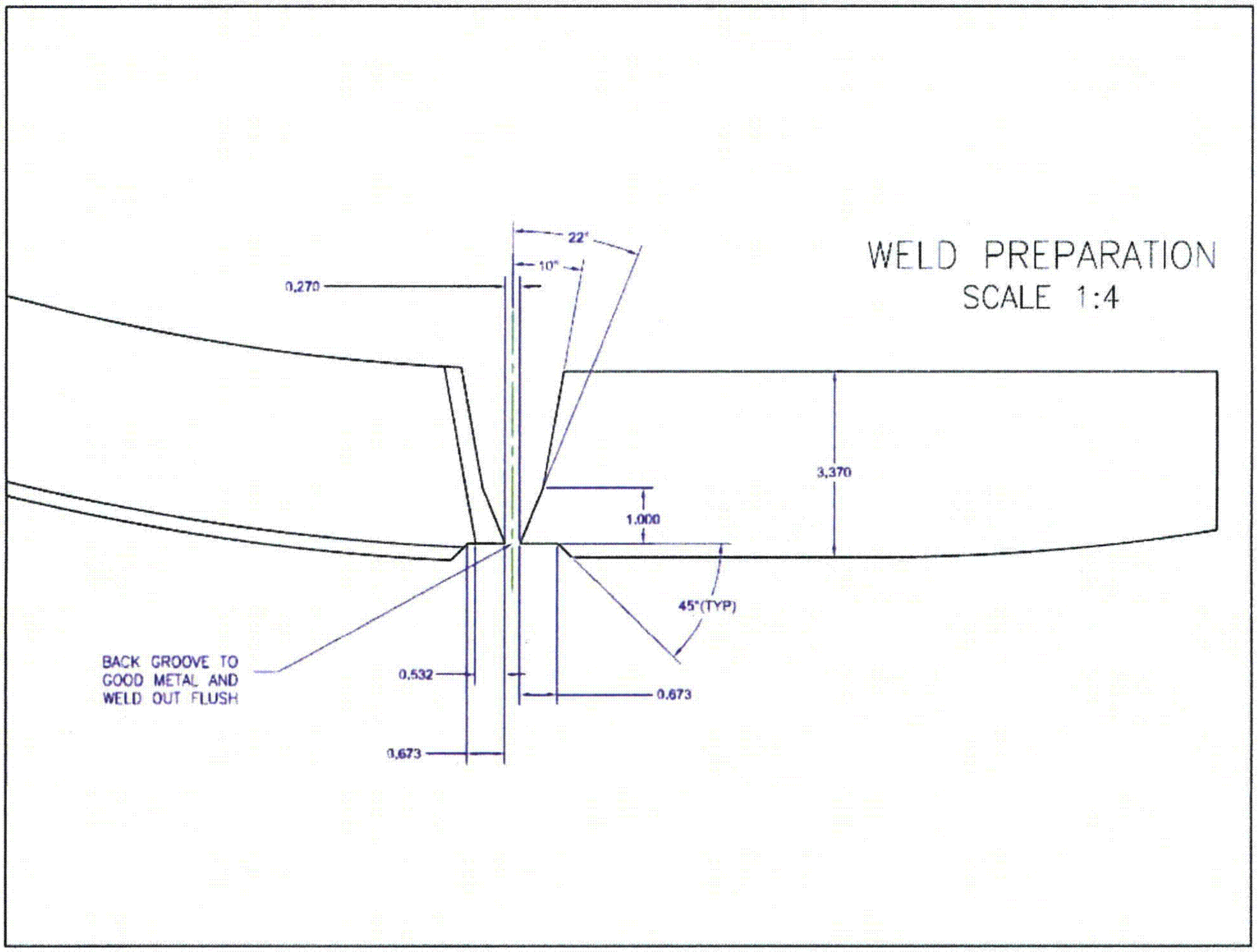

Figure A-1
Overall Dimensions of EPRI 36 in. Diameter OWOL Mockup
(Pipe & Elbow OD = 37.4 in.)

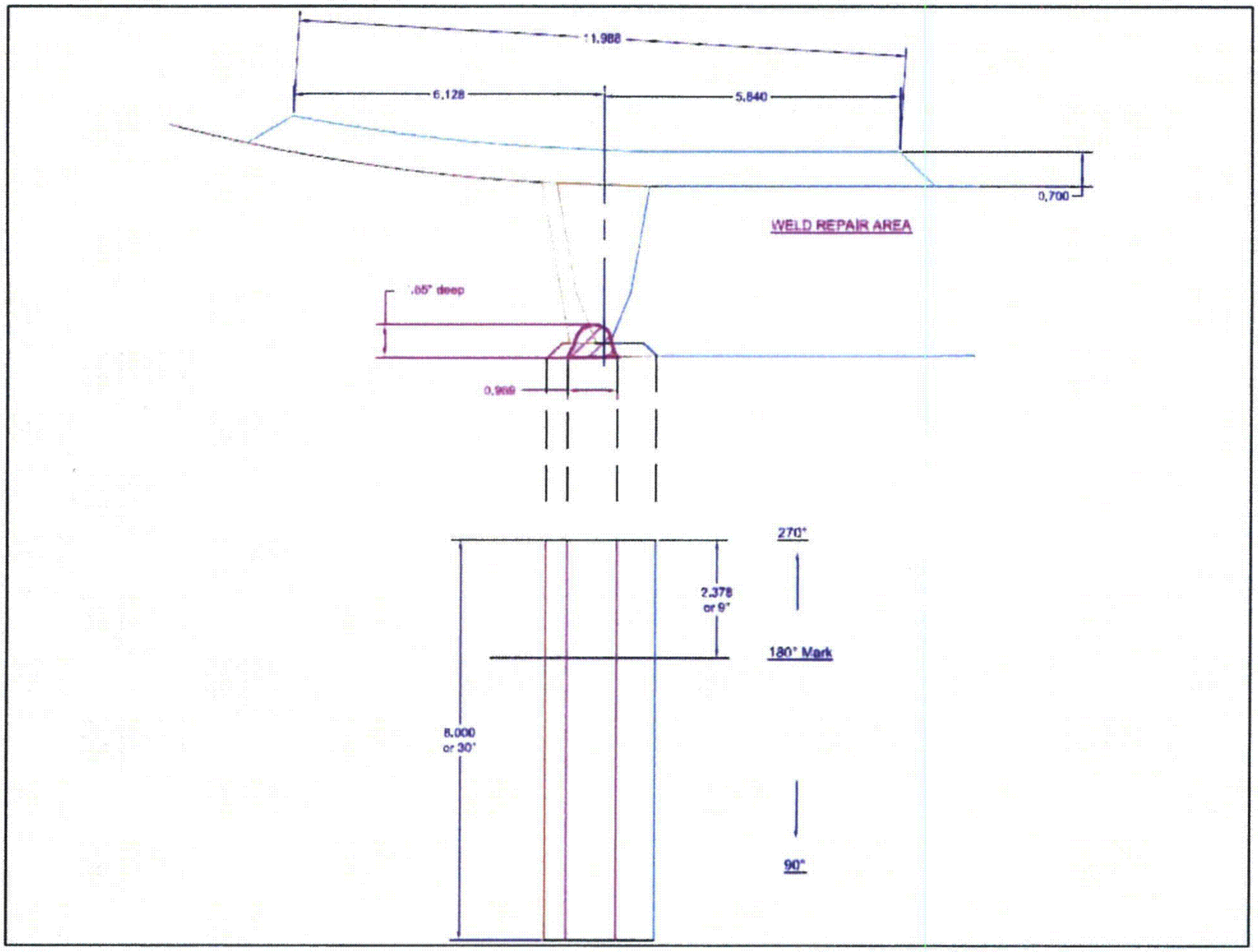

Figure A-2
Details of ID Repair and Weld Overlay in EPRI 36 in. Diameter OWOL Mockup

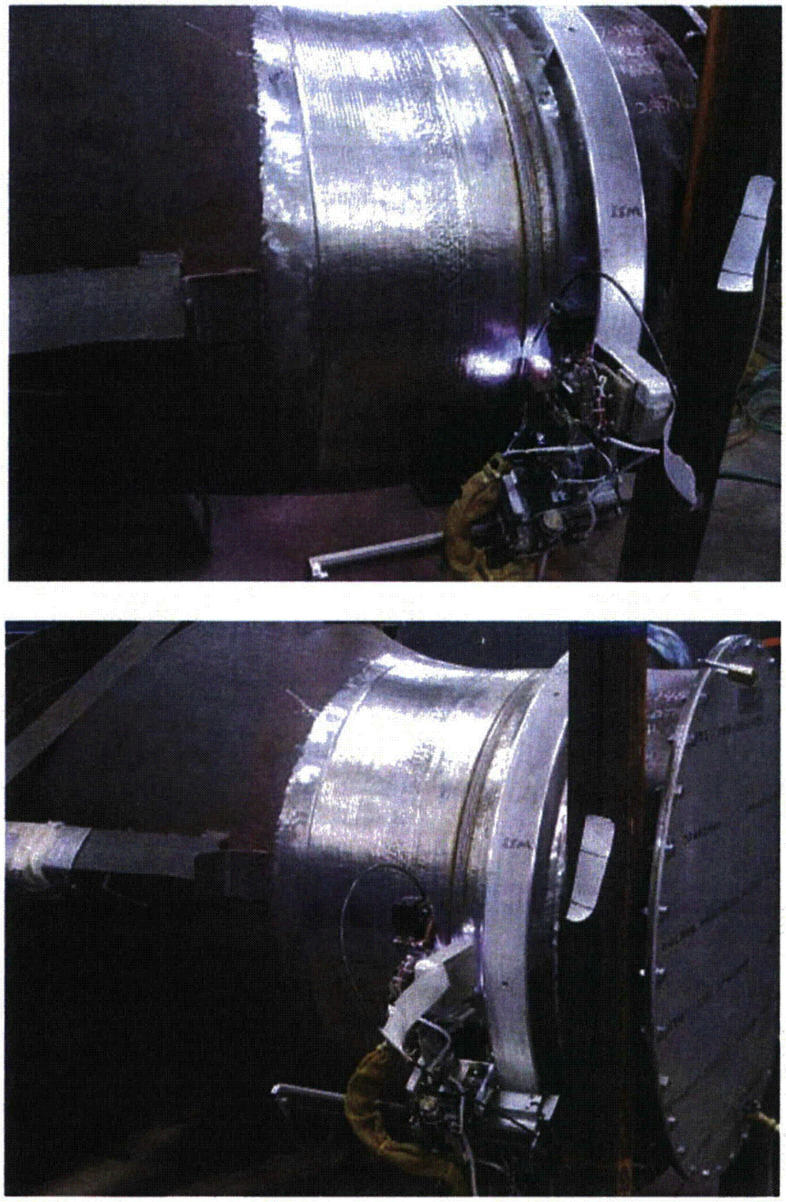

Figure A-3
Photographs of EPRI 36 in. Diameter OWOL Mockup during Weld Overlay Application

A.3 Shrinkage Measurements

Weld overlay shrinkage measurements were taken on the optimized weld overlay mockup. The shrinkage measurements taken on this mockup are summarized in Table A-2. Average shrinkage and rotation are also reported.

Table A-2
Axial Shrinkage Measurements on EPRI 36 in. Diameter Overlay Mockup

Axial Shrinkage (in.)	
Location from Top Dead Center (Degrees)	**8th Layer**
45	-0.014
135	0.036
225	-0.065
315	0.053
Ave Shrinkage	0.0025
Computed Rotation	0.162°

The table reports shrinkage measured between punchmarks on either side of the overlay at four azimuthal locations around the circumference. Computed averages and rotations are also reported, in which rotation was computed as the average difference in positive versus negative shrinkage measurements, divided by the pipe diameter and converted to degrees.

The average shrinkage and rotation at the cross section, are negligible for a pipe of this size, and would not produce significant stresses or displacements in a typical PWR large diameter pipe system.

A.4 Residual Stress Measurements and Analyses

Residual stresses were also measured on the mockup, pre- and post-weld overlay. Measurements were made via strain gage hole drilling techniques after completing the butt weld, the partial arc ID repair and the counterbore fill-in processes. Axial and hoop stress measurements were taken on the inside surface of the mockup at five axial locations (A through E in Figure A-4) at several azimuthal locations around the circumference (also illustrated in Figure A-4). Locations C, D and E are in the PWSCC susceptible material region directly under the DMW, and the 180° azimuthal location corresponds to the center of the partial arc ID repair. X-ray diffraction (XRD) measurements were also taken at select ID surface locations (post-overlay in the hoop direction only) to provide some confirmation of the strain gage results.

The resulting residual stress measurements are tabulated in Tables A-3 and A-4 and are illustrated graphically in Figures A-5 and A-6. It is seen from these results that the OWOL performed quite effectively at reducing the ID surface residual stresses in the PWSCC susceptible material locations (B, C, and D). Axial residual stresses were reduced from an average of 74.1 ksi (pre-overlay) to -0.3 ksi (post overlay) in the regions outside of the ID repair zone (i.e. all azimuths except 180°), and from an average of 94.7 ksi (pre-overlay) to 10.7 ksi (post-overlay) inside the ID repair zone (i.e. at the 180° azimuth). Hoop residual stresses were reduced from an average of 64.4 ksi (pre-overlay) to -12.4 ksi (post-overlay) outside of the ID repair zone, and from an average of 88 ksi (pre-overlay) to 22 ksi (post-overlay) inside the ID repair zone. The OWOL thus achieved approximately 70 ksi of stress improvement at all locations. The XRD measurements were in reasonably agreement with the strain gage data, within typical experimental error bands for these types of measurements.

It is noteworthy that, although the absolute residual stress results did not fully satisfy MRP-169 residual stress criteria (less than 10 ksi tensile on the ID surface), the starting residual stresses were very severe compared to typical field overlay applications, because of the combined effects of the partial arc ID surface repair followed by the counterbore fill-in step, which constituted effectively a second, 360° repair. The mockup also did not simulate a stainless steel pipe to safe-end weld, which exists in many field applications, and which is known to have a favorable effect on pre-overlay residual stresses. 70 ksi residual stress improvement is more than adequate for most, if not all, field OWOL applications.

Finally, it is noteworthy in the context of this paper that, based on analyses, increasing the coverage area of weld overlays is expected to improve, not degrade, their residual stress performance.

Table A-3
Strain Gage Residual Stress Measurements on EPRI 36 in. Diameter OWOL Mockup (Stresses in ksi)

Case	Location	30°	90°	150°	180°	210°	270°	330°
Axial; Pre-OWOL	A	20	31	28		32	25	27
	B	68	77	81	110	80	76	59
	C	73	70	75	90	72	64	69
	D	61	77	67	84	79	102	83
	E	34	46	52		39	-14	40
Axial; Post-OWOL	A	0	3	2		4	6	1
	B	-5	-3	7	12	12	-1	-3
	C	-4	-7	6	11	4	0	-5
	D	-9		6	9	5	-2	-6
	E	2	3	5		9	5	3
Hoop; Pre-OWOL	A	24	33	42		30	33	37
	B	62	59	70	82	67	50	51
	C	71	66	83	92	75	87	60
	D	70	68	79	90	47	31	64
	E	39	40	55		44	-11	47

Table A-3 (continued)
Strain Gage Residual Stress Measurements on EPRI 36 in. Diameter OWOL Mockup (Stresses in ksi)

Case	Location	30°	90°	150°	180°	210°	270°	330°
Hoop; Post-OWOL	A	-9	-7	15		-6	-1	-4
	B	-18	-12	-3	25	-15	-13	-17
	C	-32	-19	-2	22	-12	-15	-21
	D	-3	-16	8	19	-18	-6	-9
	E	-4	-2	20		-5	0	1

Note:
180° Azimuth is at center of ID repair location

Table A-4
X-ray Diffraction Residual Stress Measurements on EPRI 36 in. Diameter OWOL Mockup (Stresses in ksi)

Case	Location	0°	60°	125°	180°	235°	280°
Hoop; Post-OWOL	B	-35	0	-18	36	-32	-6
	C	-26	0	-3	20	-25	24
	D			9		-16	-7

Note:
180° Azimuth is at center of ID repair location

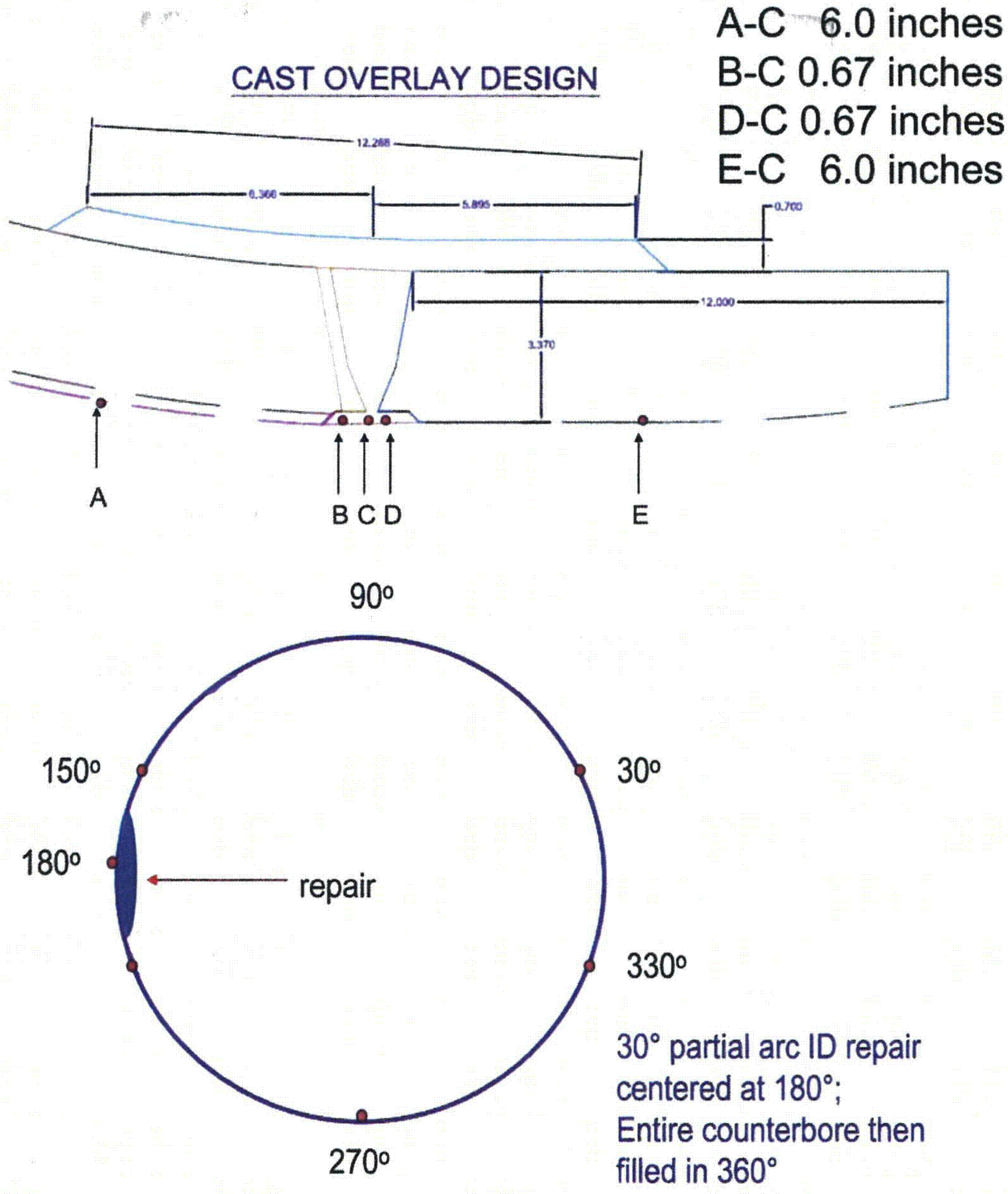

Figure A-4
Residual Stress Measurement Locations

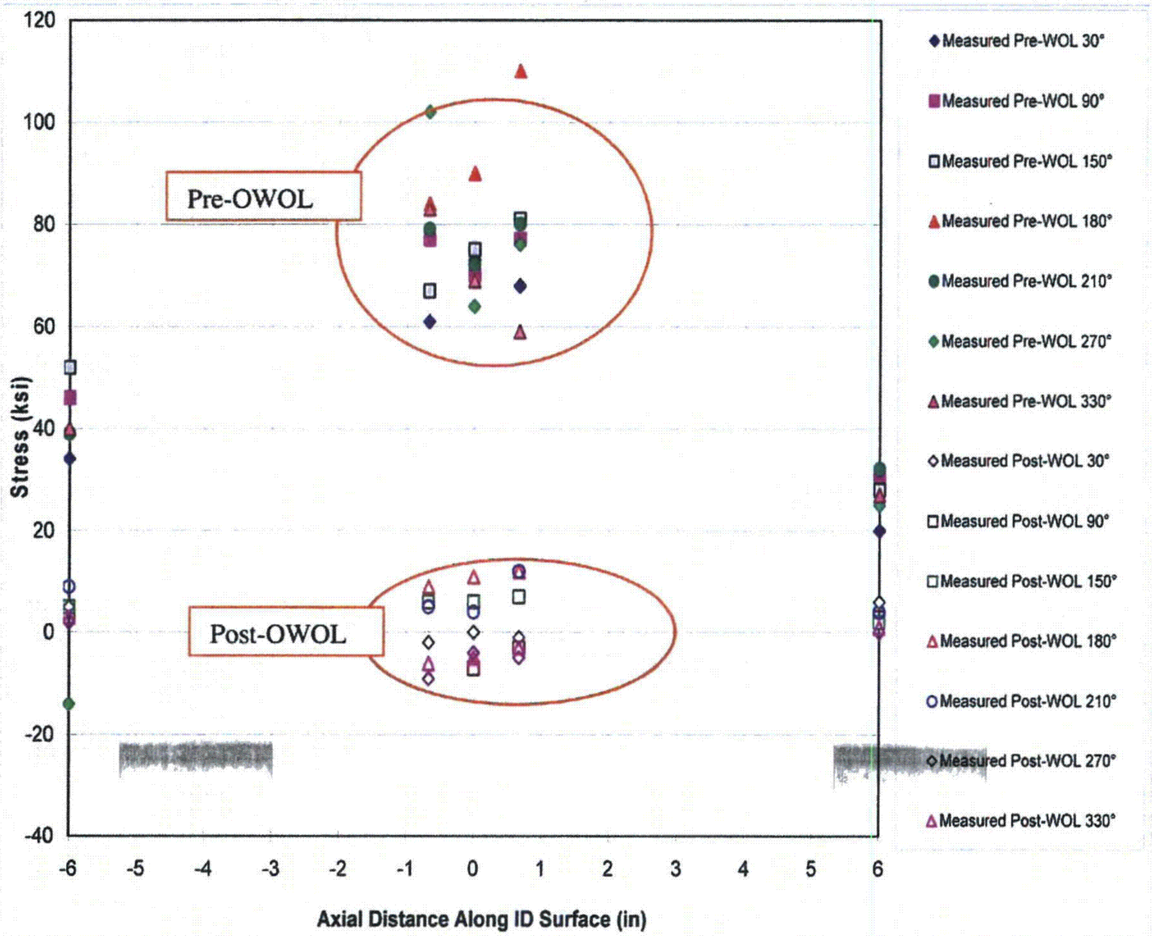

Figure A-5
EPRI 36 in. Mockup Axial Residual Stress Measurements

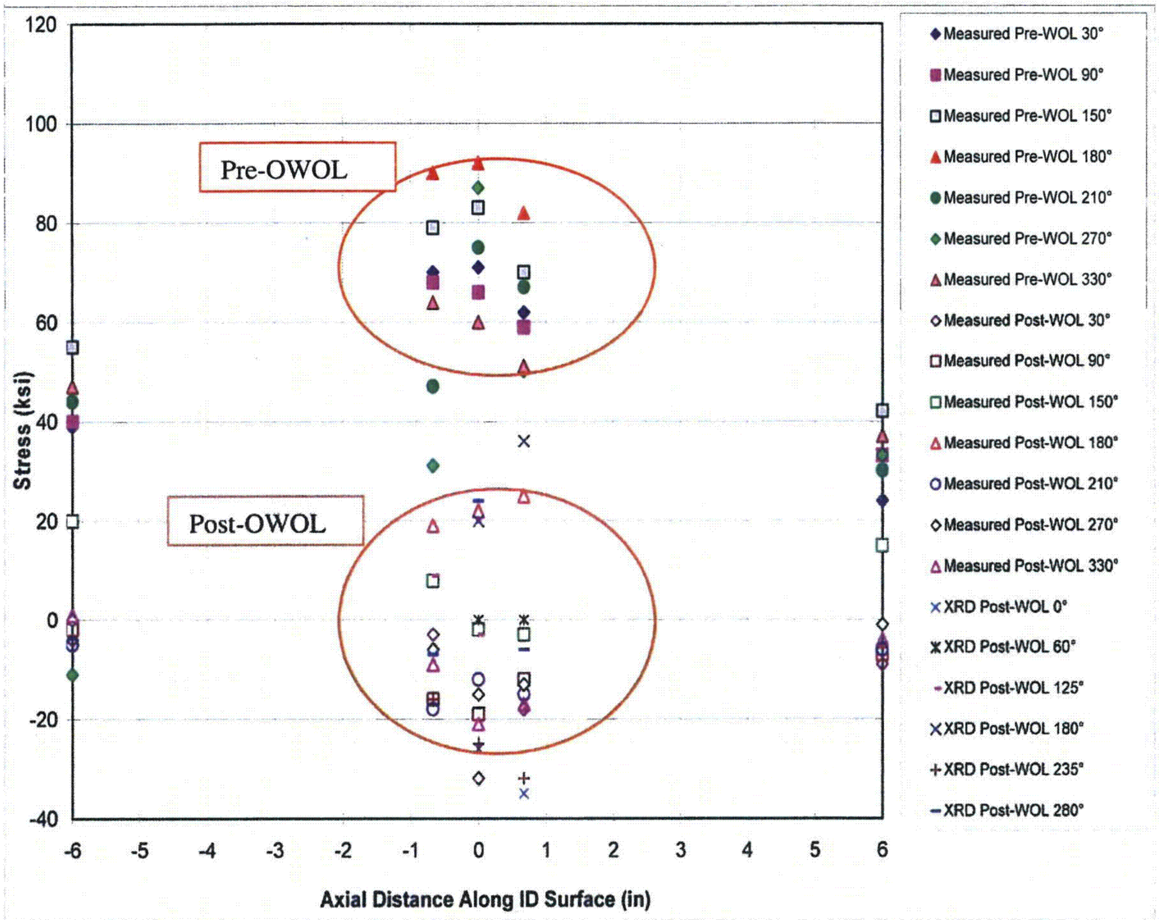

Figure A-6
EPRI 36 in. Mockup Hoop Residual Stress Measurements

A.5 Conclusions

An optimized weld overlay mockup with carbon steel coverage area approaching 700 square inches (~670 sq. in) has been performed as part of the EPRI (MRP/WRTC) program to produce samples for the NDE qualification program. In addition to its use for NDE purposes, this mockup was also instrumented to measure axial shrinkage and residual stress effects of the weld overlay. The mockup showed that a weld overlay with this amount of carbon steel coverage experienced negligible shrinkage effects, and that the overlay performed quite effectively in terms of reducing very high inside surface pre-overlay residual stresses in the mockup (average residual stress benefit on the order of 70 ksi). It is also noted that increasing the size of this overlay, and thus the amount of carbon steel coverage, would be expected based on analysis to improve the residual stress performance.

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