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CALCULATION TITLE:
Residual Stress Analysis of Reactor Coolant Pump Discharge Nozzle with Weld Overlay Repair

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1.0 OBJECTIVE

The purpose of this evaluation is to perform a weld residual stress analysis of the Reactor Coolant Pump (RCP) Discharge Nozzle safe end and an attached piping elbow for application of a weld overlay (WOL) repair. This analysis includes performing a weld repair from the inner diameter surface (ID) for a postulated flaw within the original safe end-to-pipe elbow weld (dissimilar metal weld or DMW). The ID weld repair is simulated to provide an unfavorable stress condition (prior to applying the weld overlay) due to the original fabrication of this weld. The objective of this calculation is to use finite element analysis to evaluate the weld residual stresses induced by the weld overlay repair applied to the RCP discharge nozzle and pipe elbow.

2.0 DESIGN INPUTS

2.1 Finite Element Model

The RCP discharge nozzle finite element model is developed in Reference 1 (written in an input file "DB-OUTLET-RES.INP"). The model includes the reactor coolant pump discharge nozzle, the nozzle-to-safe end weld, the safe end, the safe end-to-piping weld and weld butter, a postulated ID weld repair, a portion of attached outlet piping (elbow) and cladding, the stainless steel buffer layer, and the weld overlay repair. For the residual stress analysis the elbow connecting the RCP Discharge nozzle is conservatively modeled as a straight pipe so that the compressive stresses developed by the elbow on the safe end are not considered. Thus, the stresses on the nozzle are more tensile. The ID weld repair is included in this analysis to show that the tensile stresses generated by this weld is mitigated by the weld overlay repair. The favorable stress condition mitigates primary water stress corrosion cracking (PWSCC) and arrests any existing PWSCC-driven crack growth associated with the DMW material.

Figure 1 shows the applied boundary conditions on the axisymmetric finite element model (FEM) and mesh. Figure 2 depicts the components included in the model. The weld overlay layout used for the residual stress evaluation is shown in Figure 3. The RCP Discharge nozzle is oriented horizontally. The progression of the overlay welding is from safe end to the piping elbow. It should be noted that the state of final residual stress is essentially unaffected by the direction of weld bead placement.

2.2 Material Properties

The materials of the various components of the model are per Reference 1:

- Reactor Coolant Pump Discharge Nozzle — A-351, Grade CF8M
- Nozzle-to-Safe End Weld — Stainless Steel Type 316
- Safe End — A-376, Type 316
- Safe End-to-Pipe Weld and Butter — Alloy 82/182
- Outlet Piping (elbow) — A-516, Grade 70
- Outlet Piping (elbow) Cladding — A-240-304L
- ID Weld Repair of Safe End-to-Pipe Weld — Alloy 82/182

- Weld Overlay Buffer Layer — ER-308L
- Weld Overlay Repair — Alloy 52M

The temperature dependent nonlinear material property values are obtained from Reference 1 (input file MProp_MISO_NLinear_DB.INP). This analysis applies the multilinear isotropic hardening (MISO) material behavior available within the ANSYS finite element program [2].

3.0 ASSUMPTIONS

The residual stress analysis performed herein is based on the methodology presented in the development calculation package in Reference 3. The residual stresses in RCP discharge nozzle with weld overlay repair are determined by utilizing the following assumptions:

1. Assumptions from Reference 1 are also applicable in this calculation.

2. The convection heat transfer coefficient of air is taken as 5.0 Btu/hr-ft^2-°F at 70°F bulk ambient temperature and is applied to simulate the convection across the inside surface of the FE model during the application of the ID weld repair process.

3. Similarly a heat transfer coefficient of 5.0 Btu/hr-ft^2-°F at 70°F bulk ambient temperature is applied at the outside surface of the FE model during the application of the ID weld repair process.

4. During the weld overlay process, a heat transfer coefficient of 5.0 Btu/hr-ft^2-°F at 70°F bulk temperature was used at the inside surface of the nozzle to simulate an air backing environment.

5. The outside surface of the nozzle has a heat transfer coefficient of 5.0 Btu/hr-ft^2-°F at 70°F bulk temperature during the weld overlay process to simulate an air environment.

6. The maximum interpass temperature between the depositions of weld nuggets is assumed to be 350°F for all welding processes [5].

7. As a two-dimensional residual model was analyzed the pressure tap nozzle and spray nozzle are not evaluated. ASME Boiler and Pressure Vessel Code (Reference 7), NB 3332.1 mentions that no unreinforced opening shall have the distance between it's center and edge of a locally stressed area closer than $2.5\sqrt{Rt}$. The technical basis for this is further substantiated in the general theory of cylindrical shells [8]. It is deduced from the shell theory that the numerical value of the functions representing the deflection and bending of the shell approach zero as the distance from the area of stress concentration becomes large. This indicates that the bending produced in the shell due to the residual loading is local in character. Hence, the presence of the nozzles is not expected to change the axial or hoop stress results in the area of interest on the ID surface of the Reactor Coolant Pump (RCP) Discharge Nozzle safe end.

4.0 METHODOLOGY

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 ID weld repair and weld overlay processes.

A residual stress evaluation process was previously developed in an internal Structural Integrity project. Details of that process and its comparison to actual test data are provided in Reference 3. The same process will be used herein. A brief description of the process is described as follows:

The analyses are performed using the ANSYS finite element software [2]. Axisymmetric PLANE55 elements are used 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 monitoring is utilized in the thermal pass to ensure that the temperature between weld layer nuggets meets the required interpass temperature as well as obtain acceptable overall temperature distribution within the FEM (i.e., peak temperature, sufficient resolution of results, etc.).

In the stress pass, symmetric boundary conditions are applied on the free end of the cold leg pipe, whereas the free end of the attached discharge piping elbow is coupled in the axial direction to ensure uniform displacement of the nodes (see Figure 1).

4.1 Weld Bead Simulation

The number of equivalent lump passes for each weld is summarized as follows:

- The ID weld repair is performed in seven layers.
- The buffer layer is performed in one layer, with four nuggets across this one layer.
- The weld overlay is performed in nine layers. A total of eighty seven nuggets are defined for the weld overlay:
  - Layer one is comprised of eight nuggets
  - Layer two is comprised of twelve nuggets
  - Layer three is comprised of twelve nuggets
  - Layer four is comprised of eleven nuggets
  - Layer five is comprised of eleven nuggets

- Layer six is comprised of eleven nuggets
- Layer seven is comprised of eight nuggets
- Layer eight is comprised of seven nuggets
- Layer nine is comprised of seven nuggets

4.2 Welding Simulation

The ID weld repair is applied first. After the completion of ID weld repair, the model is cooled down to a uniform ambient temperature of 70°F. Then buffer layer is applied. After buffer layer is completed, the model is again cooled to a uniform ambient temperature of 70°F. Finally a weld overlay is applied on the model.

After the weld overlay is completed, the model is cooled to a uniform ambient temperature of 70°F, and then heated to a uniform operating temperature of 556°F [4, 6]. An operating pressure of 2255 psig [4, 6] is applied in order to obtain the combined residual and pressure/thermal stresses at room temperature and operating temperature/pressure, respectively.

4.3 Internal Pressure Loading

The internal operating pressure of 2255 psig is applied to the interior surfaces of the model. An end-cap load is applied to the free end of the attached outlet piping elbow in the form of tensile axial pressure, and the value is calculated below. See Figure 4 for applied pressure loading. Symmetry boundary conditions are applied at the free ends of the discharge nozzle, and the free end of the attached elbow piping is coupled in the axial direction as shown in Figure 1 to simulate the attached outlet piping.

$$P_{end\text{-}cap\text{-}cl} = \frac{P \cdot r_{inside}^2}{\left(r_{outside}^2 - r_{inside}^2\right)} = \frac{2255 \cdot 14.0^2}{\left(17.3^2 - 14.0^2\right)} = 4{,}279 \text{ psi}$$

where,

$P_{end\text{-}cap\text{-}cl}$ = End cap pressure on outlet piping elbow free end (psi)
P = Internal pressure (psi)
r_{inside} = Inside radius of modeled outlet pipe elbow (in) [1]
$r_{outside}$ = Outside radius of modeled outlet pipe elbow (in) [1]

The ANSYS input and output files for the analysis are listed in Table 1.

5.0 WELDMENT TEMPERATURE GUIDELINES

The analytical procedure described in Section 4.0 has provided reasonable results as seen in previous similar analyses when compared to results from test data. This can be demonstrated by observing the fusion boundary prediction of the welds. Figures 5 through 7 show the predicted fusion boundaries for the three welding processes as generated by ANSYS for this specific overlay. The fusion boundaries represent the

predicted maximum temperature contour mapping that the weld nugget elements would reach during each welding process. Note that the figures are composites showing the maximum temperature among all nuggets of each weld throughout the welding process. This is made possible by an ANSYS macro (MapTemp.mac) that reads in the maximum predicted temperatures across the different weld nugget elements during the welding process and displays it as a temperature contour plot.

Figures 5 through 7 show that the majority of weld elements have reached temperatures between 2,674°F and 3,000°F. It also shows that the heat penetration depth, where temperatures are above 1,300°F, is similar in size to the heat affected zone (HAZ) of roughly between 1/8" and 1/4".

6.0 CONCLUSIONS AND DISCUSSIONS

Figures 8 and 9 depict the axial and hoop residual stress distribution for the post-ID weld repair condition at 70°F, respectively. The axial direction and the hoop direction are with respect to the global coordinate system, the axial stress is represented as S_Y (stress along y-direction) and the hoop stress is represented as S_Z (stress along z-direction). It is shown that extensive tensile axial and hoop residual stresses occur along the inside surface of the nozzle in the vicinity of the ID weld repair.

Figures 10 and 11 depict the axial and hoop residual stress distribution for the post-buffer layer condition at 70°F, respectively. Figures 12 and 13 depict the axial and hoop residual stress distribution for the post-WOL condition at 70°F, respectively. Figures 14 and 15 depict the resultant residual and operating stress distributions for the post-WOL configuration at the maximum operating temperature of 556°F and operating pressure of 2255 psig in the axial and hoop directions, respectively.

Figures 17 and 18 are ID surface stress plots for the axial and hoop directions as a function of distance from the ID weld repair centerline, respectively. The results are plotted for post-ID weld repair, post-weld overlay at 70°F, and post-weld overlay at 556°F/2255 psig.

Furthermore, Figures 17 and 18 show that post-overlay compressive stresses for both the 70°F and operating (556°F/2255 psig) conditions are present at the ID surface of the DM weld. This would indicate that at any intermediate steady-state operating condition (i.e., temperature and pressure) that the residual stresses would remain compressive. Any additive loads (i.e., thermal transients) are short term in nature and are not relevant to PWSCC concerns. The results suggest that the weld overlay has indeed mitigated the DMW against PWSCC.

In addition, through-wall axial and hoop stress results are extracted for various paths defined in Figure 16. Three stress paths are defined through the susceptible material. The objective is to extract the stresses through locations in the PWSCC susceptible material. The results will be used for a subsequent crack growth evaluation in a separate calculation package. Two sets of data are obtained, which are for post-weld overlay at 70°F and for post-weld overlay at 556°F/2255 psig.

The post-processing outputs are listed in Table 1. They are further processed in Excel spreadsheet "*DB_0800368_324_RES.xls*".

7.0 REFERENCES

1. SI Calculation 0800368.322, "Finite Element Models of Reactor Coolant Pump Discharge Nozzle with Weld Overlay Repair," (for Revision Refers to SI Project Revision Log, Latest Revision).
2. ANSYS/Mechanical, Revision 8.1 (w/Service Pack 1), ANSYS Inc., June 2004.
3. SI Calculation 0800777.303, Rev. 0, "Residual Stress Methodology Development and Benchmarking of a Large Diameter Pipe Weld Overlay."
4. SI Calculation 0800368.311, "Design Loads for the 28" I.D. Reactor Coolant Pump (RCP) Suction and Discharge Nozzles," (for Revision Refers to SI Project Revision Log, Latest Revision).
5. ASME Boiler and Pressure Vessel Code, Code Case N-740-2, *Dissimilar Metal Weld Overlay Repair of Class 1, 2, and 3 Items, Section XI, Division 1.*
6. "Inputs List – Design Data," Rev. 1, Design Input information supplied by FirstEnergy Nuclear Operating Company on 9/12/08, SI File No. 0800368.241.
7. ASME Boiler and Pressure Vessel Code, Divison 1, Subsection NB, Class 1 Components, "Rules for Construction of Nuclear Facility Components," 2004.
8. Timoshenko Stephen P., Woinowsky-Krieger S., "Theory of Plates and Shells," Second Edition.

Table 1: ANSYS Input and Output File Listing

Input File	Description/Comment
DB-OUTLET-RES.INP	Structural geometry for 2D axisymmetric geometry [1]
MProp_MISO_NLinear_DB.INP	Material Property data of E, alpha, conductivity, specific heat, and stress strain curves [1]
BCNUGGET2D.INP	Weld nuggets definition and boundary conditions file
THERMAL2D.INP	Thermal pass for simulating weld processes
MapTemp.MAC	Create fusion boundary plots
STRESS2D.INP	Stress pass for simulating weld processes
WELD1 _mntr.INP	Contains LDREAD commands for the ID weld repair portion of the stress pass
WELD2_mntr.INP	Contains LDREAD commands for the buffer layer portion of the stress pass
WELD3_mntr.INP	Contains LDREAD commands for the weld overlay portion of the stress pass
POST2D_PATH.INP	Post-processing file to extract path stresses
POST2D_ID.INP	Post-processing file to extract ID surface stresses
Output File	**Description/Comment**
PATH_T70.OUT	Path stress outputs for post-WOL at 70°F
PATH_T556_P2255.OUT	Path stress outputs for post-WOL at 556°F and 2255 psig
ID_NLIST.OUT	ID surface nodal coordinate outputs
ID_WELD1.OUT	ID surface stress outputs for post-ID weld repair at 70°F
ID_T70.OUT	ID surface stress outputs for post-WOL at 70°F
ID_T556_P2255.OUT	ID surface stress outputs for post-WOL at 556°F and 2255 psig
DB_0800368_324_RES.xls	Excel spreadsheet containing all output data

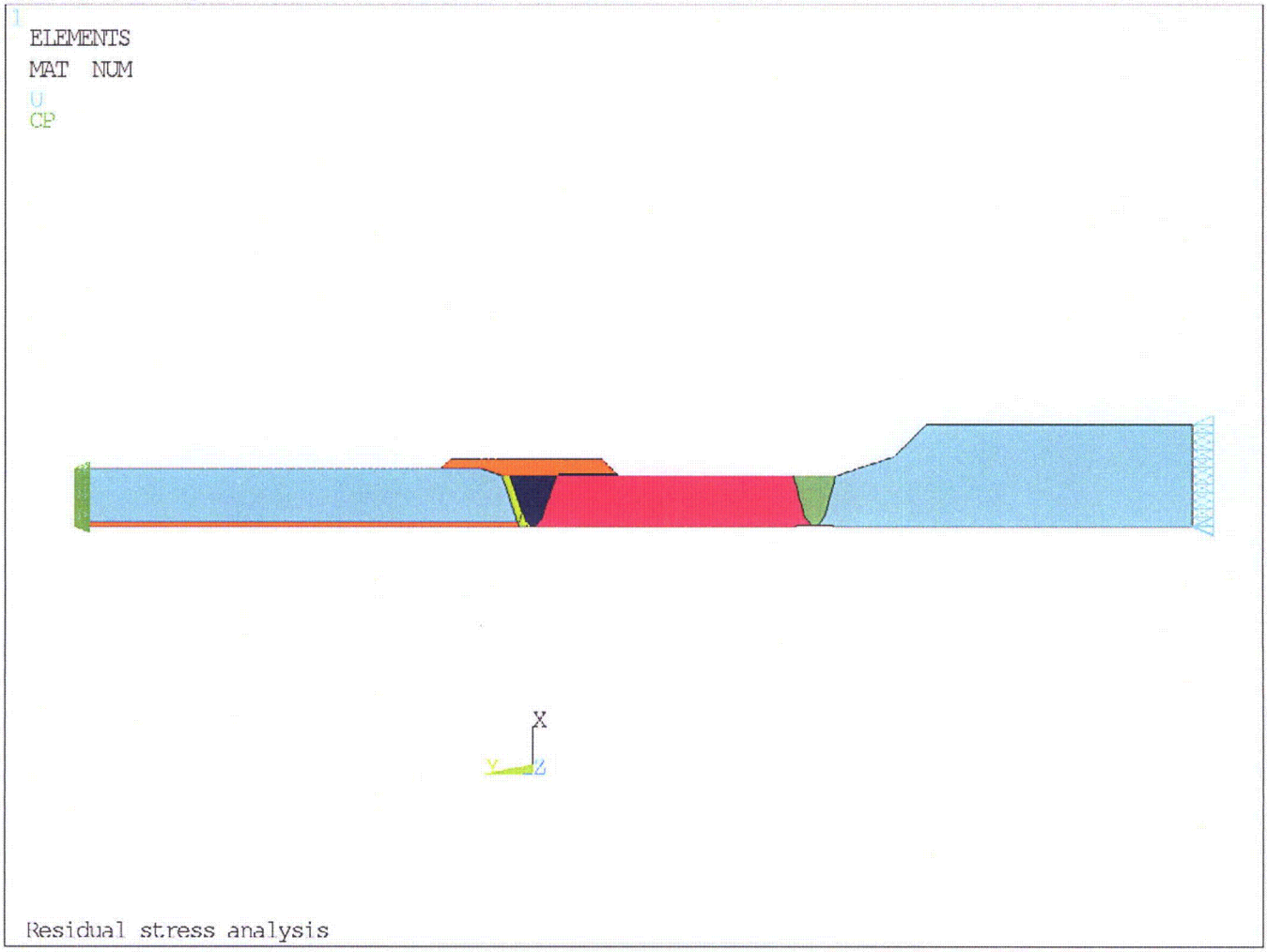

Figure 1. Applied Boundary Conditions to the Finite Element Model

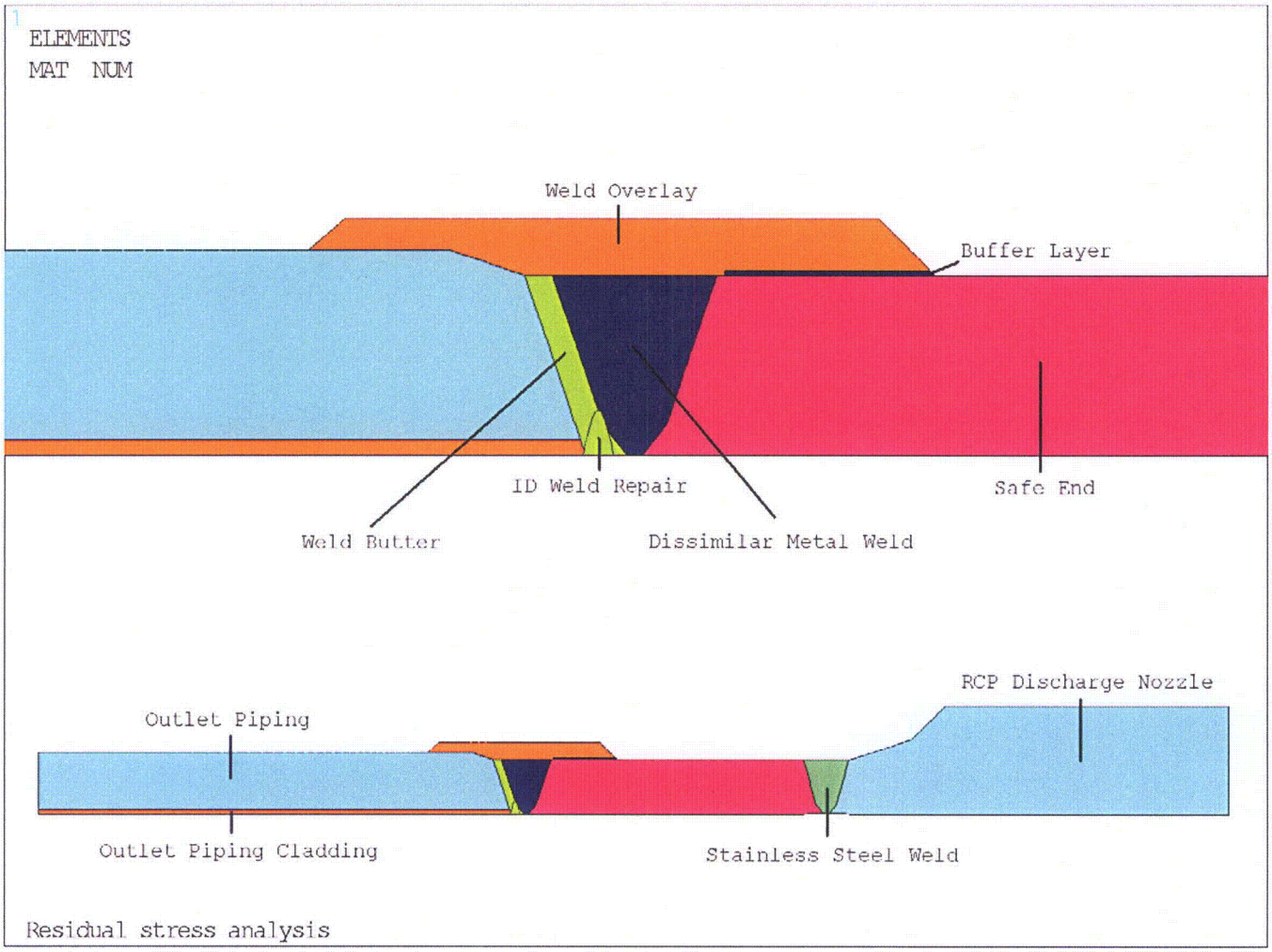

Figure 2. RCP Discharge Nozzle with Weld Overlay Repair - Model Components

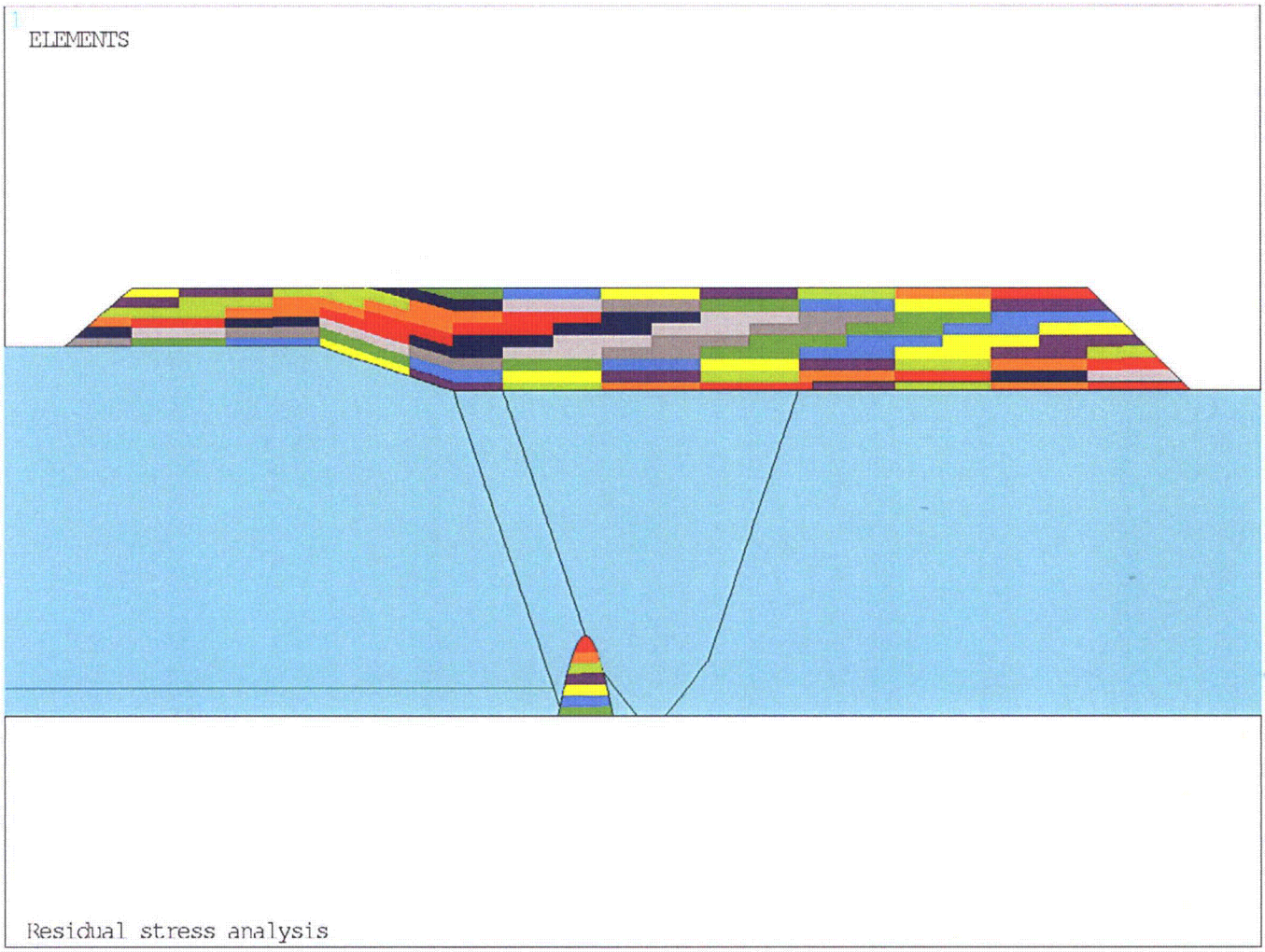

Figure 3. As-Modeled Nuggets for ID Weld Repair (7), Buffer layer (4), and Weld Overlay (87)

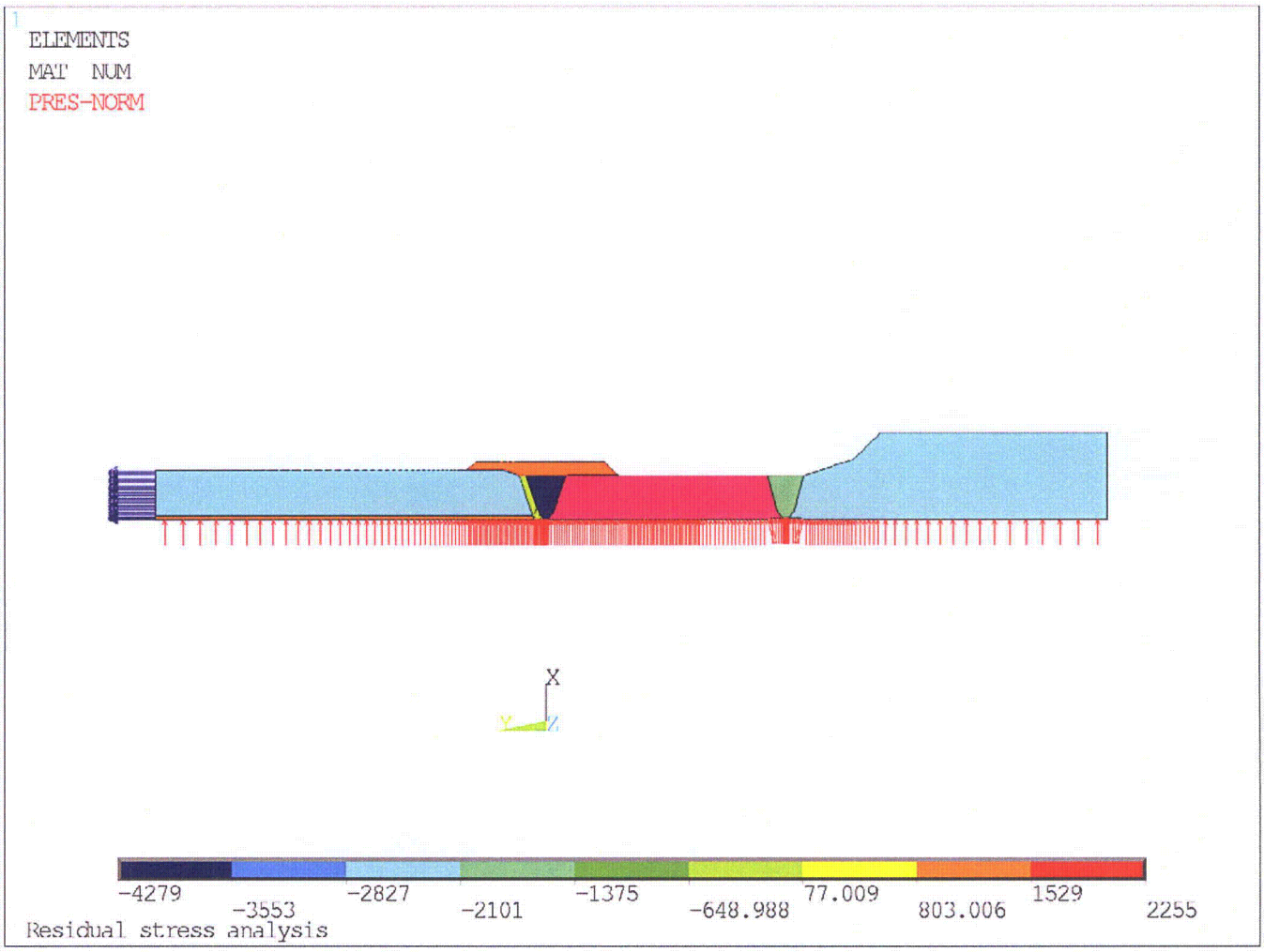

Figure 4. Internal Operating Pressure plus End Cap Loading

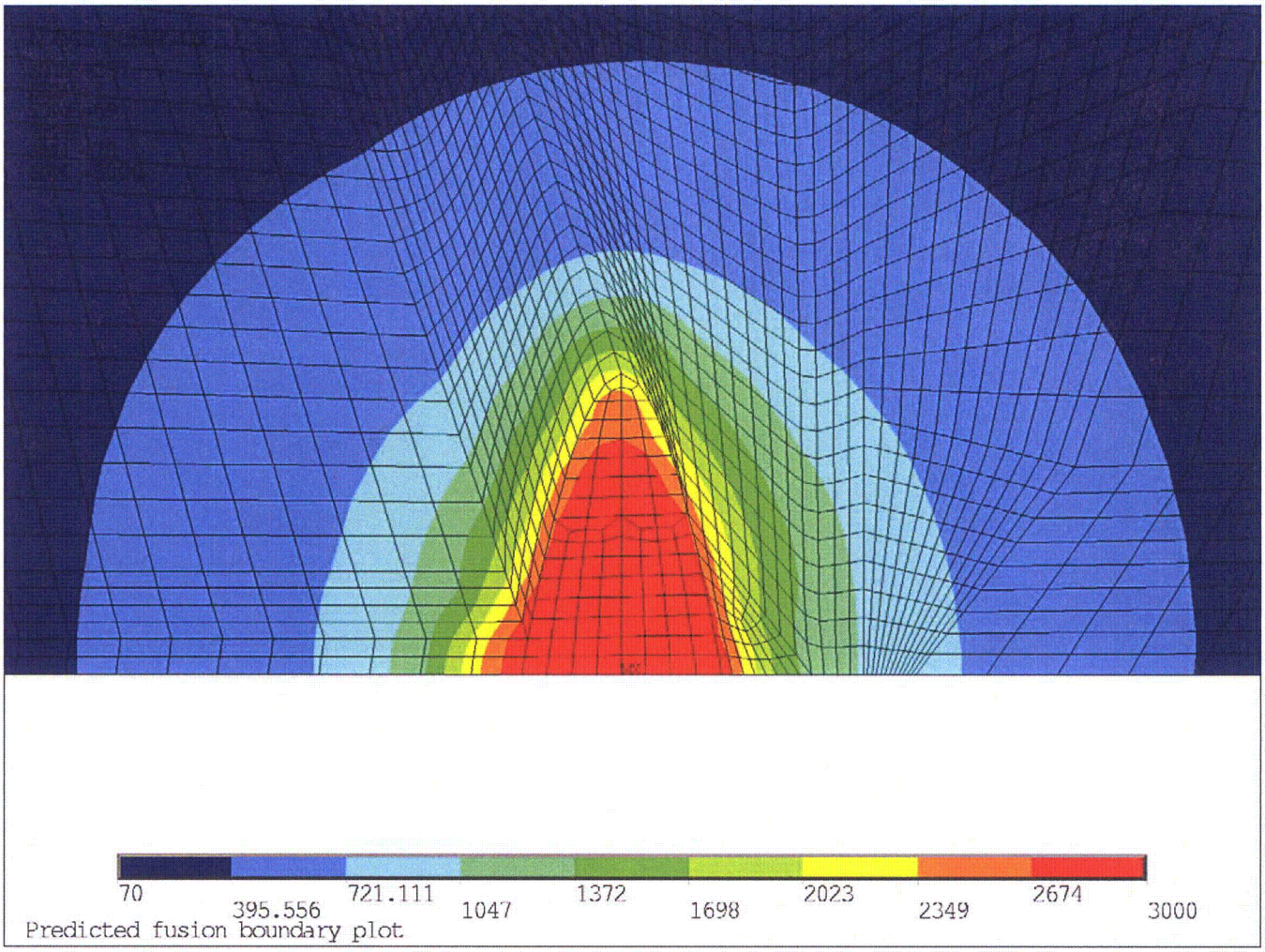

Figure 5. Predicted Fusion Boundary for ID Weld Repair

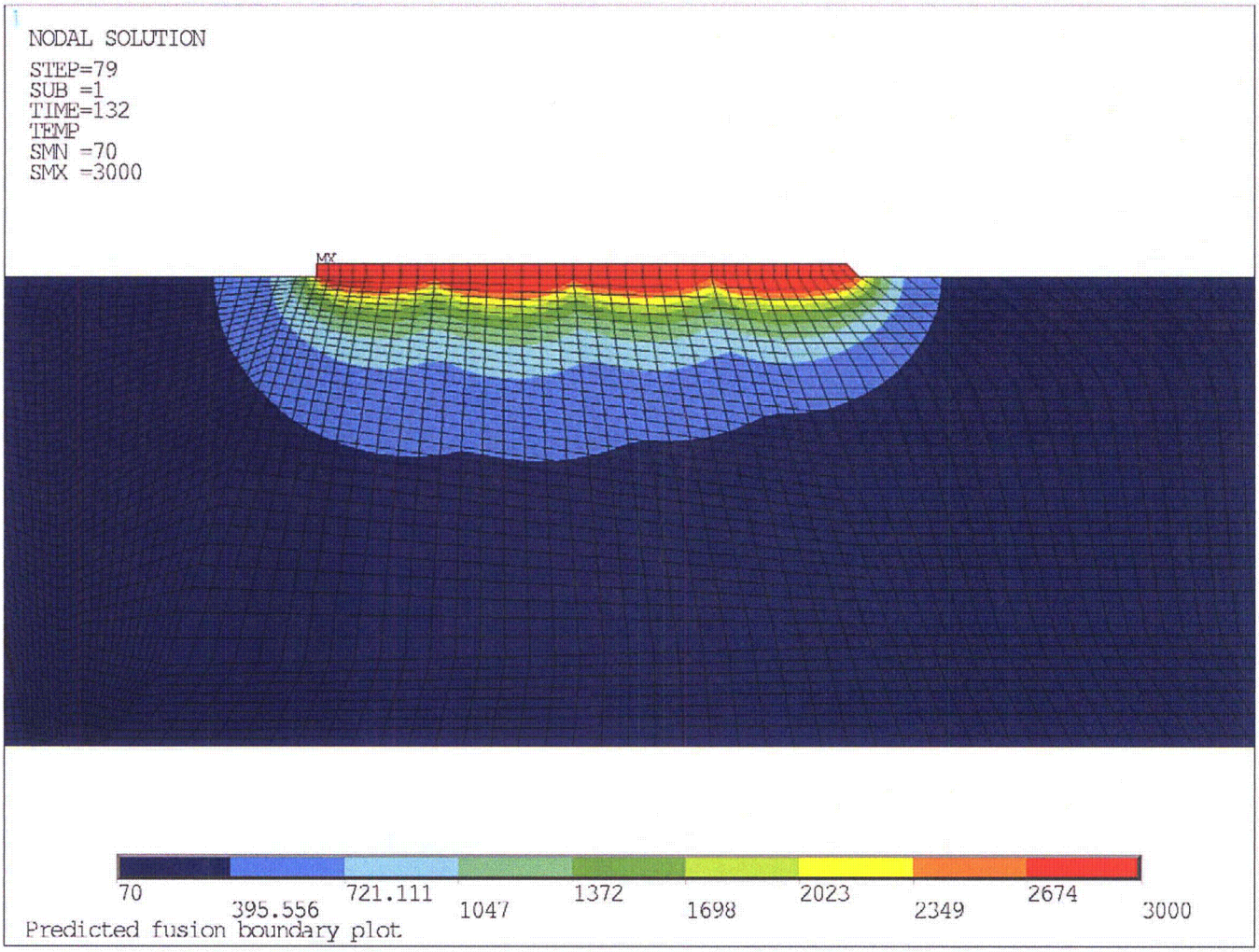

Figure 6. Predicted Fusion Boundary for Buffer Layer

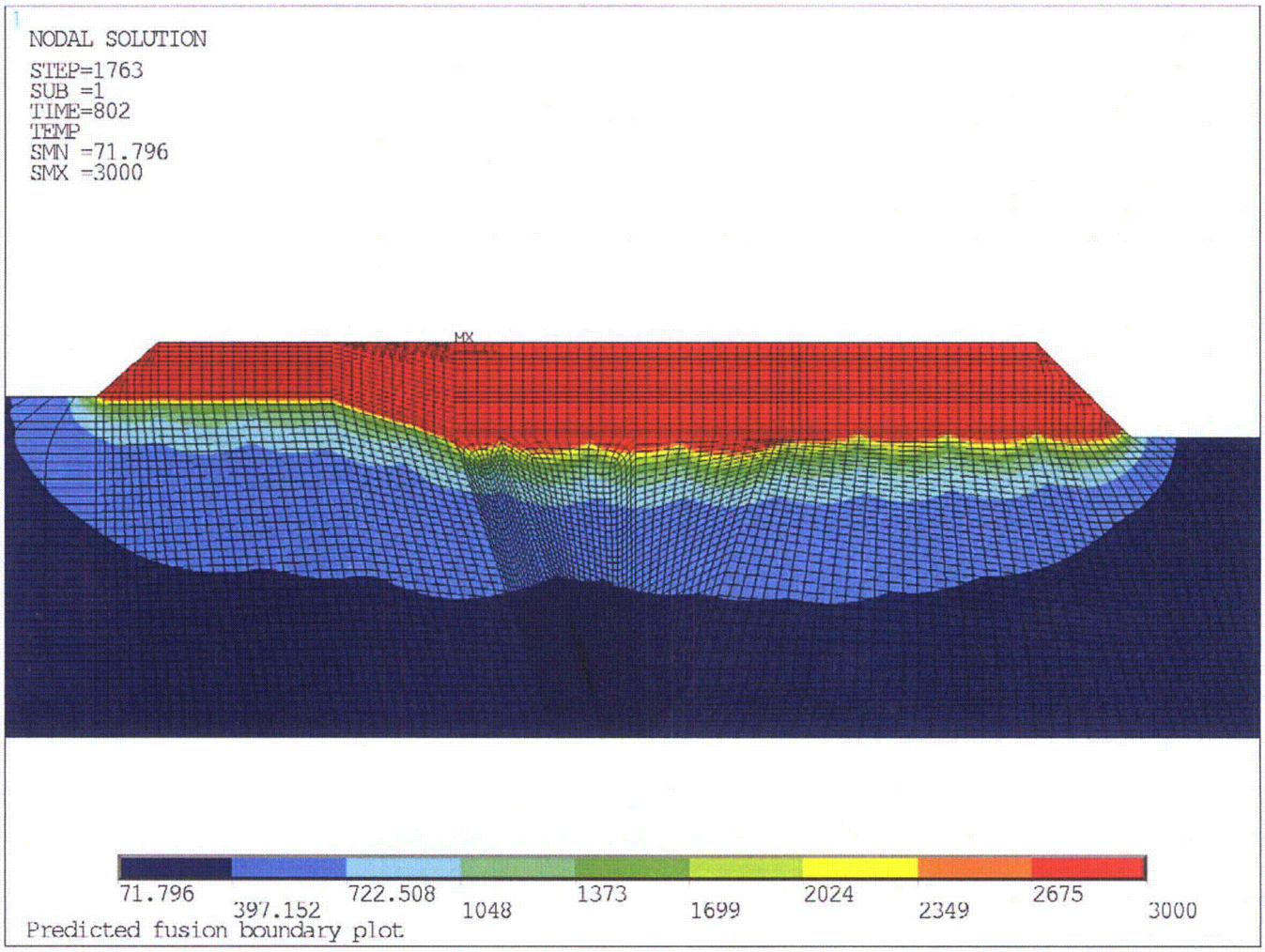

Figure 7. Predicted Fusion Boundary for Weld Overlay

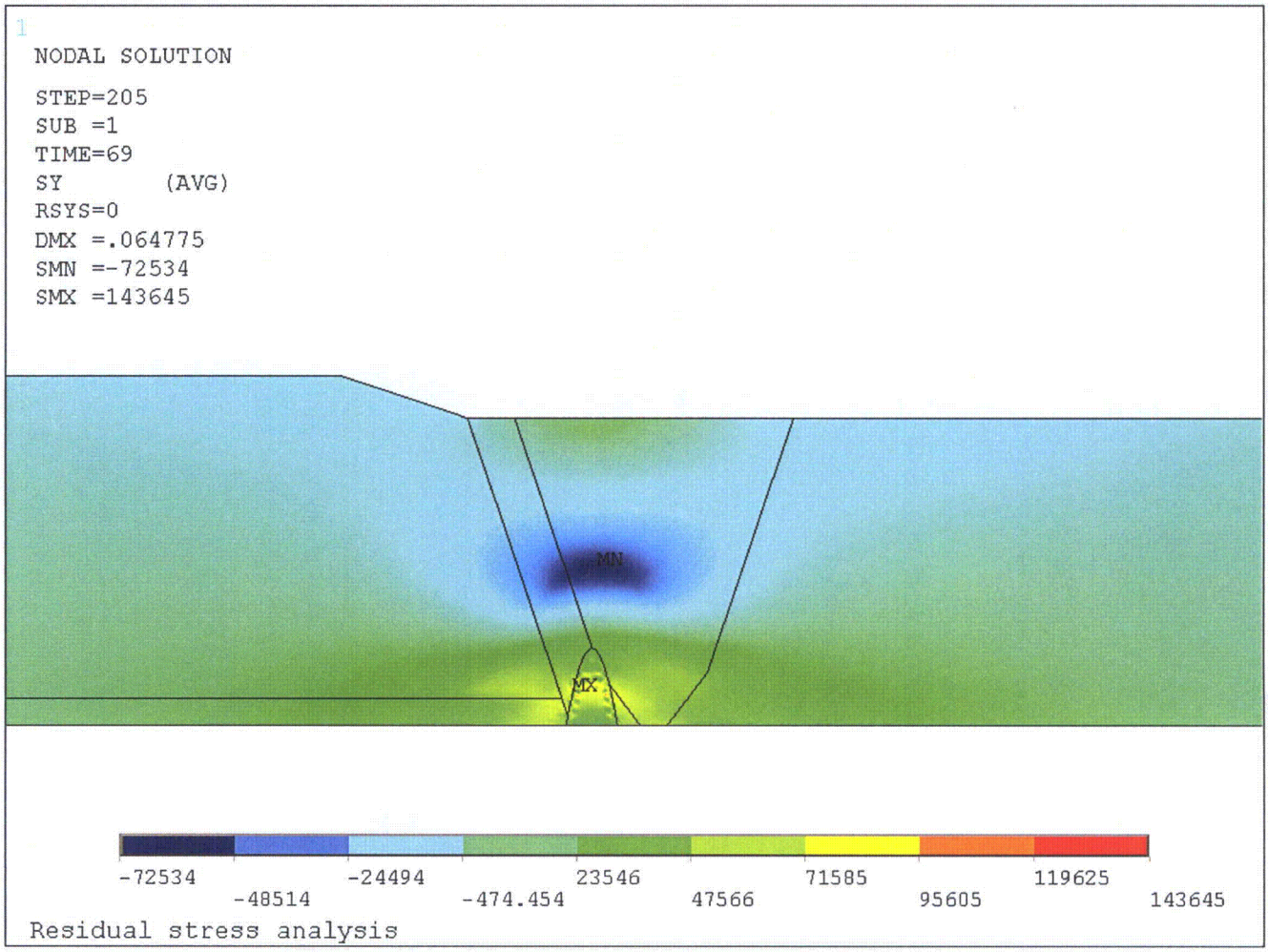

Figure 8. Post ID Weld Repair - Axial Stress at 70°F

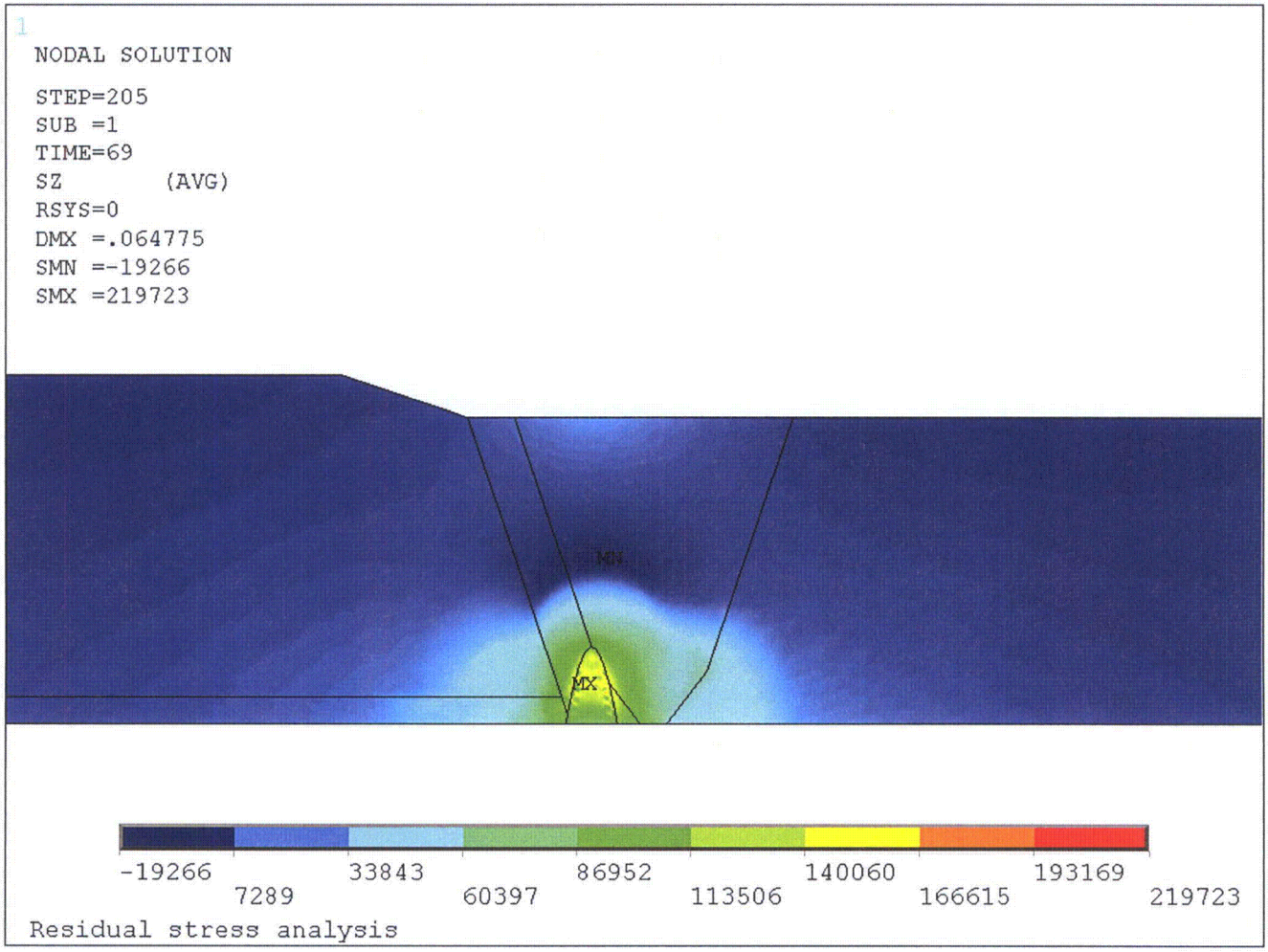

Figure 9. Post ID Weld Repair - Hoop Stress at 70°F

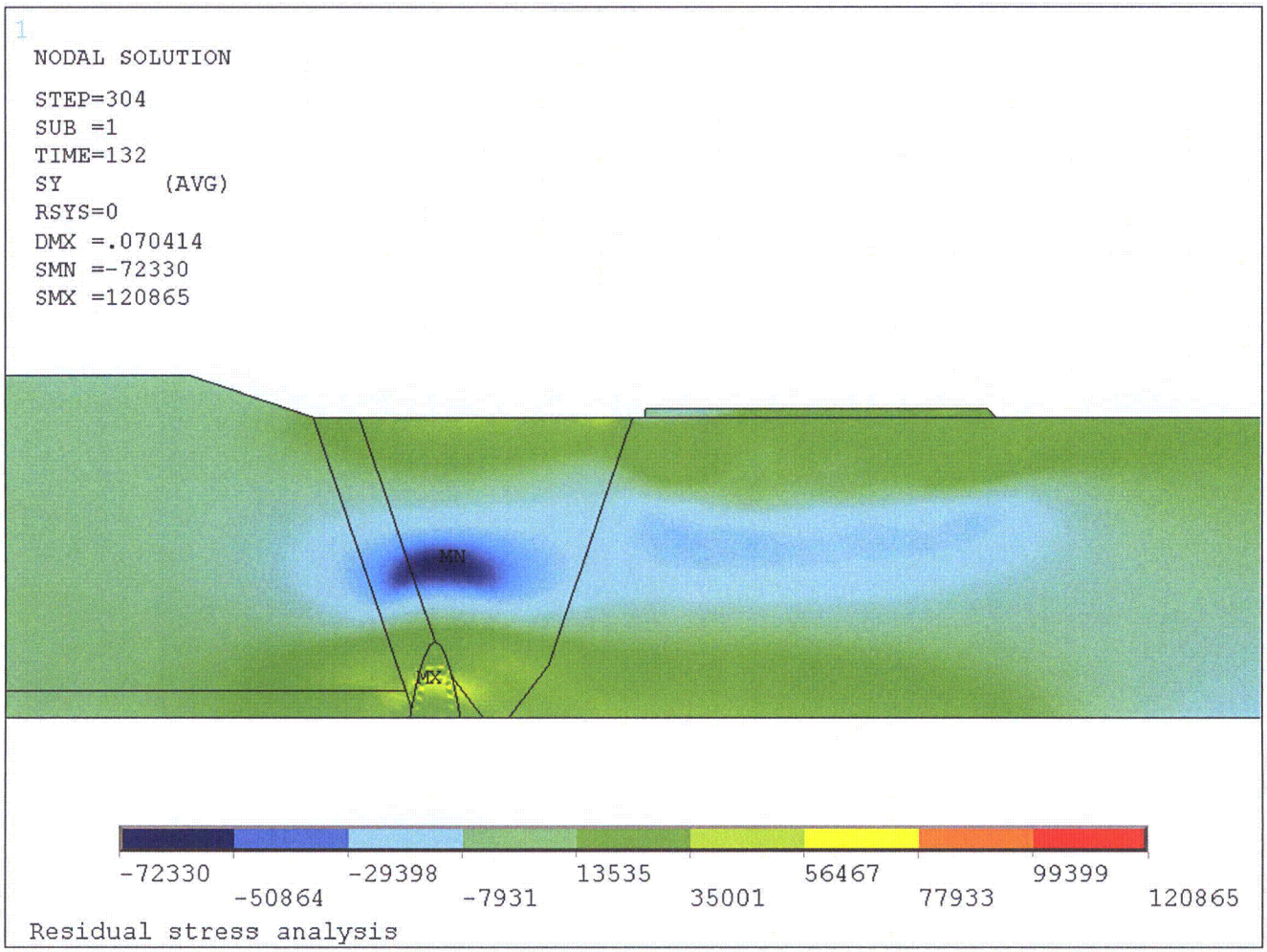

Figure 10. Post Buffer Layer - Axial Stress at 70°F

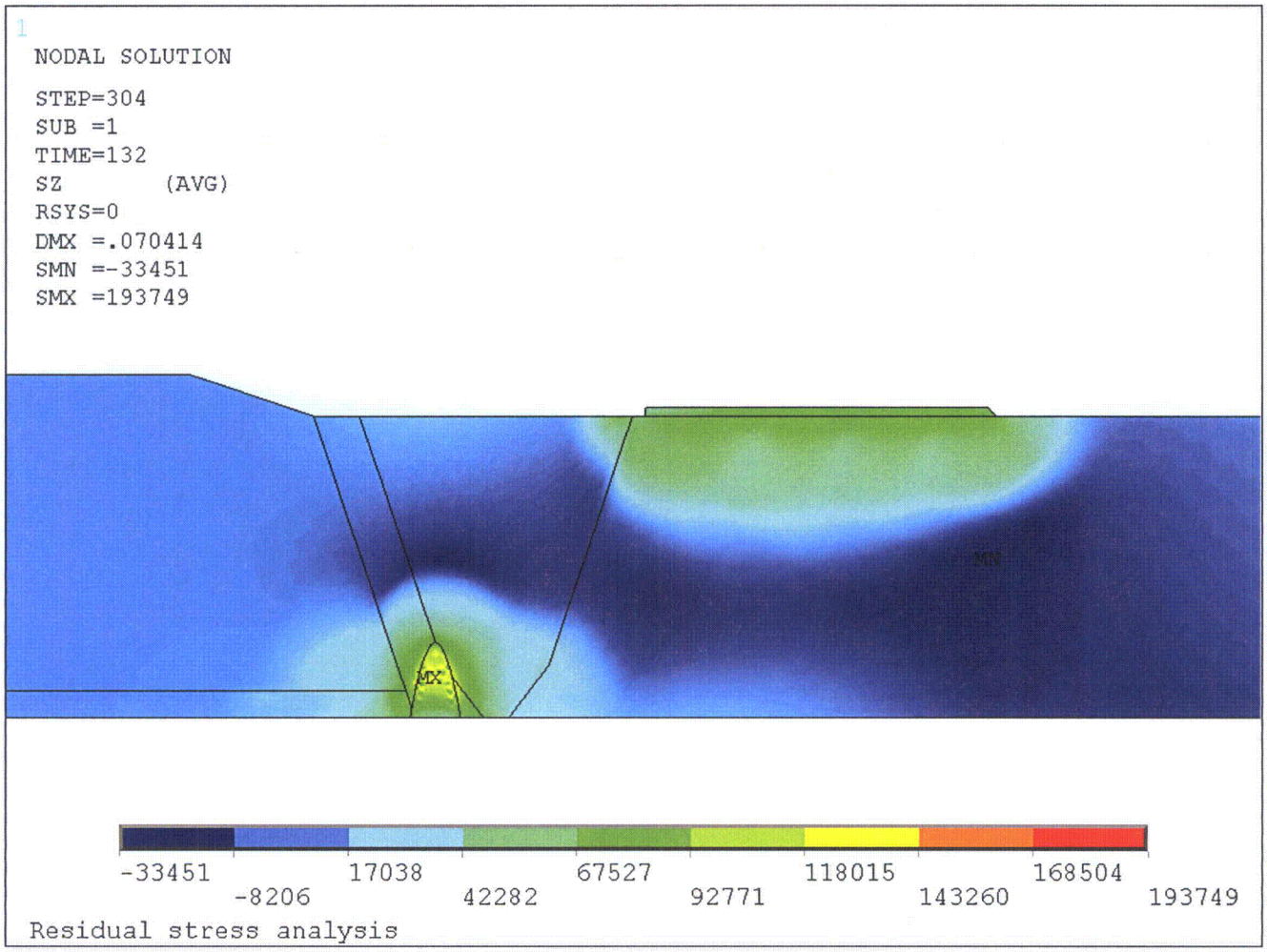

Figure 11. Post Buffer Layer - Hoop Stress at 70°F

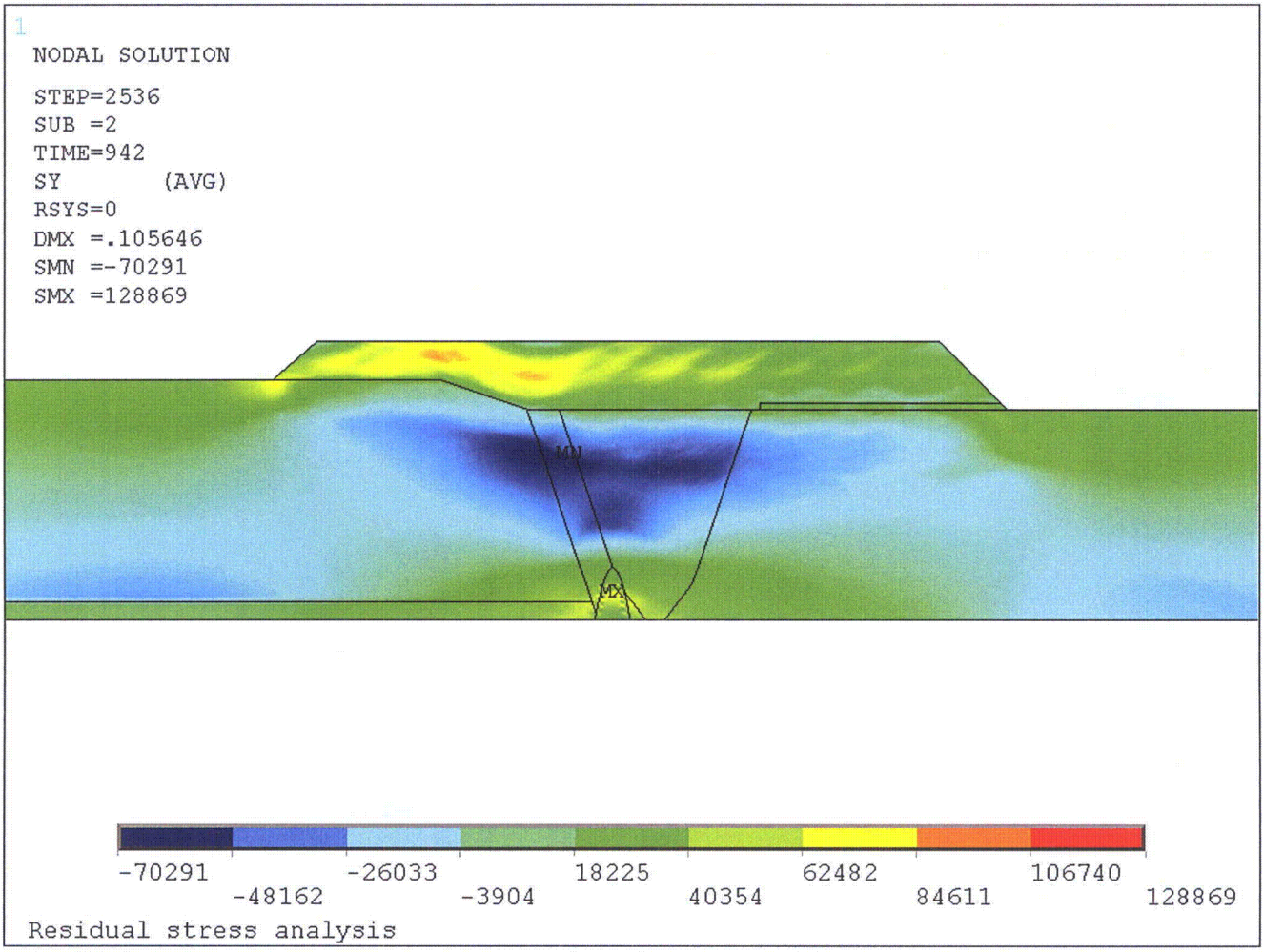

Figure 12. Post Weld Overlay Repair - Axial Stress at 70°F

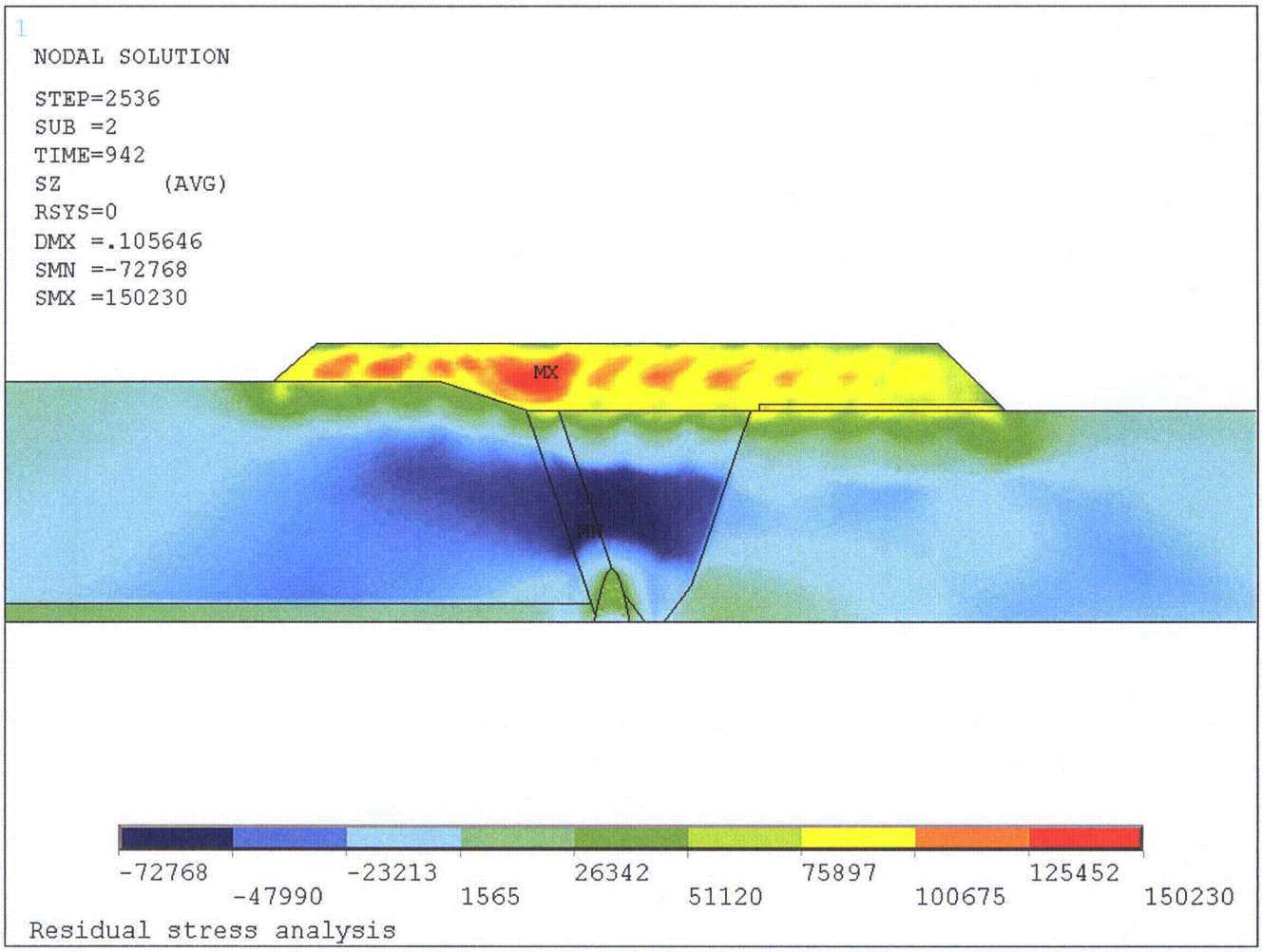

Figure 13. Post Weld Overlay Repair - Hoop Stress at 70°F

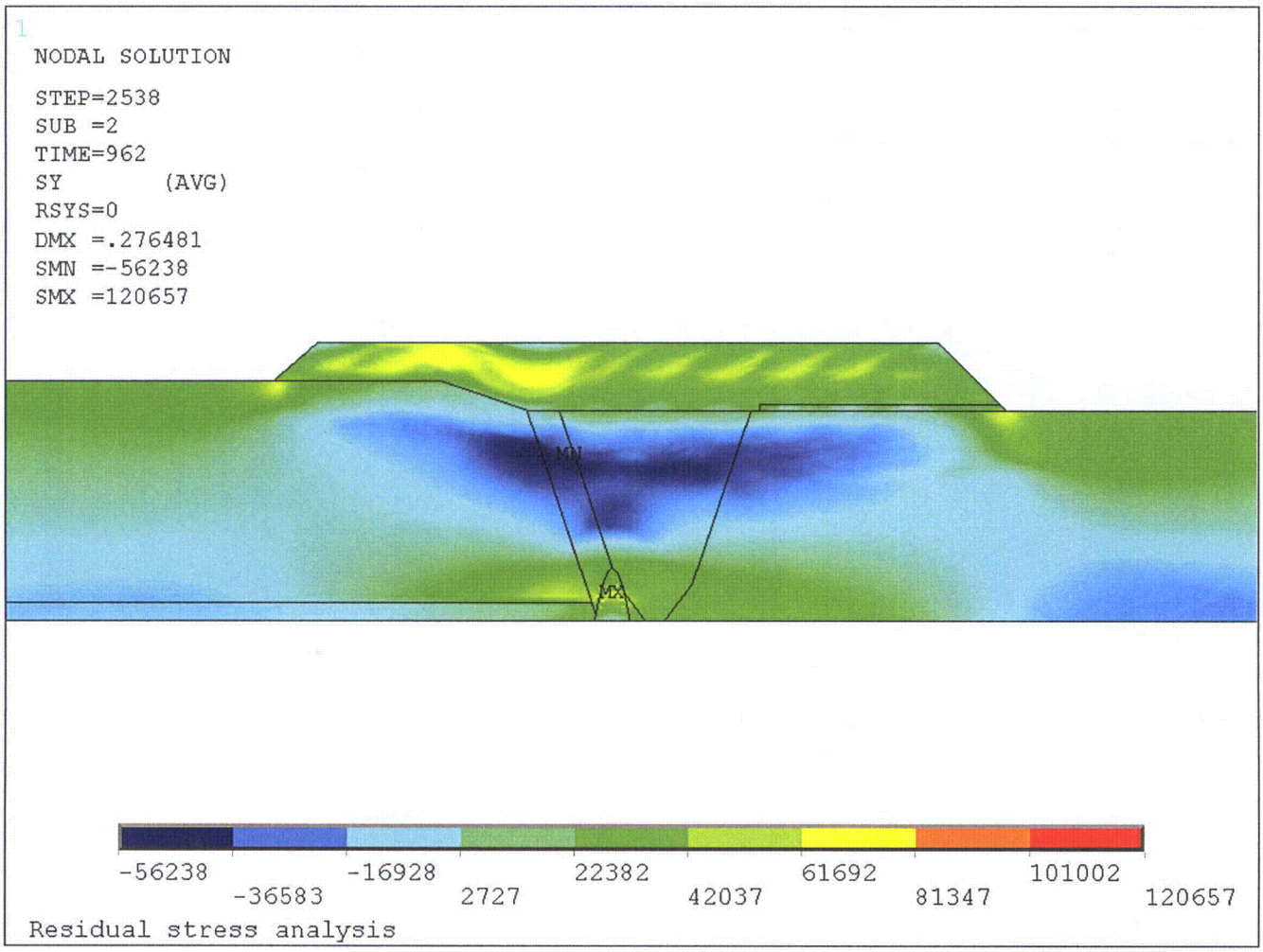

Figure 14. Post Weld Overlay Repair - Axial Stress at 556°F and 2255 Psig

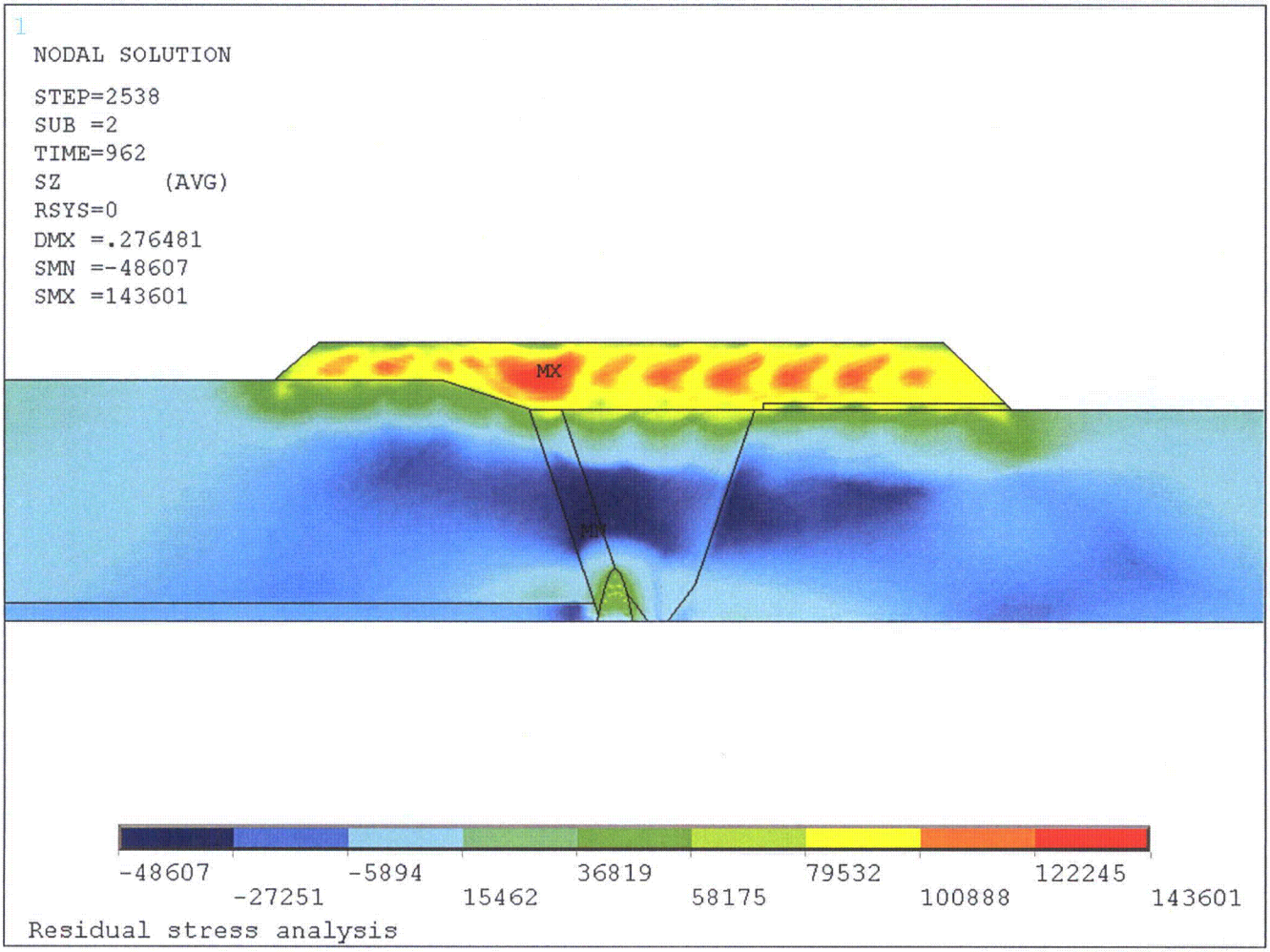

Figure 15. Post Weld Overlay Repair - Hoop Stress at 556°F and 2255 Psig

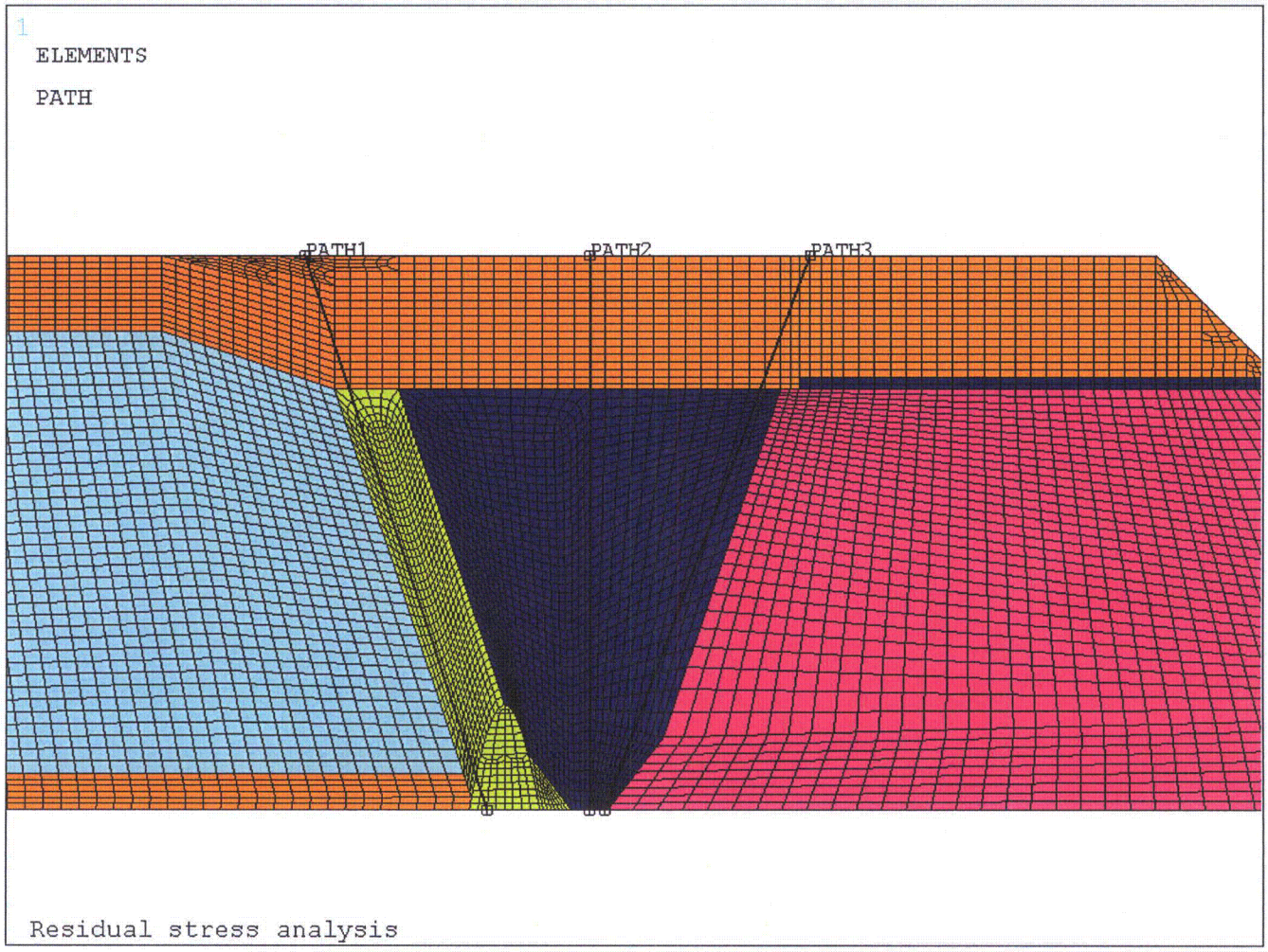

Figure 16. Path Definitions

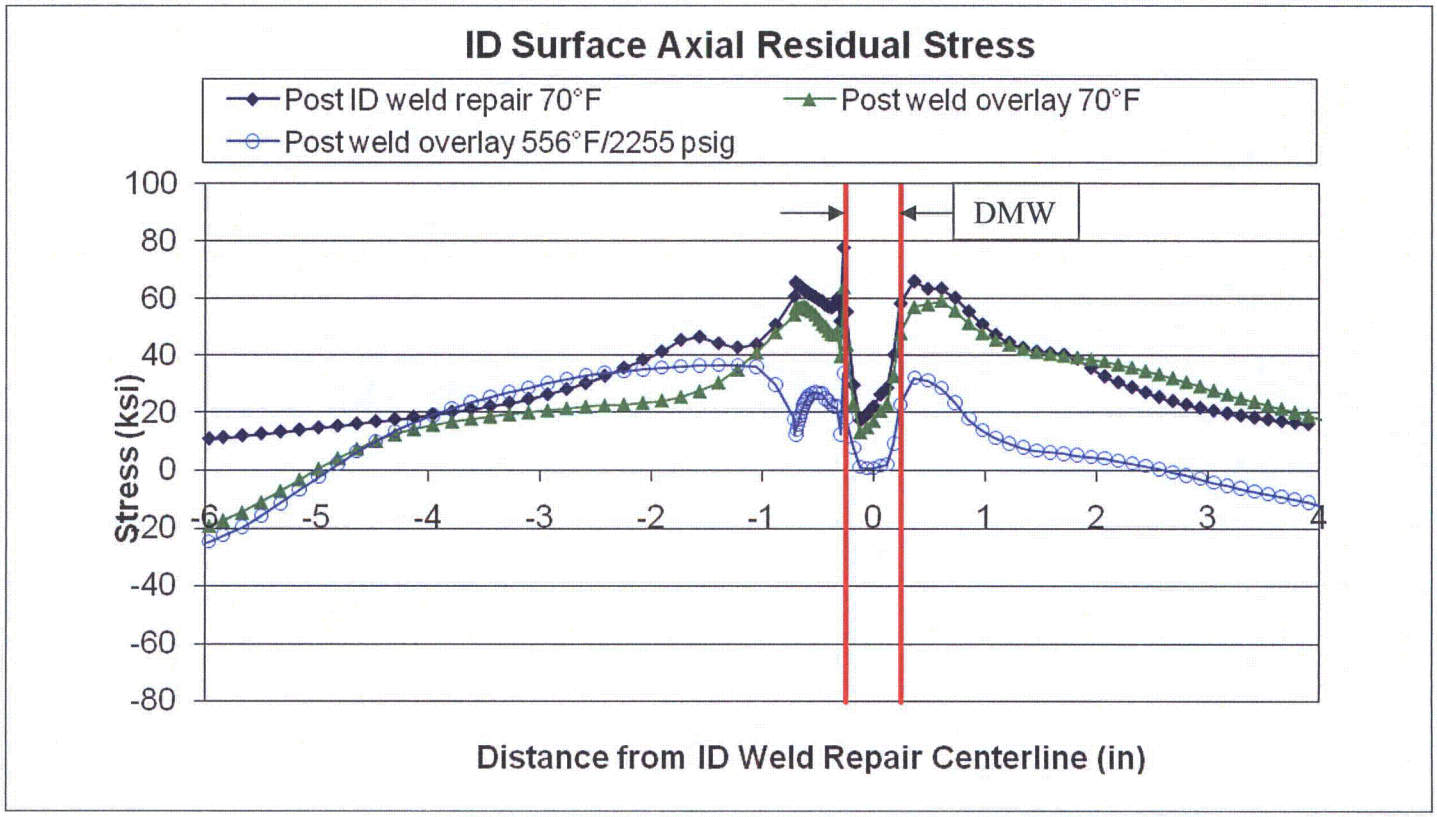

Figure 17. ID Surface Axial Residual Stress

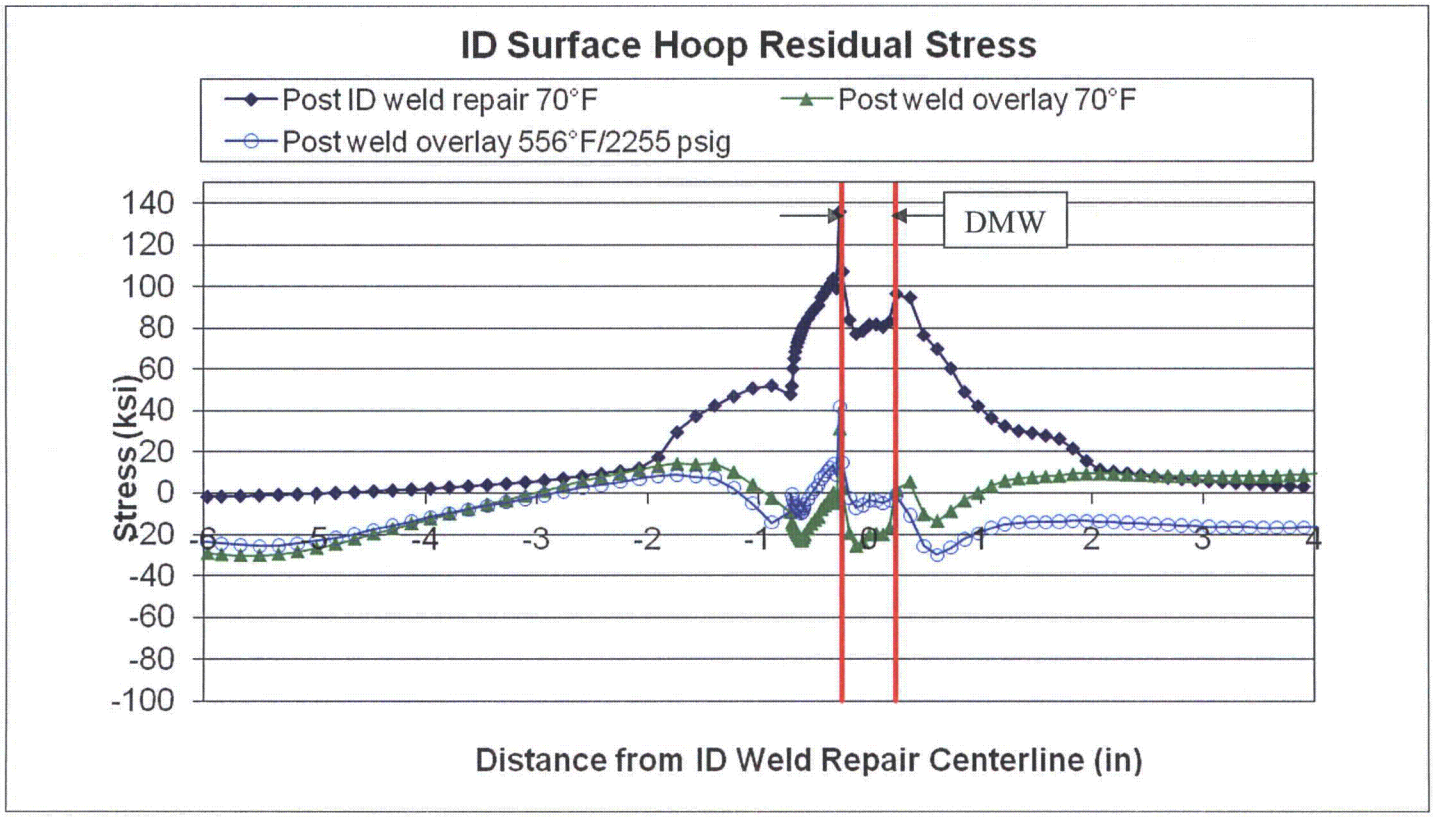

Figure 18. ID Surface Hoop Residual Stress