ENCLOSURE 6

MONTICELLO NUCLEAR GENERATING PLANT

LICENSE AMENDMENT REQUEST

REVISE THE TECHNICAL SPECIFICATIONS TO INCLUDE A PRESSURE TEMPERATURE LIMITS REPORT

CALCULATION CA 11-004

FINITE ELEMENT STRESS ANALYSIS OF MONTICELLO RPV FEEDWATER NOZZLE

(SIA No. 1000847.302)

(31 pages follow)

Xcel Energy

Calculation Signature Sheet

Document Information	
NSPM Calculation (Doc) No: 11-004	Revision: 0
Title: Finite Element Analysis of Monticello RPV Feedwater Nozzle	
Facility: ☒ MT ☐ PI	Unit: ☒ 1 ☐ 2
Safety Class: ☒ SR ☐ Aug Q ☐ Non SR	
Special Codes: ☐ Safeguards ☐ Proprietary	
Type: **Calc** Sub-Type:	

NOTE:	Print and sign name in signature blocks, as required.

Major Revisions		☐ N/A
EC Number: 17501	☒ Vendor Calc	
Vendor Name or Code: Structural Integrity Integrity (SIA)	Vendor Doc No: 1000847.302	
Description of Revision: New Calculation Issuance		
The following calculation and attachments have been reviewed and deemed acceptable as a legible QA record		☒
Prepared by: (sign) By vendor / (print) SIA	Date: 10/9/2010	
Reviewed by: (sign) Wynter A. McGruder / (print) Wynter McGruder	Date: 1/24/2011	
Type of Review: ☐ Design Verification ☐ Tech Review ☒ Suitability Review		
Method Used (For DV Only): ☐ Review ☐ Alternate Calc ☐ Test		
Approved by: (sign) S Kibler / (print) Steve Kibler	Date: 2/17/11	

Minor Revisions		☐ N/A
EC No:	☐ Vendor Calc:	
Minor Rev. No:		
Description of Change:		
Pages Affected:		
The following calculation and attachments have been reviewed and deemed acceptable as a legible QA record		☐
Prepared by: (sign) / (print)	Date:	
Reviewed by: (sign) / (print)	Date:	
Type of Review: ☐ Design Verification ☐ Tech Review ☐ Suitability Review		
Method Used (For DV Only): ☐ Review ☐ Alternate Calc ☐ Test		
Approved by: (sign) / (print)	Date:	

Record Retention: Retain this form with the associated calculation for the life of the plant.

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NOTE:	This reference table is used for data entry into the PassPort Controlled Documents Module reference tables (C012 Panel). It may also be used as the reference section of the calculation. The input documents, output documents and other references should all be listed here. Add additional lines as needed by using the "TAB" key and filling in the appropriate information in each column.

Reference Documents (PassPort C012 Panel from C020)

#	Controlled* Doc? + Type		Document Name	Document Number	Doc Rev	Ref Type**	
						INPUT	OUTPUT
1			U.S. NRC, Reactor Vessel Integrity Database, Version 2.0.1	N/A	N/A	X	
2	x	SPEC	GE Stress Report No. 22A7454, Revision 1, "Reactor Vessel (System Cycling),"	MPS-841	1	X	
3			ASME Boiler and Pressure Vessel Code, Section III including Appendices, 1977 Edition with Addenda through Summer 1978	N/A	N/A	X	
4	x	DRAW	Chicago Bridge & Iron No. 9, Revision 7, "Detail of 10" Stub Mk. # N4 A/D for 17'2" I.D x 63'-2" Ins Heads Nuclear Reactor for General Electric Company for Northern States Power," NX-8290-73	NX-8290-73	7	X	
5	X	SPEC	GE Design Specification No. 22A6996, Revision 0, "Reactor Vessel System Cycling,"	MPS-843	0	X	
6			ANSYS Mechanical and PrepPost, Release 11.0 (w/ Service Pack 1), ANSYS, Inc. August 2007	N/A	N/A	X	
7	x	SPEC	GE Design Specification No. 21A1112, Revision 6, "Reactor Pressure Vessel"	MPS-179	6	X	
8							
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Calculation Signature Sheet

16							
17							

* Controlled Doc marked with an "X" means the reference can be entered on the C012 panel in black. Unmarked lines will be yellow. If marked with an "X", also list the Doc Type, e.g., CALC, DRAW, VTM, PROC, etc.

** Mark with an "X" if the calculation provides inputs and/or outputs or both. If not, leave blank. (Corresponds to PassPort "Ref Type" codes: **Inputs / Both** = "ICALC", **Outputs** = "OCALC", **Other / Unknown** = blank)

Other PassPort Data

Associated System (PassPort C011, first three columns) **OR** **Equipment References** (PassPort C025, all five columns):

Facility	**Unit**	**System**	**Equipment Type**	**Equipment Number**
MT	1	RPV		

Superseded Calculations (PassPort C019):

Facility	**Calc Document Number**	**Title**
N/A	N/A	N/A

Description Codes - Optional (PassPort C018):

Code	**Description (optional)**	**Code**	**Description (optional)**

Notes (Nts) - Optional (PassPort X293 from C020):

Topic Notes	**Text**

Record Retention: Retain this form with the associated calculation for the life of the plant.

Xcel Energy	Calculation Signature Sheet

☐ Calc Introduction	☐ Copy directly from the calculation Intro Paragraph **or** ☐ See write-up below
☐ (Specify)	

Record Retention: Retain this form with the associated calculation for the life of the plant.

Xcel Energy	Calculation Signature Sheet

Monticello Specific Information

☒ YES ☐ N/A Topic Code(s) (See MT Form 3805): PLEX, RATE
☐ YES ☒ N/A Structural Code(s) (See MT Form 3805):_______

Does the Calculation:

☐ YES ☒ No Require Fire Protection Review? (Using MT Form 3765, "Fire Protection Program Checklist", determine if a Fire Protection Review is required.) If YES, document the engineering review in the EC. If NO, then attach completed MT Form 3765 to the associated EC.

☐ YES ☒ No Affect piping or supports? (If Yes, Attach MT Form 3544.)

☐ YES ☒ No Affect IST Program Valve or Pump Reference Values, and/or Acceptance Criteria? (If Yes, inform IST Coordinator and provide copy of calculation.)

Structural Integrity Associates, Inc.

CALCULATION PACKAGE

File No.: 1000847.302	
Project No.: 1000847	Quality Program: ☒ Nuclear ☐ Commercial

PROJECT NAME:
Monticello P-T Curves Revision According to the PTLR Methodology

CONTRACT NO.:
1005, Release 18

CLIENT:	**PLANT:**
Xcel Energy, Inc.	Monticello Nuclear Generating Plant

CALCULATION TITLE:
Finite Element Stress Analysis of Monticello RPV Feedwater Nozzle

Document Revision	Affected Pages	Revision Description	Project Manager Approval Signature & Date	Preparer(s) & Checker(s) Signatures & Date
0	1 - 25 A-1	Initial Issue	Eric Houston EJH 10/9/10	Clark Oberembt CJO 10/8/10 Yu Chen YC 10/8/10

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1.0 OBJECTIVE

The objective of this calculation is to perform finite element stress analysis on Monticello Nuclear Generating Plant's feedwater (N4) nozzles to support Pressure-Temperature (P-T) curve development. The development of P-T curves for the N4 nozzles requires the consideration of a postulated ¼ thickness flaw in the nozzle blend radius. The results of this analysis will be used to develop stress intensity factors at the postulated flaw tip.

2.0 METHODOLOGY

A three-dimensional (3-D) finite element model (FEM) is constructed for the feedwater nozzle to be evaluated. For this analysis, the region of interest is the nozzle blend radius. The FEM also includes a portion of the reactor pressure vessel (RPV) as well as the internal cladding. Appropriate boundary conditions are applied to reflect symmetry in the model. A mechanical analysis with a unit internal pressure load and two thermal transient analyses are performed. One path through the nozzle blend radius is defined based on the maximum hoop stress at the inside surface of the nozzle, due to pressure, and the shortest path to the outside of the blend radius. The selection of a single path is most appropriate to support the P-T curve evaluation because RPV hoop stress is twice membrane stress and the thermal gradient is nearly uniform around the blend radius. Experience has shown that the hoop stress distribution due to pressure loading usually produces approximately a three times greater stress intensity factor than due to thermal stresses at the tip of the postulated flaw. Mapped hoop stresses are extracted along this path for the mechanical and thermal analyses. For the thermal analyses, the auto time stepping feature in ANSYS, along with a small initial step, is used to generate the time steps for temperature and stress solutions.

The assumptions made in order to define the evaluation approach and perform the analysis are summarized in Section 4.0. The application of these assumptions is indicated throughout the document using a set of braces containing the appropriate assumption number; for example, Assumption #1 would be indicated as {1, §4.0}.

3.0 DESIGN INPUTS

The following design inputs are used in this calculation:

- RPV material = SA-533 Gr. B [1]
- N4 material = SA-508 Cl II [2]
- Cladding material = Type ER308 stainless steel [7]
- N4 Design Code of Record [2, Sheet No. 2]= ASME Section III, 1977 Edition with Addenda through Summer 1978 [3]
- Temperature dependent material properties are obtained from Reference [3] and are listed in Tables 1 through 3
- RPV and N4 geometry are taken from References [4, 5] and reproduced in Figure 1 {1, §4.0}
  - o Reference [4] shows the original N4 nozzle configuration
  - o Reference [5] shows the modified N4 nozzle configuration
- Maximum fluid temperature under normal operating condition = 546°F [5, Section 4.6.7.2.2]

- Normal operating thermal transients applicable to the N4 nozzle are defined in Reference [5, Section 4.6.7] {2, §4.0}
- The effect of the thermal sleeve is approximated by calculating the fluid temperature in the annulus when there is feedwater flow using the methods described in Reference [5, Appendix 20]
- Ambient air temperature outside of the vessel is 100°F [5, Section 4.3.2.1]
- Heat transfer coefficients (see Figures 6, 7, and 8 and Section 6.0 for region definitions and application areas on the model)
  - Exterior surface heat transfer coefficient (Btu/hr-ft^2-°F) = 0.2 [5, Section 4.3.2.1]
  - Vessel region internal heat transfer coefficient (Btu/hr-ft^2-°F) = 500 [5, Appendix 20]

4.0 ASSUMPTIONS

The assumptions made in order to define the evaluation approach and perform the analysis are summarized in the following list. The application of these assumptions is indicated throughout the document using a set of braces containing the appropriate assumption number; for example, Assumption #1 would be indicated as {1, §4.0}.

1. The following assumptions are made in regards to the modeled geometry:

   a. Some features remote from the area of interest are not modeled. This includes the safe end, safe end-to-nozzle weld, thermal sleeve and the nozzle-to-vessel weld. This simplification of the model is remote from the area of interest and the impact of this assumption is minimal.

   b. Some features remote from the area of interest are simplified. Some fillet radii are ignored and modeled as points, the nozzle ID is assumed constant at 10.88 in. upstream of the blend radius modification, and the location of the nozzle-to-vessel material transition is approximated at the centerline of the nozzle-to-vessel weld. This simplification of the model is remote from the area of interest and the impact of this assumption is minimal.

   c. For the pressure load analysis, the cladding is assumed not to contribute to the stress solution and the associated cladding volumes are removed from the analysis (cladding is not removed for the thermal transient analyses) consistent with Reference [3].

2. Reference [5] defines the thermal transients applicable to the N4 nozzle, the following assumptions are made in regard to the bounding transients:

   a. The N4 nozzle thermal shock transient from 546°F to 100°F, when feedwater flow is initiated, is assumed to occur over 1 second. The effects of the thermal sleeve are approximated using the methods described in Reference [5, Appendix 20] to calculate the annulus fluid temperature. Annulus fluid temperature variation in the nozzle axial direction is conservatively ignored.

   b. The initial vessel heatup from 100°F to 546°F at 100°F/hr is defined in Reference [5], and a cooldown transient is not defined. However, a cooldown transient typically produces more severe hoop stress at the inner surface of the nozzle and vessel. Since the analysis

will be used in generating P-T limit curves, the location of interest is near the inner surface of the nozzle blend radius. Therefore, the defined heatup transient is conservatively modeled as a cooldown transient from 546°F to 100°F at -100°F/hr.

3. The forced convection heat transfer coefficients applied to the nozzle blend radius and the nozzle region (upstream of the blend radius) during the thermal shock analysis are taken from Reference [5, Appendix 20] and are modified as follows:

    a. The nozzle blend radius heat transfer coefficient is assumed to be constant at the maximum value given from "c to f" of 1500 Btu/hr-ft^2-°F. A higher HTC will produce a larger thermal gradient, which results in higher thermal stress and is conservative.

    b. The nozzle region heat transfer coefficient is assumed to be constant at the maximum value given from "a to c" of 750 Btu/hr-ft^2-°F. A higher HTC will produce a larger thermal gradient, which produces higher stress and is conservative.

4. Although Reference [2] specifies lower natural convection heat transfer coefficients for 0% feedwater flow, the vessel region forced convection heat transfer coefficient of 500 Btu/hr-ft^2-°F is applied to the entire inner surface of the model for the cooldown transient analysis. Higher heat transfer coefficients typically produce higher thermal stresses for this type of transient.

5. The material Poisson's ratio and weight density are assumed to be temperature independent at 0.3 and 0.283 lbf/in^3, respectively.

6. Unspecified material properties at -100°F are assumed equal to properties at 70°F.

7. All analyses are performed with a stress free reference temperature of 70°F.

8. All materials are assumed to follow linear-elastic isotropic material behavior.

5.0 FINITE ELEMENT MODEL

The three-dimensional (3-D) finite element model (FEM) is developed for the N4 nozzle using the ANSYS finite element software package [6] using 8-node SOLID45 3-D linear structural elements. The SOLID45 elements are converted to thermal solid elements (SOLID70) for the thermal transient analyses. The dimensions used for the nozzle and RPV shell are provided in References [4, 5] as modified by the assumptions in {1, §4.0}. The dimensions used in the model are presented in Figure 1.

The one-quarter 3-D model extends the end of the machined portion of the nozzle a total of 5 inches, while the RPV shell extends 45° circumferentially and 60 inches axially from the nozzle axis. These dimensions are large enough to eliminate non-representative boundary effects on the nozzle blend radius region in the finite element analysis (FEA) solution. The FEM is shown in Figures 2 and 3. The ANSYS input files used to generate the FEM are included with the electronic supporting files listed in Appendix A.

6.0 ANALYSIS

A static mechanical loading stress analysis, using a unit pressure, and two thermal transient stress analyses are performed in the FEA. A mesh density study is completed using the unit pressure load case to verify the quality of the mesh. Three different mesh densities are evaluated: Mesh 1 = 5,473 nodes, Mesh 2 = 30,775 nodes, and Mesh 3 = 178,507 nodes. The results for maximum hoop stress at the blend radius converged within 0.1% from Mesh 2 to Mesh 3. Mesh 2 is used in this analysis.

6.1 Mechanical Load Stress Analysis

For the unit pressure case, a uniform pressure of 1,000 psig is applied to the inside surface of the RPV and nozzle bore. The mechanical load stress results are intended to be linearly scaled during subsequent analyses as required. Note that the cladding is not included in the unit pressure analysis {1c, §4.0}. A cap load, P_{cl1}, is applied to the upper horizontal cut plane in the model, which is calculated as:

$$P_{cl1} = \frac{P_{unit} IR_{ves}^2}{OR_{ves}^2 - IR_{ves}^2}$$

where:

P_{unit} = unit pressure, psig
IR_{ves} = inside radius of RPV excluding cladding, in.
OR_{ves} = outside radius of RPV, in.

A cap load, P_{cl2}, is also applied to the free end of the nozzle, which is calculated as:

$$P_{cl2} = \frac{P_{unit} IR_{noz}^2}{OR_{noz}^2 - IR_{noz}^2}$$

where:

IR_{noz} = inside radius of nozzle, in.
OR_{noz} = outside radius of nozzle free end, in.

Symmetry boundary conditions are applied on both of the vertical cut planes and the lower horizontal cut plane in the 3-D model. The nodes at the free end of the nozzle are coupled in the axial direction, as are the RPV nodes on the upper horizontal cut plane. The unit pressure loads and boundary conditions are shown in Figures 4 and 5, respectively. The ANSYS input file for the unit pressure load is included with the electronic supporting files listed in Appendix A.

6.2 Thermal Transient Stress Analyses

For the transient case, the model exterior and interior surfaces are broken into different regions as shown in Figure 6. The regions are defined as follows:

- Region 1 – Exterior surfaces
- Region 2 – Vessel wall (interior surfaces)
- Region 3 – Blend radius (interior surfaces)
- Region 4 – Nozzle (interior surfaces, upstream of the blend radius)

The FEM is set to steady state with appropriate initial conditions before each transient is analyzed.

6.2.1 Thermal Shock Transient

The heat transfer coefficients described in Section 3.0 with {3, §4.0} are applied to the respective regions as shown in Figure 7. The air temperature for Region 1 is set at 100°F [5]. The fluid temperature for Region 2 is equal to the vessel temperature of 546°F [5]. The fluid temperature is calculated for Regions 3 and 4 using the methods described in Reference [5, Appendix 20]. Table 4 provides a summary of the thermal shock transient definition as analyzed. The ANSYS input files used to generate the thermal stresses are included with the electronic supporting files listed in Appendix A.

6.2.2 Cooldown Transient

The heat transfer coefficients as described in Section 3.0 with {4, §4.0} are applied to the respective regions as shown in Figure 8. The air temperature for Region 1 is set at 100°F [5]. The fluid temperature for Regions 2, 3, and 4 are equal at 546°F and decrease to 100°F at -100°F/hr. Table 5 provides a summary of the cooldown transient definition as analyzed. The ANSYS input files used to generate the thermal stresses are included with the electronic supporting files listed in Appendix A.

7.0 RESULTS OF ANALYSIS

After running the unit pressure load case, the nodes along the blend radius at both cut planes are queried for the location of maximum hoop stress. This confirms that the maximum hoop stress is along the RPV axial cut plane as expected. Figure 9 shows the location of maximum hoop stress due to pressure. A stress extraction path is defined for the cut plane that includes this maximum location. The path starts at the nodal location of maximum hoop stress and extends through the blend radius along the shortest path length. Figure 10 shows the path location. The mapped hoop stresses are extracted along this path for the static unit pressure analysis. For the thermal transient load case, the mapped hoop stresses are extracted along the same path for all time steps. The stress extraction results from the FEA are contained in the ".OUT" output files listed in Appendix A. Comparing the results from the output files, verifies that the use of auto time stepping, along with a small initial step, is sufficient in capturing the peak stresses within acceptable limits.

Examples of the temperature responses due to the thermal shock transient load case are shown in Figures 11 and 12 for selected times showing that the model is behaving as expected. Examples of the temperature responses due to the cooldown transient load case are shown in Figures 13 and 14 for selected times showing that the model is behaving as expected.

8.0 REFERENCES

1. US Nuclear Regulatory Commission, Reactor Vessel Integrity Database, Version 2.0.1.
2. GE Stress Report No. 22A7454, Revision 1, "Reactor Vessel (System Cycling)," SI File No. NSP-36Q-202.
3. ASME Boiler and Pressure Vessel Code, Section III including Appendices, 1977 Edition with Addenda through Summer 1978.
4. CB&I Drawing No. 9, Revision 7, "Detail of 10"Ø Stub Mk.# N4 A/D for 17'-2" I.D. x 63'-2" Ins. Heads Nuclear Reactor for General Electric Company for Northern States Power," NX-8290-73, SI File No. NSP-21Q-235.
5. GE Design Specification No. 22A6996, Revision 0, "Reactor Vessel System Cycling," SI File No. 1000847.201.
6. ANSYS Mechanical and PrepPost, Release 11.0 (w/ Service Pack 1), ANSYS, Inc., August 2007.
7. GE Specification No. 21A1112, Revision 6, "Reactor Pressure Vessel," SI File No. MONT-14Q-204.

Table 1: RPV Material Properties (SA-533 Grade B)

Temperature (°F)	Thermal Conductivity[1] (Btu/hr-ft-°F)	Thermal Diffusivity[1] (ft^2/hr)	Specific Heat[2] (Btu/lb-°F)	Mean Coefficient of Thermal Expansion[3] x 10^{-6} (in/in/°F)	Elastic Modulus[4] x 10^6 (psi)
-100	31.5	0.5692	0.1132	6.07	30.4
70	31.5	0.5692	0.1132	6.07	29.9
200	30.0	0.5246	0.1169	6.38	29.5
300	29.1	0.4928	0.1208	6.60	29.0
400	28.1	0.4616	0.1245	6.82	28.6
500	27.2	0.4338	0.1282	7.02	28.0
600	26.2	0.4061	0.1319	7.23	27.4

Notes:
1. Reference [3], Table I-4.0 {6, § 4.0}
2. Calculated assuming constant density of 0.283 lb/in^3 {5, § 4.0}
3. Reference [3], Table I-5.0 {6, § 4.0}
4. Reference [3], Table I-6.0

Table 2: Nozzle Material Properties (SA-508 Class II)

Temperature (°F)	Thermal Conductivity[1] (Btu/hr-ft-°F)	Thermal Diffusivity[1] (ft^2/hr)	Specific Heat[2] (Btu/lb-°F)	Mean Coefficient of Thermal Expansion[3] x 10^{-6} (in/in/°F)	Elastic Modulus[4] x 10^6 (psi)
-100	31.5	0.5692	0.1132	6.07	30.4
70	31.5	0.5692	0.1132	6.07	29.9
200	30.0	0.5246	0.1169	6.38	29.5
300	29.1	0.4928	0.1208	6.60	29.0
400	28.1	0.4616	0.1245	6.82	28.6
500	27.2	0.4338	0.1282	7.02	28.0
600	26.2	0.4061	0.1319	7.23	27.4

Notes:
1. Reference [3], Table I-4.0 {6, § 4.0}
2. Calculated assuming constant density of 0.283 lb/in^3 {5, § 4.0}
3. Reference [3], Table I-5.0 {6, § 4.0}
4. Reference [3], Table I-6.0

Table 3: Cladding Material Properties (Type ER308 Stainless Steel)

Temperature (°F)	Thermal Conductivity[1] (Btu/hr-ft-°F)	Thermal Diffusivity[1] (ft^2/hr)	Specific Heat[2] (Btu/lb-°F)	Mean Coefficient of Thermal Expansion[3] x 10^{-6} (in/in/°F)	Elastic Modulus[4] x 10^6 (psi)
-100	8.35	0.1498	0.1140	9.11	29.4
70	8.35	0.1498	0.1140	9.11	28.3
200	8.90	0.1548	0.1176	9.34	27.7
300	9.35	0.1589	0.1203	9.47	27.1
400	9.80	0.1630	0.1229	9.59	26.6
500	10.23	0.1659	0.1261	9.70	26.1
600	10.70	0.1707	0.1282	9.82	25.4

Notes:

1. Reference [3], Table I-4.0 {6, § 4.0}
2. Calculated assuming constant density of 0.283 lb/in^3 {5, § 4.0}
3. Reference [3], Table I-5.0 {6, § 4.0}
4. Reference [3], Table I-6.0

Table 4: Thermal Shock Transient Definition

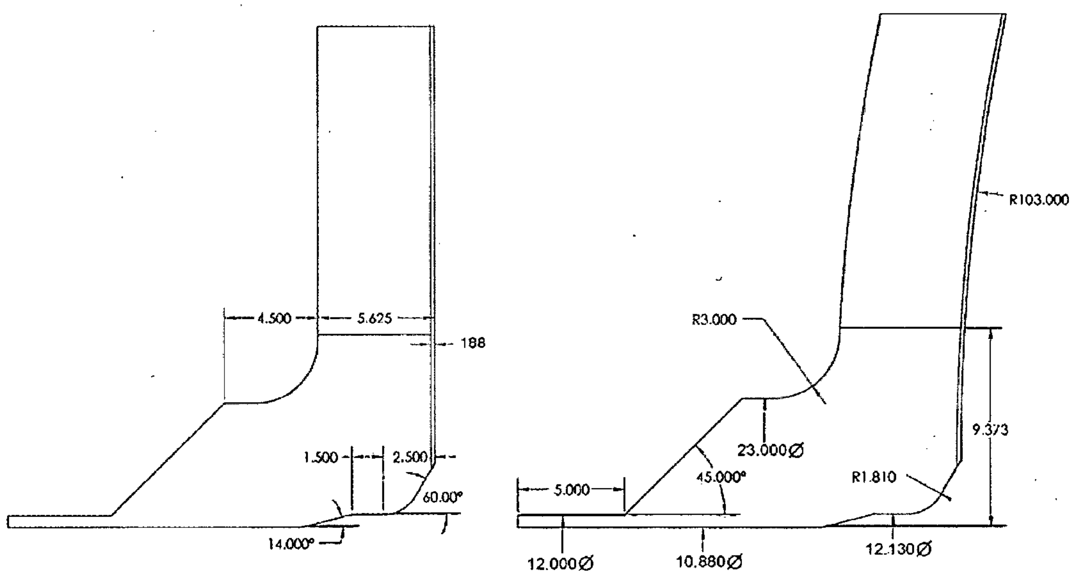
Time (s)	Temperatures (°F)[1]				Heat Transfer Coefficients (Btu/hr-ft^2-°F)			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
0	100	546	546	546	0.2	500	1500	750
1	100	546	528	510				
5100	100	546	528	510				

Notes:

1. Temperatures for Regions 3 & 4 are calculated using the methods from Reference [5, Appendix 20], based on a feedwater flow temperature of 100°F at 25% flow

Table 5: Cooldown Transient Definition

Time (s)	Temperatures (°F)				Heat Transfer Coefficients (Btu/hr-ft^2-°F)			
	Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
0	100	546	546	546	0.2	500	500	500
3600	100	446	446	446				
16056	100	100	100	100				
18156	100	100	100	100				



Notes:
1. Dimensions from References [4, 5].
2. Units in inches.

Figure 1: Finite Element Model Geometry

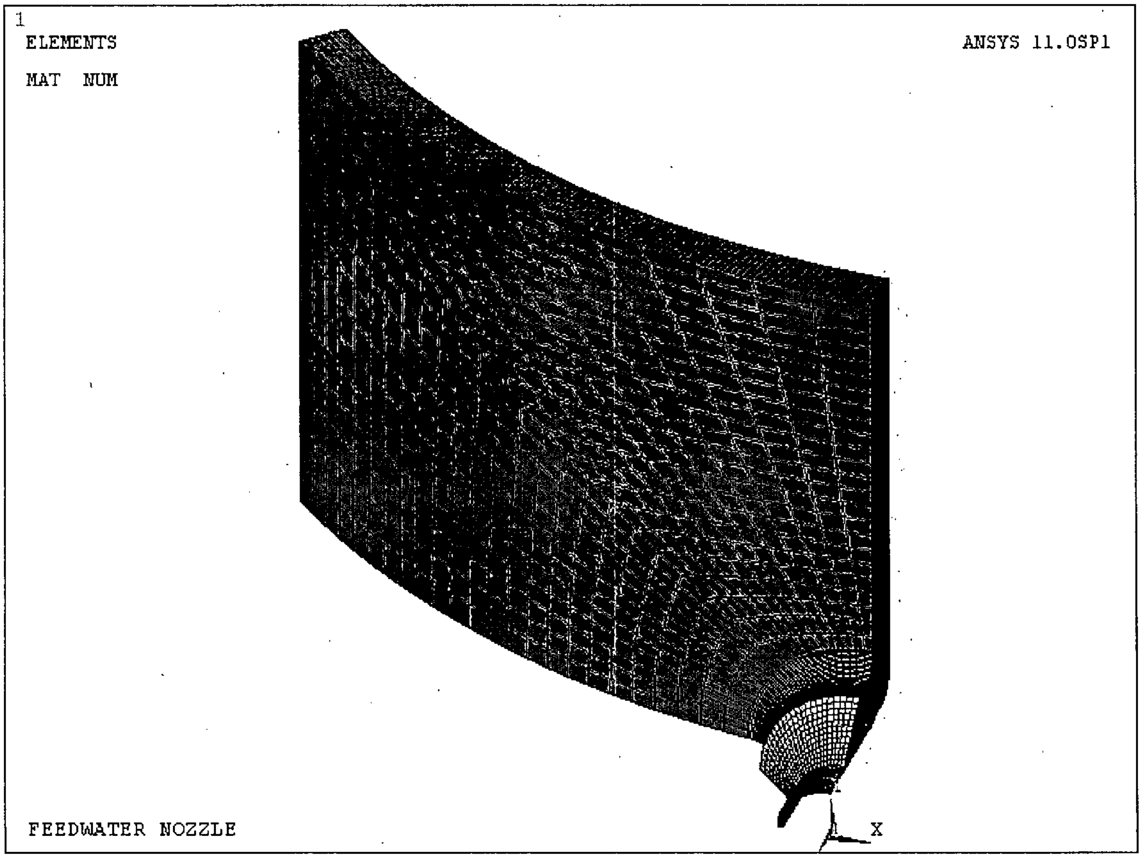


Figure 2: FEM Overview

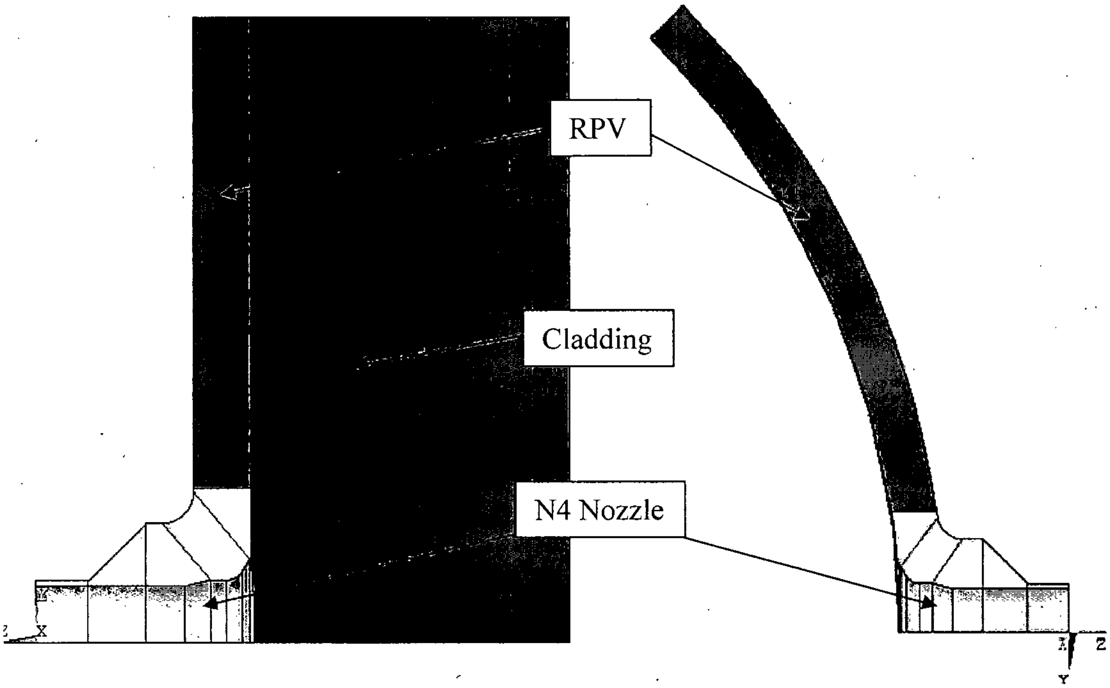


Figure 3: FEM Detail

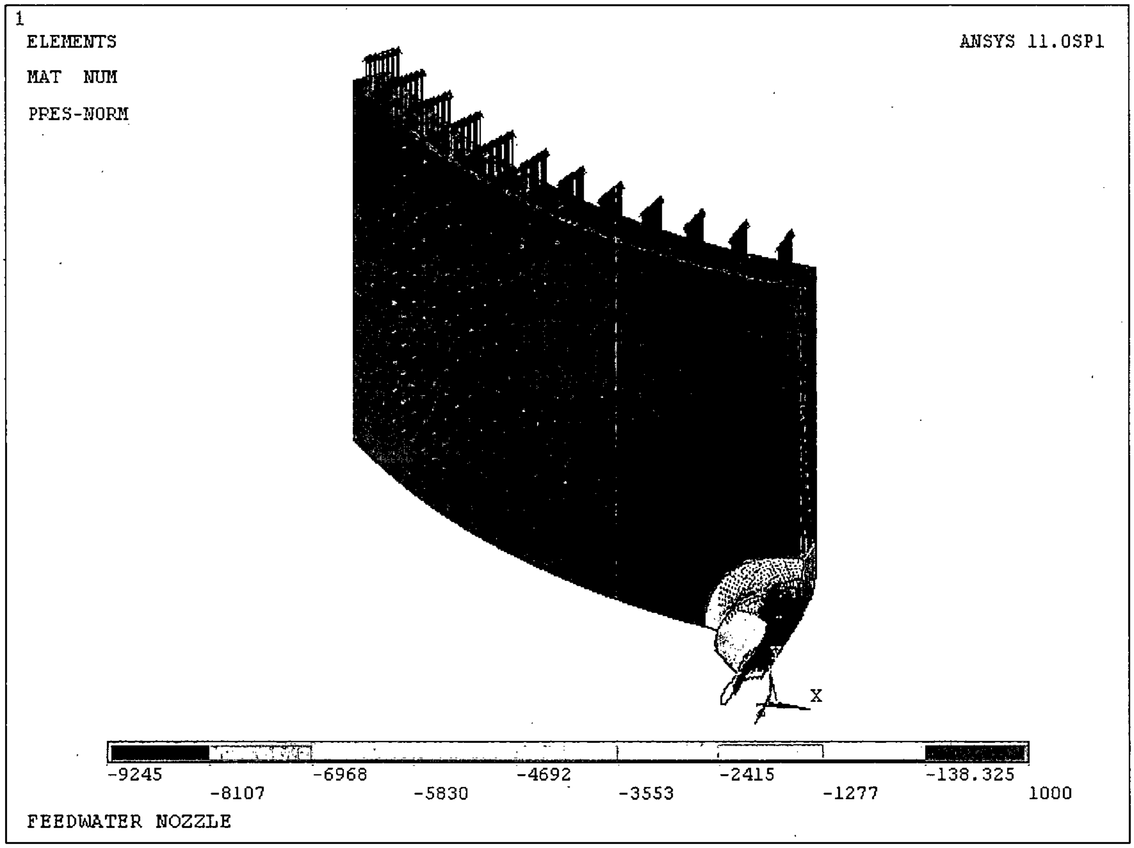


Figure 4: Unit Pressure Loading with Cap Loads (psi)

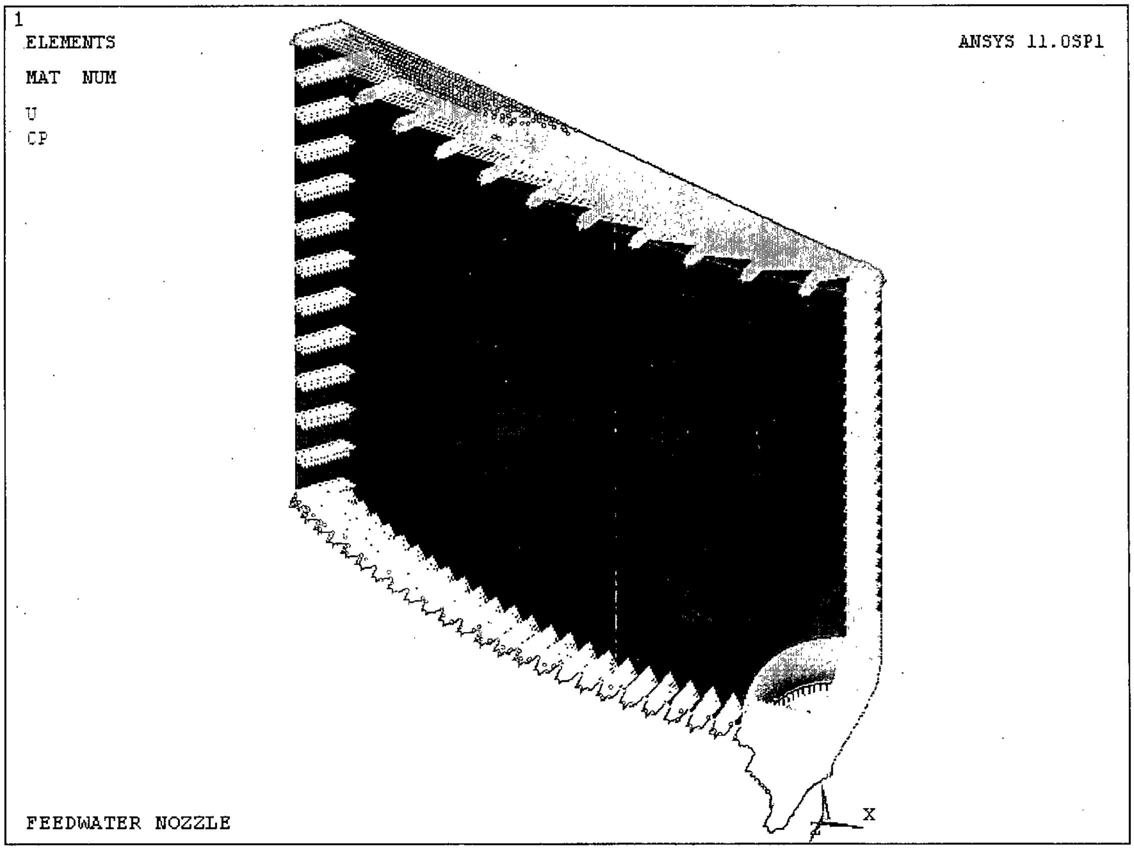


Figure 5: FEM Boundary Conditions

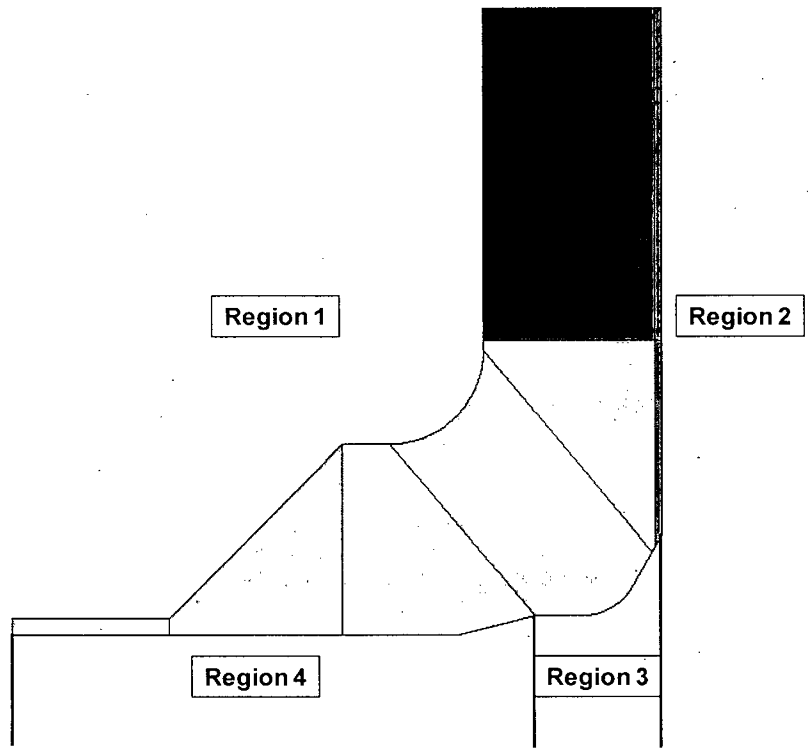


Figure 6: Heat Transfer Coefficient Regions

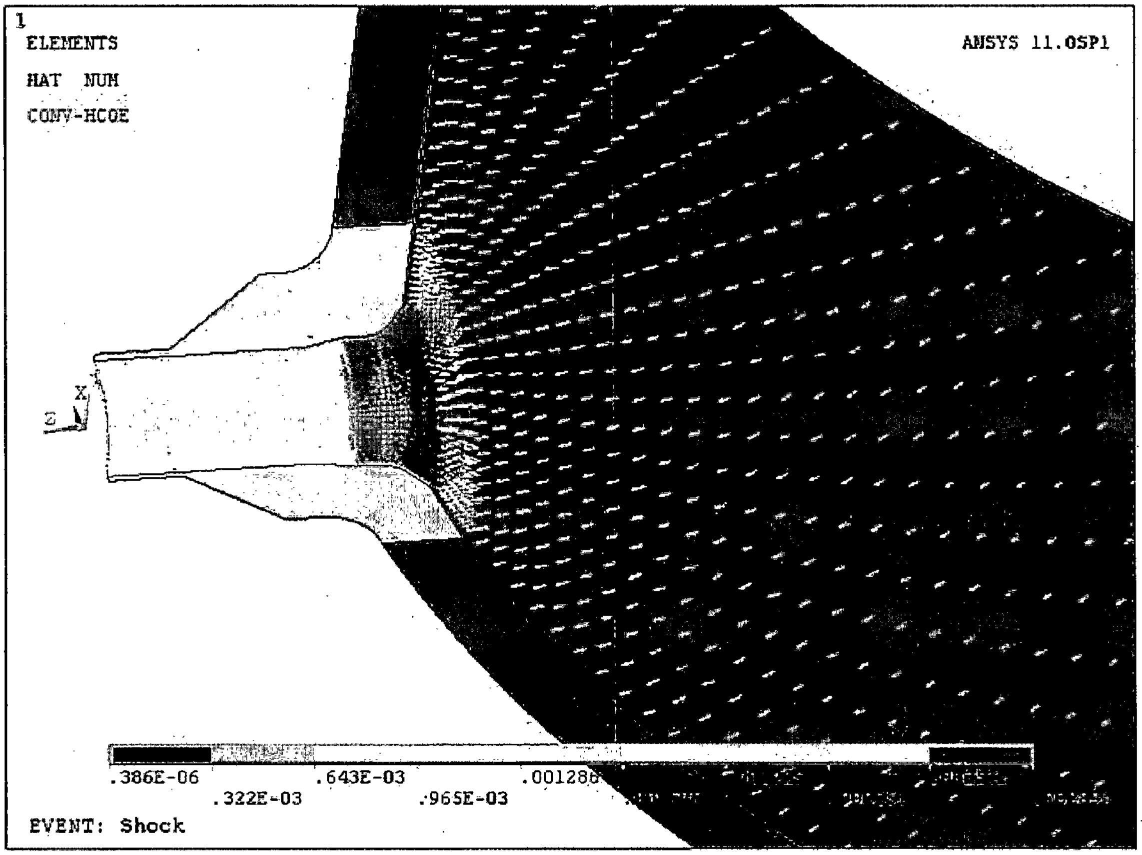


Figure 7: Thermal Shock Transient Convection Film Coefficients (Btu/sec-in^2-°F)

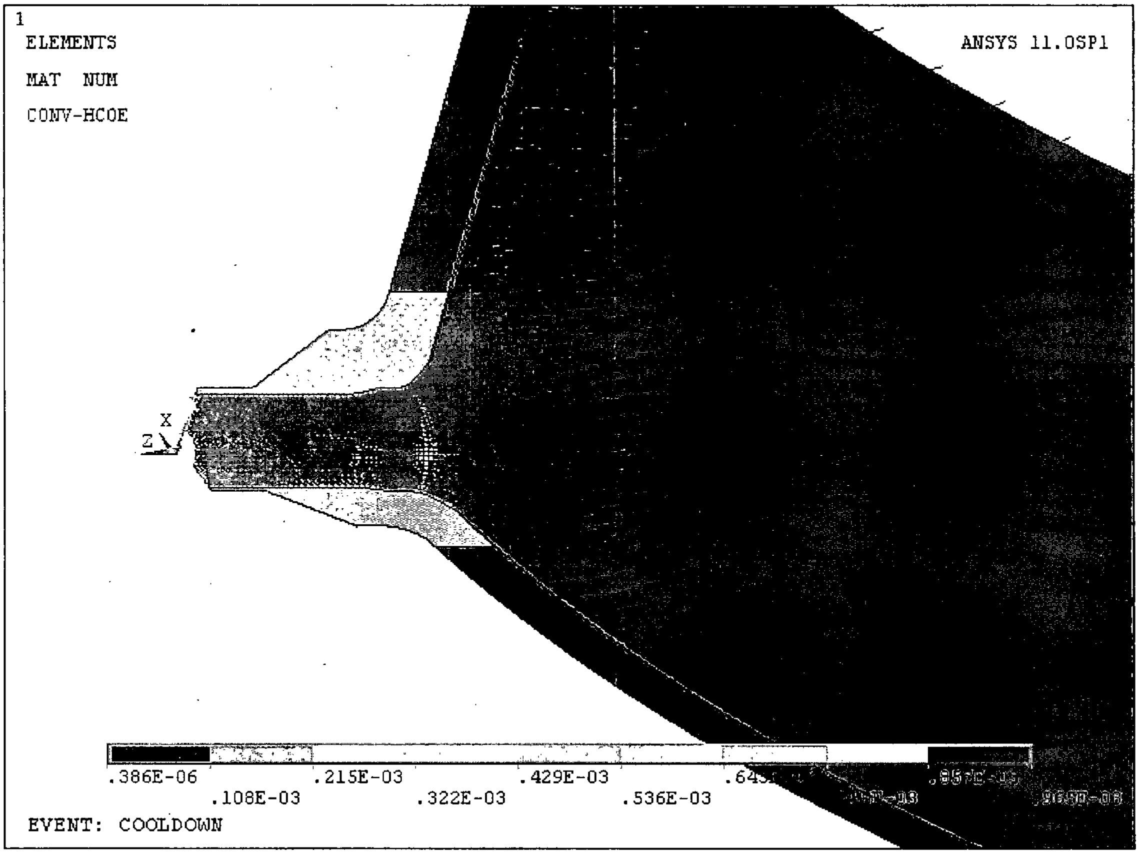


Figure 8: Cooldown Transient Convection Film Coefficients (Btu/sec-in^2-°F)

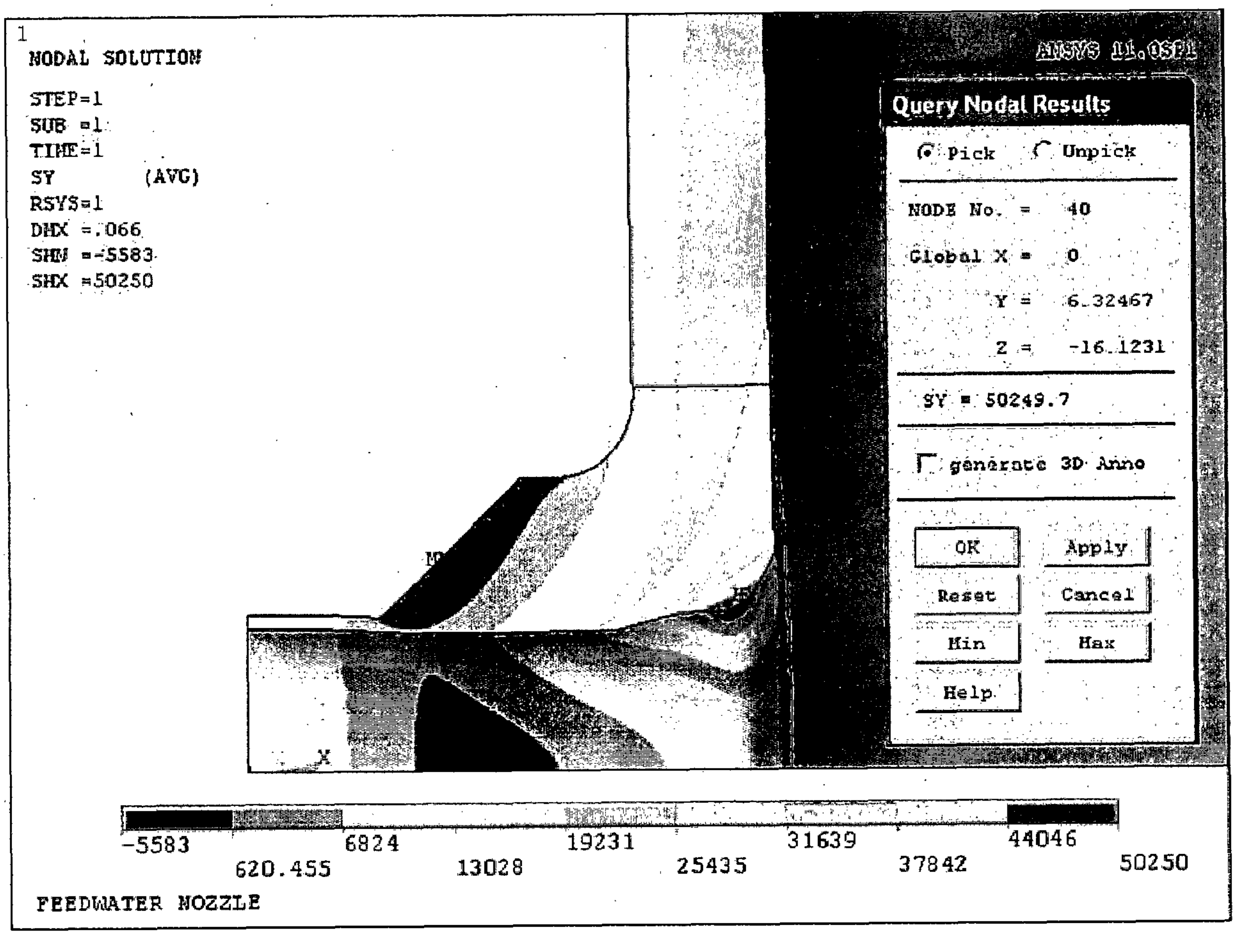


Figure 9: Location of Maximum Hoop Stress due to Pressure (psi)

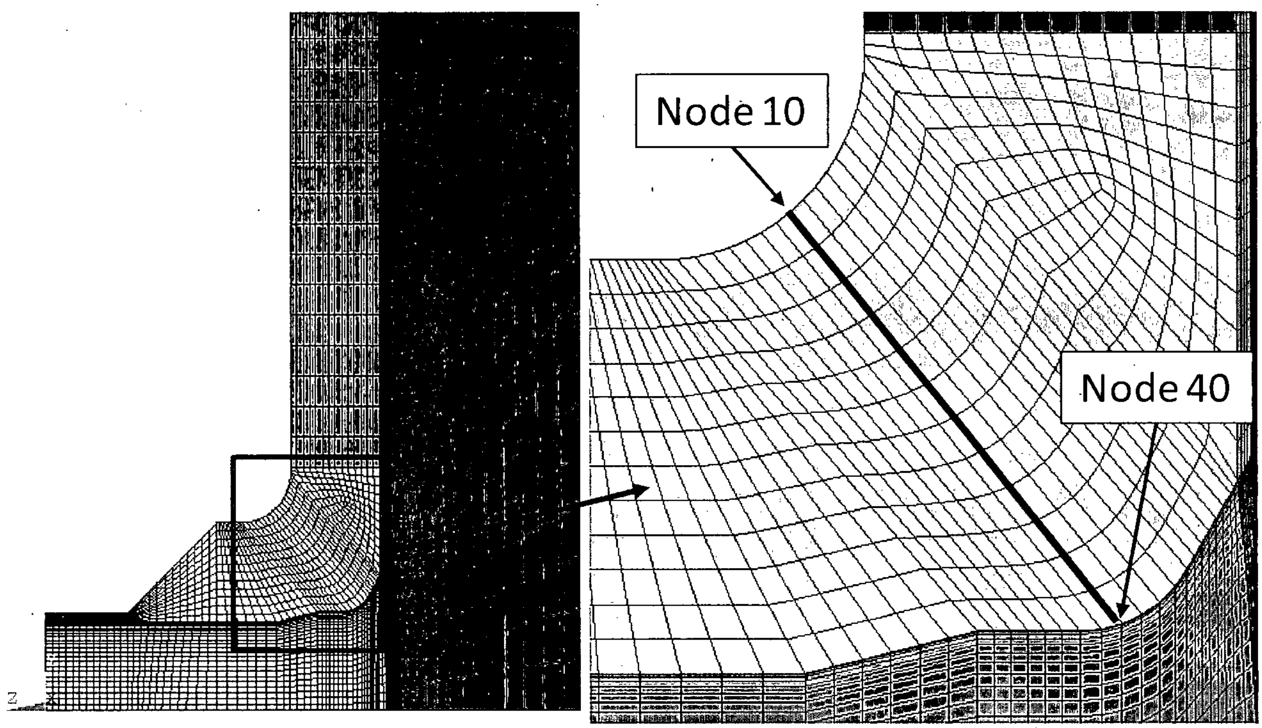


Figure 10: Path Location

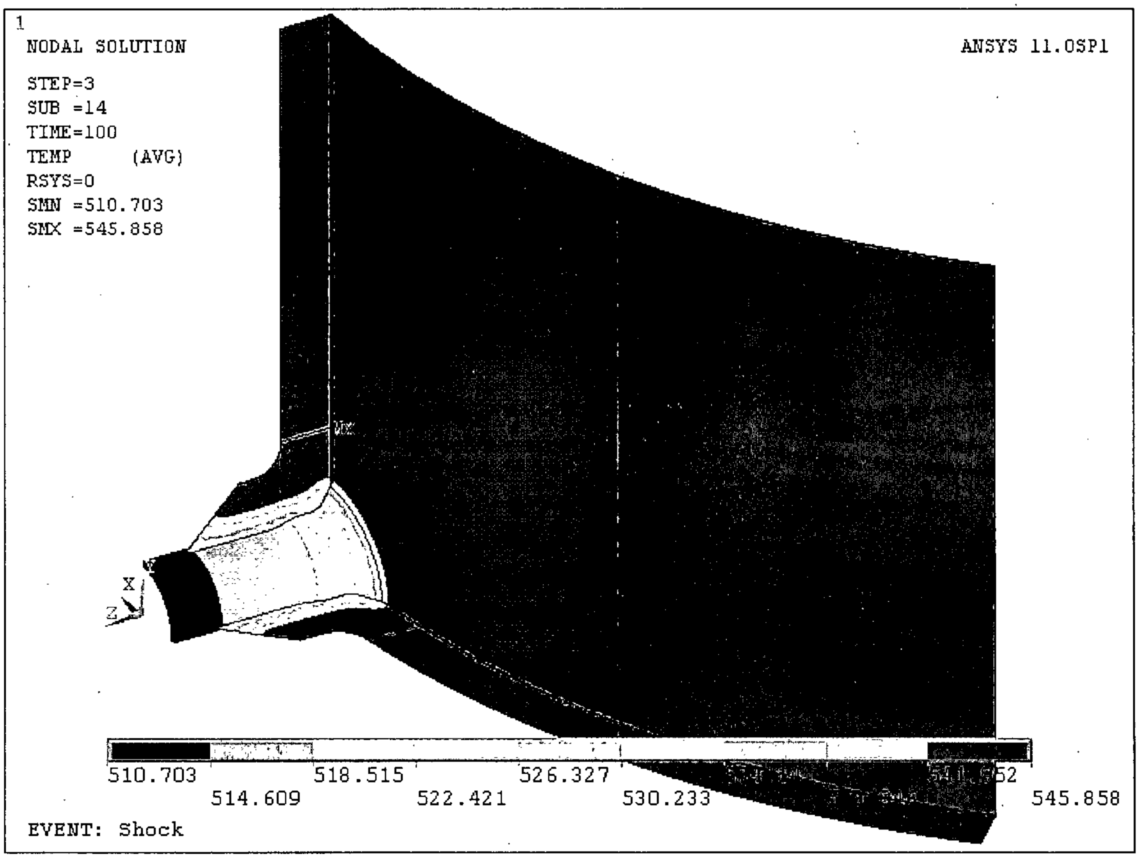


Figure 11: Thermal Shock Temperature Response (°F), Time = 100 Seconds

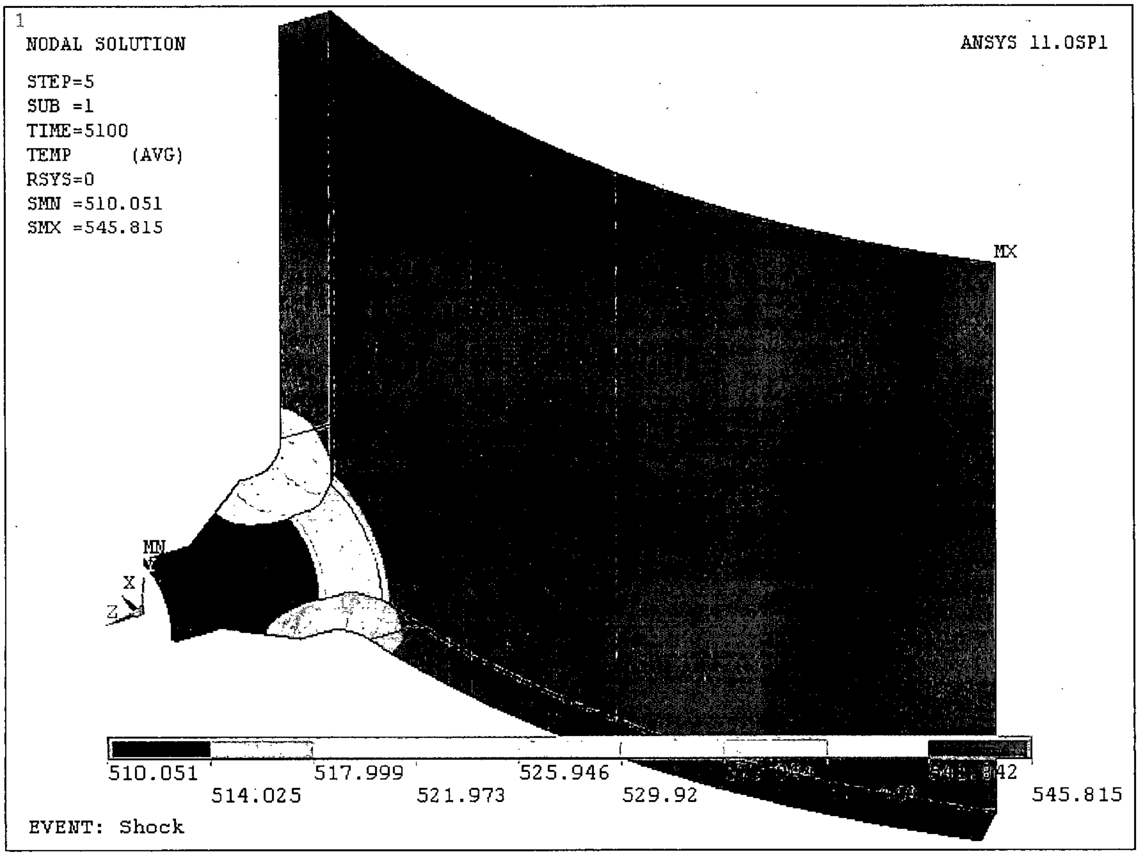


Figure 12: Thermal Shock Temperature Response (°F), Time = 5,100 Seconds

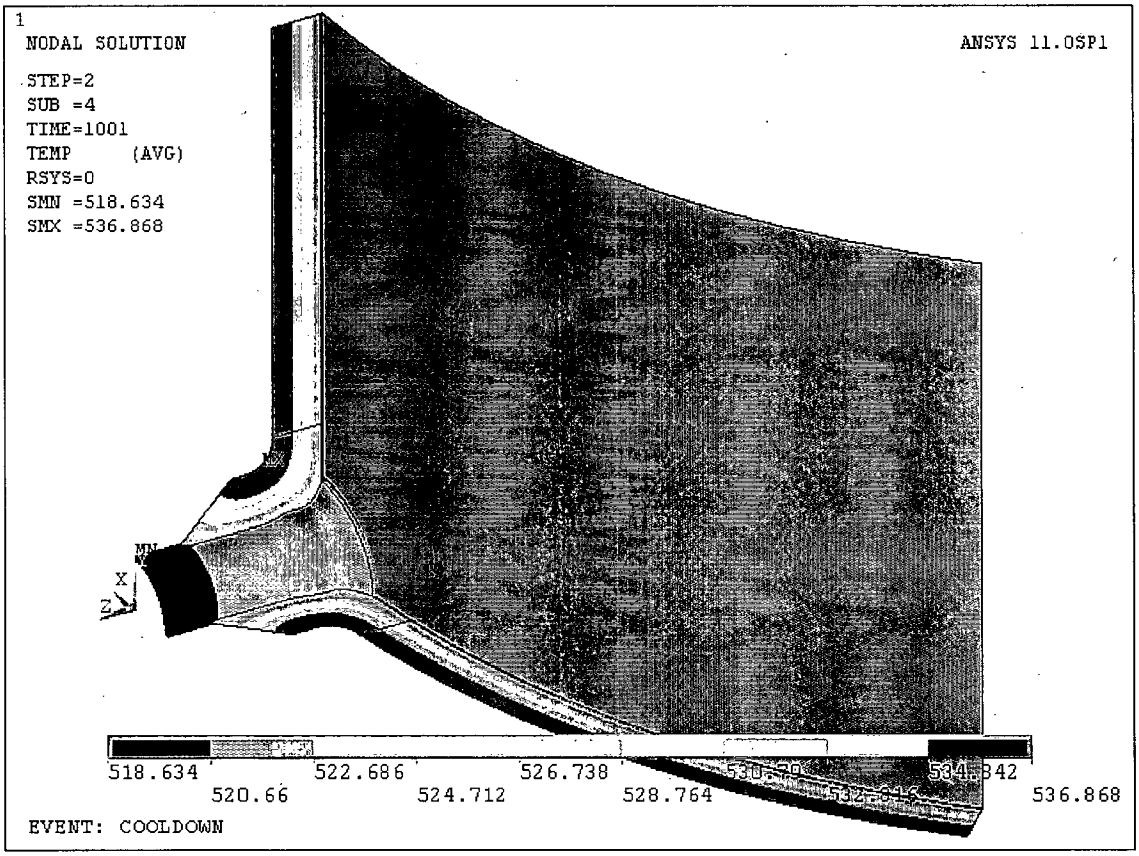


Figure 13: Cooldown Temperature Response (°F), Time = 1,001 Seconds

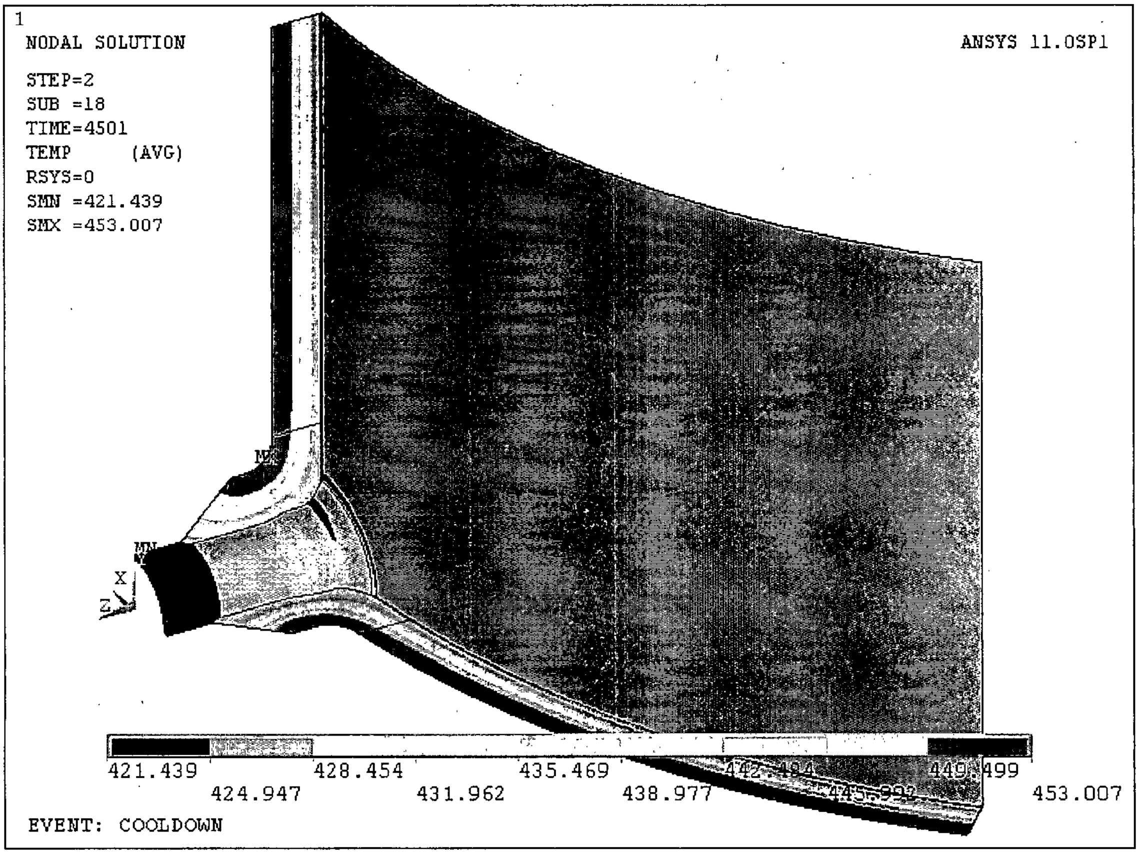


Figure 14: Cooldown Temperature Response (°F), Time = 4,501 Seconds

APPENDIX A: LIST OF SUPPORTING FILES

ANSYS File	Description
MONT_FW_QUART.INP	Finite element model geometry input file, including temperature dependent material properties
PRESSURE_QUART.INP	Unit pressure input and stress extraction file
APPLY_HTC.INP	Heat transfer coefficient region definition input file
SHOCK_FW.INP	Thermal shock transient input and stress extraction file
SHOCK_FW_mntr.INP	Thermal shock transient file containing LDREAD and SOLVE commands
COOLDOWN_FW.INP	Cooldown transient input and stress extraction file
COOLDOWN_FW_mntr.INP	Cooldown transient file containing LDREAD and SOLVE commands
PRESSTR_PATH.OUT	Hoop stress output file for unit pressure
THMSTR_PATH.OUT	Hoop stress output file for thermal shock transient
THMSTR_CD_PATH.OUT	Hoop stress output file for cooldown transient