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CALCULATION TITLE:
Finite Element Model Development for the Cold Leg Drain, Spray, and Charging Nozzles

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1.0 OBJECTIVE

The objective of this calculation package is to document the development of a bounding finite element model for the reactor cold leg spray, drain, and charging nozzles at the Palisades Nuclear Plant, which will be used to perform residual and operational-based fracture mechanics analyses to support a subsequent fracture mechanics evaluation as part of a flaw readiness program.

2.0 TECHNICAL APPROACH

One bounding three-dimensional (3-D) finite element model is developed using the ANSYS finite element analysis software package [1] to represent a group of cold leg nozzles. All three nozzles are of similar size near the forging boss area (within 1/16 inch) [2, 3, and 4]. Therefore, the largest inside diameter (ID) and smallest outside diameter (OD) of the three nozzles is chosen for the bounding model. The spray and drain nozzles have identical nozzle and boss OD dimensions of 4-9/16 inch and 6-3/16 inch, respectively, which are slightly smaller than the charging nozzle OD dimensions of 4-5/8 inch and 6-1/4 inch. For the nozzle ID, the charging nozzle is bored out to 2-5/8 inch in the first 1.5 inch to accommodate a thermal sleeve. For conservatism, it is assumed that the entire nozzle ID is 2-5/8 inch.

The area of interest is the nozzle-to-pipe weld. The model uses elastic-plastic material properties intended for weld residual stress analysis, and elastic material properties for linear elastic analyses.

3.0 ASSUMPTIONS / DESIGN INPUTS

The dimensions and material types to develop the finite element model are provided in References 2, 3, and 4 and summarized in Figure 1. The material properties are obtained from References 5 and 6. A number of assumptions were made during development of the finite element model, which are listed as follows:

- Since the area of interest is the nozzle to cold leg weld, dimensional differences between nozzles on the attached piping side are considered insignificant.
- The largest inside diameter (ID) and smallest outside diameter (OD) of the three nozzles will be chosen for the bounding model. This is conservative for pressure and mechanical loads.
- The axial length of the modeled portion of the cold leg piping is arbitrarily set at 36 inches, which is sufficiently long to negate possible end effects in the region of interest.
- The ID patch weld is added after removal of the backing ring according to the weld procedure mentioned in the drawings [2, 3]. The same material of the nozzle-to-pipe weld is used for the ID patch weld.

4.0 FINITE ELEMENT MODEL

The model includes a local portion of the cold leg pipe and cladding, the nozzle, and the nozzle-to-pipe weld, including the ID patch weld, as shown in Figure 2. As shown in the figure, a single 90° quadrant of the nozzle penetration is modeled due to geometric symmetry. The included portion of the cold leg piping measures 36 inches longitudinally and 180 degrees circumferentially. The mesh of the finite element model is shown in Figure 3.

4.1 Element Type and Mesh

The 8-node solid element (SOLID185) in ANSYS [1] is used for the model. SOLID185 elements support material plasticity which is suitable for residual stress and elastic plastic fracture mechanics (EPFM) analyses. The model contains adequate mesh refinement within the weld region to predict the residual stresses from welding.

4.2 Materials

The material designation for the modeled components is listed in Table 1. The temperature dependent nonlinear material property values are provided in a separate calculation package [6], which are based on the 2001 Edition of the ASME Code with Addenda through 2003 [5]. The material properties are listed in Table 2 through Table 9.

4.2.1 Creep Properties

Since post weld heat treatment (PWHT) will be considered in the subsequent residual stress calculation, creep properties are required. In general, creep becomes significant at temperatures above 800°F; thus, creep behavior under 800°F will not be considered in this analysis.

There are two main categories of creep: primary and secondary. The primary creep addresses the creep characteristics for a short duration at the early stages of the creep regime, while the secondary creep accounts for the creep behavior for a long duration – usually more than 10,000 hours. Based on this definition, the PWHT falls within the primary creep characteristics. However, primary creep rates for materials are difficult to obtain, so the conservative secondary creep rates are used since primary creep rate is typically an order of magnitude higher than that for secondary creep.

In general, the primary creep rate for the materials is governed by the equation:

$$\frac{d\varepsilon}{dt} = A\sigma^n$$

The creep data for the SA-516 Grade 70 cold leg material is based on carbon steel material [7]. The creep data for the Alloy 82/182 and ER308L weld metals are not available, so the creep properties for their base metals are used instead. The creep data for Type 304 (for ER308L) is provided in the same reference document as the carbon steel [7], while the creep data for the Alloy 600 (for Alloy 82/182) is provided in a separate reference document [8]. All the creep strengths, σ, are provided at two creep rates [7, 8] for each temperature point.

When creep strength is provided at two creep rates at the same temperature point, as listed in Table 10, then *A* and *n* can be calculated as follows, where subscripts 1 and 2 refer to the creep data sets 1 and 2:

$$\frac{d\varepsilon}{dt} = \dot{\varepsilon} = A\sigma^n$$

$$\dot{\varepsilon}_1 = A\sigma_1^{\ n};\ \dot{\varepsilon}_2 = A\sigma_2^{\ n}$$

$$\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2} = \left(\frac{\sigma_1}{\sigma_2}\right)^n$$

$$\ln\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right) = n\ln\left(\frac{\sigma_1}{\sigma_2}\right)$$

$$n = \frac{\ln\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)}{\ln\left(\frac{\sigma_1}{\sigma_2}\right)}$$

$$A = \frac{\dot{\varepsilon}_1}{\sigma_1^{\ n}}$$

4.3 Loads and Boundary Conditions

No loads or boundary conditions of any kind are included in the finite element model in this calculation. Specific loads and boundary conditions, appropriate to the specific analyses, will be applied in the subsequent residual and thermal/mechanical stress calculation packages.

5.0 CONCLUSIONS

A bounding finite element model for the cold leg spray, drain, and charging nozzles is developed. The model will be used in subsequent weld residual stress analyses and fracture mechanics analyses. The necessary ANSYS input file names are listed in Appendix A.

6.0 REFERENCES

1. ANSYS Mechanical APDL and PrepPost, Release 14.5 (w/ Service Pack 1), ANSYS, Inc., September 2012.
2. Combustion Engineering Drawing E232-675-4, "Nozzle Details," SI File No. 1400669.202.
3. Combustion Engineering Drawing E232-676-7, "Nozzle Details," SI File No. 1400669.202.
4. Combustion Engineering Drawing E232-673-7, "Piping Assembly & Details," SI File No. 1400669.202.
5. ASME Boiler and Pressure Vessel Code, Section II, Part D – Properties, 2001 Edition with Addenda through 2003.
6. SI Calculation No. 0800777.307, Rev. 5, "Material Properties for Residual Stress Analyses, Including MISO Properties Up To Material Flow Stress."
7. "Steels for Elevated Temperature Service," United States Steel Co., 1949.
8. Publication SMC-027, "Inconel Alloy 600," Special Metals Corp., 2004, SI File 0800777.211.
9. Palisades Design Input Record, "Palisades Alloy 600 Flaw Eval DIR 3-4-15 Rev 1.pdf," SI File No. 1400669.201.

Table 1: Component Materials

Component	Material	References
Cold Leg Piping	SA-516 Grade 70	[9]
Pipe Cladding	ER308L (1)	[4]
Bounding Nozzle	SB-166 (N06600, Alloy 600)(2)	[2, 3]
Weld	Alloy 182	[9]
ID Patch Weld	Alloy 182	[9]

Notes:
1. The material properties are based on equivalent Type 304 base material.
2. Alloy SB-166 is assumed to have the same material properties as Alloy 600.

Table 2: Elastic Properties for SA-516 Grade 70 (≤ 4" Thick)

Temperature (°F)	Elastic Modulus ($x10^3$ ksi)	Mean Thermal Expansion ($x10^{-6}$ in/in/°F)	Thermal Conductivity(2) (Btu/min-in-°F)	Specific Heat(2) (Btu/lb-°F)
70	29.5	6.4	0.0488	0.103
500	27.3	7.3	0.0410	0.128
700	25.5	7.6	0.0369	0.138
1100	18.0	8.2	0.0290	0.171
1500	5.0	8.6	0.0218	0.198
2500	0.1	9.5	0.0014	0.204
2500.1	--	0	--	--

Notes:
1. All values per [6].
2. Density (ρ) = 0.283 lb/in^3 [6], assumed temperature independent.
3. Poisson's Ratio (ν) = 0.3 [6], assumed temperature independent.

Table 3: Stress-Strain Curves for SA-516 Grade 70 (≤ 4" Thick)

Temperature (°F)	Strain (in/in)	Stress (ksi)
70	0.00128814	38.000
	0.00187809	42.000
	0.00257329	46.000
	0.00381110	50.000
	0.00600383	54.000
500	0.00113553	31.000
	0.00142679	35.875
	0.00183954	40.750
	0.00261139	45.625
	0.00415246	50.500
700	0.00106667	27.200
	0.00132412	32.550
	0.00166876	37.900
	0.00228121	43.250
	0.00354341	48.600
1100	0.00116667	21.000
	0.05116163	22.125
	0.05915444	23.250
	0.06794123	24.375
	0.07755935	25.500
1500	0.00300000	15.000
	0.16717493	15.125
	0.16992011	15.250
	0.17268761	15.375
	0.17547742	15.500
2500(2)	0.01000000	1.000
	0.10961239	1.125
	0.12781277	1.250
	0.14689940	1.375
	0.16683167	1.500

Notes:
1. All values per [6].
2. Values at 2500°F assumed arbitrarily small values for convergence stability.

Table 4: Elastic Properties for ER308L

Temperature (°F)	Elastic Modulus ($x10^3$ ksi)	Mean Thermal Expansion ($x10^{-6}$ in/in/°F)	Thermal Conductivity[(2)] (Btu/min-in-°F)	Specific Heat[(2)] (Btu/lb-°F)
70	28.3	8.5	0.0119	0.116
500	25.8	9.7	0.0151	0.131
700	24.8	10.0	0.0164	0.135
1100	22.1	10.5	0.0189	0.140
1500	18.1	10.8	0.0212	0.145
2500	0.1	11.5	0.0292	0.159
2500.1	--	0	--	--

Notes:
1. All values per [6].
2. Density (ρ) = 0.283 lb/in^3 [6], assumed temperature independent.
3. Poisson's Ratio (ν) = 0.3 [6], assumed temperature independent.

Table 5: Stress-Strain Curves for ER308L

Temperature (°F)	Strain (in/in)	Stress (ksi)
70	0.00203180	57.500
	0.02471351	61.563
	0.03107296	65.625
	0.03861377	69.688
	0.04747167	73.750
500	0.00140089	36.143
	0.00714793	40.250
	0.01065407	44.357
	0.01558289	48.464
	0.02233857	52.571
700	0.00132488	32.857
	0.00477547	37.125
	0.00743595	41.393
	0.01143777	45.661
	0.01727192	49.929
1100	0.00121913	26.943
	0.00264833	30.138
	0.00404100	33.332
	0.00634529	36.527
	0.01005286	39.721
1500	0.00117995	21.357
	0.05352064	21.563
	0.05610492	21.768
	0.05878975	21.973
	0.06157807	22.179
2500 (2)	0.01000000	1.000
	0.10961239	1.125
	0.12781277	1.250
	0.14689940	1.375
	0.16683167	1.500

Notes:
1. All values per [6].
2. Values at 2500°F assumed arbitrarily small values for convergence stability.

Table 6: Elastic Properties for Alloy 600

Temperature (°F)	Elastic Modulus ($x10^3$ ksi)	Mean Thermal Expansion ($x10^{-6}$ in/in/°F)	Thermal Conductivity(2) (Btu/min-in-°F)	Specific Heat(2) (Btu/lb-°F)
70	31.0	6.8	0.0119	0.108
500	29.0	7.6	0.0147	0.120
700	28.2	7.9	0.0161	0.125
1100	25.9	8.4	0.0192	0.139
1500	23.1	9.0	0.0222	0.148
2500	0.1	10.0	0.0306	0.177
2500.1	--	0	--	--

Notes:
1. All values per [6].
2. Density (ρ) = 0.300 lb/in^3 [6], assumed temperature independent.
3. Poisson's Ratio (ν) = 0.29 [6], assumed temperature independent.

Table 7: Stress-Strain Curves for Alloy 600

Temperature (°F)	Strain (in/in)	Stress (ksi)
70	0.00157419	48.800
	0.01658847	55.300
	0.02343324	61.800
	0.03212188	68.300
	0.04291703	74.800
500	0.00152069	44.100
	0.01539220	50.338
	0.02210610	56.575
	0.03072476	62.813
	0.04153277	69.050
700	0.00152128	42.900
	0.01634485	49.000
	0.02334760	55.100
	0.03227153	61.200
	0.04338643	67.300
1100	0.00155985	40.400
	0.02275193	44.475
	0.03004563	48.550
	0.03888203	52.625
	0.04943592	56.700
1500	0.00092641	21.400
	0.08827666	22.475
	0.09785101	23.550
	0.10796967	24.625
	0.11863796	25.700
2500 (2)	0.01000000	1.000
	0.10961239	1.125
	0.12781277	1.250
	0.14689940	1.375
	0.16683167	1.500

Notes:
1. All values per [6].
2. Values at 2500°F assumed arbitrarily small values for convergence stability.

Table 8: Elastic Properties for Alloy 82/182

Temperature (°F)	Elastic Modulus ($x10^3$ ksi)	Mean Thermal Expansion ($x10^{-6}$ in/in/°F)	Thermal Conductivity [(2)] (Btu/min-in-°F)	Specific Heat [(2)] (Btu/lb-°F)
70	31.0	6.8	0.0119	0.108
500	29.0	7.6	0.0147	0.120
700	28.2	7.9	0.0161	0.125
1100	25.9	8.4	0.0192	0.139
1500	23.1	9.0	0.0222	0.148
2500	0.1	10.0	0.0306	0.177
2500.1	–	0.0	–	–

Notes:
1. All values per [6].
2. Density (ρ) = 0.300 lb/in^3 [6], assumed temperature independent.
3. Poisson's Ratio (ν) = 0.29 [6], assumed temperature independent.

Table 9: Stress-Strain Curves for Alloy 82/182

Temperature (°F)	Strain (in/in)	Stress (ksi)
70	0.00179032	55.500
	0.03456710	60.113
	0.04292837	64.725
	0.05257245	69.338
	0.06359421	73.950
500	0.00164483	47.700
	0.02976152	52.313
	0.03809895	56.925
	0.04790379	61.538
	0.05929946	66.150
700	0.00159574	45.000
	0.02849157	49.538
	0.03680454	54.075
	0.04663682	58.613
	0.05812078	63.150
1100	0.00159073	41.200
	0.03568855	44.488
	0.04402702	47.775
	0.05360088	51.063
	0.06449835	54.350
1500	0.00106494	24.600
	0.11812735	25.325
	0.12540227	26.050
	0.13290814	26.775
	0.14064577	27.500
2500(2)	0.01000000	1.000
	0.10961239	1.125
	0.12781277	1.250
	0.14689940	1.375
	0.16683167	1.500

Notes:
1. All values per [6].
2. Values at 2500°F assumed arbitrarily small values for convergence stability.

Table 10: Creep Properties

Material	Temperature (°F)	Creep Strength (ksi)		A (ksi/hr)	n
		σ_1 (0.0001%/hr)	σ_2 (0.00001%/hr)		
SA-516 Gr. 70 (Based on carbon steel per [7])	800	19.0	12.4	1.26E-13	5.40
	900	9.0	6.7	3.59E-14	7.80
	1000	3.5	2.8	2.43E-12	10.32
	1100	1.4	0.8	2.50E-07	4.11
ER308L (Based on Type 304 per [7])	800	33.4	25.0	7.73E-19	7.95
	900	24.0	17.6	5.67E-17	7.42
	1000	17.6	11.5	1.82E-13	5.41
	1100	11.5	7.1	8.62E-12	4.77
Alloy 600 Alloy 82/182 (Based on Alloy 600 per [8])	800	40.0	30.0	1.50E-19	8.00
	900	28.0	18.0	2.87E-14	5.21
	1000	12.5	6.1	3.02E-10	3.21
	1100	6.8	3.4	1.72E-09	3.32

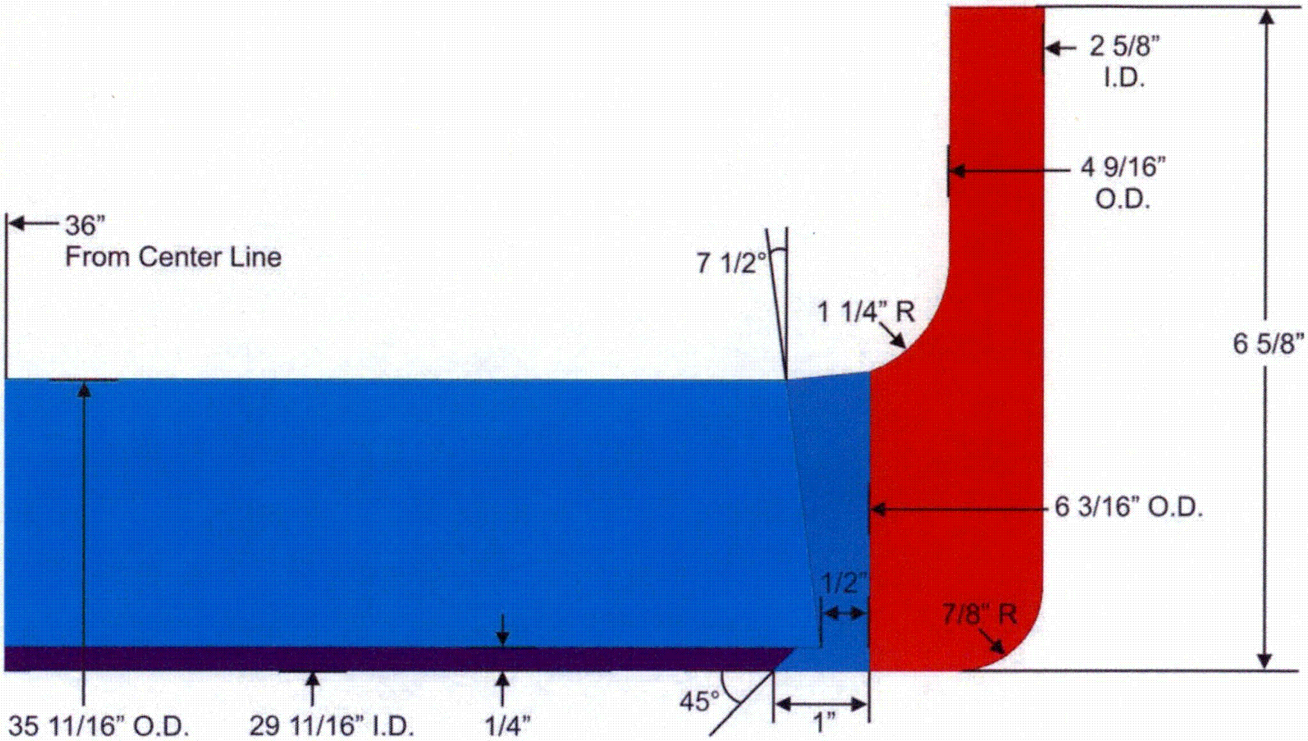

Figure 1. Finite Element Model Dimensions

Note: Dimensions obtained from [2, 3, and 4].

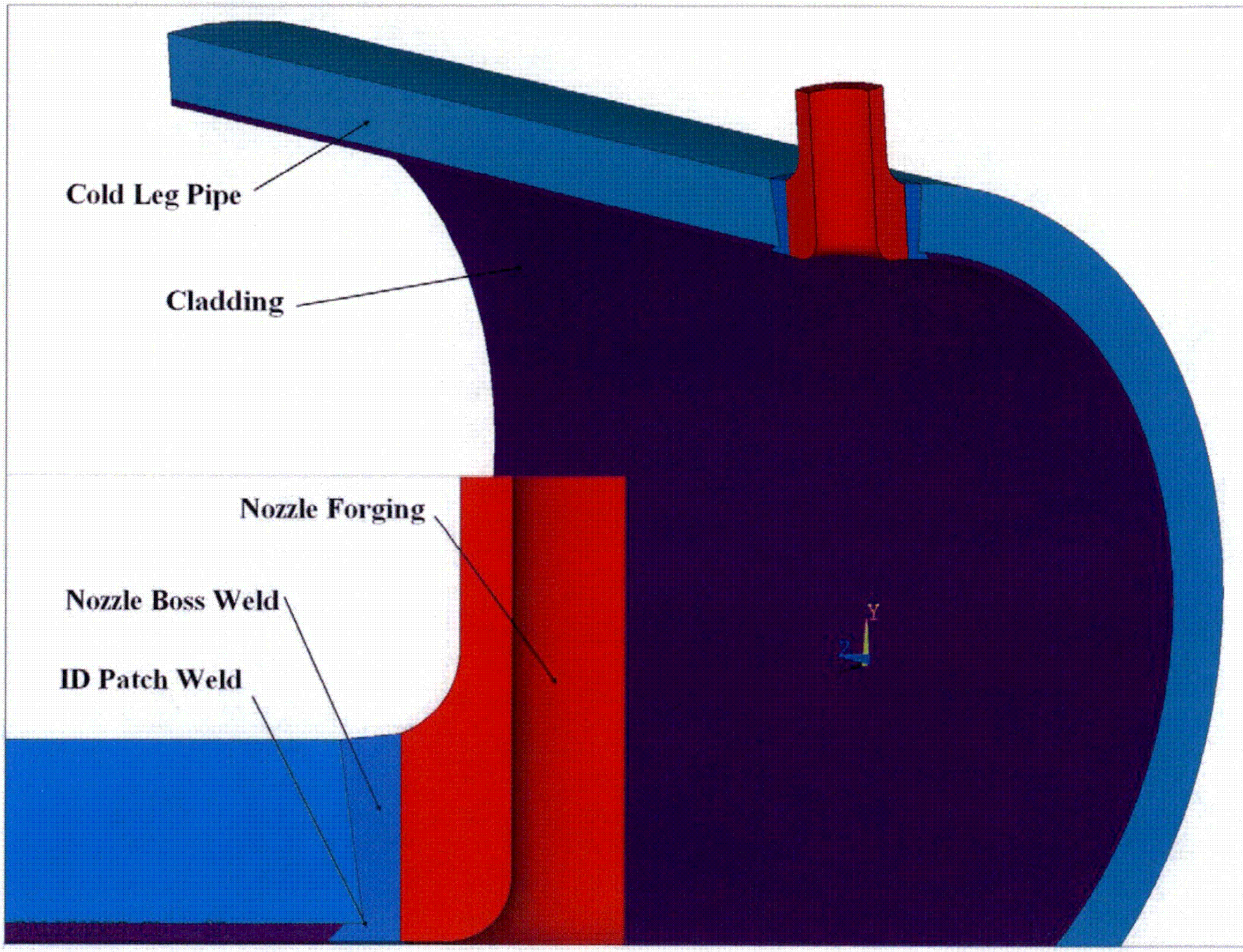

Figure 2. Components Included in the Finite Element Model

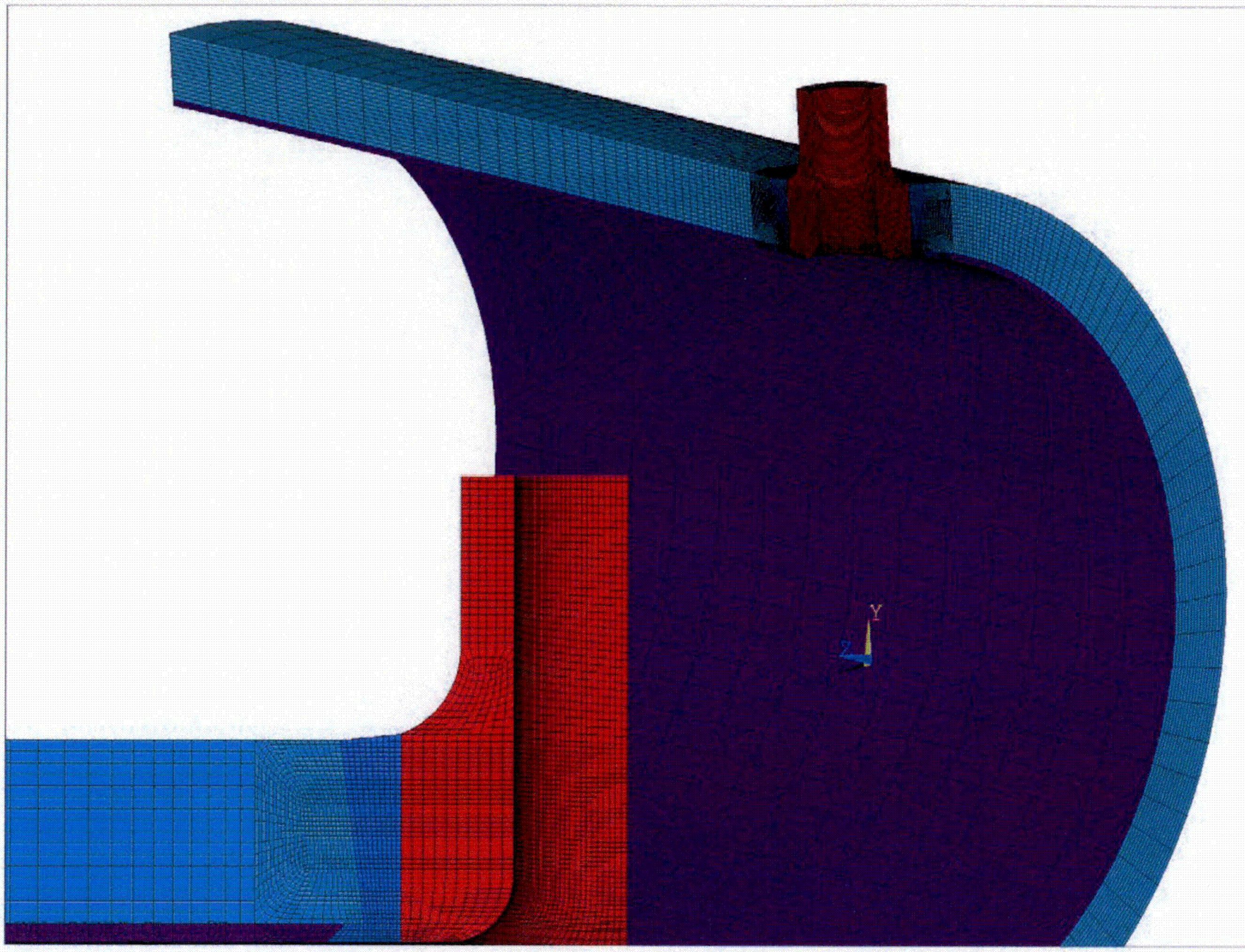

Figure 3. Isometric View of the Finite Element Model

(Nozzle detail shown in bottom left corner)

APPENDIX A

COMPUTER FILES LISTING

File Name	Description
Palisades_CL.INP	Input file to create base model geometry
MProp_Miso.INP	Elastic plastic material properties inputs
MatProp.xls	Excel spreadsheet containing calculations of elastic-plastic material properties for residual stress analysis