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Entergy Nuclear Operations, Inc.	Vermont Yankee Nuclear Power Station

CALCULATION TITLE:

Core Spray Nozzle Green's Functions

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1.0 OBJECTIVE

The objective of this calculation is to compute the pressure stresses, thermal stresses, and the Green's Functions for high (100%) and no (0%) flow thermal loading of the Vermont Yankee Nuclear Power Station Core Spray Nozzle.

2.0 CORE SPRAY NOZZLE MODEL DESCRIPTION

An axisymmetric finite element model of the core spray nozzle was developed in Reference [1] using ANSYS [2]. The geometry used in Reference [1] was utilized in this calculation. The material properties are taken at an average temperature of 300°F. This average temperature is based on a thermal shock of 500°F to 100°F, which will be applied to the FE model for Green's Function development. Table 1 lists the material properties at 300°F. The meshed model is shown in Figure 1.

Table 1: Material Properties @ 300°F (1)

Part Description	Material		Modulus of Elasticity, e+6 psi [EX]	Coefficient of Thermal Expansion, e-6, in/in/°F [ALPX]	Thermal Conductivity, Btu/hr-ft-°F [KXX]	Thermal Diffusivity, ft^2/hr	Specific Heat, Btu/lb-°F [C] (3)	Poiss Ra [NU
Safe End	SB 166	72Ni-15Cr-8Fe N06600	29.8	7.9	9.6	0.160	0.1157	0.:
Weld Overlay	INCONEL 82							
Nozzle	SA508 Class II	¾ Ni-1/2Mo-1/3 Cr-V	26.7	7.3	23.4	0.401	0.1193	0.
Vessel	SA533 Grade B	Mn-1/2Mo-1/2Ni	28.0	7.7	23.4	0.401	0.1193	0.
3/16 Clad	SA240 TP 304	18Cr-8Ni	27.0	9.8	9.8	0.160	0.1252	0.
8Ø x 10Ø Conc. Reduction(2)	SA312 TP304							
Thermal Sleeve	SA312 TP304							

Notes:

1. The material properties applied in the analyses are taken from ASME Code, Section II, Part D 1998 Edition, with 2000 A information provided in the Design Input Record (page 13 of VY EC No. 1773, SI File No. VY-16Q-209). The use of a la for the original design code is acceptable, since later editions typically reflect more accurate material properties than was Material Properties are evaluated at 300°F from the 1998 ASME Code, 2000 Addenda, Section II, Part D, except for density and Poisso values [3].
2. In the FEM, the 8Ø x 10Ø Conc. Reduction was modeled as a straight pipe with the material properties of the original des was replaced by a new material (SA403 T316L). These two stainless steels have the same modulus of elasticity and therm
3. Calculated as $[k/(\rho d)]/12^3$.

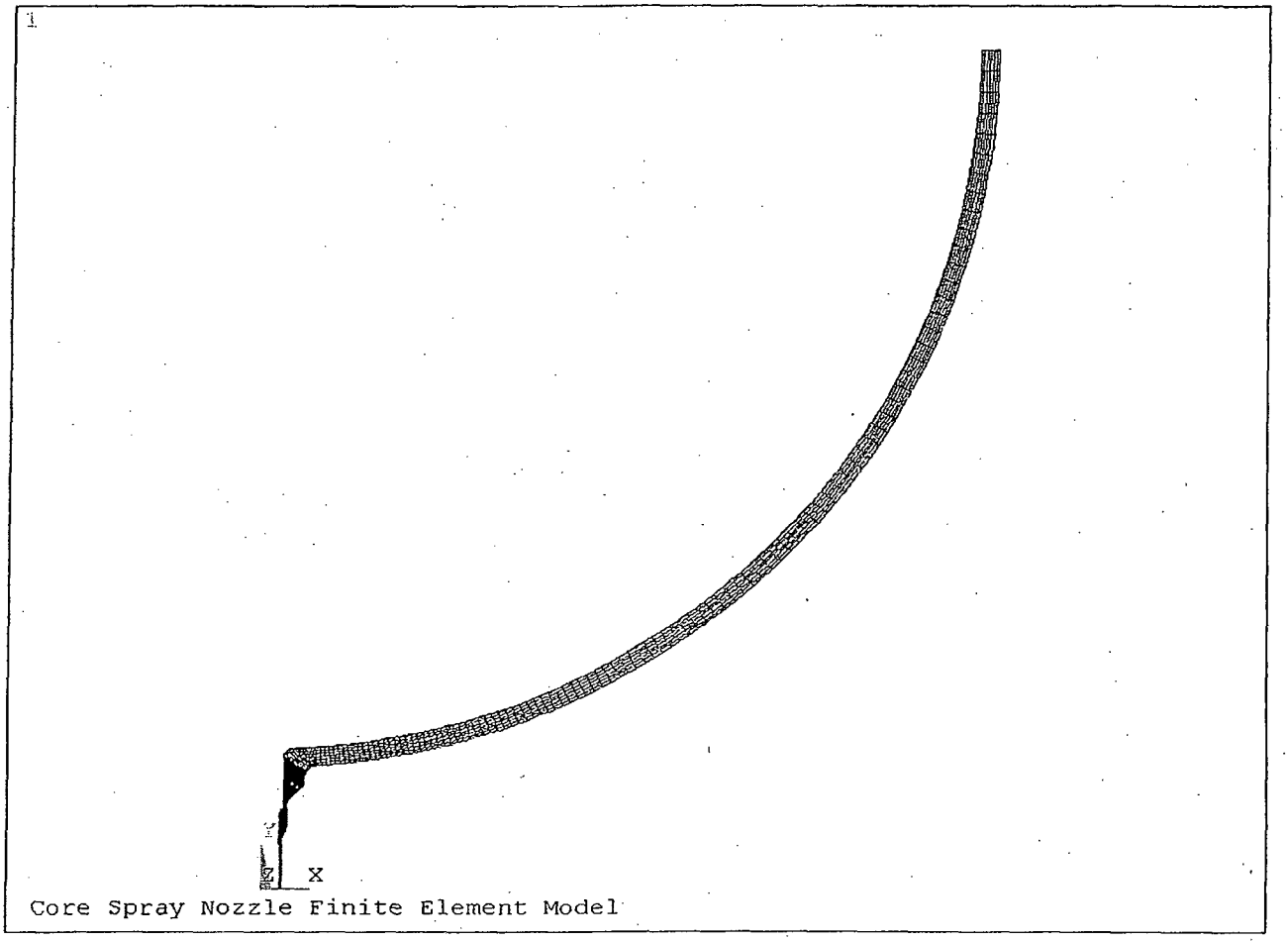

Figure 1: ANSYS Finite Element Model

3.0 APPLIED LOADS

Both pressure and thermal loads were applied to the finite element model.

3.1 Pressure Load

A uniform pressure of 1000 psi was applied along the inside surface of the core spray nozzle and the reactor vessel wall (Figure 2). A pressure load of 1000 psi was used because it is easily scaled up or down to account for different pressures that occur during transients. In addition, a cap load was applied to the piping at the end of the nozzle. This cap load was calculated as follows:

$$P_{CAP} = \frac{P \cdot D_i^2}{D_o^2 - D_i^2}$$

where:

P = Pressure = 1,000 psi
D_i = Inside Diameter = 9.834 in
D_o = Outside Diameter = 10.815 in

Therefore, the cap load is 4,774 psi. The calculated value was given a negative sign in order for it to exert tension on the end of the model. The nodes on the end of the safe end are coupled in the axial direction (UY, Figure 4) to ensure mutual displacement of the end of the nozzle due to attached piping. The boundary conditions at the end of the modeled portion of the reactor pressure vessel wall constructed to be "symmetric" (Figure 3).

The ANSYS input file VY_16Q_P.inp generates the core spray nozzle geometry from VY_CSN_Geom.inp [1] and performs the internal pressure load case just described. Figure 2, 3 and 4 show the internal pressure distribution, cap load, and symmetry conditions applied to the vessel end of the model, respectively.

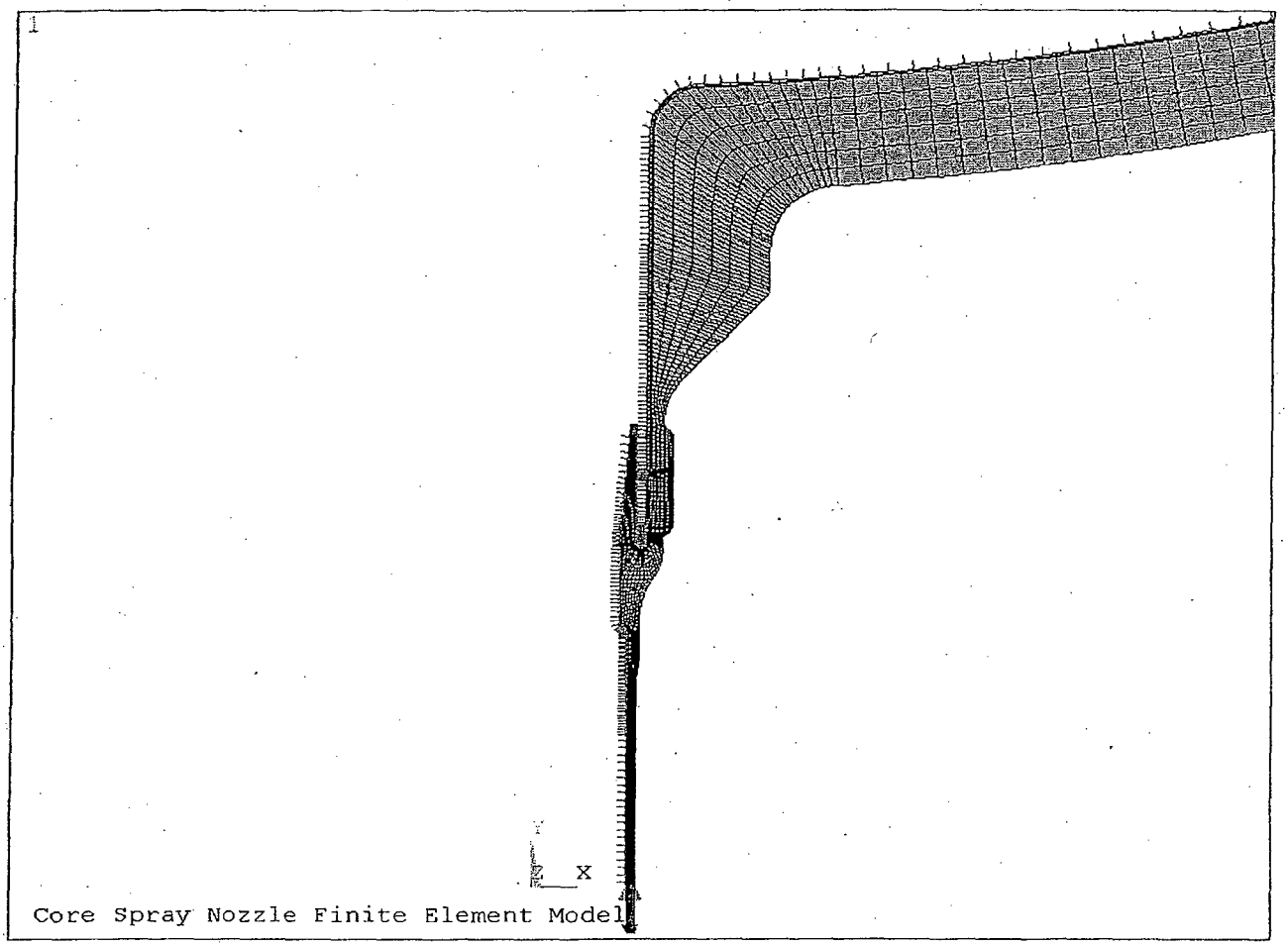

Figure 2: Core Spray Nozzle Internal Pressure Distribution

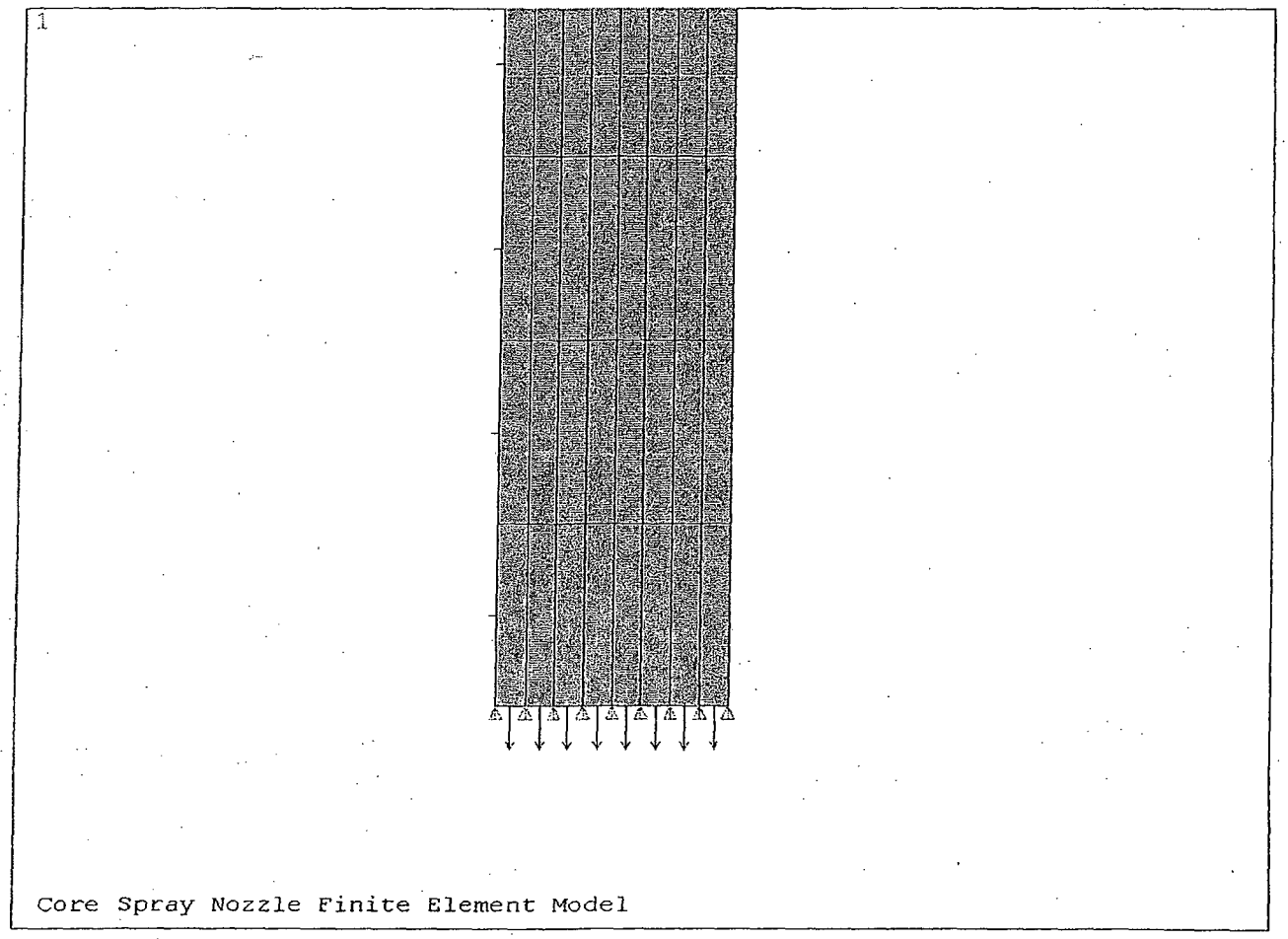

Figure 3: Core Spray Nozzle Pressure Cap Load

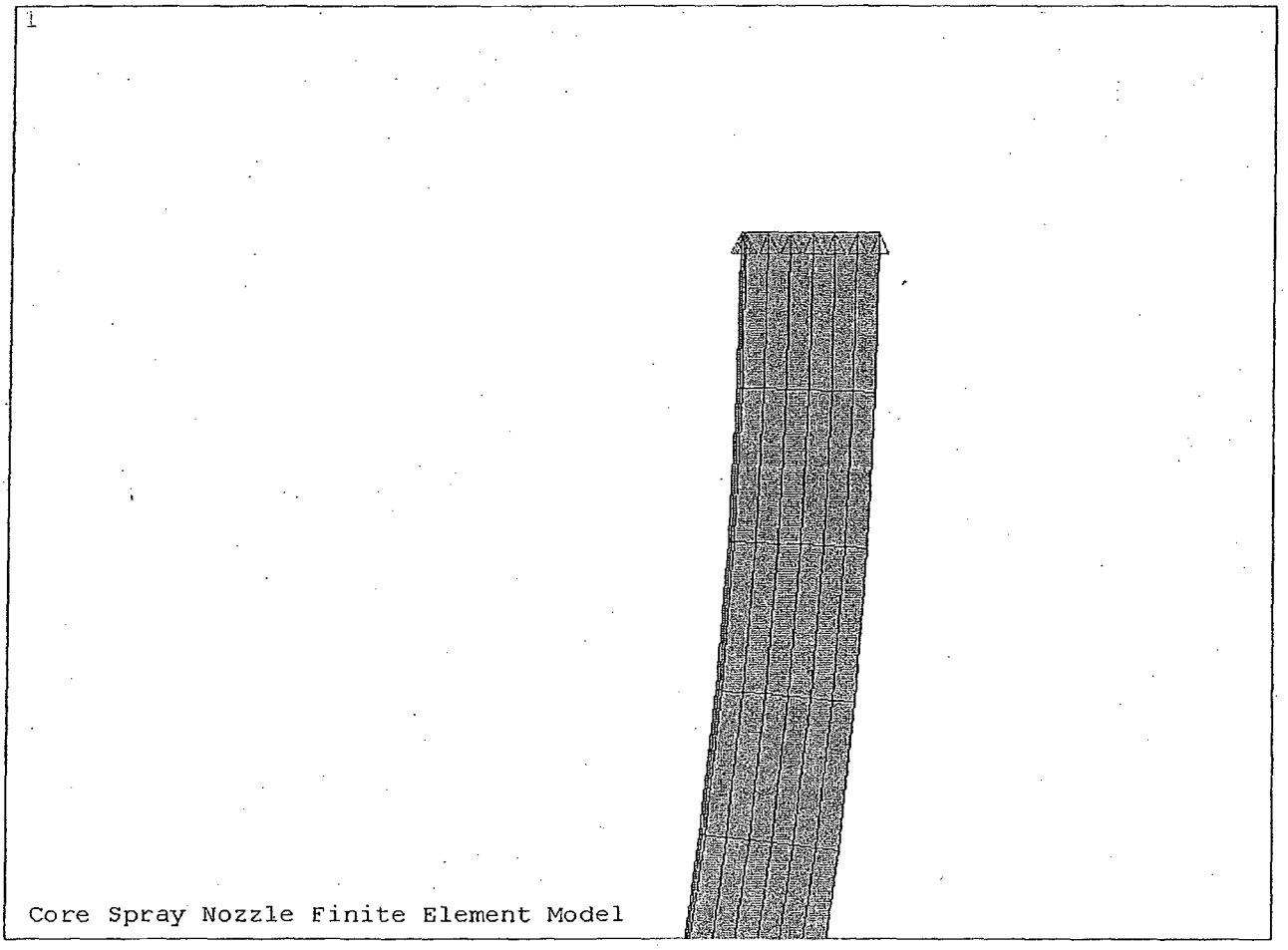

Figure 4: Core Spray Nozzle Vessel Wall Boundary Conditions

3.2 Thermal Load

Thermal loads are applied to the core spray nozzle model. The heat transfer coefficients (HTC) were determined using the methodology in the Excel spreadsheet "Heat Transfer Coefficients.xls", which is included in the project files. The HTCs were determined for various regions of the core spray FEM, (see Figure 5) for two different flow cases. The flow cases are for 100% (3200 gpm [6]) and 0% core spray flow through the nozzle.

The 0% flow case simulates a stagnant condition of the core spray nozzle when not in operation (i.e., the entire core spray nozzle is at the same temperature as the reactor pressure vessel due to reflooding). The HTCs for the no flow case are for free convection (stagnant) at the temperature of the reactor pressure vessel 500°F. The applied boundary fluid temperature is changed to simulate a thermal shock from 500°F to 100°F to develop the stress response on the core spray nozzle in the stagnant condition.

The 100% flow case simulates operational condition of the core spray nozzle (i.e., the entire core spray nozzle experiences 100°F water due to injection). The HTCs for the high flow case are for forced and free convection depending on the region of the FEM. The applied boundary fluid temperature is changed to simulate a thermal shock from 500°F to 100°F to develop the stress response on the core spray nozzle due to injection.

For both Green's Functions, a 500°F – 100°F thermal shock was run to determine the stress response. For the 0% flow case, the entire inside surface of the FEM was shocked. For the 100% flow case, only the nozzle flow path was shocked.

3.2.1 Boundary Fluid Temperatures

For the Green's Functions, a 500°F – 100°F thermal shock was run to determine the stress response to a degree change in temperature. The temperature on the exterior of the reactor, nozzle, safe end and the pipe is assumed to be 120 °F (ambient).

3.2.2 Heat Transfer Coefficients

Figure 5 shows where the heat transfer coefficients were applied to the FEM for the 0% (steady-state) and 100% core spray flow injection load case. For all the regions, the applied heat transfer coefficients and the initial temperatures are summarized in Table 2. The heat transfer coefficient for outside the reactor vessel wall is 0.2 BTU/hr-ft^2-°F and the heat transfer coefficient for inside the reactor vessel wall is 500 BTU/Hr-ft^2-°F, from page I-T7-5 of Reference [8].

Table 3 through Table 12 show the excel spreadsheets to calculate the HTC for regions 1, 3, 5, 7, and 9 respectively. These tables calculate the HTC for a certain part of the nozzle using the geometry of the bounding piping, the flow rate, and other physical fluid parameters. These tables calculate the Reynolds, Grashof and Rayleigh numbers in order to determine the HTC for inside surface/annulus forced and natural convection [4]. For several regions, the resultant HTCs had to be calculated from the partial heat transfer coefficients. These resultant HTCs are summarized in Table 13. In regions 2, 4, 6, 8, and 10 the HTCs are interpolated because of the complexity of the material profile.

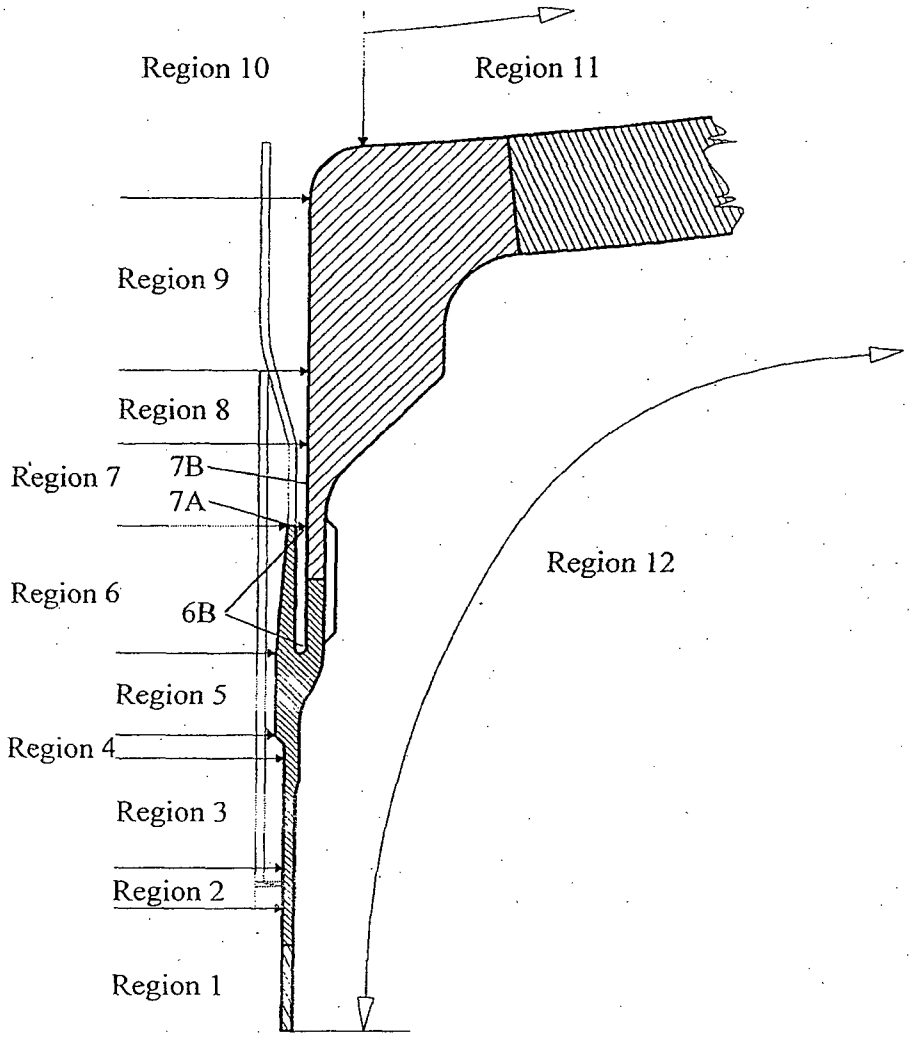

Figure 5: Nozzle and Vessel Wall Thermal and Heat Transfer Boundaries (not to scale)

Table 2: Heat Transfer Coefficients

Regions	0% Flow		100% Flow	
	Initial Temperature °F	HTC Btu/hr-ft^2-°F	Initial Temperature °F	HTC Btu/hr-ft^2-°F
R1	500	143	500	2693
R2	500	Interpolated	500	Interpolated
R3 (1)	500	39	500	52
R4	500	Interpolated	500	Interpolated
R5 (1)	500	47	500	66
R6	500	Interpolated	500	Interpolated
R6B	500	97	500	97
R7A (1)	500	38	500	50
R7B (1)	500	20	500	23
R8	500	Interpolated	500	Interpolated
R9 (1)	500	33	500	41
R10	500	Interpolated	500	Interpolated
R11	500	500	500	500
R12	120	0.20	120	0.2

(1) See Table 13

Table 3: Heat Transfer Coefficients for Region 1

Pipe Inside Diameter, D =	9.834	inches =	0.820	ft	100% rated flow =	3,200	gpm
		=	0.250	m	@ T =	549	°F
Flow, % of rated =	100%				Density, ρ =	48.087	lbm/ft³
Fluid Velocity, V =	13.517	ft/sec =	3,200.0	gpm =	1.234236214	Mlb/hr	
Characteristic Length, L = D =	0.820	ft =	0.250	m			

$T_{fluid} - T_{surface}$, ΔT = assumed to be 12% of fluid temperature =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

Note: The above assumption is based on experience with past RPV heat transfer analyses.

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70 21.11	100 37.78	200 93.33	300 148.89	400 204.44	500 260.00	600 315.56	°F °C
k (Thermal Conductivity)	1.7307	0.5997 0.3465	0.6300 0.3640	0.6784 0.3920	0.6836 0.3950	0.6611 0.3820	0.6040 0.3490	0.5071 0.2930	W/m-°C Btu/hr-ft-°F
c_p (Specific Heat)	4.1869	4.185 1.000	4.179 0.998	4.229 1.010	4.313 1.030	4.522 1.080	4.982 1.190	6.322 1.510	kJ/kg-°C Btu/lbm-°F
ρ (Density)	16.018	997.1 62.3	994.7 62.1	962.7 60.1	917.8 57.3	858.6 53.6	784.9 49.0	679.2 42.4	kg/m³ lbm/ft³
β (Volumetric Rate of Expansion)	1.8	1.89E-04 1.05E-04	3.24E-04 1.80E-04	6.66E-04 3.70E-04	1.01E-03 5.60E-04	1.40E-03 7.80E-04	1.98E-03 1.10E-03	3.15E-03 1.75E-03	m³/m³-°C ft³/ft³-°F
g (Gravitational Constant)	0.3048	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	m/s² ft/s²
μ (Dynamic Viscosity)	1.4881	9.96E-04 6.69E-04	6.82E-04 4.58E-04	3.07E-04 2.06E-04	1.93E-04 1.30E-04	1.38E-04 9.30E-05	1.04E-04 7.00E-05	8.62E-05 5.79E-05	kg/m-s lbm/ft-s
Pr (Prandtl Number)		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
Calculated Parameter	***Formula***	***70***	***100***	***200***	***300***	***400***	***500***	***600***	°F
Reynold's Number, Re	ρVD/μ	1.0307E+06	1.5019E+06	3.2317E+06	4.8825E+06	6.3843E+06	7.7540E+06	8.1118E+06	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	1.3522E+08	7.0314E+08	1.3383E+10	6.9351E+10	2.2021E+11	5.7264E+11	1.1964E+12	—
Rayleigh Number, Ra	GrPr	9.4382E+08	3.1712E+09	2.5562E+10	8.4608E+10	2.0920E+11	4.9189E+11	1.2802E+12	—
From [4]: ***Inside Surface Forced Convection Heat Transfer Coefficient:***									
H_{forced} =	$0.023Re^{0.8}Pr^{0.4}k/D$	7,765.07	9,257.25	13,050.72	15,291.12	16,581.64	16,999.27	16,154.74	W/m²-°C
		1,367.53	1,630.33	2,298.41	2,692.98	2,920.25	2,993.80	2,845.07	Btu/hr-ft²-°F
		2.638E-03	3.145E-03	4.434E-03	5.195E-03	5.633E-03	5.775E-03	5.488E-03	Btu/sec-in²-°F
From [4]: ***Inside Surface Natural Convection Heat Transfer Coefficient:***									
Case:	Enclosed cylinder		C =	0.55	n =	0.25	(see page 256 of [4])		
H_{free} =	$C(GrPr)^n k/L$	231.44	329.18	597.32	811.84	984.52	1,113.82	1,187.70	W/m²-°C
		40.76	57.97	105.20	142.98	173.39	196.16	209.17	Btu/hr-ft²-°F
		7.863E-05	1.118E-04	2.029E-04	2.758E-04	3.345E-04	3.784E-04	4.035E-04	Btu/sec-in²-°F

Table 4: First Partial Heat Transfer Coefficients for Region 3

Pipe Inside Diameter, D =	7.981	inches =	0.665	ft	100% rated flow =	3,200	gpm
		=	0.203	m	@ T =	549	°F
Flow, % of rated =	100%				Density, ρ =	48.087	lbm/ft³
Fluid Velocity, V =	20.522	ft/sec =	3,200.0	gpm =	1.234236214	Mlb/hr	
Characteristic Length, L = D =	0.665	ft =	0.203	m			

$T_{fluid} - T_{surface}$, ΔT = assumed to be 12% of fluid temperature =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
≈	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

Note: The above assumption is based on experience with past RPV heat transfer analyses.

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70	100	200	300	400	500	600	°F
		21.11	37.78	93.33	148.89	204.44	260.00	315.56	°C
k (Thermal Conductivity)	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p (Specific Heat)	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ (Density)	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m³
		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft³
β (Volumetric Rate of Expansion)	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m³/m³-°C
		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft³/ft³-°F
g (Gravitational Constant)	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s²
		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s²
μ (Dynamic Viscosity)	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr (Prandtl Number)		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	$\rho VD/\mu$	1.2700E+06	1.8507E+06	3.9821E+06	6.0161E+06	7.8665E+06	9.5543E+06	9.9952E+06	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	7.2279E+07	3.7586E+08	7.1540E+09	3.7071E+10	1.1771E+11	3.0610E+11	6.3954E+11	—
Rayleigh Number, Ra	GrPr	5.0451E+08	1.6951E+09	1.3664E+10	4.5226E+10	1.1183E+11	2.6294E+11	6.8430E+11	—
From [4]: ***Inside Surface Forced Convection Heat Transfer Coefficient:***									
H_{forced} =	$0.023Re^{0.8}Pr^{0.4}k/D$	11,307.23	13,480.10	19,004.02	22,266.42	24,145.63	24,753.78	23,524.01	W/m²-°C
		1,991.36	2,374.03	3,346.87	3,921.32	4,252.38	4,359.48	4,142.90	Btu/hr-ft²-°F
		3.841E-03	4.580E-03	6.456E-03	7.564E-03	8.203E-03	8.409E-03	7.992E-03	Btu/sec-in²-°F
From [4]: ***Inside Surface Natural Convection Heat Transfer Coefficient:***									
Case:	Enclosed cylinder		C =	0.55	n =	0.25	(see page 289 of [4])		
H_{free} =	$C(GrPr)^n k/L$	243.85	346.81	629.32	855.34	1,037.27	1,173.50	1,251.33	W/m²-°C
		42.94	61.08	110.83	150.64	182.68	206.67	220.38	Btu/hr-ft²-°F
		8.284E-05	1.178E-04	2.138E-04	2.906E-04	3.524E-04	3.987E-04	4.251E-04	Btu/sec-in²-°F

Table 5: Second Partial Heat Transfer Coefficients for Region 3

Pipe Inside Diameter, D =	9.834	inches =	0.820	ft	
		=	0.250	m	
Outer Pipe, Inside radius, r_o =	4.917	inches =	0.410	ft	
			0.125	m	
Inner Pipe Outside Diameter, D =	8.625	inches =	0.719	ft	
		=	0.219	m	
Inner Pipe, Outside radius, r_i =	4.3125	inches =	0.359	ft	
			0.110	m	
Fluid Velocity, V =	13.517	ft/sec =	3200.000	gpm	
Characteristic Length, L = D =	0.820	ft =	0.250	m	

(Outside) $T_{fluid} - T_{surface}$, ΔT =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70 21.11	100 37.78	200 93.33	300 148.89	400 204.44	500 260.00	600 315.56	°F °C
k (Thermal Conductivity)	1.7307	0.5997 0.3465	0.6300 0.3640	0.6784 0.3920	0.6836 0.3950	0.6611 0.3820	0.6040 0.3490	0.5071 0.2930	W/m-°C Btu/hr-ft-°F
c_p (Specific Heat)	4.1869	4.185 1.000	4.179 0.998	4.229 1.010	4.313 1.030	4.522 1.080	4.982 1.190	6.322 1.510	kJ/kg-°C Btu/lbm-°F
ρ (Density)	16.018	997.1 62.3	994.7 62.1	962.7 60.1	917.8 57.3	858.6 53.6	784.9 49.0	679.2 42.4	kg/m^3 lbm/ft^3
β (Volumetric Rate of Expansion)	1.8	1.89E-04 1.05E-04	3.24E-04 1.80E-04	6.66E-04 3.70E-04	1.01E-03 5.60E-04	1.40E-03 7.80E-04	1.98E-03 1.10E-03	3.15E-03 1.75E-03	m^3/m^3-°C ft^3/ft^3-°F
g (Gravitational Constant)	0.3048	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	m/s^2 ft/s^2
μ (Dynamic Viscosity)	1.4881	9.96E-04 6.69E-04	6.82E-04 4.58E-04	3.07E-04 2.06E-04	1.93E-04 1.30E-04	1.38E-04 9.30E-05	1.04E-04 7.00E-05	8.62E-05 5.79E-05	kg/m-s lbm/ft-s
Pr (Prandtl Number)		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	$\rho VD/\mu$	1030724	1501950	3231741	4882481	6384268	7754027	8111787	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	135217684.2	703144247.6	13383382850	69350803914	2.2021E+11	5.72636E+11	1.19642E+12	—
Grashof Number, Gr_δ	$g\beta\Delta T(r_o-r_i)^3/(\mu/\rho)^2$	3.14E+04	1.63E+05	3.11E+06	1.61E+07	5.11E+07	1.33E+08	2.78E+08	—
Rayleigh Number, Ra	GrPr	943819435.9	3171180557	25562261244	84607980776	2.092E+11	4.91894E+11	1.28017E+12	—
Rayleigh Number, Ra	$Gr_\delta Pr$	2.19E+05	7.37E+05	5.94E+06	1.97E+07	4.86E+07	1.14E+08	2.97E+08	—

From [4]:

Annulus Natural Convection Heat Transfer Coefficient:

Case:	Enclosed cylinder		C =	0.40	n =	0.20	(see page 291 of [5])		
H_{free}	$C(Gr_\delta Pr)^n k/(r_o-r_i)$	182.78	244.68	400.00	512.07	593.51	643.36	653.99	W/m^2-°C
		32.19	43.09	70.45	90.18	104.53	113.30	115.16	Btu/hr-ft^2-°F

Table 6: First Partial Heat Transfer Coefficients for Region 5

Pipe Inside Diameter, D =	7.981	inches =	0.665	ft		100% rated flow =	3,200	gpm
		=	0.203	m		@ T =	549	°F
Flow, % of rated =	100%					Density, ρ =	48.087	lbm/ft³
Fluid Velocity, V =	20.522	ft/sec =	3,200.0	gpm =	1.234236214	Mlb/hr		
Characteristic Length, L = D =	0.665	ft =	0.203	m				

$T_{fluid} - T_{surface}$, ΔT = assumed to be 12% of fluid temperature =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
Note: The above assumption is based on experience with past RPV heat transfer analyses. =	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70	100	200	300	400	500	600	°F
		21.11	37.78	93.33	148.89	204.44	260.00	315.56	°C
k (Thermal Conductivity)	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p (Specific Heat)	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ (Density)	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m³
		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft³
β (Volumetric Rate of Expansion)	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m³/m³-°C
		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft³/ft³-°F
g (Gravitational Constant)	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s²
		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s²
μ (Dynamic Viscosity)	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr (Prandtl Number)		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	ρVD/μ	1.2700E+06	1.8507E+06	3.9821E+06	6.0161E+06	7.8665E+06	9.5543E+06	9.9952E+06	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	7.2279E+07	3.7586E+08	7.1540E+09	3.7071E+10	1.1771E+11	3.0610E+11	6.3954E+11	—
Rayleigh Number, Ra	GrPr	5.0451E+08	1.6951E+09	1.3664E+10	4.5226E+10	1.1183E+11	2.6294E+11	6.8430E+11	—
From [4]: ***Inside Surface Forced Convection Heat Transfer Coefficient:***									
H_{forced} =	$0.023Re^{0.8}Pr^{0.4}k/D$	11,307.23	13,480.10	19,004.02	22,266.42	24,145.63	24,753.78	23,524.01	W/m²-°C
		1,991.36	2,374.03	3,346.87	3,921.42	4,252.38	4,359.48	4,142.90	Btu/hr-ft²-°F
		3.841E-03	4.580E-03	6.456E-03	7.564E-03	8.203E-03	8.409E-03	7.992E-03	Btu/sec-in²-°F
From [4]: ***Inside Surface Natural Convection Heat Transfer Coefficient:***									
Case:	Enclosed cylinder		C =	0.55	n =	0.25	(see page 289 of [4])		
H_{free} =	$C(GrPr)^n k/L$	243.85	346.81	629.32	855.34	1,037.27	1,173.50	1,251.33	W/m²-°C
		42.94	61.08	110.83	150.64	182.66	206.67	220.38	Btu/hr-ft²-°F
		8.284E-05	1.178E-04	2.138E-04	2.906E-04	3.524E-04	3.987E-04	4.251E-04	Btu/sec-in²-°F

Table 7: Second Partial Heat Transfer Coefficients for Region 5

Title =	No Flow Region between nozzle and thermal sleeve				
Pipe Inside Diameter, D =	9.000	inches =	0.750	ft	
		=	0.229	m	
Outer Pipe, Inside radius, r_o =	4.5	inches =	0.375	ft	
			0.114	m	
Inner Pipe Outside Diameter, D =	8.625	inches =	0.719	ft	
		=	0.219	m	
Inner Pipe, Outside radius, r_i =	4.3125	inches =	0.359	ft	
			0.110	m	
Fluid Velocity, V =	16.138	ft/sec =	3200.000	gpm	
Characteristic Length, L = D =	0.750	ft =	0.229	m	

(Outside) T_{fluid} - $T_{surface}$, ΔT =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70	100	200	300	400	500	600	°F
		21.11	37.78	93.33	148.89	204.44	260.00	315.56	°C
k	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
(Thermal Conductivity)		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
(Specific Heat)		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m^3
(Density)		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft^3
β	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m^3/m^3-°C
(Volumetric Rate of Expansion)		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft^3/ft^3-°F
g	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s^2
(Gravitational Constant)		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s^2
μ	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
(Dynamic Viscosity)		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
(Prandtl Number)									
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	$\rho VD/\mu$	1126238	1641130	3531215	5334924	6975877	8472567	8863480	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	103650263.4	538990790.5	10258947757	53160421562	1.68801E+11	4.3895E+11	9.17108E+11	—
Grashof Number, Gr_δ	$g\beta\Delta T(r_o-r_i)^3/(\mu/\rho)^3$	9.37E+02	4.87E+03	9.28E+04	4.81E+05	1.53E+06	3.97E+06	8.29E+06	—
Rayleigh Number, Ra	GrPr	723478838.9	2430848465	19594590215	64855714305	1.60361E+11	3.77058E+11	9.81306E+11	—
Rayleigh Number, Ra	$Gr_\delta Pr$	6.54E+03	2.20E+04	1.77E+05	5.86E+05	1.45E+06	3.41E+06	8.87E+06	—

From [4]:

Annulus Natural Convection Heat Transfer Coefficient:

Case:	*Enclosed cylinder*		C =	0.40	n =	0.20	(See Page 29 of [5])		
H_{free}	$C(Gr_\delta Pr)^n k/(r_o-r_i)$	291.94	390.80	638.87	817.88	947.95	1,027.56	1,044.55	W/m^2-°C
		51.41	68.83	112.51	144.0	166.95	180.97	183.96	Btu/hr-ft²-°F

Table 8: First Partial Heat Transfer Coefficients for Region 7

Pipe Inside Diameter, D =	7.981	inches =	0.665	ft		100% rated flow =	3,200	gpm
		=	0.203	m		@ T =	549	°F
Flow, % of rated =	100%					Density, ρ =	48.087	lbm/ft³
Fluid Velocity, V =	20.522	ft/sec =	3,200.0	gpm =	1.234236214	Mlb/hr		
Characteristic Length, L = D =	0.665	ft =	0.203	m				
$T_{fluid} - T_{surface}$, ΔT = assumed to be 12% of fluid temperature =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

Note: The above assumption is based on experience with past RPV heat transfer analyses.

		Value at Fluid Temperature, T [7]							Units
	Conversion	70	100	200	300	400	500	600	°F
Water Property	Factor [4]	21.11	37.78	93.33	148.89	204.44	260.00	315.56	°C
k	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
(Thermal Conductivity)		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
(Specific Heat)		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m³
(Density)		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft³
β	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m³/m³-°C
(Volumetric Rate of Expansion)		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft³/ft³-°F
g	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s²
(Gravitational Constant)		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s²
μ	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
(Dynamic Viscosity)		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
(Prandtl Number)									
Calculated Parameter	***Formula***	***70***	***100***	***200***	***300***	***400***	***500***	***600***	***°F***
Reynold's Number, Re	ρVD/μ	1.2700E+06	1.8507E+06	3.9821E+06	6.0161E+06	7.8665E+06	9.5543E+06	9.9952E+06	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	7.2279E+07	3.7586E+08	7.1540E+09	3.7071E+10	1.1771E+11	3.0610E+11	6.3954E+11	—
Rayleigh Number, Ra	GrPr	5.0451E+08	1.6951E+09	1.3664E+10	4.5226E+10	1.1183E+11	2.6294E+11	6.8430E+11	—
From [4]:									
Inside Surface Forced Convection Heat Transfer Coefficient:									
H_{forced} =	$0.023Re^{0.8}Pr^{0.4}k/D$	11,307.23	13,480.10	19,004.02	22,266.42	24,145.63	24,753.78	23,524.01	W/m²-°C
		1,991.36	2,374.03	3,346.87	3,921.42	4,252.38	4,359.48	4,142.90	Btu/hr-ft²-°F
		3.841E-03	4.580E-03	6.456E-03	7.564E-03	8.203E-03	8.409E-03	7.992E-03	Btu/sec-in²-°F
From [4]:									
Inside Surface Natural Convection Heat Transfer Coefficient:									
Case:	Enclosed cylinder		C =	0.55	n =	0.25	(c-s) page 289 of [4]		
H_{free} =	$C(GrPr)^n k/L$	243.85	346.81	629.32	855.34	1,037.27	1,173.50	1,251.33	W/m²-°C
		42.94	61.08	110.83	150.67	182.66	206.67	220.38	Btu/hr-ft²-°F
		8.284E-05	1.178E-04	2.138E-04	2.906E-04	3.524E-04	3.987E-04	4.251E-04	Btu/sec-in²-°F

Table 9: Second Partial Heat Transfer Coefficients for Region 7

Pipe Inside Diameter, D =	10.020	inches =	0.835	ft	
		=	0.255	m	
Outer Pipe, Inside radius, r_o =	5.01	inches =	0.418	ft	
			0.127	m	
Inner Pipe Outside Diameter, D =	8.625	inches =	0.719	ft	
		=	0.219	m	
Inner Pipe, Outside radius, r_i =	4.3125	inches =	0.359	ft	
			0.110	m	
Fluid Velocity, V =	13.020	*ft/sec =*	200.000	*gpm*	
Characteristic Length, L = D =	0.835	ft =	0.255	m	

(Outside) T_{fluid} - $T_{surface}$, ΔT =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

		Value at Fluid Temperature, T [7]							Units
Water Property	**Conversion Factor [4]**	**70.**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
		21.11	**37.78**	**93.33**	**148.89**	**204.44**	**260.00**	**315.56**	**°C**
k	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
(Thermal Conductivity)		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
(Specific Heat)		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m^3
(Density)		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft^3
β	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m^3/m^3-°C
(Volumetric Rate of Expansion)		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft^3/ft^3-°F
g	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s^2
(Gravitational Constant)		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s^2
μ	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
(Dynamic Viscosity)		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
(Prandtl Number)									
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	$\rho VD/\mu$	1011591	1474069	3171750	4791848	6265758	7610090	7961209	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	143036227.2	743801381.9	14157235436	73360798959	2.32943E+11	6.05747E+11	1.2656E+12	—
Grashof Number, Gr_δ	$g\beta\Delta T(r_o-r_i)^3/(\mu/\rho)^2$	4.82E+04	2.51E+05	4.78E+06	2.47E+07	7.86E+07	2.04E+08	4.27E+08	—
Rayleigh Number, Ra	GrPr	998392866.2	3354544233	27040319682	89500174730	2.21296E+11	5.20336E+11	1.35419E+12	—
Rayleigh Number, Ra	$Gr_\delta Pr$	3.37E+05	1.13E+06	9.12E+06	3.02E+07	7.46E+07	1.76E+08	4.57E+08	—

From [4]:

Annulus Natural Convection Heat Transfer Coefficient:

Case:	Enclosed cylinder		C =	0.40	n =	0.20	(see page 291 of [5])		
H_{free}	$C(Gr_\delta Pr)^n k/(r_o-r_i)$	172.61	231.07	377.74	483.58	560.49	607.56	617.61	W/m^2-°C
		30.40	40.69	66.53	85.16	98.71	107.00	108.77	Btu/hr-ft²-°F

Table 10: Third Partial Heat Transfer Coefficients for Region 7

Pipe Inside Diameter, D =	11.750	inches =	0.979	ft	
		=	0.298	m	
Outer Pipe, Inside radius, r_o =	5.875	inches =	0.490	ft	
			0.149	m	
Inner Pipe Outside Diameter, D =	10.750	inches =	0.896	ft	
		=	0.273	m	
Inner Pipe, Outside radius, r_i =	5.375	inches =	0.448	ft	
			0.137	m	
Fluid Velocity, V =	9.468	ft/sec =	3200.000	gpm	
Characteristic Length, L = D =	0.979	ft =	0.298	m	

(Outside) T_{fluid} - $T_{surface}$, ΔT =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70 21.11	100 37.78	200 93.33	300 148.89	400 204.44	500 260.00	600 315.56	°F °C
k (Thermal Conductivity)	1.7307	0.5997 0.3465	0.6300 0.3640	0.6784 0.3920	0.6836 0.3950	0.6611 0.3820	0.6040 0.3490	0.5071 0.2930	W/m-°C Btu/hr-ft-°F
c_p (Specific Heat)	4.1869	4.185 1.000	4.179 0.998	4.229 1.010	4.313 1.030	4.522 1.080	4.982 1.190	6.322 1.510	kJ/kg-°C Btu/lbm-°F
ρ (Density)	16.018	997.1 62.3	994.7 62.1	962.7 60.1	917.8 57.3	858.6 53.6	784.9 49.0	679.2 42.4	kg/m^3 lbm/ft^3
β (Volumetric Rate of Expansion)	1.8	1.89E-04 1.05E-04	3.24E-04 1.80E-04	6.66E-04 3.70E-04	1.01E-03 5.60E-04	1.40E-03 7.80E-04	1.98E-03 1.10E-03	3.15E-03 1.75E-03	m^3/m^3-°C ft^3/ft^3-°F
g (Gravitational Constant)	0.3048	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	9.806 32.17	m/s^2 ft/s^2
μ (Dynamic Viscosity)	1.4881	9.96E-04 6.69E-04	6.82E-04 4.58E-04	3.07E-04 2.06E-04	1.93E-04 1.30E-04	1.38E-04 9.30E-05	1.04E-04 7.00E-05	8.62E-05 5.79E-05	kg/m-s lbm/ft-s
Pr (Prandtl Number)		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	ρVD/μ	862650	1257036	2704761	4086325	5343225	6489626	6789048	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	230651605.4	1199409312	22829105215	1.18297E+11	3.75631E+11	9.76791E+11	2.04083E+12	—
Grashof Number, Gr_δ	$g\beta\Delta T(r_o-r_i)^3/(\mu/\rho)^2$	1.78E+04	9.24E+04	1.76E+06	9.12E+06	2.89E+07	7.53E+07	1.57E+08	—
Rayleigh Number, Ra	GrPr	1609948206	5409335995	43603590961	1.44323E+11	3.56849E+11	8.39063E+11	2.18369E+12	—
Rayleigh Number, Ra	$Gr_\delta Pr$	1.24E+05	4.17E+05	3.36E+06	1.11E+07	2.75E+07	6.47E+07	1.68E+08	—

From [4]:

Annulus Natural Convection Heat Transfer Coefficient:

Case:	Enclosed cylinder		C =	0.40	n =	0.20	(See page 291 of [5])		
H_{free}	$C(Gr_\delta Pr)^n k/(r_o-r_i)$	197.20	263.98	431.55	552.46	640.32	694.10	705.57	W/m^2-°C
		34.73	46.49	76.00	97.26	112.77	122.24	124.26	$Btu/hr-ft^2$-°F

Table 11: First Partial Heat Transfer Coefficients for Region 9

Pipe Inside Diameter, D =	7.981	inches =	0.665	ft					
		=	0.203	m					
Flow, % of rated =	100%								
Fluid Velocity, V =	20.522	ft/sec =	3,200.0	gpm =					
Characteristic Length, L = D =	0.665	ft =	0.203	m					

100% rated flow =	3,200	gpm					
@ T =	549	°F					
Density, ρ =	48.087	lbm/ft³					
	1.234236214	Mlb/hr					

$T_{fluid} - T_{surface}$, ΔT = assumed to be 12% of fluid temperature =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

Note: The above assumption is based on experience with past RPV heat transfer analyses.

		Value at Fluid Temperature, T [7]							Units
Water Property	**Conversion Factor [4]**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
		21.11	**37.78**	**93.33**	**148.89**	**204.44**	**260.00**	**315.56**	**°C**
k	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
(Thermal Conductivity)		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
(Specific Heat)		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m³
(Density)		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft³
β	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m³/m³-°C
(Volumetric Rate of Expansion)		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft³/ft³-°F
g	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s²
(Gravitational Constant)		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s²
μ	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
(Dynamic Viscosity)		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
(Prandtl Number)									
Calculated Parameter	**Formula**	**70**	**100**	**200**	**300**	**400**	**500**	**600**	**°F**
Reynold's Number, Re	ρVD/μ	1.2700E+06	1.8507E+06	3.9821E+06	6.0161E+06	7.8665E+06	9.5543E+06	9.9952E+06	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	7.2279E+07	3.7586E+08	7.1540E+09	3.7071E+10	1.1771E+11	3.0610E+11	6.3954E+11	—
Rayleigh Number, Ra	GrPr	5.0451E+08	1.6951E+09	1.3664E+10	4.5226E+10	1.1183E+11	2.6294E+11	6.8430E+11	—
From [4]:									
Inside Surface Forced Convection Heat Transfer Coefficient:									
H_{forced} =	$0.023Re^{0.8}Pr^{0.4}k/D$	11,307.23	13,480.10	19,004.02	22,266.42	24,145.63	24,753.78	23,524.01	W/m²-°C
		1,991.36	2,374.03	3,346.87	3,921.42	4,252.38	4,359.46	4,142.90	Btu/hr-ft²-°F
		3.841E-03	4.580E-03	6.456E-03	7.564E-03	8.203E-03	8.409E-03	7.992E-03	Btu/sec-in²-°F
From [4]:									
Inside Surface Natural Convection Heat Transfer Coefficient:									
Case:	Enclosed cylinder		C =	0.55	n =	0.25	(see page 289 of [4])		
H_{free} =	$C(GrPr)^n k/L$	243.85	346.81	629.32	855.34	1,037.27	1,173.50	1,251.33	W/m²-°C
		42.94	61.08	110.83	150.64	182.68	206.67	220.38	Btu/hr-ft²-°F
		8.284E-05	1.178E-04	2.138E-04	2.906E-04	3.524E-04	3.987E-04	4.251E-04	Btu/sec-in²-°F

Table 12: Second Partial Heat Transfer Coefficients for Region 9

Pipe Inside Diameter, D =	11.750	inches =	0.979	ft	
		=	0.298	m	
Outer Pipe, Inside radius, r_o =	5.875	inches =	0.490	ft	
			0.149	m	
Inner Pipe Outside Diameter, D =	8.625	inches =	0.719	ft	
		=	0.219	m	
Inner Pipe, Outside radius, r_i =	4.3125	inches =	0.359	ft	
			0.110	m	
Fluid Velocity, V =	9.468	ft/sec =	3200.000	gpm	
Characteristic Length, L = D =	0.979	ft =	0.298	m	

(Outside) T_{fluid} - $T_{surface}$, ΔT =	8.40	12.00	24.00	36.00	48.00	60.00	72.00	°F
=	4.67	6.67	13.33	20.00	26.67	33.33	40.00	°C

		Value at Fluid Temperature, T [7]							Units
Water Property	Conversion Factor [4]	70	100	200	300	400	500	600	°F
		21.11	37.78	93.33	148.89	204.44	260.00	315.56	°C
k	1.7307	0.5997	0.6300	0.6784	0.6836	0.6611	0.6040	0.5071	W/m-°C
(Thermal Conductivity)		0.3465	0.3640	0.3920	0.3950	0.3820	0.3490	0.2930	Btu/hr-ft-°F
c_p	4.1869	4.185	4.179	4.229	4.313	4.522	4.982	6.322	kJ/kg-°C
(Specific Heat)		1.000	0.998	1.010	1.030	1.080	1.190	1.510	Btu/lbm-°F
ρ	16.018	997.1	994.7	962.7	917.8	858.6	784.9	679.2	kg/m^3
(Density)		62.3	62.1	60.1	57.3	53.6	49.0	42.4	lbm/ft^3
β	1.8	1.89E-04	3.24E-04	6.66E-04	1.01E-03	1.40E-03	1.98E-03	3.15E-03	m^3/m^3-°C
(Volumetric Rate of Expansion)		1.05E-04	1.80E-04	3.70E-04	5.60E-04	7.80E-04	1.10E-03	1.75E-03	ft^3/ft^3-°F
g	0.3048	9.806	9.806	9.806	9.806	9.806	9.806	9.806	m/s^2
(Gravitational Constant)		32.17	32.17	32.17	32.17	32.17	32.17	32.17	ft/s^2
μ	1.4881	9.96E-04	6.82E-04	3.07E-04	1.93E-04	1.38E-04	1.04E-04	8.62E-05	kg/m-s
(Dynamic Viscosity)		6.69E-04	4.58E-04	2.06E-04	1.30E-04	9.30E-05	7.00E-05	5.79E-05	lbm/ft-s
Pr		6.980	4.510	1.910	1.220	0.950	0.859	1.070	—
(Prandtl Number)									
Calculated Parameter	**Formula**	70	100	200	300	400	500	600	°F
Reynold's Number, Re	$\rho VD/\mu$	862650	1257036	2704761	4086325	5343225	6489626	6789048	—
Grashof Number, Gr	$g\beta\Delta TL^3/(\mu/\rho)^2$	230651605.4	1199409312	22829105215	1.18297E+11	3.75631E+11	9.76791E+11	2.04083E+12	—
Grashof Number, Gr_δ	$g\beta\Delta T(r_o-r_i)^3/(\mu/\rho)^3$	5.42E+05	2.82E+06	5.37E+07	2.78E+08	8.83E+08	2.30E+09	4.80E+09	—
Rayleigh Number, Ra	GrPr	1609948206	5409335995	43603590961	1.44323E+11	3.56849E+11	8.39063E+11	2.18369E+12	—
Rayleigh Number, Ra	$Gr_\delta Pr$	3.79E+06	1.27E+07	1.03E+08	3.39E+08	8.39E+08	1.97E+09	5.13E+09	—

From [4]:

Annulus Natural Convection Heat Transfer Coefficient:

Case:	Enclosed cylinder		C =	0.40	n =	0.20	(see page 291 of [5])		
H_{free}	$C(Gr_\delta Pr)^n k/(r_o-r_i)$	125.02	167.35	273.58	350.24	405.94	440.03	447.30	W/m^2-°C
		22.02	29.47	48.18	[illegible]	71.49	77.50	78.78	Btu/hr-ft²-°F

Although the thermal sleeve was excluded from the analysis, its effect had to be included in the finite element model. For several thermal regions, the resultant HTCs had to be calculated from the partial heat transfer coefficients (HTC_i in Table 13). These are generated by "Heat Transfer Coefficients.xls".

$$\frac{1}{HTC_{Res}} = \left(\frac{1}{HTC_I} + \frac{T_I}{TC_I}\right) + \left(\frac{1}{HTC_{II}} + \frac{T_{II}}{TC_{II}}\right) + \left(\frac{1}{HTC_{III}} + \frac{T_{III}}{TC_{III}}\right)$$

Where:

HTC_{Res}	=	Resultant HTC
HTC_i	=	HTC of ith material
T_i	=	Thickness of ith material
TC_i	=	Thermal Conductivity of ith material

The reference for this equation is [4].

Table 13: Resultant Heat Transfer Coefficients for the Regions

100% Flow

Regions	HTC I	Material		HTCII	Material		HTCIII	HTC resultant
		Thermal Conductivity, Btu/hr-ft-°F	Thickness [ft]		Thermal Conductivity, Btu/hr-ft-°F	Thickness [ft]		
R1	2,692.98							2693
R2								
R3	3,921.42	9.8	0.0268	90.18				71
R4								
R5	3,921.42	9.8	0.0268	144.04				101
R6								
R6B							97.30	97
R7	3,921.42	9.8	0.0268	85.17				68
R7B	3,921.42	9.8	0.0268	85.17	9.8	0.0304	97.30	36
R8								
R9	3,921.42	9.8	0.0268	61.68				52
R10								
R10	500							500
R10	0.2							0.2

0% Flow

Regions	HTC I	Material		HTCII	Material		HTCIII	HTC resultant
		Thermal Conductivity, Btu/hr-ft-°F	Thickness [ft]		Thermal Conductivity, Btu/hr-ft-°F	Thickness [ft]		
R1	142.98							143
R2								
R3	150.64	9.8	0.0268	90.18				49
R4								
R5	150.64	9.8	0.0268	144.04				61
R6								
R6B							97.30	97
R7	150.64	9.8	0.0268	85.17				47
R7B	150.64	9.8	0.0268	85.17	9.8	0.0304	97.30	29
R8								
R9	150.64	9.8	0.0268	61.68				39
R10								
R10	500							500
R10	0.2							0.2

4.0 THERMAL AND PRESSURE LOAD RESULTS

The two flow dependent thermal load cases outlined in previous section were run on the core spray FEM. For ANSYS, the thermal transient input files "VY_16Q_T100.inp," "VY_16Q_T0.inp," for 100% and 0% flow, respectively. The stress input filenames are "VY_16Q_ST100.inp"and "VY_16Q_ST0.inp," respectively.

The limiting safe end location was chosen based on the highest thermal stress intensity at 100% flow. Node 3719 on the inside surface of the core spray nozzle was selected for the safe end analysis and shown in Figure 6.

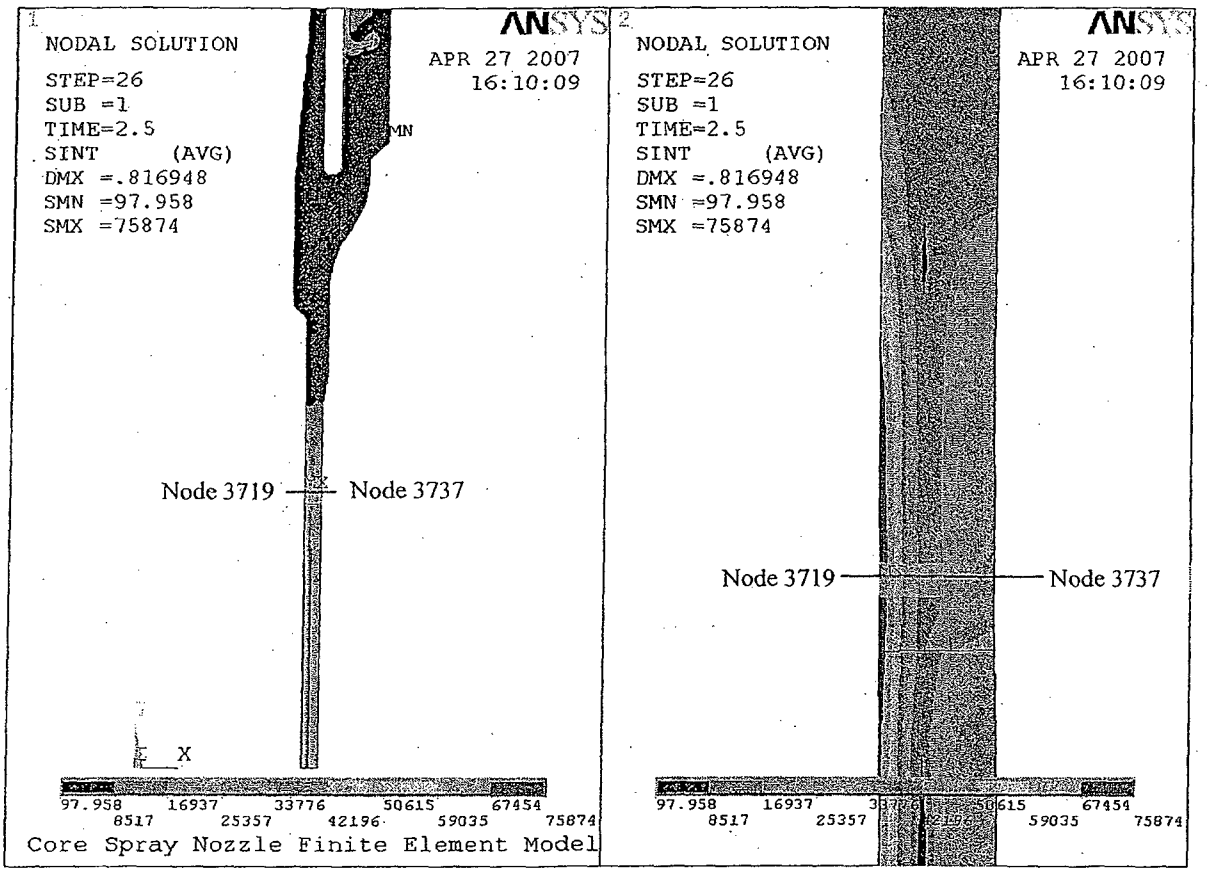

Figure 6: Safe End Critical Thermal Stress Location, Node 3719

The limiting blend radius location was chosen based upon the highest pressure stress intensity. Node 2166 on the inside surface of the blend radius was therefore selected for the nozzle forging analysis and shown in Figure 7. The highest thermal stress and pressure stress occur very close to the same location in the nozzle forging region. Therefore, this location is a reasonable choice for the limiting location.

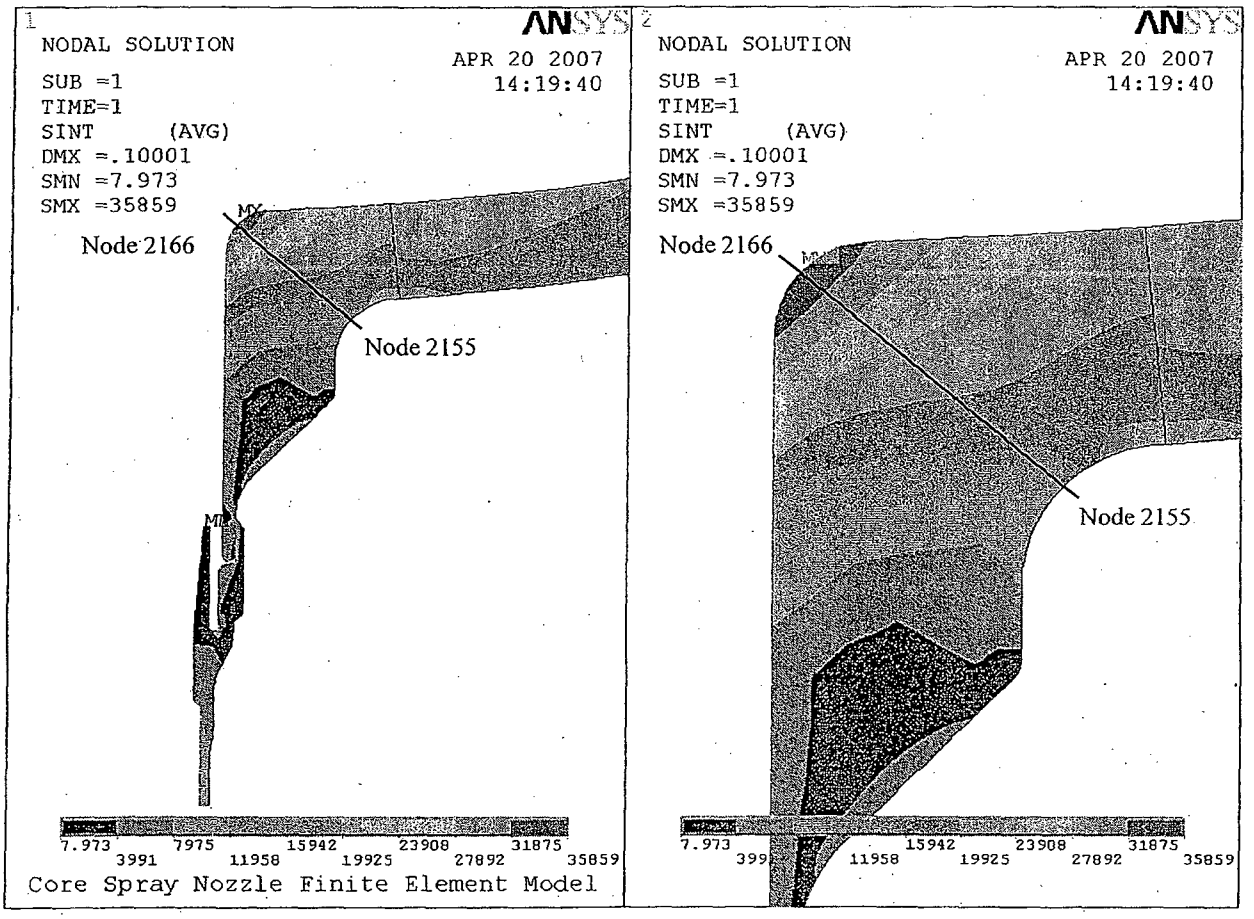

Figure 7: Blend Radius Limiting Pressure Stress Location, Node 2166

The stress intensity time history for the critical safe end and blend radius paths were extracted using the ANSYS post-processing file "extract100.inp" for 100% flow. This produced the two files, "SE_F100.out" and "BR_F100.out," which contain the thermal stress history. The membrane plus bending stresses and total stresses for the Green's Functions were extracted from these files to produce the four files "SE_F100.cln, BR_F100.cln" and "SE_F100_INSIDE.RED, BR_F100_ INSIDE.RED."

The stress intensity time history for the critical safe end and blend radius paths were extracted using the ANSYS post-processing file "extract0.inp" for 0% flow. This produced the two files, "SE_F0.out" and "BR_F0.out," which contain the thermal stress history. The membrane plus bending stresses and total stresses for the Green's Functions were extracted from these files to produce the four files "SE_F0.cln, BR_F0.cln" and "SE_F0_INSIDE.RED, BR_F0_ INSIDE.RED."

As the models were run with a 400°F step change in temperature, and the Green's Functions are for a 1°F step change in temperature, all data values were divided by 400. The governing Green's Functions for the core spray nozzle during 100% flow and 0% flow are shown in Figure 8 through Figure 11. The data for the Green's Functions is included in the files:

0% Flow Rate:

SE_Flow0_T_Green.xls
SE_Flow0_M+B-Green.xls
BLEND_Flow0_M+B_Green.xls
BLEND_Flow0_T_Green.xls

100 Flow Rate:

SE_Flow100_T_Green.xls
SE_Flow100_M+B-Green.xls
BLEND_Flow100_M+B_Green.xls
BLEND_Flow100_T_Green.xls

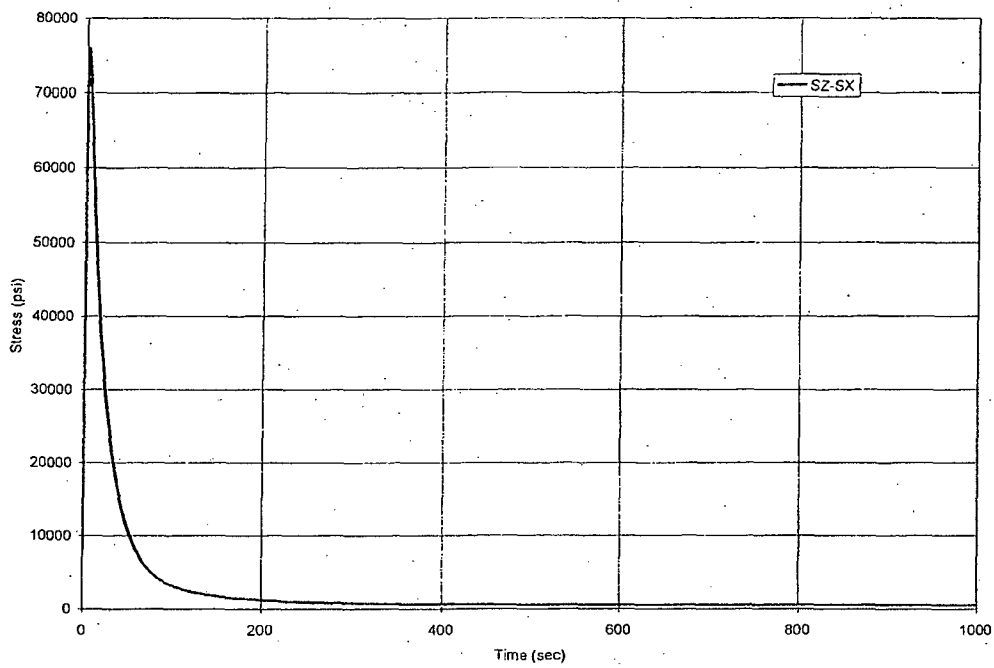

Figure 8: Safe End Total Stress History, 100% Flow

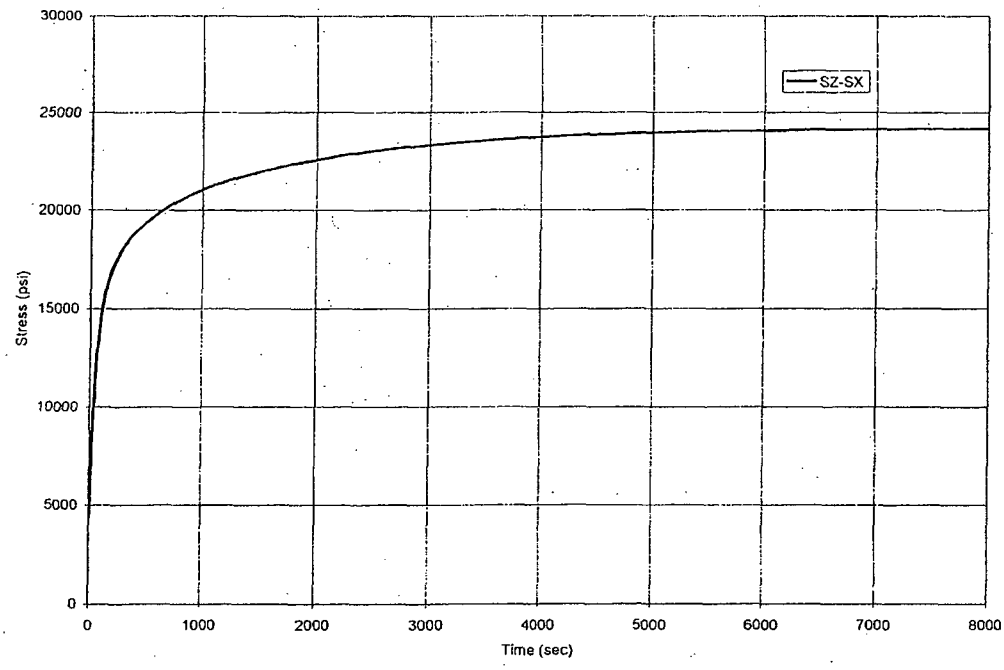

Figure 9: Blend Radius Total Stress History, 100% Flow

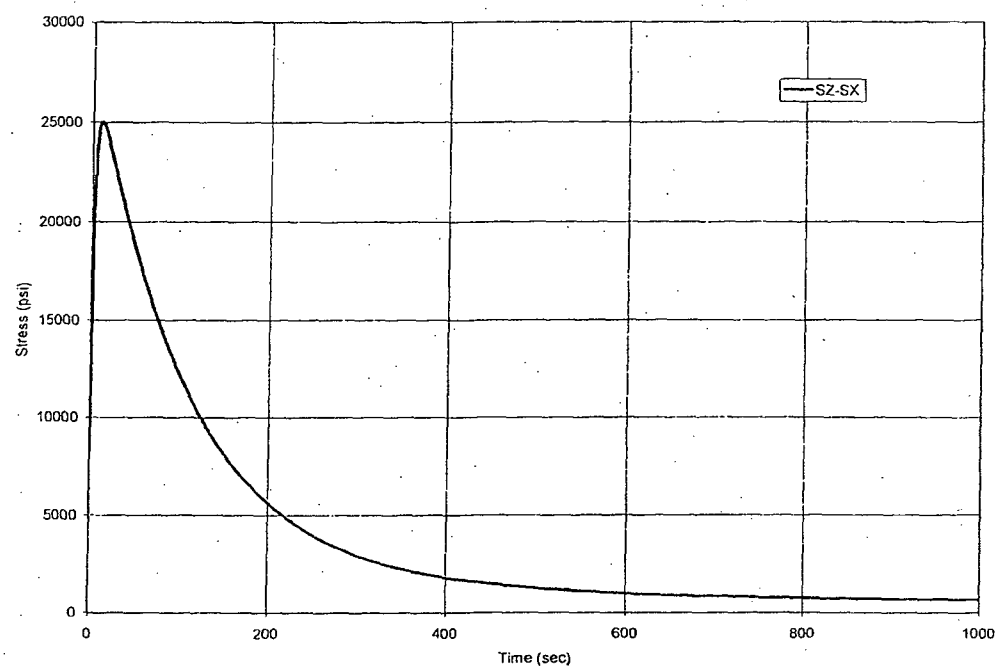

Figure 10: Safe End Total Stress History, 0% Flow

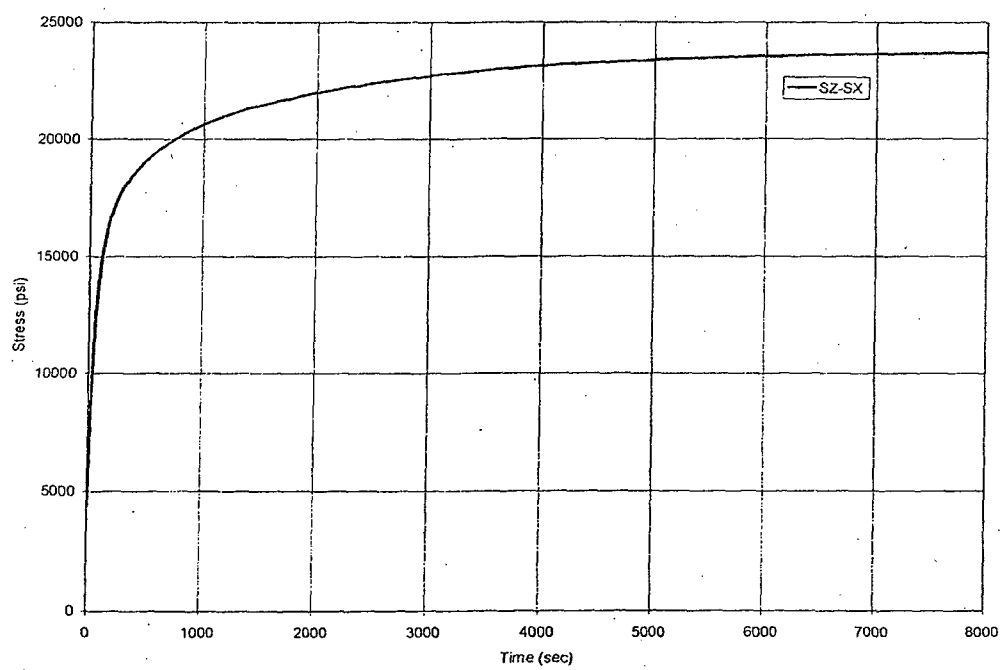

Figure 11: Blend Radius Total Stress History, 0% Flow

The pressure stress intensities for the safe end and blend radius paths were extracted using the ANSYS post-processing file "extractP.inp." This produced two files, SE_P.OUT for the safe end and BR_P.OUT for the blend radius.

Results of the internal pressure load case for Node 2166 (blend radius) is a total stress intensity of 35,860 psi and for Node 3719 (safe end), a total stress intensity of 12,030 psi. The membrane plus bending stress intensity at Node 2166 and Node 3719 are 34970 psi and 12,020 psi, respectively. Table 14 shows the final pressure results for the safe end and blend radius.

Table 14: Pressure Results (1,000 psi)

Location	Membrane plus Bending Stress Intensity (psi)	Total Stress Intensity (psi)
Safe End	12,020	12,030
Blend Radius	34,970	35,860

Results were also extracted from the vessel portion of the model to verify the accuracy of the results obtained from the ANSYS model, and to check the results due to the use of the 2.0 multiplier on the vessel radius. These results are contained in the file VESSEL_P.OUT. The radius of the finite element model (FEM) was multiplied by a factor of 2.0 [1] to account for the fact that the vessel portion of the 2D axisymmetric model is a sphere, but the true geometry is the intersection of two cylinders.

The equation for the membrane hoop stress in a sphere is:

$$\sigma = \left(\frac{(pressure) \times (radius)}{2 \times thickness} \right)$$

Considering a vessel base metal radius, R, of 105.906 inches increased by a factor of 2.0, a vessel base metal thickness, t, of 5.4375 inches, and an applied pressure, P, of 1,000 psi, the calculated stress for a sphere is PR/(2t) = 19,477 psi. This compares very well with the remote vessel wall membrane hoop stress from the ANSYS result file, VESSEL_P.OUT, of 18,530 psi. Thus, considering the peak total pressure stress of 35,860 psi reported above, the stress concentrating effect of the nozzle corner is 35,860/19,477 = 1.84. In other words, the peak nozzle corner stress is 1.84 times higher than nominal vessel wall stress for the 2D axisymmetric model.

The equation for the membrane hoop stress in a cylinder is:

$$\sigma = \left(\frac{(pressure) \times (radius)}{thickness} \right).$$

Based on the previous dimensions, the calculated stress for a cylinder without the 2.0 factor is 19,477 psi. Increasing this by a factor of 1.84 yields an expected peak nozzle corner stress of 35,838 psi, which would be expected from a cylindrical geometry that is representative of the nozzle configuration. Therefore, the result from the ANSYS file for the peak nozzle corner stress (35,860 psi) is close to the peak nozzle corner stress for a cylindrical geometry because of the use of the 2.0 multiplier. This is consistent with SI's experience where a factor of two increase in radius is typical for representing the three-dimensional (3D) effect in a 2D axisymmetric model.

5.0 REFERENCES

1. SI Calculation No. VY-16Q-308, Revision 0, "Core Spray Nozzle Finite Element Model".

2. ANSYS, Release 8.1A1 (w/Service Pack 1), ANSYS, Inc., June 2004.

3. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section II, Part D, 1998 Edition, 2000 Addenda.

4. J. P. Holman, "Heat Transfer," 4th Edition, McGraw-Hill, 1976.

5. J. P. Holman, "Heat Transfer," 5th Edition, 1981.

6. Entergy Design Input Record (DIR) EC No. 1773, Revision 0, "Environmental Fatigue Analysis for Vermont Yankee Nuclear Power Station," 7/3/07, SI File No. VY-16Q-209.

7. N. P. Cheremisinoff, "Heat Transfer Pocket Handbook," Gulf Publishing Co., 1984.

8. CB&I RPV Stress Report, Section T7, "Thermal Analysis of Core Spray Nozzle, Vermont Yankee Reactor Vessel, CB&I Contract 9-6201, SI File No. VY-16Q-206.

APPENDIX A

FINITE ELEMENT ANALYSIS FILES

ANSYS Input Files

File Name	Description
vy_csn_geom.inp	ANSYS input file includes the geometry and material properties
Heat Transfer Coefficients.xls	Excel file to calculate Heat Transfer coefficients
VY_16Q_P.inp	ANSYS input file for the pressure stress analysis
VY_16Q_T100.inp	ANSYS input file for the thermal analysis, 100% flow rate
VY_16Q_T0.inp	ANSYS input file for the thermal analysis, 0% flow rate
VY_16Q_ST100.inp	ANSYS input file for the thermal stress analysis, 100% flow rate
VY_16Q_ST0.inp	ANSYS input file for the thermal stress analysis, 0% flow rate
extract100.inp	ANSYS input file to extract the limiting paths, 100% flow rate
extract0.inp	ANSYS input file to extract the limiting paths, 100% flow rate
extractP.inp	ANSYS input file to extract the limiting paths
extractVessel.inp	ANSYS input file to extract the membrane stress in the vessel wall

ANSYS Output Files

File Name	Description
BR_F100.out	ANSYS output file, Results of running: extract100.inp, Blend Radius 100% Flow
SE_F100.out	ANSYS output file, Results of running: extract100.inp, Safe End 100% Flow
BR_F100.cln	Reduced ANSYS output file, contains the stress values in time, Blend Radius 100% Flow
SE_F100.cln	Reduced ANSYS output file, contains the stress values in time, Safe End 100% Flow
BR_F100_ INSIDE.RED	Reduced ANSYS output file, contains detailed stress values in time, Blend Radius 100% Flow
SE_F100_INSIDE.RED	Reduced ANSYS output file, contains detailed stress values in time, Safe End 100% Flow
BR_F0.out	ANSYS output file, Results of running: extract0.inp, Blend Radius 0% Flow
SE_F0.out	ANSYS output file, Results of running: extract0.inp, Safe End 0% Flow
BR_F100.cln	Reduced ANSYS output file, contains the stress values in time, Blend Radius 0% Flow
SE_F100.cln	Reduced ANSYS output file, contains the stress values in time, Safe End 0% Flow
BR_F0_ INSIDE.RED	Reduced ANSYS output file, contains detailed stress values in time, Blend Radius 0% Flow
SE_F0_INSIDE.RED	Reduced ANSYS output file, contains detailed stress values in time, Safe End 0% Flow