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Environmental Fatigue Analysis for the Vermont Yankee Reactor Pressure Vessel Core Spray Nozzle

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1.0 INTRODUCTION

In Table 4.3-3 of the Vermont Yankee License Renewal Application (LRA), the 60-year cumulative usage factor (CUF) values for the reactor pressure vessel (RPV) core spray nozzle are reported as 0.625 (nozzle) and 0.182 (safe end). The safe end value was reported as a generic value, since no plant-specific value was determined. Application of environmentally assisted fatigue (EAF) multipliers, as required for the license renewal period, resulted in unacceptable EAF CUF values of 1.53 and 2.79 for the nozzle and safe end, respectively. Therefore, further refined analysis was necessitated to show acceptable EAF CUF results for this component.

This report documents a refined fatigue evaluation for the VY core spray nozzle. The intent of this evaluation is to use refined transient definitions and the revised cyclic transient counts for 60 years for a computation of CUF, including EAF effects, that is more refined than previously performed fatigue analyses. The fatigue-limiting locations in the core spray nozzle and safe end are included in the evaluation, to be consistent with NUREG/CR-6260 [1] needs for EAF evaluation for license renewal. The EAF effects for the core spray piping, which is also a NUREG/CR-6260 location, are considered to be covered by the nozzle and safe end calculations because the nozzle region bounds the piping[1]. The resulting fatigue results will be used as a replacement to the values previously reported in the VY LRA.

The refined evaluation summarized in this report included the development of a detailed finite element model of the core spray nozzle, including relevant portions of the safe end, thermal sleeve, the RPV wall, and the weld overlay repair documented in Reference [2]. Thermal and pressure stress histories were developed for relevant transients affecting the core spray nozzle, including any effects of Extended Power Uprate (EPU), as specified by the VY RPV Design Specification [3], the VY EPU Design Specification [4] and other boiling water reactor (BWR) operating experience. The thermal and pressure stress histories were used to determine total stress and primary plus secondary stress for use in a subsequent fatigue evaluation. Stresses were also included due to loads from the attached piping for application in the stress/fatigue analysis, based on the bounding reaction loads obtained from the

[1] The nozzle stresses are more severe due to the nozzle discontinuity, and the nozzle thermal transients are more severe due to interaction with the hot RPV.

relevant design documents. The revised fatigue calculation was performed using Section III methodology from the 1998 Edition, 2000 Addenda of the ASME Code, and were performed using actual cycles from past plant operation projected out to 60 years of operation.

1.1 Green's Function Methodology

For the core spray nozzle evaluated as a part of this work, stress histories were computed by a time integration of the product of a pre-determined Green's Function and the transient data. This Green's Function integration scheme is similar in concept to the well-known Duhamel theory used in structural dynamics. A detailed derivation of this approach and examples of its application to specific plant locations is contained in Reference [5]. A general outline is provided in this section.

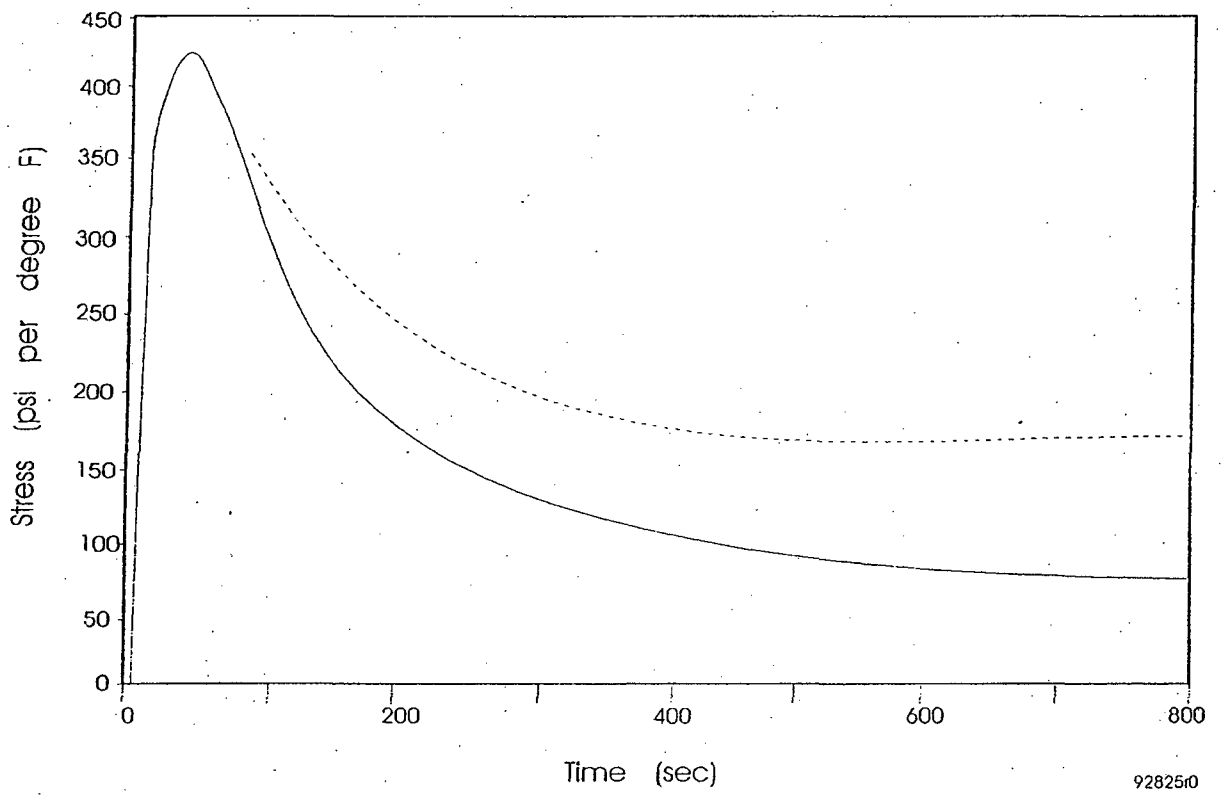
A Green's Function is derived by using finite-element methods to determine the transient stress response of the component to a step change in loading (usually a thermal shock). The critical location in the component is identified based on the maximum stress, and the thermal stress response over time is extracted for this location. This response to the input thermal step is the "Green's Function." Figure 1-1 shows a typical set of two Green's Functions, each for a different set of heat transfer coefficients (representing different flow rate conditions).

To compute the thermal stress response for an arbitrary transient, the loading parameter (usually local fluid temperature) is deconstructed into a series of step-loadings. By using the Green's Function, the response to each step can be quickly determined. By the principle of superposition, these can be added (algebraically) to determine the response to the original load history. The result is demonstrated in Figure 1-2. The input transient temperature history contains five step-changes of varying size, as shown in the upper plot in Figure 1-2. These five step changes produce the five successive stress responses in the second plot shown in Figure 1-2. By adding all five response curves, the real-time stress response for the input thermal transient is computed.

The Green's Function methodology produces identical results compared to running the input transient through the finite element model. The advantage of using Green's Functions is that many individual

transients can be run with a significant reduction of effort compared to running all transients through the finite element model. The trade-off in this process is that the Green's Functions are based on constant material properties and heat transfer coefficients. Therefore, these parameters are chosen to bound all transients that constitute the majority of fatigue usage, i.e., the heat transfer coefficients at 300°F bound the cold water injection transient. In addition, the instantaneous value for the coefficient of thermal expansion is used instead of the mean value for the coefficient of thermal expansion. This conservatism is more than offset by the benefit of not having to analyze every transient, which was done in the VY core spray nozzle evaluation.

Once the stress history is obtained for all transients using the Green's Function approach, the remainder of the fatigue analysis is carried out using traditional methodologies in accordance with ASME Code, Section III requirements.



Note: A typical set of two Green's Functions is shown, each for a different set of heat transfer coefficients (representing different flow rate conditions).

Figure 1-1: Typical Green's Functions for Thermal Transient Stress

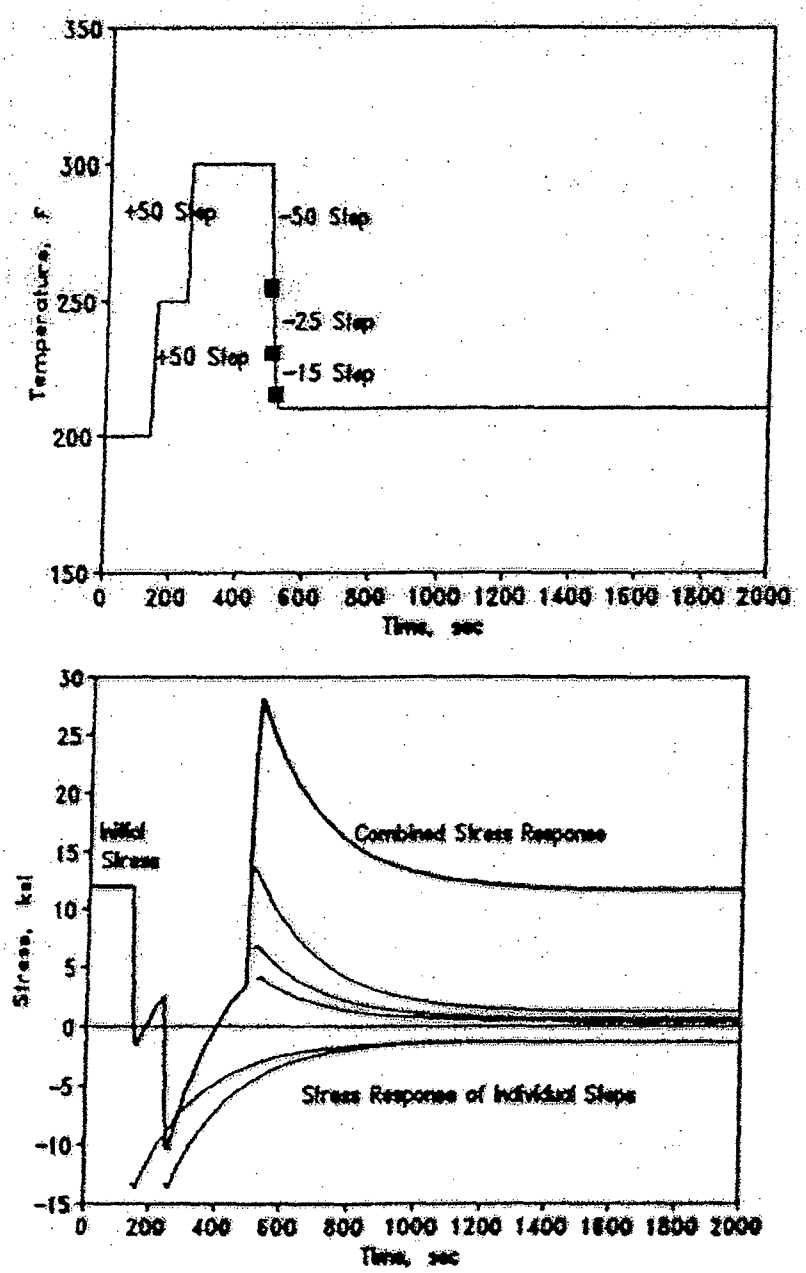


Figure 1-2: Typical Stress Response Using Green's Functions

2.0 FINITE ELEMENT MODEL

An ANSYS [6] finite element model (FEM) of the VY core spray nozzle and safe end was developed and used to perform the updated stress and fatigue analyses. The details of the model development are documented in the Reference [7] calculation.

The materials of the various components of the model are listed below:

- Safe End – SB 166 (72Ni-15Cr-8Fe, N06600)
- 8Ø x 10Ø Conc. Reduction – SA312 TP304 (18Cr-8Ni)
- Nozzle Forging – SA508 Class II (3/4Ni-1/2Mo-1/3Cr-V)
- Vessel – SA533 Grade B (Mn-1/2Mo-1/2Ni)
- Cladding – SA240 TP 304 (18Cr-8Ni)

In the FEM model, the radius of RPV was increased by a factor of two to account for the fact that the vessel portion of the finite element model is a sphere and the actual geometry is a cylinder.

Material properties were based upon the 1998 ASME Code, Section II, Part D, with 2000 Addenda [8], and are shown in Table 2-1. The properties were evaluated at an average temperature of 300°F. This average temperature is based on a thermal shock of 500°F to 100°F, which was applied to the FEM model for Green's Function development.

The finite element model, which includes the weld overlay, is shown in Figure 2-1.

Table 2-1: Material Properties @ 300°F [1]

Material ID	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, ft²/hr	Specific Heat, Btu/lb-°F [C] [3]
2	Safe End	SB 166	72Ni-15Cr-8Fe N06600	29.8	7.9	9.6	0.160	0.1157
2	Weld Overlay	INCONEL 82	72Ni-15Cr-8Fe N06600	29.8	7.9	9.6	0.160	0.1157
1	Nozzle	SA508 Class II	¾ Ni-1/2Mo-1/3 Cr-V	26.7	7.3	23.4	0.401	0.1193
3	Vessel	SA533 Grade B	Mn-1/2Mo-1/2Ni	28.0	7.7	23.4	0.401	0.1193
4	3/16 Clad	SA240 TP 304	18Cr-8Ni	27.0	9.8	9.8	0.160	0.1252
4	8Ø x 10Ø Conc. Reduction[2]	SA312 [2] TP304	18Cr-8Ni	27.0	9.8	9.8	0.160	0.1252

Note:
1. Material properties are evaluated at 300°F from the 1998 ASME Code, Section II, Part D, with 2000 Addenda [8], Poisson's ratio, which are assumed typical values and specific heat is calculated as $[k/\rho d]/12^3$.
2. The 8Ø x 10Ø concentric reduction was modeled as a straight pipe with the material properties of the original desi was replaced by a new material (SA403 T316L). These two stainless steels have the same modulus of elasticity an properties.

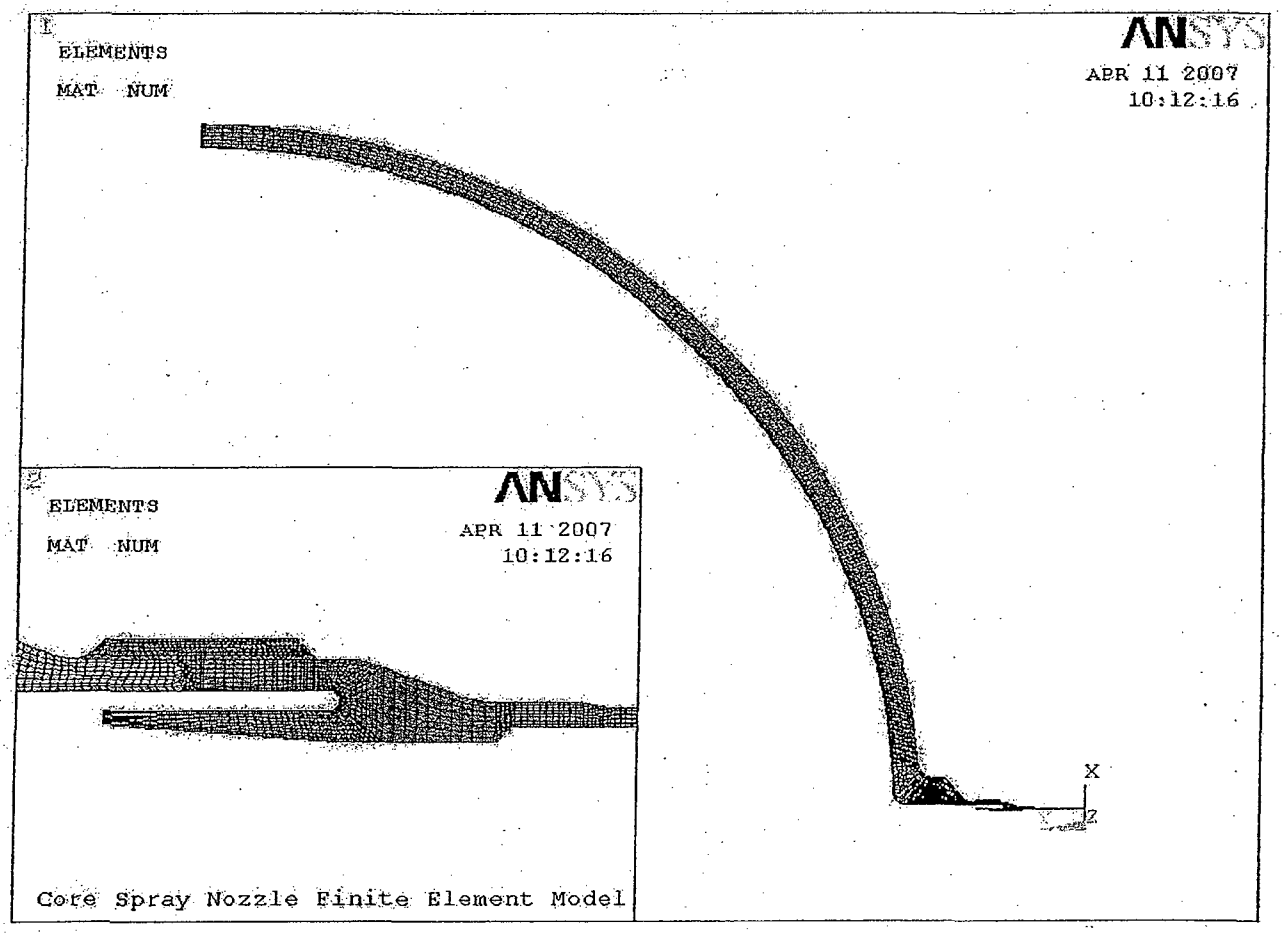


Figure 2-1: VY Core Spray Nozzle FEM

3.0 LOAD DEFINITIONS

The pressure and thermal stresses for the core spray nozzle for the revised fatigue evaluation were developed using the axisymmetric FEM model, described in Section 2.0 of this report. The details of the Green's function development and associated stress evaluation are documented in the Reference [9] and [10] calculations.

3.1 Thermal Loading

Thermal loads were applied to the core spray nozzle model to generate the Green's Function. As a first step in the Green's Function process, heat transfer coefficients were determined for various regions of the core spray FEM for two different flow cases: (1) 0% core spray flow, and (2) 100% core spray flow through the nozzle.

The 0% flow case simulates a stagnant condition of the core spray nozzle when not in operation and the entire core spray nozzle is at the same temperature as the RPV fluid. The heat transfer coefficients for the 0% flow case are for free convection (stagnant) conditions. 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 the operational condition of the core spray nozzle (i.e., the entire core spray nozzle experiences 100°F water due to injection). The heat transfer coefficients 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.

The temperature on the exterior of the reactor, nozzle, safe end and pipe was assumed to be 120°F (ambient). Figure 3-4 shows the heat transfer coefficient regions assumed for the core spray nozzle FEM. The applied heat transfer coefficients and the fluid temperatures are summarized in the sections that follow.

3.1.1 Heat Transfer Coefficients and Boundary Fluid Temperatures

Referring to Figure 3-4, heat transfer coefficients were applied as follows:

- The heat transfer coefficient for the outside surfaces of the FEM (Region 12) was a constant value of 0.2 BTU/hr-ft^2-°F (3.858×10^{-7} BTU/sec-in^2-°F).
- Table 3-1 shows the results of the heat transfer coefficient calculations for all of the thermal regions identified in Figure 3-4. The detailed heat transfer calculations for Regions 1, 3, 5, 7, 9, and 11 are contained in the Reference [9] calculation.
- In Regions 2, 4, 6, 8, and 10, the heat transfer coefficients are interpolated.

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.

3.1.2 Green's Functions

The two flow-dependent thermal load cases outlined in previous section were run on the core spray nozzle FEM with the heat transfer coefficients and the fluid temperature conditions listed in Table 3-1. Two locations were selected for analysis (see Figures 3-5 and 3-6):

1. The critical safe end location was chosen as the node with the highest stress intensity due to thermal loading under nozzle flow conditions. The highest stress intensity due to thermal loading occurred at Node 3719 (see Figure 3-5), on the inside diameter of the nozzle safe end. Therefore, this node was selected for analysis.
2. The critical blend radius location was chosen based upon the highest pressure stress intensity. The critical location was selected as Node 2166, as shown in Figure 3-6.

Two stress intensity Green's Functions were developed for each location and each flow case: (1) total stress intensity, and (2) membrane plus bending stress intensity. The total stress intensity

Green's Functions for the safe end location are shown in Figures 3-7 and 3-8. The total stress intensity Green's Functions for the blend radius location are shown in Figures 3-9 and 3-10.

3.1.3 Thermal Transients

The transients analyzed for the core spray nozzle were developed based on the definitions in the original RPV Design Specification [3], as modified for EPU [4], as well as more recent definitions based on BWR operating experience. For BWR operating experience, the transients described in the thermal cycle diagrams for a BWR-4 plant similar in design and vintage to VY were obtained, and plant data from VY applied to each transient. The resulting thermal cycle diagrams are shown in References [11 and 12]. The final transients evaluated in the stress and fatigue analyses are shown in Figures 3-11 through 3-16.

The number of cycles projected for the 60-year operating life is used for each transient [13]. Tables 3-2 and 3-3 summarize the thermal transients for the safe end and blend radius locations, respectively.

3.2 Pressure Loading

A uniform pressure of 1,000 psi was applied along the inside surface of the core spray nozzle and the RPV wall. A pressure load of 1,000 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 of 4,774 psi was applied to the piping at the end of the nozzle. This cap load was calculated as follows:

$$P_{cap} = \frac{PD_i^2}{\left(D_o^2 - D_i^2\right)}$$

where:

P_{cap}	=	end cap pressure load (psi)
P	=	unit pressure load = 1,000 psi
D_i	=	inside diameter of end of FEM = 9.834"

D_o = outside diameter of end of FEM = 10.815"

The calculated pressure was applied as a negative value so that it would exert tension on the end of the model. The nodes on the end of the FEM were coupled in the axial direction to ensure mutual displacement of the end of the nozzle due to attached piping. Figures 3-1, 3-2, and 3-3 show the internal pressure distribution, cap load, and symmetry condition applied to the vessel end of the model, respectively.

The internal pressure load case for Node 2166 (blend radius) resulted in a total stress intensity of 35,860 psi, and for Node 3719 (safe end) resulted in a total stress intensity of 12,030 psi. The membrane plus bending stress intensity at Node 2166 and Node 3719 are 34,970 psi and 12,020 psi, respectively.

3.3 Piping Loading

The piping stress intensities (stress caused by the attached piping) were determined for the two evaluated core spray nozzle locations. The design piping reactions that were used in the stress and fatigue evaluation are defined on the Reference [14] drawing. These loads represent shear and moment loadings on the nozzle resulting from thermal expansion of the attached piping and seismic loads. The loads are applicable at the piping end of the safe end, as shown in Figure 3-17. The stresses resulting from these loads were calculated by hand using classical structural mechanics formulas, as documented in Reference [10], and are shown in Tables 3-4 and 3-5 for the safe end and blend radius locations, respectively.

Table 3-1: Summary of 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

Table 3-2: Safe End Transients

Transient Number	Time (s)	Temp (°F)	Time Step (s)	Pressure (psig)	Flow Rate (GPM)
2. Design HYD Test	---	100	---	0	
120 Cycles				1100	
				50	
3. Startup	0	100		0	0
300 Cycles	16164	549	16164	1010	(0%)
	17164	549	1000	1010	
11. Loss of Feedwater	0	526		1010	0
Pumps	3	526	3	1190	(0%)
10 Cycles	13	526	10	1135	
	233	300	220	1135	
	2213	500	1980	1135	
	2393	300	180	885	
	6893	500	4500	1135	
	7313	300	420	675	
	7613	300	300	675	
	11213	400	3600	240	
	16577	549	5364	1010	
	16637	549	60	1010	
	16638	542	1	1010	
	16698	542	60	1010	
	16699	526	1	1010	
	17699	526	1000	1010	
14. SRV Blowdown	0	526		1010	0
1 Cycle	600	375	600	400	(0%)
	11580	70	10980	50	
	12580	70	1000	50	
21-23. Shutdown	0	549		1010	0
300 Cycles	6264	375	6264	50	(0%)
	6864	330	600	50	
	16224	100	9360	50	
	17224	100	1000	50	
12. Hydrostatic Test	---	100	---	50	
1 cycle				1563	
				50	
30. Emergency Shut Down	0	549		1010	3200
1 Cycle	10	406	10	250	(100%)
	11	70	1	250	
	1011	70	1000	0	

Table 3-3: Blend Radius Transients

Transient Number	Time (s)	Temp (°F)	Time Step (s)	Pressure (psig)	Flow Rate (GPM)
2. Design HYD Test	---	100	---	0	
				1100	
120 Cycles				50	
3. Startup	0	100		0	0
300 Cycles	16164	549	16164	1010	(0%)
	24164	549	8000	1010	
11. Loss of Feedwater	0	526		1010	0
Pumps	3	526	3	1190	(0%)
10 Cycles	13	526	10	1135	
	233	300	220	1135	
	2213	500	1980	1135	
	2393	300	180	885	
	6893	500	4500	1135	
	7313	300	420	675	
	7613	300	300	675	
	11213	400	3600	240	
	16577	549	5364	1010	
	16637	549	60	1010	
	16638	542	1	1010	
	16698	542	60	1010	
	16699	526	1	1010	
	24699	526	8000	1010	
14. SRV Blowdown	0	526		1010	0
1 Cycle	600	375	600	400	(0%)
	11580	70	10980	50	
	19580	70	8000	50	
21-23. Shutdown	0	549		1010	0
300 Cycles	6264	375	6264	50	(0%)
	6864	330	600	50	
	16224	100	9360	50	
	24224	100	8000	50	
24. Hydrostatic Test	---	100	---	50	
1 Cycle				1563	
				50	
30. Emergency Shut Down	0	549		1010	3200
1 Cycle	10	406	10	250	(100%)
	11	70	1	250	
	8011	70	8000	0	

Table 3-4: Stresses Due to Piping Loads for Safe End Location

Safe End External Piping Loads		
Parameters		
F_x =	2.50	kips
F_y =	4.60	kips
F_Z =	1.70	kips
M_x =	264.00	in-kips
M_y =	85.20	in-kips
M_Z =	105.60	in-kips
OD=	10.82	in
ID=	9.834	in
R_N =	5.16	in
L =	0.30	in
t_N =	0.49	in
$(M_x)_1$ =	262.60	in-kips
$(M_y)_1$ =	85.96	in-kips
M_{xy} =	276.31	in-kips
F_{xy} =	5.24	kips
N_Z =	3.35	kips/in
q_N =	-0.31	kips/in
Primary Membrane Stress Intensity		
PM_Z =	6.84	ksi
τ =	-0.63	ksi
SI_{max} =	6.95	ksi
SI_{max} =	6949.94	psi

Table 3-5: Stresses Due to Piping Loads for Blend Radius Location

Blend Radius External Piping Loads		
Parameters		
F_x =	2.50	kips
F_y =	4.60	kips
F_z =	1.70	kips
M_x =	264.00	in-kips
M_y =	85.20	in-kips
M_z =	105.60	in-kips
OD=	13.87	in
ID=	11.750	in
R_N =	7.65	in
L =	30.82	in
t_N =	3.56	in
$(M_x)_2$ =	122.24	in-kips
$(M_y)_2$ =	162.24	in-kips
M_{xy} =	203.14	in-kips
F_{xy} =	5.24	kips
N_z =	1.14	kips/in
q_N =	-0.07	kips/in
Primary Membrane Stress Intensity		
PM_z =	0.32	ksi
τ =	-0.02	ksi
SI_{max} =	0.32	ksi
SI_{max} =	322.52	psi

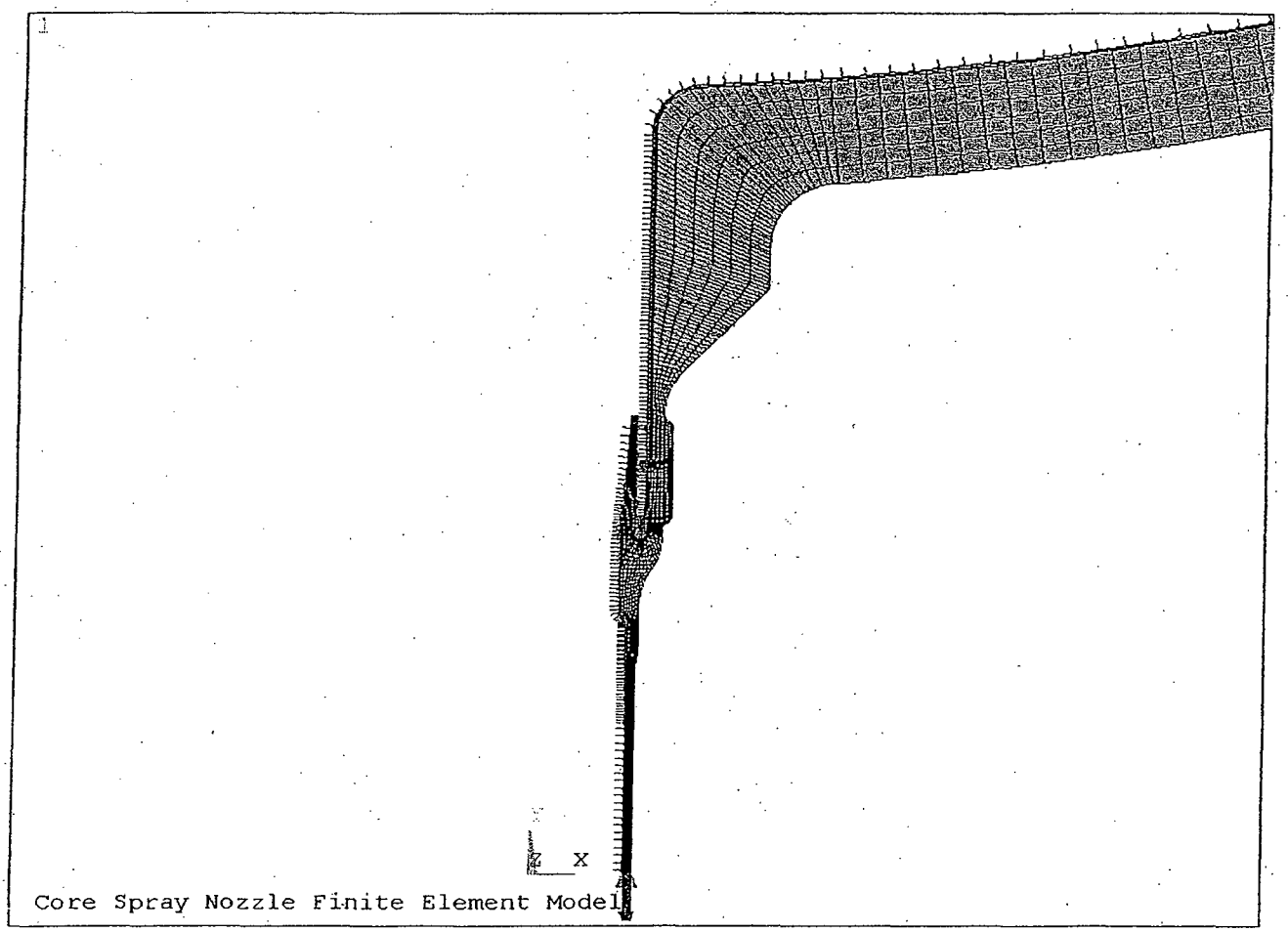


Figure 3-1: Core Spray Nozzle Internal Pressure Distribution

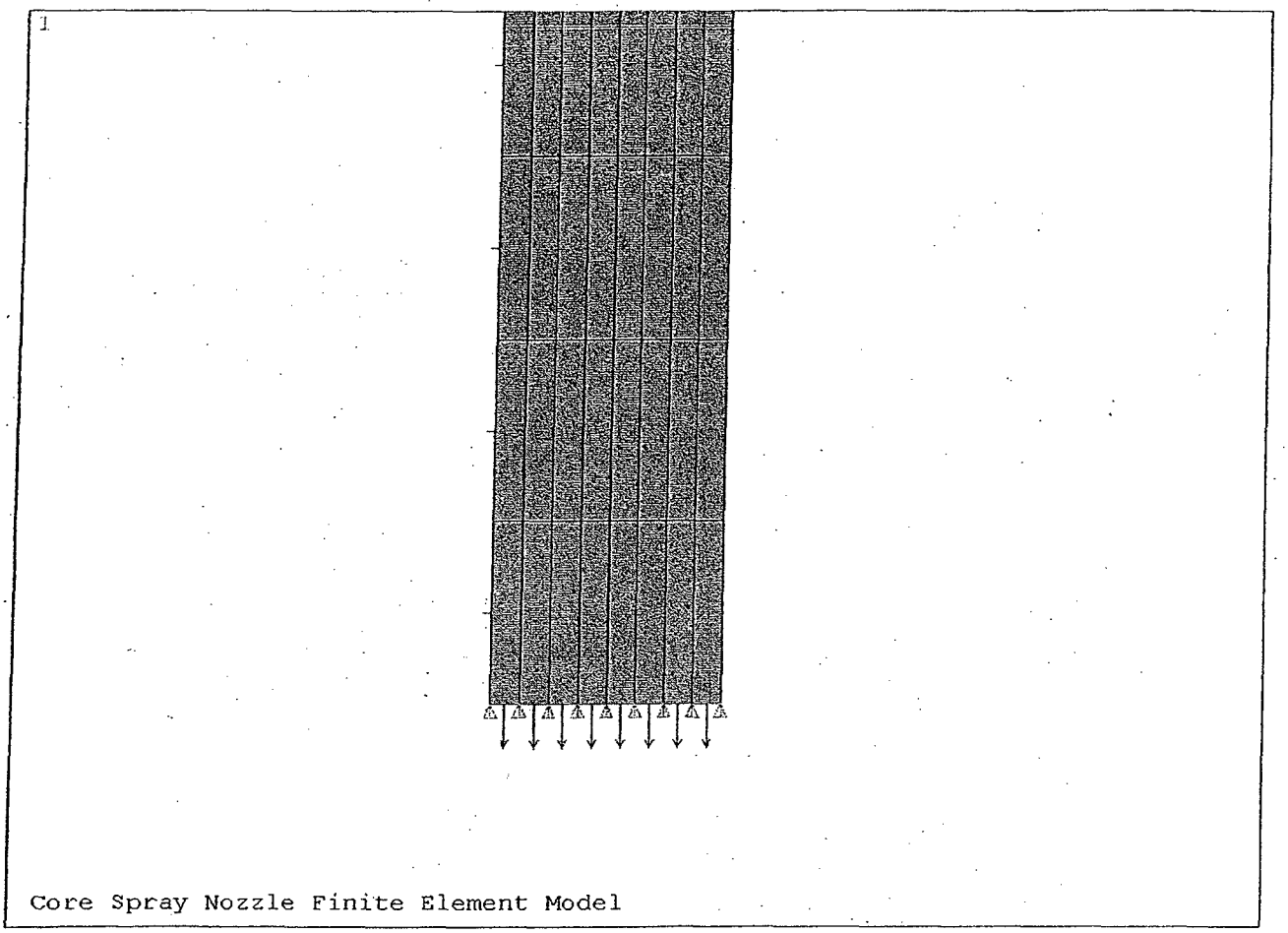


Figure 3-2: Core Spray Nozzle Pressure Cap Load

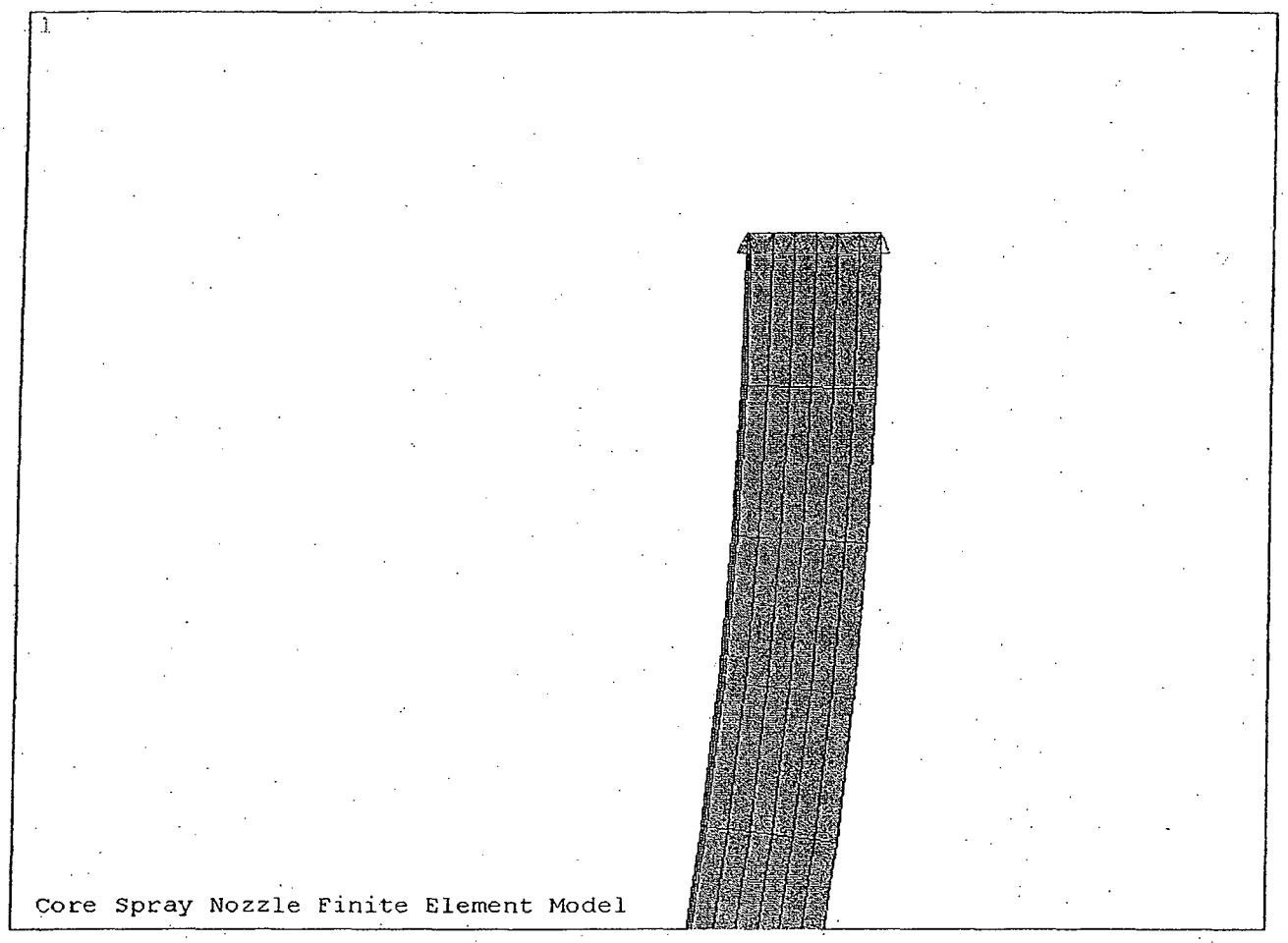


Figure 3-3: Core Spray Nozzle Vessel Boundary Condition

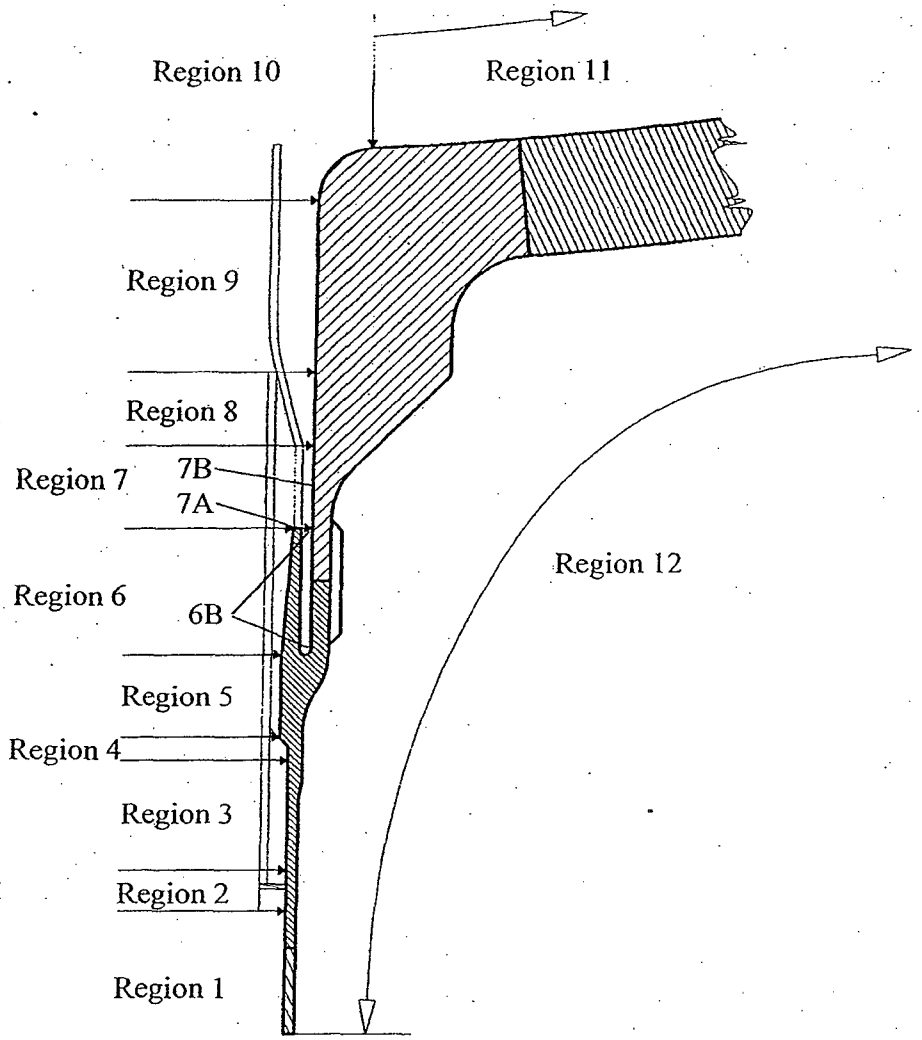


Figure 3-4: Thermal Regions

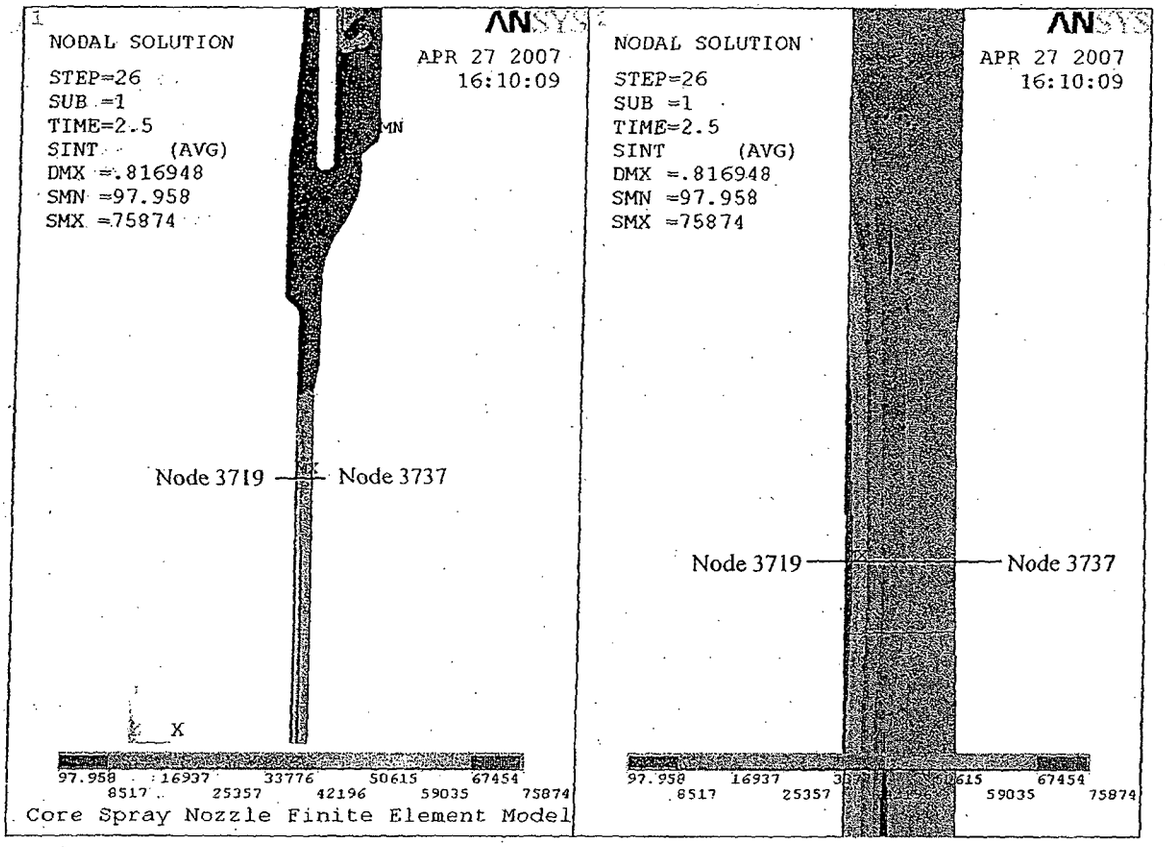


Figure 3-5: Safe End Critical Thermal Stress Location

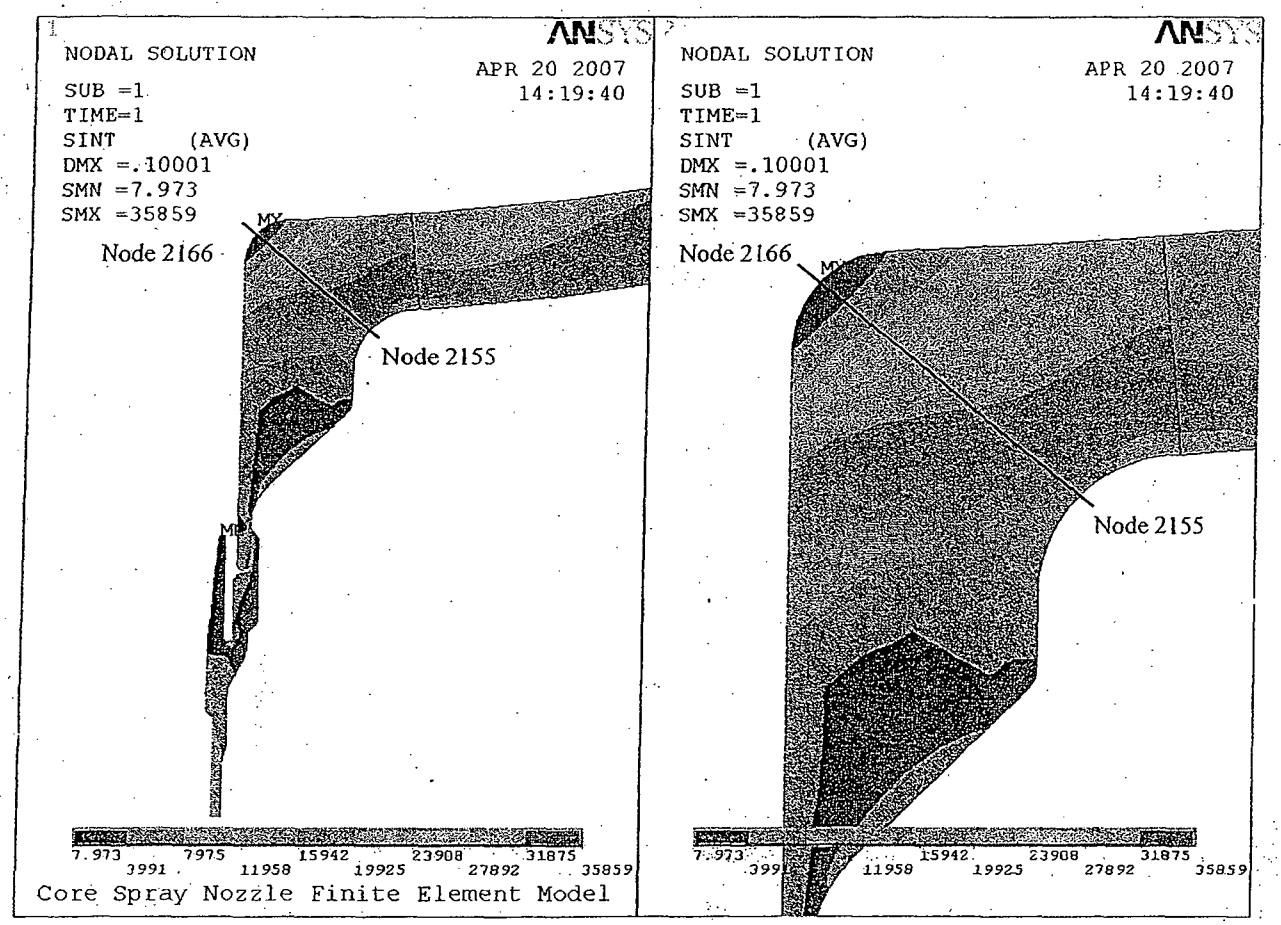


Figure 3-6: Blend Radius Critical Thermal Stress Location

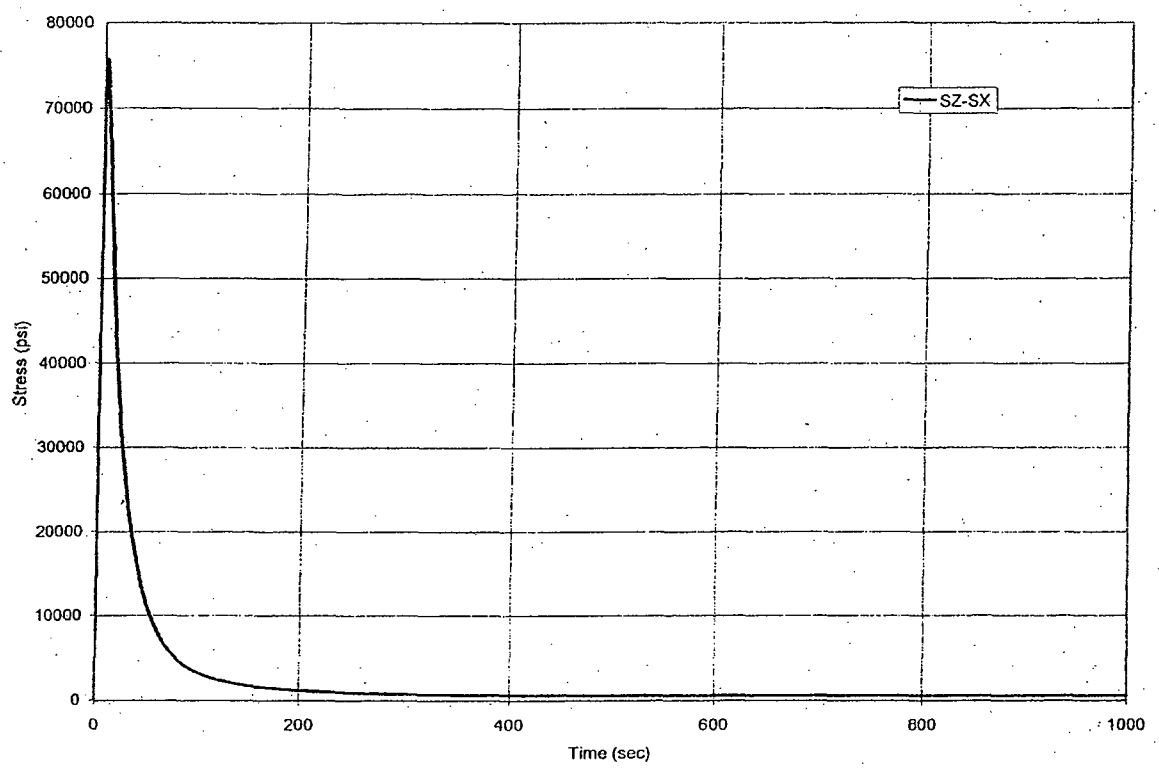


Figure 3-7: Safe End Green's Function for 100% Flow

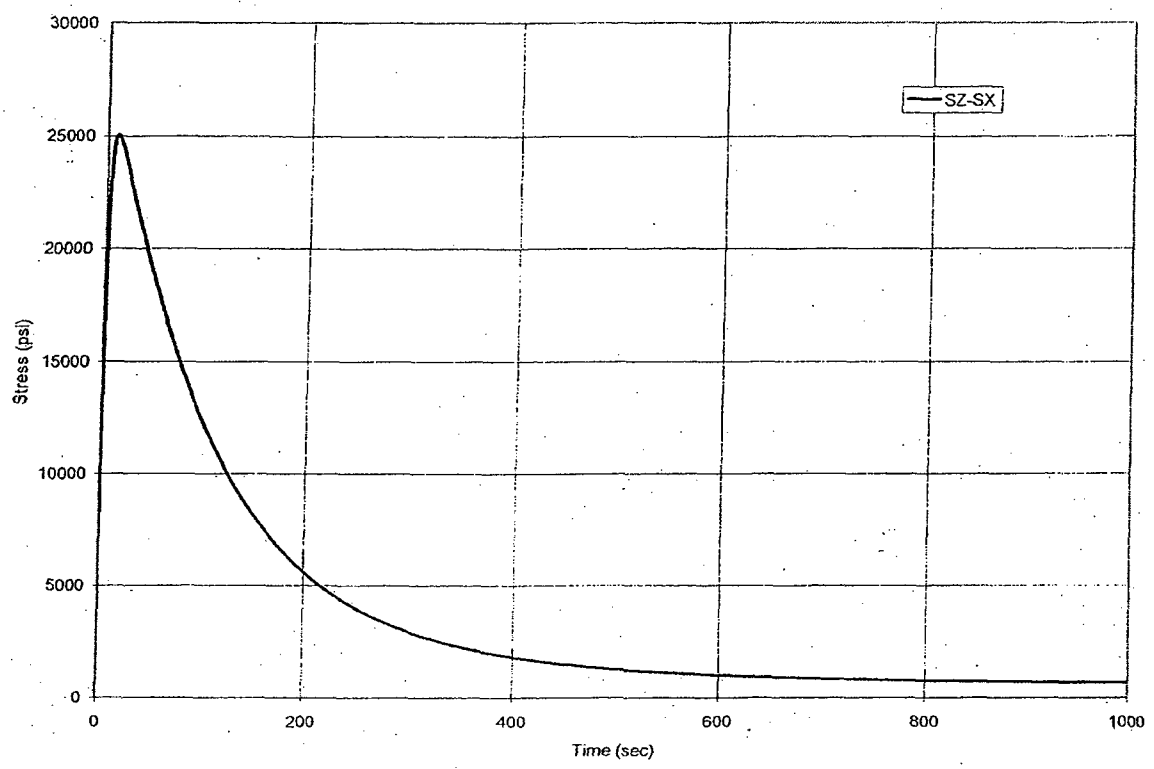


Figure 3-8: Safe End Green's Function for 0% Flow

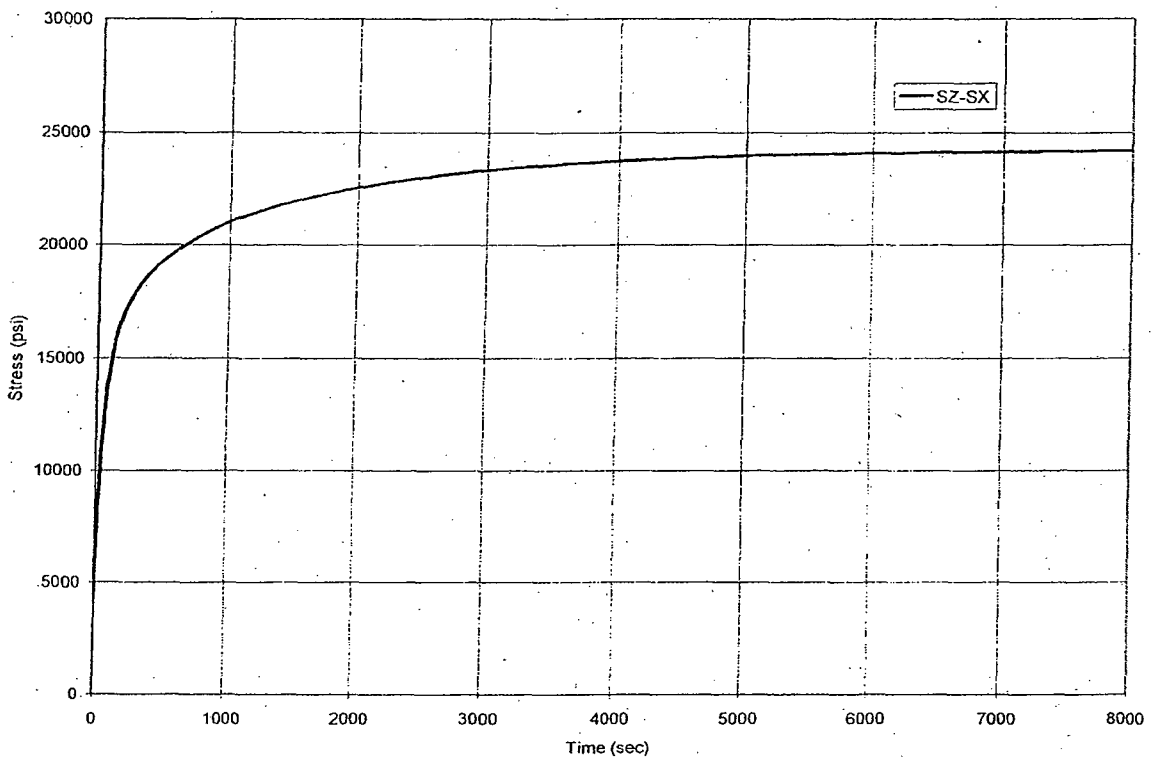


Figure 3-9: Blend Radius Green's Function for 100% Flow

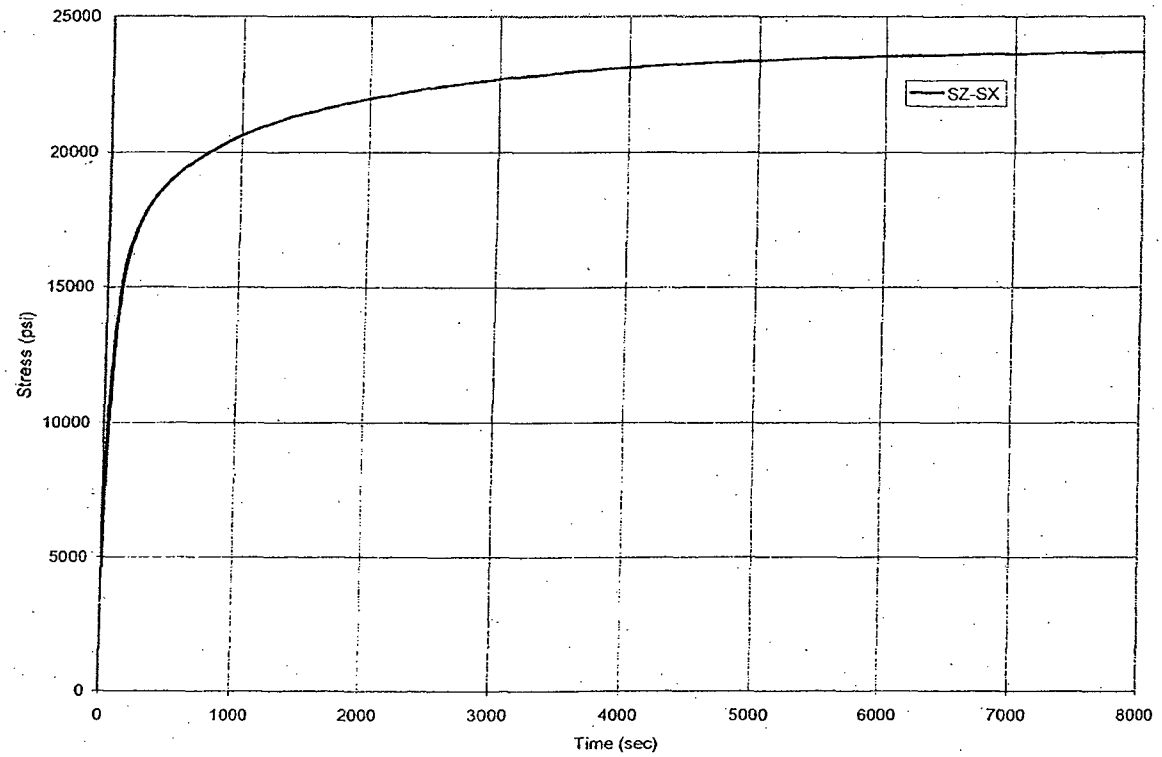


Figure 3-10: Blend Radius Green's Function for 0% Flow

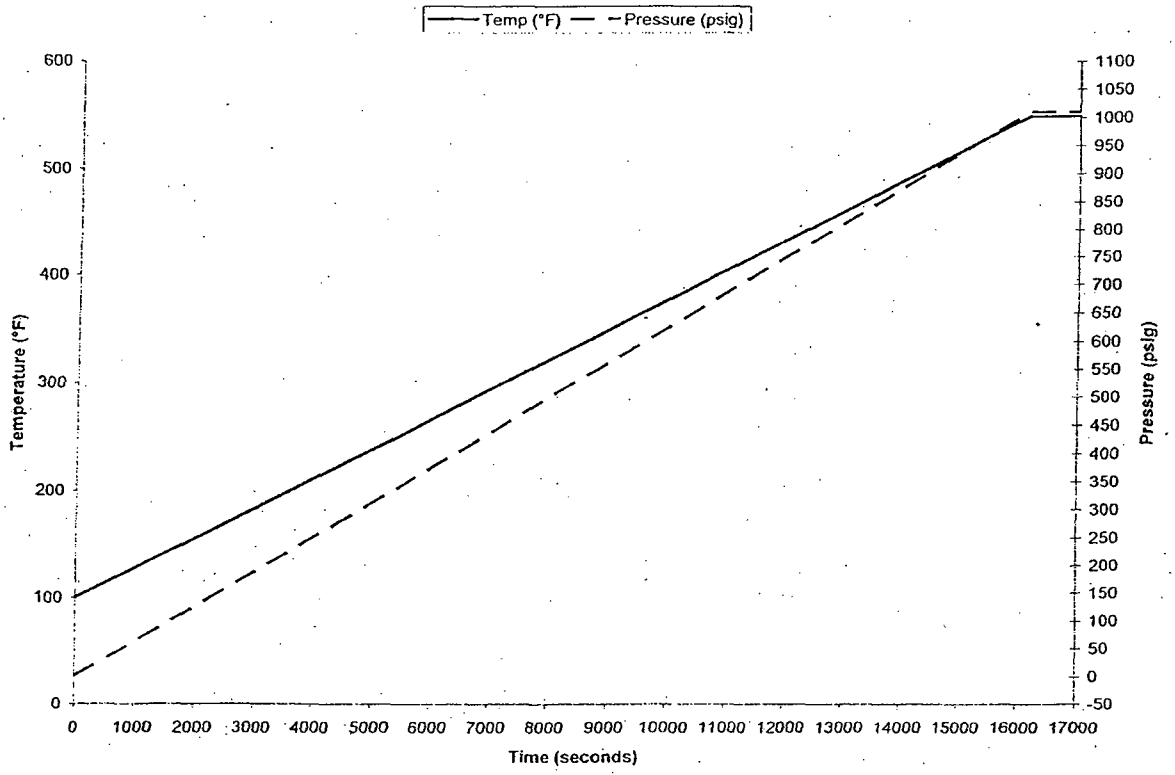


Figure 3-11: Transient 03: Startup

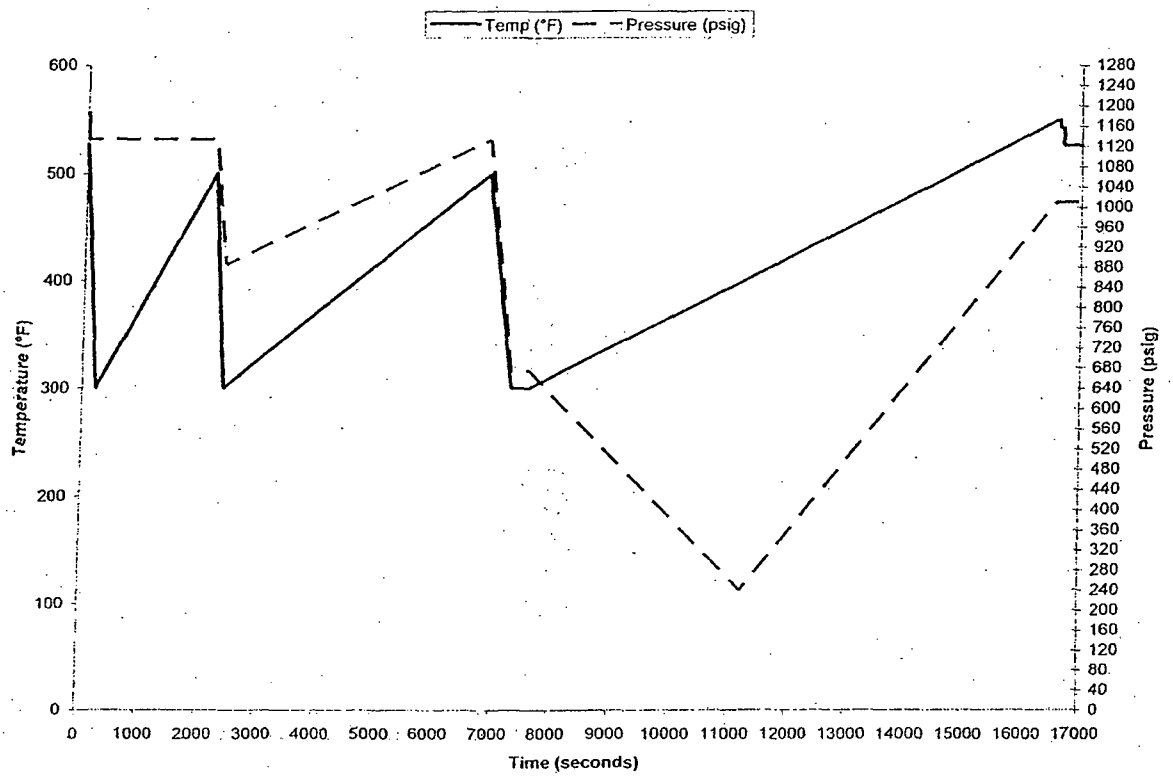


Figure 3-12: Transient 11: Loss of Feedwater Pumps, Isolation Valves Close

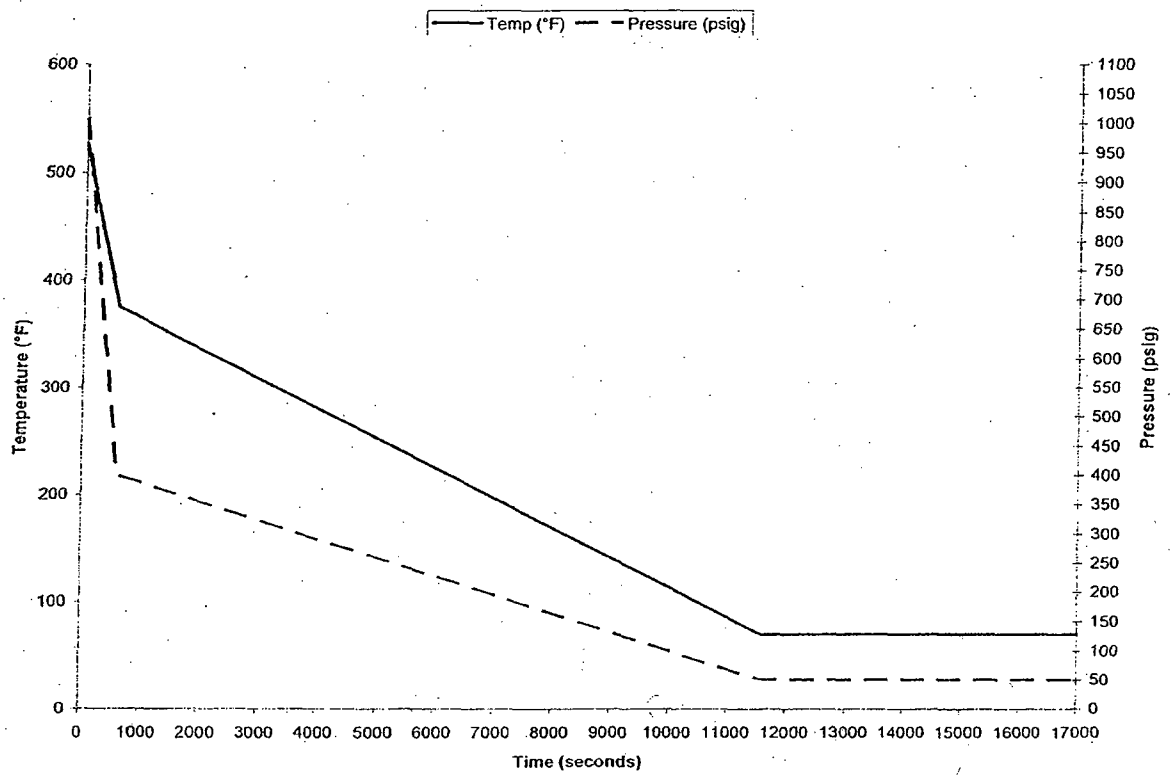


Figure 3-13: Transient 14: Single Relief of Safety Valve Blow Down

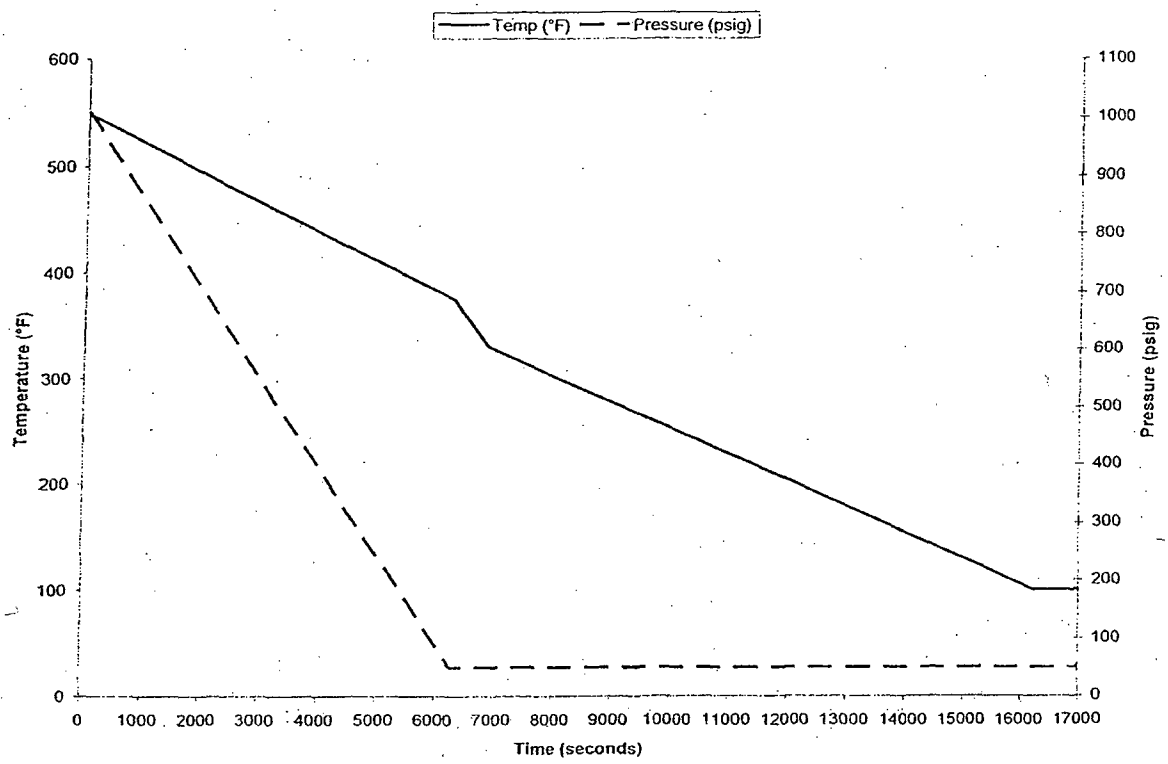


Figure 3-14: Transient 21-23: Shutdown Vessel Flooding

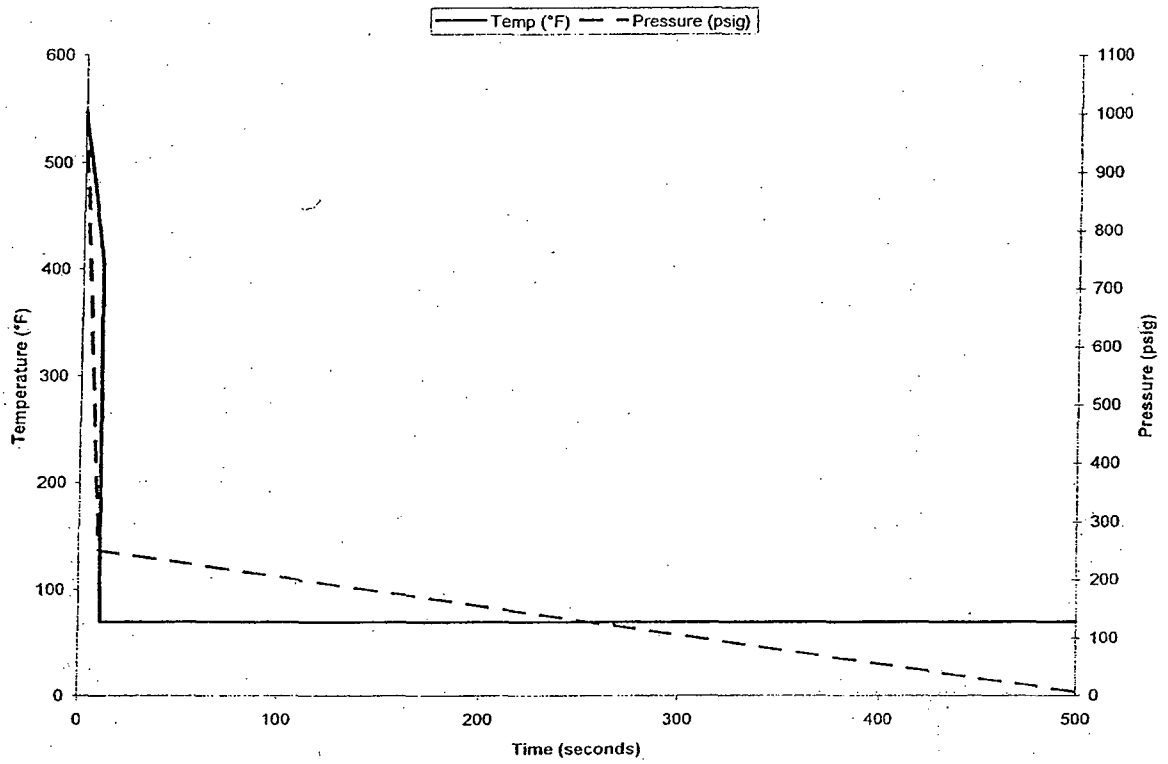


Figure 3-15: Transient 30: Emergency Shutdown 100% Flow (Safe End)

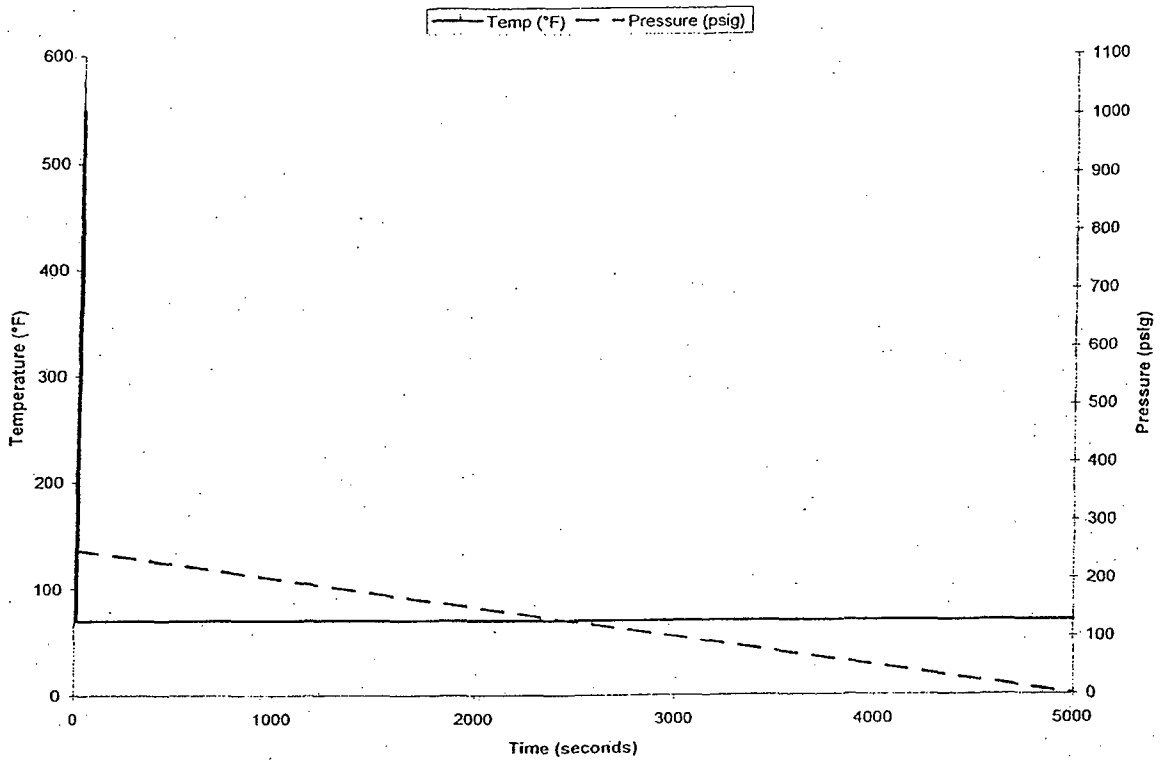


Figure 3-16: Transient 30: Emergency Shut Down 100% Flow (Blend Radius)

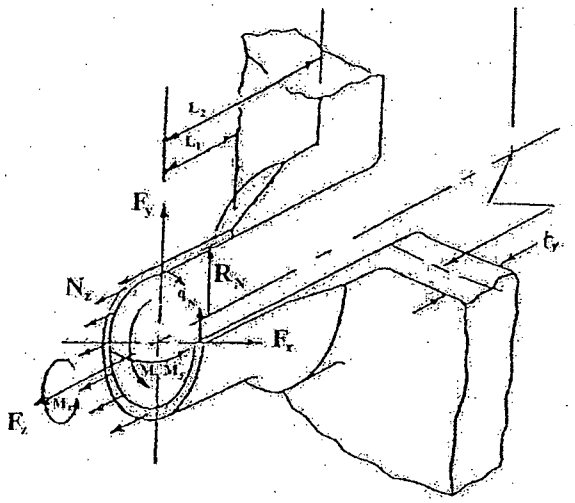


Figure 3-17: Pipe Reactions

4.0 STRESS AND FATIGUE ANALYSIS RESULTS

Fatigue calculations for the VY core spray nozzle were performed in accordance with ASME Code, Section III, Subsection NB-3200 methodology (1998 Edition, 2000 Addenda) [16]. Fatigue analysis was performed in the Reference [10] calculation for the two locations identified in Section 3.1.2, using the Green's Functions developed for these two locations and the 60-year projected cycle counts from Reference [13].

Three computer programs were used to facilitate the fatigue analysis process: STRESS.EXE, P-V.EXE, and FATIGUE.EXE. The first program, STRESS.EXE, calculates a stress history in response to a thermal transient using a Green's Function. The second program, P-V.EXE, reduces the stress history to peaks and valleys. The third program, FATIGUE.EXE, calculates fatigue from the reduced peak and valley history using ASME Code, Section III methodology. All three programs are explained in detail and were independently verified for use in the Reference [15] calculation.

In order to perform the fatigue analysis, input files with the necessary data were prepared and the three analysis programs were run. The program STRESS.EXE required the following three input files:

- **Green.dat**: This file contains the Green's Function. As discussed above, the core spray nozzle analyses utilize four Green's Functions: a membrane plus bending stress intensity Green's Function and a total stress intensity Green's Function for both the safe end and blend radius locations.
- **Green.cfg**: A configuration file containing parameters that describe the Green's Function.
- **Transnt.inp**: This file contains the input transient history defined in Tables 3-2 and 3-3.

Tables 4-1 and 4-2 show the stresses for each location that were used in the fatigue analysis. Columns 2 through 5 of Table 4-1 (for the safe end) and Table 4-2 (for the blend radius) show

the final peak and valley output. The pressure values for Column 6 in each table were determined from the transient pressures, specified in Tables 3-2 and 3-3. The pressure stress intensities from Section 3.2 were scaled appropriately for each transient case. The scaled piping stress values are shown in columns 9 and 10 of Tables 4-1 and 4-2. The piping stress intensities from Section 3.3 were scaled based on the transient case RPV fluid temperature and assuming no stress occurs at an ambient temperature of 70°F. Both of these stress intensities were then added to the thermal stress intensity peak and valley points to calculate the final stress values used for the fatigue analysis. In the case of the piping load stress intensities, the sign of the stress intensity was conservatively set to the same sign as the thermal stress intensity to ensure bounding fatigue usage results. Columns 11 and 12 of Tables 4-1 and 4-2 show the summation of all stresses for each thermal peak and valley stress point. The last column shows the number of cycles associated with each peak or valley based on the cycle counts shown in Tables 3-2 and 3-3.

The program FATIGUE.EXE performs the ASME Code peak event-pairing required to calculate a fatigue usage value. The input data for the configuration input file for FATIGUE.EXE, which is named FATIGUE.CFG, is shown in Table 4-3.

The core spray piping adjacent to the safe end was also analyzed because of its proximity to the maximum safe end thermal stress location. For this fatigue analysis, the stress results of the safe end were used with stainless steel material properties and a value of 1.8 was selected for K_t at the weld location, based on the maximum value given in ASME Code, Section III, Table NB-3681(a)-1 [16].

The results of the fatigue analysis are presented in Tables 4-4, 4-5 and 4-6 for the safe end, blend radius, and piping for 60 years, respectively.

Table 4-1: Core Spray Nozzle Safe End Stress Summary

1	2	3	4	5	6	7	8	9	10	11	12	13
Transient Number	Time (s)	Total Stress (psi)	M+B Stress (psi)	Temperature F	Pressure (psig)	Total Pressure Stress (psi)	M+B Pressure Stress (psi)	Total Piping Stress (psi)	M+B Piping Stress (psi)	Total Total Stress (psi)	Total M+B Stress (psi)	Number of Cycles (60 years)
2				100	0	0	0	413	413	413	413	120
				100	1100	13233	13222	413	413	13646	13635	120
				100	50	602	601	413	413	1014	1014	120
3	0	661	759	100	0	0	0	413	413	1074	1172	300
	17164	9240	10700	549	1010	12150	12140	6592	6592	27982	29432	300
11	0	8802	10236	526	1010	12150	12140	6276	6276	27228	28652	10
	3	8802	10236	526	1190	14316	14304	6276	6276	29393	30815	10
	13	8802	10236	526	1135	13654	13643	6276	6276	28732	30154	10
	164	11645	11598	408	1135	13654	13643	4657	4657	29956	29898	10
	672	4808	5791	344	1135	13654	13643	3775	3775	22237	23209	10
	2374	11140	10841	361	912	10971	10962	4005	4005	26116	25808	10
	2955	4722	5577	325	916	11019	11010	3509	3509	19250	20096	10
	7054	9518	10162	441	959	11537	11527	5100	5100	26155	26789	10
	7930	4491	5276	309	637	7663	7657	3287	3287	15441	16219	10
	16709	9960	11116	526	1010	12150	12140	6276	6276	28386	29532	10
	17699	8802	10236	526	1010	12150	12140	6276	6276	27228	28652	10
14	0	8802	10236	526	1010	12150	12140	6276	6276	27228	28652	1
	152	9499	10570	497	855	10286	10277	5880	5880	25664	26727	1
	12580	91	95	70	50	602	601	0	0	693	696	1
21-23	0	9242	0	549	1010	12150	12140	6592	6592	27984	18732	300
	17224	664	0	100	50	602	601	413	413	1678	1014	300
24				100	50	602	601	413	413	1014	1014	1
				100	1563	18803	18787	413	413	19216	19200	1
				100	50	602	601	413	413	1014	1014	1
30	0	9280	10800	549	1010	12150	12140	6592	6592	28022	29532	1
	13	85600	44694	162	250	3002	3000	1260	1260	89862	48953	1
	1011	12	10	70	0	0	0	0	0	12	10	1

NOTES:

Column 1:	Transient number identification.
Column 2:	Time during transient where a maximum or minimum stress intensity occurs from P-V.OUT output file.
Column 3:	Maxima or minima total stress intensity from P-V.OUT output file.
Column 4:	Maxima or minima membrane plus bending stress intensity from P-V.OUT output file.
Column 5:	Temperature per total stress intensity.
Column 6:	Pressure per Table 3-4.
Column 7:	Total pressure stress intensity from the quantity (Column 6 x 12,030)/1000.
Column 8:	Membrane plus bending pressure stress intensity from the quantity (Column 6 x 12,020)/1000.
Column 9:	Calculated using the total external stress from Table 3-4 as 6949.94 psi*(Column 5-70°F)/(575°F -70°F).
Column 10:	Same as Column 9, but for M+B stress.
Column 11:	Sum of total stresses (Columns 3, 7, and 9).
Column 12:	Sum of membrane plus bending stresses (Columns 4, 8, and 10).
Column 13:	Number of cycles for the transient (60 years).

Table 4-2: Core Spray Nozzle Blend Radius Stress Summary

1	2	3	4	5	6	7	8	9	10	11	12	13
Transient Number	Time (s)	Total Stress (psi)	M+B Stress (psi)	Temperature F	Pressure (psig)	Total Pressure Stress (psi)	M+B Pressure Stress (psi)	Total Piping Stress (psi)	M+B Piping Stress (psi)	Total Total Stress (psi)	Total M+B Stress (psi)	Number of Cycles (60 years)
2				100	0	0	0	19	19	19	19	120
				100	1100	39446	38467	19	19	39465	38486	120
				100	50	1793	1749	19	19	1812	1768	120
3	0	23700	12600	100	0	0	0	19	19	23719	12619	300
	24164	2100	3180	549	1010	36219	35320	306	306	38625	38806	300
11	0	3209	3644	526	1010	36219	35320	291	291	39719	39255	10
	3	3209	3644	526	1190	42673	41614	291	291	46174	45550	10
	1526	10458	5374	330	1135	40701	39691	166	166	51325	45231	10
	2222	5488	4664	490	1122	40235	39236	268	268	45991	41168	10
	2860	11776	7444	321	911	32668	31858	160	160	44605	39462	10
	6903	5435	3621	495	1124	40307	39306	272	272	46013	43199	10
	8012	12577	6791	390	627	22484	21926	204	204	35265	28921	10
	16640	2772	4370	542	1010	36219	35320	301	301	39292	39991	10
	16991	3389	4115	526	1010	36219	35320	291	291	39899	39726	10
	24699	3209	3644	526	1010	36219	35320	291	291	39719	39255	10
14	0	3209	3644	526	1010	36219	35320	291	291	39719	39255	1
	19580	25122	13197	70	50	1793	1749	0	0	26915	14946	1
21-23	0	2103	3161	549	1010	36219	35320	306	306	38628	38787	300
	24224	23680	12568	100	50	1793	1749	19	19	25492	14336	300
24				100	50	1793	1749	19	19	1812	1768	1
				100	1563	56049	54658	19	19	56068	54677	1
				100	50	1793	1749	19	19	1812	1768	1
30	0	2040	2950	549	1010	36219	35320	306	306	38565	38576	1
	8011	25700	14900	70	0	0	0	0	0	25706	14900	1

NOTES:
- Column 1: Transient number identification.
- Column 2: Time during transient where a maximum or minimum stress intensity occurs from P-V.OUT output file.
- Column 3: Maxima or minima total stress intensity from P-V.OUT output file.
- Column 4: Maxima or minima membrane plus bending stress intensity from P-V.OUT output file.
- Column 5: Temperature per total stress intensity.
- Column 6: Pressure per Table 3-5.
- Column 7: Total pressure stress intensity from the quantity (Column 6 x 35,860)/1000.
- Column 8: Membrane plus bending pressure stress intensity from the quantity (Column 6 x 34,970)/1000.
- Column 9: Calculated using the total external stress from Table 3-5 as 322.52 psi*(Column 5-70°F)/(575°F -70°F).
- Column 10: Same as Column 9, but for M+B stress.
- Column 11: Sum of total stresses (Columns 3, 7, and 9).
- Column 12: Sum of membrane plus bending stresses (Columns 4, 8, and 10).
- Column 13: Number of cycles for the transient (60 years).

Table 4-3: Fatigue Parameters Used in the Core Spray Nozzle Fatigue Analysis

	Blend Radius (SA508 Class II)	Safe End (N06600)	Piping (Stainless Steel)
Parameters *m* and *n* for Computing K_e	2.0 & 0.2 (low alloy steel)	1.7 & 0.3	1.7 & 0.3
Design Stress Intensity Values, S_m	26,700 psi @ 600°F	23,300 psi @ 600°F	17,000 psi @ 600°F
Elastic Modulus from Applicable Fatigue Curve	30.0×10^6 psi	28.3×10^6 psi	28.3×10^6 psi
Elastic Modulus Used in Finite Element Model (300°F)	26.7×10^6 psi	29.8×10^6 psi	27.0×10^6 psi
The Geometric Stress Concentration Factor K_t	1.0	4.0 See Note 1	1.8

Note: 1. Conservative bounding value per ASME Code, Subsection NB-3600 to conservatively cover adjacent thread and weld regions.

Table 4-4: Fatigue Results for Core Spray Nozzle Safe End

```
       LOCATION = LOCATION NO. 1 -- SAFE END
  FATIGUE CURVE = 2 (1 = CARBON/LOW ALLOY, 2 = STAINLESS STEEL)
              m = 1.7
              n =  .3
             Sm = 23300. psi
         Ecurve = 2.830E+07 psi
      Eanalysis = 2.980E+07 psi
             Kt = 4.00
```

MAX	MIN	RANGE	MEM+BEND	Ke	Salt	Napplied	Nallowed	U
89862.	-12.	89874.	48963.	1.000	112423.	1.000E+00	1.213E+03	.0008
29956.	413.	29543.	29485.	1.000	56029.	1.000E+01	1.910E+04	.0005
29393.	413.	28980.	30402.	1.000	57068.	1.000E+01	1.746E+04	.0006
28732.	413.	28319.	29741.	1.000	55813.	1.000E+01	1.946E+04	.0005
28386.	413.	27973.	29119.	1.000	54762.	1.000E+01	2.140E+04	.0005
28022.	413.	27609.	29119.	1.000	54590.	1.000E+00	2.174E+04	.0000
27984.	413.	27571.	18319.	1.000	39187.	7.900E+01	1.244E+05	.0006
27984.	693.	27291.	18036.	1.000	38651.	1.000E+00	1.341E+05	.0000
27984.	1014.	26970.	17718.	1.000	38045.	1.200E+02	1.460E+05	.0008
27984.	1014.	26970.	17718.	1.000	38045.	1.000E+00	1.460E+05	.0000
27984.	1014.	26970.	17718.	1.000	38045.	1.000E+00	1.460E+05	.0000
27984.	1074.	26910.	17560.	1.000	37792.	9.800E+01	1.514E+05	.0006
27982.	1074.	26908.	28260.	1.000	53033.	2.020E+02	2.517E+04	.0080
27982.	1678.	26304.	28418.	1.000	52971.	9.800E+01	2.532E+04	.0039
27228.	1678.	25550.	27638.	1.000	51502.	1.000E+01	2.919E+04	.0003
27228.	1678.	25550.	27638.	1.000	51502.	1.000E+01	2.919E+04	.0003
27228.	1678.	25550.	27638.	1.000	51502.	1.000E+00	2.919E+04	.0000
26155.	1678.	24477.	25775.	1.000	48339.	1.000E+01	4.021E+04	.0002
26116.	1678.	24438.	24794.	1.000	46923.	1.000E+01	4.673E+04	.0002
25664.	1678.	23986.	25713.	1.000	48017.	1.000E+00	4.159E+04	.0000
22237.	1678.	20559.	22195.	1.000	41379.	1.000E+01	9.257E+04	.0001
19250.	1678.	17572.	19082.	1.000	35526.	1.000E+01	2.135E+05	.0000
19216.	1678.	17538.	18186.	1.000	34234.	1.000E+00	2.691E+05	.0000
15441.	1678.	13763.	15205.	1.000	28195.	1.000E+01	1.001E+06	.0000
13646.	1678.	11968.	12621.	1.000	23661.	1.200E+02	1.772E+06	.0001
							TOTAL USAGE FACTOR =	.0184

Table 4-5: Fatigue Results for the Core Spray Nozzle Blend Radius

```
      LOCATION = LOCATION NO. 2 -- BLEND RADIUS
  FATIGUE CURVE = 1 (1 = CARBON/LOW ALLOY, 2 = STAINLESS STEEL)
              m = 2.0
              n =  .2
             Sm = 26700. psi
         Ecurve = 3.000E+07 psi
      Eanalysis = 2.670E+07 psi
             Kt = 1.00
```

MAX	MIN	RANGE	MEM+BEND	Ke	Salt	Napplied	Nallowed	U
56068.	19.	56049.	54658.	1.000	31488.	1.000E+00	1.896E+04	.0001
51325.	19.	51306.	45212.	1.000	28824.	1.000E+01	2.501E+04	.0004
46174.	19.	46155.	45531.	1.000	25930.	1.000E+01	3.460E+04	.0003
46013.	19.	45994.	43180.	1.000	25839.	1.000E+01	3.498E+04	.0003
45991.	19.	45972.	41149.	1.000	25827.	1.000E+01	3.503E+04	.0003
44605.	19.	44586.	39443.	1.000	25048.	1.000E+01	3.848E+04	.0003
39899.	19.	39880.	39707.	1.000	22404.	1.000E+01	5.695E+04	.0002
39719.	19.	39700.	39236.	1.000	22303.	1.000E+01	5.824E+04	.0002
39719.	19.	39700.	39236.	1.000	22303.	1.000E+01	5.824E+04	.0002
39719.	19.	39700.	39236.	1.000	22303.	1.000E+00	5.824E+04	.0000
39465.	19.	39446.	38467.	1.000	22161.	3.800E+01	6.012E+04	.0006
39465.	1812.	37653.	36718.	1.000	21153.	8.200E+01	7.572E+04	.0011
39292.	1812.	37480.	38223.	1.000	21056.	1.000E+01	7.747E+04	.0001
38628.	1812.	36816.	37019.	1.000	20683.	2.800E+01	8.466E+04	.0003
38628.	1812.	36816.	37019.	1.000	20683.	1.000E+00	8.466E+04	.0000
38628.	1812.	36816.	37019.	1.000	20683.	1.000E+00	8.466E+04	.0000
38628.	23719.	14909.	26168.	1.000	8376.	2.700E+02	5.366E+07	.0000
38625.	23719.	14906.	26187.	1.000	8374.	3.000E+01	5.375E+07	.0000
38625.	25492.	13133.	24470.	1.000	7378.	2.700E+02	3.042E+08	.0000
38565.	25492.	13073.	24240.	1.000	7344.	1.000E+00	3.374E+08	.0000
35265.	25492.	9773.	14585.	1.000	5490.	1.000E+01	1.000E+20	.0000
26915.	25492.	1423.	610.	1.000	799.	1.000E+00	1.000E+20	.0000
25700.	25492.	208.	564.	1.000	117.	1.000E+00	1.000E+20	.0000
							TOTAL USAGE FACTOR =	.0043

Table 4-6: Fatigue Results for the Core Spray Stainless Steel Piping

```
       LOCATION = LOCATION NO. 1 -- SS Piping
 FATIGUE CURVE = 2 (1 = CARBON/LOW ALLOY, 2 = STAINLESS STEEL)
              m = 1.7
              n =  .3
             Sm = 17000. psi
         Ecurve = 2.830E+07 psi
      Eanalysis = 2.700E+07 psi
             Kt = 1.80
```

MAX	MIN	RANGE	MEM+BEND	Ke	Salt	Napplied	Nallowed	U
89862.	-12.	89874.	48963.	1.000	67629.	1.000E+00	8.006E+03	.0001
29956.	413.	29543.	29485.	1.000	27845.	1.000E+01	1.042E+06	.0000
29393.	413.	28980.	30402.	1.000	27934.	1.000E+01	1.031E+06	.0000
28732.	413.	28319.	29741.	1.000	27310.	1.000E+01	1.110E+06	.0000
28386.	413.	27973.	29119.	1.000	26868.	1.000E+01	1.171E+06	.0000
28022.	413.	27609.	29119.	1.000	26678.	1.000E+00	1.198E+06	.0000
27984.	413.	27571.	18319.	1.000	22130.	7.900E+01	2.272E+06	.0000
27984.	693.	27291.	18036.	1.000	21864.	1.000E+00	2.392E+06	.0000
27984.	1014.	26970.	17718.	1.000	21563.	1.200E+02	2.539E+06	.0000
27984.	1014.	26970.	17718.	1.000	21563.	1.000E+00	2.539E+06	.0000
27984.	1014.	26970.	17718.	1.000	21563.	1.000E+00	2.539E+06	.0000
27984.	1074.	26910.	17560.	1.000	21465.	9.800E+01	2.588E+06	.0000
27982.	1074.	26908.	28260.	1.000	25950.	2.020E+02	1.311E+06	.0002
27982.	1678.	26304.	28418.	1.000	25700.	9.800E+01	1.354E+06	.0001
27228.	1678.	25550.	27638.	1.000	24978.	1.000E+01	1.485E+06	.0000
27228.	1678.	25550.	27638.	1.000	24978.	1.000E+01	1.485E+06	.0000
27228.	1678.	25550.	27638.	1.000	24978.	1.000E+00	1.485E+06	.0000
26155.	1678.	24477.	25775.	1.000	23634.	1.000E+01	1.779E+06	.0000
26116.	1678.	24438.	24794.	1.000	23202.	1.000E+01	1.889E+06	.0000
25664.	1678.	23986.	25713.	1.000	23351.	1.000E+00	1.850E+06	.0000
22237.	1678.	20559.	22195.	1.000	20080.	1.000E+01	3.442E+06	.0000
19250.	1678.	17572.	19082.	1.000	17209.	1.000E+01	7.481E+06	.0000
19216.	1678.	17538.	18186.	1.000	16816.	1.000E+00	8.600E+06	.0000
15441.	1678.	13763.	15205.	1.000	13588.	1.000E+01	1.000E+20	.0000
13646.	1678.	11968.	12621.	1.000	11564.	1.200E+02	1.000E+20	.0000
							TOTAL USAGE FACTOR =	.0005

5.0 ENVIRONMENTAL FATIGUE ANALYSIS

Environmental fatigue multipliers were computed for both normal water chemistry (NWC) and hydrogen water chemistry (HWC) conditions in Reference [17] for various regions of the VY RPV and attached piping. Based on VY-specific dates for plant startup and HWC implementation, as well as past and future predicted HWC system availability, it was determined that overall HWC availability is 47% over the sixty year operating period for VY. Therefore, for the purposes of the EAF assessment of the core spray nozzle, it was assumed that HWC conditions exist for 47% of the time, and NWC conditions exist for 53% of the time over the 60-year operating life of the plant. RPV upper region chemistry was assumed for both the core spray nozzle safe end and blend radius locations, since both locations experience reactor conditions for all times except during core spray injections, (which are rare occurrences).

For the safe end location, the environmental fatigue factors for pre-HWC and post-HWC are both 1.49 from Reference [18]. This results in an EAF adjusted CUF as follows:

60-Year CUF, U_{60} = 0.0184 (from Table 4-4)
Overall EAF multiplier, F_{en} = 1.49
60-Year EAF CUF, $U_{60\text{-}evn}$ = 0.0184 x 1.49 = 0.0274

The EAF CUF value of 0.0274 for 60 years for the safe end is acceptable (i.e., less than the allowable value of 1.0).

For the stainless steel piping, the environmental fatigue factors for pre-HWC and post-HWC are both 8.36 from Table 4 of Reference [17] for the RPV upper region. This results in an EAF adjusted CUF as follows:

60-Year CUF, U_{60} = 0.0005 (from Table 4-6)
Overall EAF multiplier, F_{en} = 8.36
60-Year EAF CUF, $U_{60\text{-}evn}$ = 0.0005 x 8.36 = 0.0042

The EAF CUF value of 0.0042 for 60 years for the blend radius is acceptable (i.e., less than the allowable value of 1.0).

The fatigue calculation documented in Section 4.0 for the blend radius location was performed for the nozzle base material, since cladding is structurally neglected in modern-day fatigue analyses, per ASME Code, Section III, NB-3122.3 [16]. This is also consistent with Sections 5.7.1 and 5.7.4 of NUREG/CR-6260 [1]. Therefore, the cladding was neglected and EAF assessment of the nozzle base material was performed for the blend radius location.

For the blend radius location, the environmental fatigue factors for pre-HWC and post-HWC are 11.14 and 8.82, respectively, from Table 4 of Reference [17] for the RPV upper region. This results in an EAF adjusted CUF as follows:

60-Year CUF, U_{60} = 0.0043 (from Table 4-5)
Overall EAF multiplier, F_{en} = (11.14 x 53% + 8.82 x 47%) = 10.05
60-Year EAF CUF, $U_{60\text{-}evn}$ = 0.0043 x 10.05 = 0.0432

The EAF CUF value of 0.0432 for 60 years for the blend radius is acceptable (i.e., less than the allowable value of 1.0).

6.0 CONCLUSIONS

This report documents a refined fatigue evaluation for the VY core spray nozzle. The intent of this evaluation is to use refined transient definitions and the revised cyclic transient counts for 60 years for a computation of CUF, including EAF effects, that is more refined than previously performed fatigue analyses. The fatigue-limiting locations in the core spray nozzle, safe end, and piping are included in the evaluation, to be consistent with NUREG/CR-6260 [1] needs for EAF evaluation for license renewal. The final fatigue results are considered to be a replacement to the values previously reported in the VY LRA.

The fatigue calculations for the VY core spray nozzle were performed in accordance with ASME Code, Section III, Subsection NB-3200 methodology (1998 Edition, 2000 Addenda) [16]. The stress evaluation is summarized in Section 3.0, and the fatigue analysis is summarized in Section 4.0. The results in Section 4.0 reveal that the CUF for the limiting safe end location is 0.0184, the CUF for the limiting blend radius location is 0.0043, and the CUF for the stainless steel piping is 0.0005. All of these values represent 60 years of plant operation, including all relevant EPU effects.

EAF calculations for the VY core spray nozzle were also performed, as summarized in Section 5.0. The results in Section 5.0 reveal that the EAF CUF for the limiting safe end location is 0.0274, the EAF CUF for the limiting blend radius location is 0.0432, and the EAF CUF for the stainless steel piping is 0.0042. All of these values represent 60 years of plant operation, including all relevant EPU effects.

All fatigue allowables, both with and without EAF effects, are met, thus demonstrating acceptability for 60 years of operation.

7.0 REFERENCES

1. NUREG/CR-6260 (INEL-95/0045), "Application of NUREG/CR-5999 Interim Fatigue Curves to Selected Nuclear Power Plant Components," March 1995.

2. Structural Integrity Associates Report No. SIR-86-037, Revision 0, "Evaluation of Modifications to Vermont Yankee Core Spray Nozzle and Safe End," January 1987, SI Project No. YAEC-08.

3. GE Design Specification No. 21A1115, Revision 4, "Vermont Yankee Reactor Pressure Vessel," October 21, 1969, SI File No. VY-05Q-210.

4. GE Design Specification No. 26A6019, Revision 1, "Reactor Vessel – Extended Power Uprate," August 29, 2003, SI File No. VY-05Q-236.

5. Kuo, A. Y., Tang, S. S., and Riccardella, P. C., "An On-Line Fatigue Monitoring System for Power Plants, Part I - Direct Calculation of Transient Peak Stress Through Transfer Matrices and Green's Functions," ASME PVP Conference, Chicago, 1986.

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

7. Structural Integrity Associates Calculation No. VY-16Q-308, Revision 0, "Core Spray Nozzle Finite Element Model."

8. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section II, Materials, Part D, "Properties (Customary)," 1998 Edition, 2000 Addenda.

9. Structural Integrity Associates Calculation No. VY-16Q-309, Revision 0, "Core Spray Nozzle Green's Functions."

10. Structural Integrity Associates Calculation No. VY-16Q-310, Revision 0, "Fatigue Analysis of Core Spray Nozzle."

11. Reactor Thermal Cycles, Attachment 1 of Entergy Design Input Record (DIR) Revision 1, EC No. 1773, Rev. 0, "Environmental Fatigue Analysis for Vermont Yankee Nuclear Power Station," 7/26/07, SI File No. VY-16Q-209.

12. Nozzle Thermal Cycles (Drain, Core Spray & Head Spray), Attachment 1 of Entergy Design Input Record (DIR) Revision 1, EC No. 1773, Rev. 0, "Environmental Fatigue Analysis for Vermont Yankee Nuclear Power Station," 7/26/07, SI File No. VY-16Q-209.

13. Reactor Thermal Cycles for 60 Years of Operation, Attachment 1 of Entergy Design Input Record (DIR) Revision 1, EC No. 1773, Rev. 0, "Environmental Fatigue Analysis for Vermont Yankee Nuclear Power Station," 7/26/07, SI File No. VY-16Q-209.

14. Vermont Yankee Drawing 5920-00024, Rev. 11, (GE Drawing No. 919D294, Sheet No. 7), "Reactor Vessel," SI File No. VY-05Q-241.

15. Structural Integrity Associates Calculation No. SW-SPVF-01Q-301, Revision 0, "STRESS.EXE, P-V.EXE, and FATIGUE.EXE Software Verification."

16. American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section III, Rules for Construction of Nuclear Facility Components, 1998 Edition, 2000 Addenda.

17. Structural Integrity Associates Calculation No. VY-16Q-303, Revision 0, "Environmental Fatigue Evaluation of Reactor Recirculation Inlet Nozzle and Vessel Shell/Bottom Head."

18. EPRI Report No. TR-105759, "An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations," December 1995.