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Appendix G

Pressure Temperature Limits

for

32 EFPY Using ASME Code Cases,

for

Arkansas Nuclear One Unit 2 Power Plant

by

A. D. Nana

FRAMATOME ANP

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APPENDIX G PRESSURE-TEMPERATURE LIMITS FOR 32 EFPY, USING ASME CODE CASES, FOR

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1. INTRODUCTION

This report presents pressure/temperature (P/T) limits for the Arkansas Nuclear One Unit 2 (ANO-2) reactor vessel at 32 effective full power years (EFPY) of operation including an estimated increase in fluence due to a proposed power uprate. The data used to develop these operational limits are based on the evaluation of the ANO-2 reactor vessel surveillance capsule.[1] Pressure-temperature limits are developed for normal heatup and cooldown operating conditions and inservice leak and hydrostatic (ISLH) test conditions.

2. BACKGROUND

The ability of the reactor pressure vessel to resist fracture is the primary factor in ensuring the safety of the primary system in light water-cooled reactors. The beltline region of the reactor vessel is the most critical region of the vessel because it is exposed to neutron irradiation. The general effects of fast neutron irradiation on the mechanical properties of low-alloy ferritic steels such as SA533, Grade B plate material used in the fabrication of the ANO-2 reactor vessel, are well characterized and documented in the literature. The effects of irradiation on these steels include an increase in the yield and ultimate strengths and a decrease in ductility. The most significant effect, however, is an increase in the temperature associated with the transition from brittle to ductile fracture and a reduction in the Charpy upper-shelf energy value.

Appendix G to 10 CFR 50, "Fracture Toughness Requirements,"[2] specifies minimum fracture toughness requirements for the ferritic materials of the pressure-retaining components of the reactor coolant pressure boundary (RCPB) of water-cooled power reactors, and provides specific guidelines for determining the pressure-temperature limitations on operation of the RCPB. The toughness and operational requirements are specified to provide adequate safety margins during any condition of normal operation, including anticipated operational occurrences and system hydrostatic tests, to which the pressure boundary may be subjected over its service lifetime. Although the requirements of Appendix G to 10 CFR 50 originally became effective on August 16, 1973, the requirements are applicable to all boiling and pressurized water-cooled nuclear power reactors, including those under construction or in operation on the effective date.

Appendix H to 10 CFR 50, "Reactor Vessel Materials Surveillance Program Requirements,"[3] defines the material surveillance program required to monitor changes in the fracture toughness properties of ferritic materials in the reactor vessel beltline region of water-cooled reactors resulting from exposure to neutron irradiation and the thermal environment. Fracture toughness test data are obtained from material specimens periodically withdrawn from the reactor vessel. These data will permit determination of the conditions under which the vessel can be operated with adequate safety margin against fracture throughout its service life.

A method for guarding against brittle fracture in reactor pressure vessels is described in Appendix G to the ASME Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components."[4] This method utilizes fracture mechanics concepts and the reference temperature for nil-ductility transition, RT_{NDT}, which is defined as the greater of the drop weight nil-ductility transition temperature (per ASTM E208[5]) or the temperature that is 60 °F below that at which the material exhibits 50 ft-lbs and 35 mils lateral expansion. The RT_{NDT} of a given material is used to index that material to a reference stress intensity factor curve (K_{Ia} or K_{Ic} curve as applicable). The K_{Ia} curve appears in Appendix G of ASME Code Section XI. ASME Code Case N-640[11] permits the use of the K_{Ic} curve as given in Appendix A of ASME Code Section XI. When a given material is indexed to the K_{Ic} curve, allowable stress intensity factors can be obtained for this material as a function of temperature. Plant operating limits can then be determined using these allowable stress intensity factors.

The RT_{NDT} of the reactor vessel materials, and in turn, the pressure/temperature limits of a reactor vessel, must be adjusted to account for the effects of irradiation. Neutron embrittlement and the resultant changes in mechanical properties of a given pressure vessel steel are monitored by a surveillance program consisting of periodic removal of surveillance capsules from an operating reactor and testing of reactor vessel material specimens obtained from the capsules. The increase in the Charpy V-notch 30 ft-lb temperature is added to the unirradiated RT_{NDT} to adjust it for neutron embrittlement. This adjusted RT_{NDT} is used to index the material to the K_{Ic} curve, which in turn, is used to set new operating limits for the nuclear power plant. These new limits take into account the effects of irradiation on the reactor vessel materials.

3. ADJUSTED NIL-DUCTILITY TRANSITION REFERENCE TEMPERATURES

The reactor pressure vessel beltline region consists of two shells, containing six heats of base metal plate, six longitudinal weld seams, and one circumferential weld seam. Table 3-1 presents a description of the reactor vessel beltline materials including their copper and nickel chemical contents and their unirradiated mechanical properties. The locations of the materials within the reactor vessel beltline region are shown in Figures 3-1 and 3-2.

The adjusted reference temperatures for the reactor vessel beltline region materials are calculated in accordance with Regulatory Guide 1.99, Revision 2[6]. The adjusted reference temperatures are calculated by adding the initial RT_{NDT}, the predicted radiation-induced ΔRT_{NDT}, and a margin term to cover the uncertainties in the values of initial RT_{NDT}, copper and nickel contents, fluence, and the calculational procedures. The predicted radiation induced ΔRT_{NDT} is calculated using the respective reactor vessel beltline materials copper and nickel contents and the neutron fluence applicable to 32 EFPY including an estimated increase in flux due to a proposed power uprate. The ¼-thickness (¼T) and ¾-thickness (¾T) wall locations for each beltline material are determined by adding the thickness of the cladding to the distance into the base metal at the ¼T and ¾T locations (i.e., ¼T = [7.875 * ¼] + 0.125 = 2.094 inches and ¾T = [7.875 * ¾] + 0.125 = 6.031 inches).

The ¼T and ¾T adjusted reference temperature results[1] for the ANO-2 reactor vessel beltline region materials applicable to 32 EFPY are presented in Table 3-2. Based on these results, the controlling beltline material for the ANO-2 reactor vessel is the lower shell plate C-8010-1.

Table 3-1. Description of Reactor Vessel Beltline Region Materials

Beltline Region Location	Material Identification	Material Type	Material Heat No.	Chemical Composition		Unirradiated RT_{NDT}, F
				Cu, wt%	Ni, wt%	
Inter. Shell Long. Welds	2-203	Subarc Weld	10120	0.046	0.082	-56
Lower Shell Long. Welds	3-203	Subarc Weld	10120	0.046	0.082	-56
Lower/Inter. Shell Girth Weld	9-203	Subarc Weld	83650	0.045	0.087	-10
Intermediate Shell	C-8009-1	SA-533B Cl.1	C8161-3	0.098	0.605	-26
Intermediate Shell	C-8009-2	SA-533B Cl.1	C8161-1	0.085	0.600	0
Intermediate Shell	C-8009-3	SA-533B Cl.1	C8182-2	0.096	0.580	0
Lower Shell	C-8010-1	SA-533B Cl.1	C8161-2	0.085	0.585	12
Lower Shell	C-8010-2	SA-533B Cl.1	B2545-1	0.083	0.668	-28
Lower Shell	C-8010-3	SA-533B Cl.1	B2545-2	0.080	0.653	-30

Table 3-2. Adjusted Reference Temperatures Applicable to 32 EFPY with Power Uprate

Material Description				Chemical Composition				32 EFPY Fluence, n/cm^2			ΔRT_{NDT}, F at 32 EFPY		ART_{NDT}, F at 32 EFPY	
Reactor Vessel Beltline Location	Matl. Ident.	Heat Number	Base Metal / Flux Type	Cu wt%	Ni wt%	Initial RT_{NDT}	Chemistry Factor	Inside Wetted Surface	T/4 Location	3/4T Location	T/4 Location	3/4T Location	T/4 Location	3/4T Location
Regulatory Guide 1.99, Revision 2, Position 1.1														
Inter. Shell Long. Weld	2-203 A	10120	Linde 0091	0.046	0.082	-56	34.0	3.568E+19	2.159E+19	8.391E+18	41.1	32.3	38.4	23.2
Inter. Shell Long. Weld	2-203 B	10120	Linde 0091	0.046	0.082	-56	34.0	2.754E+19	1.666E+19	6.477E+18	38.8	29.9	34.4	19.2
Inter. Shell Long. Weld	2-203 C	10120	Linde 0091	0.046	0.082	-56	34.0	2.754E+19	1.666E+19	6.477E+18	38.8	29.9	34.4	19.2
Lower Shell Long. Weld	3-203 A	10120	Linde 0091	0.046	0.082	-56	34.0	3.582E+19	2.167E+19	8.425E+18	41.1	32.4	38.4	23.4
Lower Shell Long. Weld	3-203 B	10120	Linde 0091	0.046	0.082	-56	34.0	2.765E+19	1.673E+19	6.502E+18	38.8	29.9	34.4	19.2
Lower Shell Long. Weld	3-203 C	10120	Linde 0091	0.046	0.082	-56	34.0	2.765E+19	1.673E+19	6.502E+18	38.8	29.9	34.4	19.2
Inter./Lower Shell Girth Weld	9-203	83650	Linde 0091	0.045	0.087	-10	34.1	3.776E+19	2.284E+19	8.880E+18	41.7	33.0	73.4	56.0
Intermediate Shell Plate	C-8009-1	C8161-3	SA-533B Cl.1	0.098	0.605	-26	63.6	3.776E+19	2.284E+19	8.880E+18	77.8	61.5	85.8	69.5
Intermediate Shell Plate	C-8009-2	C8161-1	SA-533B Cl.1	0.085	0.600	0	54.5	3.776E+19	2.284E+19	8.880E+18	66.7	52.7	100.7	86.7
Intermediate Shell Plate	C-8009-3	C8182-2	SA-533B Cl.1	0.096	0.580	0	62.2	3.776E+19	2.284E+19	8.880E+18	76.1	60.1	110.1	94.1
Lower Shell Plate	C-8010-1	C8161-2	SA-533B Cl.1	0.085	0.585	12	54.5	3.791E+19	2.293E+19	8.915E+18	66.7	52.8	[112.7]	[98.8]
Lower Shell Plate	C-8010-2	B2545-1	SA-533B Cl.1	0.083	0.668	-28	53.1	3.791E+19	2.293E+19	8.915E+18	65.0	51.4	71.0	57.4
Lower Shell Plate	C-8010-3	B2545-2	SA-533B Cl.1	0.080	0.653	-30	51.0	3.791E+19	2.293E+19	8.915E+18	62.4	49.4	66.4	53.4
Regulatory Guide 1.99, Revision 2, Position 2.1														
Inter. Shell Long. Weld	2-203 A	10120	Linde 0091	0.046	0.082	-56	14.9	3.568E+19	2.159E+19	8.391E+18	18.0	14.2	0.5	-5.0
Inter. Shell Long. Weld	2-203 B	10120	Linde 0091	0.046	0.082	-56	14.9	2.754E+19	1.666E+19	6.477E+18	17.0	13.1	-1.0	-6.5
Inter. Shell Long. Weld	2-203 C	10120	Linde 0091	0.046	0.082	-56	14.9	2.754E+19	1.666E+19	6.477E+18	17.0	13.1	-1.0	-6.5
Lower Shell Long. Weld	3-203 A	10120	Linde 0091	0.046	0.082	-56	14.9	3.582E+19	2.167E+19	8.425E+18	18.0	14.2	0.5	-5.0
Lower Shell Long. Weld	3-203 B	10120	Linde 0091	0.046	0.082	-56	14.9	2.765E+19	1.673E+19	6.502E+18	17.0	13.1	-1.0	-6.5
Lower Shell Long. Weld	3-203 C	10120	Linde 0091	0.046	0.082	-56	14.9	2.765E+19	1.673E+19	6.502E+18	17.0	13.1	-1.0	-6.5
Intermediate Shell Plate	C-8009-3	C8182-2	SA-533B Cl.1	0.096	0.580	0	40.7	3.776E+19	2.284E+19	8.880E+18	49.8	39.4	66.8	56.4

[ ] - Controlling values of the adjusted reference temperatures.

Figure 3-1. Location and Identification of Reactor Vessel Materials

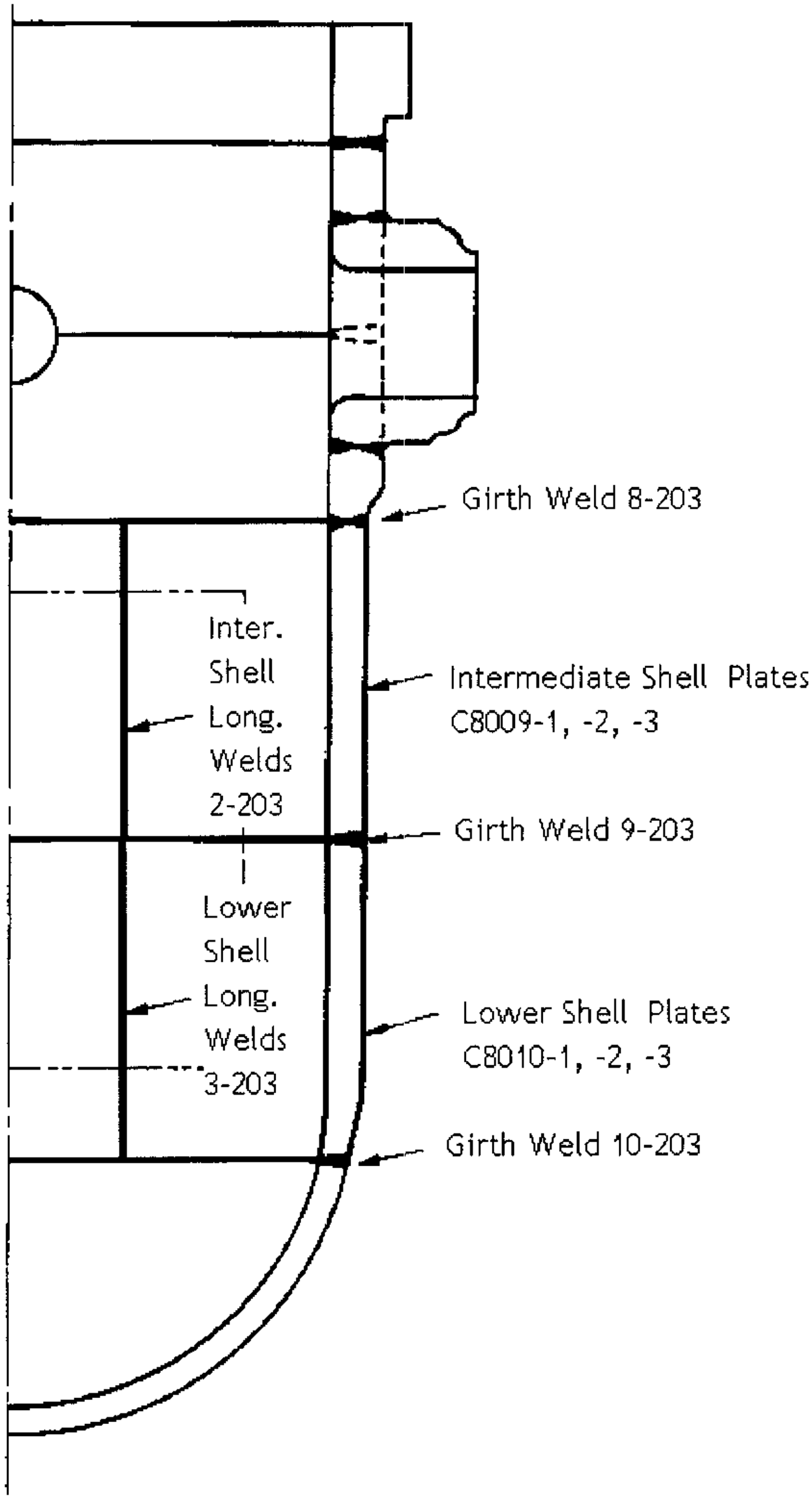
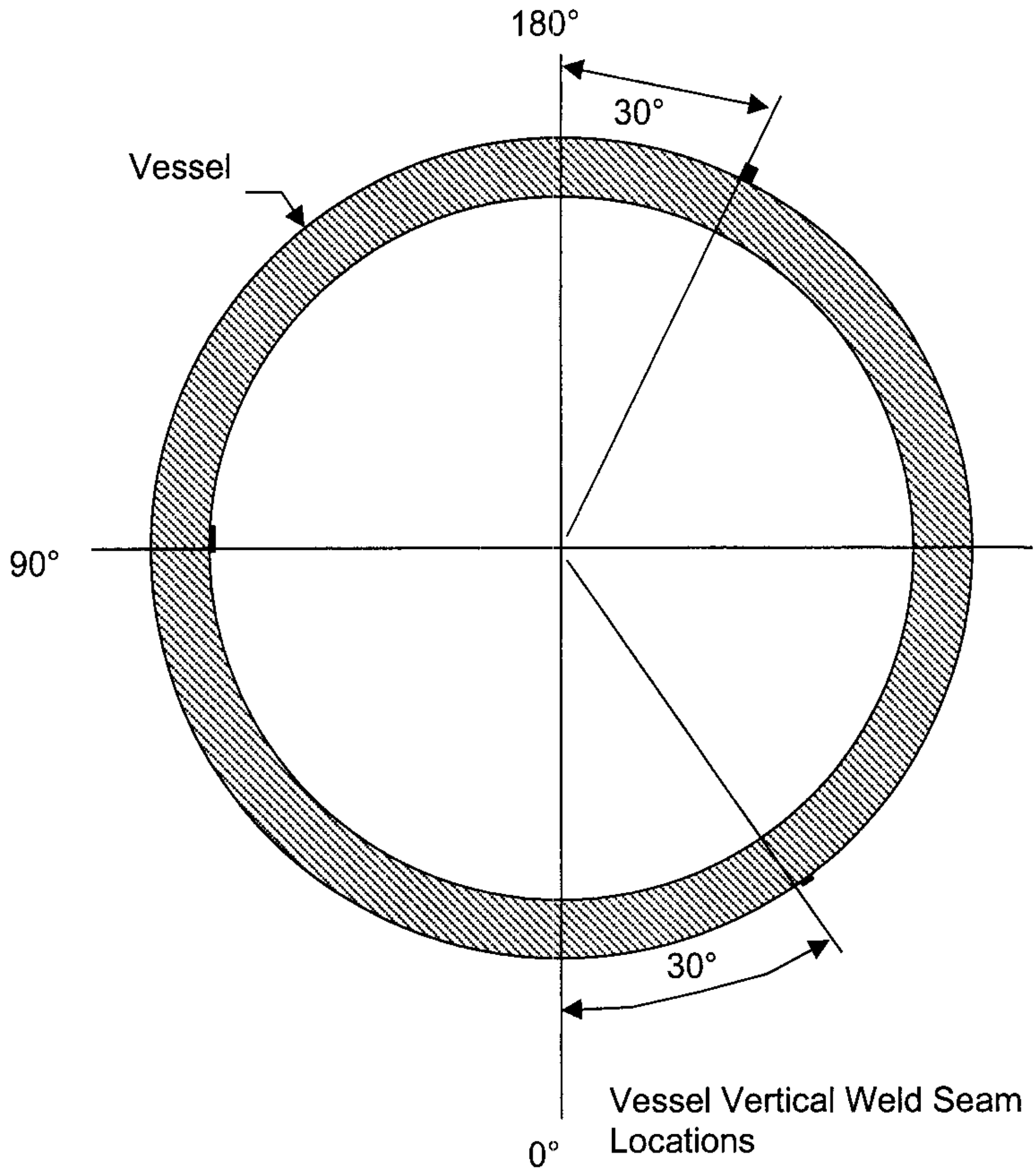


Figure 3-2. Location of Longitudinal Welds in the Reactor Vessel Upper and Lower Shell Courses



4. PRESSURIZED THERMAL SHOCK REFERENCE TEMPERATURES

A pressurized thermal shock (PTS) evaluation for the ANO-2 reactor vessel beltline materials was performed in accordance with Code of Federal Regulation, Title 10, Part 50.61 (10 CFR 50.61).[7] The results of the PTS evaluation are shown in Table 4-1. These results demonstrate that the ANO-2 reactor vessel beltline materials will not exceed the PTS screening criteria before 32 EFPY. The controlling beltline material for the ANO-2 reactor vessel with respect to PTS is the lower shell plate C-8010-1, with a RT_{PTS} value of 118.8°F that is well below the PTS screening criterion of 270°F.

Table 4-1. Pressurized Thermal Shock Reference Temperatures Applicable to 32 EFPY with Power Uprate

Material Description				Chemical Composition				Vessel/Clad Interface Fluence at					
Reactor Vessel Beltline Location	Matl. Ident.	Heat Number	Base Metal / Flux Type	Cu wt%	Ni wt%	Initial RT_{NDT}	Chemistry Factor	32 EFPY, n/cm² (a)	Fluence Factor	ΔRT_{PTS}, F	Margin F	RT_{PTS}, F	Screening Criteria
RT_{PTS} Calculation Per 10 CFR 50.61 Using Tables													
Inter. Shell Long. Weld	2-203 A	10120	Linde 0091	0.046	0.082	-56	34.0	3.432E+19	1.322	44.9	56.4	45.3	270
Inter. Shell Long. Weld	2-203 B	10120	Linde 0091	0.046	0.082	-56	34.0	2.646E+19	1.260	42.8	54.7	41.5	270
Inter. Shell Long. Weld	2-203 C	10120	Linde 0091	0.046	0.082	-56	34.0	2.646E+19	1.260	42.8	54.7	41.5	270
Lower Shell Long. Weld	3-203 A	10120	Linde 0091	0.046	0.082	-56	34.0	3.446E+19	1.323	45.0	56.4	45.4	270
Lower Shell Long. Weld	3-203 B	10120	Linde 0091	0.046	0.082	-56	34.0	2.657E+19	1.261	42.9	54.8	41.7	270
Lower Shell Long. Weld	3-203 C	10120	Linde 0091	0.046	0.082	-56	34.0	2.657E+19	1.261	42.9	54.8	41.7	270
Inter./Lower Shell Girth Weld	9-203	83650	Linde 0091	0.045	0.087	-10	34.1	3.613E+19	1.334	45.5	45.6	81.1	300
Intermediate Shell Plate	C-8009-1	C8161-3	SA-533B Cl.1	0.098	0.605	-26	63.6	3.613E+19	1.334	84.8	34.0	92.8	270
Intermediate Shell Plate	C-8009-2	C8161-1	SA-533B Cl.1	0.085	0.600	0	54.5	3.613E+19	1.334	72.7	34.0	106.7	270
Intermediate Shell Plate	C-8009-3	C8182-2	SA-533B Cl.1	0.096	0.580	0	62.2	3.613E+19	1.334	83.0	34.0	117.0	270
Lower Shell Plate	C-8010-1	C8161-2	SA-533B Cl.1	0.085	0.585	12	54.5	3.627E+19	1.335	72.8	34.0	[118.8]	270
Lower Shell Plate	C-8010-2	B2545-1	SA-533B Cl.1	0.083	0.668	-28	53.1	3.627E+19	1.335	70.9	34.0	76.9	270
Lower Shell Plate	C-8010-3	B2545-2	SA-533B Cl.1	0.080	0.653	-30	51.0	3.627E+19	1.335	68.1	34.0	72.1	270
RT_{PTS} Calculation Per 10 CFR 50.61 Using Surveillance Data													
Inter. Shell Long. Weld	2-203 A	10120	Linde 0091	0.046	0.082	-56	14.9	3.432E+19	1.322	19.7	39.3	3.0	270
Inter. Shell Long. Weld	2-203 B	10120	Linde 0091	0.046	0.082	-56	14.9	2.646E+19	1.260	18.8	38.9	1.7	270
Inter. Shell Long. Weld	2-203 C	10120	Linde 0091	0.046	0.082	-56	14.9	2.646E+19	1.260	18.8	38.9	1.7	270
Lower Shell Long. Weld	3-203 A	10120	Linde 0091	0.046	0.082	-56	14.9	3.446E+19	1.323	19.7	39.3	3.0	270
Lower Shell Long. Weld	3-203 B	10120	Linde 0091	0.046	0.082	-56	14.9	2.657E+19	1.261	18.8	38.9	1.7	270
Lower Shell Long. Weld	3-203 C	10120	Linde 0091	0.046	0.082	-56	14.9	2.657E+19	1.261	18.8	38.9	1.7	270
Intermediate Shell Plate	C-8009-3	C8182-2	SA-533B Cl.1	0.096	0.580	0	40.7	3.613E+19	1.334	54.3	17.0	71.3	270

(a) The inside surface fluence is the calculated value at the clad – base metal interface of the reactor vessel; attenuation through the cladding is based on deterministic methods.

[ ] – Limiting reactor vessel beltline material in accordance with 10 CFR 50.61.

5. DESIGN BASIS FOR PRESSURE/TEMPERATURE LIMITS

Essential geometric data and analytical parameters used in the preparation of ANO-2 P/T limits are summarized in Table 5-1. Table 5-2 presents material properties utilized in analyzing the intermediate and lower beltline shells (SA533, Grade B, Class 1 plate material) and the reactor vessel inlet nozzles (SA508, Class 2 forging material). Limiting values of the adjusted reference temperature, RT_{NDT}, are listed in Table 5-3.

For normal heatup operation, four ramped heatup transient conditions are considered in the evaluation. These transient conditions are simulated by increasing the reactor coolant system (RCS) cold leg temperature from 50 ^{0}F to 560 ^{0}F at constant rates of 50, 60, 70 and 80 ^{0}F/hr. The normal heatup transients are illustrated in Figure 5-1. The inservice leak and hydrostatic (ISLH) heatup test condition is also evaluated using the above RCS cold leg temperature ranges, at a ramp rate of 10 ^{0}F/hr.

For normal cooldown operation, the following temperature dependant rates for ramped and stepped cooldown transients are considered in the evaluation.

Actual RCS Cold Leg Temperature	Maximum Cooldown Rate
200 ^{o}F < $T_C \leq$ 560 ^{o}F	100 ^{o}F/hr (ramp) or 50 ^{o}F in any half hour period (step)
120 ^{o}F $\leq T_C \leq$ 200 ^{o}F	60 ^{o}F/hr (ramp) or 30 ^{o}F in any half hour period (step)
50 ^{o}F $\leq T_C$ < 120 ^{o}F	25 ^{o}F/hr (ramp) or 12.5 ^{o}F in any half hour period (step)

A step change is also included in the ramped and step cooldown transients to simulate the temperature change that occurs at the initiation of shutdown cooling when the last reactor coolant pump is secured.

Cooldown Transient Set 1

For the case when acid reducing is not performed during shutdown cooling, a 50 °F step is modeled at 200 °F, followed by a 30 minute hold period. The ramped and stepped cooldown transients, for this normal shutdown condition, are depicted in Figures 5-2 and 5-3, respectively.

Cooldown Transient Set 2

During an acid reducing shutdown, a 30 °F step is modeled at 120 °F, followed by a 30 minute hold period, as illustrated in Figures 5-4 and 5-5 for ramped and stepped cooldown transients, respectively.

The ISLH cooldown test condition is assessed for the RCS temperature decreasing from 560 °F to 50 °F at a ramp rate of 10 °F/hr. Steady state limits are also calculated at 5 °F intervals during heatup and cooldown, thereby providing results for "soak periods" where there is no change in the temperature of the reactor coolant (0 °F/hr rate).

Since overpressure events most likely occur during isothermal conditions in the RCS, the steady state Appendix G limit was used in developing the LTOP P/T limits. This is consistent with the Westinghouse standard methodology (WCAP-14040-NP-A) that endorses the use of steady-state Appendix G limit as the LTOP design limit. This methodology has been previously reviewed and approved by the USNRC staff. Per Code Case N-640 [11], the maximum allowable pressure in the RV is limited to 100% of the Appendix G P-T limit, which in this case is the steady state Appendix G limit.

Table 5-1

Design Data

Vessel geometry:	Beltline inner radius	= 79.719 in.
	Beltline outer radius	= 87.594 in.
	Beltline wall thickness	= 7.875 in.
	Nozzle belt inner radius	= 79.125 in.
	Nozzle belt outer radius	= 89.625 in.
	Nozzle belt wall thickness	= 10.500 in.
	Cladding thickness	= 0.2188 in.
	Core barrel outer radius	= 70.500 in.
	Nozzle radius of outlet nozzle per WRCB 175	= 24.675 in.
	Nozzle radius of inlet nozzle per WRCB 175	= 18.248 in.

Postulated flaws: 1/4T x 3/2T semi-elliptical longitudinal surface flaw in vessel beltline
one-inch inside corner flaw in nozzle

Closure head limits: When core not critical, 622 psig (uncorrected) up to 150 °F (RT_{NDT} + 120 °F)

Upper shelf fracture toughness:

200 ksi√in for vessel plate material and nozzle forging material

Safety factors on pressure:

2.0 for normal heatup and cooldown conditions

1.5 for ISLH heatup and cooldown conditions

Adjustments for sensor location and instrument error:

Beltline & Inlet nozzle:	Pressure = 47.0 psig (< 200 °F), 85.1 psig (≥ 200 °F)	
Outlet nozzle:	Pressure = 32.7 psig	
Closure head:	Pressure = 29.1 psig	
	Temperature = 0 °F	

Convection film coefficients:

520 Btu/hr-ft²-°F at clad-base metal interface

0 Btu/hr-ft²-°F at the outside surface (perfectly insulated)

Table 5-2

Material Properties[1]

Temp.	Elastic Modulus	Thermal Expansion	Thermal Conductivity	Specific Heat	Density	Poisson's Ratio
(°F)	(10^6 psi)	(10^{-6} in/in/°F)	Btu/hr-ft-°F)	(Btu/lb-°F)	(lb/ft^3)	
50	29.28	6.99	22.1	0.105	491.2	0.3
70	29.20	7.02	22.3	0.106	490.9	0.3
100	29.04	7.06	22.6	0.108	490.5	0.3
150	28.77	7.16	23.1	0.111	489.9	0.3
200	28.50	7.25	23.4	0.114	489.2	0.3
250	28.25	7.34	23.7	0.117	488.6	0.3
300	28.00	7.43	23.8	0.120	487.9	0.3
350	27.70	7.50	23.8	0.122	487.3	0.3
400	27.40	7.58	23.8	0.126	486.7	0.3
450	27.20	7.63	23.7	0.129	486.0	0.3
500	27.00	7.70	23.5	0.132	485.4	0.3
550	26.70	7.77	23.2	0.135	484.7	0.3
600	26.40	7.83	23.0	0.139	484.1	0.3
650	25.85	7.90	22.7	0.142	483.4	0.3
700	25.30	7.94	22.3	0.145	482.8	0.3

(1) Based on the 1995 Edition with Addenda through 1996 of the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices using the limiting beltline shell material, SA533, Grade B, Class 1.

Table 5-3

Limiting RT_{NDT}'s for Reactor Vessel Materials at 32 EFPY

Component	Adjusted RT_{NDT} (^{o}F)	
	at 1/4T	at 3/4T
Beltline Region, Lower Shell Plate (C-8010-1)	112.7[1]	98.8[1]
Inlet Nozzle	30.0[2]	--
Outlet Nozzle	0.0[2]	--
Closure Flange Region	30.0	30.0

(1) the P/T limit analysis conservatively used the 1/4T and 3/4T RT_{NDT} values of 113 ^{o}F and 99 ^{o}F, respectively.

(2) applicable at the one-inch flaw depth

Figure 5-1. ANO-2 Ramp Heatup Temperature Transients

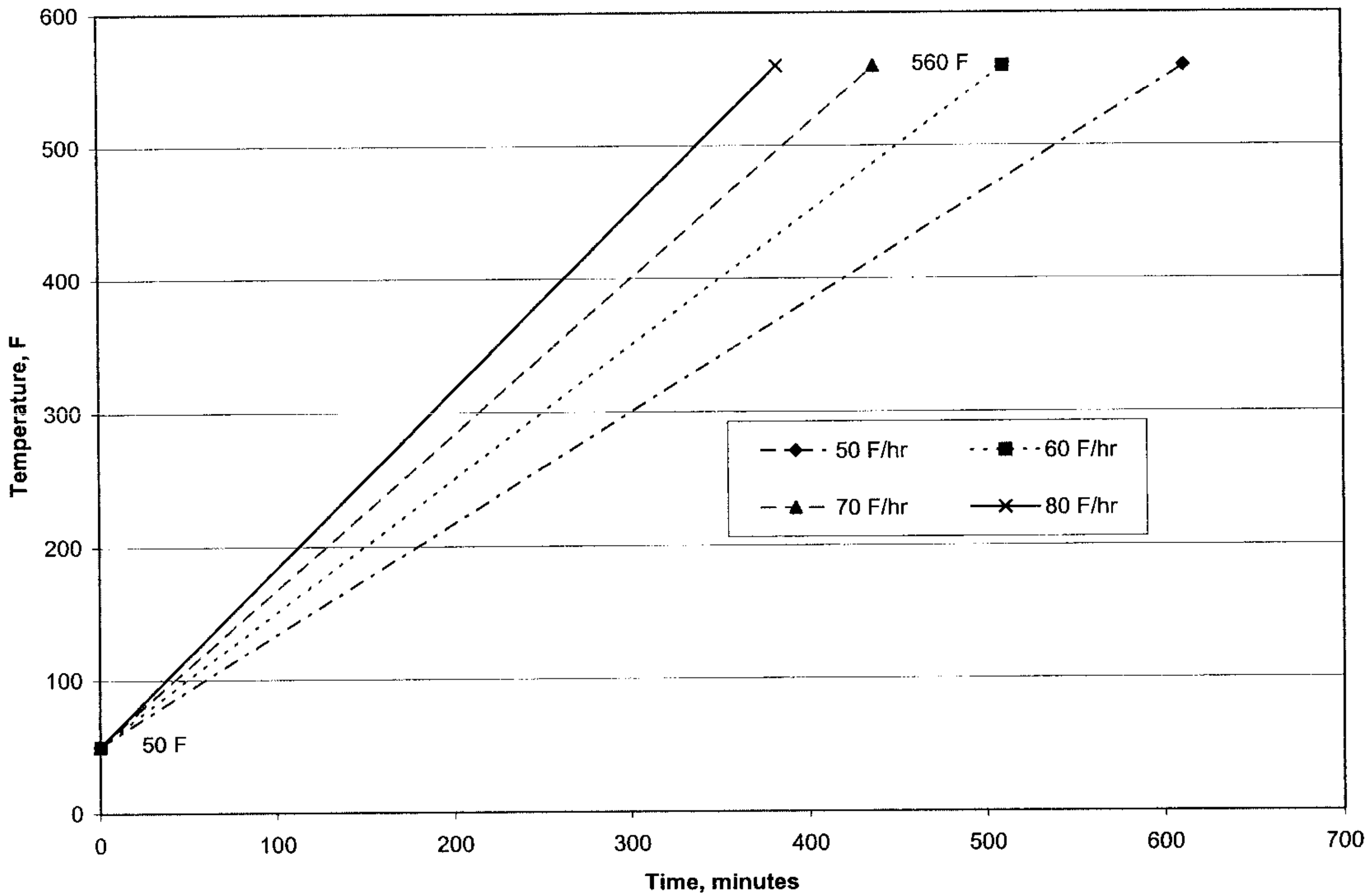


Figure 5-2. ANO-2 Ramp Cooldown Temperature Transient - Set 1 (normal shutdown)

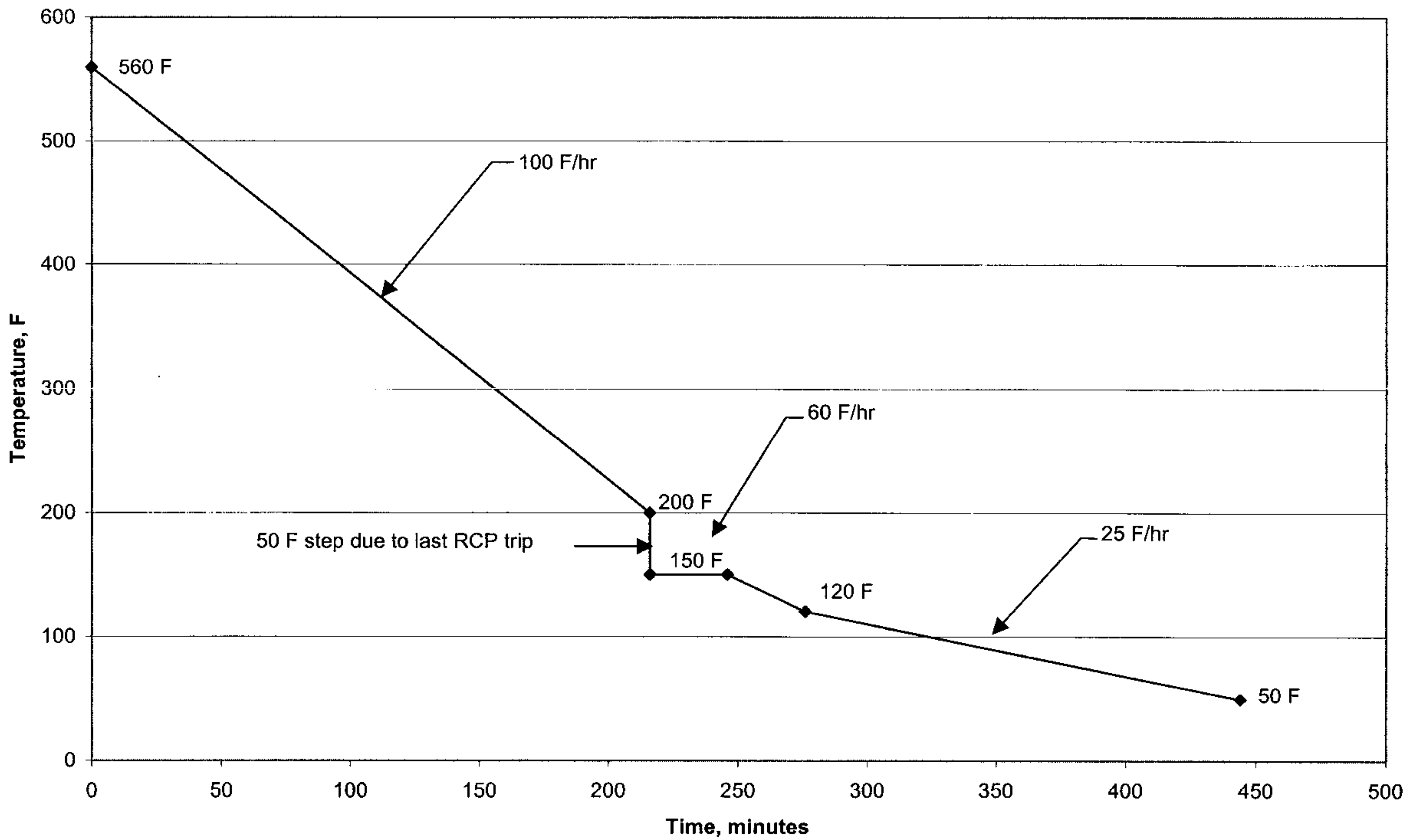


Figure 5-3. ANO-2 Step Cooldown Temperaure Transient - Set 1 (normal shutdown)

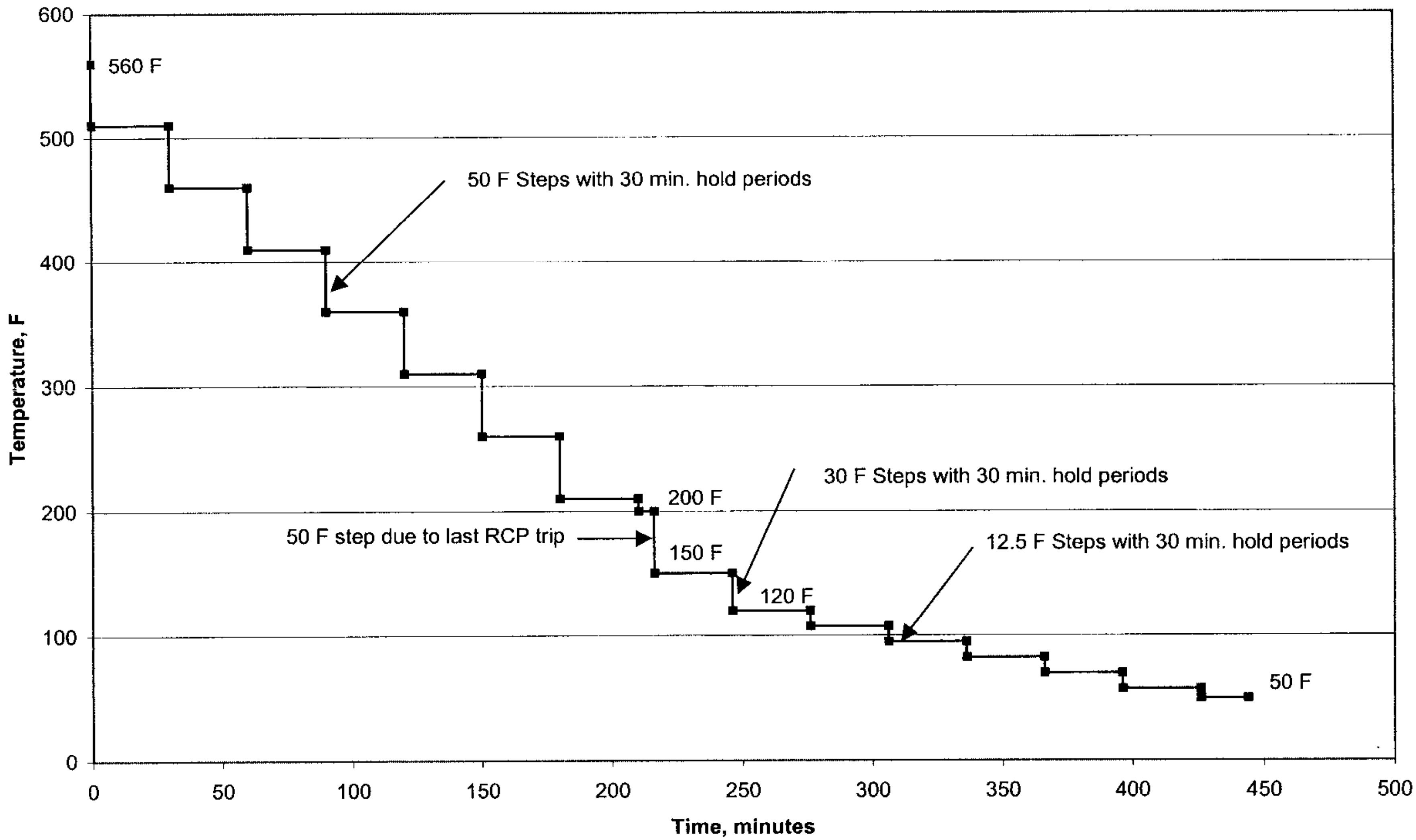


Figure 5-4. ANO-2 Ramp Cooldown Temperature Transient - Set 2 (acid reduction shutdown)

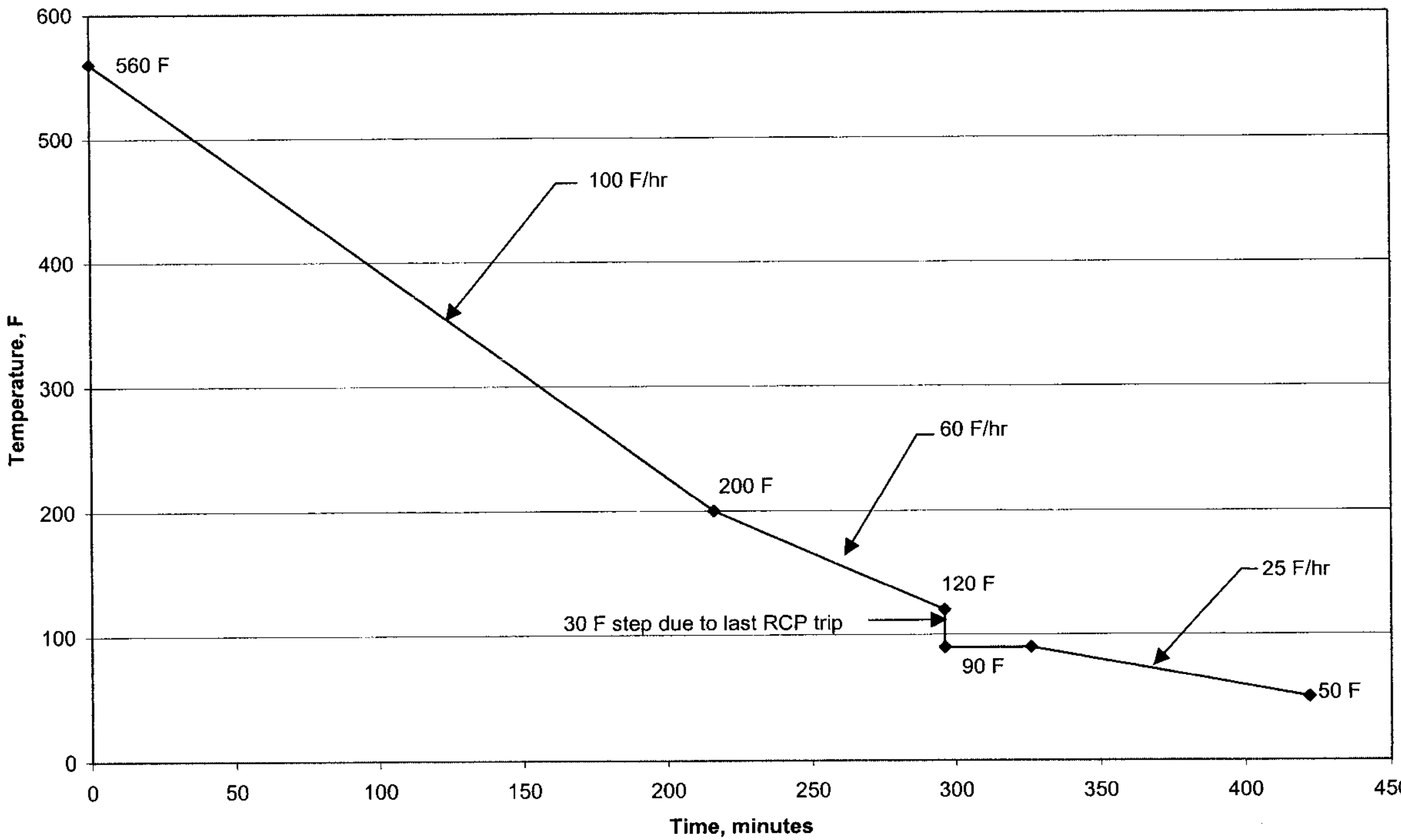
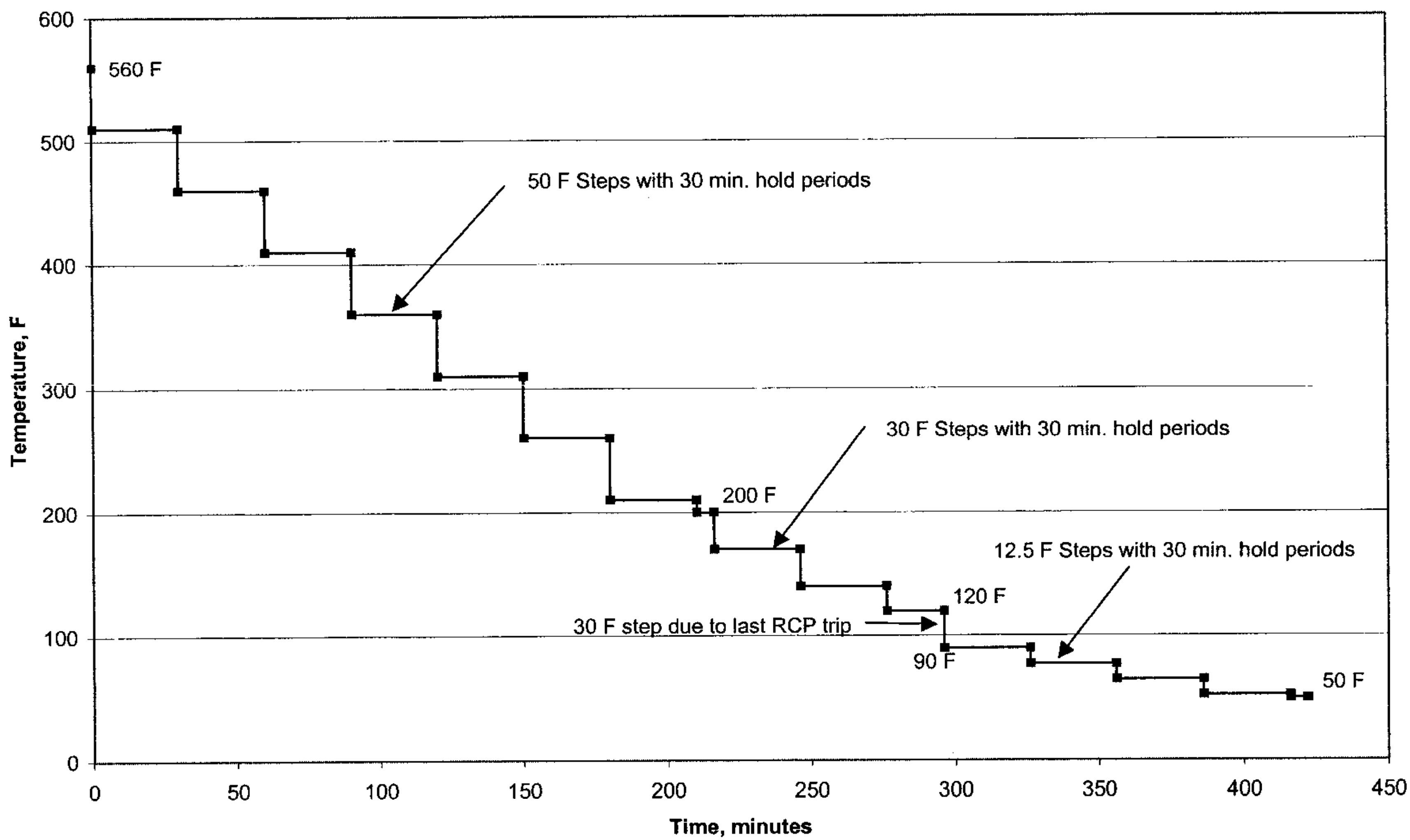


Figure 5-5. ANO-2 Step Cooldown Temperature Transient - Set 2 (acid reduction shutdown)



6. TECHNICAL BASIS FOR PRESSURE/TEMPERATURE LIMITS

Pressure/temperature limits for the ANO-2 reactor vessel are calculated to satisfy the requirements of 10 CFR Part 50, Appendix G using analytical methods and acceptance criteria of the ASME Boiler and Pressure Vessel Code, Section XI, Appendix G [4] and ASME Code Case N-640[11] for use of the K_{Ic} fracture toughness curve and ASME Code Case N-588[12] for influence coefficient solution for K_{It} and explicit method for calculating membrane correction factor (M_m). The methods and criteria employed to establish operating pressure and temperature limits are described below. The objective of these limits is to prevent nonductile failure during normal operating conditions, including anticipated operational occurrences and system hydrostatic pressure and leak tests.

Of all the components of the RCPB that are subject to the requirements of 10 CFR 50, Appendix G, the only regions that regulate the pressure/temperature limits are the closure head flange, inlet and outlet nozzle, and beltline regions of the reactor vessel. The closure head region can be significantly stressed at relatively low temperatures due to mechanical loads resulting from bolt preload and pressure. High stresses, of the order of two to three times the shell membrane stress, can also occur at the inside corners of the reactor vessel nozzles due to local stress concentrations. Typically, the closure head and nozzle regions influence the pressure-temperature limits only during the first several service periods, prior to significant neutron embrittlement of the reactor vessel beltline materials. After several years of exposure to neutron irradiation, the increase in the RT_{NDT} of the beltline region materials is such that the RCPB pressure/temperature limits are usually controlled by the beltline region of the reactor vessel. The pressure/temperature limits contained in this report are established by determining the minimum allowable pressure, as a function of fluid temperature, considering the closure head, the inlet and outlet nozzles, and the beltline regions of the reactor vessel.

The analytical procedures used to calculate P/T limits are based on linear elastic fracture mechanics methods for calculating stress intensity factors at the maximum depths of postulated semi-elliptical surface flaws.

The basic equation for allowable pressure is:

$$P_{allow} = \frac{K_{IR} - K_{IT}}{SF \times \hat{K}_{IP}}$$

where, P_{allow} = allowable pressure

K_{IR} = reference stress intensity factor (K_{Ia} or K_{Ic})

K_{IT} = thermal stress intensity factor

$\hat{K}_{IP}$ = unit pressure stress intensity factor (due to 1 psig)

SF = safety factor

For each analyzed transient and steady state condition, the allowable pressure is determined as a function of reactor coolant temperature considering postulated flaws in the reactor vessel beltline, inlet nozzle, outlet nozzle, and closure head. In the beltline region, flaws are presumed to be present at the 1/4t and 3/4t locations of the controlling material (shell plate or weld), as defined by the fluence adjusted RT_{NDT}. The nozzle flaw is located at the inside juncture (corner) of the nozzle. The closure head flange limit is not explicitly calculated. However, for the condition when the core is not critical, the uncorrected closure flange allowable pressure of 622 psig (20% of preservice hydrostatic test pressure of 3110 psig) is maintained as the limit for temperatures up to 150 ^{0}F (30 ^{0}F RT_{NDT} + 120 ^{0}F margin) per Table 1, item 2.b of 10 CFR50, Appendix G [2]. Above, 150 ^{0}F, the closure flange allowable pressure is 2500 psig. P-T limits for the beltline and nozzle regions are calculated using a factor of safety of 2 for normal operation and 1.5 for ISLH operation. These location specific P-T limits are calculated using the FRA-ANP proprietary computer code PTPC[8]. The maximum allowable pressure at a particular fluid temperature is taken as the minimum value of allowable pressure calculated for each flaw location and operating condition, including steady state. A P/T limit curve is then constructed as the collection of points that define the maximum allowable pressures as a function of fluid temperature for a particular mode of reactor operation. The P-T curves provided in this report are adjusted for sensor location but does not include instrument error. They are, "refined" as necessary to eliminate regions of negative slope by lowering the allowable pressure for temperatures less than that corresponding to the minimum pressure.

The criticality limit temperature is obtained by satisfying the requirement of Item 2.d in Table 1 of 10 CFR 50, Appendix G [2]. It requires the minimum temperature to be the larger of minimum permissible temperature for inservice system hydrostatic pressure test (taken as the leak test

temperature corresponding to the ISLH limit pressure of 2500 psig with heatup and cooldown rates up to 10 °F/hr) or the RT_{NDT} of the closure flange material + 160 °F.

Various aspects of the calculational procedures utilized in the development of P/T limits are discussed below.

6.1 Fracture Toughness

The fracture toughness of reactor vessel steels is expressed as a function of crack-tip temperature, T, indexed to the adjusted reference temperature of the material, RT_{NDT}. Pressure/temperature limits developed in accordance to ASME Code, Section XI, Appendix G utilize the expression for crack arrest fracture toughness,

$$K_{Ia} = 26.8 + 1.233 \exp [0.0145 (T - RT_{NDT} + 160\ ^{\circ}F)]$$

Exemptions to 10 CFR 50, Appendix G, that cite ASME Code Case N-640 (utilized in the generation of the P-T limits contained in this report), utilize the crack initiation fracture toughness,

$$K_{Ic} = 33.2 + 2.806 \exp [0.02 (T - RT_{NDT} + 100\ ^{\circ}F)]$$

The upper shelf fracture toughness is limited to an upper bound value of 200 ksi √in. The crack-tip temperature needed for these fracture toughness equations is obtained from the results of a transient thermal analysis, described below.

6.2 Thermal Analysis and Thermal Stress Intensity Factor

Through-wall temperature distributions are determined by solving the one-dimensional transient axisymmetric heat conduction equation,

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right),$$

subject to the following boundary conditions:

at the inside surface, where $r = R_i$,

$$-k \frac{\partial T}{\partial r} = h(T_w - T_b)$$

at the outside surface, where $r = R_o$,

$$\frac{\partial T}{\partial r} = 0$$

where,

ρ = density

C_p = specific heat

k = thermal conductivity

T = temperature

r = radial coordinate

t = time

h = convection heat transfer coefficient

T_w = wall temperature

T_b = bulk coolant temperature

R_i = inside radius of vessel

R_o = outside radius of vessel

The above equation is solved numerically using a finite difference technique to determine the temperature at 17 points through the wall as a function of time for prescribed changes in the bulk fluid temperature, such as multi-rate ramp and step changes for heatup and cooldown transients.

An equivalent linear thermal bending stresses (based on ΔT through the wall) is derived from the through-wall temperature distribution at each solution time point. Through-wall thermal stress distributions are determined by trapezoidal integration of the following expression:

Thermal hoop stresses:

$$\sigma_\theta(r) = \frac{E\alpha}{1-\nu}\frac{1}{r^2}\left(\frac{r^2+R_i^2}{R_o^2-R_i^2}\int_{R_i}^{R_o} T\,r\,dr + \int_{R_i}^{r} T\,r\,dr - T\,r^2\right) \qquad \text{[9, Eqn (255)]}$$

Expressing the thermal stress distributions by

$$\sigma(x) = C_0 + C_1\,(x/a) + C_2\,(x/a)^2 + C_3\,(x/a)^3\,,$$

where,

x = is a dummy variable that represents the radial distance

from the appropriate (i.e., inside or outside) surface, in.

a = the flaw depth, in.,

the thermal stress intensity factors are defined by the following relationships:

For a 1/4-thickness inside surface flaw during cooldown,

$$K_{It} = (1.0359\ C_0 + 0.6322\ C_1 + 0.4753\ C_2 + 0.3855\ C_3)\sqrt{\pi a}$$

For a 1/4-thickness outside surface flaw during heatup,

$$K_{It} = (1.043\ C_0 + 0.630\ C_1 + 0.481\ C_2 + 0.401\ C_3)\sqrt{\pi a}$$

6.3 Unit Pressure Stress Intensity Factor for Reactor Vessel Beltline Region

The membrane stress intensity factor in the reactor vessel shell due to a unit pressure load is

$$K_{Im} = M_m \times R_i / t$$

where

R_i = vessel inner radius, in.

t = vessel wall thickness, in.

For a longitudinal 1/4-thickness x 3/2-thickness semi-elliptical surface flaw:

at the inside surface,

$$M_m = 1.85 \text{ for } \sqrt{t} < 2$$
$$= 0.926\sqrt{t} \text{ for } 2 \le \sqrt{t} \le 3.464$$
$$= 3.21 \text{ for } \sqrt{t} > 3.464$$

at the outside surface,

$$M_m = 1.77 \text{ for } \sqrt{t} < 2$$
$$= 0.893\sqrt{t} \text{ for } 2 \le \sqrt{t} \le 3.464$$
$$= 3.09 \text{ for } \sqrt{t} > 3.464$$

6.4 Unit Pressure Stress Intensity Factor for Reactor Vessel Nozzles

Considering a nozzle as a hole in a shell, WRC Bulletin 175[10] presents the following method for estimating stress intensity factors for a nozzle corner flaw:

$$K_{Im} = \sigma\sqrt{\pi a}\ F(a/r_n)$$

where

$$\sigma = R_i / t$$

R_i = nozzle belt shell inner radius, in.

t = nozzle belt shell wall thickness, in.

a = flaw depth, in.

r_n = apparent radius of nozzle, in.

$= r_i + 0.29 r_c$

r_i = inner radius of nozzle, in.

r_c = nozzle corner radius, in.

and

$$F(a/r_n) = 2.5 - 6.108(a/r_n) + 12(a/r_n)^2 - 9.1664(a/r_n)^3$$

7. OPERATIONAL PRESSURE/TEMPERATURE LIMITS

Results of the thermal and fracture mechanics analyses[13] performed for the ANO-2 reactor vessel are presented in the form of P/T curves for (three) operating conditions; normal heatup, normal cooldown, and ISLH operations. These P/T curves are location adjusted to account for the differences between the controlling pressure location and the point of system pressure measurement in the pressurizer. They do not account for instrument error.

Pressure-temperature limits (in units of psig) for normal heatup (including criticality core limits) at 32 EFPY are presented in Table 7-1 and illustrated in Figure 7-1. The criticality limit temperature is 190 °F. It is based on the RT_{NDT} of the closure flange material (30 °F) plus 160 °F which is larger than the 175 °F value that corresponds to the ISLH limit pressure of 2500 psig per Table 7-3. Considering all the ramp and step cooldown transient scenarios shown in Figures 5-2 through 5-5, composite cooldown P/T limits are determined as reported in Table 7-2 and depicted by Figure 7-2. The ISLH P/T limits are given in Table 7-3 and illustrated in Figure 7-3. The steady state P/T limits are provided in Table 7-4. Protection against nonductile failure is ensured by using these curves to limit the reactor coolant pressure. Acceptable pressure and temperature combinations for reactor operation are below and to the right of the pressure-temperature limit curves.

Additionally, to better facilitate use by plant operations, the P/T limits are provided in units of psia. The P/T limits for normal heatup, normal cooldown, ISLH and steady state conditions are provided in Tables 7-5 though 7-8, respectively. The P/T limits for normal heatup, normal cooldown and ISLH conditions are also depicted in Figures 7-4 through 7-6, respectively.

Table 7-1. ANO-2 Summary of Ramp Heatup P/T Limits & Critical Core Limits (psig)

Fluid Temp.	Ramp Heatup 50 F/hr	Ramp Heatup 60 F/hr	Ramp Heatup 70 F/hr	Ramp Heatup 80 F/hr	Critical Core
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
50	593	593	593	593	
55	593	593	593	593	
60	593	593	593	593	
65	593	593	593	593	
70	593	593	593	593	
75	593	593	593	593	
80	593	593	593	593	
85	593	593	593	593	
90	593	593	593	593	
95	593	593	593	593	
100	593	593	593	593	
105	593	593	593	593	
110	593	593	593	593	
115	593	593	593	593	
120	593	593	593	593	
125	593	593	593	593	
130	593	593	593	593	
135	593	593	593	593	
140	593	593	593	593	
145	593	593	593	593	
150	593	593	593	593	
150	1148	1066	995	934	
155	1215	1125	1047	980	
160	1289	1191	1105	1031	
165	1371	1263	1170	1088	
170	1462	1344	1241	1152	
175	1562	1433	1320	1222	
180	1673	1532	1408	1300	
185	1795	1641	1505	1386	
190	1931	1762	1613	1482	0
190	1931	1762	1613	1482	934
195	2081	1895	1732	1588	980
200	2204	2005	1825	1667	1031
205	2378	2168	1970	1797	1088
210	2569	2348	2131	1940	1152
215	2781	2546	2308	2098	1222
220	3015	2766	2504	2273	1300
225	3263	3008	2720	2466	1386
230	3263	3263	2959	2679	1482
235	3263	3263	3223	2915	1588
240	3263	3263	3263	3175	1667
245	3263	3263	3263	3263	1797

Table 7-1. ANO-2 Summary of Ramp Heatup P/T Limits & Critical Core Limits (Cont'd)

Fluid Temp.	Ramp Heatup				Critical Core
	50 F/hr	**60 F/hr**	**70 F/hr**	**80 F/hr**	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
250	3263	3263	3263	3263	1940
255	3263	3263	3263	3263	2098
260	3263	3263	3263	3263	2273
265	3263	3263	3263	3263	2466
270	3263	3263	3263	3263	2679
275	3263	3263	3263	3263	2915
280	3263	3263	3263	3263	3175
285	3263	3263	3263	3263	3263
290	3263	3263	3263	3263	3263
295	3263	3263	3263	3263	3263
300	3263	3263	3263	3263	3263
305	3263	3263	3263	3263	3263
310	3263	3263	3263	3263	3263
315	3263	3263	3263	3263	3263
320	3263	3263	3263	3263	3263
325	3263	3263	3263	3263	3263
330	3263	3263	3263	3263	3263
335	3263	3263	3263	3263	3263
340	3263	3263	3263	3263	3263
345	3263	3263	3263	3263	3263
350	3263	3263	3263	3263	3263
355	3263	3263	3263	3263	3263
360	3263	3263	3263	3263	3263
365	3263	3263	3263	3263	3263
370	3263	3263	3263	3263	3263
375	3263	3263	3263	3263	3263
380	3263	3263	3263	3263	3263
385	3263	3263	3263	3263	3263
390	3263	3263	3263	3263	3263
395	3263	3263	3263	3263	3263
400	3263	3263	3263	3263	3263
405	3263	3263	3263	3263	3263
410	3263	3263	3263	3263	3263
415	3263	3263	3263	3263	3263
420	3263	3263	3263	3263	3263
425	3263	3263	3263	3263	3263
430	3263	3263	3263	3263	3263
435	3263	3263	3263	3263	3263
440	3263	3263	3263	3263	3263
445	3263	3263	3263	3263	3263
450	3263	3263	3263	3263	3263
455	3263	3263	3263	3263	3263
460	3263	3263	3263	3263	3263
465	3263	3263	3263	3263	3263

Table 7-1. ANO-2 Summary of Ramp Heatup P/T Limits & Critical Core Limits (Cont'd)

Fluid Temp.	Ramp Heatup				Critical Core
	50 F/hr	**60 F/hr**	**70 F/hr**	**80 F/hr**	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
470	3263	3263	3263	3263	3263
475	3263	3263	3263	3263	3263
480	3263	3263	3263	3263	3263
485	3263	3263	3263	3263	3263
490	3263	3263	3263	3263	3263
495	3263	3263	3263	3263	3263
500	3263	3263	3263	3263	3263
505	3263	3263	3263	3263	3263
510	3263	3263	3263	3263	3263
515	3263	3263	3263	3263	3263
520	3263	3263	3263	3263	3263
525	3263	3263	3263	3263	3263
530	3263	3263	3263	3263	3263
535	3263	3263	3263	3263	3263
540	3263	3263	3263	3263	3263
545	3263	3263	3263	3263	3263
550	3263	3263	3263	3263	3263
555	3263	3263	3263	3263	3263
560	3263	3263	3263	3263	3263

Table 7-2. ANO-2 Cooldown Composite P/T Limits (psig)

Fluid Temp. (F)	Composite Cooldown Limit (psig)	Fluid Temp. (F)	Composite Cooldown Limit (psig)	Fluid Temp. (F)	Composite Cooldown Limit (psig)
50	593	265	2699	485	2952
55	593	270	2700	490	2969
60	593	275	2700	495	2986
65	593	280	2701	500	3004
70	593	285	2702	505	3023
75	593	290	2703	510	3043
80	593	295	2704	515	3064
85	593	300	2706	520	3086
90	593	305	2707	525	3108
95	593	310	2709	530	3132
100	593	315	2710	535	3156
105	593	320	2712	540	3181
110	593	325	2716	545	3206
115	593	330	2718	550	3231
120	593	335	2720	555	3252
125	593	340	2723	560	3263
130	593	345	2726		
135	593	350	2729		
140	593	355	2732		
145	593	360	2736		
150	593	365	2739		
150	1410	370	2743		
155	1497	375	2747		
160	1593	380	2750		
165	1699	385	2755		
170	1816	390	2761		
175	1946	395	2767		
180	2089	400	2773		
185	2247	405	2779		
190	2422	410	2786		
195	2700	415	2794		
200	2700	420	2801		
205	2700	425	2810		
210	2700	430	2818		
215	2700	435	2828		
220	2699	440	2837		
225	2700	445	2847		
230	2699	450	2858		
235	2699	455	2870		
240	2699	460	2882		
245	2699	465	2894		
250	2699	470	2908		
255	2699	475	2922		
260	2699	480	2937		

Table 7-3. ANO-2 ISLH P/T Limits (psig)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
50	943	1935	1408	593	593
55	953	2029	1461	593	593
60	967	2152	1531	593	593
65	984	2295	1612	593	593
70	1004	2457	1704	593	593
75	1026	2638	1807	593	593
80	1050	2840	1921	593	593
85	1077	3063	2048	593	593
90	1107	3311	2188	593	593
95	1140	3586	2344	593	593
100	1176	3889	2515	593	593
105	1216	4224	2705	593	593
110	1261	4362	2916	593	593
115	1310	4362	3148	593	593
120	1364	4362	3405	593	593
125	1424	4362	3688	593	593
130	1490	4362	4002	593	593
135	1563	4362	4348	593	593
140	1643	4362	4491	593	593
145	1733	4362	4491	593	593
150	1831	4362	4491	593	593
150	1831	4362	4491	2500	1831
155	1940	4362	4491		1940
160	2061	4362	4491		2061
165	2194	4362	4491		2194
170	2341	4362	4491		2341
175	2503	4362	4491		**2503**
180	2683	4362	4491		2683
185	2881	4362	4491		2881
190	3100	4362	4491		3100
195	3342	4362	4491		3342
200	3572	4362	4453		3572
205	3868	4362	4453		3868
210	4196	4362	4453		4196
215	4557	4362	4453		4362
220	4957	4362	4453		4362
225	4984	4362	4453		4362
230	4984	4362	4453		4362
235	4984	4362	4453		4362
240	4984	4362	4453		4362
245	4984	4362	4453		4362
250	4984	4362	4453		4362
255	4984	4362	4453		4362

Table 7-3. ANO-2 ISLH P/T Limits (Cont'd.)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
260	4984	4362	4453		4362
265	4984	4362	4453		4362
270	4984	4362	4453		4362
275	4984	4362	4453		4362
280	4984	4362	4453		4362
285	4984	4362	4453		4362
290	4984	4362	4453		4362
295	4984	4362	4453		4362
300	4984	4362	4453		4362
305	4984	4362	4453		4362
310	4984	4362	4453		4362
315	4984	4362	4453		4362
320	4984	4362	4453		4362
325	4984	4362	4453		4362
330	4984	4362	4453		4362
335	4984	4362	4453		4362
340	4984	4362	4453		4362
345	4984	4362	4453		4362
350	4984	4362	4453		4362
355	4984	4362	4453		4362
360	4984	4362	4453		4362
365	4984	4362	4453		4362
370	4984	4362	4453		4362
375	4984	4362	4453		4362
380	4984	4362	4453		4362
385	4984	4362	4453		4362
390	4984	4362	4453		4362
395	4984	4362	4453		4362
400	4984	4362	4453		4362
405	4984	4362	4453		4362
410	4984	4362	4453		4362
415	4984	4362	4453		4362
420	4984	4362	4453		4362
425	4984	4362	4453		4362
430	4984	4362	4453		4362
435	4984	4362	4453		4362
440	4984	4362	4453		4362
445	4984	4362	4453		4362
450	4984	4362	4453		4362
455	4984	4362	4453		4362
460	4984	4362	4453		4362
465	4984	4362	4453		4362
470	4984	4362	4453		4362
475	4984	4362	4453		4362
480	4984	4362	4453		4362

Table 7-3. ANO-2 ISLH P/T Limits (Cont'd.)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
485	4984	4362	4453		4362
490	4984	4362	4453		4362
495	4984	4362	4453		4362
500	4984	4362	4453		4362
505	4984	4362	4453		4362
510	4984	4362	4453		4362
515	4984	4362	4453		4362
520	4984	4362	4453		4362
525	4984	4362	4453		4362
530	4984	4362	4453		4362
535	4984	4362	4453		4362
540	4984	4362	4453		4362
545	4984	4362	4453		4362
550	4984	4362	4453		4362
555	4984	4362	4453		4362
560	4984	4362	4453		4362

Table 7-4. ANO-2 Steady-State "Isothermal Condition" P/T Limits (psig)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
50	696	1444	1045	593	593
55	708	1541	1100	593	593
60	721	1649	1161	593	593
65	735	1768	1228	593	593
70	751	1900	1303	593	593
75	768	2045	1386	593	593
80	788	2206	1477	593	593
85	809	2384	1578	593	593
90	833	2581	1689	593	593
95	859	2799	1813	593	593
100	888	3039	1949	593	593
105	920	3263	2099	593	593
110	955	3263	2266	593	593
115	994	3263	2449	593	593
120	1037	3263	2652	593	593
125	1085	3263	2877	593	593
130	1138	3263	3125	593	593
135	1196	3263	3356	593	593
140	1260	3263	3356	593	593
145	1331	3263	3356	593	593
150	1410	3263	3356	593	593
150	1410	3263	3356	2500	1410
155	1497	3263	3356		1497
160	1593	3263	3356		1593
165	1699	3263	3356		1699
170	1816	3263	3356		1816
175	1946	3263	3356		1946
180	2089	3263	3356		2089
185	2247	3263	3356		2247
190	2422	3263	3356		2422
195	2616	3263	3356		2616
200	2791	3263	3318		2791
205	3027	3263	3318		3027
210	3288	3263	3318		3263
215	3577	3263	3318		3263
220	3716	3263	3318		3263
225	3716	3263	3318		3263
230	3716	3263	3318		3263
235	3716	3263	3318		3263
240	3716	3263	3318		3263
245	3716	3263	3318		3263
250	3716	3263	3318		3263
255	3716	3263	3318		3263

Table 7-4. ANO-2 Steady-State "Isothermal Condition" P/T Limits (Cont'd)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
260	3716	3263	3318		3263
265	3716	3263	3318		3263
270	3716	3263	3318		3263
275	3716	3263	3318		3263
280	3716	3263	3318		3263
285	3716	3263	3318		3263
290	3716	3263	3318		3263
295	3716	3263	3318		3263
300	3716	3263	3318		3263
305	3716	3263	3318		3263
310	3716	3263	3318		3263
315	3716	3263	3318		3263
320	3716	3263	3318		3263
325	3716	3263	3318		3263
330	3716	3263	3318		3263
335	3716	3263	3318		3263
340	3716	3263	3318		3263
345	3716	3263	3318		3263
350	3716	3263	3318		3263
355	3716	3263	3318		3263
360	3716	3263	3318		3263
365	3716	3263	3318		3263
370	3716	3263	3318		3263
375	3716	3263	3318		3263
380	3716	3263	3318		3263
385	3716	3263	3318		3263
390	3716	3263	3318		3263
395	3716	3263	3318		3263
400	3716	3263	3318		3263
405	3716	3263	3318		3263
410	3716	3263	3318		3263
415	3716	3263	3318		3263
420	3716	3263	3318		3263
425	3716	3263	3318		3263
430	3716	3263	3318		3263
435	3716	3263	3318		3263
440	3716	3263	3318		3263
445	3716	3263	3318		3263
450	3716	3263	3318		3263
455	3716	3263	3318		3263
460	3716	3263	3318		3263
465	3716	3263	3318		3263
470	3716	3263	3318		3263
475	3716	3263	3318		3263
480	3716	3263	3318		3263

Table 7-4. ANO-2 Steady-State "Isothermal Condition" P/T Limits (Cont'd)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psig)	(psig)	(psig)	(psig)	(psig)
485	3716	3263	3318		3263
490	3716	3263	3318		3263
495	3716	3263	3318		3263
500	3716	3263	3318		3263
505	3716	3263	3318		3263
510	3716	3263	3318		3263
515	3716	3263	3318		3263
520	3716	3263	3318		3263
525	3716	3263	3318		3263
530	3716	3263	3318		3263
535	3716	3263	3318		3263
540	3716	3263	3318		3263
545	3716	3263	3318		3263
550	3716	3263	3318		3263
555	3716	3263	3318		3263
560	3716	3263	3318		3263

Table 7-5. ANO-2 Summary of Ramp Heatup P/T Limits & Critical Core Limits (psia)

Fluid Temp.	Ramp Heatup 50 F/hr	60 F/hr	70 F/hr	80 F/hr	Critical Core
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
50	608	608	608	608	
55	608	608	608	608	
60	608	608	608	608	
65	608	608	608	608	
70	608	608	608	608	
75	608	608	608	608	
80	608	608	608	608	
85	608	608	608	608	
90	608	608	608	608	
95	608	608	608	608	
100	608	608	608	608	
105	608	608	608	608	
110	608	608	608	608	
115	608	608	608	608	
120	608	608	608	608	
125	608	608	608	608	
130	608	608	608	608	
135	608	608	608	608	
140	608	608	608	608	
145	608	608	608	608	
150	608	608	608	608	
150	1163	1081	1010	949	
155	1230	1140	1062	995	
160	1304	1206	1120	1046	
165	1386	1278	1185	1103	
170	1477	1359	1256	1167	
175	1577	1448	1335	1237	
180	1688	1547	1423	1315	
185	1810	1656	1520	1401	
190	1946	1777	1628	1497	15
190	1946	1777	1628	1497	949
195	2096	1910	1747	1603	995
200	2219	2020	1840	1682	1046
205	2393	2183	1985	1812	1103
210	2584	2363	2146	1955	1167
215	2796	2561	2323	2113	1237
220	3030	2781	2519	2288	1315
225	3278	3023	2735	2481	1401
230	3278	3278	2974	2694	1497
235	3278	3278	3238	2930	1603
240	3278	3278	3278	3190	1682
245	3278	3278	3278	3278	1812

Table 7-5. ANO-2 Summary of Ramp Heatup P/T Limits & Critical Core Limits (Cont'd.)

Fluid Temp.	Ramp Heatup				Critical Core
	50 F/hr	**60 F/hr**	**70 F/hr**	**80 F/hr**	
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
250	3278	3278	3278	3278	1955
255	3278	3278	3278	3278	2113
260	3278	3278	3278	3278	2288
265	3278	3278	3278	3278	2481
270	3278	3278	3278	3278	2694
275	3278	3278	3278	3278	2930
280	3278	3278	3278	3278	3190
285	3278	3278	3278	3278	3278
290	3278	3278	3278	3278	3278
295	3278	3278	3278	3278	3278
300	3278	3278	3278	3278	3278
305	3278	3278	3278	3278	3278
310	3278	3278	3278	3278	3278
315	3278	3278	3278	3278	3278
320	3278	3278	3278	3278	3278
325	3278	3278	3278	3278	3278
330	3278	3278	3278	3278	3278
335	3278	3278	3278	3278	3278
340	3278	3278	3278	3278	3278
345	3278	3278	3278	3278	3278
350	3278	3278	3278	3278	3278
355	3278	3278	3278	3278	3278
360	3278	3278	3278	3278	3278
365	3278	3278	3278	3278	3278
370	3278	3278	3278	3278	3278
375	3278	3278	3278	3278	3278
380	3278	3278	3278	3278	3278
385	3278	3278	3278	3278	3278
390	3278	3278	3278	3278	3278
395	3278	3278	3278	3278	3278
400	3278	3278	3278	3278	3278
405	3278	3278	3278	3278	3278
410	3278	3278	3278	3278	3278
415	3278	3278	3278	3278	3278
420	3278	3278	3278	3278	3278
425	3278	3278	3278	3278	3278
430	3278	3278	3278	3278	3278
435	3278	3278	3278	3278	3278
440	3278	3278	3278	3278	3278
445	3278	3278	3278	3278	3278

Table 7-5. ANO-2 Summary of Ramp Heatup P/T Limits & Critical Core Limits (Cont'd.)

Fluid Temp.	Ramp Heatup 50 F/hr	Ramp Heatup 60 F/hr	Ramp Heatup 70 F/hr	Ramp Heatup 80 F/hr	Critical Core
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
450	3278	3278	3278	3278	3278
455	3278	3278	3278	3278	3278
460	3278	3278	3278	3278	3278
465	3278	3278	3278	3278	3278
470	3278	3278	3278	3278	3278
475	3278	3278	3278	3278	3278
480	3278	3278	3278	3278	3278
485	3278	3278	3278	3278	3278
490	3278	3278	3278	3278	3278
495	3278	3278	3278	3278	3278
500	3278	3278	3278	3278	3278
505	3278	3278	3278	3278	3278
510	3278	3278	3278	3278	3278
515	3278	3278	3278	3278	3278
520	3278	3278	3278	3278	3278
525	3278	3278	3278	3278	3278
530	3278	3278	3278	3278	3278
535	3278	3278	3278	3278	3278
540	3278	3278	3278	3278	3278
545	3278	3278	3278	3278	3278
550	3278	3278	3278	3278	3278
555	3278	3278	3278	3278	3278
560	3278	3278	3278	3278	3278

Table 7-6. ANO-2 Cooldown Composite P/T Limits (psia)

Fluid Temp.	Composite Cooldown Limit	Fluid Temp.	Composite Cooldown Limit	Fluid Temp.	Composite Cooldown Limit
(F)	(psia)	(F)	(psia)	(F)	(psia)
50	608	265	2714	485	2967
55	608	270	2715	490	2984
60	608	275	2715	495	3001
65	608	280	2716	500	3019
70	608	285	2717	505	3038
75	608	290	2718	510	3058
80	608	295	2719	515	3079
85	608	300	2721	520	3101
90	608	305	2722	525	3123
95	608	310	2724	530	3147
100	608	315	2725	535	3171
105	608	320	2727	540	3196
110	608	325	2731	545	3221
115	608	330	2733	550	3246
120	608	335	2735	555	3267
125	608	340	2738	560	3278
130	608	345	2741		
135	608	350	2744		
140	608	355	2747		
145	608	360	2751		
150	608	365	2754		
150	1425	370	2758		
155	1512	375	2762		
160	1608	380	2765		
165	1714	385	2770		
170	1831	390	2776		
175	1961	395	2782		
180	2104	400	2788		
185	2262	405	2794		
190	2437	410	2801		
195	2715	415	2809		
200	2715	420	2816		
205	2715	425	2825		
210	2715	430	2833		
215	2715	435	2843		
220	2714	440	2852		
225	2715	445	2862		
230	2714	450	2873		
235	2714	455	2885		
240	2714	460	2897		
245	2714	465	2909		
250	2714	470	2923		
255	2714	475	2937		
260	2714	480	2952		

Table 7-7. ANO-2 ISLH P/T Limits (psia)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
50	958	1950	1423	608	608
55	968	2044	1476	608	608
60	982	2167	1546	608	608
65	999	2310	1627	608	608
70	1019	2472	1719	608	608
75	1041	2653	1822	608	608
80	1065	2855	1936	608	608
85	1092	3078	2063	608	608
90	1122	3326	2203	608	608
95	1155	3601	2359	608	608
100	1191	3904	2530	608	608
105	1231	4239	2720	608	608
110	1276	4377	2931	608	608
115	1325	4377	3163	608	608
120	1379	4377	3420	608	608
125	1439	4377	3703	608	608
130	1505	4377	4017	608	608
135	1578	4377	4363	608	608
140	1658	4377	4506	608	608
145	1748	4377	4506	608	608
150	1846	4377	4506	608	608
150	1846	4377	4506	2515	1846
155	1955	4377	4506		1955
160	2076	4377	4506		2076
165	2209	4377	4506		2209
170	2356	4377	4506		2356
175	2518	4377	4506		2518
180	2698	4377	4506		2698
185	2896	4377	4506		2896
190	3115	4377	4506		3115
195	3357	4377	4506		3357
200	3587	4377	4468		3587
205	3883	4377	4468		3883
210	4211	4377	4468		4211
215	4572	4377	4468		4377
220	4972	4377	4468		4377
225	4999	4377	4468		4377
230	4999	4377	4468		4377
235	4999	4377	4468		4377
240	4999	4377	4468		4377
245	4999	4377	4468		4377

Table 7-7. ANO-2 ISLH P/T Limits (Cont'd.)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
250	4999	4377	4468		4377
255	4999	4377	4468		4377
260	4999	4377	4468		4377
265	4999	4377	4468		4377
270	4999	4377	4468		4377
275	4999	4377	4468		4377
280	4999	4377	4468		4377
285	4999	4377	4468		4377
290	4999	4377	4468		4377
295	4999	4377	4468		4377
300	4999	4377	4468		4377
305	4999	4377	4468		4377
310	4999	4377	4468		4377
315	4999	4377	4468		4377
320	4999	4377	4468		4377
325	4999	4377	4468		4377
330	4999	4377	4468		4377
335	4999	4377	4468		4377
340	4999	4377	4468		4377
345	4999	4377	4468		4377
350	4999	4377	4468		4377
355	4999	4377	4468		4377
360	4999	4377	4468		4377
365	4999	4377	4468		4377
370	4999	4377	4468		4377
375	4999	4377	4468		4377
380	4999	4377	4468		4377
385	4999	4377	4468		4377
390	4999	4377	4468		4377
395	4999	4377	4468		4377
400	4999	4377	4468		4377
405	4999	4377	4468		4377
410	4999	4377	4468		4377
415	4999	4377	4468		4377
420	4999	4377	4468		4377
425	4999	4377	4468		4377
430	4999	4377	4468		4377
435	4999	4377	4468		4377
440	4999	4377	4468		4377
445	4999	4377	4468		4377

Table 7-7. ANO-2 ISLH P/T Limits (Cont'd.)

Fluid Temp.	Allowable Pressures Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	Minimum
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
450	4999	4377	4468		4377
455	4999	4377	4468		4377
460	4999	4377	4468		4377
465	4999	4377	4468		4377
470	4999	4377	4468		4377
475	4999	4377	4468		4377
480	4999	4377	4468		4377
485	4999	4377	4468		4377
490	4999	4377	4468		4377
495	4999	4377	4468		4377
500	4999	4377	4468		4377
505	4999	4377	4468		4377
510	4999	4377	4468		4377
515	4999	4377	4468		4377
520	4999	4377	4468		4377
525	4999	4377	4468		4377
530	4999	4377	4468		4377
535	4999	4377	4468		4377
540	4999	4377	4468		4377
545	4999	4377	4468		4377
550	4999	4377	4468		4377
555	4999	4377	4468		4377
560	4999	4377	4468		4377

Table 7-8. ANO-2 Steady-State "Isothermal Condition" P/T Limits (psia)

	Allowable Pressures				
Fluid Temp.	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	Minimum
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
50	711	1459	1060	608	608
55	723	1556	1115	608	608
60	736	1664	1176	608	608
65	750	1783	1243	608	608
70	766	1915	1318	608	608
75	783	2060	1401	608	608
80	803	2221	1492	608	608
85	824	2399	1593	608	608
90	848	2596	1704	608	608
95	874	2814	1828	608	608
100	903	3054	1964	608	608
105	935	3278	2114	608	608
110	970	3278	2281	608	608
115	1009	3278	2464	608	608
120	1052	3278	2667	608	608
125	1100	3278	2892	608	608
130	1153	3278	3140	608	608
135	1211	3278	3371	608	608
140	1275	3278	3371	608	608
145	1346	3278	3371	608	608
150	1425	3278	3371	608	608
150	1425	3278	3371	2515	1425
155	1512	3278	3371		1512
160	1608	3278	3371		1608
165	1714	3278	3371		1714
170	1831	3278	3371		1831
175	1961	3278	3371		1961
180	2104	3278	3371		2104
185	2262	3278	3371		2262
190	2437	3278	3371		2437
195	2631	3278	3371		2631
200	2806	3278	3333		2806
205	3042	3278	3333		3042
210	3303	3278	3333		3278
215	3592	3278	3333		3278
220	3731	3278	3333		3278
225	3731	3278	3333		3278
230	3731	3278	3333		3278
235	3731	3278	3333		3278
240	3731	3278	3333		3278
245	3731	3278	3333		3278

Table 7-8. ANO-2 Steady-State "Isothermal Condition" P/T Limits (Cont'd)

Fluid Temp.	Allowable Pressures Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	Minimum
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
250	3731	3278	3333		3278
255	3731	3278	3333		3278
260	3731	3278	3333		3278
265	3731	3278	3333		3278
270	3731	3278	3333		3278
275	3731	3278	3333		3278
280	3731	3278	3333		3278
285	3731	3278	3333		3278
290	3731	3278	3333		3278
295	3731	3278	3333		3278
300	3731	3278	3333		3278
305	3731	3278	3333		3278
310	3731	3278	3333		3278
315	3731	3278	3333		3278
320	3731	3278	3333		3278
325	3731	3278	3333		3278
330	3731	3278	3333		3278
335	3731	3278	3333		3278
340	3731	3278	3333		3278
345	3731	3278	3333		3278
350	3731	3278	3333		3278
355	3731	3278	3333		3278
360	3731	3278	3333		3278
365	3731	3278	3333		3278
370	3731	3278	3333		3278
375	3731	3278	3333		3278
380	3731	3278	3333		3278
385	3731	3278	3333		3278
390	3731	3278	3333		3278
395	3731	3278	3333		3278
400	3731	3278	3333		3278
405	3731	3278	3333		3278
410	3731	3278	3333		3278
415	3731	3278	3333		3278
420	3731	3278	3333		3278
425	3731	3278	3333		3278
430	3731	3278	3333		3278
435	3731	3278	3333		3278
440	3731	3278	3333		3278
445	3731	3278	3333		3278

Table 7-8. ANO-2 Steady-State "Isothermal Condition" P/T Limits (Cont'd)

Fluid Temp.	Allowable Pressures				Minimum
	Limiting Beltline	Outlet Nozzle	Inlet Nozzle	Closure Head	
(F)	(psia)	(psia)	(psia)	(psia)	(psia)
450	3731	3278	3333		3278
455	3731	3278	3333		3278
460	3731	3278	3333		3278
465	3731	3278	3333		3278
470	3731	3278	3333		3278
475	3731	3278	3333		3278
480	3731	3278	3333		3278
485	3731	3278	3333		3278
490	3731	3278	3333		3278
495	3731	3278	3333		3278
500	3731	3278	3333		3278
505	3731	3278	3333		3278
510	3731	3278	3333		3278
515	3731	3278	3333		3278
520	3731	3278	3333		3278
525	3731	3278	3333		3278
530	3731	3278	3333		3278
535	3731	3278	3333		3278
540	3731	3278	3333		3278
545	3731	3278	3333		3278
550	3731	3278	3333		3278
555	3731	3278	3333		3278
560	3731	3278	3333		3278

Figure 7-1. ANO-2 Ramp Heatup & Critical Core P/T Limit Curves (psig)

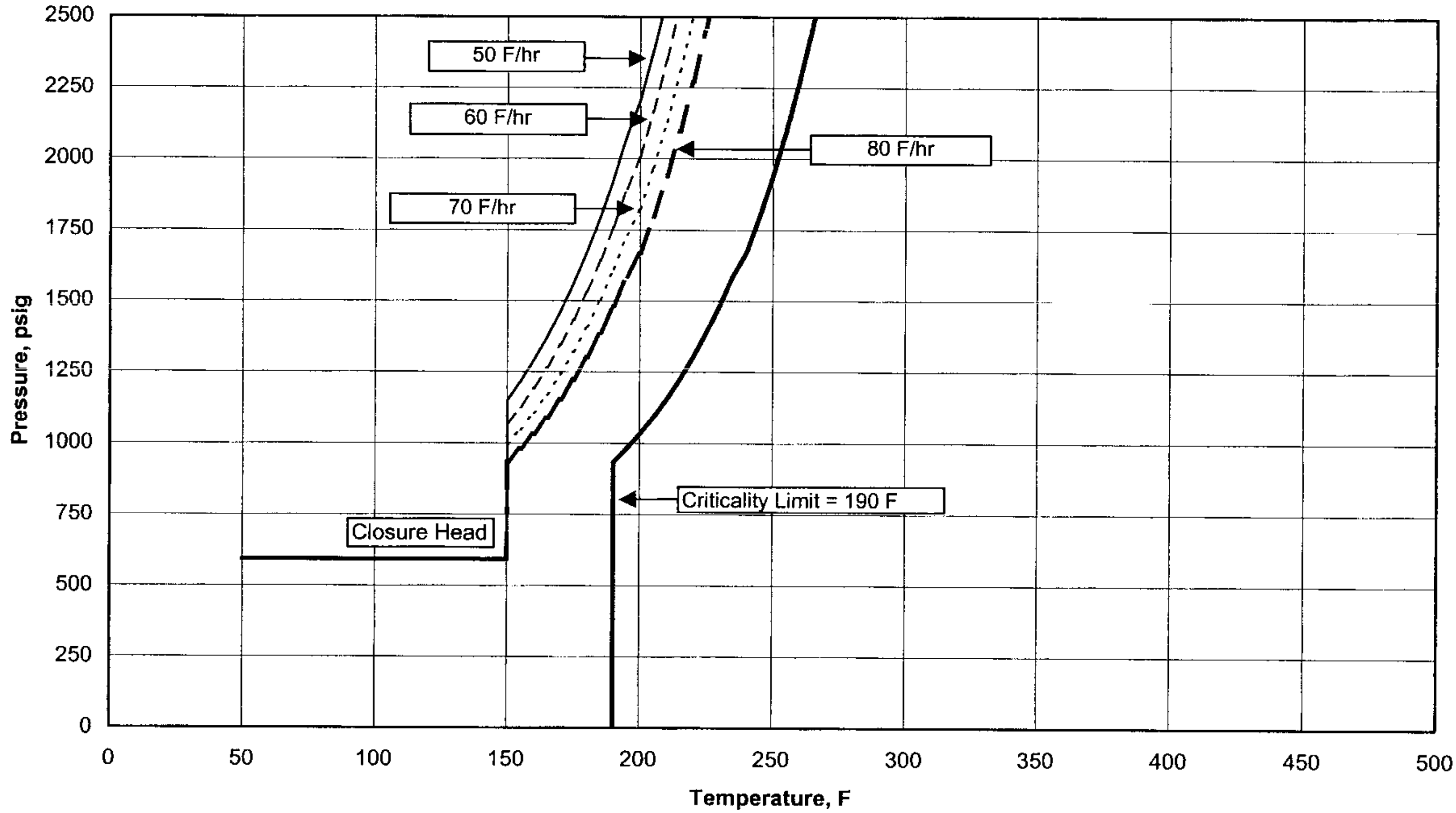


Figure 7-2. ANO-2 Composite Cooldown P/T Limit Curve (psig)

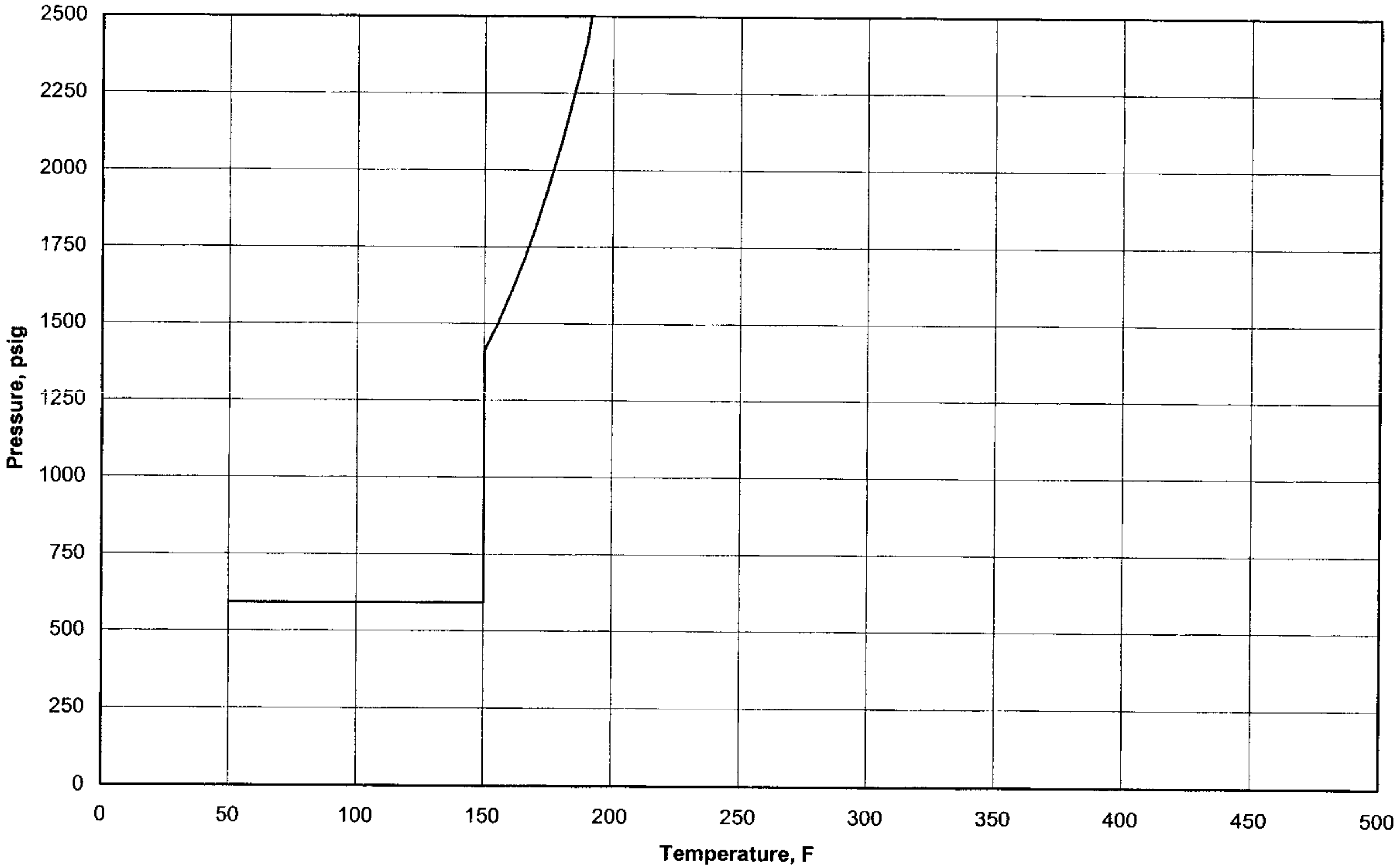


Figure 7-3. ANO-2 ISLH P/T Limit Curve (psig)

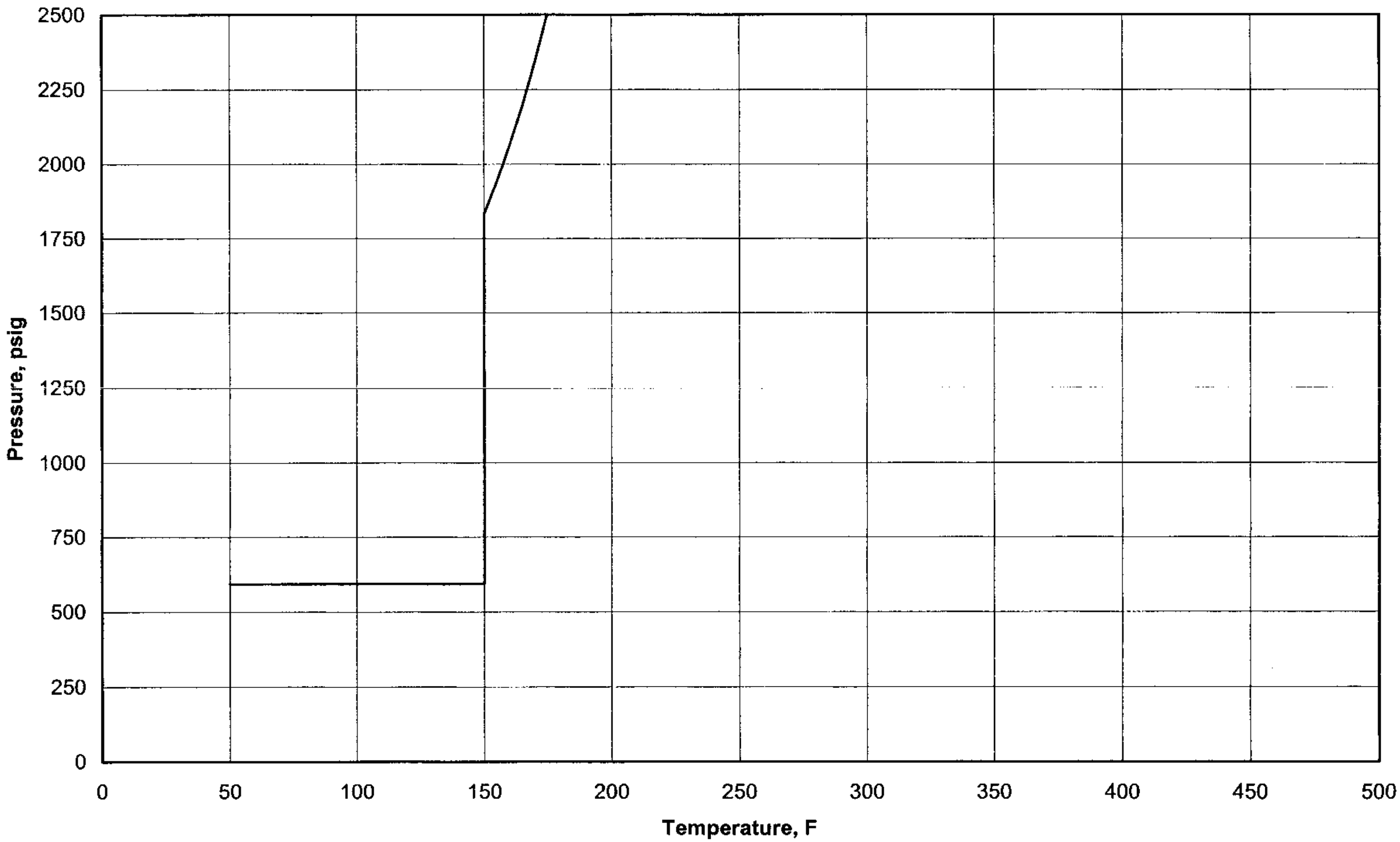
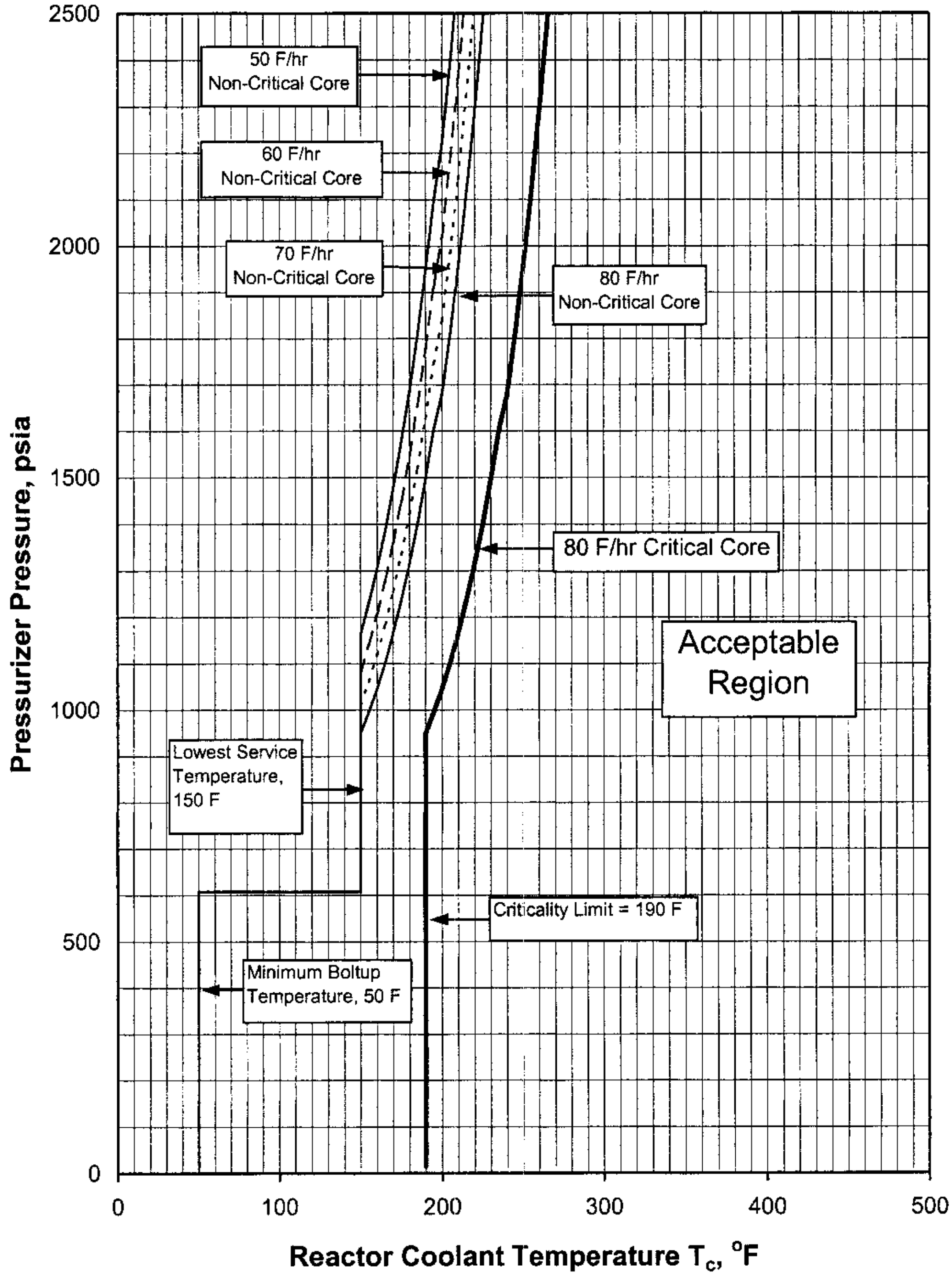


Figure 7-4

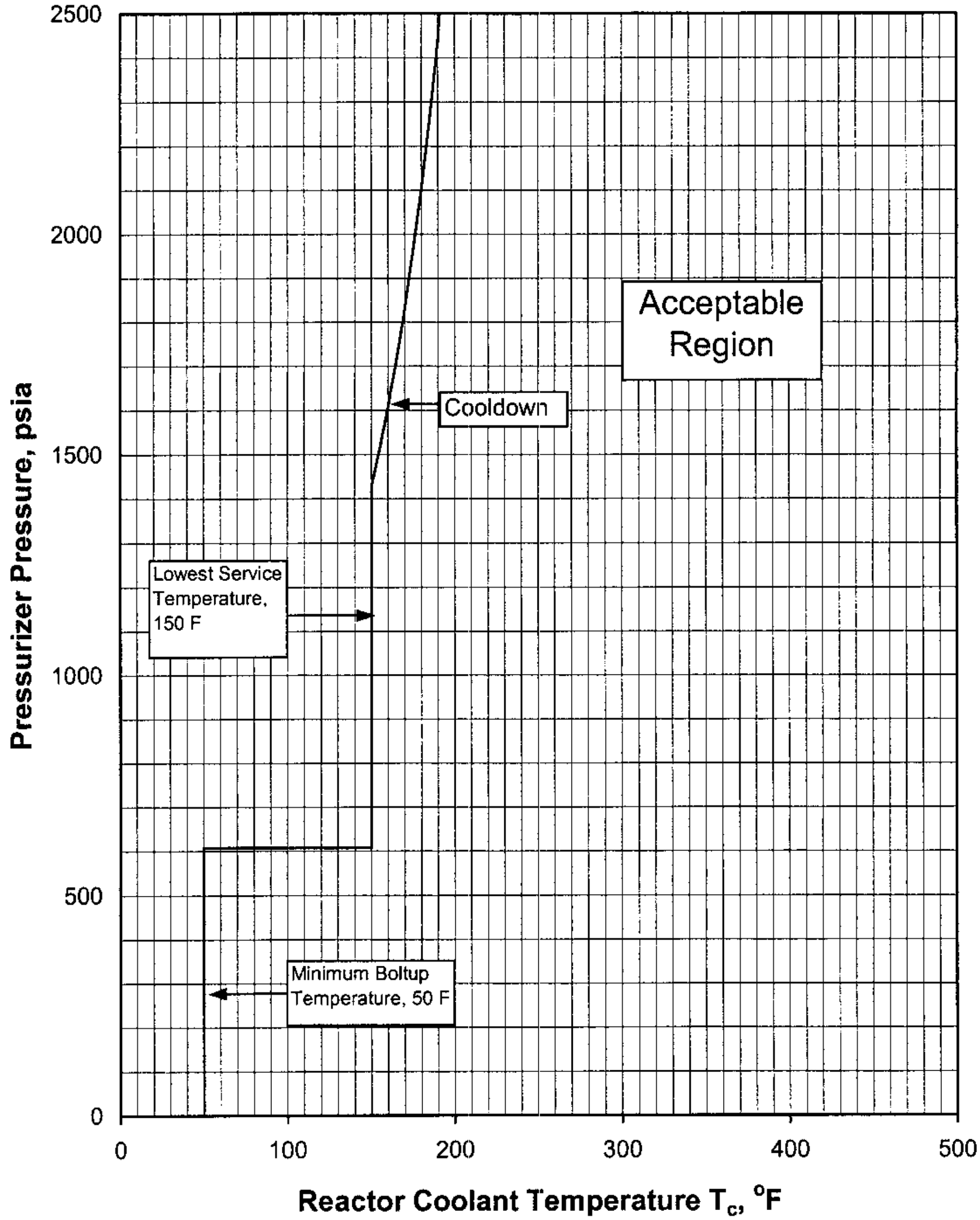
The following page contains Figure 7-4, which depicts ANO-2 Ramp Heatup and Critical Core P/T Limit Curves for 32 EFPY (psia).



(Curves do not include margins for instrument uncertainties)

Figure 7-5

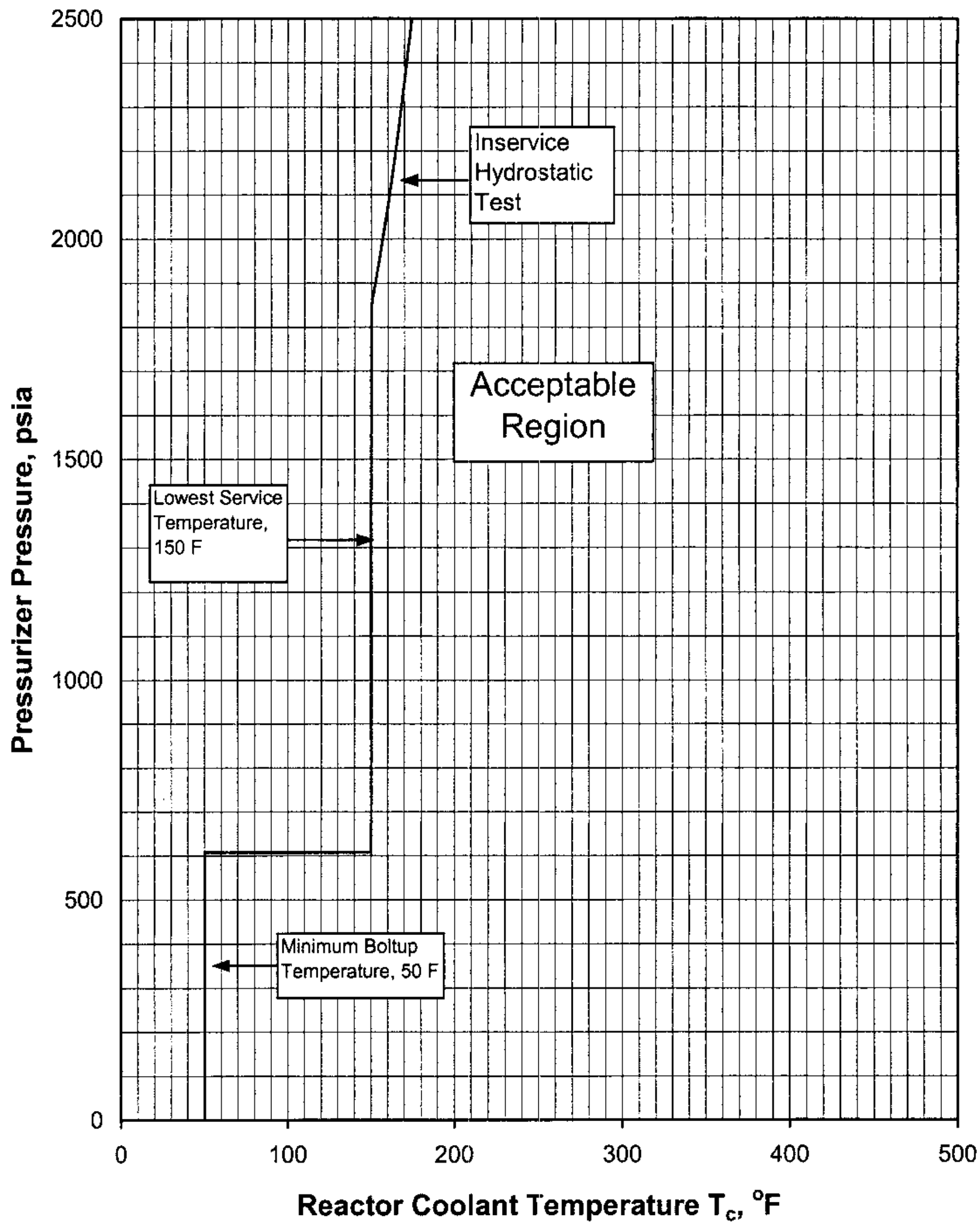
The following page contains Figure 7-5, which depicts ANO-2 Composite Cooldown P/T Limit Curve for 32 EFPY (psia).



(Curves do not include margins for instrument uncertainties)

Figure 7-6

The following page contains Figure 7-6, which depicts ANO-2 Inservice Leak and Hydrostatic (ISLH) P/T Limit Curve for 32 EFPY (psia).



(Curves do not include margins for instrument uncertainties)

8. LTOP PRESSURE/TEMPERATURE LIMITS

The pressure/temperature results developed for K_{Ic} measure of fracture toughness is used to develop LTOP P/T limits [13].

The ASME Code, Section XI, Appendix G[4] states that LTOP systems shall be effective at coolant temperatures less than 200 °F or at coolant temperatures corresponding to a reactor vessel metal temperature less than RT_{NDT} + 50 °F, whichever is greater. Since the RT_{NDT} of the controlling beltline material is 113 °F, the metal temperature at the 1/4T depth from the inside surface of the beltline region is RT_{NDT} + 50 °F or 163 °F. During normal plant heatup the metal temperature is lower and lags the coolant temperature. The maximum temperature difference occurs during the maximum plant heatup rate at 80 °F/hr when the corresponding coolant temperature is 186.4 °F. The minimum LTOP enable temperature for ANO-2 is therefore the greater of 186.4 °F, plus any adjustment for instrument error, or 200 °F.

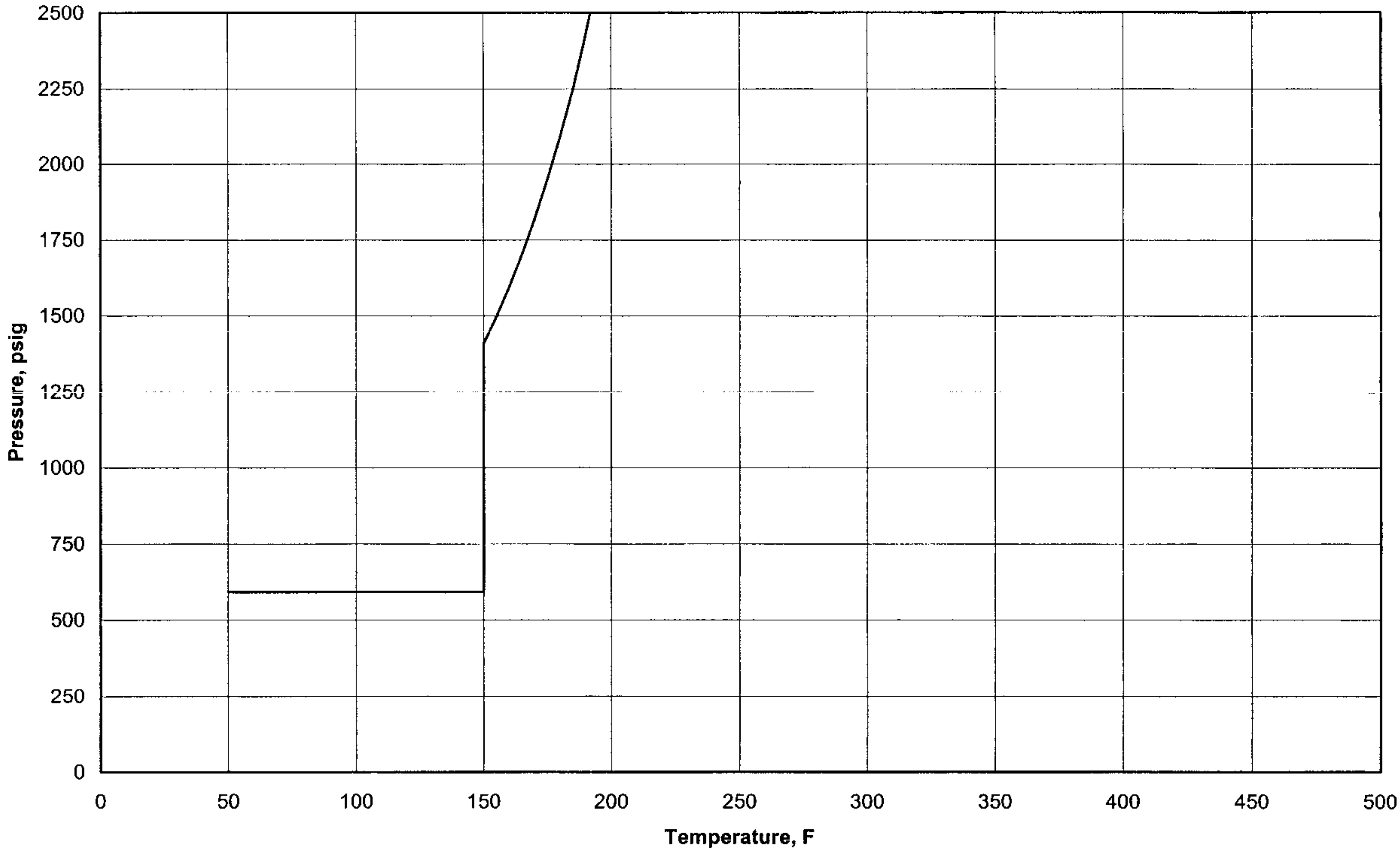
LTOP systems must also limit the maximum pressure in the vessel to 100% of the pressure associated with the P/T limits reported in Section 7 when K_{Ic} is used for fracture toughness[11].

LTOP P/T limits are presented in Table 8-1 and illustrated in Figure 8-1.

Table 8-1. ANO-2 P/T Limits for LTOP (psig)

Fluid Temp. (F)	Minimum (psig)	Fluid Temp. (F)	Minimum (psig)	Fluid Temp. (F)	Minimum (psig)
50	593	260	3263	475	3263
55	593	265	3263	480	3263
60	593	270	3263	485	3263
65	593	275	3263	490	3263
70	593	280	3263	495	3263
75	593	285	3263	500	3263
80	593	290	3263	505	3263
85	593	295	3263	510	3263
90	593	300	3263	515	3263
95	593	305	3263	520	3263
100	593	310	3263	525	3263
105	593	315	3263	530	3263
110	593	320	3263	535	3263
115	593	325	3263	540	3263
120	593	330	3263	545	3263
125	593	335	3263	550	3263
130	593	340	3263	555	3263
135	593	345	3263	560	3263
140	593	350	3263		
145	593	355	3263		
150	593	360	3263		
150	1410	365	3263		
155	1497	370	3263		
160	1593	375	3263		
165	1699	380	3263		
170	1816	385	3263		
175	1946	390	3263		
180	2089	395	3263		
185	2247	400	3263		
190	2422	405	3263		
195	2616	410	3263		
200	2791	415	3263		
205	3027	420	3263		
210	3263	425	3263		
215	3263	430	3263		
220	3263	435	3263		
225	3263	440	3263		
230	3263	445	3263		
235	3263	450	3263		
240	3263	455	3263		
245	3263	460	3263		
250	3263	465	3263		
255	3263	470	3263		

Figure 8-1. ANO-2 P/T Limits for LTOP (psig)



9. CERTIFICATION

Pressure/temperature limits for the ANO-2 reactor vessel have been calculated to satisfy the requirements of 10 CFR Part 50, Appendix G using analytical methods and acceptance criteria of the ASME Boiler and Pressure Vessel Code, Section XI, Appendix G, 1995 Edition with Addenda through 1996 and ASME Code Cases N-588 & N640.

A.D. Nana — 9/27/01 — Date
Materials and Structural Analysis Unit

This report has been reviewed for technical content and accuracy.

J.B. Hall (Material Analysis) — 9-27-01 — Date
Materials and Structural Analysis Unit

K.K. Yoon (Fracture Analysis) — 9/27/01 — Date
Materials and Structural Analysis Unit

Verification of independent review.

D.R. Cofflin — 9/27/01 — Date
Manager, Materials and Structural Analysis Unit

This report is approved for release.

D.L. Howell — 9/28/01 — Date
Program Manager

10. REFERENCES

1. J. B. Hall and J. W. Newman, Jr., *"Analysis of Capsule W-104 Entergy Operations, Inc., Arkansas Nuclear One Unit 2 Power Plant, Reactor Vessel Material Surveillance Program,"* BAW-2399, Framatome ANP, Inc., Lynchburg, Virginia, September 2001.
2. Code of Federal Regulation, Title 10, Part 50, "*Domestic Licensing of Production and Utilization Facilities*," Appendix G, Fracture Toughness Requirements, Federal Register, December 19, 1995.
3. Code of Federal Regulation, Title 10, Part 50, "*Domestic Licensing of Production and Utilization Facilities*," Appendix H, Reactor Vessel Material Surveillance Program Requirements, Federal Register, December 19, 1995.
4. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, "*Rules for Inservice Inspection of Nuclear Power Plant Components*," Appendix G, Fracture Toughness Criteria for Protection Against Failure, 1995 Edition with Addenda through 1996.
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10. PVRC Ad Hoc Group on Toughness Requirements, "PVRC Recommendations on Toughness Requirements for Ferritic Materials," Bulletin No. 175, Welding Research Council, August 1972.

11. ASME Boiler and Pressure Vessel Code Case N-640, "Alternative Reference Fracture Toughness for Development of P-T Limit Curves," Section XI, Division 1. Approval date: February 26, 1999.

12. ASME Boiler and Pressure Vessel Code Case N-588, "Alternative to Reference Flaw Orientation of Appendix G for Circumferential Welds in Reactor Vessels," Section XI, Division 1. Approval date: December 12, 1997.

13. FRA-ANP Document 32-5014182-00, "ANO-2 KIC Based Corrected P-T Limits at 32 EFPY," September, 2001.