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1.0 INTRODUCTION

This calculation updates the Cooper Nuclear Station (CNS) pressure-temperature (P-T) curves for the beltline, bottom head, limiting flange and non-beltline locations (feedwater nozzle / upper vessel). The P-T curves are developed for 32 and 54 effective full power years (EFPY) of operation, and are developed using the methodology of the 2001 Edition through 2003 Addendum of the ASME Code, Section XI, Appendix G [1] and 10CFR50 Appendix G [2]. This calculation has been developed in accordance with the Boiling Water Reactor Owner's Group (BWROG) Licensing Topical Report (LTR), "Pressure Temperature Limits Report Methodology for Boiling Water Reactors" [3].

2.0 METHODOLOGY

A full set of P-T curves are computed, including the following plant conditions: Pressure Test (Curve A), Normal Operation – Core Not Critical (Curve B), and Normal Operation – Core Critical (Curve C). The curves are consolidated into three evaluation regions of the reactor pressure vessel (RPV): (1) the beltline, (2) the bottom head, and (3) the feedwater nozzle / upper vessel. The beltline region, which is typically the most limiting region, is the region adjacent to the core where the fluence exceeds 1.0×10^{17} n/cm^2 [3].

The methodology for calculating P-T curves described below is taken from Reference [3] unless specified otherwise. The P-T curves are calculated by means of an iterative procedure, in which the following steps are completed:

Step 1: A fluid temperature, T, is assumed. The P-T curves are calculated considering a postulated flaw that has extended ¼ of the way through the vessel wall. According to Reference [3], the temperature at the assumed flaw tip, $T_{1/4}$, may be treated as equal to the coolant temperature.

Step 2: The static fracture toughness factor, K_{Ic}, is computed using the following equation:

$$K_{Ic} = 20.734 \cdot e^{0.02(T-ART)} + 33.2 \qquad (1)$$

where:

K_{Ic} = the lower bound static fracture toughness (ksi√in).

T = the metal temperature at the tip of the postulated ¼ through-wall flaw (°F). Note that the coolant temperature is typically used, as described above.

ART = the Adjusted Reference Temperature (ART) for the limiting material in the RPV region under consideration (°F).

Step 3: The allowable stress intensity factor due to pressure, K_{Ip}, is calculated as:

$$K_{Ip} = \frac{K_{Ic} - K_{It}}{SF} \quad (2)$$

where:
- K_{Ip} = the allowable stress intensity factor due to membrane (pressure) stress (ksi√in).
- K_{Ic} = the lower bound static fracture toughness factor calculated in Equation 1 (ksi√in).
- K_{It} = the thermal stress intensity factor (ksi√in) from through wall thermal gradients.
- SF = the ASME Code recommended safety factor, based on the reactor condition.

Note: For hydrostatic and leak test conditions (i.e., P-T Curve A), the SF = 1.5. For normal operation, both non-critical and critical reactor (i.e., P-T Curves B and C), the SF = 2.0. When calculating values for Curve A, the thermal stress intensity factor is neglected (K_{It} = 0), since the hydrostatic leak test is performed at or near isothermal conditions (typically, the rate of temperature change is 25°F/hr or less).

For Curve B and Curve C calculations, K_{It} is computed in different ways based on the evaluated region. For the beltline and bottom head regions, K_{It} is determined using the following equation:

$$K_{It} = 0.953 \times 10^{-3} \cdot CR \cdot t^{2.5} \quad (3)$$

where:
- CR = the cooldown rate of the vessel (°F/hr).
- t = the RPV wall thickness, per region (in).

For the feedwater nozzle / upper vessel region K_{It} is obtained from the stress distribution output of a finite element model (FEM). A thermal transient finite element analysis (FEA) is performed, and a polynomial curve-fit is applied to the through-wall stress distribution at each time point. The subsequent method to evaluate K_{It} is:

$$K_{It} = \sqrt{\pi a}\left[0.706C_{0t} + \frac{2a}{\pi}\cdot 0.537C_{1t} + \frac{a^2}{2}\cdot 0.448C_{2t} + \frac{4a^3}{3\pi}\cdot 0.393C_{3t}\right] \quad (4)$$

where:
- a = ¼ through-wall postulated flaw depth, a = ¼ t (in).
- t = thickness of the cross-section through the limiting nozzle inner blend radius corner (in).

The thermal stress polynomial coefficients are based on the assumed polynomial form of $\sigma(x) = C_0 + C_1 \cdot x + C_2 \cdot x^2 + C_3 \cdot x^3$. In this equation, "$x$" represents the radial distance in inches from the inside surface to any point on the crack front.

Step 4: The allowable internal pressure of the RPV is calculated differently for each evaluation region. For the beltline region the allowable pressure is determined as follows:

$$P_{allow} = \frac{K_{Ip} \cdot t}{M_m \cdot R_i} \tag{5}$$

where:
- P_{allow} = the allowable RPV internal pressure (psig).
- K_{Ip} = the allowable stress intensity factor due to membrane (pressure) stress, as defined in Equation 2 (ksi√in).
- t = the RPV wall thickness, per region (in).
- M_m = the membrane correction factor for an inside surface axial flaw:
  $M_m = 1.85$ for $\sqrt{t} < 2$
  $M_m = 0.926\sqrt{t}$ for $2 \leq \sqrt{t} \leq 3.464$
  $M_m = 3.21$ for $\sqrt{t} > 3.464$.
- R_i = the inner radius of the RPV, per region (in).

For the bottom head region, the allowable pressure is calculated with the following equation:

$$P_{allow} = \frac{2 \cdot K_{Ip} \cdot t}{SCF \cdot M_m \cdot R_i} \tag{6}$$

where:
- SCF = conservative stress concentration factor to account for bottom head penetration discontinuities; SCF = 3.0 per Reference [3].

P_{allow}, K_{Ip}, t, M_m and R_i are defined in the footnotes of Equation 5.

For the feedwater nozzle / upper vessel region, the allowable pressure is determined from a ratio of the allowable and applied stress intensity factors. The applied factor can be determined from a FEM that outputs the stresses due to the internal pressure on the nozzle / RPV. The methodology for this approach is as follows:

$$P_{allow} = \frac{K_{Ip} \cdot P_{ref}}{K_{Ip-app}} \tag{7}$$

where:
- P_{ref} = RPV internal pressure at which the FEA stress coefficients (Equation 8) are valid (psi).
- K_{Ip-app} = the applied pressure stress intensity factor (ksi√in).

P_{allow} and K_{Ip} are defined in the footnotes of Equation 5.

The applied pressure stress intensity factor is determined using a polynomial curve-fit approximation for the through-wall pressure stress distribution from a FEA, similar to the methodology of Equation 4:

$$K_{IP} = \sqrt{\pi a}\left[0.706C_{0P} + \frac{2a}{\pi}\cdot 0.537C_{1P} + \frac{a^2}{2}\cdot 0.448C_{2P} + \frac{4a^3}{3\pi}\cdot 0.393C_{3P}\right] \quad (8)$$

where:

	a	=	¼ through-wall postulated flaw depth, a = ¼ t (in).
	t	=	thickness of the cross-section through the limiting nozzle inner blend radius corner (in).

The core differential pressure (CDP) nozzle is located in the thinner portion of the bottom head. The methodology for analyzing the bottom head, specifically Equation 6, proves to be overly restrictive for the CDP nozzle. The effect of the penetration on the bottom head may be accounted for by determining an applied pressure stress intensity factor. Using a polynomial curve-fit approximation for the through-wall pressure stress distribution from a FEA, the CDP nozzle applied stress intensity factor is calculated by [3, Equation 2.5.3-2a]:

$$K_{Ip-app} = \sqrt{\pi a}\left(0.723C_0 + 0.551C_1\frac{2a}{\pi} + 0.462C_2\frac{a^2}{2} + 0.408C_3\frac{4a^3}{3\pi}\right) \quad (9)$$

where:

	K_{Ip-app}	=	plant specific K_{Ip-app} for CDP nozzle (ksi√in).
	a	=	¼ through-wall postulated flaw depth, a = ¼ t (in).
	t	=	thickness of the cross-section through the limiting nozzle inner blend radius corner (in).
	C_0, C_1, C_2, C_3	=	pressure stress polynomial coefficients, obtained from curve-fit of the extracted stresses from FEA.

Step 5: Steps 1 through 4 are repeated in order to generate a series of P-T points; the fluid temperature is incremented with each repetition. Calculations proceed in this iterative manner until 1,300 psig. This value bounds expected pressures.

Step 6: The following minimum temperature requirements apply to the feedwater nozzle / upper vessel region according to Table 1 of 10CFR50, Appendix G [2]:

- If the pressure is greater than 20% of the pre-service hydro-test pressure, the temperature must be greater than the RT_{NDT} of the limiting flange material plus a temperature adjustment. For Curve A calculations, the temperature adjustment is 90°F; for Curve B, the temperature adjustment is 120°, and for Curve C the temperature adjustment is the highest value between the minimum permissible temperature for the inservice system hydrostatic pressure test and the sum of the highest reference temperature of the material in the closure flange region that is highly stressed by the bolt preload plus 160°F.

- If the pressure is less than or equal to 20% of the pre-service hydro-test pressure, the minimum temperature must be greater than or equal to the RT_{NDT} of the limiting flange material. For Curve A and B calculations, the minimum temperature is the highest reference temperature of the material in the closure flange region that is highly stressed by the bolt preload; for Curve C calculations, the minimum temperature is the highest value between the minimum permissible temperature for the inservice system hydrostatic pressure test and the sum of the highest reference temperature of the material in the closure flange region that is highly stressed by the bolt preload plus 40°F.

Step 7: The final P-T limits are calculated using the following equations:

$$T_{P-T} = T + U_T \tag{10}$$

$$P_{P-T} = P_{allow} - P_H - U_P \tag{11}$$

where:

T_{P-T}	=	The allowable coolant (metal) temperature (°F).
U_T	=	The coolant temperature instrument uncertainty (°F).
P_{P-T}	=	The allowable reactor pressure (psig).
P_H	=	The pressure head to account for the water in the RPV (psig). Can be calculated from the following expression: $P_H = \rho \cdot \Delta h$.
ρ	=	Water density at ambient temperature (lb/in^3).
Δh	=	Elevation of full height water level in RPV (in).
U_P	=	The pressure instrument uncertainty (psig).

These additional pressure and temperature limits are not applicable to the 10CFR50 Appendix G [2] limits described in Step 6.

The P-T Curves for hydrostatic leak test (Curve A) and normal operation – core not critical (Curve B) may be computed by following Steps 1 through 7. Table 1 of Reference [2] requires that core critical (Curve C) P-T limits be 40°F above any Curve A or Curve B limits at all pressures. Therefore, values for Curve C are generated from the requirements of 10CFR50 Appendix G [2] and the Curve A and Curve B limits. 10CFR50 Appendix G [2] also stipulates that, above 20% of the pre-service system hydrostatic test pressure the Curve C temperatures must be either the reference temperature (RT_{NDT}) of the closure flange region plus 160°F, or the temperature required for the hydrostatic pressure test, whichever is greater.

For P-T Curves A and B, the initial fluid temperature assumed in Step 1 is typically taken at the bolt-up temperature of the closure flange minus coolant temperature instrument uncertainty. According to Reference [2], the minimum bolt-up temperature is equal to the limiting material RT_{NDT} of the regions affected by bolt-up stresses. Consistent with Reference [3], the minimum bolt-up temperature shall not be lower than 60°F. Thus, the minimum bolt-up temperature shall be 60°F, the material RT_{NDT}, or other plant specific limit identified by the plant owner, whichever is higher.

For P-T Curve C, when the reactor is critical, the initial fluid temperature is equal to the calculated minimum core critical temperature in the reactor region. Table 1 of Reference [2] indicates that, for a BWR with normal operating water levels, the minimum core critical temperature at the closure flange region is equal to the reference temperature (RT_{NDT}) at the flange region plus 60°F. Thus, the minimum core critical temperature shall be the limiting closure flange region material RT_{NDT}+60°F or other plant specific limit identified by the plant owner, whichever is higher.

3.0 ASSUMPTIONS / DESIGN INPUTS

The design inputs and assumptions used to develop the CNS P-T curves are discussed below. Design inputs and assumptions are summarized in the input listings in Appendix A.

The adjusted reference temperature (ART) values in the CNS beltline region are obtained for 32 and 54 EFPY from Reference [4]. Note that the height of the beltline increases in direct proportion with EFPY; this change in the beltline region from initial startup to end of life is referred to as the extended beltline. The ART value calculations are performed in accordance with Nuclear Regulatory Commission (NRC) Regulatory Guide 1.99, Revision 2 (RG1.99) [5]. Based on Tables 1 and 2 of Reference [4], the limiting beltline material is the Lower/Intermediate shell plate, which has an ART value of 105.8°F for 32 EFPY and 131.2°F for 54 EFPY.

Non-beltline regions are not subjected to the effects of fluence; therefore, reference temperature (RT_{NDT}) values are valid substitutions for corresponding ART values. RT_{NDT} values for non-beltline regions are obtained from Reference [6].

The upper bound for the calculated static fracture toughness (K_{Ic}) is assumed to be 200 ksi$\sqrt{in}$. This limit is assumed based on earlier versions of the ASME Code and is the limit of applicability for linear elastic fracture mechanics, rather than a material property limit.

The inner radius of the RPV at the beltline region is 110.375 inches [7]. The vessel shell thickness is taken as 5.375 inches at the beltline region from the same source. Dimensions for the bottom head radius and the thicknesses are obtained from Reference [7]. The bottom head radius is 110.5 inches and the thickness is 3.188 inches in the thin portion and 6.813 inches in the thick portion.

The GE design pressure is defined in Reference [8] as 1,250 psig. Typically, the pre-service system hydrostatic test pressure is taken as 1.25 times the design pressure, resulting in a value of 1,563 psig. The instrument uncertainties for both temperature and pressure are given in Reference [9] as follow:

- Reactor Vessel Metal Temperature is bounded by ± 5°F.
- Reactor Vessel Pressure is bounded by ± 25 psig.

The full vessel height in the RPV is 831.75 inches, as shown in Reference [10]. The normal operating temperature in the RPV is 547°F [8]. However, the water density is conservatively taken at a lower temperature. Thus, the static pressure adjustment due to the pressure head of the water in the RPV is conservatively calculated as 30 psi for all evaluation regions and all temperatures using a water density of 62.4 lbm/ft^3. The maximum cool-down rate of the vessel is 100°F/hr per Reference [8].

According to Section 2.8 of Reference [3], the minimum bolt-up temperature for the RPV shall not be lower than 60°F. Since the RT_{NDT} values for all regions highly stressed by bolt preload are all less than 60°F (in this case, that of the closure flange region: 20°F [6]), the initial assumed fluid temperature in the iterative P-T curve calculation process should be set equal to 60°F minus coolant temperature uncertainty (5°F in this case [9]). However, the minimum containment temperature is 70°F, which bounds the shutdown margin analysis [11]. Therefore, as specified in Section 2.0, the minimum bolt-up and minimum criticality temperature shall not be less than 70°F. A temperature increment of 2°F between subsequent iterations is assumed.

The 70°F initial temperature does not include the additional 60°F add-on margin for Curves A and B that was previously applied. This additional conservatism was required in pre-1971 ASME Section III Code, but is no longer required in ASME Section XI, Appendix G [1] or 10CFR50, Appendix G [2]. When the LTR [3] was developed, SI consciously recognized the additional 60°F margin and chose to exclude it, as it is not technically required.

Vessel nozzles are generally incorporated into P-T curve calculations using stress distributions from FEAs and applying them to geometry specific fracture mechanics models. The feedwater nozzle (upper vessel region) and the core differential pressure (CDP) nozzle require this type of analysis due to bounding transients they experience, limiting ART (RT_{NDT} outside beltline) values, and/or stress concentration effects. The core differential pressure CDP nozzle (bottom head region) is analyzed because it is the limiting discontinuity in the thin portion of the bottom head. FEA is performed in Reference [12] for the CDP nozzle.

The feedwater nozzle is the bounding component in the upper vessel because it is a stress concentrator (essentially a hole in a plate) and because it typically experiences more severe thermal transients compared to the rest of the upper vessel region. A two-dimensional finite element model (FEM) of the feedwater nozzle is created as described in Section 2.0 of Reference [13]. The stress distribution acting normal to the postulated ¼ thickness crack (or hoop stress distribution) due to a 1,000 psig unit pressure is obtained along a limiting path in the nozzle-to-RPV blend radius [13]. Pressure stress coefficients are obtained from Table 2 of Reference [13] and used to calculate the applied pressure stress intensity factor using Equation 8.

The hoop stress distribution in the feedwater nozzle is also obtained along the same path for a thermal down shock of 450°F [13]. Stress coefficients are calculated for all time steps in Table 3 of Reference [13] and used to calculate a thermal stress intensity factor, K_{It}, due to the 450°F thermal shock using Equation 4. The maximum K_{It} for all time steps is used in the evaluation. Because operation is along the saturation curve, the limiting K_{It} is scaled to reflect the worst-case step change due to the available temperature difference. It is recognized that at low temperatures, the available temperature difference is insignificant, which could result in a near zero K_{It}. Therefore, a minimum K_{It} is calculated based on the shutdown transient; scaling of the upper vessel / feedwater nozzle K_{It} based on the available temperature difference is not allowed below this minimum K_{It}. The feedwater nozzle shutdown transient is analyzed with the hoop stress distribution given along the same limiting path in Reference [14]. The analysis in Reference [14] provides results for a stress free reference temperature of 70°F as well as 550°F. The choice of stress free reference temperature affects the magnitude of the differential thermal expansion stresses in the component. Both analyses are curve fit with a third order polynomial for all time points, and a thermal stress intensity factor is calculated using Equation 4. The maximum K_{It} for all time steps considering both stress free reference temperatures is used as the minimum K_{It} for the upper vessel / feedwater nozzle. The limiting path defines the nozzle corner thickness to be 5.75 inches [14] and the postulated flaw location at 1/4t to be 1.44 inches.

The CNS bottom head exhibits a variation in thickness for different sections. It is observed that a nozzle exists in the thinner section of the bottom head. Although the nozzle is not ferritic and does not specifically require evaluation, the stress concentration effects of the penetration must be accounted for. Per Reference [3] a nozzle specific evaluation is performed to ensure that the CDP nozzle is not limiting for any part of the bottom head curve. Initially, only Curve B is analyzed because it utilizes a higher safety factor and also incorporates the effects of through wall thermal stresses. If any portion of the CDP nozzle proves to be limiting for the bottom head, a composite bottom head curve will be created for Curve A, Curve B, and Curve C.

For the CDP nozzle a unit pressure FEA is performed in Reference [12] and a third order polynomial curve-fit is applied to the through-wall stress distribution [12, Table 1]. The K_{IP} value is calculated using Equation 9. The K_{It} value for the CDP nozzle is calculated using Equation 3.

4.0 CALCULATIONS

The P-T curves in this calculation were developed using an Excel spreadsheet, which is independently verified for use on a project-specific basis in accordance with SI's Nuclear QA program.

For the feedwater nozzle shutdown thermal transient analysis, the stress free temperature of 70°F is the bounding case. The K_{It} value is calculated for all time steps with the bounding K_{It} values shown in the plot of the polynomial curve fit (Figure 1) for time = 6792 seconds.

The feedwater nozzle polynomial stress coefficients due to pressure, thermal shock, and thermal ramp are given in Table 1 and are applied to Equations 4 and 8 to calculate the stress intensity factors shown in Table 1. The resulting applied pressure stress intensity factor, $K_{Ip\text{-}app}$, is 38.9 ksi√in, the thermal stress intensity factor due to thermal down shock is 63.5 ksi√in, and the thermal stress intensity factor due to thermal ramp is 11.1 ksi√in.

For the analysis of the core differential pressure nozzle, the resulting applied pressure stress intensity factor, $K_{Ip\text{-}app}$ is 35.2 ksi√in and the thermal stress intensity factor due to the 100°F/hr cooldown rate is calculated using Equation 3 as 1.7 ksi√in.

4.1 Pressure Test (Curve A)

The minimum bolt-up temperature of 70°F minus instrument uncertainty (5°F) is applied to all regions as the initial temperature in the iterative calculation process. The static fracture toughness (K_{Ic}) is calculated for all regions using Equation 1. The resulting value of K_{Ic}, along with a safety factor of 1.5 is used in Equation 2 to calculate the pressure stress intensity factor (K_{Ip}). The allowable RPV pressure is calculated for the beltline, bottom head and upper vessel regions using Equations 5, 6, and 7, as appropriate. For the feedwater nozzle / upper vessel region, the additional constraints specified in Step 6 of Section 2.0 are applied. Final P-T limits for temperature and pressure are obtained from Equations 10 and 11, respectively.

The data resulting from each P-T curve calculation is tabulated. Values for the beltline region at 32 and 54 EFPY are provided in Table 2 and Table 3, respectively. Data for the bottom head region is listed in Table 4, and data for the feedwater nozzle / upper vessel region is presented in Table 5. The data for each region is graphed, and the resulting P-T curves for 32 and 54 EFPY are provided in Figure 2 and Figure 3, respectively. Additionally, a composite Curve A for the beltline, bottom head, and upper vessel regions is graphed and the resulting P-T curves for 32 and 54 EFPY are provided in Figure 4 and Figure 5.

4.2 Normal Operation – Core Not Critical (Curve B)

The minimum bolt-up temperature of 70°F minus coolant temperature instrument uncertainty (5°F) is applied to all regions as the initial temperature in the iterative calculation process. The static fracture toughness (K_{Ic}) is calculated for all regions using Equation 1. The thermal stress intensity factor (K_{It}) is calculated for the beltline plate and bottom head regions using Equation 3 and for the feedwater nozzle using Equation 4.

The resulting values of K_{Ic} and K_{It}, along with a safety factor of 2.0, are used in Equation 2 to calculate the pressure stress intensity factor (K_{Ip}). The allowable RPV pressure is calculated for the beltline, bottom head, and upper vessel regions using Equations 5, 6, and 7, as appropriate. For the feedwater nozzle / upper vessel region, the additional constraints specified in Step 6 of Section 2.0 are applied. Final P-T limits for temperature and pressure are obtained from Equations 10 and 11, respectively.

The data resulting from each P-T curve calculation is tabulated. Values for the beltline region at 32 and 54 EFPY are given in Table 6 and Table 7. Data for the bottom head region is listed in Table 8 and data for the bottom head region represented by the CDP nozzle is listed in Table 9. Comparison of these two tables show that data from Table 8 is bounding, therefore the CDP nozzle in the bottom head region is not included as part of the composite curve for Curve A, Curve B, or Curve C. Data for the feedwater nozzle / upper vessel region is presented in Table 10. The data for each region is graphed, and the resulting P-T curves for 32 and 54 EFPY are provided in Figure 6 and Figure 7, respectively. Additionally, a composite Curve B for the beltline, bottom head, and upper vessel regions is graphed, and the resulting P-T curves for 32 and 54 EFPY are provided in Figure 8 and Figure 9.

4.3 Normal Operation – Core Critical (Curve C)

The pressure and temperature values for Curve C are calculated in a similar manner as Curve B, with several exceptions. The initial evaluation temperature is calculated as the limiting upper vessel RT_{NDT} that is highly stressed by the bolt preload (in this case, that of the closure flange region: 20°F per Section 3.0) plus 60°F, resulting in a minimum critical temperature of 80°F. When the pressure exceeds 20% of the pre-service system hydrostatic test pressure (20% of 1,563 psig = 313 psig), the P-T limits are specified as 40°F higher than the Curve B values. The minimum temperature above the 20% of the pre-service system hydrostatic test pressure is always greater than the reference temperature (RT_{NDT}) of the closure region plus 160°F, or is taken as the minimum temperature required for the hydrostatic pressure test. The final Curve C values are taken as the absolute maximum between the regions of the beltline, the bottom head, and the upper vessel.

Tabulated overall values of Curve C are provided at 32 and 54 EFPY in Table 11 and Table 12, respectively. The corresponding P-T curve plots for 32 and 54 EFPY are given in Figure 10 and Figure 11, respectively.

5.0 CONCLUSIONS

P-T curves are developed for CNS using the methodology in Section 2.0 and the design inputs and assumptions defined in Section 3.0. A full set of P-T curves are developed at 32 EFPY and 54 EFPY, for the following plant conditions: Pressure Test (Curve A), Normal Operation – Core Not Critical (Curve B), and Normal Operation – Core Critical (Curve C). Calculations are performed for the beltline, bottom head, and feedwater nozzle / upper vessel regions.

Tabulated pressure and temperature values are provided for all regions and EFPY levels in Table 2 through Table 12. The accompanying P-T curve plots are provided in Figure 2 through Figure 11.

6.0 REFERENCES

1. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, Rules for In-Service Inspection of Nuclear Power Plant Components, Appendix G, "Analysis of Flaws," 2001 Edition including the 2003 Addenda.

2. U. S. Code of Federal Regulations, Title 10, Energy, Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix G, "Fracture Toughness Requirements," (60 FR 65474, Dec. 19, 1995; 73 FR 5723, Jan. 2008).

3. Structural Integrity Associates Report No. SIR-05-044, Revision 1, "Pressure-Temperature Limits Report Methodology for Boiling Water Reactors," June 2011, SI File No. GE-10Q-401.

4. Cooper Nuclear Station Calculation No. NEDC07-045, Structural Integrity Associates Calculation No. 1100445.301, Revision 1, "ΔRT_{NDT} and ART Evaluation."

5. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," May 1988.

6. GE Document No. GE-NE-523-159-1292 (DRF B13-01662), "Cooper Nuclear Station Vessel Surveillance Materials Testing and Fracture Toughness Analysis," Revision 0, February 1993, SI File No. COOP-05Q-202.

7. Combustion Engineering Drawing No. E-232-230, Revision 3, "General Arrangement Elevation for: General Electric Co. APED 218" I.D. BWR," SI File No. NPPD-06Q-208.

8. Cooper Nuclear Station Drawing Change Notice No. 08-1427, "RPV Thermal Cycles," SI File No. 1100445.203.

9. NPPD Memo DED 2003-005, Alan Able to Ken Thomas, dated August 14, 2003, "Instrument Uncertainty Associated With Technical Specification 3.4.9," SI File No. COOP-05Q-203.

10. General Electric Drawing No. 729E479-B, Revision 0, "Reactor Primary SYS. WTS. & Vols.," Sheet 1 of 3, SI File No. NPPD-06Q-204.

11. Email Correspondence between Kenneth Thomas (NPPD) and Eric Houston (SI), Received on 5/18/2011, "RE: DRAFT P-T Curves," SI File No. 1100445.103.

12. Structural Integrity Associates Calculation No. 1100445.304, Revision 0, "Core Differential Pressure Nozzle Finite Element Model and Stress Analysis."

13. NPPD File No. NEDC99-020, Structural Integrity Associates Calculation No. NPPD-13Q-302, Revision 1, "Feedwater Nozzle Stress Analysis."

14. Cooper Nuclear Station Calculation No. NEDC99-020, Structural Integrity Associates Calculation No.1100445.302, Revision 0, "Finite Element Stress Analysis of Cooper RPV Feedwater Nozzle."

15. Combustion Engineering, Inc. Drawing No. E-232-242, Revision 7, "Nozzle Details For: General Electric Corp. APED 218" I.D. BWR," SI File No. 1100445.204.

Table 1: CNS Polynomial Coefficients for Feedwater Nozzle Stress Intensity Distributions

Feedwater Nozzle Pressure Stress Coefficients					K_{Ip-app} (psi√in)
c0	c1	c2	c3		
30388	-7238.8	967.40	-82.863		38,904
Feedwater Nozzle Thermal Stress Coefficients (Step)					K_{It} (psi√in)
c0	c1	c2	c3		
62433	-34071	5810.3	-339.94		63,449
Feedwater Nozzle Thermal Stress Coefficients (Ramp)					K_{It} (psi√in)
c0	c1	c2	c3		
11322	-6463.6	931.8	-45.270		11,105

Table 2: CNS Beltline Region, Curve A, for 32 EFPY

Plant = CNS
Component = Beltline
Vessel thickness, t = 5.375 inches
Vessel Radius, R = 110.375 inches
ART = 105.8 °F ======> 32 EFPY
K_{IT} = 0.00 (no thermal effects)
Safety Factor = 1.50
M_m = 2.147
Temperature Adjustment = 5.0 °F (applied after bolt-up, instrument uncertainty)
Height of Water for a Full Vessel = 831.75 inches
Pressure Adjustment = 30.0 psig (hydrostatic pressure head for a full vessel at 70°F)
Pressure Adjustment = 25.0 psig (instrument uncertainty)

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Im} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65.0	42.37	28.25	70.0	0
65.0	42.37	28.25	70.0	586
67.0	42.74	28.50	72.0	591
69.0	43.13	28.75	74.0	597
71.0	43.54	29.02	76.0	603
73.0	43.96	29.31	78.0	610
75.0	44.40	29.60	80.0	616
77.0	44.86	29.90	82.0	623
79.0	45.33	30.22	84.0	630
81.0	45.83	30.55	86.0	638
83.0	46.34	30.89	88.0	646
85.0	46.88	31.25	90.0	654
87.0	47.44	31.62	92.0	662
89.0	48.02	32.01	94.0	671
91.0	48.62	32.41	96.0	680
93.0	49.25	32.83	98.0	690
95.0	49.91	33.27	100.0	700
97.0	50.59	33.73	102.0	710
99.0	51.30	34.20	104.0	721
101.0	52.04	34.69	106.0	732
103.0	52.80	35.20	108.0	743
105.0	53.60	35.74	110.0	756
107.0	54.44	36.29	112.0	768
109.0	55.30	36.87	114.0	781
111.0	56.21	37.47	116.0	795
113.0	57.15	38.10	118.0	809
115.0	58.12	38.75	120.0	824
117.0	59.14	39.43	122.0	839
119.0	60.20	40.13	124.0	855
121.0	61.30	40.87	126.0	872
123.0	62.45	41.63	128.0	889
125.0	63.64	42.43	130.0	907
127.0	64.88	43.26	132.0	926
129.0	66.18	44.12	134.0	946
131.0	67.52	45.01	136.0	966
133.0	68.92	45.95	138.0	987
135.0	70.38	46.92	140.0	1,009
137.0	71.90	47.93	142.0	1,032
139.0	73.48	48.98	144.0	1,056
141.0	75.12	50.08	146.0	1,081
143.0	76.83	51.22	148.0	1,107
145.0	78.61	52.41	150.0	1,134
147.0	80.47	53.64	152.0	1,162
149.0	82.39	54.93	154.0	1,191
151.0	84.40	56.27	156.0	1,221
153.0	86.49	57.66	158.0	1,253
155.0	88.67	59.11	160.0	1,286
157.0	90.93	60.62	162.0	1,320

Table 3: CNS Beltline Region, Curve A, for 54 EFPY

Plant =	CNS	
Component =	Beltline	
Vessel thickness, t =	5.375	inches
Vessel Radius, R =	110.375	inches
ART =	131.2	°F ======> 54 EFPY
K_{IT} =	0.00	(no thermal effects)
Safety Factor =	1.50	
M_m =	2.147	
Temperature Adjustment =	5.0	°F (applied after bolt-up, instrument uncertainty)
Height of Water for a Full Vessel =	831.75	inches
Pressure Adjustment =	30.0	psig (hydrostatic pressure head for a full vessel at 70°F)
Pressure Adjustment =	25.0	psig (instrument uncertainty)

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Im} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65 0	38.72	25.81	70.0	0
65.0	38.72	25.81	70.0	530
67 0	38.94	25.96	72.0	534
69.0	39.18	26.12	74.0	537
71.0	39.42	26.28	76.0	541
73.0	39.67	26.45	78.0	545
75.0	39.94	26.63	80.0	549
77.0	40.21	26.81	82.0	553
79.0	40.50	27.00	84.0	557
81.0	40.80	27.20	86.0	562
83.0	41.11	27.40	88.0	567
85.0	41.43	27 62	90.0	571
87.0	41 77	27.84	92.0	577
89.0	42.12	28.08	94.0	582
91.0	42.48	28.32	96.0	587
93.0	42.86	28 57	98.0	593
95.0	43.25	28.83	100.0	599
97.0	43.66	29.11	102.0	605
99.0	44.09	29.39	104.0	612
101.0	44.53	29.69	106.0	618
103.0	45.00	30.00	108.0	625
105.0	45.48	30.32	110.0	633
107.0	45.98	30.65	112.0	640
109.0	46.50	31.00	114.0	648
111.0	47.04	31.36	116.0	656
113.0	47.61	31.74	118 0	665
115.0	48.20	32.13	120.0	674
117.0	48.81	32.54	122.0	683
119.0	49.44	32.96	124.0	693
121.0	50.11	33.41	126.0	703
123.0	50.80	33.87	128.0	713
125.0	51.52	34.34	130.0	724
127.0	52.26	34.84	132.0	735
129.0	53.04	35.36	134.0	747
131.0	53.85	35.90	136.0	759
133.0	54.69	36.46	138.0	772
135.0	55.57	37.05	140.0	785
137.0	56.48	37.66	142.0	799
139.0	57.43	38.29	144.0	814
141.0	58.42	38.95	146.0	828
143.0	59.45	39.64	148.0	844
145.0	60.52	40.35	150.0	860
147.0	61.64	41.09	152.0	877
149.0	62.80	41.87	154.0	895
151.0	64.01	42.67	156.0	913
153.0	65.27	43.51	158.0	932
155.0	66.57	44.38	160.0	952
157.0	67.94	45.29	162.0	972
159.0	69.35	46.24	164.0	994
161.0	70.83	47.22	166.0	1,016
163.0	72.36	48.24	168 0	1,039
165.0	73.96	49.31	170.0	1,063
167.0	75.63	50.42	172.0	1,089
169.0	77 36	51.57	174.0	1,115
171.0	79.16	52.77	176.0	1,142
173.0	81.04	54.02	178.0	1,170
175.0	82.99	55.33	180.0	1,200
177.0	85.02	56.68	182.0	1,231
179.0	87.13	58.09	184 0	1,263
181.0	89.34	59.56	186.0	1,296
183.0	91.63	61.08	188.0	1,331

Table 4: CNS Bottom Head Region, Curve A, for All EFPY

Plant =	**CNS**	
Component =	**Bottom Head**	(penetrations portion)
Bottom Head thickness, t =	**6.813**	inches
Bottom Head Radius, R =	**110.5**	inches
ART =	**28.0**	°F ======> **All EFPY**
K_{It} =	**0.00**	(no thermal effects)
Safety Factor =	**1.50**	
Stress Concentration Factor =	**3.00**	(bottom head penetrations)
M_m =	**2.417**	
Temperature Adjustment =	**5.0**	°F (applied after bolt-up, instrument uncertainty)
Height of Water for a Full Vessel =	**831.75**	inches
Pressure Adjustment =	**30.0**	psig (hydrostatic pressure head for a full vessel at 70°F)
Pressure Adjustment =	**25.0**	psig (instrument uncertainty)

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Im} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65.0	76.66	51.10	70	0
65.0	76.66	51.10	70	814
67.0	78.43	52.29	72	834
69.0	80.28	53.52	74	855
71.0	82.20	54.80	76	877
73.0	84.20	56.13	78	900
75.0	86.28	57.52	80	923
77.0	88.44	58.96	82	948
79.0	90.70	60.47	84	973
81.0	93.05	62.03	86	1,000
83.0	95.49	63.66	88	1,028
85.0	98.03	65.35	90	1,056
87.0	100.68	67.12	92	1,086
89.0	103.43	68.95	94	1,118
91.0	106.30	70.86	96	1,150
93.0	109.28	72.85	98	1,184
95.0	112.38	74.92	100	1,219
97.0	115.62	77.08	102	1,256
99.0	118.98	79.32	104	1,294

Table 5: CNS, Upper Vessel Region, Curve A, for All EFPY

Plant =	CNS		
Component =	Upper Vessel		
ART =	20.0	°F ======>	All EFPY
Vessel Radius, R =	110.375	inches	
Nozzle corner thickness, t' =	5.753	inches, approximate	
K_{It} =	0.00	(no thermal effects)	
$K_{Ip\text{-}applied}$ =	38.90	ksi*inch$^{1/2}$	
Crack Depth, a =	1.438	inches	
Safety Factor =	1.50		
Temperature Adjustment =	5.0	°F (applied after bolt-up, instrument uncertainty)	
Height of Water for a Full Vessel =	831.75	inches	
Pressure Adjustment =	30.0	psig (hydrostatic pressure head for a full vessel at 70°F)	
Pressure Adjustment =	25.0	psig (instrument uncertainty)	
Reference Pressure =	1,000	psig (pressure at which the FEA stress coefficients are valid)	
Unit Pressure =	1,563	psig (hydrostatic pressure)	
Flange RT_{NDT} =	20.0	°F ======>	All EFPY

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Ip} (ksi*inch$^{1/2}$)	P-T Curve Temperature (°F)	P-T Curve 10CFR50 Adjustments (psig)
65.0	84.20	56.13	70	0
65.0	84.20	56.13	70	313
67.0	86.28	57.52	110	313
69.0	88.44	58.96	110	1461
71.0	90.70	60.47	110	1499
73.0	93.05	62.03	110	1539
75.0	95.49	63.66	110	1581
77.0	98.03	65.35	110	1625

Table 6: CNS, Beltline Region, Curve B, for 32 EFPY

Plant =	CNS		
Component =	Beltline		
Vessel thickness, t =	5.375	inches	
Vessel Radius, R =	110.375	inches	
ART =	105.8	°F ======>	32 EFPY
K_{It} =	6.38	ksi*inch$^{1/2}$	
Safety Factor =	2.00		
M_m =	2.147		
Temperature Adjustment =	5.0	°F (applied after bolt-up, instrument uncertainty)	
Height of Water for a Full Vessel =	831.75	inches	
Pressure Adjustment =	30.0	psig (hydrostatic pressure head for a full vessel at 70°F)	
Pressure Adjustment =	25.0	psig (instrument uncertainty)	
Heat Up and Cool Down Rate =	100	°F/Hr	

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Im} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65.0	42.37	17.99	70.0	0
65.0	42.37	17.99	70.0	353
67.0	42.74	18.18	72.0	357
69.0	43.13	18.37	74.0	362
71.0	43.54	18.58	76.0	366
73.0	43.96	18.79	78.0	371
75.0	44.40	19.01	80.0	376
77.0	44.86	19.24	82.0	381
79.0	45.33	19.47	84.0	387
81.0	45.83	19.72	86.0	392
83.0	46.34	19.98	88.0	398
85.0	46.88	20.25	90.0	404
87.0	47.44	20.53	92.0	411
89.0	48.02	20.82	94.0	417
91.0	48.62	21.12	96.0	424
93.0	49.25	21.43	98.0	431
95.0	49.91	21.76	100.0	439
97.0	50.59	22.10	102.0	446
99.0	51.30	22.46	104.0	454
101.0	52.04	22.83	106.0	463
103.0	52.80	23.21	108.0	471
105.0	53.60	23.61	110.0	481
107.0	54.44	24.03	112.0	490
109.0	55.30	24.46	114.0	500
111.0	56.21	24.91	116.0	510
113.0	57.15	25.38	118.0	521
115.0	58.12	25.87	120.0	532
117.0	59.14	26.38	122.0	543
119.0	60.20	26.91	124.0	555
121.0	61.30	27.46	126.0	568
123.0	62.45	28.03	128.0	581
125.0	63.64	28.63	130.0	594
127.0	64.88	29.25	132.0	608
129.0	66.18	29.90	134.0	623
131.0	67.52	30.57	136.0	638
133.0	68.92	31.27	138.0	654
135.0	70.38	32.00	140.0	671
137.0	71.90	32.76	142.0	688
139.0	73.48	33.55	144.0	706
141.0	75.12	34.37	146.0	725
143.0	76.83	35.22	148.0	744
145.0	78.61	36.11	150.0	764
147.0	80.47	37.04	152.0	785
149.0	82.39	38.01	154.0	807
151.0	84.40	39.01	156.0	830
153.0	86.49	40.05	158.0	854
155.0	88.67	41.14	160.0	878
157.0	90.93	42.27	162.0	904
159.0	93.29	43.45	164.0	931
161.0	95.74	44.68	166.0	958
163.0	98.29	45.95	168.0	987
165.0	100.95	47.28	170.0	1,017
167.0	103.71	48.66	172.0	1,049
169.0	106.59	50.10	174.0	1,081
171.0	109.58	51.60	176.0	1,115
173.0	112.70	53.16	178.0	1,151
175.0	115.95	54.78	180.0	1,188
177.0	119.32	56.47	182.0	1,226
179.0	122.84	58.23	184.0	1,266
181.0	126.50	60.06	186.0	1,307

Table 7: CNS, Beltline Region, Curve B, for 54 EFPY

Plant =	CNS		
Component =	Beltline		
Vessel thickness, t =	5.375	inches	
Vessel Radius, R =	110.375	inches	
ART =	131.2	°F ======>	54 EFPY
K_{It} =	6.38	ksi*inch$^{1/2}$	
Safety Factor =	2.00		
M_m =	2.147		
Temperature Adjustment =	5.0	°F (applied after bolt-up, instrument uncertainty)	
Height of Water for a Full Vessel =	831.75	inches	
Pressure Adjustment =	30.0	psig (hydrostatic pressure head for a full vessel at 70°F)	
Pressure Adjustment =	25.0	psig (instrument uncertainty)	
Heat Up and Cool Down Rate =	100	°F/Hr	

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Im} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65.0	38.72	16.17	70 0	0
65.0	38.72	16.17	70 0	312
67.0	38.94	16 28	72.0	314
69.0	39 18	16.40	74.0	317
71.0	39.42	16.52	76.0	320
73.0	39.67	16.65	78.0	323
75.0	39 94	16.78	80.0	326
77.0	40.21	16.91	82.0	329
79.0	40.50	17.06	84.0	332
81.0	40.80	17.21	86 0	335
83.0	41.11	17 36	88 0	339
85.0	41.43	17.52	90 0	342
87.0	41.77	17.69	92.0	346
89.0	42.12	17.87	94.0	350
91.0	42 48	18.05	96.0	354
93.0	42.86	18.24	98 0	359
95.0	43.25	18.43	100.0	363
97.0	43.66	18.64	102.0	368
99.0	44 09	18.85	104.0	373
101.0	44.53	19.08	106.0	378
103.0	45.00	19 31	108 0	383
105.0	45.48	19 55	110.0	388
107.0	45.98	19 80	112.0	394
109.0	46.50	20.06	114.0	400
111.0	47.04	20.33	116.0	406
113.0	47.61	20.61	118.0	413
115.0	48.20	20.91	120 0	419
117.0	48.81	21.21	122 0	426
119.0	49.44	21.53	124 0	433
121.0	50.11	21.86	126 0	441
123.0	50.80	22 21	128.0	449
125.0	51.52	22.57	130.0	457
127.0	52.26	22.94	132.0	465
129.0	53.04	23.33	134.0	474
131.0	53.85	23.73	136.0	483
133.0	54.69	24.16	138.0	493
135.0	55.57	24.59	140 0	503
137.0	56 48	25.05	142.0	513
139.0	57.43	25.53	144 0	524
141.0	58.42	26.02	146.0	535
143.0	59 45	26.53	148 0	547
145.0	60.52	27.07	150 0	559
147.0	61.64	27.63	152.0	572
149.0	62.80	28 21	154 0	585
151.0	64.01	28.81	156 0	599
153.0	65.27	29.44	158.0	613
155.0	66.57	30.10	160 0	628
157.0	67.94	30.78	162 0	643
159.0	69 35	31.49	164 0	659
161.0	70.83	32.22	166 0	676
163.0	72.36	32.99	168.0	693
165.0	73.96	33.79	170 0	711
167.0	75 63	34.62	172.0	730
169.0	77.36	35.49	174 0	750
171.0	79.16	36.39	176 0	770
173 0	81.04	37.33	178.0	792
175.0	82.99	38.30	180.0	814
177.0	85 02	39.32	182 0	837
179.0	87.13	40.38	184 0	861
181.0	89 34	41.48	186.0	886
183.0	91 63	42.62	188 0	912
185 0	94.01	43.81	190 0	939
187.0	96 49	45.05	192 0	967
189 0	99.08	46.35	194.0	996
191.0	101.76	47.69	196.0	1,027
193 0	104.56	49.09	198.0	1,058
195.0	107.48	50.55	200.0	1,092
197 0	110 51	52.08	202.0	1,126
199 0	113.66	53 64	204 0	1,162
201.0	116.94	55.28	206.0	1,199
203.0	120.36	56.99	208.0	1,238
205.0	123.92	58.77	210.0	1,278
207.0	127 62	60 62	212.0	1,320

Table 8: CNS Bottom Head, Curve B for All EFPY

Plant =	CNS	
Component =	Bottom Head	(penetrations portion)
Bottom Head thickness, t =	6.813	inches
Bottom Head Radius, R =	110.5	inches
ART =	28.0	°F ======> **All EFPY**
K_{It} =	1.73	ksi*inch$^{1/2}$
Safety Factor =	2.00	
Stress Concentration Factor =	3.00	(bottom head penetrations)
M_m =	2.417	
Temperature Adjustment =	5.0	°F (applied after bolt-up, instrument uncertainty)
Height of Water for a Full Vessel =	831.75	inches
Pressure Adjustment =	30.0	psig (hydrostatic pressure head for a full vessel at 70°F)
Pressure Adjustment =	25.0	psig (instrument uncertainty)
Heat Up and Cool Down Rate =	100	°F/Hr

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Im} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65.0	76.66	37.46	70	0
65.0	76.66	37.46	70	582
67.0	78.43	38.35	72	597
69.0	80.28	39.27	74	613
71.0	82.20	40.23	76	629
73.0	84.20	41.23	78	646
75.0	86.28	42.27	80	664
77.0	88.44	43.36	82	682
79.0	90.70	44.49	84	701
81.0	93.05	45.66	86	721
83.0	95.49	46.88	88	742
85.0	98.03	48.15	90	764
87.0	100.68	49.47	92	786
89.0	103.43	50.85	94	810
91.0	106.30	52.28	96	834
93.0	109.28	53.78	98	859
95.0	112.38	55.33	100	886
97.0	115.62	56.94	102	913
99.0	118.98	58.63	104	942
101.0	122.48	60.38	106	972
103.0	126.12	62.20	108	1,003
105.0	129.92	64.09	110	1,035
107.0	133.86	66.07	112	1,068
109.0	137.97	68.12	114	1,103
111.0	142.25	70.26	116	1,140
113.0	146.70	72.48	118	1,178
115.0	151.33	74.80	120	1,217
117.0	156.15	77.21	122	1,258

Table 9: CNS Bottom Head-CDP Nozzle, Curve B for All EFPY

Plant =	CNS		
Component =	Core Differential Pressure Nozzle		
ART =	28.00	°F ======>	ALL EFPY
Heat up/Cool down Rate	100.00	°F/hr	
Nominal Vessel Radius, R =	110.50	inches	
Vessel Thickness, t_v	3.19	inches	
Nozzle Thickness, t_n	0.28	inches	
K_{It} =	1.73	ksi*inch$^{1/2}$	
$K_{Ip\text{-}applied}$ =	35.17	ksi*inch$^{1/2}$	
Height of Water for a Full Vessel =	831.75	inches	
Reference Pressure =	1000.00	psig	
Pressure Adjustment =	30.04	psig (hydrostatic pressure head for a full vessel at 70°F)	
Pressure Adjustment =	25.00	psig (instrument uncertainty)	

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Ip} (ksi*inch$^{1/2}$)	Temperature for P-T Curve (°F)	Adjusted Pressure for P-T Curve (psig)
65.0	76.66	37.46	70.0	0
65.0	76.66	37.46	70.0	1,010
67.0	78.43	38.35	72.0	1,035
69.0	80.28	39.27	74.0	1,062
71.0	82.20	40.23	76.0	1,089
73.0	84.20	41.23	78.0	1,117
75.0	86.28	42.27	80.0	1,147
77.0	88.44	43.36	82.0	1,178
79.0	90.70	44.49	84.0	1,210
81.0	93.05	45.66	86.0	1,243
83.0	95.49	46.88	88.0	1,278
85.0	98.03	48.15	90.0	1,314
87.0	100.68	49.47	92.0	1,352
89.0	103.43	50.85	94.0	1,391
91.0	106.30	52.28	96.0	1,431
93.0	109.28	53.78	98.0	1,474
95.0	112.38	55.33	100.0	1,518
97.0	115.62	56.94	102.0	1,564

Table 10: CNS Upper Vessel, Curve B for All EFPY

Plant =	CNS		
Component =	Upper Vessel		
ART =	20.0	°F ======>	All EFPY
Vessel Radius, R =	110.375	inches	
Nozzle corner thickness, t =	5.753	inches, approximate	
K_{It} =	63.45	ksi*inch$^{1/2}$	
$K_{Ip\text{-}applied}$ =	38.90	ksi*inch$^{1/2}$	
Crack Depth, a =	1.438	inches	
Safety Factor =	2.00		
Temperature Adjustment =	5.0	°F (applied after bolt-up, instrument uncertainty)	
Height of Water for a Full Vessel =	831.75	inches	
Pressure Adjustment =	30.0	psig (hydrostatic pressure head for a full vessel at 70°F)	
Pressure Adjustment =	25.0	psig (instrument uncertainty)	
Reference Pressure =	1,000	psig (pressure at which the FEA stress coefficients are valid)	
Unit Pressure =	1,563	psig (hydrostatic pressure)	
Flange RT_{NDT} =	20.0	°F ======>	All EFPY

Gauge Fluid Temperature (°F)	K_{Ic} (ksi*inch$^{1/2}$)	K_{Ip} (ksi*inch$^{1/2}$)	P-T Curve Temperature (°F)	P-T Curve Pressure (psig)
65.0	84.20	10.37	70	0
65.0	84.20	19.46	70	313
67.0	86.28	20.51	140	313
69.0	88.44	19.26	140	440
71.0	90.70	20.06	140	461
73.0	93.05	20.91	140	482
75.0	95.49	21.80	140	505
77.0	98.03	22.73	140	529
79.0	100.68	23.71	140	554
81.0	103.43	24.74	140	581
83.0	106.30	25.82	140	609
85.0	109.28	26.95	140	638
87.0	112.38	28.15	140	668
89.0	115.62	29.40	140	701
91.0	118.98	30.71	140	734
93.0	122.48	32.09	140	770
95.0	126.12	33.54	140	807
97.0	129.92	35.04	140	846
99.0	133.86	36.63	140	887
101.0	137.97	38.30	140	929
103.0	142.25	40.04	140	974
105.0	146.70	41.87	140	1021
107.0	151.33	43.79	140	1071
109.0	156.15	45.80	140	1122
111.0	161.17	47.90	140	1176
113.0	166.39	50.10	140	1233
115.0	171.83	52.39	140	1292

Table 11: CNS Curve C for 32 EFPY

Plant =	CNS	
Curve A Leak Test Temperature =	148.0	°F
Curve A Pressure =	1,100.0	psig
Unit Pressure =	1,563	psig (hydrostatic pressure)
Flange RT_{NDT} =	20.0	°F

P-T Curve Temperature	P-T Curve Pressure
80.00	0
80.00	50
80.00	100
80.00	150
80.00	200
88.08	250
95.00	300
95.00	312
180.00	313
180.00	350
180.00	400
180.00	450
180.00	500
180.00	550
180.00	600
180.00	650
183.34	700
188.60	750
193.35	800
197.70	850
201.70	900
205.40	950
208.84	1000
212.07	1050
215.09	1100
217.96	1150
220.65	1200
223.21	1250
225.65	1300

Table 12: CNS Curve C for 54 EFPY

Plant =	CNS	
Curve A Leak Test Temperature =	174.0	°F
Curve A Pressure =	1,100.0	psig
Unit Pressure =	1,563	psig (hydrostatic pressure)
Flange RT_{NDT} =	20.0	°F

P-T Curve Temperature	P-T Curve Pressure
80.00	0
80.00	50
80.00	100
80.00	150
80.00	200
88.08	250
99.65	300
110.24	312
180.00	313
180.00	350
180.00	400
180.00	450
180.00	500
188.52	550
196.21	600
202.86	650
208.74	700
214.01	750
218.75	800
223.10	850
227.09	900
230.79	950
234.25	1000
237.47	1050
240.49	1100
243.35	1150
246.06	1200
248.61	1250
251.05	1300

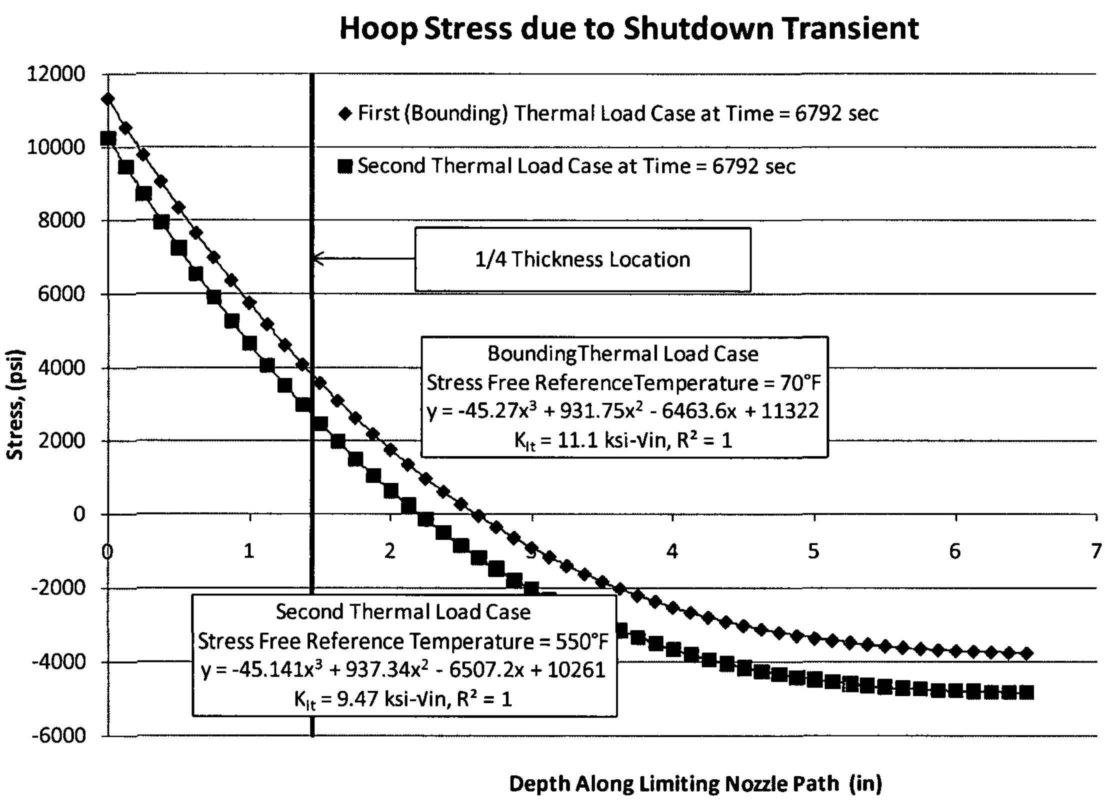

Figure 1: Feedwater Nozzle Path Stress Distribution

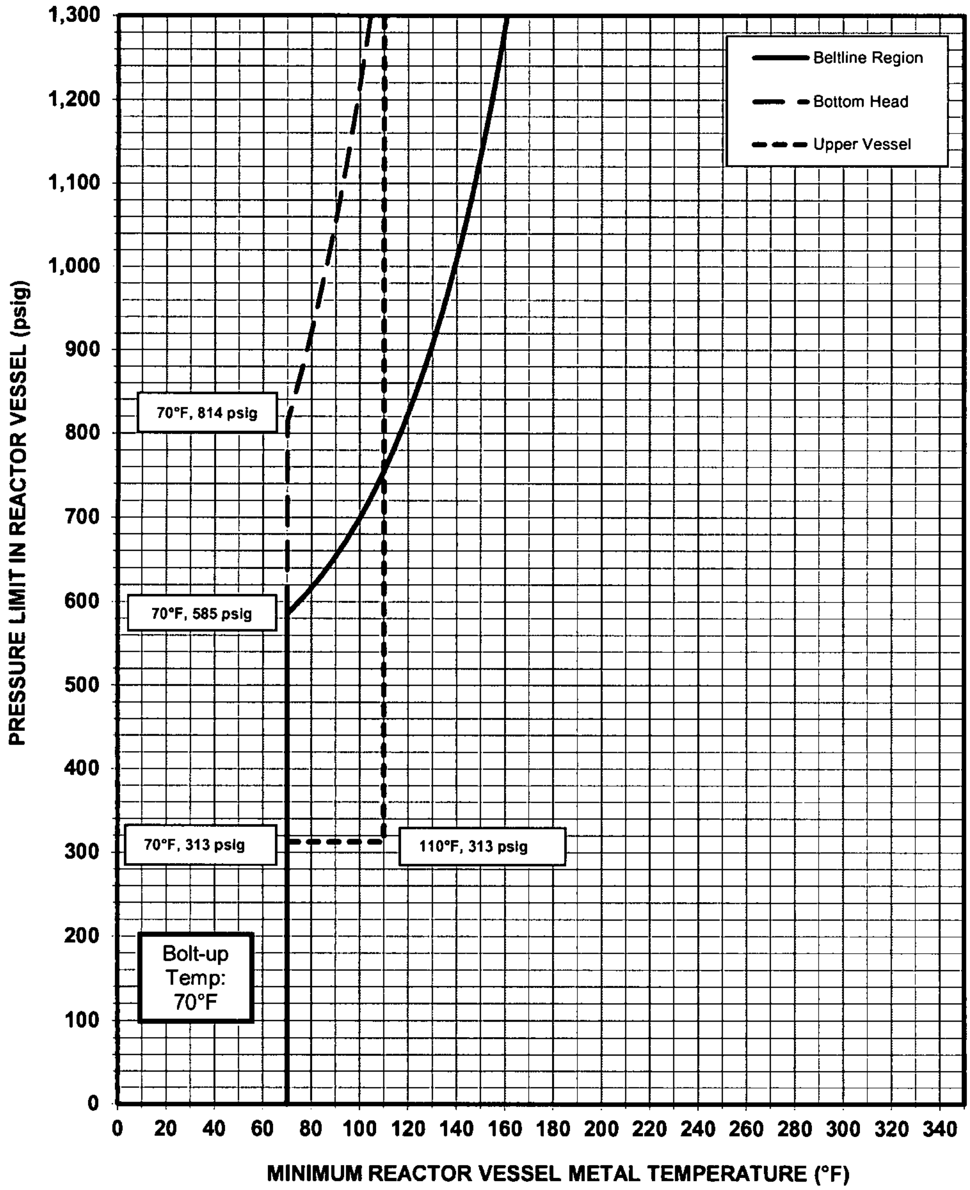

Figure 2: CNS (Hydrostatic Pressure and Leak Test) P-T Curve A for 32 EFPY

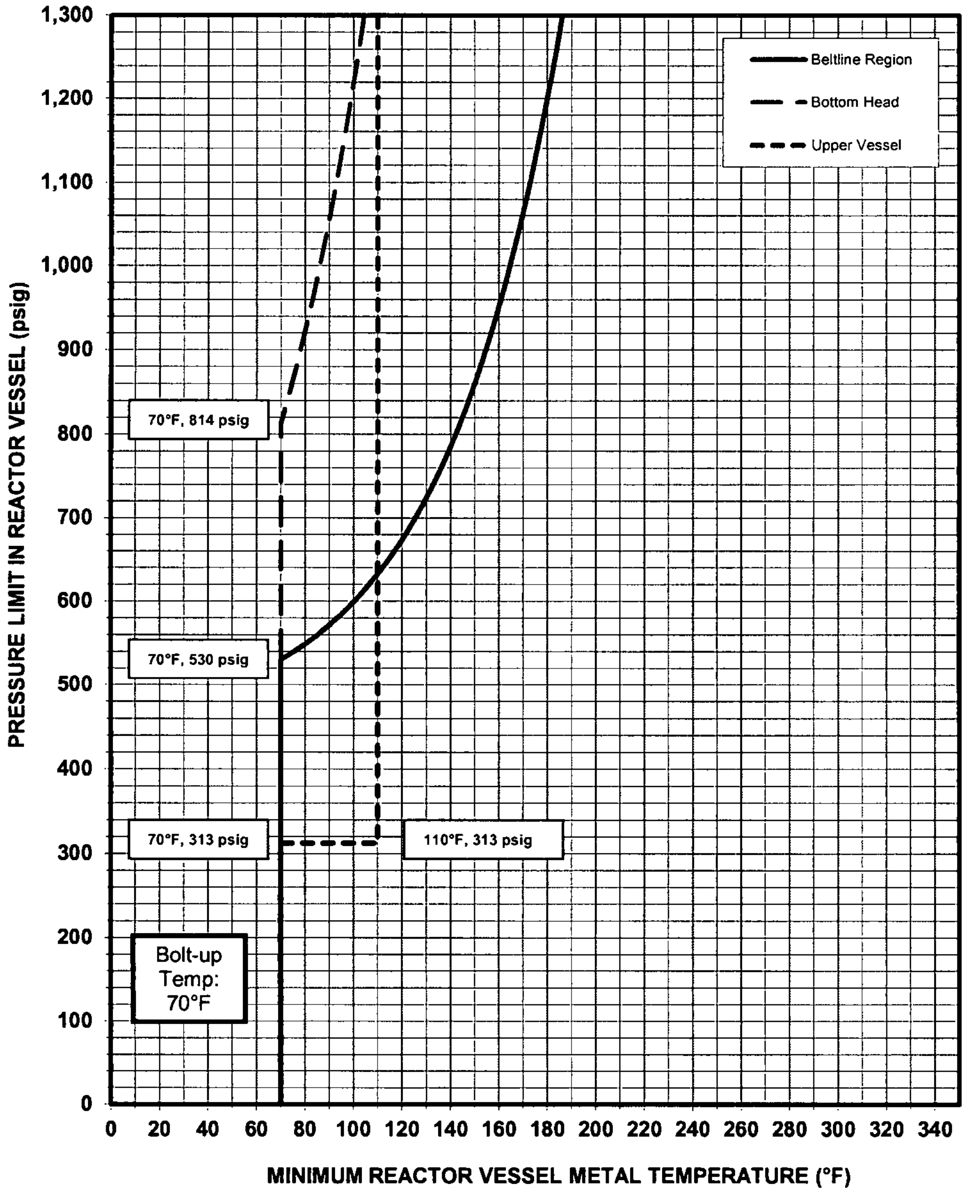

Figure 3: CNS (Hydrostatic Pressure and Leak Test) P-T Curve A for 54 EFPY

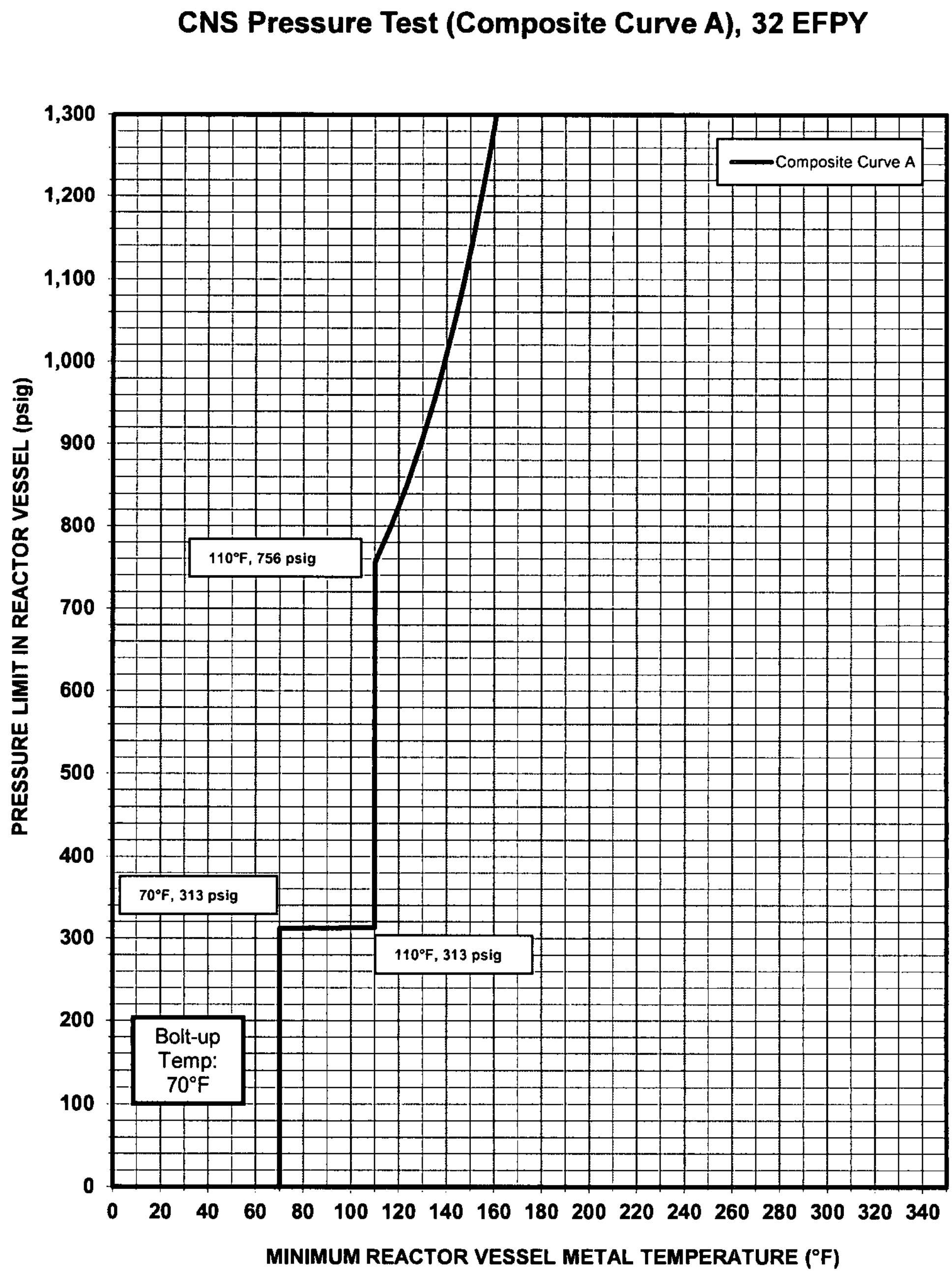

Figure 4: CNS (Hydrostatic Pressure and Leak Test) Composite P-T Curve A for 32 EFPY

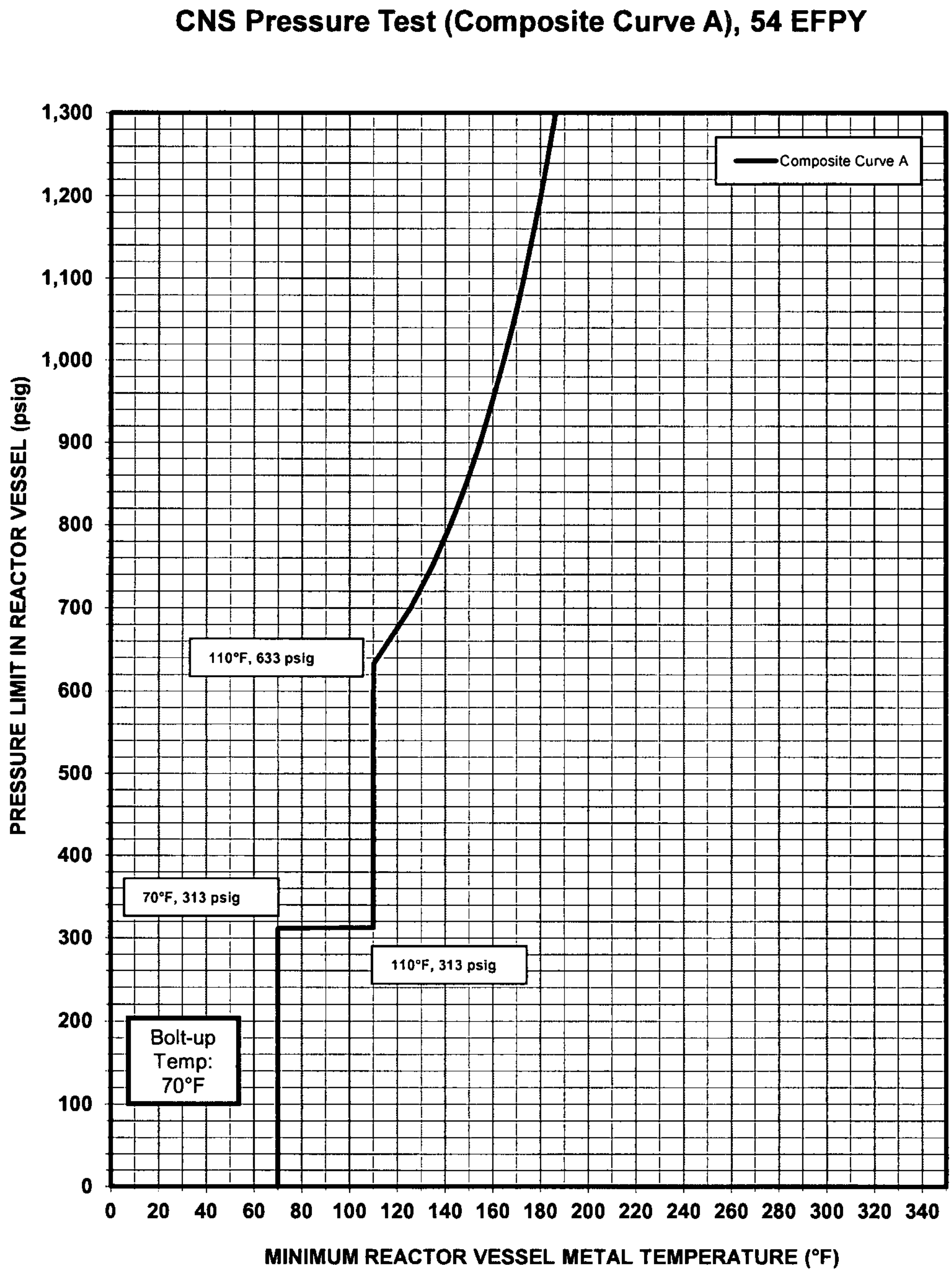

Figure 5: CNS (Hydrostatic Pressure and Leak Test) Composite P-T Curve A for 54 EFPY

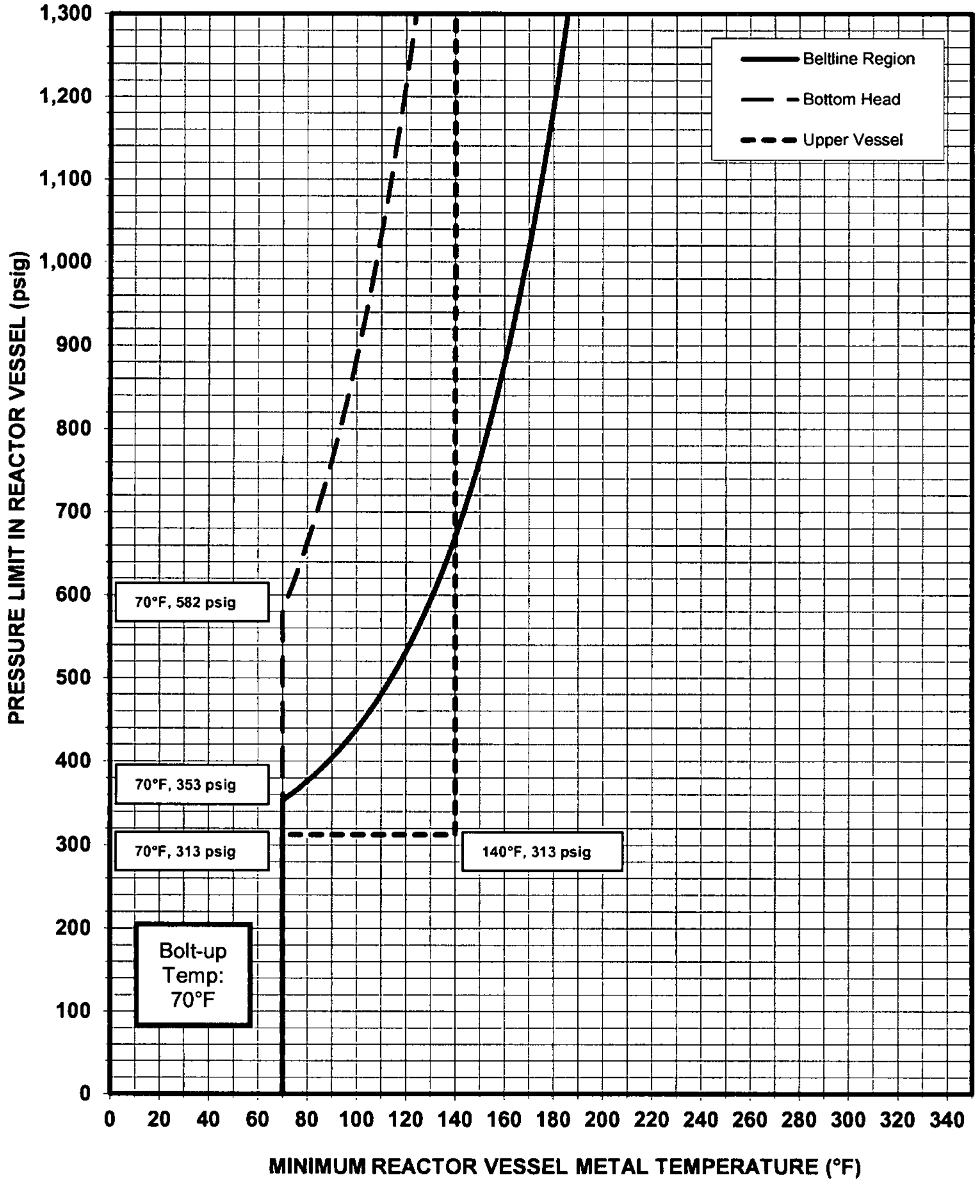

Figure 6: CNS P-T Curve B (Normal Operation – Core Not Critical) for 32 EFPY

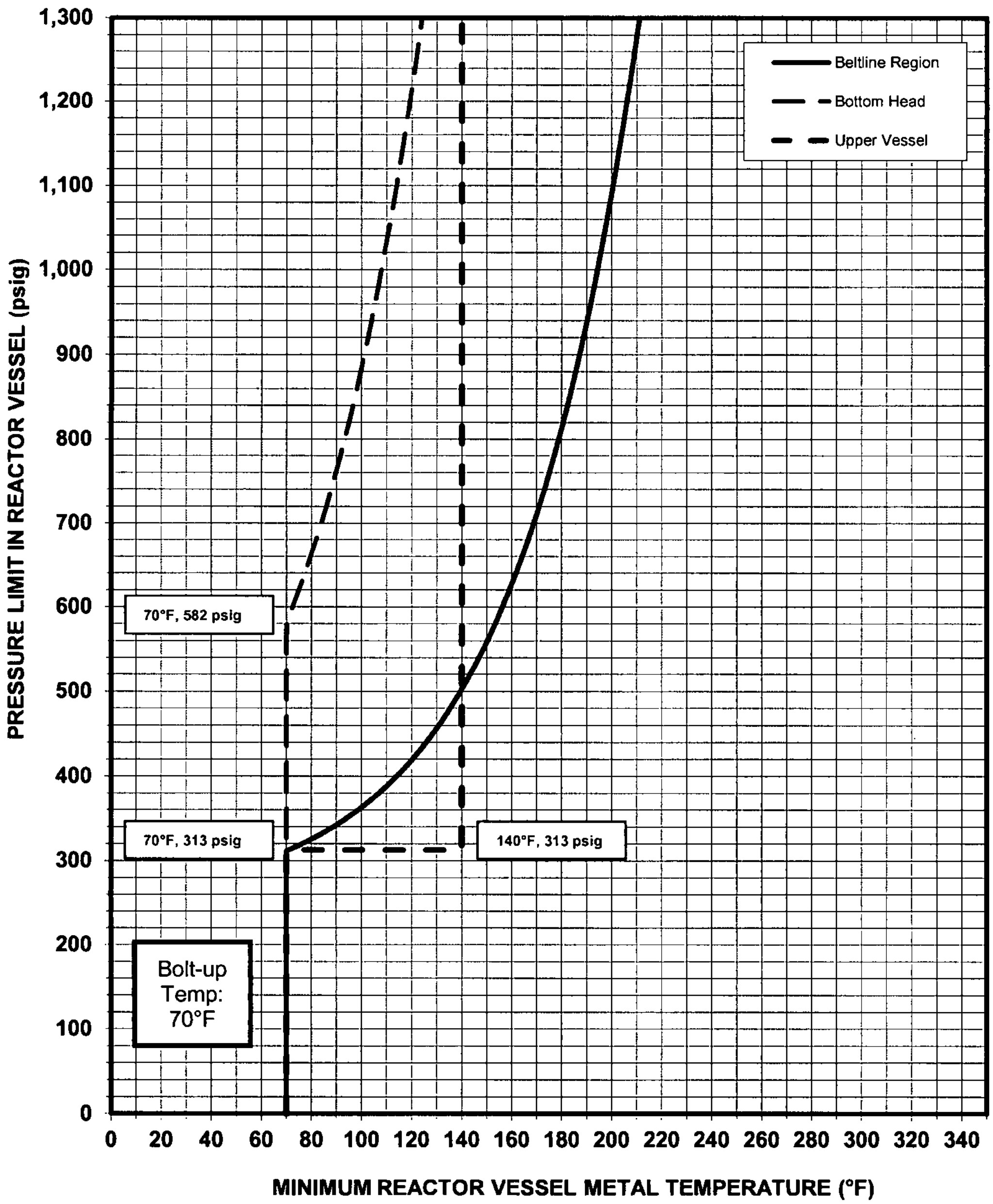

Figure 7: CNS P-T Curve B (Normal Operation – Core Not Critical) for 54 EFPY

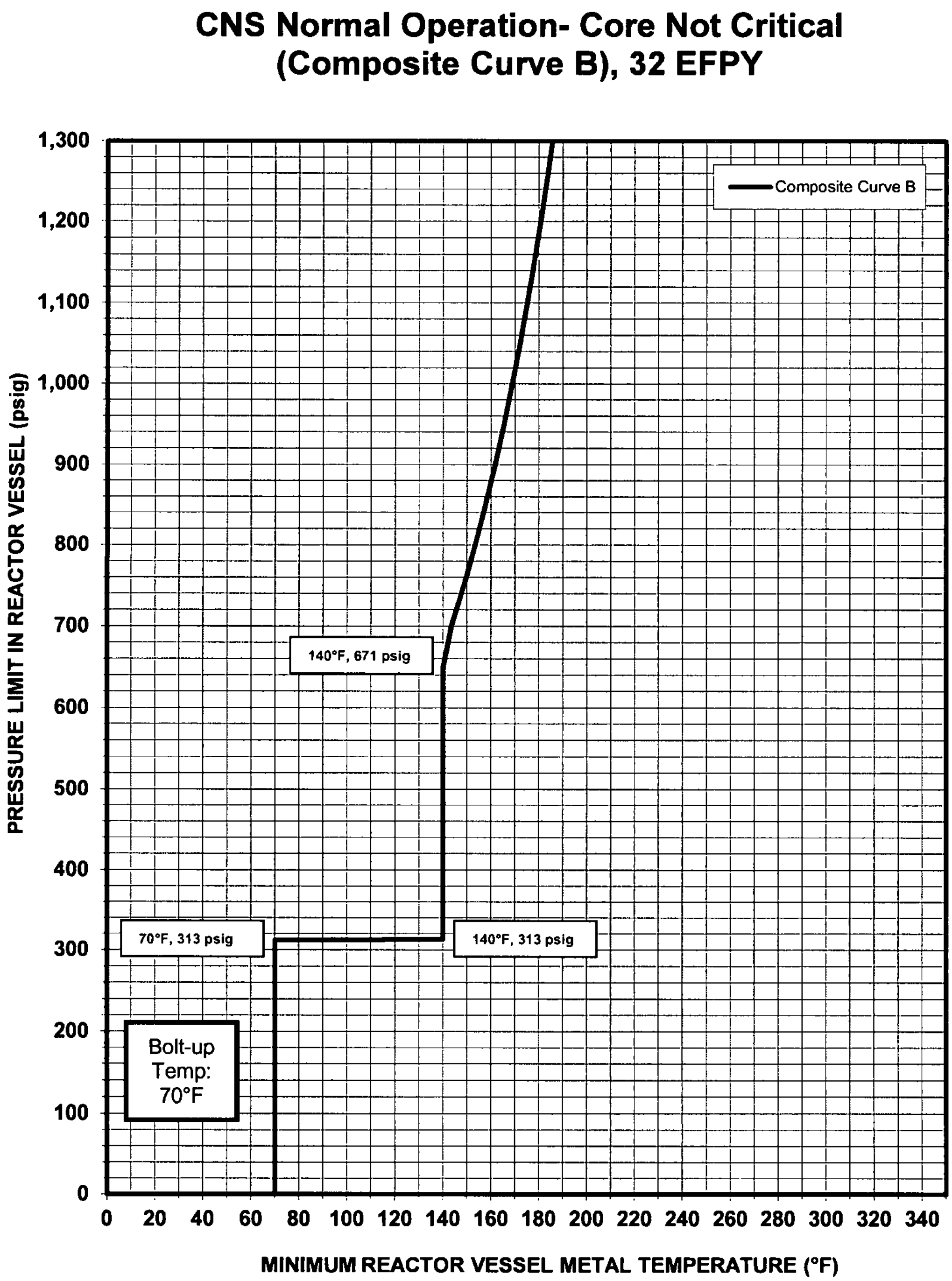

Figure 8: CNS (Normal Operation – Core Not Critical) Composite P-T Curve B for 32 EFPY

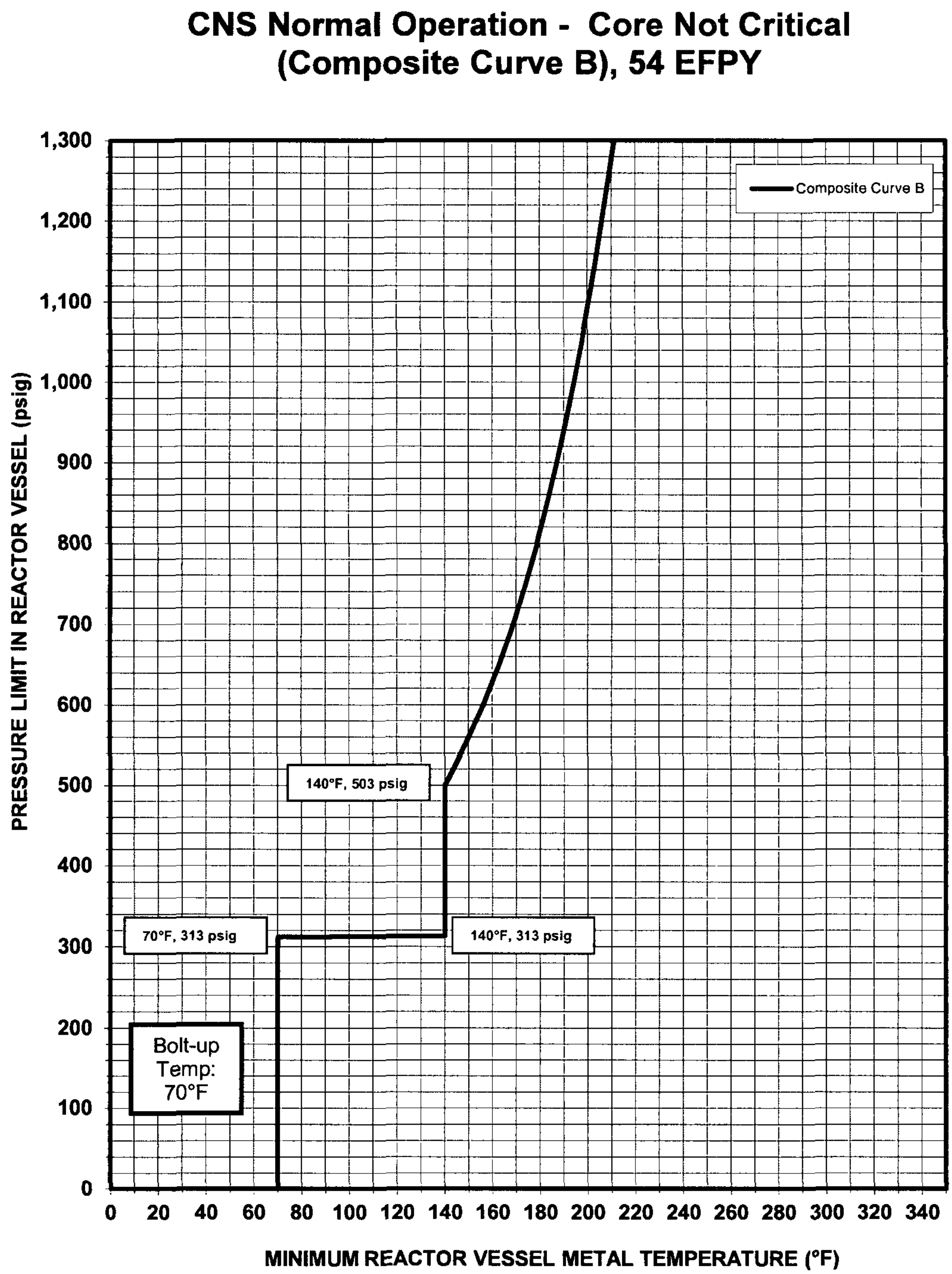

Figure 9: CNS (Normal Operation – Core Not Critical) Composite P-T Curve B for 54 EFPY

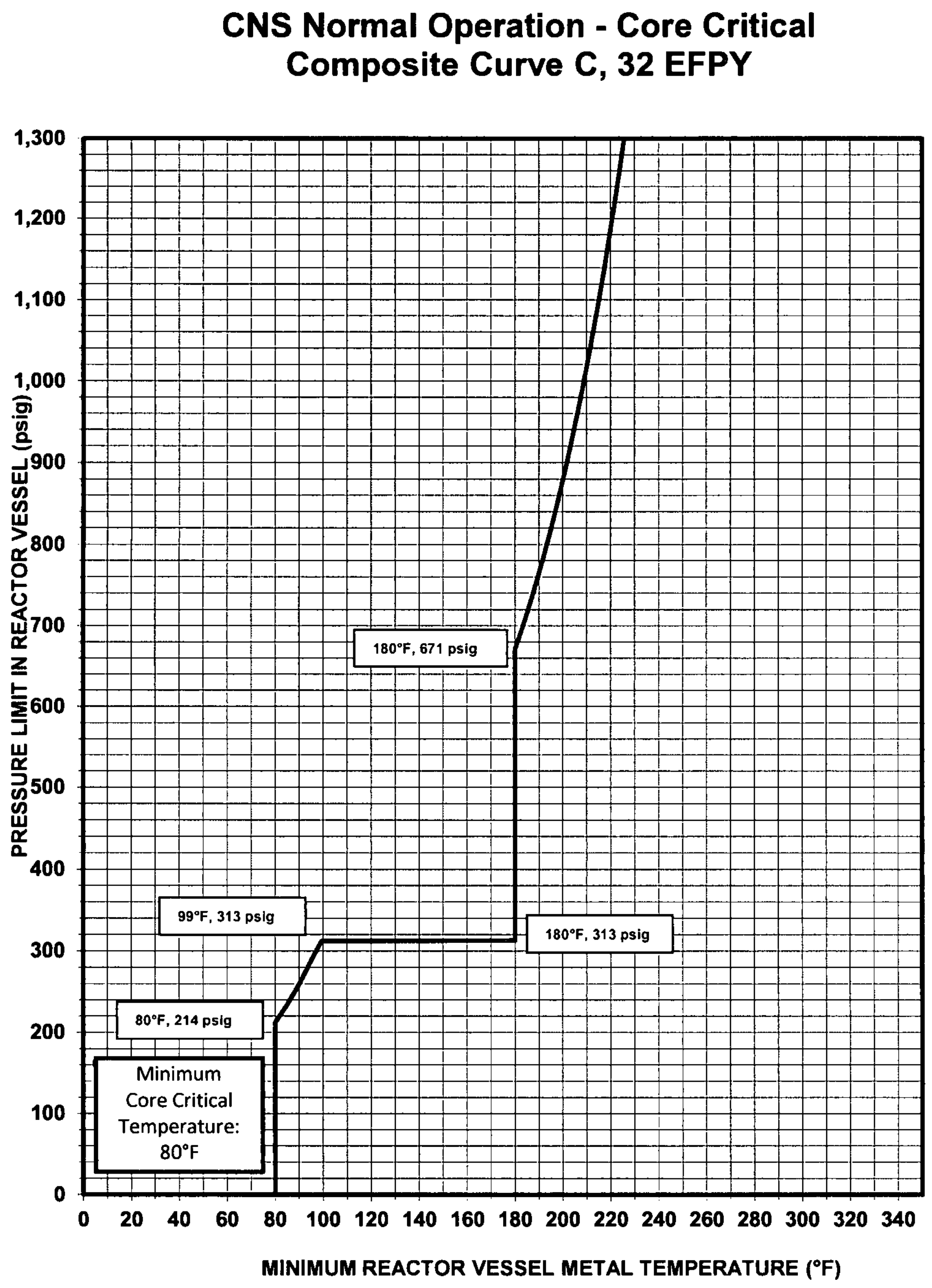

Figure 10: CNS P-T Curve C (Normal Operation – Core Critical) for 32 EFPY

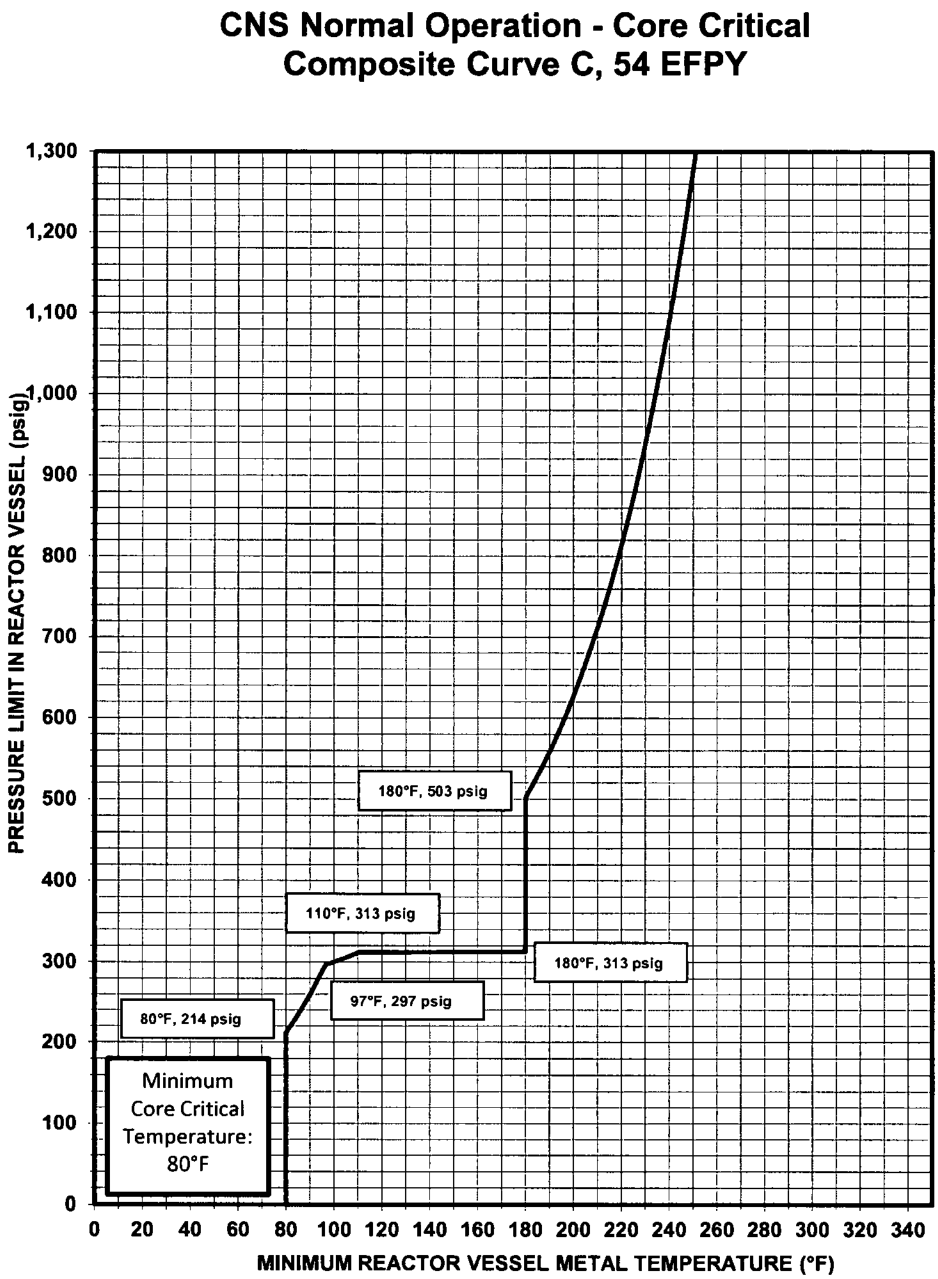

Figure 11: CNS P-T Curve C (Normal Operation – Core Critical) for 54 EFPY

APPENDIX A:

P – T CURVE INPUT LISTING

32 EFPY Input Listing:

P-T Curve Inputs

Instrument Uncertainty			**Reference:**
	Reactor Vessel Metal Temp	5 °F	[10]
	Reactor Vessel Pressure	25 psig	[10]
Geometry			
	Vessel Radius	110.375 in.	[8]
	Vessel Shell thickness	5.375 in.	[8]
	Bottom Head Thickness	6.8125 in.	[8]
	Bottom Head Radius	110.5 in.	[8]
	Feedwater Nozzle Thickness	10.87 in.	[15]
	Bottom Head Thickness (CDP Nozzle)	3.1875 in.	[8]
	Core Differential Pressure Nozzle Thickness	0.281 in.	[16]
ART/RT_{NDT}			
32 EFPY	Limiting Beltine	105.8 °F	[5]
	Limiting Bottom Head	28 °F	[7]
	Limiting Upper Vessel (Feedwater) RT_{NDT}	20 °F	[7]
	Flange Material (Bolt-up) RT_{NDT}	20 °F	[7]
Safety Factor/Stress Concentration Factor			
	Core Not Critical (Curve B) Core Critical (Curve C)	2	[3]
	Pressure (Curve A)	1.5	[3]
	Lower Penetrations (SCF)	3	[3]
K_{It}			
	During Pressure Test (near isothermal conditions)	0 ksi√in	[3]
Water			
	Density	62.4 lb/ft^3	Assumed
	Pressure	1250 psig	[9]
	Full Water Elevation (pressure head)	831.75 in	[11]
	Hydrostatic Test Pressure	1563 psig	Calculated
	Static Head Pressure Adjustment	30.0 psig	Calculated
Assumed Temperature			
	Bolt Up Temperature	70 °F	[12]
	Increment	2 °F	Assumed
Rate of Temp Change			
	Heat Up and Cool Down Rate	100 °F/hour	[8]

54 EFPY Input Listing:

P-T Curve Inputs

			Reference:
Instrument Uncertainty			
	Reactor Vessel Metal Temp	5 °F	[10]
	Reactor Vessel Pressure	25 psig	[10]
Geometry			
	Vessel Radius	110.375 in.	[8]
	Vessel Shell thickness	5.375 in.	[8]
	Bottom Head Thickness	6.8125 in.	[8]
	Bottom Head Radius	110.5 in.	[8]
	Feedwater Nozzle Thickness	10.87 in.	[15]
	Bottom Head Thickness (CDP Nozzle)	3.1875 in.	[8]
	Core Differential Pressure Nozzle Thickness	0.281 in.	[16]
ART/RT_{NDT}			
54 EFPY	Limiting Beltine	131.2 °F	[5]
	Limiting Bottom Head	28 °F	[7]
	Limiting Upper Vessel (Feedwater) RT_{NDT}	20 °F	[7]
	Flange Material (Bolt-up) RT_{NDT}	20 °F	[7]
Safety Factor/Stress Concentration Factor			
	Core Not Critical (Curve B) Core Critical (Curve C)	2	[3]
	Pressure (Curve A)	1.5	[3]
	Lower Penetrations (SCF)	3	[3]
K_{It}			
	During Pressure Test (near isothermal conditions)	0 ksi√in	[3]
Water			
	Density	62.4 lb/ft^3	Assumed
	Pressure	1250 psig	[9]
	Full Water Elevation (pressure head)	831.75 in	[11]
	Hydrostatic Test Pressure	1563 psig	Calculated
	Static Head Pressure Adjustment	30.0 psig	Calculated
Assumed Temperature			
	Bolt Up Temperature	70 °F	[12]
	Increment	2 °F	Assumed
Rate of Temp Change			
	Heat Up and Cool Down Rate	100 °F/hour	[8]