Westinghouse Non-Proprietary Class 3

WCAP-16305-NP
Revision 0

August 2004

V. C. Summer
Heatup and Cooldown Limit Curves for Normal Operation

Westinghouse

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AUGUST 2004

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PREFACE

This report has been technically reviewed and verified by:

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RECORD OF REVISION

Revision 0: Original Issue

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EXECUTIVE SUMMARY

This report provides the methodology and results of the generation of heatup and cooldown pressure temperature (PT) limit curves for normal operation of the V. C. Summer reactor vessel. The PT curves were generated based on the latest available reactor vessel information and updated calculated fluences. The new V. C. Summer heatup and cooldown pressure-temperature limit curves were generated using the "axial flaw" methodology of the 1998 ASME Code, Section XI through the 2000 Addenda[6.4]. Included in this methodology, is the use of the K_{IC} stress intensity factors, which was formerly documented under ASME Code Case N-641[6.3]. The material with the highest adjusted reference temperature (ART) was the Intermediate shell plate A9154-1. The PT limit curves were generated for 32 and 56 EFPY using heatup rates of 50 and 100°F/hr and cooldown rates of 0, 25, 50 and 100°F/hr. These curves can be found in Figures 1, 2, 3 and 4.

1. INTRODUCTION & PURPOSE

Heatup and cooldown limit curves are calculated using the adjusted RT_{NDT} (reference nil-ductility temperature) corresponding to the limiting beltline region material of the reactor vessel. The adjusted RT_{NDT} of the limiting material in the core region of the reactor vessel is determined by using the unirradiated reactor vessel material fracture toughness properties, estimating the radiation-induced ΔRT_{NDT}, and adding a margin. The unirradiated RT_{NDT} is designated as the higher of either the drop weight nil-ductility transition temperature (NDTT) or the temperature at which the material exhibits at least 50 ft-lbs of impact energy and 35-mil lateral expansion (normal to the major working direction) minus 60°F.

RT_{NDT} increases as the material is exposed to fast-neutron radiation. Therefore, to find the most limiting RT_{NDT} at any time period in the reactor's life, ΔRT_{NDT} due to the radiation exposure associated with that time period must be added to the unirradiated RT_{NDT} (IRT_{NDT}). The extent of the shift in RT_{NDT} is enhanced by certain chemical elements (such as copper and nickel) present in reactor vessel steels. The Nuclear Regulatory Commission (NRC) has published a method for predicting radiation embrittlement in Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials"[6.1]. Regulatory Guide 1.99, Revision 2, is used for the calculation of Adjusted Reference Temperature (ART) values (IRT_{NDT} + ΔRT_{NDT} + margins for uncertainties) at the 1/4T and 3/4T locations, where T is the thickness of the vessel at the beltline region measured from the clad/base metal interface.

The heatup and cooldown curves documented in this report were generated using the most limiting ART values and the NRC approved methodology documented in WCAP-14040-NP-A, Revision 4[6.2], "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves".

The purpose of this report is to present the calculations and the development of the V. C. Summer heatup and cooldown curves for 32 and 56 EFPY. This report documents the calculated ART values and the development of the PT limit curves for normal operation. The PT curves herein were generated without margins for instrumentation errors. The PT curves include a hydrostatic leak test limit curve from 2485 psig to 2000 psig, along with the pressure-temperature limits for the vessel flange region per the requirements of 10 CFR Part 50, Appendix G[6.5].

2. FRACTURE TOUGHNESS PROPERTIES

The fracture-toughness properties of the ferritic materials in the reactor coolant pressure boundary are determined in accordance with the NRC Standard Review Plan[6.6]. The beltline material properties of the V. C. Summer reactor vessel are presented in Table 1.

Best estimate copper (Cu) and nickel (Ni) weight percent values used to calculate chemistry factors (CF) in accordance with Regulatory Guide 1.99, Revision 2, are provided in Table 1. Additionally, surveillance capsule data is available for five capsules (Capsules U, V, X, W and Z) already removed from the V. C. Summer reactor vessel. This surveillance capsule data was also used to calculate CF values per Position 2.1 of Regulatory Guide 1.99, Revision 2 in Table 3. These CF values are summarized in Table 4.

The Regulatory Guide 1.99, Revision 2 methodology used to develop the heatup and cooldown curves documented in this report is the same as that documented in WCAP-14040, Revision 4[6.2].

TABLE 1

Summary of the Best Estimate Cu and Ni Weight Percent and Initial RT_{NDT} Values for the V. C. Summer Reactor Vessel Materials

Material Description	**Cu (%)**	**Ni(%)**	**Initial RT_{NDT}[(a)]**
Closure Head Flange 5297-V1[(b)]	--	--	10°F[(b)]
Vessel Flange 5301-V-1	--	--	0°F[(b)]
Intermediate Shell Plate A9154-1	0.10	0.51	30°F
Intermediate Shell Plate A9153-2	0.09	0.45	-20°F
Lower Shell Plate C9923-1	0.08	0.41	10°F
Lower Shell Plate C9923-2	0.08	0.41	10°F
Intermediate Shell Longitudinal Weld Seams BC & BD	0.05	0.91	-44°F
Intermediate Shell Longitudinal Weld Seams BA & BB	0.05	0.91	-44°F
Intermediate to Lower Shell Plate Circumferential Weld Seam AB	0.05	0.91	-44°F
Surveillance Program Weld Metal	0.04	0.95	---

(a) The initial RT_{NDT} values for the plates and welds are based on measured data per WCAP-12867[6,7]

(b) In the past the closure head flange was reported as Heat A9231 with an IRT_{NDT} of -20°F. Based on a review of Westinghouse files, the correct data is Heat # 5297-V1 with an IRT_{NDT} of 10°F. Also, the vessel flange reported an IRT_{NDT} of 10°F., however, based on a review Westinghouse files, the correct IRT_{NDT} is 0°F.

The chemistry factors are calculated using Regulatory Guide 1.99 Revision 2, Positions 1.1 and 2.1. Position 1.1 uses the Tables from the Reg. Guide along with the best estimate copper and nickel weight percents. Position 2.1 uses the surveillance capsule data from all capsules withdrawn to date. The fluence values used to determine the CFs in Table 3 are the calculated fluence values at the surveillance capsule locations. Hence, the calculated fluence values were used for all cases. Included in Table 2 are the calculated fluence values for V. C. Summer. All capsule fluence values were determined using ENDF/B-VI cross-sections and followed the guidance in Regulatory Guide 1.190[6.10].

It should be noted that in the calculation of chemistry factor in Table 3, the ratio was applied to account for chemistry differences between the vessel weld material and the surveillance weld material. As for temperature adjustments, the V. C. Summer data does not require any adjustments since it is being applied to its own plant.

TABLE 2
Calculated Integrated Neutron Exposure of the Surveillance Capsules @ V. C. Summer

Capsule	Fluence[a]
U	6.77×10^{18} n/cm^2, (E > 1.0 MeV)
V	1.56×10^{19} n/cm^2, (E > 1.0 MeV)
X	2.53×10^{19} n/cm^2, (E > 1.0 MeV)
W	4.63×10^{19} n/cm^2, (E > 1.0 MeV)
Z	6.54×10^{19} n/cm^2, (E > 1.0 MeV)

(a) Per Capsule Z Report, WCAP-16298[6.8]

TABLE 3

Calculation of Chemistry Factors using V. C. Summer Surveillance Capsule Data

Material	Capsule	Capsule $f^{(a)}$	$FF^{(b)}$	$\Delta RT_{NDT}{}^{(c)}$	$FF*\Delta RT_{NDT}$	FF^2
Intermediate Shell	U	0.677	0.891	36.1	32.2	0.793
Plate A9154-1	V	1.56	1.123	53.2	59.7	1.261
(Longitudinal)	X	2.53	1.249	38.3	47.8	1.560
	W	4.63	1.387	66.2	91.8	1.924
	Z	6.54	1.452	98.9	143.6	2.108
Intermediate Shell	U	0.677	0.891	14.5	12.9	0.793
Plate A9154-1	V	1.56	1.123	32.1	36.0	1.261
(Transverse)	X	2.53	1.249	26.7	33.3	1.560
	W	4.63	1.387	57.8	80.2	1.924
	Z	6.54	1.452	87.0	126.3	2.108
				SUM:	663.8	15.292
	$CF_{A9154\text{-}1} = \Sigma(FF * RT_{NDT}) \div \Sigma(FF^2) = (663.8) \div (15.292) =$ **43.4°F**					
Surveillance Weld	U	0.677	0.891	28.6 (22.7)(d)	25.4	0.793
Material	V	1.56	1.123	59.2 (47.0)(d)	66.5	1.261
	X	2.53	1.249	28.6 (22.7)(d)	35.7	1.560
	W	4.63	1.387	54.8 (43.5)(d)	76.0	1.924
	Z	6.54	1.452	82.2 (65.2)(d)	119.3	2.108
				SUM:	323.0	7.646
	$CF_{Surv. Weld} = \Sigma(FF * RT_{NDT}) \div \Sigma(FF^2) = (323.0) \div (7.646) =$ **42.2°F**					

(a) f = fluence. See Table 2, [x 10^{19} n/cm^2, E > 1.0 MeV]

(b) FF = fluence factor = $f^{(0.28 - 0.1*\log f)}$

(c) ΔRT_{NDT} values are the measured 30 ft-lb shift values taken from Capsule Z Report, WCAP-16298[6.8], Appendix B [°F]

(d) The Surveillance Weld ΔRT_{NDT} values have been adjusted by a ratio of 1.26, Pre-adjusted values in parenthesis

TABLE 4
Summary of the V. C. Summer Reactor Vessel Beltline Material Chemistry Factors

Material	Reg. Guide 1.99, Rev. 2 Position 1.1 CF's	Reg. Guide 1.99, Rev. 2 Position 2.1 CF's
Intermediate Shell Plate A9154-1	65.0°F	43.4°F[(a)]
Intermediate Shell Plate A9153-2	58.0°F	---
Lower Shell Plate C9923-1	51.0°F	---
Lower Shell Plate C9923-2	51.0°F	---
Intermediate Shell Longitudinal Weld Seams BC & BD	68.0°F	42.2°F[(a)]
Lower Shell Longitudinal Weld Seams BA & BB	68.0°F	42.2°F[(a)]
Intermediate to Lower Shell Plate Circumferential Weld Seam AB	68.0°F	42.2°F[(a)]

(a) See Capsule Z Report, WCAP-16298[6.8], for the credibility evaluation of the V.C. Summer Unit 1 surveillance data. The Intermediate Shell Plate A9154-1 was deemed "non-credible" while the weld was deemed "credible".

3. CRITERIA FOR ALLOWABLE PRESSURE-TEMPERATURE RELATIONSHIPS

3.1 OVERALL APPROACH

The ASME approach for calculating the allowable limit curves for various heatup and cooldown rates specifies that the total stress intensity factor, K_I, for the combined thermal and pressure stresses at any time during heatup or cooldown cannot be greater than the reference stress intensity factor, K_{Ic}, for the metal temperature at that time. K_{Ic} is obtained from the reference fracture toughness curve, defined in Code Case N-641, "Alternative Pressure-Temperature Relationship and Low Temperature Overpressure Protection System Requirements Section XI, Division 1"[6.3 & 6.4] of the ASME Appendix G to Section XI. The K_{Ic} curve is given by the following equation:

$$K_{Ic} = 33.2 + 20.734 * e^{[0.02(T - RT_{NDT})]} \qquad (1)$$

where,

K_{Ic} = reference stress intensity factor as a function of the metal temperature T and the metal reference nil-ductility temperature RT_{NDT}

This K_{Ic} curve is based on the lower bound of static critical K_I values measured as a function of temperature on specimens of SA-533 Grade B Class1, SA-508-1, SA-508-2, SA-508-3 steel.

3.2 METHODOLOGY FOR PRESSURE-TEMPERATURE LIMIT CURVE DEVELOPMENT

The governing equation for the heatup-cooldown analysis is defined in Appendix G of the ASME Code as follows:

$$C^* K_{Im} + K_{It} < K_{Ic} \qquad (2)$$

where,

K_{Im} = stress intensity factor caused by membrane (pressure) stress

K_{It} = stress intensity factor caused by the thermal gradients

K_{Ic} = function of temperature relative to the RT_{NDT} of the material

C = 2.0 for Level A and Level B service limits

C = 1.5 for hydrostatic and leak test conditions during which the reactor core is not critical

For membrane tension, the corresponding K_I for the postulated defect is:

$$K_{Im} = M_m \times (pR_i / t) \qquad (3)$$

where, M_m for an inside surface flaw is given by:

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 $\sqrt{t} > 3.464$

Similarly, M_m for an outside surface flaw is given by:

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

and p = internal pressure, Ri = vessel inner radius and t = vessel wall thickness.

For bending stress, the corresponding K_I for the postulated defect is:

$K_{Ib} = M_b$ * Maximum Stress, where M_b is two-thirds of M_m

The maximum K_I produced by radial thermal gradient for the postulated inside surface defect of G-2120 is $K_{It} = 0.953 \times 10^{-3} \times CR \times t^{2.5}$, where CR is the cooldown rate in °F/hr., or for a postulated outside surface defect, $K_{It} = 0.753 \times 10^{-3} \times HU \times t^{2.5}$, where HU is the heatup rate in °F/hr.

The through-wall temperature difference associated with the maximum thermal K_I can be determined from Figure G-2214-1. The temperature at any radial distance from the vessel surface can be determined from Figure G-2214-2 for the maximum thermal K_I.

(a) The maximum thermal K_I relationship and the temperature relationship in Figure G-2214-1 are applicable only for the conditions given in G-2214.3(a)(1) and (2).

(b) Alternatively, the K_I for radial thermal gradient can be calculated for any thermal stress distribution and at any specified time during cooldown for a ¼-thickness inside surface defect using the relationship:

$$K_{It} = (1.0359C_0 + 0.6322C_1 + 0.4753C_2 + 0.3855C_3) * \sqrt{\pi a} \tag{4}$$

or similarly, K_{IT} during heatup for a ¼-thickness outside surface defect using the relationship:

$$K_{It} = (1.043C_0 + 0.630C_1 + 0.481C_2 + 0.401C_3) * \sqrt{\pi a} \tag{5}$$

where the coefficients C_0, C_1, C_2 and C_3 are determined from the thermal stress distribution at any specified time during the heatup or cooldown using the form:

$$\sigma(x) = C_0 + C_1(x/a) + C_2(x/a)^2 + C_3(x/a)^3 \tag{6}$$

and *x* is a variable that represents the radial distance from the appropriate (i.e., inside or outside) surface to any point on the crack front and *a* is the maximum crack depth.

Note, that equations 3, 4 and 5 were implemented in the OPERLIM computer code, which is the program used to generate the pressure-temperature (P-T) limit curves. No other changes were made to the OPERLIM computer code with regard to P-T calculation methodology. Therefore, the P-T curve methodology is unchanged from that described in WCAP-14040, "Methodology used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves"[6.2] with the exceptions just described above.

At any time during the heatup or cooldown transient, K_{Ic} is determined by the metal temperature at the tip of a postulated flaw at the 1/4T and 3/4T location, the appropriate value for RT_{NDT}, and the reference fracture toughness curve. The thermal stresses resulting from the temperature gradients through the vessel wall are calculated and then the corresponding (thermal) stress intensity factors, K_{It}, for the reference flaw are computed. From Equation 2, the pressure stress intensity factors are obtained and, from these, the allowable pressures are calculated.

For the calculation of the allowable pressure versus coolant temperature during cooldown, the reference flaw of Appendix G to the ASME Code is assumed to exist at the inside of the vessel wall. During cooldown, the controlling location of the flaw is always at the inside of the wall because the thermal gradients produce tensile stresses at the inside, which increase with increasing cooldown rates. Allowable pressure-temperature relations are generated for both steady-state and finite cooldown rate situations. From these relations, composite limit curves are constructed for each cooldown rate of interest.

The use of the composite curve in the cooldown analysis is necessary because control of the cooldown procedure is based on the measurement of reactor coolant temperature, whereas the limiting pressure is actually dependent on the material temperature at the tip of the assumed flaw. During cooldown, the 1/4T vessel location is at a higher temperature than the fluid adjacent to the vessel inner diameter. This condition, of course, is not true for the steady-state situation. It follows that, at any given reactor coolant temperature, the ΔT (temperature) developed during cooldown results in a higher value of K_{Ic} at the 1/4T location for finite cooldown rates than for steady-state operation. Furthermore, if conditions exist so that the increase in K_{Ic} exceeds K_{It}, the calculated allowable pressure during cooldown will be greater than the steady-state value.

The above procedures are needed because there is no direct control on temperature at the 1/4T location and, therefore, allowable pressures may unknowingly be violated if the rate of cooling is decreased at various intervals along a cooldown ramp. The use of the composite curve eliminates this problem and ensures conservative operation of the system for the entire cooldown period.

Three separate calculations are required to determine the limit curves for finite heatup rates. As is done in the cooldown analysis, allowable pressure-temperature relationships are developed for steady-state conditions as well as finite heatup rate conditions assuming the presence of a 1/4T defect at the inside of the wall. The heatup results in compressive stresses at the inside surface that alleviate the tensile stresses produced by internal pressure. The metal temperature at the crack tip lags the coolant temperature; therefore, the K_{Ic} for the 1/4T crack during heatup is lower than the K_{Ic} for the 1/4T crack during steady-state conditions at the same coolant temperature. During heatup, especially at the end of the transient, conditions may exist so that the effects of compressive thermal stresses and lower K_{Ic} values do not offset each other, and the pressure-temperature curve based on steady-state conditions no longer represents a lower bound of all similar curves for finite heatup rates when the 1/4T flaw is considered. Therefore, both cases have to be analyzed in order to ensure that at any coolant temperature the lower value of the allowable pressure calculated for steady-state and finite heatup rates is obtained.

The second portion of the heatup analysis concerns the calculation of the pressure-temperature limitations for the case in which a 1/4T flaw located at the 1/4T location from the outside surface is assumed. Unlike the situation at the vessel inside surface, the thermal gradients established at the outside surface during heatup produce stresses which are tensile in nature and therefore tend to reinforce any pressure stresses present. These thermal stresses are dependent on both the rate of heatup and the time (or coolant temperature) along the heatup ramp. Since the thermal stresses at the outside are tensile and increase with increasing heatup rates, each heatup rate must be analyzed on an individual basis.

Following the generation of pressure-temperature curves for both the steady-state and finite heatup rate situations, the final limit curves are produced by constructing a composite curve based on a point-by-point comparison of the steady-state and finite heatup rate data. At any given temperature, the allowable pressure is taken to be the lesser of the three values taken from the curves under consideration. The use of the composite curve is necessary to set conservative heatup limitations because it is possible for conditions to exist wherein, over the course of the heatup ramp, the controlling condition switches from the inside to the outside, and the pressure limit must at all times be based on analysis of the most critical criterion.

3.3 CLOSURE HEAD/VESSEL FLANGE REQUIREMENTS

10 CFR Part 50, Appendix G[6.5] addresses the metal temperature of the closure head flange and vessel flange regions. This rule states that the metal temperature of the closure flange regions must exceed the material unirradiated RT_{NDT} by at least 120°F for normal operation when the pressure exceeds 20 percent of the pre-service hydrostatic test pressure (3106 psi), which is 621 psig for V. C. Summer. The limiting unirradiated RT_{NDT} of 10°F occurs in the closure head flange of the V. C. Summer reactor vessel, so the minimum allowable temperature of this region is 130°F at pressures greater than 621 psig. This limit is shown in Figures 1, 2, 3 and 4 wherever applicable.

4. CALCULATION OF ADJUSTED REFERENCE TEMPERATURE

From Regulatory Guide 1.99, Revision 2, the adjusted reference temperature (ART) for each material in the beltline region is given by the following expression:

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin} \quad (7)$$

Initial RT_{NDT} is the reference temperature for the unirradiated material as defined in paragraph NB-2331 of Section III of the ASME Boiler and Pressure Vessel Code[6,9]. If measured values of initial RT_{NDT} for the material in question are not available, generic mean values for that class of material may be used if there are sufficient test results to establish a mean and standard deviation for the class.

ΔRT_{NDT} is the mean value of the adjustment in reference temperature caused by irradiation and should be calculated as follows:

$$\Delta RT_{NDT} = CF * f^{(0.28 - 0.10 \log f)} \quad (8)$$

To calculate ΔRT_{NDT} at any depth (e.g., at 1/4T or 3/4T), the following formula must first be used to attenuate the fluence at the specific depth.

$$f_{(depth\ x)} = f_{surface} * e^{(-0.24x)} \quad (9)$$

where x inches (vessel beltline thickness is 7.75 inches) is the depth into the vessel wall measured from the vessel clad/base metal interface. The resultant fluence is then placed in Equation 8 to calculate the ΔRT_{NDT} at the specific depth.

The Westinghouse Radiation Engineering and Analysis Group evaluated the vessel fluence projections and the results of the calculated peak fluence values at various azimuthal locations on the vessel clad/base metal interface are presented in Table 5. The evaluation used the ENDF/B-VI scattering cross-section data set. This is consistent with methods presented in WCAP-14040-NP-A. Tables 6 and 7 contain the 1/4T and 3/4T calculated fluences and fluence factors, per the Regulatory Guide 1.99, Revision 2, used to calculate the ART values for all beltline materials in the V. C. Summer reactor vessel at 32 and 56 EFPY.

TABLE 5
Summary of the Peak Pressure Vessel Neutron Fluence Values(a)
at the Clad/Base Metal Interface (n/cm^2, E > 1.0 MeV)

EFPY	Azimuthal Location			
	0°	15°	30°	45°
32	3.92×10^{19}	2.41×10^{19}	1.85×10^{19}	1.36×10^{19}
56	6.80×10^{19}	4.15×10^{19}	3.18×10^{19}	2.35×10^{19}

(a) Obtained from the Capsule Z Report, WCAP-16298[6.8]. These fluence projection are the calculated fluence projections determined following the methodology of Reg. Guide 1.190[6.10].

TABLE 6
Summary of the Vessel Surface, 1/4T and 3/4T Fluence Values
used for the Generation of the 32 EFPY Heatup/Cooldown Curves

Material	Surface (n/cm^2, E > 1.0 MeV)	1/4T (n/cm^2, E > 1.0 MeV)	3/4T (n/cm^2, E > 1.0 MeV)
Intermediate Shell Plate A9154-1	3.92×10^{19}	2.46×10^{19}	0.97×10^{19}
Intermediate Shell Plate A9153-2	3.92×10^{19}	2.46×10^{19}	0.97×10^{19}
Lower Shell Plate C9923-1	3.92×10^{19}	2.46×10^{19}	0.97×10^{19}
Lower Shell Plate C9923-2	3.92×10^{19}	2.46×10^{19}	0.97×10^{19}
Intermediate to Lower Shell Circumferential Weld Seam AB	3.92×10^{19}	2.46×10^{19}	0.97×10^{19}
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	1.36×10^{19}	0.85×10^{19}	0.34×10^{19}

TABLE 7
Summary of the Vessel Surface, 1/4T and 3/4T Fluence Values
used for the Generation of the 56 EFPY Heatup/Cooldown Curves

Material	Surface (n/cm^2, E > 1.0 MeV)	1/4T (n/cm^2, E > 1.0 MeV)	3/4T (n/cm^2, E > 1.0 MeV)
Intermediate Shell Plate A9154-1	6.80×10^{19}	4.27×10^{19}	1.69×10^{19}
Intermediate Shell Plate A9153-2	6.80×10^{19}	4.27×10^{19}	1.69×10^{19}
Lower Shell Plate C9923-1	6.80×10^{19}	4.27×10^{19}	1.69×10^{19}
Lower Shell Plate C9923-2	6.80×10^{19}	4.27×10^{19}	1.69×10^{19}
Intermediate to Lower Shell Circumferential Weld Seam AB	6.80×10^{19}	4.27×10^{19}	1.69×10^{19}
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	2.35×10^{19}	1.48×10^{19}	0.58×10^{19}

Contained in Tables 8 and 9 is a summary of the fluence factor (FF) values used in the calculation of adjusted reference temperatures for the V. C. Summer reactor vessel beltline materials for 32 and 56 EFPY.

TABLE 8
Calculation of the 1/4T and 3/4T Fluence Factor Values
used for the Generation of the 32 EFPY Heatup/Cooldown Curves

Material	1/4T F[(a)]	1/4T FF	3/4T F[(a)]	3/4T FF
Intermediate Shell Plate A9154-1	2.46×10^{19}	1.242	0.97×10^{19}	0.991
Intermediate Shell Plate A9153-2	2.46×10^{19}	1.242	0.97×10^{19}	0.991
Lower Shell Plate C9923-1	2.46×10^{19}	1.242	0.97×10^{19}	0.991
Lower Shell Plate C9923-2	2.46×10^{19}	1.242	0.97×10^{19}	0.991
Intermediate to Lower Shell Circumferential Weld Seam AB	2.46×10^{19}	1.242	0.97×10^{19}	0.991
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	0.85×10^{19}	0.954	0.34×10^{19}	0.703

(a) Units: n/cm^2, E > 1.0 MeV

TABLE 9

Calculation of the 1/4T and 3/4T Fluence Factor Values used for the Generation of the 56 EFPY Heatup/Cooldown Curves

Material	1/4T F[(a)]	1/4T FF	3/4T F[(a)]	3/4T FF
Intermediate Shell Plate A9154-1	4.27×10^{19}	1.370	1.69×10^{19}	1.144
Intermediate Shell Plate A9153-2	4.27×10^{19}	1.370	1.69×10^{19}	1.144
Lower Shell Plate C9923-1	4.27×10^{19}	1.370	1.69×10^{19}	1.144
Lower Shell Plate C9923-2	4.27×10^{19}	1.370	1.69×10^{19}	1.144
Intermediate to Lower Shell Circumferential Weld Seam AB	4.27×10^{19}	1.370	1.69×10^{19}	1.144
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	1.48×10^{19}	1.109	0.58×10^{19}	0.848

(a) Units: n/cm^2, E > 1.0 MeV

Margin is calculated as, $M = 2\sqrt{\sigma_i^2 + \sigma_\Delta^2}$. The standard deviation for the initial RT_{NDT} margin term, is σ_i 0°F when the initial RT_{NDT} is a measured value, and 17°F when a generic value is available. The standard deviation for the ΔRT_{NDT} margin term, σ_Δ, is 17°F for plates or forgings, and 8.5°F for plates or forgings when surveillance data is used. For welds, σ_Δ is equal to 28°F when surveillance capsule data is not used, and is 14°F (half the value) when credible surveillance capsule data is used. σ_Δ need not exceed 0.5 times the mean value of ΔRT_{NDT}.

Contained in Tables 10 and 11 are the calculated ART values used for the generation of the heatup and cooldown curves at 32 EFPY. Contained in Tables 12 and 13 are the calculated ART values used for the generation of the heatup and cooldown curves at 56 EFPY.

TABLE 10
Calculation of the ART Values for the 1/4T Location @ 32 EFPY

Material	Reg. Guide 1.99 Rev. 2 Method	CF[a] (°F)	¼ T FF	IRT_{NDT}[b] (°F)	ΔRT_{NDT}[c] (°F)	M[d] (°F)	ART[e] (°F)
Intermediate Shell Plate A9154-1	Position 1.1	65.0	1.242	30	80.73	34.0	145
	Position 2.1	43.4	1.242	30	53.90	34.0[f]	118
Intermediate Shell Plate A9153-2	Position 1.1	58.0	1.242	-20	72.04	34.0 34.0	86
Lower Shell Plate C9923-1	Position 1.1	51.0	1.242	10	63.34	34.0	107
Lower Shell Plate C9923-2	Position 1.1	51.00	1.242	10	63.34	34.0	107
Intermediate to Lower Shell Circumferential Weld Seam AB	Position 1.1	68.0	1.242	-44	84.46	56.0	96
	Position 2.1	42.2	1.242	-44	52.41	28.0	36
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	Position 1.1	68.0	0.954	-44	64.87	56.0	77
	Position 2.1	42.2	0.954	-44	40.26	28.0	24

(a) Chemistry Factors taken from Table 4

(b) Initial RT_{NDT} values are measured values; see Table 1

(c) $\Delta RT_{NDT} = CF * FF$

(d) Margin = $2*(\sigma_i^2 + \sigma_\Delta^2)^{1/2}$

(e) ART = $IRT_{NDT} + \Delta RT_{NDT} + M$ (This value was rounded per ASTM E29, using the "Rounding Method")

(f) Surveillance Plate Data is not-credible, thus the full σ_Δ was used

TABLE 11
Calculation of the ART Values for the 3/4T Location @ 32 EFPY

Material	Reg. Guide 1.99 Rev. 2 Method	CF[(a)] (°F)	¾ T FF	IRT_{NDT}[(b)] (°F)	ΔRT_{NDT}[(c)] (°F)	M[(d)] (°F)	ART[(e)] (°F)
Intermediate Shell Plate A9154-1	Position 1.1	65.0	0.991	30	64.42	34.0	128
	Position 2.1	43.4	0.991	30	43.01	34.0[(f)]	107
Intermediate Shell Plate A9153-2	Position 1.1	58.0	0.991	-20	57.48	34.0 34.0	71
Lower Shell Plate C9923-1	Position 1.1	51.0	0.991	10	50.54	34.0	95
Lower Shell Plate C9923-2	Position 1.1	51.00	0.991	10	50.54	34.0	95
Intermediate to Lower Shell Circumferential Weld Seam AB	Position 1.1	68.0	0.991	-44	67.39	56.0	79
	Position 2.1	42.2	0.991	-44	41.82	28.0	26
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	Position 1.1	68.0	0.703	-44	47.80	56.0	60
	Position 2.1	42.2	0.703	-44	29.67	28.0	14

(a) Chemistry Factors taken from Table 4

(b) Initial RT_{NDT} values are measured values; see Table 1

(c) ΔRT_{NDT} = CF * FF

(d) Margin = $2*(\sigma_I^2 + \sigma_\Delta^2)^{1/2}$

(e) ART = IRT_{NDT} + ΔRT_{NDT} + M (This value was rounded per ASTM E29, using the "Rounding Method")

(f) Surveillance Plate Data is not-credible, thus the full σ_Δ was used

TABLE 12
Calculation of the ART Values for the 1/4T Location @ 56 EFPY

Material	Reg. Guide 1.99 Rev. 2 Method	CF[(a)] (°F)	¼ T FF	IRT_{NDT}[(b)] (°F)	ΔRT_{NDT}[(c)] (°F)	M[(d)] (°F)	ART[(e)] (°F)
Intermediate Shell Plate A9154-1	Position 1.1	65.0	1.370	30	89.05	34.0	153
	Position 2.1	43.4	1.370	30	59.46	34.0[(f)]	123
Intermediate Shell Plate A9153-2	Position 1.1	58.0	1.370	-20	79.46	34.0 34.0	93
Lower Shell Plate C9923-1	Position 1.1	51.0	1.370	10	69.87	34.0	114
Lower Shell Plate C9923-2	Position 1.1	51.00	1.370	10	69.87	34.0	114
Intermediate to Lower Shell Circumferential Weld Seam AB	Position 1.1	68.0	1.370	-44	93.16	56.0	105
	Position 2.1	42.2	1.370	-44	57.81	28.0	42
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA & BB (45° Azimuth)	Position 1.1	68.0	1.109	-44	75.41	56.0	87
	Position 2.1	42.2	1.109	-44	46.80	28.0	31

(a) Chemistry Factors taken from Table 4

(b) Initial RT_{NDT} values are measured values; see Table 1

(c) ΔRT_{NDT} = CF * FF

(d) Margin = $2*(\sigma_i^2 + \sigma_\Delta^2)^{1/2}$

(e) ART = IRT_{NDT} + ΔRT_{NDT} + M (This value was rounded per ASTM E29, using the "Rounding Method")

(f) Surveillance Plate Data is not-credible, thus the full σ_Δ was used

TABLE 13
Calculation of the ART Values for the 3/4T Location @ 56 EFPY

Material	Reg. Guide 1.99 Rev. 2 Method	CF[a] (°F)	¾ T FF	IRT_{NDT}[b] (°F)	ΔRT_{NDT}[c] (°F)	M[d] (°F)	ART[e] (°F)
Intermediate Shell Plate A9154-1	Position 1.1	65.0	1.144	30	74.36	34.0	138
	Position 2.1	43.4	1.144	30	49.65	34.0[f]	114
Intermediate Shell Plate A9153-2	Position 1.1	58.0	1.144	-20	66.35	34.0 34.0	80
Lower Shell Plate C9923-1	Position 1.1	51.0	1.144	10	58.34	34.0	102
Lower Shell Plate C9923-2	Position 1.1	51.00	1.144	10	58.34	34.0	102
Intermediate to Lower Shell Circumferential Weld Seam AB	Position 1.1	68.0	1.144	-44	77.79	56.0	90
	Position 2.1	42.2	1.144	-44	48.28	28.0	32
Intermediate Lower Shell Longitudinal Weld Seam BC, BD, BA, BB (45° Azimuth)	Position 1.1	68.0	0.848	-44	57.66	56.0	70
	Position 2.1	42.2	0.848	-44	35.79	28.0	20

(a) Chemistry Factors taken from Table 4
(b) Initial RT_{NDT} values are measured values; see Table 1
(c) ΔRT_{NDT} = CF * FF
(d) Margin = $2*(\sigma_I^2 + \sigma_\Delta^2)^{1/2}$
(e) ART = IRT_{NDT} + ΔRT_{NDT} + M (This value was rounded per ASTM E29, using the "Rounding Method")
(f) Surveillance Plate Data is not-credible, thus the full σ_Δ was used

The Intermediate Shell Plate A9154-1 is the limiting beltline material for all the PT limit curves to be generated. Contained in Table 14 is a summary of the limiting ART values to be used in the generation of the V. C. Summer reactor vessel PT limit curves. These limiting curves will be presented in Section 5.

TABLE 14
Summary of the Limiting ART Values Used in the Generation of the V. C. Summer Heatup/Cooldown Curves

EFPY	¼ T Limiting ART	¾ T Limiting ART
32	145	128
56	153	138

5. HEATUP AND COOLDOWN PRESSURE-TEMPERATURE LIMIT CURVES

Pressure-temperature limit curves for normal heatup and cooldown of the primary reactor coolant system have been calculated for the pressure and temperature in the reactor vessel beltline region using the methods discussed in Sections 3 and 4 of this report. This approved methodology is also presented in WCAP-14040-NP-A, Revision 4.

Figures 1 and 3 present the limiting heatup curves without margins for possible instrumentation errors using heatup rates of 50 and 100°F/hr applicable for 32 and 56 EFPY. These curves were generated using the1998 ASME Code Section XI, Appendix G with the limiting ART values. Figures 2 and 4 present the limiting cooldown curves without margins for possible instrumentation errors using cooldown rates of 0, 25, 50 and 100°F/hr applicable for 32 and 56 EFPY. Again, these curves were generated using the1998 ASME Code Section XI, Appendix G with the limiting ART values. Allowable combinations of temperature and pressure for specific temperature change rates are below and to the right of the limit line shown in Figures 1, 2, 3 and 4. This is in addition to other criteria, which must be met before the reactor is made critical, as discussed below in the following paragraphs.

The reactor must not be made critical until pressure-temperature combinations are to the right of the criticality limit line shown in Figure 1. The straight-line portion of the criticality limit is at the minimum permissible temperature for the 2485 psig inservice hydrostatic test as required by Appendix G to 10 CFR Part 50. The governing equation for the hydrostatic test is defined in the 1998 ASME Code[6.4] as follows:

$$1.5\ K_{Im} < K_{Ic}$$

where,

K_{Im} is the stress intensity factor covered by membrane (pressure) stress

$K_{Ic} = 33.2 + 20.734\ e^{[0.02\ (T - RT_{NDT})]}$

T is the minimum permissible metal temperature

RT_{NDT} is the metal reference nil-ductility temperature

The criticality limit curve specifies pressure-temperature limits for core operation to provide additional margin during actual power production as specified in [6.5]. The pressure-temperature limits for core operation (except for low power physics tests) are that the reactor vessel must be at a temperature equal to or higher than the minimum temperature required for the inservice hydrostatic test, and at least 40°F higher than the minimum permissible temperature in the corresponding pressure-temperature curve for heatup and cooldown calculated as described in Section 4 of this report. For the heatup and cooldown curves without margins for instrumentation errors, the minimum temperatures for the in service hydrostatic leak tests for the V. C. Summer reactor vessel at 32 EFPY is 202°F and at 56 EFPY is 210°F. The vertical line drawn from these points on the pressure-temperature curve, intersecting a curve 40°F higher than the pressure-temperature limit curve constitutes the limit for core operation for the reactor vessel.

Figures 1, 2, 3 and 4 define all of the above limits for ensuring prevention of non-ductile failure for the V. C. Summer reactor vessel for 32 and 56 EFPY. The data points used for the heatup and cooldown pressure-temperature limit curves shown in Figures 1, 2, 3 and 4 are presented in Tables 15, 16, 17 and 18.

MATERIAL PROPERTY BASIS: Limiting Material: Intermediate Shell Plate A9154-1

Limiting ART Values @ 32 EFPY: 1/4T: 145°F, 3/4T: 128°F

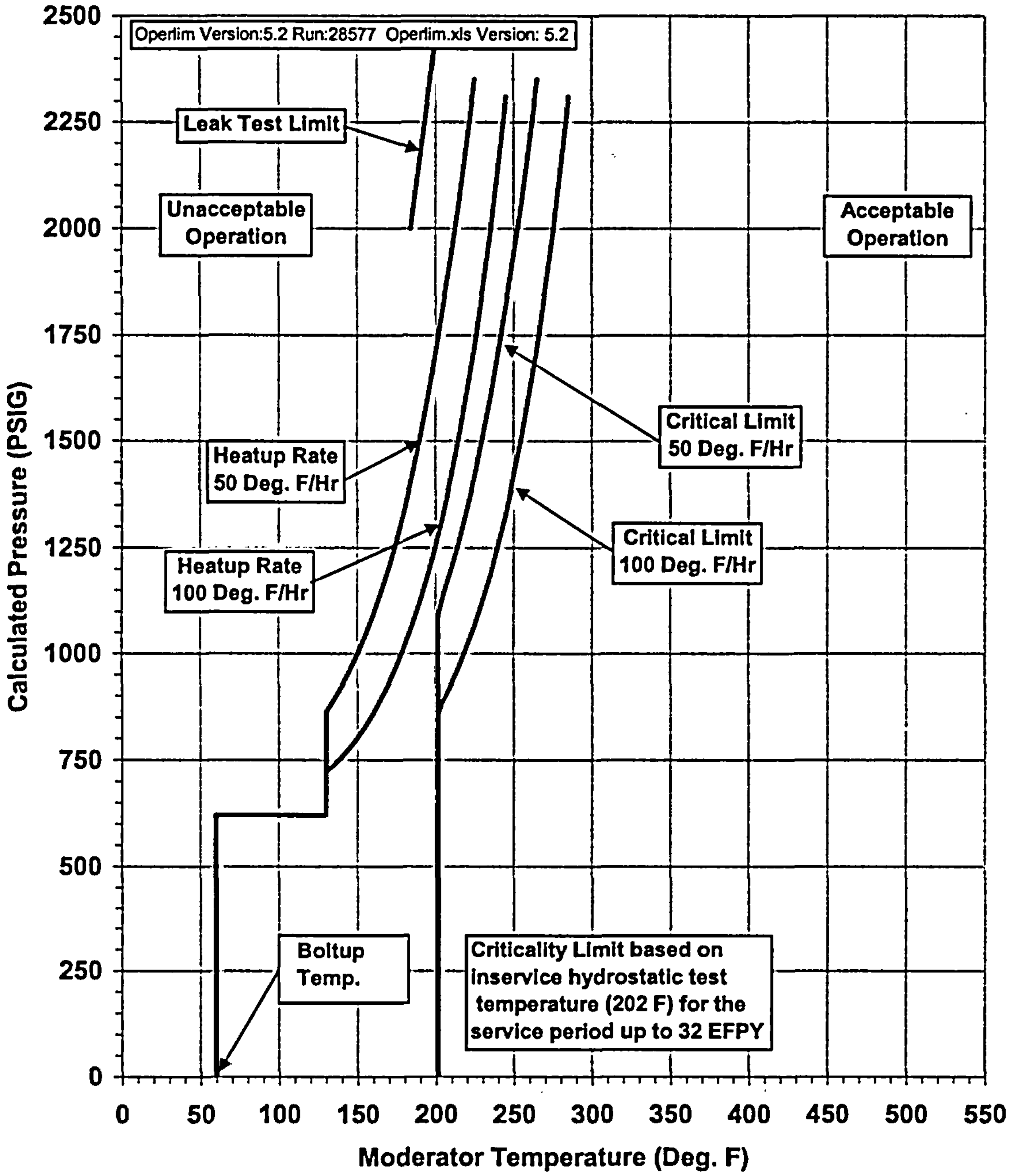

Figure 1 V. C. Summer Reactor Coolant System Heatup Limitations (Heatup Rates of 50 and 100°F/hr) Applicable for 32 EFPY (Without Margins for Instrumentation Errors) Using 1998 Appendix G Methodology

MATERIAL PROPERTY BASIS: Limiting Material: Intermediate Shell Plate A9154-1
Limiting ART Values @ 32 EFPY: 1/4T: 145°F, 3/4T: 128°F

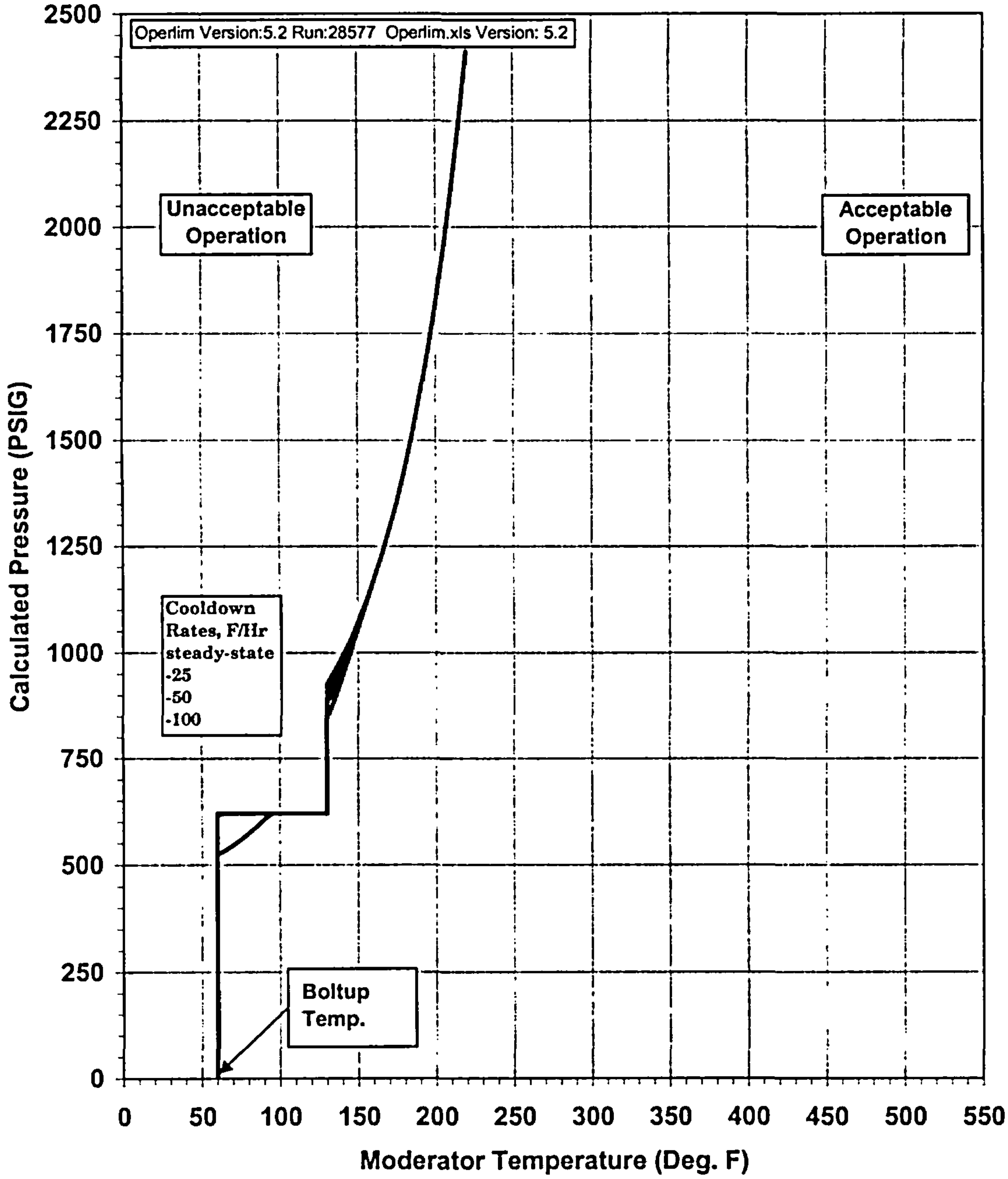

Figure 2 **V. C. Summer Reactor Coolant System Cooldown Limitations (Cooldown Rates up to 100°F/hr) Applicable for 32 EFPY (Without Margins for Instrumentation Errors) Using 1998 Appendix G Methodology**

MATERIAL PROPERTY BASIS: Limiting Material: Intermediate Shell Plate A9154-1

Limiting ART Values @ 56 EFPY: 1/4T: 153°F, 3/4T: 138°F

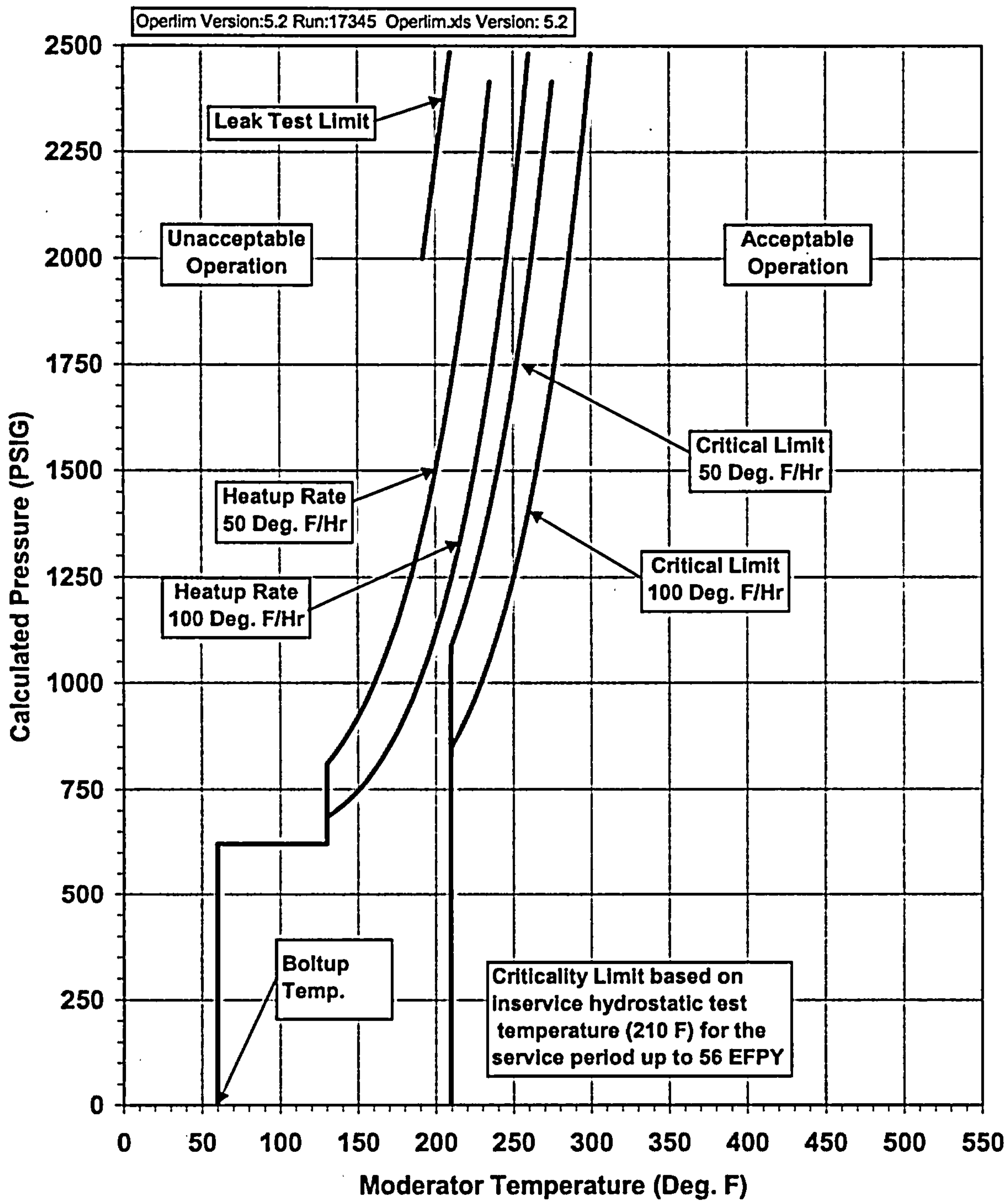

Figure 3 V. C. Summer Reactor Coolant System Heatup Limitations (Heatup Rates of 50 and 100°F/hr) Applicable for 56 EFPY (Without Margins for Instrumentation Errors) Using 1998 Appendix G Methodology

MATERIAL PROPERTY BASIS: Limiting Material: Intermediate Shell Plate A9154-1

Limiting ART Values @ 56 EFPY: 1/4T: 153°F, 3/4T: 138°F

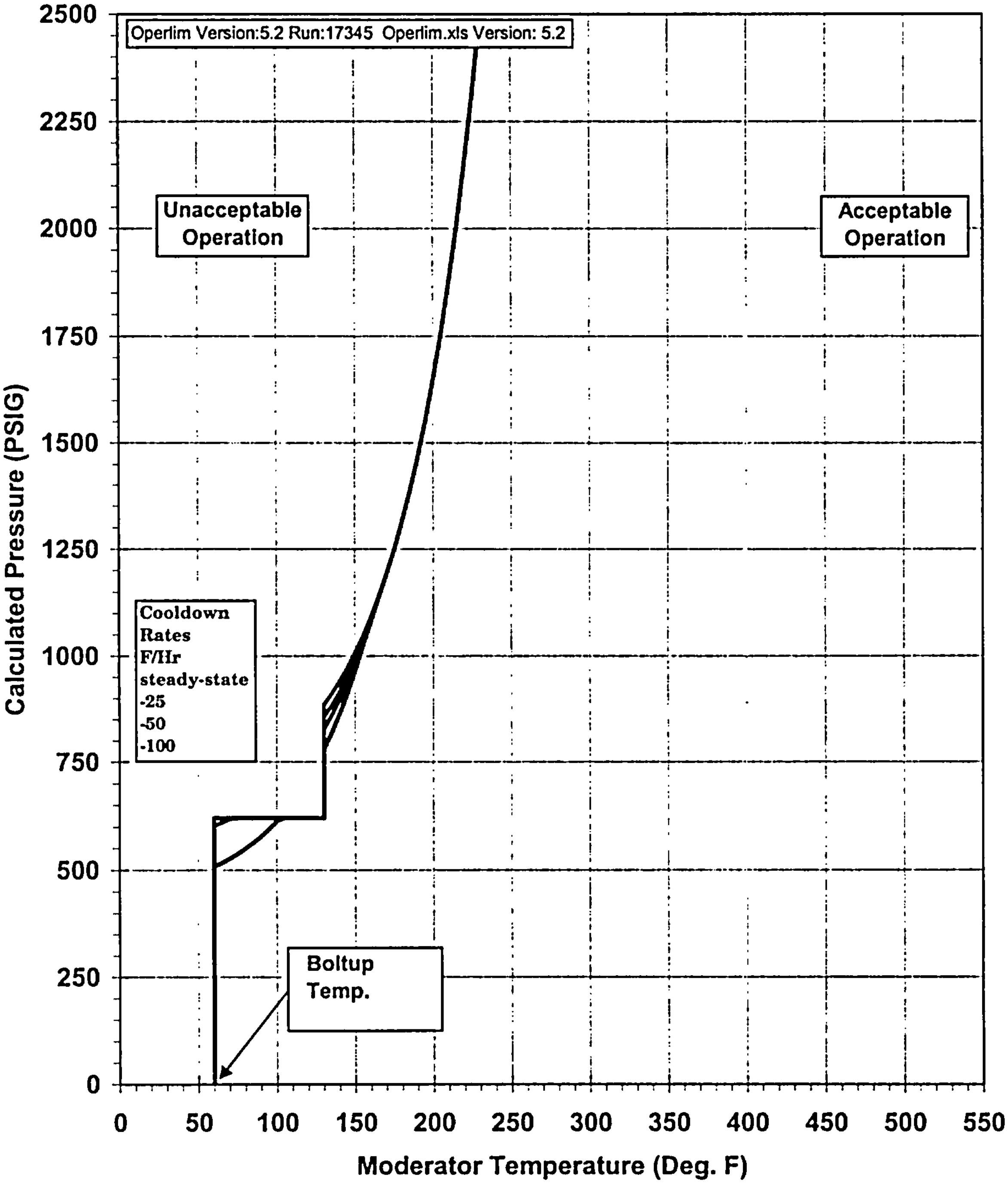

Figure 4 V. C. Summer Reactor Coolant System Cooldown Limitations (Cooldown Rates up to 100°F/hr) Applicable for 56 EFPY (Without Margins for Instrumentation Errors) Using 1998 Appendix G Methodology

TABLE 15

32 EFPY Heatup Curve Data Points Using 1998 Appendix G Methodology

(without Uncertainties for Instrumentation Errors)

50 Heatup		Critical. Limit		100 Heatup		Critical. Limit		Leak Test Limit	
T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)
60	0	202	0	60	0	202	0	184	2000
60	621	202	621	60	621	202	621	202	2485
65	621	202	621	65	621	202	621		
70	621	202	621	70	621	202	621		
75	621	202	621	75	621	202	621		
80	621	202	621	80	621	202	621		
85	621	202	621	85	621	202	621		
90	621	202	621	90	621	202	621		
95	621	202	621	95	621	202	621		
100	621	202	621	100	621	202	621		
105	621	202	621	105	621	202	621		
110	621	202	621	110	621	202	621		
115	621	202	621	115	621	202	621		
120	621	202	621	120	621	202	621		
125	621	202	621	125	621	202	621		
130	621	202	862	130	621	202	723		
130	862	202	891	130	723	202	739		
135	891	202	923	135	739	202	757		
140	923	202	958	140	757	202	778		
145	958	202	997	145	778	202	801		
150	997	202	1041	150	801	202	828		
155	1041	202	1089	155	828	202	858		
160	1089	205	1142	160	858	205	891		
165	1142	210	1201	165	891	210	929		
170	1201	215	1266	170	929	215	970		
175	1266	220	1337	175	970	220	1016		
180	1337	225	1416	180	1016	225	1067		
185	1416	230	1504	185	1067	230	1123		
190	1504	235	1600	190	1123	235	1186		
195	1600	240	1707	195	1186	240	1255		
200	1707	245	1824	200	1255	245	1331		
205	1824	250	1937	205	1331	250	1416		
210	1937	255	2062	210	1416	255	1509		
215	2062	260	2199	215	1509	260	1612		
220	2199	265	2351	220	1612	265	1725		
225	2351			225	1725	270	1851		
				230	1851	275	1989		
				235	1989	280	2141		
				240	2141	285	2310		
				245	2310				

TABLE 16

32 EFPY Cooldown Curve Data Points Using 1998 Appendix G Methodology

(without Uncertainties for Instrumentation Errors)

Steady State		25°F/hr.		50°F/hr.		100°F/hr.	
T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)
60	0	60	0	60	0	60	0
60	621	60	621	60	617	60	524
65	621	65	621	65	621	65	535
70	621	70	621	70	621	70	546
75	621	75	621	75	621	75	559
80	621	80	621	80	621	80	574
85	621	85	621	85	621	85	590
90	621	90	621	90	621	90	608
95	621	95	621	95	621	95	621
100	621	100	621	100	621	100	621
105	621	105	621	105	621	105	621
110	621	110	621	110	621	110	621
115	621	115	621	115	621	115	621
120	621	120	621	120	621	120	621
125	621	125	621	125	621	125	621
130	621	130	621	130	621	130	621
130	928	130	904	130	881	130	846
135	959	135	938	135	919	135	892
140	993	140	975	140	960	140	944
145	1031	145	1017	145	1006	145	1001
150	1073	150	1063	150	1057	150	1057
155	1119	155	1114	155	1114	155	1114
160	1170	160	1170	160	1170	160	1170
165	1226	165	1226	165	1226	165	1226
170	1288	170	1288	170	1288	170	1288
175	1357	175	1357	175	1357	175	1357
180	1433	180	1433	180	1433	180	1433
185	1517	185	1517	185	1517	185	1517
190	1610	190	1610	190	1610	190	1610
195	1712	195	1712	195	1712	195	1712
200	1825	200	1825	200	1825	200	1825
205	1951	205	1951	205	1951	205	1951
210	2089	210	2089	210	2089	210	2089
215	2242	215	2242	215	2242	215	2242
220	2411	220	2411	220	2411	220	2411

TABLE 17

56 EFPY Heatup Curve Data Points Using 1998 Appendix G Methodology

(without Uncertainties for Instrumentation Errors)

50 Heatup		Critical. Limit		100 Heatup		Critical. Limit		Leak Test Limit	
T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)
60	0	210	0	60	0	210	0	192	2000
60	621	210	621	60	621	210	621	210	2485
65	621	210	621	65	621	210	621		
70	621	210	621	70	621	210	621		
75	621	210	621	75	621	210	621		
80	621	210	621	80	621	210	621		
85	621	210	621	85	621	210	621		
90	621	210	621	90	621	210	621		
95	621	210	621	95	621	210	621		
100	621	210	621	100	621	210	621		
105	621	210	621	105	621	210	621		
110	621	210	621	110	621	210	621		
115	621	210	621	115	621	210	621		
120	621	210	621	120	621	210	621		
125	621	210	621	125	621	210	621		
130	621	210	810	130	621	210	684		
130	810	210	833	130	684	210	697		
135	833	210	859	135	697	210	711		
140	859	210	888	140	711	210	728		
145	888	210	920	145	728	210	747		
150	920	210	956	150	747	210	768		
155	956	210	995	155	768	210	792		
160	995	210	1039	160	792	210	819		
165	1039	210	1087	165	819	210	850		
170	1087	215	1140	170	850	215	883		
175	1140	220	1198	175	883	220	921		
180	1198	225	1263	180	921	225	962		
185	1263	230	1334	185	962	230	1008		
190	1334	235	1413	190	1008	235	1059		
195	1413	240	1500	195	1059	240	1115		
200	1500	245	1597	200	1115	245	1178		
205	1597	250	1703	205	1178	250	1247		
210	1703	255	1820	210	1247	255	1323		
215	1820	260	1950	215	1323	260	1407		
220	1950	265	2092	220	1407	265	1500		
225	2092	270	2250	225	1500	270	1602		
230	2250	275	2415	230	1602	275	1715		
235	2415			235	1715	280	1840		
				240	1840	285	1978		
				245	1978	290	2129		
				250	2129	295	2297		
				255	2297	300	2481		
				260	2481				

TABLE 18

32 EFPY Cooldown Curve Data Points Using 1998 Appendix G Methodology

(without Uncertainties for Instrumentation Errors)

Steady State		25°F/hr.		50°F/hr.		100°F/hr.	
T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)
60	0	60	0	60	0	60	0
60	621	60	621	60	604	60	508
65	621	65	621	65	611	65	517
70	621	70	621	70	619	70	527
75	621	75	621	75	621	75	538
80	621	80	621	80	621	80	550
85	621	85	621	85	621	85	564
90	621	90	621	90	621	90	579
95	621	95	621	95	621	95	596
100	621	100	621	100	621	100	615
105	621	105	621	105	621	105	621
110	621	110	621	110	621	110	621
115	621	115	621	115	621	115	621
120	621	120	621	120	621	120	621
125	621	125	621	125	621	125	621
130	621	130	621	130	621	130	621
130	885	130	856	130	828	130	781
135	911	135	885	135	860	135	820
140	940	140	917	140	896	140	864
145	972	145	952	145	935	145	912
150	1008	150	991	150	978	150	966
155	1047	155	1035	155	1026	155	1025
160	1091	160	1082	160	1079	160	1079
165	1139	165	1136	165	1136	165	1136
170	1192	170	1192	170	1192	170	1192
175	1250	175	1250	175	1250	175	1250
180	1315	180	1315	180	1315	180	1315
185	1386	185	1386	185	1386	185	1386
190	1465	190	1465	190	1465	190	1465
195	1553	195	1553	195	1553	195	1553
200	1649	200	1649	200	1649	200	1649
205	1756	205	1756	205	1756	205	1756
210	1874	210	1874	210	1874	210	1874
215	2004	215	2004	215	2004	215	2004
220	2148	220	2148	220	2148	220	2148
225	2308	225	2308	225	2308	225	2308
230	2484	230	2484	230	2484	230	2484

6. REFERENCES

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

6.2 WCAP-14040-NP-A, Revision 4, "Methodology used to Develop Cold Overpressure Mitigating system Setpoints and RCS Heatup and Cooldown Limit Curves", J.D. Andrachek, et. al., May 2004

6.3 ASME Code Case N-641, "Alternative Pressure-Temperature Relationship and Low Temperature Overpressure Protection System Requirements Section XI, Division 1", January 17, 2000.[*Sub Reference 1: ASME Code Case N-640, "Alternative Reference Fracture Toughness for Development of P-T Limit Curves for Section XI, Division 1", February 26, 1999*]

6.4 ASME Code 1998 Edition through the 2000 Addenda of Section XI, Appendix G

6.5 Code of Federal Regulations, 10 CFR Part 50, Appendix G, "Fracture Toughness Requirements", U.S. Nuclear Regulatory Commission, Washington, D.C., Federal Register, Volume 60, No. 243, dated December 19, 1995

6.6 "Fracture Toughness Requirements", Branch Technical Position MTEB 5-2, Chapter 5.3.2 in Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, LWR Edition, NUREG-0800, 1981

6.7 WCAP-12867, "Analysis of Capsule X from the South Carolina Electric & Gas Company Virgil C. Summer Unit 1 Reactor Vessel Radiation Surveillance Program", J. M. Chicots, et. al., March 1991

6.8 WCAP-16298-NP, "Analysis of Capsule Z From The South Carolina Electric & Gas Company, V. C. Summer Reactor Vessel Radiation Surveillance Program", C. M. Burton, et. al., August 2004

6.9 1989 Section III, Division 1 of the ASME Boiler and Pressure Vessel Code, Paragraph NB-2331, "Material for Vessels"

6.10 Regulatory Guide 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence", March 2001

APPENDIX A

Thermal Stress Intensity Factors (K_{It})

Thermal Stress Intensity Factors

In order to aid in the review and approval process, the NRC has typically requested that the thermal stress intensity factors be provided. This request was performed under the condition that only the thermal stress intensity factors for the maximum heatup and cooldown rates would be supplied for information. In recent history, this was accomplished via a letter report after the issuance of the PT limit curve. Now that it is known that the NRC will request this information upon each PT limit curve submittal, Westinghouse has decided to include the thermal stress intensity factors directly in the WCAP Report.

Presented in Tables A1 through A4 are the thermal stress intensity factors for the maximum heatup and maximum cooldown rates for the 32 and 56 EFPY PT limit curves. Note the following:

Vessel Radius to the ¼T and ¾T Locations are as follows:

- ¼T Radius = 80.563"
- ¾T Radius = 84.438"

TABLE A1
K_{It} Values for 100°F/hr Heatup Curve (32 EFPY)

Water Temp. (°F)	Vessel Temperature @ 1/4T Location for 100°F/hr Heatup (°F)	1/4T Thermal Stress Intensity Factor (KSI SQ. RT. IN.)	Vessel Temperature @ 3/4T Location for 100°F/hr Heatup (°F)	3/4T Thermal Stress Intensity Factor (KSI SQ. RT. IN.)
60	56.16	-0.9848	55.07	0.4968
65	58.99	-2.3617	55.45	1.4567
PT Curves are Limited by Steady State Conditions up to 65°F and ¾T Limited for the Remainder of the Curve				
70	62.22	-3.4855	56.39	2.3654
75	65.68	-4.5265	57.88	3.1790
80	69.41	-5.3899	59.83	3.8791
85	73.25	-6.1620	62.20	4.4877
90	77.29	-6.8111	64.93	5.0115
95	81.43	-7.3918	67.96	5.4680
100	85.70	-7.8834	71.25	5.8624
105	90.05	-8.3232	74.77	6.2068
110	94.49	-8.6987	78.47	6.5079
115	98.99	-9.0368	82.34	6.7728
120	103.56	-9.3271	86.35	7.0052
125	108.18	-9.5901	90.47	7.2108
130	112.84	-9.8175	94.70	7.3923
135	117.54	-10.0250	99.02	7.5542
140	122.28	-10.2059	103.42	7.6982
145	127.04	-10.3726	107.87	7.8277
150	131.82	-10.5191	112.39	7.9441
155	136.63	-10.6556	116.95	8.0498
160	141.45	-10.7767	121.56	8.1456
165	146.29	-10.8909	126.20	8.2336
170	151.14	-10.9932	130.87	8.3143
175	156.01	-11.0907	135.57	8.3892
180	160.88	-11.1791	140.29	8.4587
185	165.76	-11.2644	145.03	8.5239
190	170.65	-11.3425	149.78	8.5851
195	175.55	-11.4186	154.56	8.6430
200	180.45	-11.4891	159.34	8.6980
205	185.35	-11.5585	164.13	8.7507
210	190.26	-11.6233	168.94	8.8011
215	195.17	-11.6877	173.75	8.8498
220	200.09	-11.7483	178.57	8.8968
225	205.01	-11.8089	183.39	8.9426
230	209.93	-11.8665	188.22	8.9871
235	214.85	-11.9244	193.06	9.0307
240	219.77	-11.9798	197.89	9.0734
245	224.70	-12.0356	202.73	9.1154

TABLE A2

K_{It} Values for 100°F/hr Cooldown Curve (32 EFPY)

Water Temp. (°F)	Vessel Temperature @ 1/4T Location for 100°F/hr Cooldown (°F)	100°F/hr Cooldown 1/4T Thermal Stress Intensity Factor (KSI SQ. RT. IN.)
220	241.83	13.0578
215	236.76	13.0038
210	231.68	12.9503
205	226.61	12.8962
200	221.54	12.8428
195	216.47	12.7888
190	211.40	12.7354
185	206.33	12.6815
180	201.26	12.6282
175	196.18	12.5745
170	191.11	12.5214
165	186.04	12.4678
160	180.97	12.4149
155	175.90	12.3615
100°F Cooldown Rate is limited by the Steady State Condition from T = 155°F to 220°F		
150	170.83	12.3087
145	165.76	12.2556
140	160.69	12.2030
135	155.62	12.1501
130	150.55	12.0977
125	145.47	12.0450
120	140.40	11.9928
115	135.33	11.9403
110	130.26	11.8884
105	125.19	11.8362
100	120.12	11.7844
95	115.05	11.7325
90	109.98	11.6810
85	104.92	11.6292
80	99.85	11.5780
75	94.78	11.5265
70	89.71	11.4755
65	84.64	11.4242
60	79.57	11.3727

TABLE A3

K_{It} Values for 100°F/hr Heatup Curve (56 EFPY)

Water Temp. (°F)	Vessel Temperature @ 1/4T Location for 100°F/hr Heatup (°F)	1/4T Thermal Stress Intensity Factor (KSI SQ. RT. IN.)	Vessel Temperature @ 3/4T Location for 100°F/hr Heatup (°F)	3/4T Thermal Stress Intensity Factor (KSI SQ. RT. IN.)
60	56.16	-0.9848	55.07	0.4968
65	58.99	-2.3617	55.45	1.4567
PT Curves are Limited by the ¼T Location up to 65°F and ¾T Limited for the Remainder of the Curve				
70	62.22	-3.4855	56.39	2.3654
75	65.68	-4.5265	57.88	3.1790
80	69.41	-5.3899	59.83	3.8791
85	73.25	-6.1620	62.20	4.4877
90	77.29	-6.8111	64.93	5.0115
95	81.43	-7.3918	67.96	5.4680
100	85.70	-7.8834	71.25	5.8624
105	90.05	-8.3232	74.77	6.2068
110	94.49	-8.6987	78.47	6.5079
115	98.99	-9.0368	82.34	6.7728
120	103.56	-9.3271	86.35	7.0052
125	108.18	-9.5901	90.47	7.2108
130	112.84	-9.8175	94.70	7.3923
135	117.54	-10.0250	99.02	7.5542
140	122.28	-10.2059	103.42	7.6982
145	127.04	-10.3726	107.87	7.8277
150	131.82	-10.5191	112.39	7.9441
155	136.63	-10.6556	116.95	8.0498
160	141.45	-10.7767	121.56	8.1456
165	146.29	-10.8909	126.20	8.2336
170	151.14	-10.9932	130.87	8.3143
175	156.01	-11.0907	135.57	8.3892
180	160.88	-11.1791	140.29	8.4587
185	165.76	-11.2644	145.03	8.5239
190	170.65	-11.3425	149.78	8.5851
195	175.55	-11.4186	154.56	8.6430
200	180.45	-11.4891	159.34	8.6980
205	185.35	-11.5585	164.13	8.7507
210	190.26	-11.6233	168.94	8.8011
215	195.17	-11.6877	173.75	8.8498
220	200.09	-11.7483	178.57	8.8968
225	205.01	-11.8089	183.39	8.9426
230	209.93	-11.8665	188.22	8.9871
235	214.85	-11.9244	193.06	9.0307
240	219.77	-11.9798	197.89	9.0734
245	224.70	-12.0356	202.73	9.1154
250	229.62	-12.0893	207.58	9.1567
255	234.55	-12.1436	212.42	9.1976
260	239.48	-12.1962	217.27	9.2379

TABLE A4

K_{It} Values for 100°F/hr Cooldown Curve (56 EFPY)

Water Temp. (°F)	Vessel Temperature @ 1/4T Location for 100°F/hr Cooldown (°F)	100°F/hr Cooldown 1/4T Thermal Stress Intensity Factor (KSI SQ. RT. IN.)
230	251.97	13.1653
225	246.90	13.1113
220	241.83	13.0578
215	236.76	13.0038
210	231.68	12.9503
205	226.61	12.8962
200	221.54	12.8428
195	216.47	12.7888
190	211.40	12.7354
185	206.33	12.6815
180	201.26	12.6282
175	196.18	12.5745
170	191.11	12.5214
165	186.04	12.4678
100°F Cooldown Rate is limited by the Steady State Condition from T = 165°F to 230°F		
160	180.97	12.4149
155	175.90	12.3615
150	170.83	12.3087
145	165.76	12.2556
140	160.69	12.2030
135	155.62	12.1501
130	150.55	12.0977
125	145.47	12.0450
120	140.40	11.9928
115	135.33	11.9403
110	130.26	11.8884
105	125.19	11.8362
100	120.12	11.7844
95	115.05	11.7325
90	109.98	11.6810
85	104.92	11.6292
80	99.85	11.5780
75	94.78	11.5265
70	89.71	11.4755
65	84.64	11.4242
60	79.57	11.3727