WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-15047
Revision 2

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D.C. Cook Unit 2 WOG Reactor Vessel 60-Year Evaluation Minigroup Heatup and Cooldown Limit Curves for Normal Operation

Westinghouse Electric Company LLC

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D.C. Cook Unit 2
WOG Reactor Vessel 60-Year Evaluation Minigroup
Heatup and Cooldown Limit Curves
For Normal Operation

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May 2002

Prepared by the Westinghouse Electric Company LLC
for the WOG Reactor Vessel 60-Year Evaluation Minigroup

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PREFACE

This report has been technically reviewed and verified by:

T. Laubham ____ 5/30/02

Revision 1:

An error was detected in the "OPERLIM" Computer Program that Westinghouse uses to generate pressure-temperature (PT) limit curves (Documented in NSAL Letter NSAL-01-004, "Pressure/Temperature Limit Curves", Dated May 2, 2001). This error potentially effects the heatup curves when the 1996 Appendix G Methodology is used in generating the PT curves. It has been determined that WCAP-15047 Rev. 0 was impacted by this error. Thus, this revision provides corrected curves from WCAP-15047 Rev. 0.

Note that only the heatup curves and associated data points tables in Section 9 have changed. The cooldown curves and data points remain valid and were not changed.

Revision 2:

The PT curves documented in Revisions 0 and 1 were based on "best estimate" fluences. WCAP-13515 was revised to update the fluence methodology (ie. Reg. Guide 1.190) and to include the "calculated" fluences. Thus, this report was revised to incorporate the "calculated" fluences into the D.C. Cook Unit 2 PT curves. In addition to this change, the PT curves were also updated to incorporate the use of the methodology from the 1995 ASME Code Section XI through the 1996 Addenda, Appendix G and Code Case N-641, which allows the use of K_{Ic} for PT Curve Generation and alternative methods for calculating the enable temperature (Section 10.0). Text has been updated to support the use of the '96 App. G and K_{Ic} methodologies.

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1.0 INTRODUCTION

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-lb 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"[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 2[10], "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves" with exception of the following: 1) **The fluence values used in this report are calculated fluence values (i.e. comply with Reg. Guide 1.190), not the best estimate fluence values.** 2) The K_{Ic} critical stress intensities are used in place of the K_{Ia} critical stress intensities. This methodology is taken from approved ASME Code Case N-641[13] (which covers Code Cases N-640[12]). 3) The 1996 Version of Appendix G to Section XI[3] will be used rather than the 1989 version.

2.0 PURPOSE

D.C. Cook Unit 2, as members of the WOG Reactor Vessel 60-year Mini-group, has contracted Westinghouse to generate new heatup and cooldown curves for the current end of license and life extension. The D.C. Cook Unit 2 heatup and cooldown curves were generated without margins for instrumentation errors. The curves include a hydrostatic leak test limit curve from 2485 to 2000 psig and pressure-temperature limits for the vessel flange regions per the requirements of 10 CFR Part 50, Appendix G[2].

The purpose of this report is to present the calculations and the development of D.C. Cook Unit 2 heatup and cooldown curves for the current end of license and license renewal. This report documents the calculated adjusted reference temperature (ART) values following the methods of Regulatory Guide 1.99, Revision 2[1], for all the beltline materials and the development of the heatup and cooldown pressure-temperature limit curves for normal operation.

3.0 CRITERIA FOR ALLOWABLE PRESSURE-TEMPERATURE RELATIONSHIPS

3.1 Overall Approach

Appendix G to 10 CFR Part 50, "Fracture Toughness Requirements"[2] specifies fracture toughness requirements for ferritic materials of pressure-retaining components of the reactor coolant pressure boundary of light water nuclear power reactors to provide adequate margins of safety during any condition of normal operation, including anticipated operational occurrences and system hydrostatic tests, to which the pressure boundary may be subjected over its service lifetime. The ASME Boiler and Pressure Vessel Code forms the basis for these requirements. Section XI, Division 1, "Rule for Inservice Inspection of Nuclear Power Plant Components", Appendix G[3], contains the conservative methods of analysis.

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 of Appendix G of the ASME Code, 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 K_I values measured as a function of temperature on specimens of SA-533 Grade B Class 1, SA-508-1, SA-508-2, and SA-508-3 steels.

3.2 Methodology for Pressure-Temperature Limit Curve Development

The governing equation for the heatup-cooldown analysis is defined in Code Case N-640 of 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 K_I corresponding to membrane tension for the postulated defect is:

$$K_{Im} = M_m * (pR_i \div t) \qquad (3)$$

Where M_m for an inside surface is given by:

$M_m = 1.85$ for $\sqrt{t} < 2$,

$M_m = 0.926 \sqrt{t}$ for $2 \leq \sqrt{t} \leq 3.464$, and

$M_m = 3.21$ 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 $2 \leq \sqrt{t} \leq 3.464$, and

$M_m = 3.09$ for $\sqrt{t} > 3.464$.

Where:

R_i = vessel inner radius,

t = vessel wall thickness, and

p = internal pressure,

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

$K_{Ib} = M_b$ * maximum bending stress, where M_b is two-thirds of M_m

For the Radial Thermal Gradient, the maximum K_I produced by radial thermal gradient for the postulated inside surface defect is:

$$K_{It} = 0.953x10^{-3} \text{ x } CR \text{ x } t^{2.5} \tag{4}$$

where:

CR = the cooldown rate in °F/hr.

For the Radial Thermal Gradient, the maximum K_I produced by radial thermal gradient for the postulated outside surface defect is:

$$K_{It} = 0.753x10^{-3} \text{ x } HU \text{ x } t^{2.5} \tag{5}$$

where:

HU = the heatup rate in °F/hr.

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

(a) The maximum thermal K_I relationship and the temperature relationship in Fig. G-2214-1 are applicable only for the conditions given in G-2214.3 (a)(1) and (2) of Appendix G to ASME Section XI.

(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:

$$K_{It} = (1.0359C_0 + 0.6322C_1 + 0.4753C_2 + 0.3855C_3) * \sqrt{\pi a} \tag{6}$$

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

$$K_{It} = (1.043C_0 + 0.630C_1 + 0.481C_2 + 0.401C_3) * \sqrt{\pi a} \qquad (7)$$

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:

$$\sigma(x) = C_0 + C_1(x/a) + C_2(x/a)^2 + C_3(x/a)^3 \qquad (8)$$

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 through 8 were added to the OPERLIM computer program, which is the Westinghouse computer program used to generate pressure-temperature limit curves. No other changes were made to the OPERLIM computer program with regard to the pressure-temperature curve calculation methodology. Hence, the pressure-temperature curve methodology described in WCAP-14040[10] Section 2.6 (equations 2.6.2-4 and 2.6.3-1) remains valid for the generation of the pressure-temperature curves documented in this report with the exceptions 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 ¼T and ¾T 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 ¼T 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 ¼T 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 ¼T 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 ¼T 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 ¼T crack during heatup is lower than the K_{IC} for the ¼T 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 ¼T 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 ¼T flaw located at the ¼T 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.

10 CFR Part 50, Appendix G 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 psig), which is 621 psig[4] for the D.C. Cook Unit 2 reactor vessel.

The limiting unirradiated RT_{NDT} of 30°F occurs in the vessel flange of the D.C. Cook Unit 2 reactor vessel, so the minimum allowable temperature of this region is 150°F at pressure greater than 621 psig without uncertainties. This limit is reflected in the heatup and cooldown curves shown in Figures 9-1 through 9-4.

4.0 CHEMISTRY FACTOR DETERMINATION

4.1 Chemistry Factor Methodology:

The calculations of chemistry factor (CF) values for the D.C. Cook Unit 2 reactor vessel beltline materials are performed in accordance with Regulatory Guide 1.99, Revision 2 as follows:

The CF is based on the Cu and Ni weight % of the material or it is based on the results of surveillance capsule test data. When the weight percent of copper and nickel is used to determine the CF, the CF is obtained from either Table 1 or Table 2 of Regulatory Guide 1.99, Revision 2. The results of this method are given in Table 1-4.

When surveillance capsule data is used to determine the CF, the CF is determined as follows:

$$CF = \frac{\sum_{i=1}^{n} [A_i \, x \, fi^{(0.28-0.1 \log fi)}]}{\sum_{i=1}^{n} [f_i^{(0.28-0.1 \log fi)}]^2} \qquad (9)$$

Where:	n	=	The Number of Surveillance Data Points
	A_i	=	The Measured Value of ΔRT_{NDT}
	f_i	=	Fluence for each Surveillance Data Point

When the surveillance weld copper and nickel content differs from that of the vessel weld, the measured values of ΔRT_{NDT} are adjusted by multiplying them by the ratio of the chemistry factor for the vessel weld to that for the surveillance weld based on the copper and nickel content of the materials. The Ratio Procedure is documented in Regulatory Guide 1.99 Revision 2 Position 2.1, and shown below.

4.1.1 Application of the Ratio Procedure:

The D.C. Cook Unit 2 intermediate and lower shell axial weld seams, the intermediate to lower shell girth weld seam, and the surveillance program weld metal were all fabricated with weld wire type ADCOM INMM, Heat Number S3986 and Flux Type Linde 124, Lot Number 934. Despite the fact that all the welds are made of the same heat and flux, the weight percent copper and nickel of the surveillance weld metal differs slightly versus the overall best estimate chemistry for the vessel weld metal (Per D.C. Cook Design Information Transmittal, DIT-B-02230[11]). As reported in Table 4-1, the chemistry factor of the surveillance weld is 75.0°F, while the vessel weld chemistry factor is 76.4°F. This produces a ratio of 1.019. Therefore, a ratio of 1.019 was applied to the measure weld metal ΔRT_{NDT} values.

4.1.2 Temperature Effects on Surveillance Data:

Studies have shown that for temperatures near 550°F, a 1°F decrease in irradiation temperature will result in approximately 1°F increase in ΔRT_{NDT}. Thus, for plants that use surveillance data from other reactor vessels that operate at a different temperature or when the capsule is at a different temperature than the plant, then this difference must be considered.

The temperature adjustment is as follows:

$$\text{Temp. Adjusted } \Delta RT_{NDT} = \Delta RT_{NDT} \text{ Measured} + (T_{capsule} - T_{plant})$$

The D.C. Cook Unit 2 capsules are located in the reactor between the thermal shield and the vessel wall and are positioned opposite the center of the core. The test capsules are in guide tubes attached to the thermal shield. The location of the specimens with respect to the reactor vessel beltline provides assurance that the reactor vessel wall and the specimens experience equivalent operating conditions and the temperatures will not differ by more than 25°F. Hence, no temperature adjustment was made.

Following in Table 4-1 are best estimate chemistry values for all the beltline materials, including the surveillance capsule weld along with the chemistry factors (CF) as determined per Regulatory Guide 1.99, Revision 2, Position 1 or 2

TABLE 4-1			
Reactor Vessel Beltline Material Copper and Nickel Content and Calculated CF			
Material Description	wt. % Cu[(a)]	wt. % Ni[(a)]	CF
Inter. Shell Axial Welds	0.056	0.956	76.4°F
Inter. Shell Plate 10-1 (C5556-2)	0.150	0.570	108.4°F
Inter. Shell Plate 10-2 (C5521-2)	0.130[(b)]	0.580	90.4°F
Int/Lower Shell Circ. Weld	0.056	0.956	76.4°F
Lower Shell Axial Welds	0.056	0.956	76.4°F
Lower Shell Plate 9-1 (C5540-2)	0.110	0.640	74.6°F
Lower Shell Plate 9-2 (C5592-1)	0.140	0.590	99.5°F
Surveillance Weld Metal	0.055	0.97	75°F

NOTES:

(a) These values were determined by ATI and Transmitted to Westinghouse via DIT-B-02230-00[11].

(b) Actual value was 0.125 and was conservatively rounded to 0.130. It should also be noted that Inter. Shell Plate 10-2 has credible surveillance data, overriding the weight percent Cu & Ni.

Table 4-2 provides the calculation of the CF values for the surveillance materials per Regulatory Guide 1.99, Revision 2, Position 2.1. The ratio procedure of Regulatory Guide 1.99, Revision 2, Position 2.1 will be applied to the weld metal (ie. Ratio = Vessel CF ÷ Surv. CF = 76.4 ÷ 75.0 = 1.019).

TABLE 4-2						
Calculation of Chemistry Factors using D.C. Cook Unit 2 Surveillance Capsule Data						
Material	Capsule	Fluence[a,b]	FF	ΔRT_{NDT}[b]	FF * ΔRT_{NDT}	FF^2
Intermediate Shell C5521-2 (longitudinal)	T	2.38×10^{18}	0.612	55	33.66	0.375
	Y	6.64×10^{18}	0.885	90	79.65	0.783
	X	1.019×10^{19}	1.005	95	95.48	1.010
	U	1.583×10^{19}	1.127	95	107.07	1.270
Intermediate Shell C5521-2 (Transverse)	T	2.38×10^{18}	0.612	80	48.96	0.375
	Y	6.64×10^{18}	0.885	100	88.50	0.783
	X	1.019×10^{19}	1.005	103	103.52	1.010
	U	1.583×10^{19}	1.127	130	146.51	1.270
				SUM:	703.35	6.876
	CF = Σ(FF * RT_{NDT}) ÷ Σ(FF^2) = (703.35) ÷ (6.876) = **102.3°F**					
Weld Metal	T	2.38×10^{18}	0.612	40.76 (40)[c]	24.95	0.375
	Y	6.64×10^{18}	0.885	50.95 (50)[c]	45.09	0.783
	X	1.019×10^{19}	1.005	71.33 (70)[c]	71.68	1.010
	U	1.583×10^{19}	1.127	76.43 (75)[c]	86.14	1.270
				SUM:	227.86	3.438
	CF = Σ(FF * RT_{NDT}) ÷ Σ(FF^2) = (227.86) ÷ (3.438) = **66.3°F**					

(a) Calculated Fluence values are in units of n/cm^2, E > 1.0 MeV.

(b) Data obtained from WCAP-13515 Rev. 1[4], revised Capsule U Analysis.

(c) Increased by a ratio of 1.019 to account for difference between the vessel weld chemistry and the surveillance weld chemistry (76.4/75.0). The original ΔRT_{NDT} values are in parenthesis.

4.2 Surveillance Program Credibility Evaluation:

Regulatory Guide 1.99, Revision 2, describes general procedures acceptable to the NRC staff for calculating the effects of neutron radiation embrittlement of the low-alloy steels currently used for light-water-cooled reactor vessels. Position C.2 of Regulatory Guide 1.99, Revision 2, describes the methodology for calculating the adjusted reference temperature and Charpy upper-shelf energy of reactor vessel beltline materials using surveillance capsule data. The methods of Position C.2 can only be applied when two or more credible surveillance data sets become available from the reactor in question.

To date, there have been four surveillance capsules removed from the D.C. Cook Unit 2 reactor vessel. This capsule data must be shown to be credible. In accordance with the discussion of Regulatory Guide 1.99, Revision 2, there are five requirements that must be met for the surveillance data to be judged credible.

The purpose of this evaluation is to apply the credibility requirements of Regulatory Guide 1.99, Revision 2, to the D.C. Cook Unit 2 reactor vessel surveillance data and determine if the Cook Unit 2 surveillance data is credible.

Criterion 1: Materials in the capsules should be those judged most likely to be controlling with regard to radiation embrittlement.

The beltline region of the reactor vessel is defined in Appendix G to 10 CFR Part 50, "Fracture Toughness Requirements", December 19, 1995 to be:

"the reactor vessel (shell material including welds, heat affected zones, and plates or forgings) that directly surrounds the effective height of the active core and adjacent regions of the reactor vessel that are predicted to experience sufficient neutron radiation damage to be considered in the selection of the most limiting material with regard to radiation damage."

Hence, the D.C. Cook Unit 2 reactor vessel consists of the following beltline region materials:

a) Intermediate Shell Plate C5556-2,
b) Intermediate Shell Plate C5521-2,
c) Lower Shell Plate C5540-2,
d) Lower Shell Plate C5592-1, and
e) Intermediate and lower shell axial weld seams and the intermediate to lower shell girth weld seams were fabricated with weld wire type ADCOM INMM, Heat # S3986 and Flux Type Linde 124, Lot # 934. The surveillance weld was fabricated for the same weld wire and flux. (See Reference 2)

Per WCAP-8512, the D.C. Cook Unit 2 surveillance program was based on ASTM E185-73, "Standard Recommended Practice for Surveillance Tests for Nuclear Reactor Vessels" Per Section 4 of ASTM E185-73, "*The test materials should be selected on the basis of initial transition temperature, upper shelf energy level, and estimated increase in transition temperature considering chemical composition (copper(Cu) and phosphorus(P)) and neutron fluence. Recommended procedures for selection of materials are presented in Annex A1*" (ie. Annex A1 of ASTM E185-73). Following is the evaluation of the selection of the D.C. Cook Unit 2 surveillance materials.

Weld Metal:

All vessel beltline welds were fabricated with weld wire type ADCOM INMM, Heat # S3986 and Flux Type Linde 124, Lot # 934. The surveillance weld was fabricated from the same weld wire heat and flux. Hence, the surveillance weld metal is the same as all beltline welds and therefore, is representative of all beltline weld seams.

Plates:

Per Paragraph A1.1.1 of Annex to ASTM E185-73, "Base metals exhibiting differences in initial RT_{NDT} temperatures of 30°F (-1.1°C) or less shall be considered equivalent."

The lower shell plates have an initial RT_{NDT} temperature of -20°F. These initial RT_{NDT} temperatures are well below the initial RT_{NDT} temperatures of the intermediate shell plates, therefore, intermediate shell plates are considered more limiting than the lower shell plates.

Intermediate shell plate C5556-2 has an initial RT_{NDT} temperature of 58°F and the intermediate shell plate C5521-2 has an initial RT_{NDT} temperature of 38°F. Hence, based on the above criteria these two initial RT_{NDT} temperatures are considered equivalent.

Per Paragraph A1.1.1 of Annex to ASTM E185-73, "...base metals (or weld metals) having differences in copper content of 0.03 weight % or less and differences in phosphorus content of 0.003 weight % or less shall be considered equivalent.

The difference in copper content of intermediate shell plate C5556-2 and C5521-2 is 0.01% and the difference in phosphorus content of intermediates shell plate C5556-2 and C5521-2 is 0.001%. Hence based on the above criteria these two plates are considered equivalent.

Per Figure A1 of the Annex to ASTM E185-73, when the initial RT_{NDT} temperatures, copper content and phosphorus content are all equivalent, the base material with the lowest initial upper shelf energy (USE) should be selected. The initial USE of intermediate shell plate C5556-2 is 90 ft-lb and the initial USE of intermediate shell plate C5521-2 is 86 ft-lb. Hence, based on the preceding evaluation and the available methodology at the time that the D.C. Cook Unit 2 surveillance program was developed intermediate shell plate C5521-2 was the limiting beltline plate material.

Therefore, the materials selected for use in the D.C. Cook Unit 2 surveillance program were those judged to be most likely controlling with regard to radiation embrittlement according to the accepted methodology at the time the surveillance program was developed. Based on engineering judgment the D.C. Cook Unit 2 surveillance program meets the intent of this criteria.

Criterion 2: *Scatter in the plots of Charpy energy versus temperature for the irradiated and unirradiated conditions should be small enough to permit the determination of the 30 ft-lb temperature and upper shelf energy, unambiguously.*

Plots of Charpy energy versus temperature for the unirradiated and irradiated conditions are presented in References 4, 6, 7 and 8. Based on engineering judgment, the scatter in the data presented in those reports is small enough to determine the 30 ft-lb temperature and upper shelf energy of the D.C. Cook Unit 2 surveillance materials unambiguously. Therefore, the D.C. Cook Unit 2 surveillance program meets this criteria.

Criterion 3: *When there are two or more sets of surveillance data from one reactor, the scatter of ΔRT_{NDT} values about a best-fit line drawn as described in Regulatory Position 2.1 normally should be less than 28° F for welds and 17° F for base metal. Even if the fluence range is large (two or more orders of magnitude), the scatter should not exceed twice those values. Even if the data fail this criterion for use in shift calculations, they may be credible for determining decrease in upper shelf energy if the upper shelf can be clearly determined, following the definition given in ASTM E185-82.*

The least squares method, as described in Regulatory Position 2.1, will be utilized in determining a best-fit line for this data to determine if this criteria is met.

TABLE 4-3

Calculation of Chemistry Factors using D.C. Cook Unit 2 Surveillance Capsule Data

Material	Capsule	Fluence[a,b]	FF	ΔRT_{NDT}[b]	FF * ΔRT_{NDT}	FF^2
Intermediate Shell C5521-2 (longitudinal)	T	2.38×10^{18}	0.612	55	33.66	0.375
	Y	6.64×10^{18}	0.885	90	79.65	0.783
	X	1.019×10^{19}	1.005	95	95.48	1.010
	U	1.583×10^{19}	1.127	95	107.07	1.270
Intermediate Shell C5521-2 (Transverse)	T	2.38×10^{18}	0.612	80	48.96	0.375
	Y	6.64×10^{18}	0.885	100	88.50	0.783
	X	1.019×10^{19}	1.005	103	103.52	1.010
	U	1.583×10^{19}	1.127	130	146.51	1.270
				SUM:	703.35	6.876
	$CF = \Sigma(FF * RT_{NDT}) \div \Sigma(FF^2) = (703.35) \div (6.876) =$ **102.3°F**					
Weld Metal	T	2.38×10^{18}	0.612	40	24.48	0.375
	Y	6.64×10^{18}	0.885	50	44.25	0.783
	X	1.019×10^{19}	1.005	70	70.35	1.010
	U	1.583×10^{19}	1.127	75	84.53	1.270
				SUM:	223.61	3.438
	$CF = \Sigma(FF * RT_{NDT}) \div \Sigma(FF^2) = (223.61) \div (3.438) =$ **65.0°F**					

(a) Calculated Fluence values are in units of n/cm^2, E > 1.0 MeV.

(b) Data obtained from WCAP-13515 Rev. 1[4], revised Capsule U Analysis.

Plate Material:

TABLE 4-4				
D.C. Cook Unit 2 Surveillance Capsule Data Scatter about the Best-Fit Line for the Intermediate Shell Plate C5521-2 Material				
Intermediate Shell Plate C5521-2 Orientation	FF	Measured ΔRT_{NDT} (30 ft-lb) (°F)	Best Fit ΔRT_{NDT} (°F)	Scatter of ΔRT_{NDT} (°F)
Longitudinal (CF = 102.3°F)	0.612	55	62.6	7.6
	0.885	90	90.5	0.5
	1.005	95	102.8	7.8
	1.127	95	115.3	20.3
Transverse (CF = 102.3°F)	0.612	80	62.6	-17.4
	0.885	100	90.5	-9.5
	1.005	103	102.8	-0.2
	1.127	130	115.3	-14.7

Table 4-4 indicates that one measured plate ΔRT_{NDT} value is above the upper bound 1σ of 17ºF by less than 1ºF. Meaning the best-fit line is slightly under predicting this measured ΔRT_{NDT} value. Table 4-4 also indicates that one measured plate ΔRT_{NDT} value is below the lower bound 1σ of 17ºF by approximately 3ºF. From a statistical point of view, $\pm 1\sigma$ (17ºF) would be expected to encompass 68% of the data. Therefore, it is still statistically acceptable to have two of the plate data points fall outside the $\pm 1\sigma$ bounds. The fact that two of the measured plate ΔRT_{NDT} values are outside of 1σ bound of 17ºF can be attributed to several factors, such as 1) the inherent uncertainty in Charpy test data, 2) the use of hand-fit Charpy curves, using engineering judgment, for the ΔRT_{NDT} versus an asymmetric or symmetric tangent Charpy curve fitting program and/or 3) rounding errors.

Weld Metal:

TABLE 4-5			
D.C. Cook Unit 2 Surveillance Capsule Data Scatter about the Best-Fit Line for the Weld Material			
FF	Measured ΔRT_{NDT} (30 ft-lb) (°F)	Best Fit[(a)] ΔRT_{NDT} (°F)	Scatter of ΔRT_{NDT} (°F)
0.612	40	39.8	-0.2
0.885	50	57.5	7.5
1.005	70	65.3	-4.7
1.127	75	73.3	-1.7

NOTES:

(a) The Chemistry Factor used for the best fit ΔRT_{NDT} is 65.0°F.

The scatter of ΔRT_{NDT} values about a best-fit line drawn, as described in Regulatory Position 2.1, is less than 28°F as shown above. Therefore, this criteria is met for the D.C. Cook Unit 2 surveillance weld material. Since surveillance Weld data is credible, a σ_Δ margin of 14°F will be used when predicting the Cook Unit 2 beltline weld material properties.

Criterion 4: The irradiation temperature of the Charpy specimens in the capsule should match the vessel wall temperature at the cladding/base metal interface within +/- 25 °F.

The D.C. Cook Unit 2 capsule specimens are located in the reactor between the thermal shield and the vessel wall and are positioned opposite the center of the core. The test capsules are in the guide tubes attached to the thermal shield. The location of the specimens with respect to the reactor vessel beltline provides assurance that the reactor vessel wall and the specimens experience equivalent operating conditions and the temperatures will not differ by more than 25°F. This engineering judgment is accepted by the NRC.

Criterion 5: The surveillance data for the correlation monitor material in the capsule should fall within the scatter band of the data base for that material.

The D.C. Cook Unit 2 surveillance program does not include correlation monitor material. Therefore, this criteria is not applicable to D.C. Cook Unit 2.

Based on the preceding responses to the criteria of Regulatory Guide 1.99, Revision 2, Section B, and the application of engineering judgment, the D.C. Cook Unit 2 surveillance data is credible.

4.2.1 Application of the Credibility Criteria:

The D.C. Cook Unit 2 surveillance data is deemed credible per Regulatory Guide 1.99, Revision 2. Hence, ½ σ_Δ will be used in the ART evaluations for the surveillance program materials.

4.2.2 σ_Δ and How it was Determined:

Per Regulatory Guide 1.99, Revision, 2 Position 1.1, the values of σ_Δ are referred to as "28°F for welds and 17°F for base metal, except that σ_Δ need not exceed 0.50 times the mean value of ΔRT_{NDT}." The "mean value of ΔRT_{NDT}" is defined in Regulatory Guide 1.99, Revision 2, by Equation 2. The chemistry factor in Regulatory Guide 1.99, Revision 2, Equation 2 is calculated from Tables 1 and 2 or Position 2.1 of Regulatory Guide .99, Revision 2.

Per Regulatory Guide 1.99, Revision, 2 Position 2.1, when there is credible surveillance data, σ_Δ is taken to be the lesser of ½ ΔRT_{NDT} or 14°F (28°F/2) for welds, or 8.5°F (17°F/2) for base metal. ΔRT_{NDT} again is defined herein by Equation 13, while utilizing a "Best-Fit Chemistry Factor" calculated in accordance with Position 2.1 of Regulatory Guide 1.99, Revision 2 and is shown herein on Table 4-1.

5.0 UNIRRADIATED PROPERTIES

5.1 Initial RT_{NDT} of Beltline Materials

Charpy V-notch impact specimens from the base material plates of the reactor vessel were machined in the longitudinal orientation (longitudinal axis of the specimen parallel to the major working direction of the plate) and the transverse orientation (longitudinal axis of the specimen perpendicular to the major working direction of the plate). The core region weld Charpy impact specimen was perpendicular to the weld direction. The notch of the weld metal Charpy specimen was machined such that the direction of crack propagation in the specimen was in the welding direction.

Table 5-1 contains a description of the beltline materials and their initial RT_{NDT} values.

TABLE 5-1

Reactor Vessel Material Initial RT_{NDT}

Material Description	Heat #	Flux Type	Flux Lot	Initial RT_{NDT} [a]
D.C. Cook Unit 2				
Inter. Shell Axial Welds	S3986	Linde 124	0934	-35°F
Inter. Shell Plate 10-1	C5556-2	--	--	58°F
Inter. Shell Plate 10-2	C5521-2	--	--	38°F
Int/Lower Shell Circ. Weld	S3986	Linde 124	0934	-35°F
Lower Shell Axial Welds	S3986	Linde 124	0934	-35°F
Lower Shell Plate 9-1	C5540-2	--	--	-20°F
Lower Shell Plate 9-2	C5592-1	--	--	-20°F
Surveillance Weld	S3986	Linde 124	0934	--
Closure Head Flange (4437-V-1)	--	--	--	-20°F
Vessel Flange (4436-V-2)	--	--	--	30°F

NOTES:

(a) The Initial RT_{NDT} values were obtained from WCAP-13515[4] and are measured values.

5.2 Determination of σ_I :

Since the initial RT_{NDT} values are measured values, the D.C. Cook Unit 2 σ_I values are 0°F.

5.3 Bolt-up Temperature:

The minimum bolt-up temperature requirements for the D.C. Cook Unit 2 reactor pressure vessels are according to Paragraph G-2222 of the ASME Boiler and Pressure Vessel (B&PV) Code, Section XI, Appendix G, the reactor vessel may be bolted up and pressurized to 20 percent of the initial hydrostatic test pressure at the initial RT_{NDT} of the material stressed by the bolt-up. Therefore, since the most limiting initial RT_{NDT} value is 30°F (vessel flange), the reactor vessel can be bolted up at 30°F. However, based on engineering judgment Westinghouse recommends a bolt-up of at least 60°F.

6.0 REACTOR VESSEL GEOMETRIC & SYSTEM PARAMETERS

6.1 Reactor Vessel Physical Dimensions and Operating Conditions:

The following are the D.C. Cook Unit 2 reactor vessel physical dimensions and operating conditions:

Reactor vessel inner diameter (to clad)	= 173 inches
Clad thickness	= 7/32 inches
Reactor Vessel Beltline Thickness	= 8.5 inches
Pre-Service System Hydrostatic Pressure	= 3106 psig
Capacity Factor (Future Cycles)	= 90%

System and Component Operating Conditions/Dimensions:

Design Pressure	= 2485 psig
Operating Pressure	= 2235 psig

7.0 FLUENCE FACTOR DETERMINATION

7.1 Peak Clad Base Metal Interface Fluence for each Beltline Material:

Contained in Table 7-1 are the reactor vessel clad/base metal interface fluences. These values were obtained from WCAP-13515 Revision 1[4], "Analysis of Capsule U from the Indiana Michigan Power Company D.C. Cook Unit 2 Reactor Vessel Radiation Surveillance Program".

TABLE 7-1

Calculated Fluence (10^{19} n/cm^2, E > 1.0 MeV) at the Pressure Vessel Clad/Base Metal Interface for the D.C. Cook Unit 2 Reactor Vessel

EFPY	0°	15°	30°	45°
12.20 (EOC 11)	0.231	0.357	0.435	0.626
13.60 (EOC 12)	0.248	0.384	0.469	0.676
32	0.527	0.837	1.128	1.625
48	0.771	1.232	1.706	2.457

Per AEP the current end of license (EOL) EFPY is 32 EFPY and the EOL license renewal EFPY is 48 EFPY.

Thus, the EFPY values used to generate pressure/temperature curves and the calculated fluence values are:

Current EOL = 32 EFPY
Renewal EOL = 48 EFPY

Cook Unit 2 has longitudinal weld seams at 0° and 10° azimuthal angles. However, all beltline welds were fabricated with the same weld wire and flux, thus the girth weld will receive the peak vessel fluence. Since the girth weld seam will receive a higher fluence than the longitudinal weld seams, only the peak vessel fluence will be used for the ART calculations (ie. The girth weld will bound all other beltline weld seams). In addition, all beltline plates will receive the peak vessel fluence.

7.2 1/4T & 3/4T Thickness Fluence for each Beltline Material:

The neutron fluence at the 1/4T & 3/4T depth in the vessel wall was calculated per Regulatory Guide 1.99, Revision 2, as follows:

$$f = f_{surf} * e^{\{-0.24(x)\}} \text{ , } 10^{19} \text{ n/cm}^2 \text{ (E > 1.0 MeV)} \qquad (10)$$

where: f_{surf} = Vessel inner wall surface fluence, 10^{19} n/cm^2 (E > 1.0 MeV) (See Table 7-1)
x = is the depth into the vessel wall from the inner surface, inches
(0.25 * 8.5 inches or 0.75 * 8.5 inches)

Contained in Table 7-2 is a summary of the fluence values used to calculate the D.C. Cook Unit 2 ART values used to develop the pressure-temperature curves for normal operation.

TABLE 7-2			
Summary of Fluence Values Used to Calculate the D.C. Cook Unit 2 ART Values			
EFPY	Peak Clad/Base Metal Fluence (E > 1.0 MeV)	1/4T Fluence (E > 1.0 MeV)	3/4T Fluence (E > 1.0 MeV)
32	1.625 x 10^{19} n/cm^2	9.75 x 10^{18} n/cm^2	3.51 x 10^{18} n/cm^2
48	2.457 x 10^{19} n/cm^2	1.475 x 10^{19} n/cm^2	5.32 x 10^{18} n/cm^2

7.3 Fluence Factors:

The fluence factors were calculated per Regulatory Guide 1.99, Revision 2, using the following equation.

$$FF = \text{fluence factor} = f^{(0.28 - 0.1 \log(f))} \qquad (11)$$

where: f = Vessel inner wall surface fluence, 1/4 T fluence or 3/4T fluence, [10^{19} n/cm^2 (E > 1.0 MeV) ÷ 10^{19} n/cm^2 (E > 1.0 MeV)]

Contained in Table 7-3 is a summary of the calculated fluence factors for 32 and 48 EFPY.

TABLE 7-3				
Summary of Fluence Factors Used to Calculate the D.C. Cook Unit 2 ART Values				
EFPY	1/4T Fluence (E > 1.0 MeV)	Fluence Factor	3/4T Fluence (E > 1.0 MeV)	Fluence Factor
32	9.75×10^{18} n/cm^2	.993	3.51×10^{18} n/cm^2	.711
48	1.475×10^{19} n/cm^2	1.108	5.32×10^{18} n/cm^2	.824

8.0 CALCULATION OF ADJUSTED REFERENCE TEMPERATURE

8.1 Methodology:

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:

$$ART = Initial\ RT_{NDT} + \Delta\ RT_{NDT} + Margin \qquad (12)$$

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[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:

$$\Delta\ RT_{NDT} = CF * f^{(0.28-0.10\log f)} \qquad (13)$$

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. The resultant fluence is then placed in the equation above to calculate the ΔRTNDT at the specific depth. The calculated CF and FF values are given in Tables 4-1, 4-2 and 7-3 of this report.

$$f_{(depth\ x)} = f_{surface} * e^{(-0.24x)} \qquad (14)$$

When there are "two or more credible surveillance data sets"[1] available, Regulatory Guide 1.99 Revision 2, Position 2.1, states "To calculate the Margin in this case, use Equation 4; the values given there for σ_Δ may be cut in half". Equation 4 from Regulatory Guide 1.99 Revision 2, is as follows:

$$M = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2} \qquad (15)$$

The values of σ_Δ are referred to as "28°F for welds and 17°F for base metals."

Standard Deviation for Initial RT_{NDT} Margin Term, σ_I: If the initial RT_{NDT} values are measured values, then σ_I is taken to be 0°F, otherwise use 17°F.

Standard Deviation for ΔRT_{NDT} Margin Term, σ_Δ: Per Regulatory Guide 1.99 Revision 2, Position 1.1, the values of σ_Δ are referred to as "28°F for welds and 17°F for base metal, except that σ_Δ need not exceed 0.50 times the mean value of ΔRT_{NDT}." The "mean value of ΔRT_{NDT}" is defined in Regulatory Guide 1.99

Revision 2, by Equation 2. The chemistry factor in Regulatory Guide 1.99, Revision 2, Equation 2 is calculated from Tables 1 and 2 of Regulatory Guide 1.99 Revision 2.

Per Regulatory Guide 1.99, Revision 2, Position 2.1, when there is credible surveillance data, σ_Δ is taken to be the lesser of ½ΔRT_{NDT} or 14°F (28°F/2) for welds, or 8.5°F (17°F/2) for base metal. ΔRT_{NDT} again is defined herein by Equation 4, while utilizing a "Best-Fit Chemistry Factor" calculated in accordance with Position 2.1 of Regulatory Guide 1.99, Revision 2.

Since σ_I is taken to be zero when a heat-specific measured value of initial RT_{NDT} are available (as they are in this case), the total margin term, based on Equation 4 of Regulatory Guide 1.99, Revision 2, is as follows:

Position 1.1: Lesser of ΔRT_{NDT} or 56°F for Welds
Lesser of ΔRT_{NDT} or 34°F for Base Metal

Position 2.1: Lesser of ΔRT_{NDT} or 28°F for Welds
Lesser of ΔRT_{NDT} or 17°F for Base Metal

8.2 Adjusted Reference Temperature (ART) Calculations:

The ART calculations along with the actual margin terms used for D.C. Cook Unit 2 are listed in Tables 8-1 through 8-4.

TABLE 8-1							
Calculation of the ART Values for D.C. Cook Unit 2 for the 1/4T Location and 32 EFPY							
Material	RG 1.99 R2 Method	CF	FF	ΔRT_{NDT}	Margin	IRT_{NDT}	ART
Intermediate Shell Plate C5556-2	Position 1.1	108.4°F	.993	107.6°F	34°F	58°F	200
Intermediate Shell Plate C5521-2	Position 1.1	90.4°F	.993	89.8°F	34°F	38°F	162
	Position 2.1	102.3°F	.993	101.6°F	17°F	38°F	157
Lower Shell Plate C5540-2	Position 1.1	74.6°F	.993	74.1°F	34°F	-20°F	88
Lower shell Plate C5592-1	Position 1.1	99.5°F	.993	98.8°F	34°F	-20°F	113
Beltline Weld Seams (Circ. Weld is Limiting)	Position 1.1	76.4°F	.993	75.9°F	56°F	-35°F	97
	Position 2.1	66.3°F	.993	65.8°F	28°F	-35°F	59

TABLE 8-2							
Calculation of the ART Values for D.C. Cook Unit 2 for the 3/4T Location and 32 EFPY							
Material	RG 1.99 R2 Method	CF	FF	ΔRT_{NDT}	Margin	IRT_{NDT}	ART
Intermediate Shell Plate C5556-2	Position 1.1	108.4°F	.711	77.1°F	34°F	58°F	169°F
Intermediate Shell Plate C5521-2	Position 1.1	90.4°F	.711	64.3°F	34°F	38°F	136°F
	Position 2.1	102.3°F	.711	72.7°F	17°F	38°F	128°F
Lower Shell Plate C5540-2	Position 1.1	74.6°F	.711	53.0°F	34°F	-20°F	67°F
Lower shell Plate C5592-1	Position 1.1	99.5°F	.711	70.7°F	34°F	-20°F	85°F
Beltline Weld Seams (Circ. Weld is Limiting)	Position 1.1	76.4°F	.711	54.3°F	54.3°F	-35°F	74°F
	Position 2.1	66.3°F	.711	47.1°F	28°F	-35°F	40°F

TABLE 8-3							
Calculation of the ART Values for D.C. Cook Unit 2 for the 1/4T Location and 48 EFPY							
Material	RG 1.99 R2 Method	CF	FF	ΔRT_{NDT}	Margin	IRT_{NDT}	ART
Intermediate Shell Plate C5556-2	Position 1.1	108.4°F	1.108	120.1°F	34°F	58°F	212°F
Intermediate Shell Plate C5521-2	Position 1.1	90.4°F	1.108	100.2°F	34°F	38°F	172°F
	Position 2.1	102.3°F	1.108	113.3°F	17°F	38°F	168°F
Lower Shell Plate C5540-2	Position 1.1	74.6°F	1.108	82.7°F	34°F	-20°F	97°F
Lower shell Plate C5592-1	Position 1.1	99.5°F	1.108	110.2°F	34°F	-20°F	124°F
Beltline Weld Seams (Circ. Weld is Limiting)	Position 1.1	76.4°F	1.108	84.7°F	56°F	-35°F	106°F
	Position 2.1	66.3°F	1.108	73.5°F	28°F	-35°F	67°F

Material	RG 1.99 R2 Method	CF	FF	ΔRT_{NDT}	Margin	IRT_{NDT}	ART
Intermediate Shell Plate C5556-2	Position 1.1	108.4°F	.824	89.3°F	34°F	58°F	181°F
Intermediate Shell Plate C5521-2	Position 1.1	90.4°F	.824	74.5°F	34°F	38°F	146°F
	Position 2.1	102.3°F	.824	84.3°F	17°F	38°F	139°F
Lower Shell Plate C5540-2	Position 1.1	74.6°F	.824	61.5°F	34°F	-20°F	75°F
Lower shell Plate C5592-1	Position 1.1	99.5°F	.824	82.0°F	34°F	-20°F	96°F
Beltline Weld Seams (Circ. Weld is Limiting)	Position 1.1	76.4°F	.824	63.0°F	56°F	-35°F	84°F
	Position 2.1	66.3°F	.824	54.6°F	28°F	-35°F	48°F

TABLE 8-4

Calculation of the ART Values for D.C. Cook Unit 2 for the 3/4T Location and 48 EFPY

Contained in Table 8-5 is a summary of the limiting ART values used in the generation of the D.C. Cook Unit 2 reactor vessel heatup and cooldown curves.

TABLE 8-5		
Summary of the Limiting ART Values* to be Used in the Generation of the Cook Unit 2 Reactor Vessel Heatup and Cooldown Curves		
EFPY	1/4 T Limiting ART	3/4 Limiting ART
32	200°F	169°F
48	212°F	181°F

* Intermediate shell plate 10-1 (Heat # C5556-2) is the limiting material for all cases.

9.0 HEATUP AND COOLDOWN PRESSURE-TEMPERATURE LIMIT CURVES

9.1 Introduction and Methodology:

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 8 of this report.

Figure 9-1 presents the heatup curves without margins for possible instrumentation errors for a heatup rate of 60°F/hr. This curve is applicable to 32 EFPY (current end of license). Figure 9-2 presents the cooldown curves without margins for possible instrumentation errors for cooldown rates of 0, 20, 40, 60, and 100°F/hr. These curves are also applicable to 32 EFPY (current end of license). Figure 9-3 presents the heatup curves without margins for possible instrumentation uncertainty for a heatup rates of 60°F/hr. This curve is applicable to 48 EFPY (end of license renewal). Figure 9-4 presents the cooldown curves without margins for possible instrumentation uncertainty for cooldown rates of 0, 20, 40, 60, and 100°F/hr. These curves are also applicable to 48 EFPY (end of license renewal). Allowable combinations of temperature and pressure for specific temperature change rates are below and to the right of the limit lines shown in Figures 9-1 through 9-4. This is in addition to other criteria, which must be met before the reactor is made critical, as discussed 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 Figures 9-1 and 9-3. 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 Code Case N-640[12] and Appendix G to Section XI of the ASME Code[3] as follows:

$$1.5\,K_{Im} < K_{Ic} \tag{15}$$

where,

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

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

T is the minimum permissible metal temperature, and

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 Reference 2. 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 3 of this report. For the heatup and cooldown curves without margins for instrumentation errors, the minimum temperature for the in service hydrostatic leak tests for D.C. Cook Unit 2 reactor vessel at 32 and 48 EFPY is 260°F and 272°F, respectively. 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 9-1 through 9-4 define all of the above limits for ensuring prevention of nonductile failure for the D.C. Cook Unit 2 reactor vessel. The data points for the heatup and cooldown pressure-temperature limit curves shown in Figures 9-1 through 9-4 are presented in Tables 9-1 through 9-4.

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate C5556-2
LIMITING ART VALUES AT 32 EFPY: 1/4T, 200°F
3/4T, 169°F

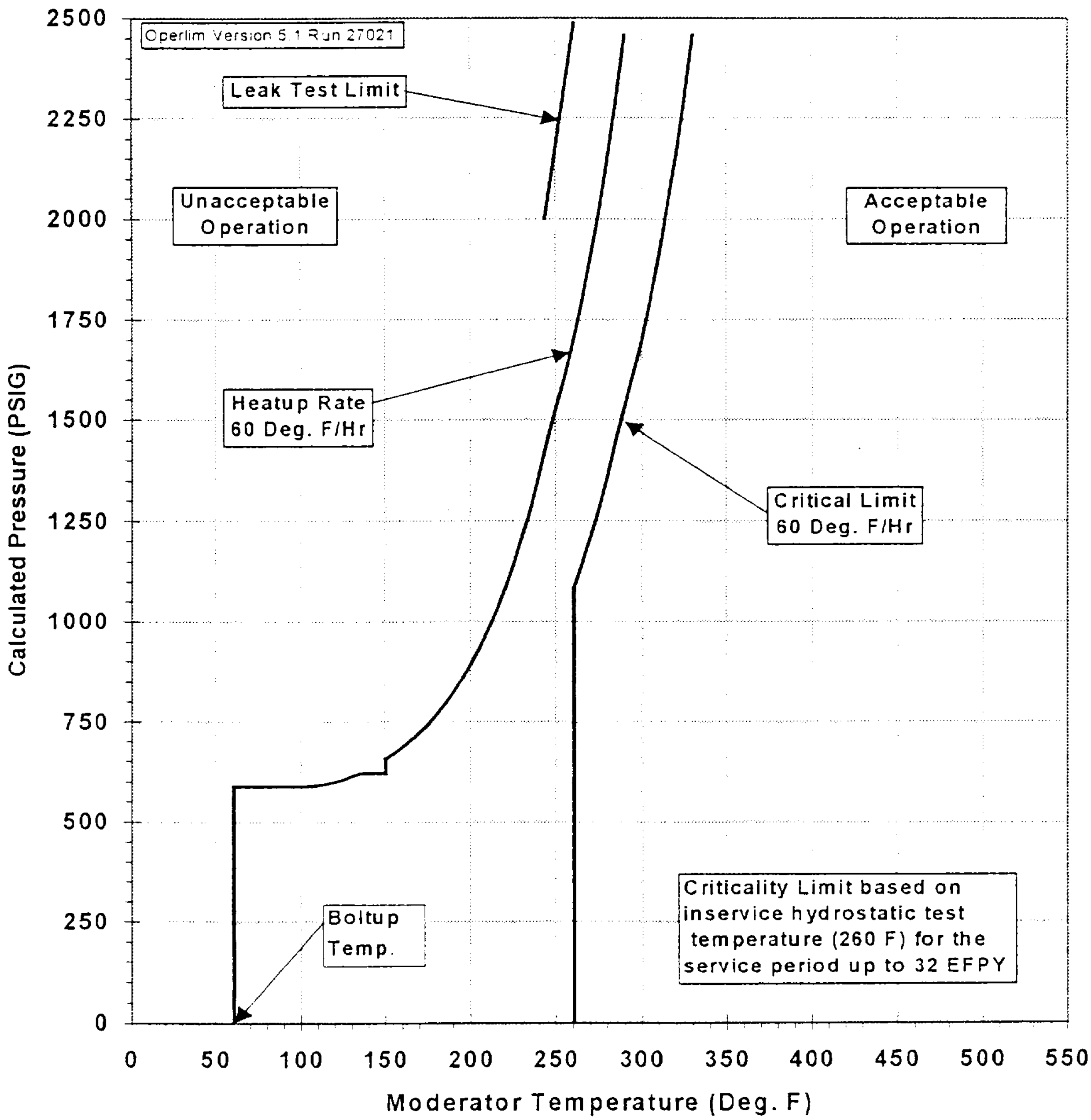

FIGURE 9-1 D.C. Cook Unit 2 Reactor Coolant System Heatup Limitations (Heatup Rate of 60°F/hr) Applicable for 32 EFPY (Without Margins for Instrumentation Errors) (Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate C5556-2
LIMITING ART VALUES AT 32 EFPY: 1/4T, 200°F
3/4T, 169°F

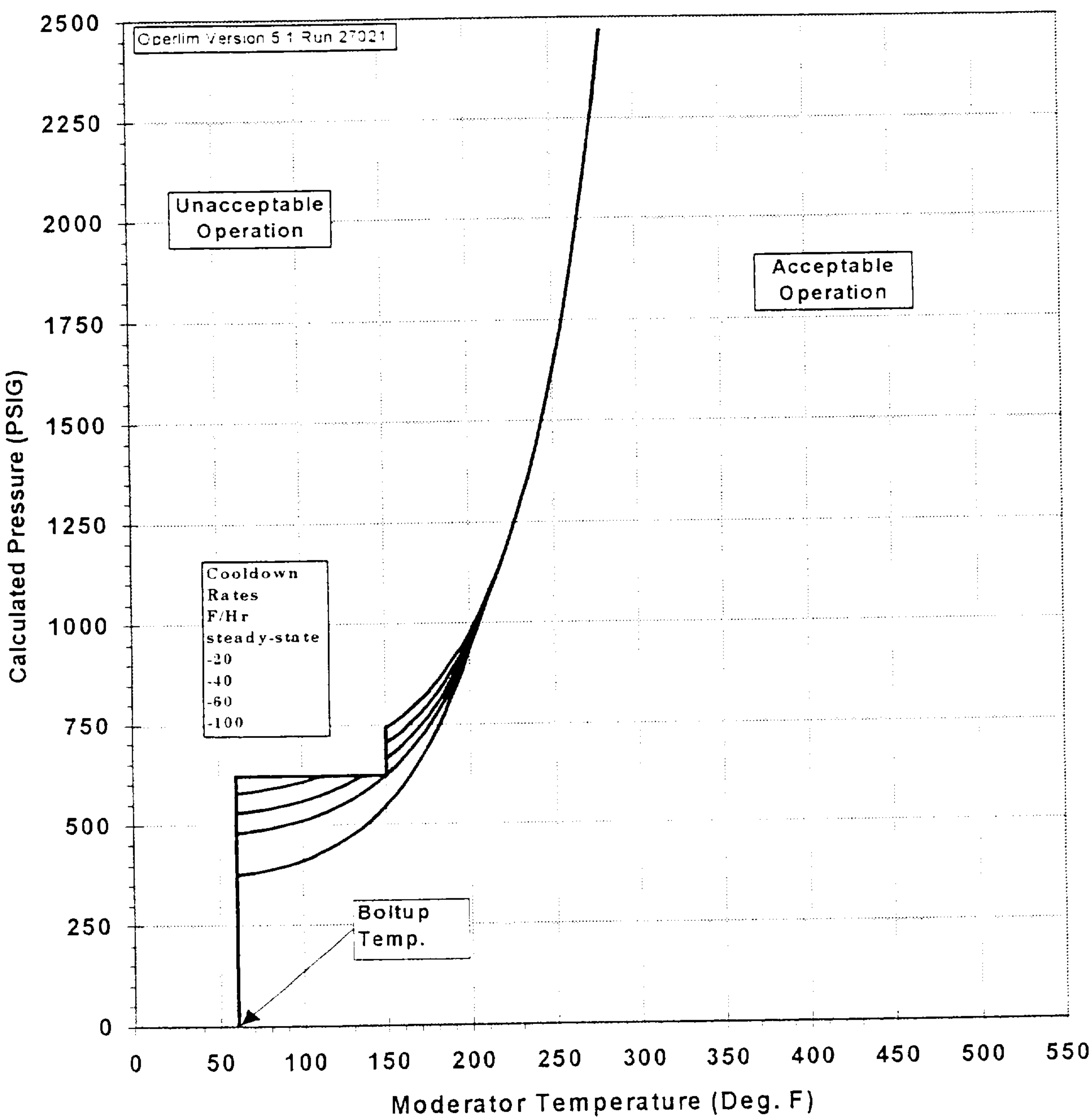

FIGURE 9-2 D.C. Cook Unit 2 Reactor Coolant System Cooldown Limitations (Cooldown Rates of 0, 20, 40, 60 and 100°F/hr) Applicable for 32 EFPY (Without Margins for Instrumentation Errors) (Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate C5556-2
LIMITING ART VALUES AT 48 EFPY: 1/4T, 212°F
3/4T, 181F

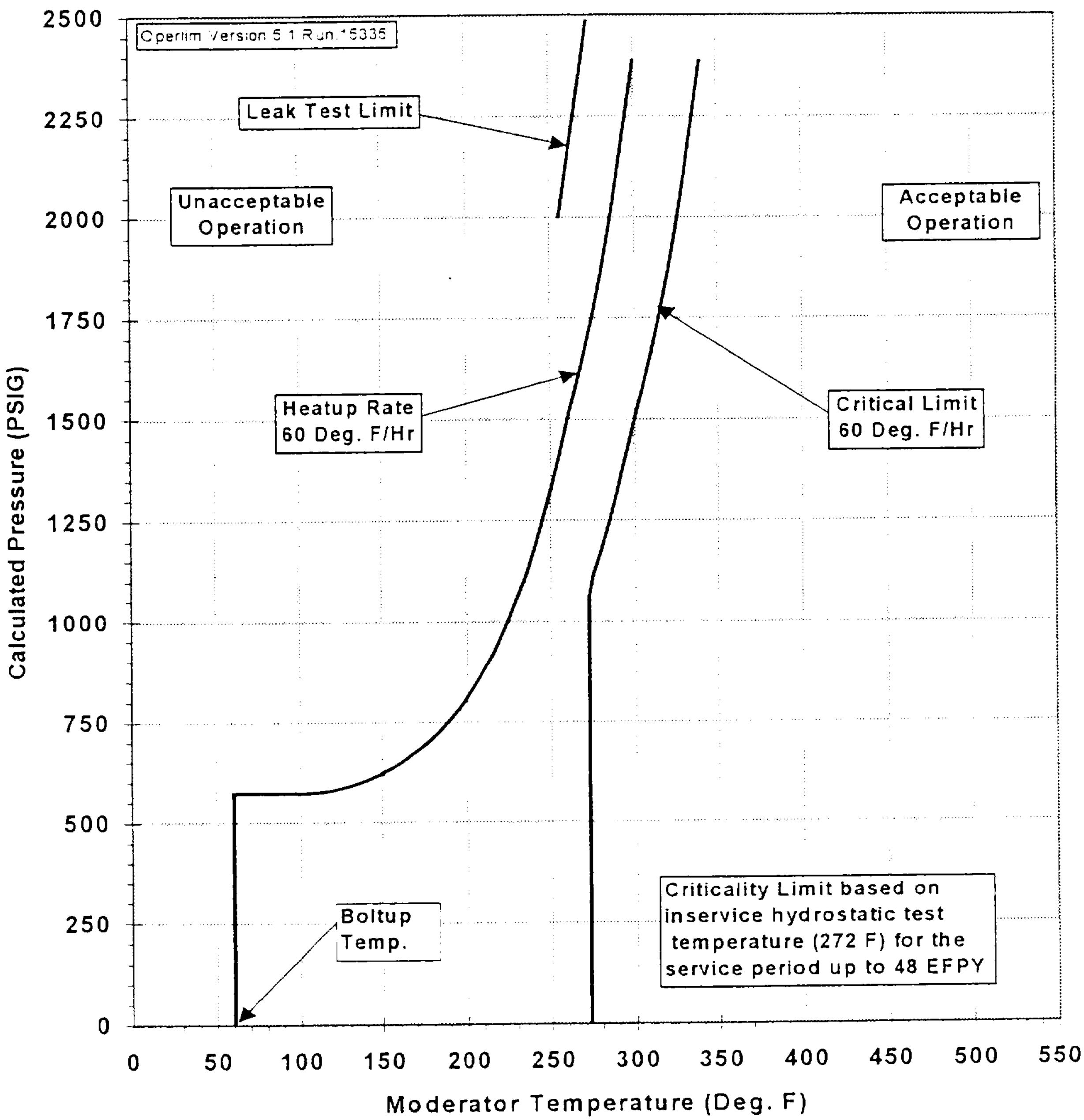

FIGURE 9-3 D.C. Cook Unit 2 Reactor Coolant System Heatup Limitations (Heatup Rate of 60°F/hr) Applicable for 48 EFPY (Without Margins for Instrumentation Errors) (Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate C5556-2
LIMITING ART VALUES AT 48 EFPY: 1/4T, 212°F
3/4T, 181F

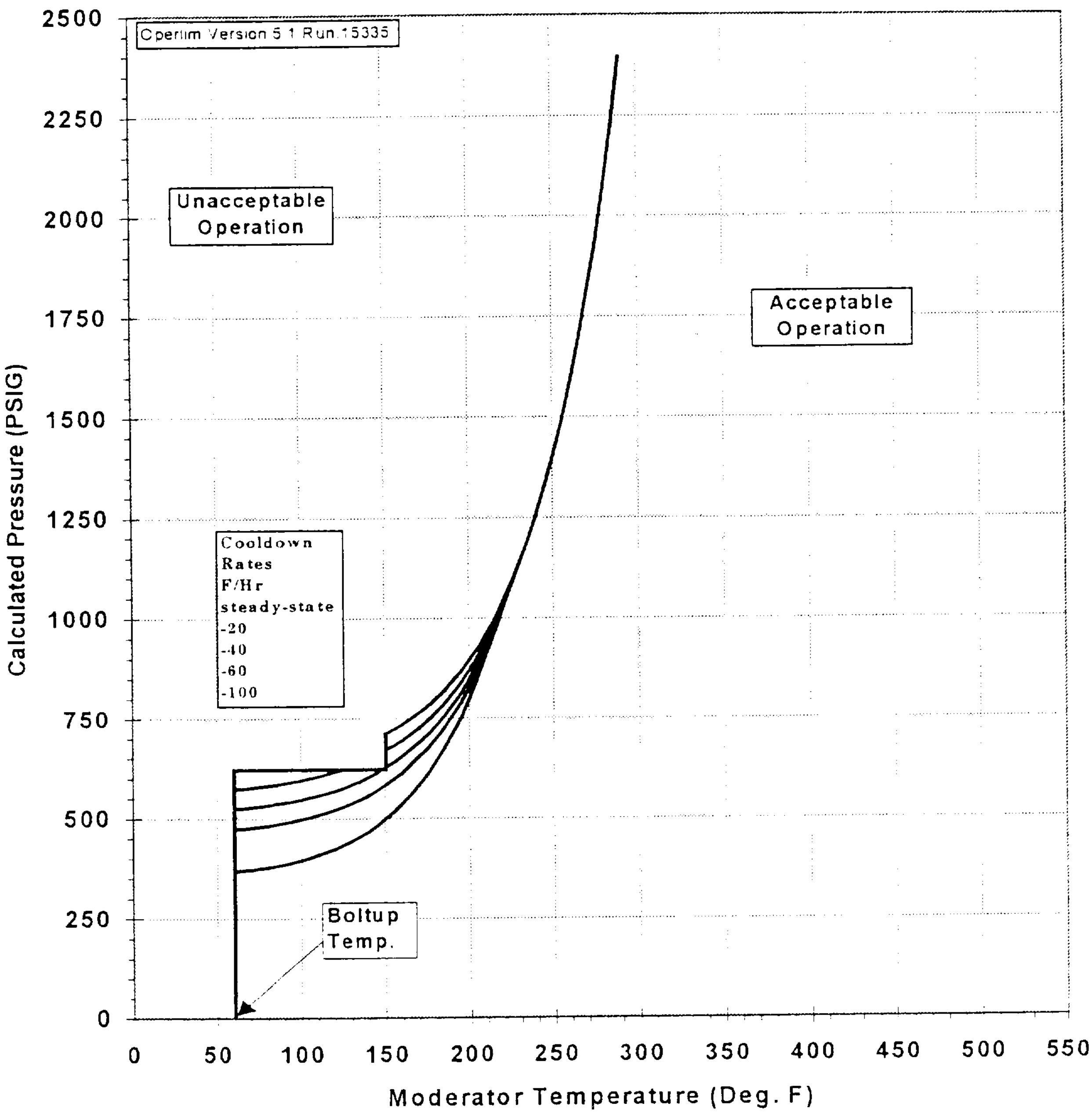

FIGURE 9-4 D.C. Cook Unit 2 Reactor Coolant System Cooldown Limitations (Cooldown Rates of 0, 20, 40, 60 and 100°F/hr) Applicable for 48 EFPY (Without Margins for Instrumentation Errors) (Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

TABLE 9-1

D.C. Cook Unit 2 Reactor Vessel Heatup Curve Data Points for 32 EFPY

Without Margins for Instrumentation Errors

(Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

Composite 60		Critical Limit 60		Leak Test Limit	
T (°F)	P (psig)	T (°F)	P (psig)	T (°F)	P (psig)
60	0	260	0	243	2000
60	588	260	588	260	2485
65	588	260	588		
70	588	260	589		
75	588	260	590		
80	588	260	592		
85	588	260	594		
90	588	260	595		
95	588	260	600		
100	588	260	600		
105	589	260	606		
110	592	260	608		
115	595	260	614		
120	600	260	620		
125	606	260	621		
130	614	260	621		
135	621	260	621		
140	621	260	621		
145	621	260	621		
150	621	260	656		
150	656	260	670		
155	670	260	686		
160	686	260	704		
165	704	260	724		
170	724	260	746		
175	746	260	770		
180	770	260	797		
185	797	260	827		
190	827	260	860		
195	860	260	896		
200	896	260	936		
205	936	260	981		
210	981	260	1030		
215	1030	260	1084		
220	1084	265	1144		
225	1144	270	1211		
230	1211	275	1284		
235	1284	280	1365		
240	1365	285	1454		
245	1454	290	1531		

250	1531	295	1611		
255	1611	300	1699		
260	1699	305	1796		
265	1796	310	1903		
270	1903	315	2022		
275	2022	320	2152		
280	2152	325	2296		
285	2296	330	2455		
290	2455				

TABLE 9-2
D.C. Cook Unit 2 Reactor Vessel Cooldown Curve Data Points for 32 EFPY
Without Margins for Instrumentation Errors
(Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

Steady State		20 °F/hr.		40°F/hr.		60°F/hr.		100°F/hr.	
T(°F)	P (psig)	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	0
60	621	60	578	60	529	60	479	60	376
65	621	65	580	65	532	65	482	65	379
70	621	70	583	70	534	70	485	70	382
75	621	75	586	75	537	75	488	75	386
80	621	80	589	80	541	80	492	80	390
85	621	85	593	85	545	85	496	85	395
90	621	90	597	90	549	90	500	90	400
95	621	95	602	95	554	95	506	95	406
100	621	100	607	100	559	100	511	100	413
105	621	105	613	105	566	105	518	105	421
110	621	110	619	110	572	110	525	110	429
115	621	115	621	115	580	115	533	115	439
120	621	120	621	120	588	120	542	120	450
125	621	125	621	125	597	125	552	125	462
130	621	130	621	130	608	130	564	130	475
135	621	135	621	135	619	135	576	135	490
140	621	140	621	140	621	140	590	140	507
145	621	145	621	145	621	145	605	145	526
150	621	150	621	150	621	150	623	150	547
150	741	150	701	150	662	155	642	155	570
155	756	155	717	155	679	160	663	160	596
160	772	160	735	160	698	165	686	165	625
165	789	165	754	165	720	170	713	170	657
170	809	170	776	170	743	175	741	175	693
175	831	175	799	175	770	180	774	180	733
180	855	180	826	180	799	185	809	185	776
185	881	185	855	185	831	190	848	190	825
190	911	190	887	190	866	195	892	195	879
195	943	195	923	195	906	200	941	200	939
200	979	200	962	200	949	205	994	205	1006
205	1019	205	1006	205	998	210	1054	210	1062
210	1062	210	1054	210	1051	215	1108	215	1108
215	1111	215	1108	215	1108	220	1164	220	1164
220	1164	220	1164	220	1164	225	1223	225	1223
225	1223	225	1223	225	1223	230	1288	230	1288
230	1288	230	1288	230	1288	235	1361	235	1361
235	1361	235	1361	235	1361	240	1440	240	1440
240	1440	240	1440	240	1440	245	1528	245	1528
245	1528	245	1528	245	1528	250	1626	250	1626
250	1626	250	1626	250	1626	255	1733	255	1733

255	1733	255	1733	255	1733	260	1852	260	1852
260	1852	260	1852	260	1852	265	1984	265	1984
265	1984	265	1984	265	1984	270	2129	270	2129
270	2129	270	2129	270	2129	275	2289	275	2289
275	2289	275	2289	275	2289	280	2467	280	2467
280	2467	280	2467	280	2467				

TABLE 9-3

D.C. Cook Unit 2 Reactor Vessel Heatup Curve Data Points for 48 EFPY
Without Margins for Instrumentation Errors
(Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

60°F/hr. Heatup		60°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	272	0	255	2000
60	575	272	575	272	2485
65	575	272	575		
70	575	272	576		
75	575	272	576		
80	575	272	579		
85	575	272	579		
90	575	272	582		
95	575	272	583		
100	575	272	586		
105	575	272	590		
110	576	272	592		
115	579	272	598		
120	582	272	599		
125	586	272	606		
130	592	272	611		
135	598	272	614		
140	606	272	621		
145	614	272	621		
150	621	272	624		
150	624	272	635		
155	635	272	647		
160	647	272	661		
165	661	272	676		
170	676	272	693		
175	693	272	712		
180	712	272	733		
185	733	272	757		
190	757	272	782		
195	782	272	811		
200	811	272	843		
205	843	272	878		
210	878	272	916		
215	916	272	959		
220	959	272	1006		
225	1006	272	1058		
230	1058	275	1115		
235	1115	280	1179		
240	1179	285	1249		
245	1249	290	1326		

250	1326	295	1411		
255	1411	300	1501		
260	1501	305	1578		
265	1578	310	1662		
270	1662	315	1756		
275	1756	320	1858		
280	1858	325	1972		
285	1972	330	2097		
290	2097	335	2235		
295	2235	340	2387		
300	2387				

TABLE 9-4
D.C. Cook Unit 2 Reactor Vessel Cooldown Curve Data Points for 48 EFPY
Without Margins for Instrumentation Errors
(Includes Vessel Flange Requirements of 150°F and 621 psi per 10CFR50)

Steady State		20 °F/hr.		40°F/hr.		60°F/hr.		100°F/hr.	
T(°F)	P (psig)	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	0
60	621	60	572	60	523	60	473	60	368
65	621	65	574	65	525	65	475	65	370
70	621	70	576	70	527	70	477	70	373
75	621	75	579	75	529	75	479	75	375
80	621	80	581	80	532	80	482	80	378
85	621	85	584	85	535	85	485	85	382
90	621	90	587	90	538	90	488	90	386
95	621	95	591	95	542	95	492	95	390
100	621	100	595	100	546	100	497	100	395
105	621	105	599	105	551	105	502	105	401
110	621	110	604	110	556	110	507	110	407
115	621	115	610	115	562	115	514	115	415
120	621	120	616	120	569	120	521	120	423
125	621	125	621	125	576	125	528	125	432
130	621	130	621	130	584	130	537	130	443
135	621	135	621	135	593	135	547	135	454
140	621	140	621	140	603	140	558	140	467
145	621	145	621	145	614	145	570	145	482
150	621	150	621	150	626	150	583	150	498
150	711	150	669	155	639	155	598	155	516
155	723	155	681	160	654	160	614	160	536
160	736	160	695	165	671	165	633	165	559
165	750	165	710	170	690	170	653	170	584
170	765	170	727	175	710	175	676	175	612
175	782	175	746	180	733	180	701	180	642
180	801	180	766	185	758	185	729	185	677
185	822	185	789	190	786	190	759	190	715
190	845	190	815	195	817	195	794	195	757
195	870	195	843	200	851	200	831	200	804
200	899	200	874	205	889	205	874	205	856
205	930	205	908	210	931	210	920	210	914
210	964	210	946	215	977	215	972	215	972
215	1002	215	988	220	1029	220	1029	220	1029
220	1044	220	1034	225	1086	225	1086	225	1086
225	1091	225	1086	230	1142	230	1142	230	1142
230	1142	230	1142	235	1199	235	1199	235	1199

235	1199	235	1199	240	1262	240	1262	240	1262
240	1262	240	1262	245	1331	245	1331	245	1331
245	1331	245	1331	250	1407	250	1407	250	1407
250	1407	250	1407	255	1492	255	1492	255	1492
255	1492	255	1492	260	1586	260	1586	260	1586
260	1586	260	1586	265	1689	265	1689	265	1689
265	1689	265	1689	270	1803	270	1803	270	1803
270	1803	270	1803	275	1929	275	1929	275	1929
275	1929	275	1929	280	2069	280	2069	280	2069
280	2069	280	2069	285	2223	285	2223	285	2223
285	2223	285	2223	290	2394	290	2394	290	2394
290	2394	290	2394						

10.0 ENABLE TEMPERATURE CALCULATION:

10.1 ASME Code Case N-641 Methodology:

ASME Code Case N-641[13] presents alternative procedures for calculating pressure-temperature relationships and low temperature overpressure protection (LTOP) system effective temperatures and allowable pressures. "These procedures take into account alternative fracture toughness properties, circumferential and axial reference flaws, and plant-specific LTOP effective temperature calculations."

ASME Code Case N-641 provides the following temperature condition to protect against failure during reactor startup and shutdown. The code requires that the LTOP or COMS system be effective at coolant temperatures less than 200°F or at coolant temperatures less than a temperature corresponding to a reactor vessel metal temperature calculated below:

(1) $T_e = RT_{NDT} + 40 + \max(\Delta T_{metal})$, °F

(2) $T_e = RT_{NDT} + 50 \ln [((F * M_m (pR_i / t)) - 33.2) / 20.734]$, °F,

where,

$M_m = 0.926(t)^{(1/2)}$, for an inside surface flaw (Ref. 3),

F = 1.1, accumulation factor for safety relief valves (Ref. 13)

p = 2.485, vessel design pressure, ksi (Section 6.1)

R_i = 173 / 2 = 86.5, vessel inner radius, in. (Section 6.1)

t = 8.5, vessel wall thickness, in. (Section 6.1)

RT_{NDT} is the highest adjusted reference temperature (ART) for the limiting beltline material at a distance one fourth of the vessel section thickness from the vessel inside surface (ie. clad/base metal interface), as determined by Regulatory Guide 1.99, Revision 2. The highest of the three temperatures determines the LTOP system effective temperature

10.2 32 EFPY Enable Temperature:

The highest calculated 1/4T ART for the D.C. Cook Unit 2 reactor vessel beltline regions at 32 EFPY is 200°F.

From the OPERLIM computer code output for the D.C. Cook Unit 2 32 EFPY Pressure-Temperature limit curves without margins the maximum ΔT_{metal} is:

Cooldown Rate (Steady-State Cooldown):

max (ΔT_{metal}) at 1/4T = 0°F

Heatup Rate of 60°F/Hr:

max (ΔT_{metal}) at 1/4T = 17.902°F

Enable Temperature, T_e (1) $= RT_{NDT} + 40 + \max(\Delta T_{metal})$, °F
$= (200 + 40 + 17.902)$ °F
$= 257.902$°F

Enable Temperature, T_e (2) $= RT_{NDT} + 50 \ln[((F * M_m (pR_i / t)) - 33.2) / 20.734]$, °F
$= 200 + 50 \ln[((1.1 * .926(8.5)^{(1/2)} * 2.485 * 86.5 / 8.5)-33.2) / 20.734]$, °F
$= 200 + 50 \ln[41.90 / 20.734]$, °F
$= 200 + 50 \ln[2.021]$
$= 235.180$°F

The minimum required enable temperature for the D.C. Cook Unit 2 Reactor Vessels will be conservatively chosen to be 260°F for 32 EFPY.

10.3 48 EFPY Enable Temperature:

The highest calculated 1/4T ART for the D.C. Cook Unit 2 reactor vessel beltline regions at 48 EFPY is 212°F.

From the OPERLIM computer code output for the D.C. Cook Unit 2 48 EFPY Pressure-Temperature limit curves without margins the maximum ΔT_{metal} is:

Cooldown Rate (Steady-State Cooldown):
$\max(\Delta T_{metal})$ at $1/4T = 0$°F

Heatup Rate of 60°F/Hr:
$\max(\Delta T_{metal})$ at $1/4T = 17.902$°F

Enable Temperature (ENBT) $= RT_{NDT} + 40 + \max(\Delta T_{metal})$, °F
$= (212 + 40 + 17.902)$ °F
$= 269.902$°F

Enable Temperature, T_e (2) $= RT_{NDT} + 50 \ln[((F * M_m (pR_i / t)) - 33.2) / 20.734]$, °F
$= 212 + 50 \ln[((1.1 * .926(8.5)^{(1/2)} * 2.485 * 86.5 / 8.5)-33.2) / 20.734]$, °F
$= 212 + 50 \ln[41.90 / 20.734]$, °F
$= 212 + 50 \ln[2.021]$
$= 247.180$°F

The minimum required enable temperature for the D.C. Cook Unit 2 Reactor Vessels will be conservatively chosen to be 270°F for 48 EFPY.

11.0 REFERENCES

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

2 10 CFR Part 50, Appendix G, "Fracture Toughness Requirements", Federal Register, Volume 60, No. 243, dated December 19, 1995.

3 ASME Boiler and Pressure Vessel Code, Section XI, "Rule for Inservice Inspection of Nuclear Power Plant Components", Appendix G, "Fracture Toughness Criteria for Protection Against Failure", December 1995.

4 WCAP-13515, Revision 1, "Analysis of Capsule U from the Indiana Michigan Power Company D.C. Cook Unit 2 Reactor Vessel Radiation Surveillance Program", T.J. Laubham, et. al., dated April 2002.

5 WCAP-8512, "American Electric Power Company Donald C. Cook Unit No. 2 Reactor Vessel Radiation Surveillance Program", A. Davidson, et. al., November 1975.

6 SwRI Project No. 02-5928, "Reactor Vessel Material Surveillance Program for Donald C. Cook Unit No. 2 Analysis of Capsule T", E.B. Norris, September 16, 1981.

7 SwRI Project No. 06-7244-002, "Reactor Vessel Material Surveillance Program for Donald C. Cook Unit No. 2 Analysis of Capsule Y", E.B. Norris, February 1984.

8 SwRI Project No. 06-8888, "Reactor Vessel Material Surveillance Program for Donald C. Cook Unit No. 2: Analysis of Capsule X", P.K. Nair, et. al., May 1987.

9. 1989 Section III, Division 1 of the ASME Boiler and Pressure Vessel Code, Paragraph NB-2331, "Material for Vessels".

10. WCAP-14040-NP-A, Revision 2, "Methodology used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves", J. D. Andrachek, et al., January 1996.

11. AEP Design Information Transmittal (DIT), DIT-B-02230-00, "Material Chemistry of the Reactor Vessel Belt-line Materials for Cook Nuclear Plant Units 1 & 2", T.Satyan-Sharma, 10/23/01.

12. Cases of ASME Boiler and Pressure Vessel Code, Case N-640, "Alternative Reference Fracture Toughness for Development of P-T Limit Curves for Section XI, Division 1", Approved March 1999.

13. Cases of ASME Boiler and Pressure Vessel Code, Case N-641, "Alternative Pressure-Temperature Relationship and Low Temperature Overpressure Protection System Requirements," Approved 03/99.

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Attachment 5 to AEP:NRC:2349-01

WCAP-13517, Revision 1
"Evaluation of Pressurized Thermal Shock for D. C. Cook Unit 2"
Dated May 2002