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"Indian Point Unit 2 Heatup and Cooldown Limit Curves for Normal Operation"

Westinghouse Electric Co, January 2008

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Indian Point Unit 2 Heatup and Cooldown Limit Curves for Normal Operation

Westinghouse

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Indian Point Unit 2
Heatup and Cooldown Limit Curves
for Normal Operation

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PREFACE

This report has been technically reviewed and verified by: F.C. Gift*

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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 Indian Point Unit 2 reactor vessel. The PT curves were generated based on the latest available reactor vessel information and updated calculated fluences. The new Indian Point Unit 2 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 (which allows the use of the K_{Ic} methodology) and the less restrictive "Circ-Flaw" methodology (both methodologies formally known as ASME Code Cases N-640 and N-588, respectively). The material with the highest adjusted reference temperature (ART) was Intermediate Shell Plate B-2002-3 (Heat Number B4782-1) for the "Axial-Flaw" methodology and circumferential weld wire heat B34009 for the "Circ-Flaw" methodology. The PT limit curves were generated for 29.2 and 48 EFPY using heatup rates of 60 and 100°F/hr and cooldown rates of 0, 20, 40, 60 and 100°F/hr. Lastly, the PT Curves were developed without instrumentation errors. These curves can be found in Figures 5-1 through 5-4.

1 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" [Reference 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 [Reference 2], "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves." Specifically, the heatup and cooldown curves documented in this report were generated using the most limiting ART values, specifically for the "Axial-Flaw" and "Circ-Flaw" methodologies of the 1998 ASME Code, Section XI through the 2000 Addenda which makes use of the K_{Ic} methodology.
The purpose of this report is to present the calculations and the development of the Indian Point Unit 2 heatup and cooldown curves for 29.2 and 48 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 instrumentation errors. The PT curves include the pressure-temperature limits for the vessel flange region per the requirements of 10 CFR Part 50, Appendix G [Reference 3].

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 [Reference 4]. The beltline material properties of the Indian Point Unit 2 reactor vessel are presented in Table 2-1. 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 2-1. Additionally, surveillance capsule data is available for four capsules (Capsules V, Z, Y and T) already removed from the Indian Point Unit 2 reactor vessel. The fluence data for the surveillance capsules is presented in Table 2-2 and is used to calculate CF values per Position 2.1 of Regulatory Guide 1.99, Revision 2. It should be noted that in addition to Indian Point Unit 2, surveillance weld data from Indian Point Unit 3 and H.B. Robinson Unit 2 was used in the determination of CF. In addition, all the surveillance data has been determined to be credible, with exception of surveillance plate B-2002-2.

The chemistry factors were 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, including those capsules from Indian Point Unit 3 and H.B. Robinson Unit 2. The measured ΔRT_{NDT} values for the weld data were adjusted for the temperature difference between differing plants and for chemistry using the ratio procedure given in Position 2.1 of Regulatory Guide 1.99, Revision 2. Table 2-3 contains the T_{cold} operating temperatures at Indian Point Units 2 and 3 and H.B. Robinson Unit 2. Table 2-4 details the calculation of the surveillance material chemistry factors. A summary of the resulting CF values for all of the vessel and surveillance materials is presented in Table 2-5.

TABLE 2-1
Summary of the Best Estimate Cu and Ni Weight Percent and Initial RT_{NDT} Values for the Indian Point Unit 2 Reactor Vessel Materials

Material Description	Cu (%)	Ni (%)	Initial RT_{NDT} [(a)]
Closure Head Flange	---	---	60°F
Vessel Flange	---	---	60°F
Intermediate Shell Plate B-2002-1[(e)]	0.19 (0.21)	0.65 (0.62)	34°F
Intermediate Shell Plate B-2002-2[(e)]	0.17 (0.15)	0.46 (0.44)	21°F
Intermediate Shell Plate B-2002-3[(e)]	0.25 (0.20)	0.60 (0.59)	21°F
Lower Shell Plate B-2003-1	0.20	0.66	20°F
Lower Shell Plate B-2003-2	0.19	0.48	-20°F
Intermediate & Lower Shell Longitudinal Weld Seams (Heat # W5214)[(b, d)]	0.21	1.01	-56°F
Intermediate to Lower Shell Girth Weld (Heat # 34B009)[(c, d)]	0.19	1.01	-56°F
Indian Point Unit 2 Surveillance Weld (Heat # W5214)[(b, d)]	0.20	0.94	---
Indian Point Unit 3 Surveillance Weld (Heat # W5214)[(b, d)]	0.16	1.12	---
H.B. Robinson Unit 2 Surveillance Weld (Heat # W5214)[(b, d)]	0.32	0.66	---

Notes:

(a) The Initial RT_{NDT} values are measured values, with exception to the weld materials.

(b) The weld material in the Indian Point Unit 2 surveillance program was made of the same wire and flux as the reactor vessel intermediate shell longitudinal weld seams (Wire Heat No. W5214 RACO3 + Ni200, Flux Type Linde 1092, Flux Lot No. 3600). The lower shell longitudinal weld seam also had the same heat and flux type but different flux lot. Indian Pt. Unit 3 and H.B. Robinson Unit 2 also contain surveillance material of this heat.

(c) The intermediate to lower shell circ. weld material was made of Wire Heat No. 34B009 RACO3 + Ni200, Flux Type Linde 1092, Flux Lot No. 3708.

(d) The weld best estimate copper and nickel weight percents were obtained from CE Reports NPSD-1039, Rev. 2 [Reference 5] and/or NPSD-1119, Rev. 1[Reference 6]. The values from the CE Report NPSD-1119, Rev. 1 for the Indian Point 2 vessel axial and circ. welds match those in the NRC database RVID2. The values were rounded to two decimal points.

(e) Copper and Nickel Values were obtained from WCAP-12796 [Reference 7], which in turn used Southwest Research Report 17-2108 (Capsule V Analysis). This report calculated a best estimate Copper/Nickel weight percent excluding values that appeared to be outliers. If all data was considered, then the best estimate would match the RVID2 values shown in parenthesis. The data above for the intermediate shell plates are conservative with exception to plate B-2002-1. The RVID2 chemistry for plate B-2002-1 produces a Regulatory Guide 1.99 Position 1.1 chemistry factor of 156.2°F as compared to the chemistry factor of 144°F calculated in Reference 7. Credible surveillance data (See Tables 2-4 & 2-5) is used to provide a Position 2.1 chemistry factor of 114°F. Intermediate shell plate B-2002-3 is more limiting than B-2002-1 even if the highest CF were used for B-2002-1. Values from WCAP-12796 will be used herein.

TABLE 2-2

Calculated Integrated Neutron Exposure of the Surveillance Capsules @ Indian Point Unit 2, Indian Point Unit 3 and H.B. Robinson Unit 2 [Reference 8, 15, 16]

Capsule	Fluence
Indian Point Unit 2	
T	2.53 x 10^{18} n/cm^2, (E > 1.0 MeV)
Y	4.55 x 10^{18} n/cm^2, (E > 1.0 MeV)
Z	1.02 x 10^{19} n/cm^2, (E > 1.0 MeV)
V	4.92 x 10^{18} n/cm^2, (E > 1.0 MeV)
Indian Point Unit 3	
T	2.63 x 10^{18} n/cm^2, (E > 1.0 MeV) [(a)]
Y	6.92 x 10^{18} n/cm^2, (E > 1.0 MeV) [(a)]
Z	1.04 x 10^{19} n/cm^2, (E > 1.0 MeV) [(a)]
X	8.74 x 10^{18} n/cm^2, (E > 1.0 MeV) [(a)]
H.B. Robinson Unit 2	
S	4.79 x 10^{18} n/cm^2, (E > 1.0 MeV) [(a)]
V	5.30 x 10^{18} n/cm^2, (E > 1.0 MeV) [(a)]
T	3.87 x 10^{19} n/cm^2, (E > 1.0 MeV) [(a)]
X	4.49 x 10^{18} n/cm^2, (E > 1.0 MeV) [(a)]

(a) Fluence values have been adjusted to be consistent with the methodology of Regulatory Guide 1.190 [Reference 13]

TABLE 2-3
Inlet (T_{cold}) Operating Temperatures [Reference 8]

Indian Point Unit 2	Indian Point Unit 3	H.B. Robinson Unit 2
543°F (Cycle 1)	540°F (Capsule T)	547°F (Capsule S)
543°F (Cycle 2)	540°F (Capsule Y)	547°F (Capsule T)
522.5°F (Cycle 3)	540°F (Capsule Z)	547°F (Capsule X)
522.5°F (Cycle 4)	540°F (Capsule X)	
522.8°F (Cycle 5)		
522.8°F (Cycle 6)		
522.8°F (Cycle 7)		
522.5°F (Cycle 8)	---	---
528°F (Average)[(a)]	**540°F (Average)**	**547°F (Average)**

(a) The temperatures listed above are consistent with historical treatment in previous Pressure-Temperature WCAP's, but are slightly conservative compared to measured operating history.

TABLE 2-4
Calculation of Chemistry Factors using Indian Point Unit 2 Surveillance Capsule Data

Material	Capsule	Capsule $f^{(a)}$	$FF^{(b)}$	$\Delta RT_{NDT}^{(c)}$	$FF*\Delta RT_{NDT}$	FF^2
Intermediate Shell Plate B-2002-1	T	0.253	0.627	55.0	34.49	0.393
	Z	1.02	1.006	125.0	125.75	1.012
				SUM:	160.24	1.405
	$CF_{B\text{-}2002\text{-}1} = \sum(FF * RT_{NDT}) \div \sum(FF^2) = (160.24) \div (1.405) = \mathbf{114.0°F}$					
Intermediate Shell Plate B-2002-2	T	0.253	0.627	95.0	59.57	0.393
	Z	1.02	1.006	120.0	120.72	1.012
	V	0.492	0.802	77.0	61.75	0.643
				SUM:	242.04	2.048
	$CF_{B\text{-}2002\text{-}2} = \sum(FF * RT_{NDT}) \div \sum(FF^2) = (242.04) \div (2.048) = \mathbf{118.2°F}$					
Intermediate Shell Plate B-2002-3	T	0.253	0.627	115.0	72.11	0.393
	Y	0.455	0.781	145.0	113.25	0.610
	Z	1.02	1.006	180.0	181.08	1.012
				SUM:	366.44	2.015
	$CF_{B\text{-}2002\text{-}2} = \sum(FF * RT_{NDT}) \div \sum(FF^2) = (366.44) \div (2.015) = \mathbf{181.9°F}$					
Surveillance Weld Material(d)	Y (IP2)	0.455	0.781	208.7 (195)	162.9	0.610
	V (IP2)	0.492	0.802	218.3 (204)	175.1	0.643
	T (IP3)	0.263	0.637	183.2(151.6)	116.7	0.405
	Y (IP3)	0.692	0.897	206.1(172.0)	184.8	0.804
	Z (IP3)	1.04	1.011	270.1 (229.2)	273.1	1.022
	X(IP3)	.874	.962	229.8 (193.2)	221.1	0.926
	V(HBR2)	0.530	0.823	248.9(209.3)	204.7	0.677
	T(HBR2)	3.87	1.349	334.8 (288.2)	451.6	1.820
	X(HBR2)	4.49	1.381	310.6 (265.9)	428.8	1.906
				SUM:	2218.9	8.813
	$CF_{Surv.\ Weld} = \sum(FF * RT_{NDT}) \div \sum(FF^2) = (2218.9°F) \div (8.813) = \mathbf{251.8°F}$					

Notes:

(a) f = fluence. See Table 2-3, ($x\ 10^{19}$ 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 the following documents:
- Indian Point Unit 2 Plate and Weld...WCAP-12796 (Refers back to the original Southwest Research Institute Report for each capsule.) [Reference 7]
- Indian Point Unit 3 Weld...WCAP-16251 [Reference 16].
- H.B.Robinson Unit 2...Letter Report CPL-96-203 [Reference 10]

(d) Per Table 2 Indian Point Unit 3 operates with an inlet temperature of approximately 540°F, H.B. Robinson Unit 2 operates with an inlet temperature of approximately 547°F, and Indian Point Unit 2 operates with an inlet temperature of approximately 528°F. The measured ΔRT_{NDT} values from the Indian Point Unit 3 surveillance program were adjusted by adding 12°F to each measured ΔRT_{NDT} and the H.B. Robinson Unit 2 surveillance program values were adjusted by adding 19°F to each measured ΔRT_{NDT} value before applying the ratio procedure. The surveillance weld metal ΔRT_{NDT} values have been adjusted by a ratio factor of:
Ratio IP2 = 230.2 ÷ 214.3 = 1.07 for the Indian Point Unit 2 data.
Ratio IP3 = 230.2 ÷ 206.2 = 1.12 for the Indian Point Unit 3 data.
Ratio HBR2 = 230.2 ÷ 210.7 = 1.09 for the H.B. Robinson Unit 2 data.
Refer to Table 2-5 for the longitudinal weld seam CF of 230.2°F .
(The pre-adjusted values are in parenthesis.)

TABLE 2-5
Summary of the Indian Point Unit 2 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 B-2002-1	144°F	114
Intermediate Shell Plate B-2002-2	115.1°F	118.2
Intermediate Shell Plate B-2002-3	176°F	181.9
Lower Shell Plate B-2003-1	152°F	- - -
Lower Shell Plate B-2003-2 [a]	128.8°F	- - -
Intermediate & Lower Shell Longitudinal Weld Seams (Heat # W5214)	230.2°F	251.8
Intermediate to Lower Shell Girth Weld Seam (Heat # 34B009)	220.9°F	- - -
Indian Point Unit 2 Surveillance Weld (Heat # W5214)	214.3°F	- - -
Indian Point Unit 3 Surveillance Weld (Heat # W5214)	206.2°F	- - -
H.B. Robinson Unit 2 Surveillance Weld (Heat # W5214)	210.7°F	- - -

(a) The 128.8°F CF listed here differs from previous analyses that used an excessively conservative CF of 142°F for this material. If the 142°F CF had been used in this analysis, this material would still not be limiting.

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 the 1998 Edition through the 2000 Addenda of Section XI, Appendix G of the ASME Code [Reference 11]. 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 Class_1, 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 Fig. G-2214-1. The temperature at any radial distance from the vessel surface can be determined from Fig. 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).

(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:

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

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

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

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:

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

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 (PT) limit curves. No other changes were made to the OPERLIM computer code with regard to PT calculation methodology. Therefore, the PT curve methodology is unchanged from that described in WCAP-14040-NP-A, "Methodology used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves" [Reference 2] Section 2.6 (equations 2.6.2-4 and 2.6.3-1) 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 [Reference 3] 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 preservice hydrostatic test pressure (3107 psi), which is 621 psig for Indian Point Unit 2. The limiting unirradiated RT_{NDT} of 60°F occurs in both the vessel flange and the closure head flange of the Indian Point Unit 2 reactor vessel, so the minimum allowable temperature of this region is 180°F at pressures greater than 621 psig (without instrument uncertainties). This limit is shown in Figures 5-1 through 5-4 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:

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

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 [Reference 12]]. 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:

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

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.

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

where x inches (vessel beltline thickness is 8.625 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.

Table 4-1 provides neutron exposure information pertinent to the Indian Point Unit 2 (IPP) Stretch Power Uprating Program for the reactor pressure vessel. Neutron fluence information for the Indian Point Unit 2 reactor pressure vessel is based on an assessment of the projected reactor vessel fluence that accounts for a mid-cycle uprate from 3071.4 MWt to 3115 MWt during the current operating Cycle 16 design; incorporation of recently developed loading patterns that are anticipated for use in Cycles 17 through 19 operating at 3216 MWt; and utilization of the Cycle 19 loading pattern with the peripheral assembly powers increased by a factor of 1.05 operating at 3216 MWt from the onset of Cycle 20. In Table 4-1, the calculated maximum fast neutron fluence experienced by the Indian Point Unit 2 reactor pressure vessel is provided as a function of operating time.

The fluence calculations were based on the latest available nuclear cross-section data derived from ENDF/B-VI and made use of the latest available calculational tools for neutron source generation and neutron transport. Furthermore, this neutron transport methodology follows the guidance and meets the requirements of Regulatory Guide 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence" [Reference 13]. Tables 4-2 and 4-3 provide a summary of the 1/4T and 3/4T fluence and fluence factor values.

Margin is calculated as, $M = 2\sqrt{\sigma_i^2 + \sigma_\Delta^2}$. The standard deviation for the initial RT_{NDT} margin term (σ_i) is 0°F when the initial RT_{NDT} is a measured value and 17°F when a generic value is

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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 credible 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 4-4 through 4-7 are the Indian Point Unit 2 29.2 and 48 EFPY ART calculations used for generation of the heatup and cooldown curves. Based on a review of the ART values, Intermediate Shell Plate B-2002-3 is the most limiting material in the "Axial-Flaw" case and circumferential weld 34B009 is the limiting material in the "Circ-Flaw" case. Contained in Table 4-8 is a summary of the limiting ART values that will be used in generation of the Indian Point Unit 2 reactor vessel PT limit curves. These limiting curves will be presented in Section 5.

Table 4-1
Maximum Fast Neutron (E > 1.0 MeV) Fluence Projections at the Pressure Vessel Clad/Base Metal Interface – Indian Point Unit 2 [Reference 13]

Cumulative Operating Time [EFPY]	Neutron Fluence (E > 1.0 MeV) [n/cm²] Azimuthal Location			
	0°	15°	30°	45°
18.7 (EOC 15)	2.775e+18	4.472e+18	5.391e+18	8.074e+18
20.6 (EOC 16)	2.995e+18	4.803e+18	5.835e+18	8.750e+18
25.7 (EOC 19)	3.599e+18	5.766e+18	7.084e+18	1.056e+19
32.0	4.452e+18	7.124e+18	8.741e+18	1.296e+19
48.0	6.619e+18	1.057e+19	1.295e+19	1.906e+19

TABLE 4-2
Summary of the Vessel Surface, 1/4T and 3/4T Fluence Values used for the Generation of the 29.2 and 48 EFPY Heatup/Cooldown Curves for Indian Point Unit 2

Material	Surface (n/cm², E > 1.0 MeV)	1/4T Fluence (n/cm², E > 1.0 MeV)	3/4T Fluence (n/cm², E > 1.0 MeV)
29.2 EFPY			
Intermediate and Lower Shell Axial Welds (Heat # W5214)	8.005×10^{18}	4.771×10^{18}	1.695×10^{18}
All other beltline materials	1.189×10^{19}	7.087×10^{18}	2.517×10^{18}
48 EFPY			
Intermediate and Lower Shell Axial Welds (Heat # W5214)	1.295×10^{19}	7.718×10^{18}	2.742×10^{18}
All other beltline materials	1.906×10^{19}	1.136×10^{19}	4.035×10^{18}

TABLE 4-3
Summary of the 1/4T and 3/4T Fluence Factor Values used for the Generation of the 29.2 and 48 EFPY Heatup/Cooldown Curves for Indian Point Unit 2

Material	1/4T Fluence ($x\ 10^{19}\ n/cm^2$, E > 1.0 MeV)	1/4T FF	3/4T Fluence ($x\ 10^{19}\ n/cm^2$, E > 1.0 MeV)	3/4T FF
29.2 EFPY				
Intermediate and Lower Shell Axial Welds (Heat # W5214)	0.4771	0.7937	0.1695	0.5306
All other beltline materials	0.7087	0.9034	0.2517	0.6257
48 EFPY				
Intermediate and Lower Shell Axial Welds (Heat # W5214)	0.7718	0.9273	0.2742	0.6473
All other beltline materials	1.136	1.0356	0.4035	0.7483

TABLE 4-4
Calculation of the Indian Point Unit 2 ART Values for the 1/4T Location @ 29.2 EFPY

Material	FF	CF (°F)	ΔRT_{NDT}[(a)] (°F)	Margin[(b)] (°F)	$RT_{NDT(U)}$[(c)] (°F)	ART[(d)] (°F)
Inter. Shell Plate B-2002-1	0.9034	144	130.09	34.0	34	198
- Using S/C Data	*0.9034*	*114*	*102.99*	*17.0*	*34*	*154*
Inter. Shell Plate B-2002-2	0.9034	115.1	103.98	34.0	21	159
- Using S/C Data	0.9034	118.2	106.79	34.0	21	162
Inter. Shell Plate B-2002-3	0.9034	176	159.00	34.0	21	**214**
- Using S/C Data	0.9034	181.9	164.33	17.0	21	202
Lower Shell Plate B-2003-1	0.9034	152	137.32	34.0	20	191
Lower Shell Plate B-2003-2	0.9034	128.8	116.36	34.0	-20	130
Intermediate & Lower Shell Axial Welds (Heat # W5214)	0.7937	230.2	182.72	65.5	-56	192
- Using S/C Data	0.7937	251.8	199.9	44.0	-56	188
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	0.9034	220.9	199.57	65.5	-56	**209**

NOTES:

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

(b) All surveillance data deemed credible with the exception of lower shell plate B-2002-2.

(c) Initial RT_{NDT} values are measured values except for the welds.

(d) $ART = RT_{NDT(U)} + \Delta RT_{NDT} + Margin$.

TABLE 4-5
Calculation of the Indian Point Unit 2 ART Values for the 3/4T Location @ 29.2 EFPY

Material	FF	CF (°F)	ΔRT_{NDT}[(a)] (°F)	Margin[(b)] (°F)	$RT_{NDT(U)}$[(c)] (°F)	ART[(d)] (°F)
Inter. Shell Plate B-2002-1	0.6257	144	90.10	34.0	34	158
- Using S/C Data	0.6257	114	71.33	17.0	34	122
Inter. Shell Plate B-2002-2	0.6257	115.1	72.02	34.0	21	127
- Using S/C Data	0.6257	118.2	73.96	34.0	21	129
Inter. Shell Plate B-2002-3	0.6257	176	110.12	34.0	21	**165**
- Using S/C Data	0.6257	181.9	113.81	17.0	21	152
Lower Shell Plate B-2003-1	0.6257	152	95.10	34.0	20	149
Lower Shell Plate B-2003-2	0.6257	128.8	80.59	34.0	-20	95
Intermediate & Lower Shell Axial Welds (Heat # W5214)	0.5306	230.2	122.14	65.5	-56	132
- Using S/C Data	0.5306	251.8	133.6	44.0	-56	122
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	0.6257	220.9	138.21	65.5	-56	**148**

NOTES:

(a) $\Delta RT_{NDT} = CF * FF$.
(b) All surveillance data deemed credible with the exception of lower shell plate B-2002-2.
(c) Initial RT_{NDT} values are measured values except for the welds.
(d) $ART = RT_{NDT(U)} + \Delta RT_{NDT} + Margin$.

TABLE 4-6

Calculation of the Indian Point Unit 2 ART Values for the 1/4T Location @ 48 EFPY

Material	FF	CF (°F)	ΔRT_{NDT} [(a)] (°F)	Margin[(b)] (°F)	$RT_{NDT(U)}$ [(c)] (°F)	ART[(d)] (°F)
Inter. Shell Plate B-2002-1	1.0356	144	149.13	34.0	34	217
- Using S/C Data	1.0356	114	118.06	17.0	34	169
Inter. Shell Plate B-2002-2	1.0356	115.1	119.20	34.0	21	174
- Using S/C Data	1.0356	118.2	122.41	34.0	21	177
Inter. Shell Plate B-2002-3	1.0356	176	182.27	34.0	21	**237**
- Using S/C Data	1.0356	181.9	188.38	17.0	21	226
Lower Shell Plate B-2003-1	1.0356	152	157.41	34.0	20	211
Lower Shell Plate B-2003-2	1.0356	128.8	133.39	34.0	-20	147
Intermediate & Lower Shell Axial Welds (Heat # W5214)	0.9273	230.2	213.47	65.5	-56	223
- Using S/C Data	0.9273	251.8	233.5	44.0	-56	222
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	1.0356	220.9	228.77	65.5	-56	**238**

NOTES:

(a) ΔRT_{NDT} = CF * FF.

(b) All surveillance data deemed credible with the exception of lower shell plate B-2002-2.

(c) Initial RT_{NDT} values are measured values except for the welds.

(d) ART = $RT_{NDT(U)}$ + ΔRT_{NDT} + Margin.

TABLE 4-7
Calculation of the Indian Point Unit 2 ART Values for the 3/4T Location @ 48 EFPY

Material	FF	CF (°F)	ΔRT_{NDT}[(a)] (°F)	Margin[(b)] (°F)	$RT_{NDT(U)}$[(c)] (°F)	ART[(d)] (°F)
Inter. Shell Plate B-2002-1	0.7483	144	107.76	34.0	34	176
- Using S/C Data	0.7483	114	85.31	17.0	34	136
Inter. Shell Plate B-2002-2	0.7483	115.1	86.13	34.0	21	141
- Using S/C Data	0.7483	118.2	88.45	34.0	21	143
Inter. Shell Plate B-2002-3	0.7483	176	131.71	34.0	21	**187**
- Using S/C Data	0.7483	181.9	136.12	17.0	21	174
Lower Shell Plate B-2003-1	0.7483	152	113.75	34.0	20	168
Lower Shell Plate B-2003-2	0.7483	128.8	96.39	34.0	-20	110
Intermediate & Lower Shell Axial Welds (Heat # W5214)	0.6473	230.2	149.00	65.5	-56	159
- Using S/C Data	0.6473	251.8	163.0	44.0	-56	151
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	0.7483	220.9	165.31	65.5	-56	**175**

NOTES:

(a) ΔRT_{NDT} = CF * FF.
(b) All surveillance data deemed credible with the exception of lower shell plate B-2002-2.
(c) Initial RT_{NDT} values are measured values except for the welds.
(d) ART = $RT_{NDT(U)}$ + ΔRT_{NDT} + Margin.

TABLE 4-8
Summary of the Limiting ART Values Used in the Generation of the Indian Point Unit 2 Heatup/Cooldown Curves

EFPY	Limiting "Circ-Flaw" ART (Circumferential Weld Heat #34B009)		Limiting "Axial-Flaw" ART (Intermediate Shell Plate B-2002-3)	
	1/4T (°F)	3/4T (°F)	1/4T (°F)	3/4T (°F)
Indian Point Unit 2				
29.2	**209**	**148**	**214**	**165**
48	**238**	**175**	**237**	**187**

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.

Figure 5-1 presents the limiting heatup curves without margins for possible instrumentation errors using heatup rates of 60 and 100°F/hr applicable for 29.2 EFPY with the "Flange-Notch" requirement using the "Axial-flaw" methodology. This curve was generated using the1998 ASME Code Section XI, Appendix G. Figure 5-2 presents the limiting cooldown curve without margins for possible instrumentation errors using cooldown rates of 0, 20, 40, 60 and 100°F/hr applicable for 29.2 EFPY with the "Flange-Notch" requirement. Again, this curve was generated using the1998 ASME Code Section XI, Appendix G. These PT limit curves bound those generated using the "Circ-flaw" methodology with the limiting circ-weld ART value from circumferential weld B34009.

Figure 5-3 presents the limiting heatup curves without margins for possible instrumentation errors using heatup rates of 60 and 100°F/hr applicable for 48 EFPY with the "Flange-Notch" requirement using the "Axial-flaw" methodology. This curve was generated using the1998 ASME Code Section XI, Appendix G. Figure 5-4 presents the limiting cooldown curve without margins for possible instrumentation errors using cooldown rates of 0, 20, 40, 60 and 100°F/hr applicable for 48 EFPY with the "Flange-Notch" requirement. Again, this curve was generated using the1998 ASME Code Section XI, Appendix G. These PT limit curves bound those generated using the "Circ-flaw" methodology with the limiting circ-weld ART value from circumferential weld B34009.

Allowable combinations of temperature and pressure for specific temperature change rates are below and to the right of the limit line shown in Figures 5-1 through 5-4. The criticality limit curve that specifies pressure-temperature limits for core operation have not been included in this report per customer request.

Figures 5-1 through 5-4 define all of the above limits for ensuring prevention of non-ductile failure for the Indian Point Unit 2 reactor vessel for 29.2 and 48 EFPY with the "Flange-Notch" requirement (without instrumentation uncertainties). The data points used for developing the heatup and cooldown pressure-temperature limit curves shown in Figures 5-1 through 5-4 are presented in Tables 5-1 through 5-4. The resulting data for the "Circ-flaw" methodology is presented in Appendix B.

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate B-2002-3
LIMITING ART VALUES AT 29.2 EFPY: 1/4T, 214°F
3/4T, 165°F

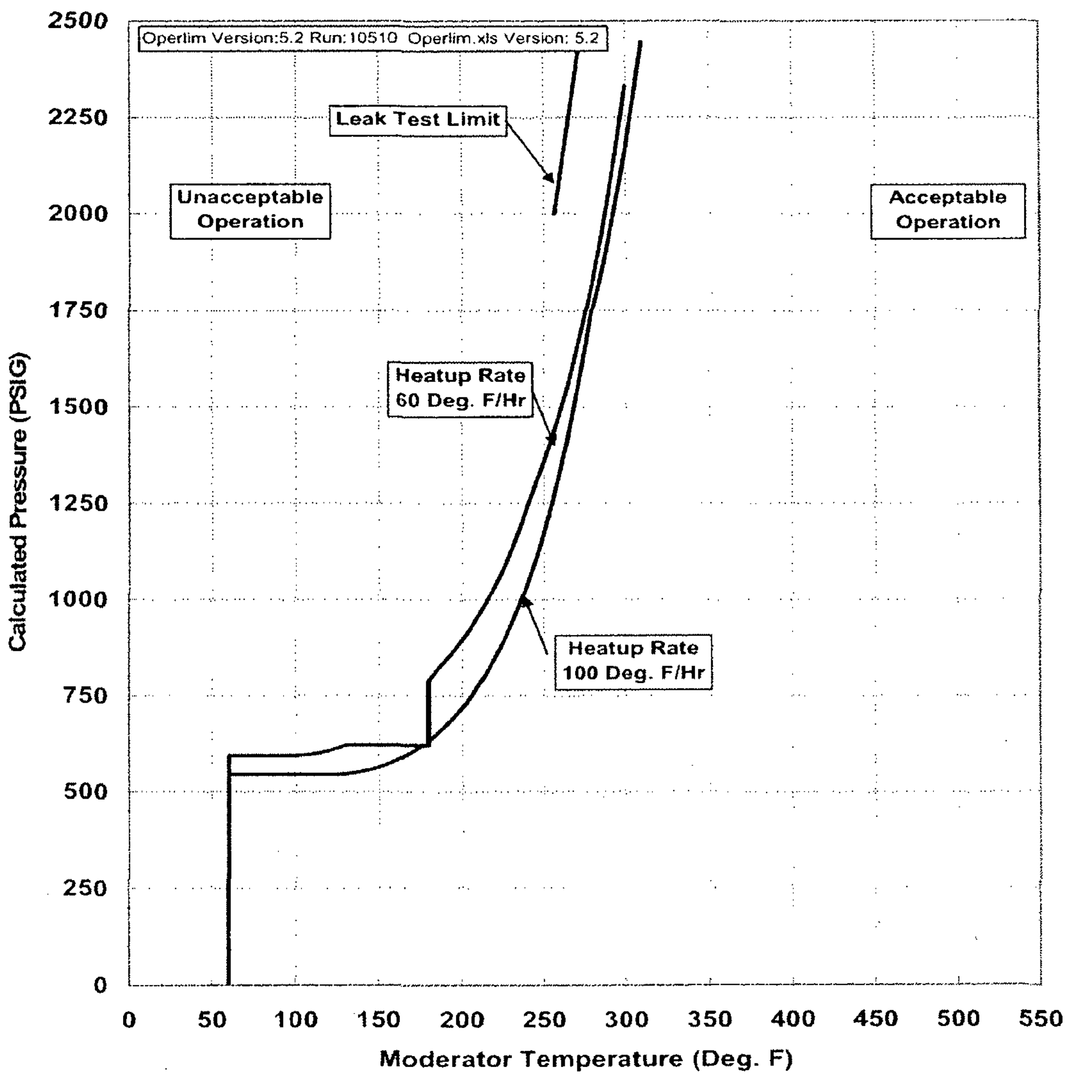
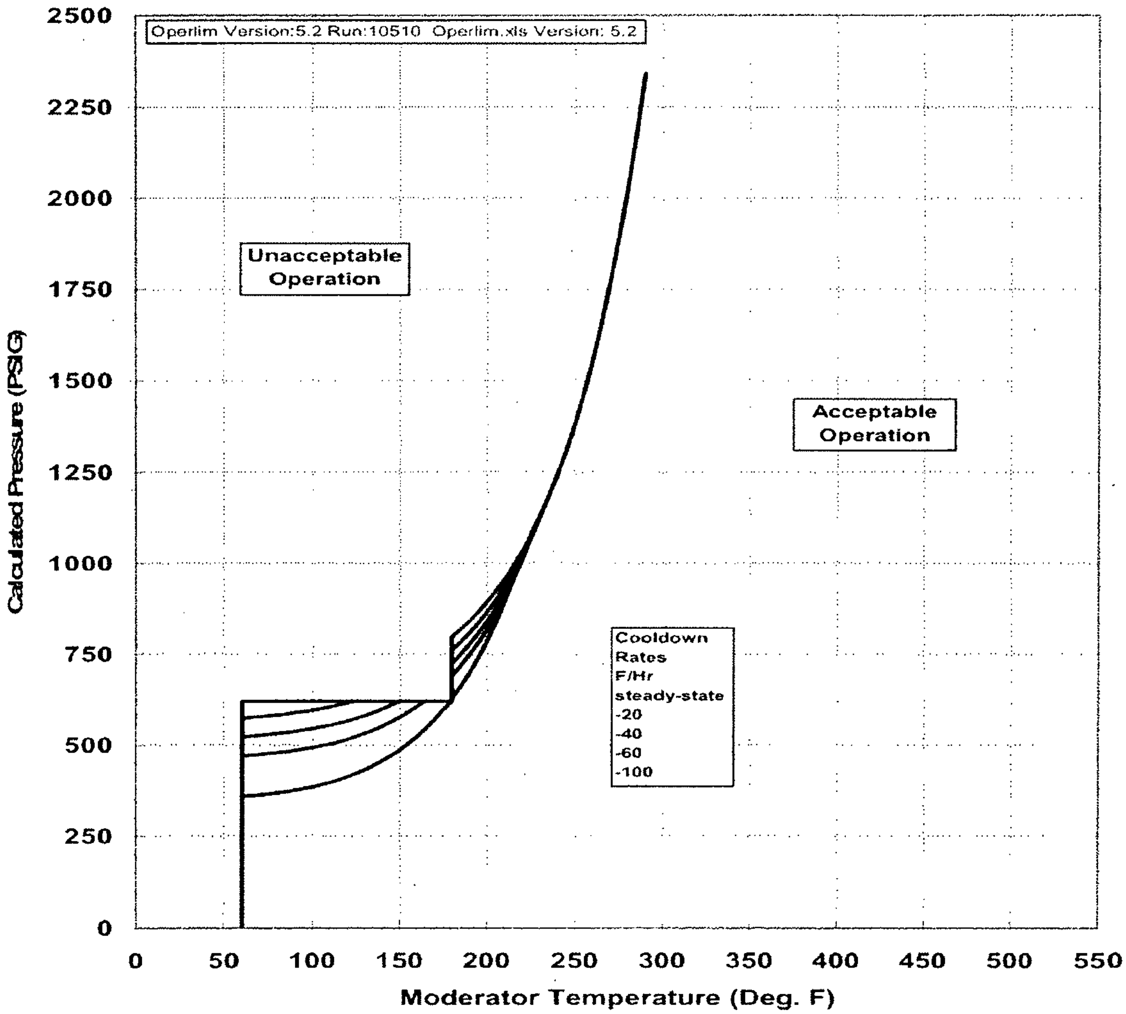


Figure 5-1 Indian Point Unit 2 Reactor Coolant System Heatup Limitations (Heatup Rates of 60 and 100°F/hr) Applicable for 29.2 EFPY (w/ the "Flange-Notch" and w/o Margins for Instrumentation Errors) Using 1998 App. G Methodology (w/K_{Ic})

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate B-2002-3
LIMITING ART VALUES AT 29.2 EFPY: 1/4T, 214°F



3/4T, 165°F

Figure 5-2 **Indian Point Unit 2 Reactor Coolant System Cooldown Limitations (Cooldown Rates up to 100°F/hr) Applicable for 29.2 EFPY (w/ the "Flange-Notch" and w/o Margins for Instrumentation Errors) Using 1998 App. G Methodology (w/K_{Ic})**

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate B-2002-3
LIMITING ART VALUES AT 48 EFPY: 1/4T, 237°F
3/4T, 187°F

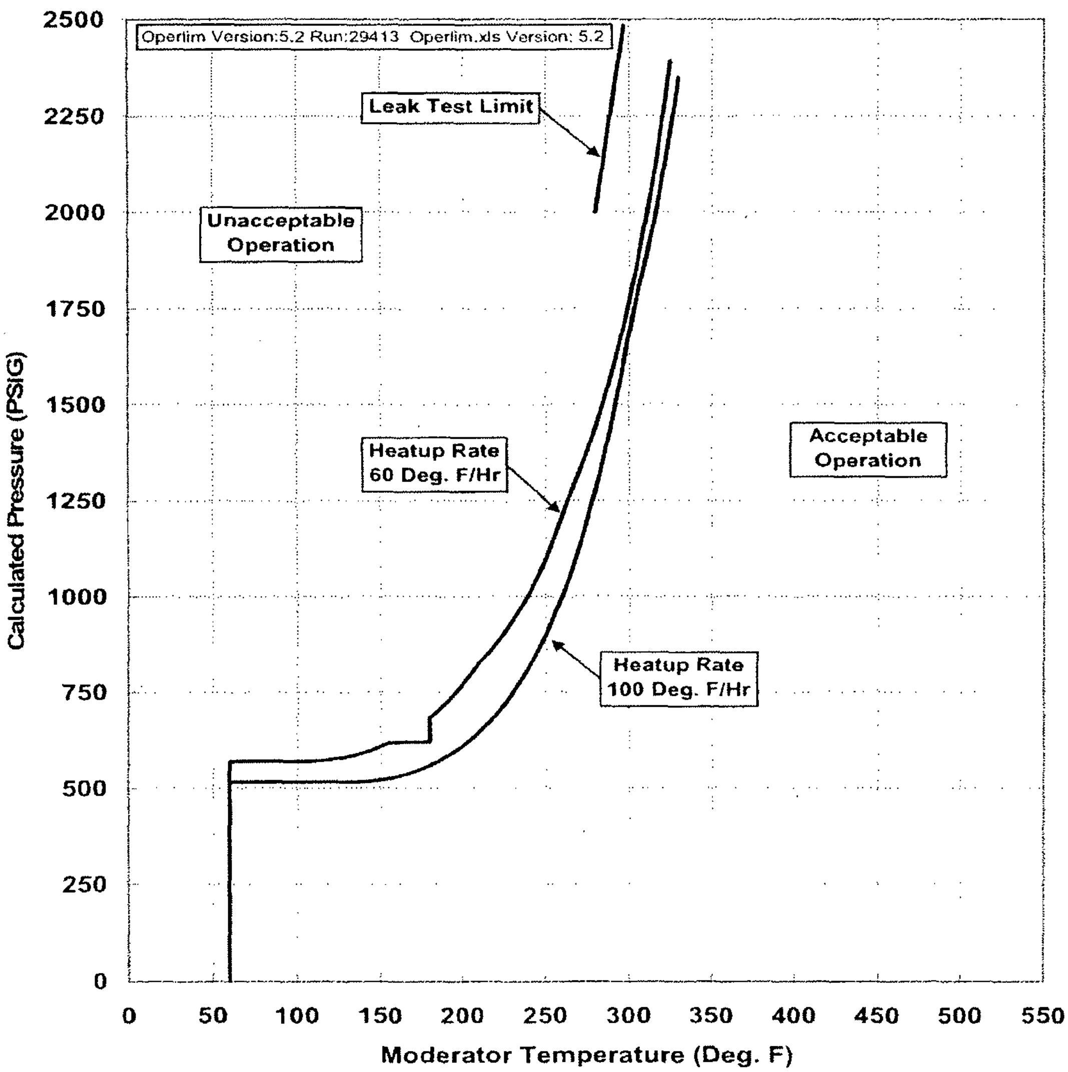


Figure 5-3 Indian Point Unit 2 Reactor Coolant System Heatup Limitations (Heatup Rates of 60 and 100°F/hr) Applicable for 48 EFPY (w/ the "Flange-Notch" and w/o Margins for Instrumentation Errors) Using 1998 App. G Methodology (w/K_{Ic})

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: Intermediate Shell Plate B-2002-3
LIMITING ART VALUES AT 48 EFPY: 1/4T, 237°F
3/4T, 187°F

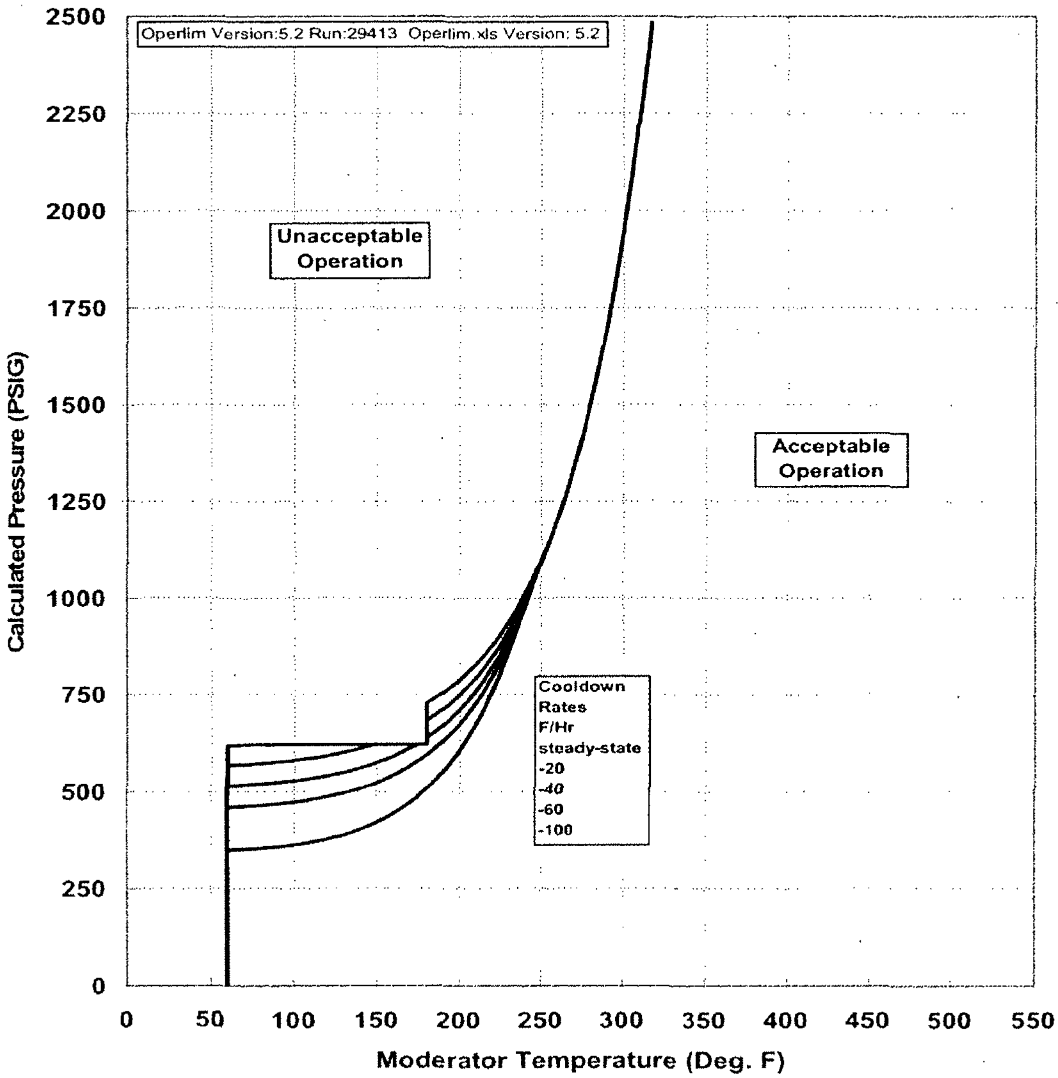


Figure 5-4 Indian Point Unit 2 Reactor Coolant System Cooldown Limitations (Cooldown Rates up to 100°F/hr) Applicable for 48 EFPY (w/ the "Flange-Notch" and w/o Margins for Instrumentation Errors) Using 1998 App. G Methodology (w/K_{Ic})

TABLE 5-1

29.2 EFPY Heatup Curve Data Points Using 1998 App. G Methodology (w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

60°F/hr		100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0
60	594	60	546
65	594	65	546
70	594	70	546
75	594	75	546
80	594	80	546
85	594	85	546
90	594	90	546
95	594	95	546
100	594	100	546
105	596	105	546
110	598	110	546
115	602	115	546
120	607	120	546
125	614	125	546
130	621	130	547
135	621	135	550
140	621	140	553
145	621	145	558
150	621	150	564
155	621	155	572
160	621	160	581
165	621	165	592
170	621	170	604
175	621	175	618
180	621	180	621
180	789	180	633
185	818	185	651
190	842	190	671
195	866	195	693
200	894	200	718
205	924	205	745
210	957	210	776
215	994	215	810
220	1034	220	847
225	1079	225	889
230	1129	230	935
235	1184	235	986
240	1245	240	1042
245	1302	245	1104
250	1357	250	1173
255	1417	255	1249
260	1484	260	1332
265	1557	265	1425
270	1638	270	1526
275	1728	275	1639

60°F/hr		**100°F/hr**	
Temp (°F)	**Press (psig)**	**Temp (°F)**	**Press (psig)**
280	1826	280	1753
285	1935	285	1842
290	2055	290	1941
295	2188	295	2049
300	2334	300	2169
304.7	2485	305	2300
		310	2446
		311.2	2485
Leak Test Limit		257	2000
		274	2485

TABLE 5-2
29.2 EFPY Cooldown Curve Data Points Using 1998 App. G Methodology
(w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

Steady-State		-20°F/hr		-40°F/hr		-60°F/hr		-100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0	60	0	60	0	60	0
60	621	60	574	60	522	60	470	60	360
65	621	65	576	65	524	65	471	65	362
70	621	70	578	70	526	70	473	70	364
75	621	75	580	75	528	75	476	75	366
80	621	80	583	80	531	80	478	80	369
85	621	85	585	85	534	85	481	85	372
90	621	90	588	90	537	90	485	90	376
95	621	95	592	95	541	95	488	95	381
100	621	100	596	100	545	100	493	100	386
105	621	105	600	105	549	105	497	105	391
110	621	110	605	110	554	110	503	110	397
115	621	115	610	115	560	115	509	115	405
120	621	120	616	120	566	120	516	120	413
125	621	125	621	125	573	125	523	125	422
130	621	130	621	130	581	130	532	130	432
135	621	135	621	135	590	135	541	135	443
140	621	140	621	140	599	140	552	140	456
145	621	145	621	145	610	145	563	145	470
150	621	150	621	150	621	150	576	150	486
155	621	155	621	155	621	155	591	155	504
160	621	160	621	160	621	160	607	160	524
165	621	165	621	165	621	165	621	165	546
170	621	170	621	170	621	170	621	170	570
175	621	175	621	175	621	175	621	175	597
180	621	180	621	180	621	180	621	180	621
180	799	180	762	180	726	180	691	180	628
185	819	185	784	185	750	185	718	185	661
190	842	190	809	190	777	190	748	190	699
195	866	195	836	195	807	195	782	195	740
200	894	200	866	200	841	200	819	200	787
205	924	205	899	205	878	205	860	205	838
210	957	210	936	210	918	210	905	210	895
215	994	215	977	215	964	215	955	215	955
220	1034	220	1022	220	1014	220	1011	220	1011
225	1079	225	1072	225	1069	225	1069	225	1069
230	1129	230	1127	230	1127	230	1127	230	1127
235	1184	235	1184	235	1184	235	1184	235	1184
240	1245	240	1245	240	1245	240	1245	240	1245
245	1312	245	1312	245	1312	245	1312	245	1312
250	1386	250	1386	250	1386	250	1386	250	1386
255	1468	255	1468	255	1468	255	1468	255	1468
260	1558	260	1558	260	1558	260	1558	260	1558
265	1658	265	1658	265	1658	265	1658	265	1658
270	1769	270	1769	270	1769	270	1769	270	1769
275	1891	275	1891	275	1891	275	1891	275	1891

Steady-State		-20°F/hr		-40°F/hr		-60°F/hr		-100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
280	2026	280	2026	280	2026	280	2026	280	2026
285	2176	285	2176	285	2176	285	2176	285	2176
290	2341	290	2341	290	2341	290	2341	290	2341
294	2485	294	2485	294	2485	294	2485	294	2485

TABLE 5-3
48 EFPY Heatup Curve Data Points Using 1998 App. G Methodology
(w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

60°F/hr		100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0
60	570	60	516
65	570	65	516
70	570	70	516
75	570	75	516
80	570	80	516
85	570	85	516
90	570	90	516
95	570	95	516
100	570	100	516
105	570	105	516
110	571	110	516
115	572	115	516
120	574	120	516
125	578	125	516
130	582	130	516
135	587	135	516
140	594	140	517
145	601	145	519
150	609	150	522
155	619	155	525
160	621	160	530
165	621	165	536
170	621	170	543
175	621	175	551
180	621	180	560
180	686	185	571
185	704	190	583
190	725	195	596
195	747	200	612
200	772	205	629
205	800	210	648
210	828	215	669
215	851	220	693
220	877	225	719
225	905	230	749
230	937	235	781
235	971	240	817
240	1010	245	856
245	1052	250	900
250	1099	255	949
255	1150	260	1002
260	1208	265	1061
265	1271	270	1126
270	1324	275	1198
275	1381	280	1278

60°F/hr		100°F/hr	
Temp (°F)	**Press (psig)**	**Temp (°F)**	**Press (psig)**
280	1443	285	1365
285	1512	290	1461
290	1588	295	1568
295	1672	300	1685
300	1765	305	1786
305	1867	310	1878
310	1980	315	1980
315	2104	320	2092
320	2241	325	2215
325	2393	330	2351
327.8	2485	334.5	2485
Leak Test Limit		280	297
		2000	2485

TABLE 5-4
48 EFPY Cooldown Curve Data Points Using 1998 App. G Methodology
(w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

Steady-State		-20°F/hr		-40°F/hr		-60°F/hr		-100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0	60	0	60	0	60	0
60	618	60	567	60	515	60	461	60	349
65	619	65	568	65	516	65	462	65	350
70	620	70	569	70	517	70	463	70	351
75	621	75	571	75	518	75	464	75	352
80	621	80	572	80	519	80	465	80	353
85	621	85	574	85	521	85	467	85	355
90	621	90	576	90	523	90	469	90	357
95	621	95	578	95	525	95	471	95	359
100	621	100	580	100	527	100	473	100	362
105	621	105	583	105	530	105	476	105	365
110	621	110	585	110	533	110	479	110	368
115	621	115	589	115	536	115	483	115	373
120	621	120	592	120	540	120	487	120	377
125	621	125	596	125	544	125	491	125	382
130	621	130	601	130	549	130	496	130	388
135	621	135	606	135	554	135	502	135	395
140	621	140	611	140	560	140	508	140	403
145	621	145	617	145	567	145	516	145	411
150	621	150	621	150	574	150	523	150	421
155	621	155	621	155	582	155	532	155	431
160	621	160	621	160	591	160	542	160	443
165	621	165	621	165	601	165	553	165	457
170	621	170	621	170	613	170	565	170	472
175	621	175	621	175	621	175	579	175	489
180	621	180	621	180	621	180	594	180	507
180	728	180	683	180	639	185	611	185	528
185	741	185	697	185	654	190	630	190	551
190	755	190	713	190	671	195	651	195	577
195	771	195	730	195	690	200	674	200	606
200	788	200	749	200	711	205	699	205	638
205	807	205	770	205	734	210	728	210	673
210	828	210	793	210	759	215	759	215	712
215	851	215	818	215	788	220	794	220	756
220	877	220	847	220	819	225	833	225	805
225	905	225	878	225	854	230	876	230	859
230	937	230	913	230	892	235	924	235	918
235	971	235	951	235	935	240	976	240	976
240	1010	240	994	240	982	245	1035	245	1035
245	1052	245	1041	245	1035	250	1093	250	1093
250	1099	250	1093	250	1093	255	1150	255	1150
255	1150	255	1150	255	1150	260	1208	260	1208
260	1208	260	1208	260	1208	265	1271	265	1271
265	1271	265	1271	265	1271	270	1341	270	1341
270	1341	270	1341	270	1341	275	1418	275	1418
275	1418	275	1418	275	1418	280	1503	280	1503

Steady-State		-20°F/hr		-40°F/hr		-60°F/hr		-100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
280	1503	280	1503	280	1503	285	1597	285	1597
285	1597	285	1597	285	1597	290	1701	290	1701
290	1701	290	1701	290	1701	295	1816	295	1816
295	1816	295	1816	295	1816	300	1944	300	1944
300	1944	300	1944	300	1944	305	2084	305	2084
305	2084	305	2084	305	2084	310	2240	310	2240
310	2240	310	2240	310	2240	315	2411	315	2411
315	2411	315	2411	315	2411	317	2485	317	2485
317	2485	317	2485	317	2485				

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APPENDIX A
Thermal Stress Intensity Factors (K_{It})

The following pages contain the thermal stress intensity factors (K_{It}) for the maximum heatup and cooldown rates. The vessel radii to the ¼T and ¾T locations are as follows:

- 1/4T Radius = 88.875"
- 3/4T Radius = 93.188"

TABLE A-1
K_{It} Values for 100°F/hr Heatup Curve for Indian Point Unit 2

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	-0.995	55	0.473
65	59	-2.452	55	1.438
70	62	-3.712	56	2.426
75	65	-4.910	57	3.356
80	68	-5.945	59	4.190
85	72	-6.892	61	4.938
90	76	-7.714	63	5.599
95	80	-8.465	65	6.192
100	84	-9.123	68	6.719
105	88	-9.721	71	7.189
110	92	-10.247	75	7.609
115	97	-10.728	78	7.988
120	101	-11.154	82	8.327
125	106	-11.544	85	8.634
130	110	-11.891	89	8.910
135	115	-12.210	93	9.160
140	119	-12.495	97	9.387
145	124	-12.759	102	9.593
150	129	-12.996	106	9.781
155	133	-13.217	110	9.953
160	138	-13.417	115	10.111
165	143	-13.604	119	10.257
170	147	-13.774	123	10.391
175	152	-13.934	128	10.515
180	157	-14.082	133	10.631
185	162	-14.221	137	10.739
190	167	-14.351	142	10.840
195	172	-14.474	146	10.936
200	176	-14.589	151	11.026

TABLE A-2
K_{It} Values for 100°F/hr Cooldown Curve for Indian Point Unit 2

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.)
200.000	227	17.002
195.000	222	16.933
190.000	217	16.864
185.000	212	16.795
180.000	207	16.726
175.000	201	16.656
170.000	196	16.587
165.000	191	16.517
160.000	186	16.448
155.000	181	16.378
150.000	176	16.309
145.000	171	16.239
140.000	166	16.170
135.000	161	16.100
130.000	156	16.031
125.000	151	15.962
120.000	145	15.893
115.000	140	15.824
110.000	135	15.755
105.000	130	15.686
100.000	125	15.617
95.000	120	15.548
90.000	115	15.480
85.000	110	15.412
80.000	105	15.344
75.000	100	15.275
70.000	95	15.207
65.000	90	15.139
60.000	84	15.071

APPENDIX B
Indian Point Unit 2 PT Limit Curve "Circ-Flaw" Methodology Data Results for 29.2 and 48 EFPY

TABLE B-1

29.2 EFPY Heatup Curve Data Points Using 1998 App. G "Circ-Flaw" Methodology (w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

60°F/hr		100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0
60	621	60	621
65	621	65	621
70	621	70	621
75	621	75	621
80	621	80	621
85	621	85	621
90	621	90	621
95	621	95	621
100	621	100	621
105	621	105	621
110	621	110	621
115	621	115	621
120	621	120	621
125	621	125	621
130	621	130	621
135	621	135	621
140	621	140	621
145	621	145	621
150	621	150	621
155	621	155	621
160	621	160	621
165	621	165	621
170	621	170	621
175	621	175	621
180	621	180	621
180	1713	180	1444
185	1759	185	1496
190	1811	190	1553
195	1868	195	1618
200	1931	200	1689
205	2000	205	1768
210	2077	210	1856
215	2162	215	1953
220	2256	220	2061
225	2360	225	2180
230	2475	230	2312
		235	2457
Leak Test Limit		147	195
		2000	2485

TABLE B-2
29.2 EFPY Cooldown Curve Data Points Using 1998 App. G "Circ-Flaw" Methodology (w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

Steady-State		-20°F/hr		-40°F/hr		-60°F/hr		-100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0	60	0	60	0	60	0
60	621	60	621	60	621	60	621	60	621
65	621	65	621	65	621	65	621	65	621
70	621	70	621	70	621	70	621	70	621
75	621	75	621	75	621	75	621	75	621
80	621	80	621	80	621	80	621	80	621
85	621	85	621	85	621	85	621	85	621
90	621	90	621	90	621	90	621	90	621
95	621	95	621	95	621	95	621	95	621
100	621	100	621	100	621	100	621	100	621
105	621	105	621	105	621	105	621	105	621
110	621	110	621	110	621	110	621	110	621
115	621	115	621	115	621	115	621	115	621
120	621	120	621	120	621	120	621	120	621
125	621	125	621	125	621	125	621	125	621
130	621	130	621	130	621	130	621	130	621
135	621	135	621	135	621	135	621	135	621
140	621	140	621	140	621	140	621	140	621
145	621	145	621	145	621	145	621	145	621
150	621	150	621	150	621	150	621	150	621
155	621	155	621	155	621	155	621	155	621
160	621	160	621	160	621	160	621	160	621
165	621	165	621	165	621	165	621	165	621
170	621	170	621	170	621	170	621	170	621
175	621	175	621	175	621	175	621	175	621
180	621	180	621	180	621	180	621	180	621
180	1713	180	1639	180	1569	180	1502	180	1384
185	1759	185	1691	185	1625	185	1565	185	1462
190	1811	190	1747	190	1688	190	1635	190	1549
195	1868	195	1810	195	1758	195	1712	195	1645
200	1931	200	1880	200	1835	200	1797	200	1752
205	2000	205	1957	205	1920	205	1892	205	1871
210	2077	210	2042	210	2015	210	1998	210	1998
215	2162	215	2136	215	2119	215	2114	215	2114
220	2256	220	2240	220	2235	220	2235	220	2235
225	2360	225	2355	225	2355	225	2355	225	2355
230	2475	230	2475	230	2475	230	2475	230	2475

TABLE B-3
48 EFPY Heatup Curve Data Points Using 1998 App. G "Circ-Flaw" Methodology (w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

60°F/hr		100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0
60	621	60	621
65	621	65	621
70	621	70	621
75	621	75	621
80	621	80	621
85	621	85	621
90	621	90	621
95	621	95	621
100	621	100	621
105	621	105	621
110	621	110	621
115	621	115	621
120	621	120	621
125	621	125	621
130	621	130	621
135	621	135	621
140	621	140	621
145	621	145	621
150	621	150	621
155	621	155	621
160	621	160	621
165	621	165	621
170	621	170	621
175	621	175	621
180	621	180	621
180	1484	180	1201
185	1532	185	1230
190	1572	190	1262
195	1604	195	1298
200	1639	200	1338
205	1678	205	1383
210	1721	210	1433
215	1769	215	1488
220	1822	220	1550
225	1880	225	1618
230	1944	230	1693
235	2015	235	1777
240	2094	240	1869
245	2180	245	1972
250	2276	250	2085
255	2382	255	2209
		260	2347
Leak Test Limit		176	224
		2000	2485

TABLE B-4
48 EFPY Cooldown Curve Data Points Using 1998 App. G "Circ-Flaw" Methodology (w/K_{IC}, w/Flange Notch and w/o Uncertainties for Instrumentation Errors)

Steady-State		-20°F/hr		-40°F/hr		-60°F/hr		-100°F/hr	
Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)	Temp (°F)	Press (psig)
60	0	60	0	60	0	60	0	60	0
60	621	60	621	60	621	60	621	60	621
65	621	65	621	65	621	65	621	65	621
70	621	70	621	70	621	70	621	70	621
75	621	75	621	75	621	75	621	75	621
80	621	80	621	80	621	80	621	80	621
85	621	85	621	85	621	85	621	85	621
90	621	90	621	90	621	90	621	90	621
95	621	95	621	95	621	95	621	95	621
100	621	100	621	100	621	100	621	100	621
105	621	105	621	105	621	105	621	105	621
110	621	110	621	110	621	110	621	110	621
115	621	115	621	115	621	115	621	115	621
120	621	120	621	120	621	120	621	120	621
125	621	125	621	125	621	125	621	125	621
130	621	130	621	130	621	130	621	130	621
135	621	135	621	135	621	135	621	135	621
140	621	140	621	140	621	140	621	140	621
145	621	145	621	145	621	145	621	145	621
150	621	150	621	150	621	150	621	150	621
155	621	155	621	155	621	155	621	155	621
160	621	160	621	160	621	160	621	160	621
165	621	165	621	165	621	165	621	165	621
170	621	170	621	170	621	170	621	170	621
175	621	175	621	175	621	175	621	175	621
180	621	180	621	180	621	180	621	180	621
180	1517	180	1423	180	1329	180	1235	180	1052
185	1543	185	1452	185	1360	185	1270	185	1094
190	1572	190	1483	190	1395	190	1308	190	1142
195	1604	195	1518	195	1433	195	1351	195	1195
200	1639	200	1557	200	1476	200	1398	200	1253
205	1678	205	1600	205	1523	205	1450	205	1319
210	1721	210	1647	210	1576	210	1509	210	1391
215	1769	215	1700	215	1634	215	1573	215	1472
220	1822	220	1758	220	1698	220	1645	220	1561
225	1880	225	1822	225	1770	225	1724	225	1661
230	1944	230	1893	230	1849	230	1812	230	1771
235	2015	235	1972	235	1936	235	1910	235	1894
240	2094	240	2059	240	2033	240	2018	240	2018
245	2180	245	2155	245	2140	245	2137	245	2137
250	2276	250	2262	250	2259	250	2259	250	2259
255	2382	255	2379	255	2379	255	2379	255	2379

APPENDIX C
Pressurized Thermal Shock (PTS) Results for 48 EFPY

The 48 EFPY operating term has an associated fluence value for the beltline materials of:

- For the intermediate and lower shell longitudinal welds, Fluence $_{48\ EFPY}$ = 1.295 x 10^{19} n/cm^2
- For the remaining beltline materials, Peak Fluence $_{48\ EFPY}$ = 1.906 x 10^{19} n/cm^2

RT_{PTS} predicted values for 48 EFPY are shown in Table C-1.

Table C-1
RT_{PTS} Calculations for Indian Point Unit 2 Beltline Region Materials at 48 EFPY

Material	Fluence (n/cm^2, E>1.0 MeV)	FF	CF (°F)	ΔRT_{PTS} (a) (°F)	Margin (°F)	$RT_{NDT(U)}$ (b) (°F)	RT_{PTS} (c) (°F)
Inter. Shell Plate B-2002-1	1.906 x 10^{19}	1.176	144	169.34	34	34	237
- Using S/C Data	1.906 x 10^{19}	1.176	114	134.06	17	34	185
Inter. Shell Plate B-2002-2	1.906 x 10^{19}	1.176	115.1	135.36	34	21	190
- Using S/C Data	1.906 x 10^{19}	1.176	118.2	139.00	34	21	194
Inter. Shell Plate B-2002-3	1.906 x 10^{19}	1.176	176	206.98	34	21	262
- Using S/C Data	1.906 x 10^{19}	1.176	181.9	213.91	17	21	252
Lower Shell Plate B-2003-1	1.906 x 10^{19}	1.176	152	178.75	34	20	233
Lower Shell Plate B-2003-2	1.906 x 10^{19}	1.176	128.8	151.53	34	-20	166
Intermediate & Lower Shell Long. Welds (Heat # W5214)	1.295 x 10^{19}	1.072	230.2	246.78	65.5	-56	256
- Using S/C Data	1.295 x 10^{19}	1.072	251.8	269.9	44.0	-56	258
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	1.906 x 10^{19}	1.176	220.9	259.78	65.5	-56	269

Notes:

(a) ΔRT_{PTS} = CF * FF

(b) Initial RT_{NDT} values are measured values, except for the weld materials.

(c) $RT_{PTS} = RT_{NDT(U)} + \Delta RT_{PTS}$ + Margin (°F)

RT_{PTS} Assessment Conclusion:

Indian Point Unit 2 vessel materials will remain below the screening criteria for axial welds and plates (270°F) and for circumferential welds (300°F) at 48 EFPY.

APPENDIX D
Predicted Upper Shelf Energy (USE) Values for 48 EFPY

Based on the projected fluences detailed in Section 4, the calculated 1/4T values are shown in Table D-1 and the projected USE drops are shown in Table D-2.

Table D-1
48 EFPY 1/4T Fluence Values for all the Indian Point Unit 2 Beltline Materials

Material	Fluence @ 48 EFPY[(a)]	1/4T Fluence @ 48 EFPY[(b)]
Intermediate Shell Plate B-2002-1	1.906	1.136
Intermediate Shell Plate B-2002-2	1.906	1.136
Intermediate Shell Plate B-2002-3	1.906	1.136
Lower Shell Plate B-2003-1	1.906	1.136
Lower Shell Plate B-2003-2	1.906	1.136
Intermediate & Lower Shell Longitudinal Welds (Heat # W5214)	1.295	0.772
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	1.906	1.136

Notes:
(a) f @ 48 EFPY is the 48 EFPY fluence at the clad/base metal interface (x 10^{19} n/cm^2, E > 1.0 MeV).
(b) 1/4T f @ 48 EFPY = f @ 48 EFPY * $e^{(-0.24*X)}$, where X is the depth into the vessel wall (X = 0.25 * 8.625 inches = 2.156 inches).

Table D-2
Predicted 48 EFPY USE Calculations for all the Beltline Region Materials

Material	Weight % of Cu	1/4T EOL Fluence (10^{19} n/cm^2)	Unirradiated USE[(a)] (ft-lb)	Projected USE Decrease (%)	Projected EOL USE (ft-lb)
Intermediate Shell Plate B-2002-1	0.19	1.136	70	29	49.7
Intermediate Shell Plate B-2002-2	0.17	1.136	73	28	52.6
Intermediate Shell Plate B-2002-3	0.25	1.136	74	35	48.1
Lower Shell Plate B-2003-1	0.20	1.136	71	30	49.7
Lower Shell Plate B-2003-2	0.19	1.136	88	29	62.5
Intermediate & Lower Shell Longitudinal Welds (Heat # W5214)	0.21	0.772	121	33	81.1
Intermediate to Lower Shell Girth Weld (Heat # 34B009)	0.19	1.136	82	34	54.1

Notes:
(a) These values were obtained from WCAP-15629, Rev. 1.

USE Assessment Conclusion:

Several materials would drop below the 50 ft-lb threshold set by 10 CFR 50 Appendix G. An alternative analysis method would need to be performed to justify continued operation. This was actually done as part of the WOG back in 1993 for all WOG participants. WCAP-13587, Revision 1, "Reactor Vessel Upper Shelf Energy Bounding Evaluation for Westinghouse Pressurized Water Reactors" documents that the minimal acceptable USE value is 43 ft-lbs for 4-loop plants. All of the Indian Point 2 vessel beltline materials exceed this minimum acceptable value. Per NUREG-1511, "Reactor Pressure Vessel Status Report," dated December 1994, licensees wanting to utilize the WCAP-13587 analyses to demonstrate compliance with USE requirements need to make a submittal to the NRC describing applicability of the WCAP to their plant and make a request to the NRC for review and approval.