MSE-REME-0076

INDIAN POINT UNIT 2
HEATUP AND COOLDOWN LIMIT CURVES
FOR NORMAL OPERATION

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PREFACE

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SECTION 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 most limiting ART values are used in the generation of heatup and cooldown pressure-temperature limit curves.

SECTION 2.0
FRACTURE TOUGHNESS PROPERTIES

The fracture-toughness properties of the ferritic material in the reactor coolant pressure boundary are determined in accordance with the NRC Standard Review Plan[2]. The pertinent chemical and mechanical properties of beltline region plate and weld materials of the Indian Point Unit 2 reactor vessel are presented in Table 1. This data was obtained from WCAP-12796[3], *Heatup and Cooldown Limit Curves for the Consolidated Edison Company Indian Pint Unit 2 Reactor Vessel*, dated January 1991. (Per Art Ginsberg of Consolidated Edison, the same adjusted reference temperatures documented in WCAP-12796 are to be used in the generation of the current heatup and cooldown limit curves. Therefore, the pertinent vessel information presented in WCAP-12796 is also presented here for completeness.)

The chemistry factor (CF) values and margin terms also shown in Table 1 were determined in accordance with Tables 1 and 2 of Regulatory Guide 1.99, Revision 2. Chemistry factor (CF) values and margin terms in Table 1 that were based upon credible surveillance measurements are also given for the beltline region materials where this data was available. Table 2 presents the chemistry factor values based on surveillance data in addition to those calculated per Tables 1 and 2 of Regulatory Guide 1.99, Revision 2. (Complete calculations are presented in WCAP-12796.)

TABLE 1

Indian Point Unit 2 Reactor Vessel Beltline Region Material Properties

Material	Cu (wt %)	Ni (wt %)	CF [g] (°F)	IRT_{NDT} [a] (°F)	M [b,c,d] (°F)
Intermediate Shell B2002-1[f]	0.19	0.65	144 (108.85)	34	34 (17)
Intermediate Shell B2002-2[f]	0.17	0.46	115 (115.86)	21	34 (17)
Intermediate Shell B2002-3[f]	0.25	0.60	176 (183.02)	21	34 (17)
Lower Shell B2003-1	0.20	0.66	152	20	34
Lower Shell B2003-2	0.19	0.60	142	-20	34
Weld Metal	0.20	1.03	226 (236.01)	-56	66 (44.05)
Closure Head Flange [e]	--	--	--	60	--
Vessel Flange [e]	--	--	--	60	--

NOTES:

(a) The initial RT_{NDT} (IRT_{NDT}) values for the plates are measured values; the initial RT_{NDT} value for the weld is generic.

(b) Margin (M) as per Regulatory Guide 1.99, Revision 2; the standard deviation for the IRT_{NDT} margin term for the plates are assumed to be 0°F since the IRT_{NDT} values were obtained from conservative (i.e. "upper bound") test results.

(c) Margin (M) as per Regulatory Guide 1.99, Revision 2; the standard deviation for the IRT_{NDT} margin term for the weld is 17°F.

(d) Numbers is parenthesis ( ) correspond to surveillance capsule data.

(e) Initial RT_{NDT} values for the closure head flange and vessel flange will be considered for the adjustment of heatup/cooldown curves per 10 CFR Part 50, Appendix G.

(f) Cu and Ni contents are based on the Capsule V report, SwRI Report 17-2108[4] (revised) March 1990.

(g) Chemistry Factor (CF) values are based on Regulatory Guide 1.99, Revision 2, Tables 1 and 2, and surveillance capsule data (shown in parenthesis).

TABLE 2

Chemistry Factor Values Using Indian Point Unit 2 Surveillance Capsule Data

Material	Chemistry Factor (°F)
Intermediate Shell B2002-1	108.85
Intermediate Shell B2002-2	115.86
Intermediate Shell B2002-3	183.02
Weld Metal	236.02

SECTION 3.0

CRITERIA FOR ALLOWABLE PRESSURE-TEMPERATURE RELATIONSHIPS

Appendix G to 10 CFR Part 50, "Fracture Toughness Requirements"[5] 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, "Rules for Inservice Inspection of Nuclear Power Plant Components"[6], *Fracture Toughness Criteria for Protection Against Failure*, 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_{Ia}, for the metal temperature at that time. K_{Ia} is obtained from the reference fracture toughness curve, defined in Appendix G of the ASME Code, Section XI. The K_{Ia} curve is given by the following equation:

$$K_{Ia} = 26.78 + 1.233 * e^{[0.0145 (T - RTNDT + 160)]} \tag{1}$$

where,

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

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

$$C * K_{Im} + K_{It} < K_{Ia} \tag{2}$$

where,

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

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

K_{Ia} = 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

New ASME Section XI, Appendix G Methodology[6]

Appendix G was recently revised to incorporate the most recent elastic solutions for K_I due to pressure and radial thermal gradients. The new solutions are based on finite element analyses for inside surface flaws performed at Oak Ridge National Laboratories and sponsored by NRC, and work published for outside surface flaws. These solutions provide results that are essentially the same as those obtained by using solutions previously developed by Raju and Newman[7]

This revision now provides consistent computation methods for pressure and thermal K_I for thermal gradient through the vessel wall at any time during the transient. Consistent with the original version of Appendix G, no contribution for crack face pressure is included in the K_I due to pressure, and cladding effects are neglected.

Using these most recent elastic solutions in the low temperature region will provide some relief to restrictions associated with reactor operation at relatively low temperature. Although the relief is relatively small in terms of absolute allowable pressure, the benefits are substantial because even a small increase in the allowable pressure can be a significant percentage increase in the operating window at relatively low temperatures. Implementing this revision results in an economic and potential safety benefit (less likelihood of lifting LTOP pressure relieving devices) with no reduction in vessel integrity.

The following revisions were made to ASME Section XI, Appendix G:

G-2214.1 Membrane Tension:

$$K_{Im} = M_m \, x \, (pR_i/t) \tag{3}$$

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 $2\leq\sqrt{t}\leq3.464$,

$M_m = 3.21$ 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 $2\leq\sqrt{t}\leq3.464$,

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

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

G-2214.3 Radial Thermal Gradient:

The maximum K_I produced by a 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 inside 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 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 1/4-thickness inside surface defect using the relationship:

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

or, similarly, K_{It} during heatup for a 1/4-thickness outside surface defect using the relationship:

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

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:

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

and x is a dummy 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.

Raju-Newman Methodology[7]

The Raju-Newman method calculates the stress intensity factor K_I for a given surface flaw using the actual stress profile through the wall (e.g., reactor vessel wall thickness). The stress is normal to the plane of the flaw at the flaw location and its distribution through the wall is represented by a third order polynomial:

$$\sigma(x) = \sum_{j=0}^{3} A_j x^j = A_0 + A_1 x + A_2 x^2 + A_3 x^3 \tag{7}$$

where,

x - is the distance through the wall measured from the flawed surface,

A_j - coefficients of the third order polynomial fit,

σ - stress normal to the plane of the flaw

The stress intensity factors are determined by:

$$K_I = \sqrt{\frac{\pi a}{Q}} \sum_{j=0}^{3} G_j(a/c, a/t, t/R, \phi)\, A_j a^j \tag{8}$$

where,

a - flaw depth, (e.g., 1/4 thickness of reactor vessel wall for P-T limit curves),

a/c - ratio of crack depth to 1/2 crack length (a: semi-minor axis, c: semi-major axis),

a/t - ratio of crack depth to thickness of cylinder,

t/R - ratio of thickness to inside radius,

ϕ - crack front location in degrees,

Q - is the square of the complete elliptic integral of the second kind and is approximated by $Q = 1 + 1.464(a/c)^{1.65}$,

G_j - influence coefficient corresponding to the jth stress distribution

The Raju-Newman method results in very similar values of stress intensity factor to those calculated by the revised Appendix G method described above, as demonstrated in Appendix A of this report.

<u>Calculation of P-T Limit Curves</u>

At any time during the heatup or cooldown transient, K_{Ia} 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_{Ia} at the 1/4T location for finite cooldown rates than for steady-state operation. Furthermore, if conditions exist so that the increase in K_{Ia} 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_{Ia} for the 1/4T crack during heatup is lower than the K_{Ia} 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_{Ia} 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.

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 preservice hydrostatic test pressure (3107 psig), which is 621 psig for Indian Point Unit 2.

Table 1 indicates that the limiting unirradiated RT_{NDT} of 60°F occurs in the closure head and vessel 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. This limit (where the horizontal line indicates that the pressure shall not exceed 621 psig for temperatures less than 180°F) is shown as a notch in the curves, presented wherever applicable in Figures 1 through 4.

SECTION 4.0

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:

$$ART = Initial\ RT_{NDT} + \Delta RT_{NDT} + Margin \quad (9)$$

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[8]. If measured values of initial RT_{NDT} for the material in question are not available, generic mean values for that class of material may be used if there are sufficient test results to establish a mean and standard deviation for the class.

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

$$\Delta RT_{NDT} = CF * f^{(0.28 - 0.10 \log f)} \quad (10)$$

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

$$f_{(depth\ x)} = f_{surface} * e^{(-0.24x)} \quad (11)$$

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 10 to calculate the ΔRT_{NDT} at the specific depth. The fluence (E > 1.0 MeV) values on the pressure vessel clad/base metal interface for the Indian Point Unit 2 reactor vessel are presented in Table 3.

TABLE 3

Fluence (10^{19} n/cm^2, E > 1.0 MeV) on the Pressure Vessel Clad/Base Metal Interface for Indian Point Unit 2 [3]

EFPY	0°	15°	30°	45° (a)
21.63	0.4260	0.6716	0.6778	0.9809

NOTE:
(a) Maximum point on the pressure vessel.

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 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 (half the value) when surveillance data is used. For welds, σ_Δ is equal to 28°F when surveillance capsule data is not used, and is 14°F (half the value) when credible surveillance capsule data is used. σ_Δ need not exceed one-half the mean value of ΔRT_{NDT}.

All materials in the beltline region of Indian Point Unit 2 reactor vessel were considered in determining the limiting material. Sample calculations to determine the ART values for Intermediate Shell B2002-3 are shown in Table 4. The resulting ART values for all beltline materials at the 1/4T and 3/4T locations are summarized in Table 5. From Table 5, it can be seen that the limiting material is Intermediate Shell B2002-3. The 1/4T and 3/4T ART values for Intermediate Shell B2002-3 will be used in the generation of the heatup and cooldown curves.

TABLE 4

Calculation of ART Values for the Limiting Indian Point Unit 2 Reactor Vessel Material -- Intermediate Shell B2002-3

Parameter		
Operating Time	21.63 EFPY	
Location	1/4T ART	3/4T ART
Chemistry Factor, CF (°F)	176 (183.02)	176 (183.02)
Fluence, f (10^{19} n/cm^2)(a,b)	0.5846	0.2077
Fluence Factor, FF	0.85	0.58
ΔRT_{NDT} = CF x FF (°F)	149.6 (155.5)	101.8 (105.9)
Initial RT_{NDT}, I (°F)	21	21
Margin, M (°F)	34 (17)	34 (17)
Adjusted Reference Temperature (ART), (°F) per Regulatory Guide 1.99, Revision 2	204.6 (193.5)	156.8 (143.9)

NOTES:
(a) Fluence, f, is based upon f_{surf} (10^{19} n/cm^2, E > 1.0 MeV) the peak fluence presented in Table 3.
(b) The Indian Point Unit 2 reactor vessel wall thickness is 8.625 inches at the beltline region.
(c) Numbers in parenthesis ( ) were calculated using surveillance capsule data.

TABLE 5

Summary of ART Values at the 1/4T and 3/4T Locations

Material	21.63 EFPY ART[a]	
	1/4T ART (°F)	3/4T ART (°F)
Intermediate Shell B2002-1	(144)	(114)
Intermediate Shell B2002-2	(137)	(105)
Intermediate Shell B2002-3	(194)[b]	(144)[b]
Lower Shell B2003-1	183	142
Lower Shell B2003-2	135	96
Weld Metal	(189)	(125)

NOTES:

(a) Numbers within ( ) are using chemistry factor based on surveillance capsule data.

(b) Adjusted reference temperature (ART) values used to generate heatup/cooldown curves.

(Note: When two or more credible surveillance data sets become available, the data sets may be used to determine ART values as described in Regulatory Guide 1.99, Revision 2, Position 2.1. If the ART values based on surveillance capsule data are larger than those calculated per Regulatory Guide 1.99, Revision 2, Position 1.1, the surveillance data should be used. If the surveillance capsule data gives lower values, either may be used.)

SECTION 5.0

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[9] discussed in Section 3.0 and 4.0 of this report.

Figure 1 presents the heatup curves without margins for possible instrumentation errors using heatup rates up to 100°F/hr applicable for the first 21.63 EFPY. Figure 2 presents the cooldown curves without margins for possible instrumentation errors using cooldown rates up to 100°F/hr applicable for 21.63 EFPY. Allowable combinations of temperature and pressure for specific temperature change rates are below and to the right of the limit lines shown in Figures 1 through 4. This is in addition to other criteria which must be met before the reactor is made critical, as discussed below in the following paragraphs. The pressure difference between the wide-range pressure transmitter and the limiting beltline region must be accounted for when using the pressure-temperature limits presented in Figures 1 through 4.

The reactor must not be made critical until pressure-temperature combinations are to the right of the criticality limit line shown in Figures 1 and 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 Appendix G to Section XI of the ASME Code as follows:

$$1.5\ K_{Im} < K_{Ia} \qquad (12)$$

where,

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

$K_{Ia} = 26.78 + 1.233\ e^{[0.0145\ (T\ -\ RTNDT\ +\ 160)]}$,

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 5. The pressure-temperature limits for core operation (except for low power physics tests) are that the reactor vessel must be at a temperature equal to or higher than the minimum temperature required for the inservice hydrostatic test, and at least 40°F higher than the minimum permissible temperature in the corresponding pressure-temperature curve for heatup and cooldown calculated as described in Section 3.0 of this report. Using the new ASME Section XI, Appendix G methodology for the calculation of K_I, the minimum temperatures for the inservice hydrostatic leak tests for the Indian Point Unit 2 reactor vessel at 21.63 EFPY is 318°F. Using the Raju-Newman methodology, the minimum temperatures for the inservice hydrostatic leak tests for the Indian Point Unit 2 reactor vessel at 21.63 EFPY is 327°F. The vertical line drawn from these points on the pressure-temperature curve, intersecting a curve 40°F higher than the pressure-temperature limit curve, constitutes the limit for core operation for the reactor vessel.

Figures 1 through 4 define all of the above limits for ensuring prevention of nonductile failure for the Indian Point Unit 2 reactor vessel.

The data points used for the heatup and cooldown pressure-temperature limit curves shown in Figures 1 through 4 are presented in Tables 6 and 7.

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: INTERMEDIATE SHELL B2002-3
LIMITING ART VALUES AT 21.63 EFPY: 1/4T, 194°F
3/4T, 144°F

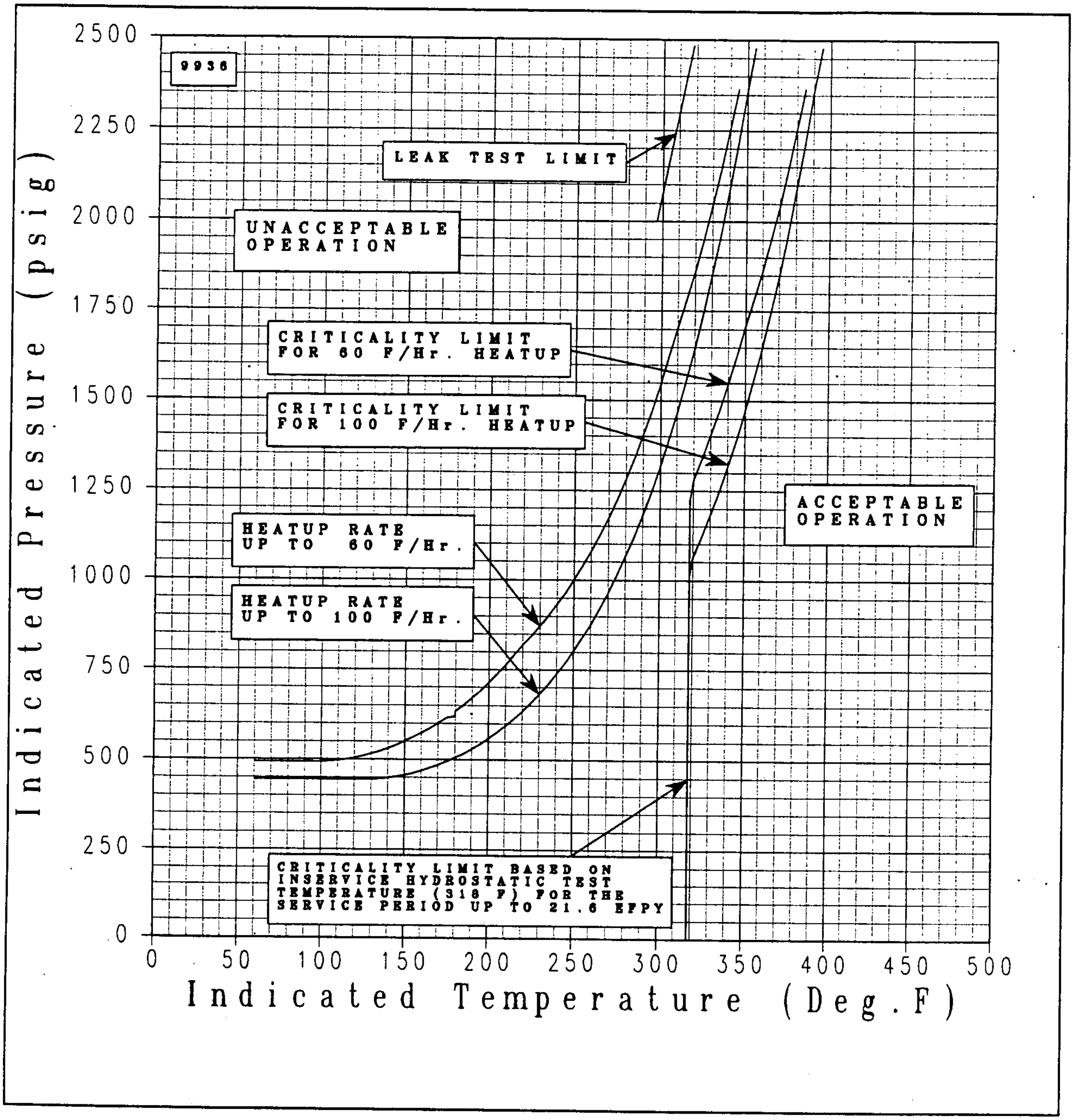

FIGURE 1 Indian Point Unit 2 Reactor Coolant System Heatup Limitations (Heatup Rates up to 100°F/hr) Applicable for the First 21.63 EFPY Using ASME Section XI, Appendix G Methodology (Without Margins for Instrumentation Errors)
Includes vessel flange requirements of 180°F and 621 psig per 10CFR50, Appendix G.

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: INTERMEDIATE SHELL B2002-3
LIMITING ART VALUES AT 21.63 EFPY: 1/4T, 194°F
3/4T, 144°F

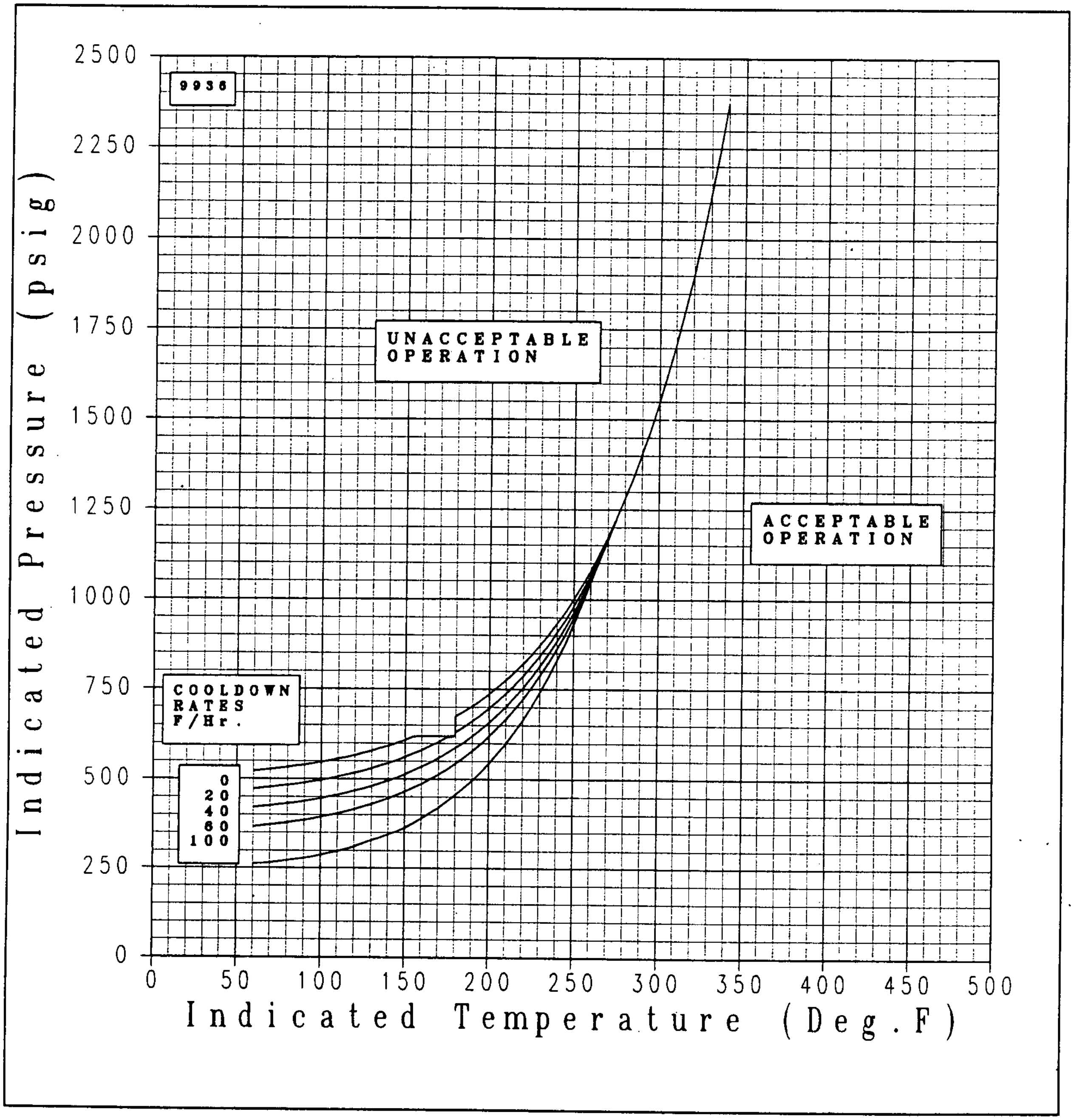

FIGURE 2 Indian Point Unit 2 Reactor Coolant System Cooldown Limitations (Cooldown Rates up to 100°F/hr) Applicable for the First 21.63 EFPY Using ASME Section XI, Appendix G Methodology (Without Margins for Instrumentation Errors)
Includes vessel flange requirements of 180°F and 621 psig per 10CFR50, Appendix G.

TABLE 6

21.63 EFPY Heatup and Cooldown Curve Data Points Using Appendix G (without Margins for Instrumentation Errors)

Cooldown Curves

Steady State

T	P
60	522
65	525
70	527
75	530
80	533
85	536
90	540
95	544
100	548
105	552
110	557
115	562
120	567
125	573
130	580
135	586
140	594
145	601
150	610
155	619
160	621
165	621
170	621
175	621
180	621
180	675
185	689
190	704
195	720
200	738
205	756
210	776
215	798
220	821
225	846
230	873
235	901
240	932
245	966
250	1001
255	1040
260	1081
265	1126
270	1174
275	1225
280	1280
285	1340
290	1404
295	1472
300	1546
305	1625
310	1711
315	1803
320	1901
325	2007
330	2121
335	2244
340	2376

20F

T	P
60	472
65	475
70	477
75	480
80	483
85	487
90	490
95	494
100	498
105	503
110	507
115	513
120	518
125	524
130	531
135	538
140	545
145	554
150	562
155	572
160	582
165	593
170	605
175	618
180	621
180	632
185	646
190	662
195	680
200	698
205	718
210	739
215	762
220	787
225	814
230	843
235	874
240	907
245	943
250	981
255	1023
260	1067
265	1115
270	1167
275	1222

40F

T	P
60	421
65	424
70	426
75	429
80	432
85	435
90	439
95	443
100	447
105	452
110	457
115	462
120	468
125	474
130	481
135	489
140	497
145	505
150	514
155	524
160	535
165	547
170	560
175	573
180	588
185	604
190	621
195	639
200	659
205	680
210	703
215	728
220	755
225	783
230	814
235	848
240	883
245	922
250	964
255	1008
260	1057
265	1109
270	1164
275	1225

60F

T	P
60	369
65	371
70	374
75	377
80	380
85	383
90	387
95	391
100	395
105	400
110	405
115	411
120	417
125	423
130	431
135	438
140	447
145	456
150	466
155	476
160	488
165	500
170	514
175	528
180	544
185	561
190	579
195	599
200	620
205	643
210	668
215	694
220	723
225	754
230	787
235	823
240	862
245	904
250	949
255	997
260	1050
265	1106
270	1167

100F

T	P
60	261
65	263
70	265
75	268
80	271
85	275
90	279
95	283
100	288
105	293
110	299
115	305
120	312
125	319
130	327
135	336
140	345
145	355
150	367
155	379
160	392
165	406
170	422
175	438
180	456
185	476
190	497
195	520
200	545
205	572
210	600
215	632
220	665
225	702
230	741
235	783
240	829
245	878
250	931
255	988
260	1050
265	1117

Heatup Curves

60F

T	P
60	494
65	494
70	494
75	494
80	494
85	494
90	494
95	494
100	494
105	495
110	498
115	501
120	505
125	511
130	517
135	524
140	532
145	541
150	551
155	562
160	574
165	587
170	602
175	617
180	621
180	634
185	652
190	671
195	692
200	715
205	739
210	765
215	793
220	821
225	846
230	873
235	901
240	932
245	966
250	1001
255	1040
260	1081
265	1126
270	1174
275	1225
280	1280
285	1340
290	1404
295	1472
300	1546
305	1625
310	1705
315	1781
320	1862
325	1949
330	2042
335	2143
340	2250
345	2366

Crit. Limit

T	P
318	0
318	525
318	527
318	515
318	507
318	501
318	497
318	495
318	494
318	495
318	498
318	501
318	505
318	511
318	517
318	524
318	532
318	541
318	551
318	562
318	574
318	587
318	602
318	617
318	634
318	652
318	671
318	692
318	715
318	739
318	765
318	793
318	821
318	846
318	873
318	901
318	932
318	966
318	1001
318	1040
318	1081
318	1126
318	1174
318	1225
320	1280
325	1340
330	1404
335	1472
340	1546
345	1625
350	1705
355	1781
360	1862
365	1949
370	2042
375	2143
380	2250
385	2366

100F

T	P
60	445
65	445
70	445
75	445
80	445
85	445
90	445
95	445
100	445
105	445
110	445
115	445
120	445
125	445
130	446
135	447
140	450
145	453
150	458
155	463
160	470
165	477
170	486
175	495
180	506
185	517
190	530
195	544
200	560
205	576
210	594
215	614
220	635
225	658
230	683
235	710
240	739
245	770
250	803
255	839
260	878
265	920
270	965
275	1013
280	1065
285	1121
290	1181
295	1245
300	1314
305	1388
310	1467
315	1553
320	1645
325	1743
330	1849
335	1962
340	2084
345	2214
350	2354
355	2480

Crit. Limit

T	P
318	0
318	525
318	527
318	511
318	497
318	484
318	474
318	466
318	459
318	454
318	450
318	447
318	445
318	445
318	446
318	447
318	450
318	453
318	458
318	463
318	470
318	477
318	486
318	495
318	506
318	517
318	530
318	544
318	560
318	576
318	594
318	614
318	635
318	658
318	683
318	710
318	739
318	770
318	803
318	839
318	878
318	920
318	965
318	1013
320	1065
325	1121
330	1181
335	1245
340	1314
345	1388
350	1467
355	1553
360	1645
365	1743
370	1849
375	1962
380	2084
385	2214
390	2354
395	2480

Leak Test Limit

T	P
297	2000
318	2485

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: INTERMEDIATE SHELL B2002-3
LIMITING ART VALUES AT 21.63 EFPY: 1/4T, 194°F
3/4T, 144°F

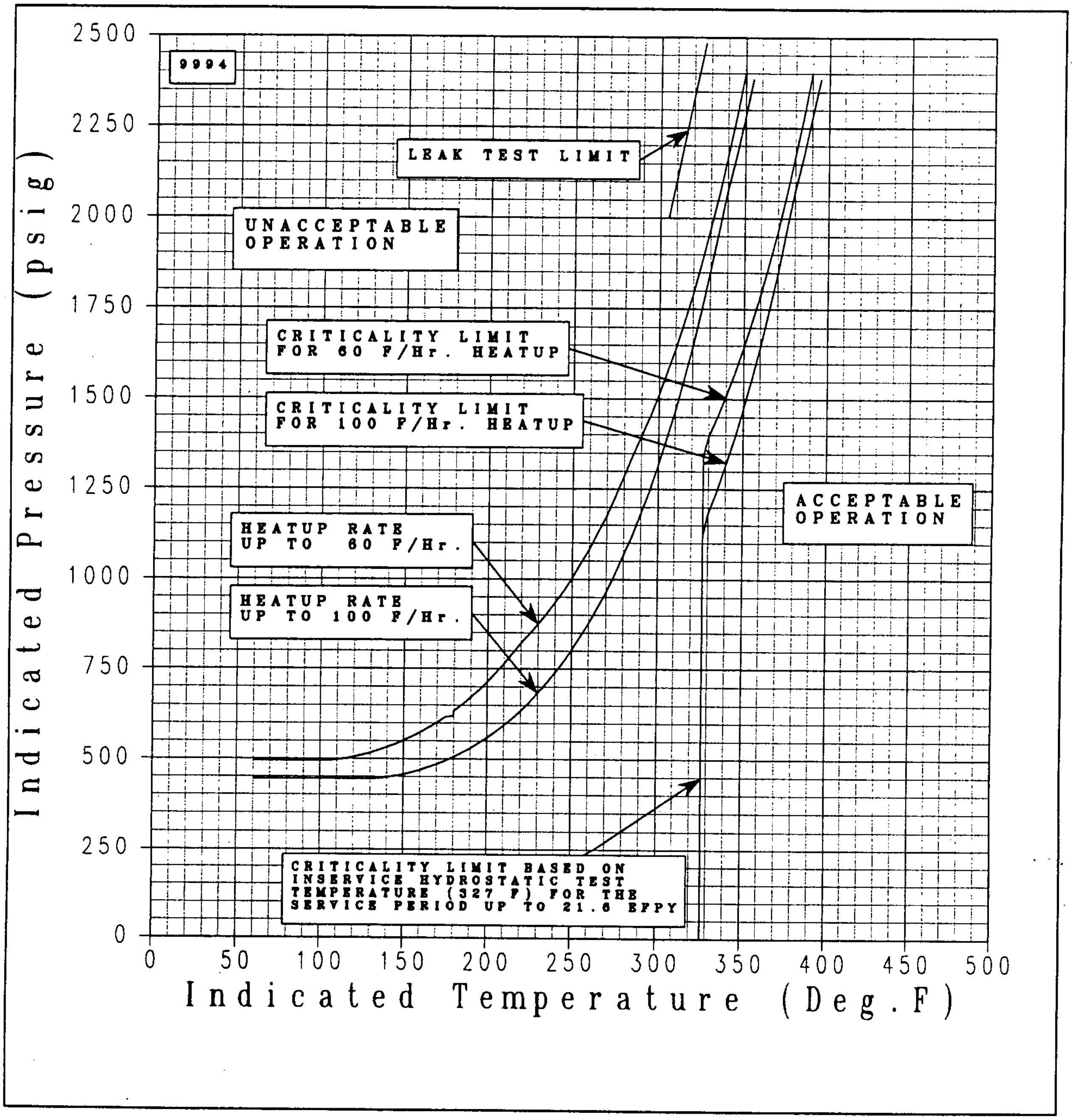

FIGURE 3 Indian Point Unit 2 Reactor Coolant System Heatup Limitations (Heatup Rates up to 100°F/hr) Applicable for the First 21.63 EFPY Using the Raju-Newman Methodology (Without Margins for Instrumentation Errors)
Includes Vessel flange requirements of 180°F and 621 psig per 10CFR50, Appendix G.

MATERIAL PROPERTY BASIS

LIMITING MATERIAL: INTERMEDIATE SHELL B2002-3
LIMITING ART VALUES AT 21.63 EFPY: 1/4T, 194°F
3/4T, 144°F

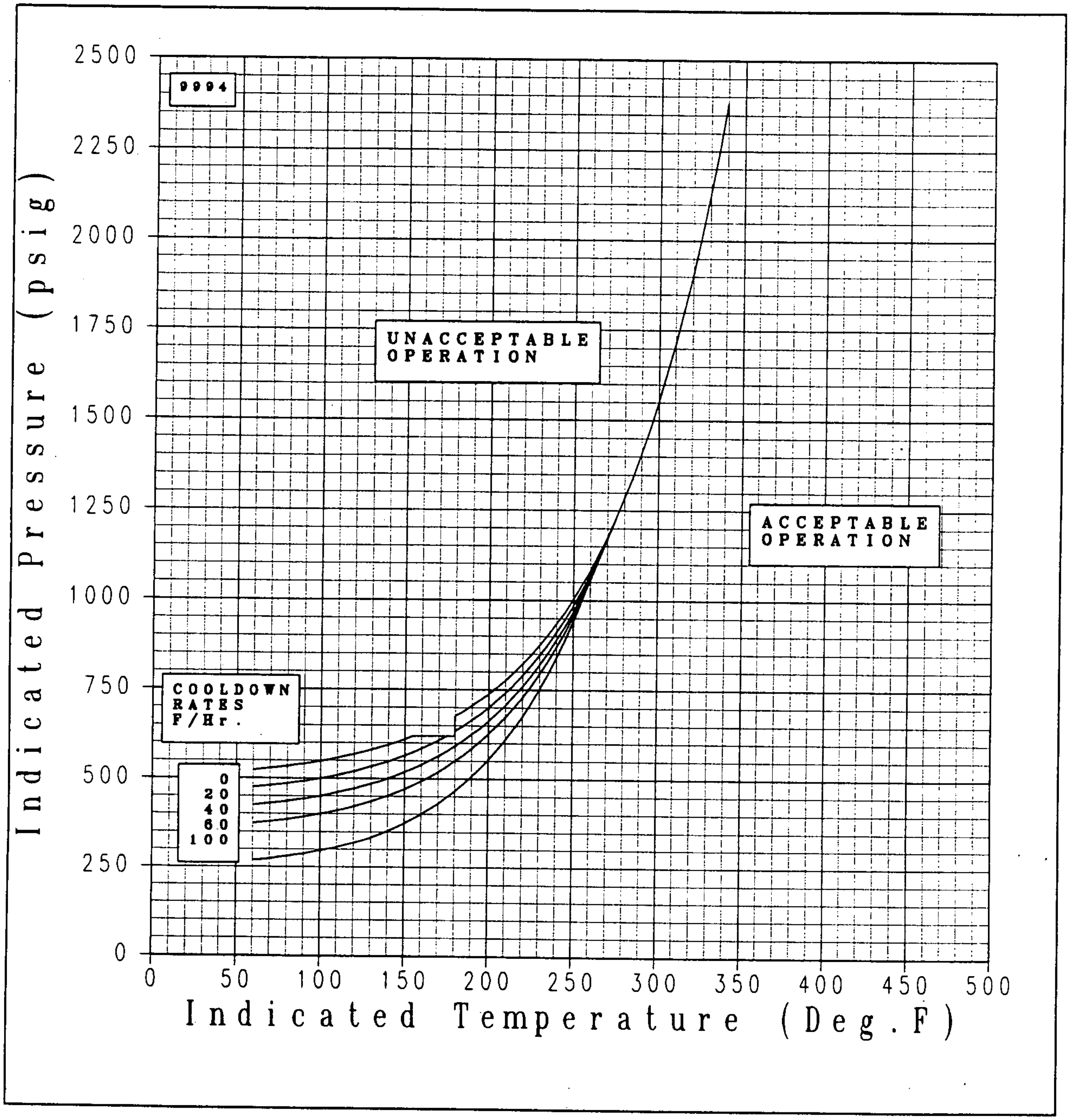

FIGURE 4 Indian Point Unit 2 Reactor Coolant System Cooldown Limitations (Cooldown Rates up to 100°F/hr) Applicable for the First 21.63 EFPY Using the Raju-Newman Method (Without Margins for Instrumentation Errors)
Includes vessel flange requirements of 180°F and 621 psig per 10CFR50, Appendix G.

TABLE 7

21.63 EFPY Heatup and Cooldown Curve Data Points Using Raju-Newman (without Margins for Instrumentation Errors)

Cooldown Curves

Steady State T	Steady State P	20F T	20F P	40F T	40F P	60F T	60F P	100F T	100F P
60	524	60	475	60	425	60	375	60	269
65	526	65	478	65	428	65	377	65	271
70	529	70	480	70	430	70	379	70	274
75	532	75	483	75	433	75	382	75	277
80	535	80	486	80	436	80	385	80	280
85	538	85	489	85	440	85	389	85	283
90	542	90	493	90	443	90	393	90	287
95	545	95	497	95	447	95	397	95	292
100	549	100	501	100	452	100	401	100	296
105	554	105	505	105	456	105	406	105	302
110	559	110	510	110	461	110	411	110	307
115	564	115	516	115	467	115	417	115	314
120	569	120	521	120	472	120	423	120	320
125	575	125	527	125	479	125	429	125	328
130	581	130	534	130	486	130	437	130	336
135	588	135	541	135	493	135	444	135	345
140	595	140	549	140	501	140	453	140	354
145	603	145	557	145	510	145	462	145	364
150	612	150	566	150	519	150	472	150	376
155	621	155	575	155	529	155	482	155	388
160	621	160	585	160	540	160	494	160	401
165	621	165	596	165	552	165	507	165	416
170	621	170	608	170	564	170	520	170	431
175	621	175	621	175	578	175	535	175	448
180	621	180	621	180	593	180	550	180	466
180	677	180	635	185	609	185	567	185	486
185	691	185	650	190	626	190	586	190	507
190	706	190	666	195	644	195	605	195	530
195	722	195	683	200	664	200	627	200	555
200	740	200	702	205	685	205	650	205	582
205	758	205	722	210	708	210	675	210	611
210	779	210	743	215	733	215	701	215	642
215	800	215	766	220	760	220	730	220	676
220	823	220	791	225	789	225	761	225	712
225	848	225	818	230	820	230	795	230	752
230	875	230	847	235	853	235	831	235	794
235	904	235	878	240	889	240	870	240	840
240	935	240	911	245	928	245	912	245	889
245	968	245	947	250	970	250	957	250	943
250	1004	250	986	255	1015	255	1006	255	1000
255	1043	255	1027	260	1063	260	1058	260	1062
260	1084	260	1072	265	1115	265	1114	265	1129
265	1129	265	1120	270	1171	270	1175		
270	1177	270	1172						
275	1228	275	1228						
280	1284								
285	1343								
290	1408								
295	1476								
300	1550								
305	1630								
310	1716								
315	1808								
320	1907								
325	2013								
330	2127								
335	2250								
340	2383								

Heatup Curves

60F T	60F P	Critical. Limit T	Critical. Limit P	100F T	100F P	Critical. Limit T	Critical. Limit P
60	495	327	0	60	445	327	0
65	495	327	526	65	445	327	526
70	495	327	527	70	445	327	528
75	495	327	516	75	445	327	511
80	495	327	507	80	445	327	497
85	495	327	501	85	445	327	485
90	495	327	497	90	445	327	475
95	495	327	495	95	445	327	466
100	495	327	495	100	445	327	459
105	496	327	496	105	445	327	454
110	498	327	498	110	445	327	450
115	501	327	501	115	445	327	447
120	506	327	506	120	445	327	446
125	511	327	511	125	445	327	445
130	517	327	517	130	446	327	446
135	524	327	524	135	448	327	448
140	533	327	533	140	450	327	450
145	542	327	542	145	454	327	454
150	552	327	552	150	458	327	458
155	563	327	563	155	464	327	464
160	575	327	575	160	470	327	470
165	588	327	588	165	478	327	478
170	602	327	602	170	486	327	486
175	618	327	618	175	496	327	496
180	621	327	634	180	506	327	506
180	634	327	652	185	518	327	518
185	652	327	672	190	531	327	531
190	672	327	693	195	545	327	545
195	693	327	715	200	560	327	560
200	715	327	739	205	577	327	577
205	739	327	766	210	595	327	595
210	766	327	794	215	615	327	615
215	794	327	823	220	636	327	636
220	823	327	848	225	659	327	659
225	848	327	875	230	684	327	684
230	875	327	904	235	710	327	710
235	904	327	935	240	739	327	739
240	935	327	968	245	771	327	771
245	968	327	1004	250	804	327	804
250	1004	327	1043	255	840	327	840
255	1043	327	1084	260	879	327	879
260	1084	327	1129	265	921	327	921
265	1129	327	1177	270	966	327	966
270	1177	327	1228	275	1014	327	1014
275	1228	327	1284	280	1066	327	1066
280	1284	327	1343	285	1122	327	1122
285	1343	330	1396	290	1181	330	1181
290	1396	335	1451	295	1246	335	1246
295	1451	340	1510	300	1315	340	1315
300	1510	345	1573	305	1389	345	1389
305	1573	350	1641	310	1469	350	1469
310	1641	355	1714	315	1554	355	1554
315	1714	360	1793	320	1646	360	1646
320	1793	365	1877	325	1744	365	1744
325	1877	370	1967	330	1850	370	1850
330	1967	375	2064	335	1963	375	1963
335	2064	380	2169	340	2075	380	2075
340	2169	385	2280	345	2171	385	2171
345	2280	390	2401	350	2275	390	2275
350	2401			355	2386	395	2386

Leak Test Limit

T	P
305	2000
327	2485

SECTION 6.0

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3. WCAP-12796, "Heatup and Cooldown Limit Curves for the Consolidated Edison Company Indian Point Unit 2 Reactor Vessel", N. K. Ray, January 1991.

4. SwRI Project No. 17-2018 (Revised), "Reactor Vessel Material Surveillance Program for Indian Point Unit No. 2 Analysis of Capsule V", March 1990.

5. 10 CFR 50, Appendix G, "Fracture Toughness Requirements", Federal Register, Volume 60, No. 243, dated December 19, 1995.

6. ASME Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components", Appendix G, "Fracture Toughness Criteria for Protection Against Failure", 1996 Addendum (to be published in December 1996).

7. I. S. Raju and J. C. Newman, Jr., "Stress Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical vessels", in Aspect of Fracture Mechanics in Pressure Vessels and Piping, ed. S. S. Palusamy and S. G. Sampath, PVP-Volume 58, ASME 1982.

8. 1989 Section III, Division 1 of the ASME Boiler and Pressure Vessel Code, Paragraph NB-2331, "Material for Vessels".

9. 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, January 1996.

APPENDIX A

TABULATION OF PRESSURE AND K_I VALUES FOR THE NEW APPENDIX G AND RAJU-NEWMAN METHODOLOGIES

TABLE A-1
Comparison Between ASME Appendix G and Raju-Newman P-T Limit Curves at Select Temperatures

Cooldown Curves											Heatup Curves				
	Steady State		20F		40F		60F		100F			60F		100F	
	App. G	Raju-New.	App. G	Raju-New.	App. G	Raju-New.	App. G	Raju-New.	App. G	Raju-New.		App. G	Raju-New.	App. G	Raju-New.
T	P	P	P	P	P	P	P	P	P	P	T	P	P	P	P
60	522	524	472	475	421	425	369	375	261	269	60	494	495	445	445
100	548	549	498	501	447	452	395	401	288	296	100	494	495	445	445
150	610	612	562	566	514	519	466	472	367	376	150	551	552	458	458
200	738	740	698	702	659	664	620	627	545	555	200	715	715	560	560
250	1001	1004	981	986	964	970	949	957	931	943	250	1001	1004	803	804
265	1126	1129	1115	1120	1109	1115	1106	1114	1117	1129	300	1546	1510	1314	1315
270	1174	1177	1167	1172	1164	1171	1167	1175			340	2250	2169	2084	2075
275	1225	1228	1222	1228											
300	1546	1550													
340	2376	2383													

TABLE A-2
ASME Appendix G Versus Raju-Newman Stress Intensity Factor Values
Steady State and Cooldown Curves

Cooldown Rate	Water Temp. (°F)	ASME Appendix G		Raju-Newman	
		1/4T K_{IT}	1/4T K_{IP}	1/4T K_{IT}	1/4T K_{IP}
Steady State	60	0	14.2798	0	14.2798
	100	0	14.9800	0	14.9800
	150	0	16.6734	0	16.6734
	200	0	20.1686	0	20.1686
	250	0	27.3828	0	27.3828
	300	0	42.2728	0	42.2728
20°F/Hr. Cooldown	60	2.85144	12.9168	2.77403	12.9555
	100	2.95196	13.6192	2.87182	13.6592
	150	3.08146	15.3788	2.99780	15.4206
	200	3.21394	19.0875	3.12668	19.1312
	250	3.34944	26.8313	3.25851	26.8767
	300	3.48802	42.9268	3.39333	42.9742
40°F/Hr. Cooldown	60	5.77743	11.5223	5.62053	11.6007
	100	5.98498	12.2287	5.82244	12.3100
	150	6.24883	14.0654	6.07912	14.1502
	200	6.51887	18.0142	6.34182	18.1027
	250	6.79517	26.3488	6.61061	26.4411
	300	7.07775	43.7879	6.88552	43.8840
60°F/Hr. Cooldown	60	8.78722	10.0923	8.54850	10.2117
	100	9.10406	10.8075	8.85672	10.9312
	150	9.50754	12.7334	9.24924	12.8626
	200	9.92051	16.9525	9.65098	17.0873
	250	10.3423	25.9481	10.0613	26.0886
	300	10.7694	44.8866	10.4768	45.0329
100°F/Hr. Cooldown	60	15.0711	7.1231	14.6614	7.3279
	100	15.6173	7.8706	15.1927	8.0829
	150	16.3089	10.0224	15.8655	10.2441
	200	17.0021	14.8963	16.5398	15.1274
	250	17.6708	25.4627	17.1904	25.7029
	300	18.2502	47.8686	17.7541	48.1167

TABLE A-3
ASME Appendix G Versus Raju-Newman Stress Intensity Factor Values
Heatup Curves

Cooldown Rate	Water Temp. (°F)	ASME Appendix G				Raju-Newman			
		K_{IT} @ 1/4T	K_{IT} @ 3/4T	K_{IP} @ 1/4T	K_{IP} @ 3/4T	K_{IT} @ 1/4T	K_{IT} @ 3/4T	K_{IP} @ 1/4T	K_{IP} @ 3/4T
60 °F/Hr. Heatup	60	-1.0968	0.5960	14.7831	14.8049	-1.0429	0.5965	14.7562	14.8046
	100	-7.0929	5.3230	18.2750	13.0365	-6.7917	5.3211	18.1243	13.0375
	150	-8.6781	6.5715	20.4071	14.5381	-8.3111	6.5691	20.2236	14.5393
	200	-9.2249	6.9920	23.4742	18.8425	-8.8349	6.9895	23.2792	18.8438
	250	-9.6338	7.3025	29.4169	27.9174	-9.2266	7.2998	29.2133	27.9188
	300	-10.0291	7.6018	41.3759	46.5448	-9.6052	7.5990	41.1639	46.5462
	340	-10.3484	7.8434	59.3419	74.6521	-9.9110	7.8406	59.1231	74.6535
100 °F/Hr. Heatup	60	-0.9954	0.4731	14.7272	14.8642	-0.9439	0.4740	14.7014	14.8637
	100	-9.1226	6.7187	19.2114	12.1035	-8.7316	6.7165	19.0160	12.1046
	150	-12.9964	9.7812	22.2943	12.0742	-12.4451	9.7777	22.0187	12.0760
	200	-14.5894	11.0256	25.4989	14.7555	-13.9718	11.0216	25.1901	14.7575
	250	-15.5151	11.7373	30.9113	21.1851	-14.8586	11.7331	30.5830	21.1872
	300	-16.2447	12.2924	41.3927	34.6435	-15.5575	12.2880	41.0491	34.6457
	340	-16.7870	12.7030	56.9262	54.9433	-16.0768	12.6985	56.5712	54.9456

APPENDIX B

SUMMARY OF VESSEL AND MATERIAL PROPERTIES USED IN THE GENERATION OF THE HEATUP/COOLDOWN CURVES

Pressure vessel inner radius = 86.719 inches

Pressure vessel outer radius = 95.344 inches

Beltline region wall thickness = 8.625 inches

Limiting temperature for vessel flange = 180°F

Limiting pressure for vessel flange = 621 psig

ATTACHMENT IV

ASME PROPOSED CHANGES TO SECTION XI APPENDIX G

CONSOLIDATED EDISON COMPANY OF NEW YORK, INC.
INDIAN POINT UNIT NO. 2
DOCKET NO. 50-247
OCTOBER, 1996

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Dept. | Phone # (412) 374-5438
Fax # (414) 737-8364 | Fax #

(Revised 4/30/96)

ISI 94-40

Proposed Revision to Appendix G Stress Intensity Factors

Appendix G is being revised to incorporate the most recent elastic solutions for K_I due to pressure and radial thermal gradients. The new solutions are based on finite element analyses for inside surface flaws performed at Oak Ridge National Laboratories and sponsored by NRC [1], and work published by EPRI for outside surface flaws [2]. These solutions provide results that are essentially the same as those obtained by using solutions previously developed by Raju and Newman [3].

The proposed Section XI, Appendix G code change is attached. ~~Also included are the results from sample problems to calculate the allowable pressure-temperature limits using the new method for comparison with the current Appendix G approach.~~

This revision now provides consistent computation methods for pressure and thermal K_I, and provides a method to compute thermal K_I for any thermal gradient through the vessel wall at any time during the transient. Consistent with the original version of Appendix G no contribution for crack face pressure is included in the K_I due to pressure, and cladding effects are neglected.

These new solutions are elastic solutions that do not include the plastic zone size correction in the current Code solutions for pressure stress. These new solutions better characterize the conditions for irradiated vessels in the low temperature region where the thermal stresses and allowable pressure are low. For these conditions the plastic zone size is negligible, and the elastic solutions are the technically correct solutions. Plastic zone size corrections and other high stress considerations are no longer used in Appendix G generally because applications where plastic conditions may be important for integrity evaluations are now addressed in other code appendices (e.g., upper shelf toughness in Appendix K).

Using these most recent elastic solutions in the low temperature region will provide some relief to restrictions associated with reactor operation at relatively low temperature. Although the relief is relatively small in terms of absolute allowable pressure, the benefits are substantial because even a small increase in the allowable pressure can be a significant percentage increase in the operating window at relatively low temperatures. Implementing this revision results in an economic and potential safety benefit (less likelihood of lifting LTOP pressure relieving devices) with no reduction in vessel integrity.

---

1. J. A. Keeney and T. L. Dickson, "Stress-Intensity-Factor Influence Coefficients for Axially Oriented Semielliptical Inner-Surface Flaws in Clad Pressure Vessels (R/t=10)", ORNL/NRC/LTR-93/33, Revision 1, September 30, 1995.

2. Zahoor, A. Ductile Fracture Handbook, Volume 3, published jointly by EPRI, NP-6301-D and Novetech, N14-3, January, 1991.

3. I.S. Raju and J.C. Newman, Jr., " Stress Intensity Factors for Internal and External Surface Cracks in Cylindrical Vessels," Journal of Pressure Vessel Technology, Vol. 104, pp 283-298, November 1982.

ARTICLE G-1000
INTRODUCTION

This Appendix presents a procedure for obtaining the allowable loadings for ferritic pressure retaining materials in components. This procedure is based on the principles of linear elastic fracture mechanics. At each location being investigated a maximum postulated flaw is assumed. At the same location the *mode I stress intensity factor*[1] K_I is produced by each of the specified loadings as calculated and the summation of the K_I values is compared to a reference value K_{IR} which is the highest critical value of K_I that can be ensured for the material and temperature involved. Different procedures are recommended for different components and operating conditions.

---

[1] The *stress intensity factor* as used in fracture mechanics has no relation to and must not be confused with the *stress intensity* used in Section III, Division 1. Furthermore, stresses referred to in this Appendix are calculated normal tensile stresses not stress intensities in a defect free stress model at the surface nearest the location of the assumed defect.

ARTICLE G-2000
VESSELS

G-2100 GENERAL REQUIREMENTS

G-2110 REFERENCE CRITICAL STRESS INTENSITY FACTOR

(a) Figure G-2210-1 is a curve showing the relationship that can be conservatively expected between the critical, or reference, stress intensity factor K_{Ia}, ksi$\sqrt{\text{in.}}$, and a temperature which is related to the reference nil-ductility temperature RT_{NDT} determined in NB-2331. This curve is based on the lower bound of static, dynamic, and crack arrest critical K_I values measured as a function of temperature on specimens of SA-533 Grade B Class 1, and SA-508-1, SA-508-2, and SA-508-3 steel. No available data points for static, dynamic, or arrest tests fall below the curve. An analytical approximation to the curve is:

$$K_{Ia} = 26.78 + 1.233\exp[0.0145(T - RT_{NDT} + 160)]$$

Unless higher K_{Ia} values can be justified for the particular material and circumstances being considered, Fig. G-2210-1 may be used for ferritic steels which meet the requirements of NB-2331 and which have a specified minimum yield strength at room temperature of 50.0 ksi or less.

(b) For materials which have specified minimum yield strengths at room temperature greater than 50.0 ksi but not exceeding 90.0 ksi, Fig. G-2210-1 may be used provided fracture mechanics data (similar to the K_{ID} data referenced in WRCB 175) are obtained on at least three heats of the material on a sufficient number of specimens to cover the temperature range of interest, including the weld metal and heat-affected zone, and provided that the data are equal to or above the curve of Fig. G-2210-1. These data shall be documented by the Owner. Where these materials of higher yield strengths (specified minimum yield strength greater than 50.0 ksi but not exceeding 90.0 ksi) are to be used in conditions where radiation may affect the material properties, the effect of radiation on the K_{Ia} curve shall be determined for the material. This information shall be documented by the Owner.

G-2120 MAXIMUM POSTULATED DEFECT

The postulated defect used in this recommended procedure is a sharp, surface defect normal to the direction of maximum stress. For section thicknesses of 4 in. to 12 in., it has a depth of one-fourth of the section thickness and a length of $1^1/_2$ times the section thickness. ← Insert ①
For sections greater than 12 in. thick, the postulated defect for the 12 in. section is used. For sections less than 4 in. thick, the 1 in. deep defect is conservatively postulated. These postulated effects of thickness were used in developing the curves of Fig. G-2214-1. Smaller defect sizes[1] may be used on an individual case basis if a smaller size of maximum postulated defect can be ensured. Due to the safety factors recommended here, the prevention of nonductile fracture is ensured for some of the most important situations even if the defects were to be about twice as large in linear dimensions as this postulated maximum defect.

G-2200 LEVEL A AND LEVEL B SERVICE LIMITS

G-2210 SHELLS AND HEADS REMOTE FROM DISCONTINUITIES

G-2211 Recommendations

The assumptions of this Subarticle are recommended for shell and head regions during Level A and B Service Limits.

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[1] WRCB 175 (Welding Research Council Bulletin 175) "PVRC Recommendations on Toughness Requirements for Ferritic Materials" provides procedures in Paragraph 5(c)(2) for considering maximum postulated defects smaller than those described.

Revised 4/30/96
(CHANGES ARE CIRCLED)

INSERT 1

Defects are postulated at both the inside and outside surfaces.

INSERT 2

(pR_i / t), 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 $\sqrt{t} > 3.464$,

where p = internal pressure (ksi), R_i = vessel inner radius (in.), t = vessel wall thickness (in.).

INSERT 3

The maximum K_I produced by a 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 and the temperature relationship in Fig. G-2214-1 are applicable only for the conditions in G-2214.3 (a)(1) and (2).

INSERT 4

(b) Alternatively, the K_I for radial thermal gradient can be calculated for any thermal stress distribution at any specified time during cooldown for a 1/4-thickness surface defect.

For an inside surface defect during cooldown

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

Revised 4/30/96
(CHANGES ARE CIRCLED)

For an outside surface defect during heatup

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

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

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

add

where x is a dummy variable that represents the radial distance, (in.), from the appropriate (i.e., inside or outside) surface and a is the maximum crack depth, (in.).

(c) For the startup condition, the allowable pressure vs. temperature relationship is the minimum pressure at any temperature, determined from (1) the calculated steady state results for the 1/4-thickness inside surface defect, (2) the calculated steady state results for the 1/4-thickness outside surface defect, and (3) the calculated results for the maximum allowable heatup rate using a 1/4-thickness outside surface defect.

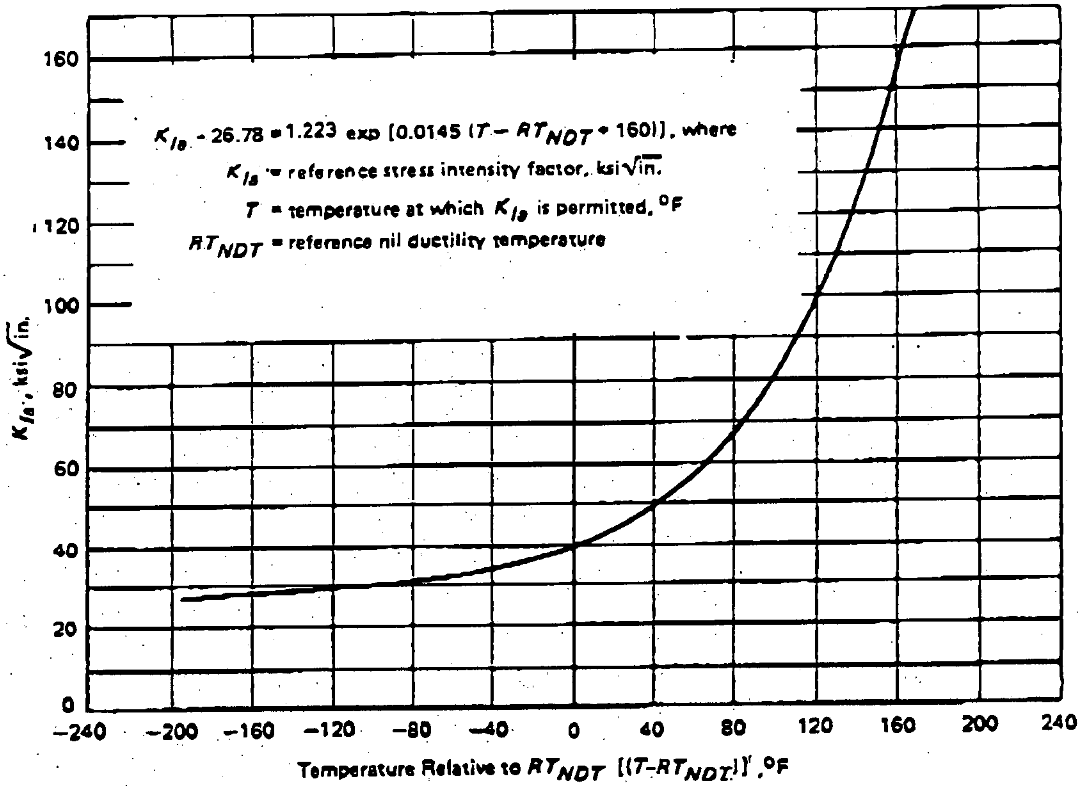

FIG. G-2210-1

G-2212 Material Fracture Toughness

G-2212.1 Reference Critical Stress Intensity Factor for Material. The K_{Ia} values of Fig. G-2210-1 are recommended.

G-2212.2 Irradiation Effects. Subarticle A-4400 of Appendix A is recommended to define the change in reference critical stress intensity factor due to irradiation.

G-2213 Maximum Postulated Defect

The recommended maximum postulated defect is that described in G-2120.

G-2214 Calculated Stress Intensity Factors

G-2214.1 Membrane Tension. The K_I corresponding to membrane tension for the postulated defect of G-2120 is $K_{Im} = M_m \times$ ~~membrane stress, where M_m is as shown in Fig. G-2214-1.~~ ← replace with Insert 2.

G-2214.2 Bending Stress. The K_I corresponding to bending stress for the postulated defect of G-2120 is $K_{Ib} = M_b \times$ maximum bending stress, where M_b is two-thirds of the M_m ~~shown in Fig. G-2214-1~~.

G-2214.3 Radial Thermal Gradient. The K_I produced by a radial thermal gradient across a wall thickness for the postulated defect of G-2120 is $K_{It} = M_t \times$ temperature difference through the wall, °F, where M_t is as shown in Fig. G-2214-2. ← replace with Insert 3

(a) The M_t values in Fig. G-2214-2 are applicable only for the conditions given in G-2214.3(a)(1) and (2).

(1) An assumed shape of the temperature gradient is approximately as shown in Fig. G-2214-~~X~~ - 2.

(2) The temperature change starts from a steady state condition and has a rate, associated with startup and shutdown, less than about 100°F/hr. The results would be overly conservative if applied to rapid temperature changes.

(b) If the conditions of G-2214.3(a) are not met, other means must be used for calculating the K_I produced by thermal stress. For example, the moment produced by the radial thermal gradient may be calculated

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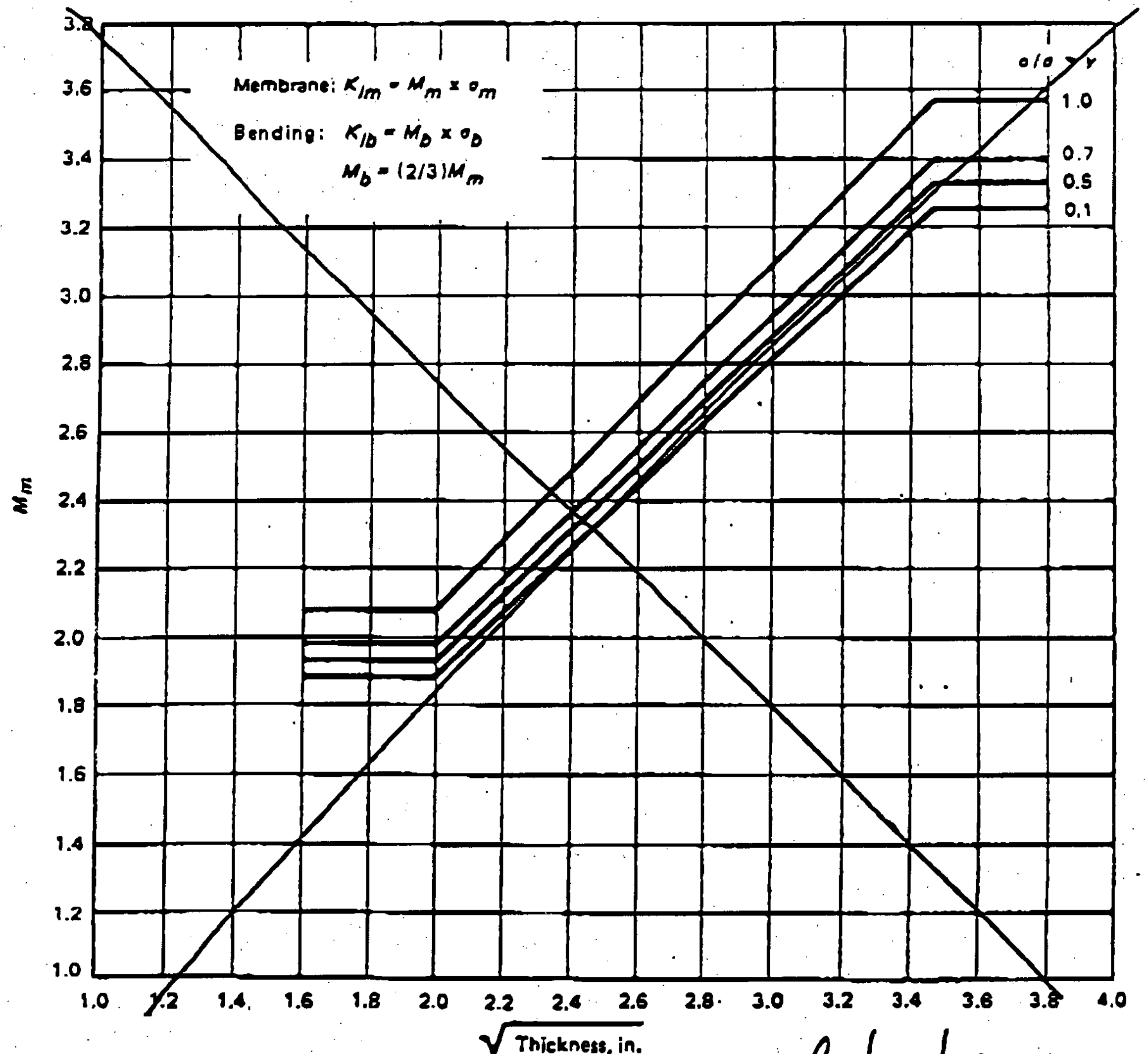

FIG. G-2214-1

~~and the equivalent linear stress [NB-3213.13(a)(3)] considered by the provisions of G-2214.2.~~

~~G-2214.4 Stresses Exceeding Material Yield Strength. WRCB 175 provides procedures in Paragraph 5C(3) for considering elastically calculated stresses which exceed the yield strength of the material. This method may be used in lieu of using Figs. G-2214-1, G-2214-2, and G-2214-3, which are not applicable for combined stresses above the material yield strength.~~

G-2215 Allowable Pressure

The equations given in this Subarticle provide the basis for determination of the allowable pressure at any temperature at the depth of the postulated defect during Service Conditions for which Level A and Level B Service Limits are specified. In addition to the conservatism of these assumptions, it is recommended that a factor of 2 be applied to the calculated K_I values produced by primary stresses. In shell and head regions remote from discontinuities, the only significant loadings are: (1) general primary membrane stress due to pressure; and (2) thermal stress due to thermal gradient through the thickness during startup and shutdown. Therefore, the requirement to be satisfied and from which the allowable pressure for any assumed rate of temperature change can be determined is:

$$2K_{Im} + K_{It} < K_{Ia} \qquad (1)$$

$\Delta T_w = K_{It}/M_t$, where

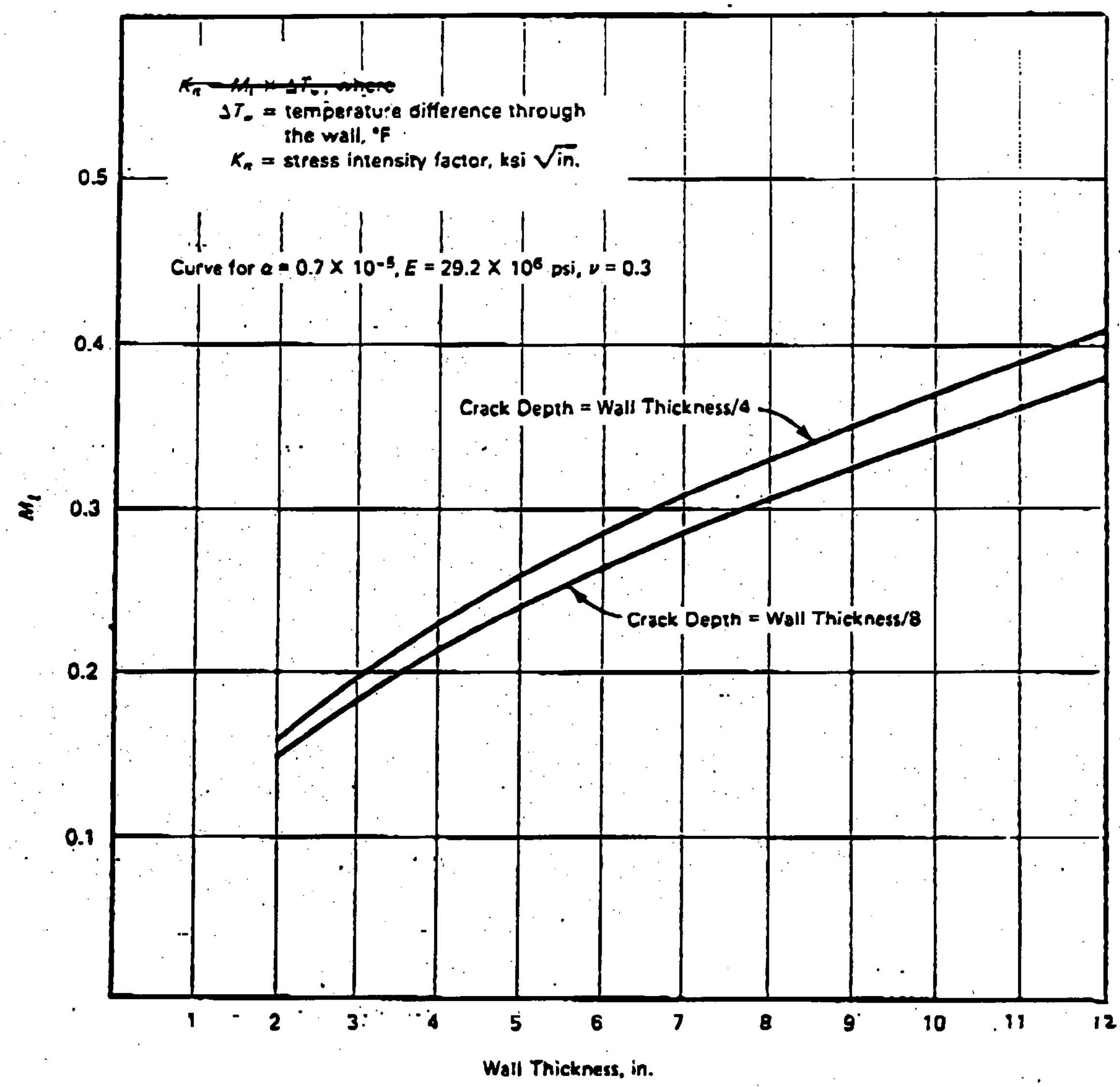

FIG. G-2214-1

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(CHANGES ARE CIRCLED)

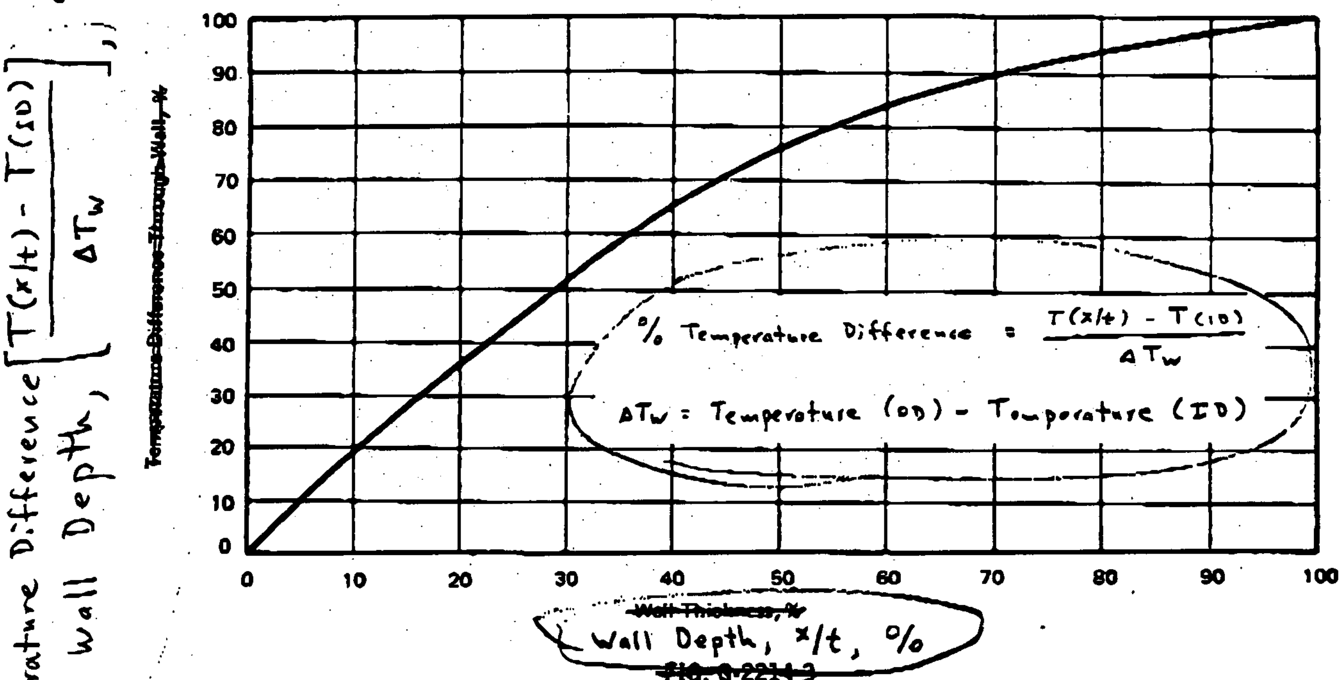

FIG. G-2214-2

throughout the life of the component at each temperature with K_{Im} from G-2214.1, K_{Il} from G-2214.~~2~~3, and K_{Ia} from Fig. G-2210-1.

G-2220 NOZZLES, FLANGES, AND SHELL REGIONS NEAR GEOMETRIC DISCONTINUITIES

G-2221 General Requirements

The same general procedure as was used for the shell and head regions in G-2210 may be used for areas where more complicated stress distributions occur, but certain modifications of the procedures for determining allowable applied loads shall be followed in order to meet special situations, as stipulated in G-2222 and G-2223.

G-2222 Consideration of Membrane and Bending Stresses

(a) Equation (1) of G-2215 requires modification to include the bending stresses which may be important contributors to the calculated K_I value at a point near a flange or nozzle. The terms whose sum must be $< K_{Ia}$ for normal and upset operating conditions are:

(1) $2K_{Im}$ from G-2214.1 for primary membrane stress;

(2) $2K_{Ib}$ from G-2214.2 for primary bending stress;

(3) K_{Im} from G-2214.1 for secondary membrane stress;

(4) K_{Ib} from G-2214.2 for secondary bending stress.

(b) For purposes of this evaluation, stresses which result from bolt preloading shall be considered as primary.

(c) It is recommended that when the flange and adjacent shell region are stressed by the full intended bolt preload and by pressure not exceeding 20% of the preoperational system hydrostatic test pressure, minimum metal temperature in the stressed region should be at least the initial RT_{NDT} temperature for the material in the stressed regions plus any effects of irradiation ~~at the stressed regions~~.

(d) Thermal stresses shall be considered as secondary except as provided in ~~NB-3213.13(b)~~ G-2214-3b. The K_I of ~~Fig. G-2214-2~~ is ~~not~~ recommended for the evaluation of thermal stress ~~because more complicated stress distributions are not adequately represented by the simplified approach of Fig. G-2214-2~~.

G-2223 Toughness Requirements for Nozzles

(a) A quantitative evaluation of the fracture toughness requirements for nozzles is not feasible at this

(3) K_{Im} from G-2214.1 for secondary membrane stress;

(4) K_{Ib} from G-2214.2 for secondary bending stress.

(b) For purposes of this evaluation, stresses which result from bolt preloading shall be considered as primary.

(c) It is recommended that when the flange and adjacent shell region are stressed by the full intended bolt preload and by pressure not exceeding 20% of the preoperational system hydrostatic test pressure, minimum metal temperature in the stressed region should be at least the initial RT_{NDT} temperature for the material in the stressed regions plus any effects of irradiation at the stressed regions. G-2214-1

(d) Thermal stresses shall be considered as secondary except as provided in NB-3213.13(b). The K_I of Fig. ~~G-2214-2~~ is not recommended for the evaluation of thermal stress because more complicated stress distributions are not adequately represented by the simplified approach of Fig. ~~G-2214-2~~ G-2214-1.

G-2223 Toughness Requirements for Nozzles

(a) A quantitative evaluation of the fracture toughness requirements for nozzles is not feasible at this

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INSERT 1

Defects are postulated at both the inside and outside surfaces.

INSERT 2

1.85

(pR_i / t), where M_m for an inside surface flaw is given by

M_m = 1.84 for $\sqrt{t} < 2$,

M_m = 0.918 $\sqrt{t}$ for $2 \leq \sqrt{t} \leq 3.464$, 0.926

M_m = 3.18 for $\sqrt{t} > 3.464$. 3.21

1.77 0.893

Similarly, M_m for an outside surface flaw is given by

M_m = 1.68 for $\sqrt{t} < 2$,

M_m = 0.839 $\sqrt{t}$ for $2 \leq \sqrt{t} \leq 3.464$,

M_m = 2.92 for $\sqrt{t} > 3.464$, 3.09

where p = internal pressure (ksi), R_i = vessel inner radius (in.), t = vessel wall thickness (in.).

INSERT 3

0.753

The maximum K_I produced by a 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, $K_{It} = 0.781 \times 10^{-3} \times HU \times t^{2.5}$, 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 and the temperature relationship in Fig. G-2214-1 are applicable only for the conditions in G-2214.3 (a)(1) and (2).

INSERT 4

(b) Alternatively, the K_I for radial thermal gradient can be calculated for any thermal stress distribution at any specified time during cooldown for a 1/4-thickness surface defect.

For an inside surface defect during cooldown

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

time, but preliminary data indicate that the design defect size for nozzles, considering the combined effects of internal pressure, external loading and thermal stresses, may be a fraction of that postulated for the vessel shell. Nondestructive examination methods shall be sufficiently reliable and sensitive to detect these smaller defects.

(b) WRCB 175 provides an approximate method in Paragraph 5C(2) for analyzing the inside corner of a nozzle and cylindrical shell for elastic stresses due to internal pressure stress.

(c) Fracture toughness analysis to demonstrate protection against nonductile failure is not required for portions of nozzles and appurtenances having a thickness of 2.5 in. or less, provided the lowest service temperature is not lower than RT_{NDT} plus 60°F.

G-2300 LEVEL C AND LEVEL D SERVICE LIMITS

G-2310 RECOMMENDATIONS

The possible combinations of loadings, defect sizes, and material properties which may be encountered during Level C and Level D Service Limits are too diverse to allow the application of definitive rules, and it is recommended that each situation be studied on an individual case basis. The principles given in this Appendix may be applied, where applicable, with any postulated loadings, defect sizes, and material toughness which can be justified for the situation involved.

G-2400 HYDROSTATIC TEST TEMPERATURE

(a) For system and component hydrostatic tests performed prior to loading fuel in the reactor vessel, it is recommended that hydrostatic tests be performed at a temperature not lower than RT_{NDT} plus 60°F. The 60°F margin is intended to provide protection against nonductile failure at the test pressure.

(b) For system and component hydrostatic tests performed subsequent to loading fuel in the reactor vessel, the minimum test temperature should be determined by evaluating K_I. The terms given in (1) through (4) below should be summed in determining K_I:

(1) $1.5K_{Im}$ from G-2214.1 for primary membrane stress;

(2) $1.5K_{Ib}$ from G-2214.2 for primary bending stress;

(3) K_{Im} from G-2214.1 for secondary membrane stress;

(4) K_{Ib} from G-2214.2 for secondary bending stress.

K_I, calculated by summing the four values given in (1) through (4) above, shall not exceed the applicable K_{Ia} value.

(c) The system hydrostatic test to satisfy G-2400(a) or (b) should be performed at a temperature not lower than the highest required temperature for any component in the system.

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For an outside surface defect during heatup 1.043

$$K_{It} = (1.079C_0 + 0.630C_1 + 0.481C_2 + 0.401C_3) \bullet \sqrt{\pi a}$$

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

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

where x is a dummy variable that represents the radial distance, (in.), from the appropriate (i.e., inside or outside) surface and a is the maximum crack depth, (in.).

(c) For the startup condition, the allowable pressure vs. temperature relationship is the minimum pressure at any temperature, determined from (1) the calculated steady state results for the 1/4-thickness inside surface defect, (2) the calculated steady state results for the 1/4-thickness outside surface defect, and (3) the calculated results for the maximum allowable heatup rate using a 1/4-thickness outside surface defect.

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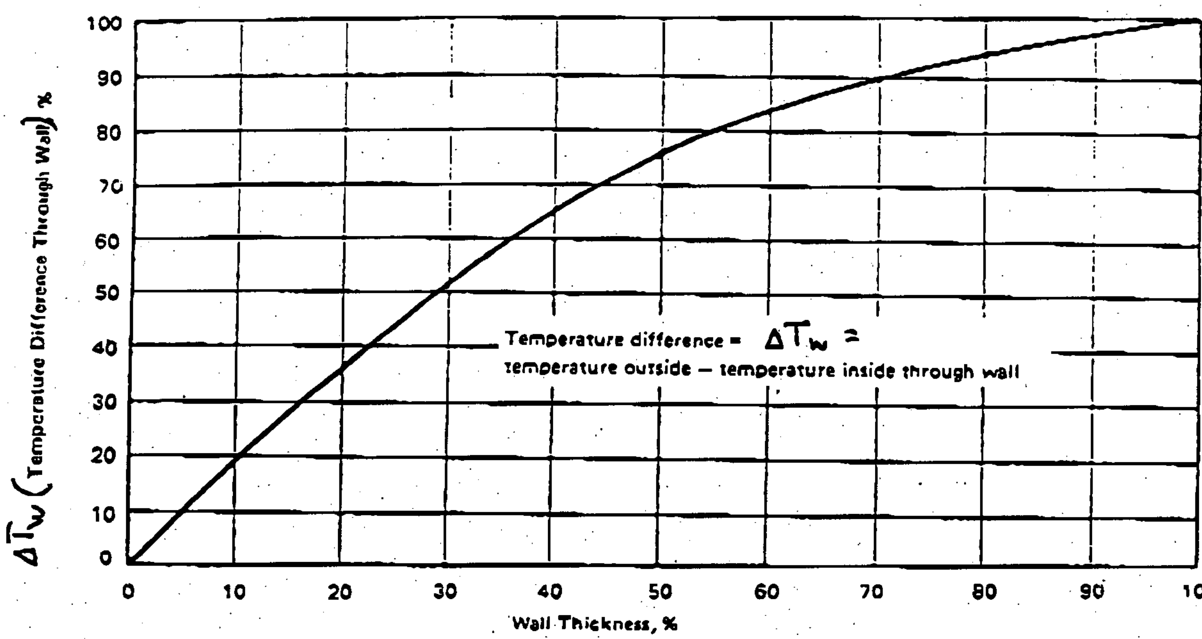

FIG. G-2214-2

throughout the life of the component at each temperature with K_{Im} from G-2214.1, K_{It} from G-2214.3, and K_{Ia} from Fig. G-2210-1.

Those plants having low temperature overpressure protection (LTOP) systems can use the following load and temperature conditions to provide protection against failure during reactor start-up and shutdown operation due to low temperature overpressure events that have been classified as Service Levels A or B events. LTOP systems shall be effective at coolant temperatures less than 200°F or at coolant temperatures corresponding to a reactor vessel metal temperature less than RT_{NDT} + 50°F, whichever is greater.[2,3] LTOP systems shall limit the maximum pressure in the vessel to 110% of the pressure determined to satisfy Eq. (1).

A93 [2]The coolant temperature is the reactor coolant inlet temperature.

A93 [3]The vessel metal temperature is the temperature at a distance one fourth of the vessel section thickness from the inside wetted surface in the vessel beltline region. RT_{NDT} is the highest adjusted reference temperature (for weld or base metal in the beltline region) at a distance one fourth of the vessel section thickness from the vessel wetted inner surface as determined by Regulatory Guide 1.99, Rev. 2.

G-2220 NOZZLES, FLANGES, AND SHELL REGIONS NEAR GEOMETRIC DISCONTINUITIES

G-2221 General Requirements

The same general procedure as was used for the shell and head regions in G-2210 may be used for areas where more complicated stress distributions occur, but certain modifications of the procedures for determining allowable applied loads shall be followed in order to meet special situations, as stipulated in G-2222 and G-2223.

G-2222 Consideration of Membrane and Bending Stresses

(a) Equation (1) of G-2215 requires modification to include the bending stresses which may be important contributors to the calculated K_I value at a point near a flange or nozzle. The terms whose sum must be $< K_{Ia}$ for normal and upset operating conditions are:

(1) $2K_{Im}$ from G-2214.1 for primary membrane stress;

(2) $2K_{Ib}$ from G-2214.2 for primary bending stress;

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(3) K_{Im} from G-2214.1 for secondary membrane stress;

(4) K_{Ib} from G-2214.2 for secondary bending stress.

(b) For purposes of this evaluation, stresses which result from bolt preloading shall be considered as primary.

(c) It is recommended that when the flange and adjacent shell region are stressed by the full intended bolt preload and by pressure not exceeding 20% of the preoperational system hydrostatic test pressure, minimum metal temperature in the stressed region should be at least the initial RT_{NDT} temperature for the material in the stressed regions plus any effects of irradiation at the stressed regions.

(d) Thermal ~~stresses shall be considered~~ as secondary except as provided in NB-~~3213.13(b)~~. The K_I of ~~Fig. G-2214-2~~ is ~~not~~ recommended for the evaluation of thermal stress. ~~because more complicated stress distributions are not adequately represented by the simplified approach of Fig. G-2214-2~~. G-2214.3(b)

G-2223 Toughness Requirements for Nozzles

(a) A quantitative evaluation of the fracture toughness requirements for nozzles is not feasible at this

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ATTACHMENT V

CALCULATIONS OF STRESS INTENSITY FACTORS

CONSOLIDATED EDISON COMPANY OF NEW YORK, INC.
INDIAN POINT UNIT NO. 2
DOCKET NO. 50-247
OCTOBER, 1996