

Westinghouse Non-Proprietary Class 3



**Reactor Vessel Closure  
Head/Vessel Flange  
Requirements Evaluation  
for Operating PWR and  
BWR Plants**

WCAP-15315



Westinghouse Electric Company, LLC

WCAP-15315

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## 1.0 INTRODUCTION

10 CFR Part 50, Appendix G contains requirements for pressure-temperature limits for the primary system, and requirements for the metal temperature of the closure head flange and vessel flange regions. The pressure-temperature limits are to be determined using the methodology of ASME Section XI, Appendix G, but the flange temperature requirements are specified in 10CFR50 Appendix G. This rule states that the metal temperature of the closure flange regions must exceed the material unirradiated  $RT_{NDT}$  by at least 120°F for normal operation when the pressure exceeds 20 percent of the pre-service hydrostatic test pressure, which is 621 psig for a typical PWR, and 300 psig for a typical BWR.

This requirement was originally based on concerns about the fracture margin in the closure flange region. During the boltup process, outside surface stresses in this region typically reach over 70 percent of the steady state stress, without being at steady state temperature. The margin of 120°F and the pressure limitation of 20 percent of hydrotest pressure were developed using the  $K_{Ic}$  fracture toughness, in the mid 1970s, to ensure that appropriate margins would be maintained.

Improved knowledge of fracture toughness and other issues which affect the integrity of the reactor vessel have led to the recent change to allow the use of  $K_{Ic}$  in the development of pressure-temperature curves, as contained in ASME Code Case N640, "Alternative Reference Fracture Toughness for Development of P-T Limit Curves for Section XI, Division 1".

Figure 1-1 illustrates the problem created by the flange requirements for a typical PWR heatup curve. It is easy to see that the heatup curve using  $K_{Ic}$  provides for a much higher allowable pressure through the entire range of temperatures. For this plant, however, the benefit is negated at temperatures below  $RT_{NDT} + 120^\circ\text{F}$  because of the flange requirement of 10 CFR Part 50, Appendix G. The flange requirement of 10 CFR 50 was originally developed using the  $K_{Ic}$  fracture toughness, and this report will show that use of the newly accepted  $K_{Ic}$  fracture toughness for flange considerations leads to the conclusion that the flange requirement can be eliminated.

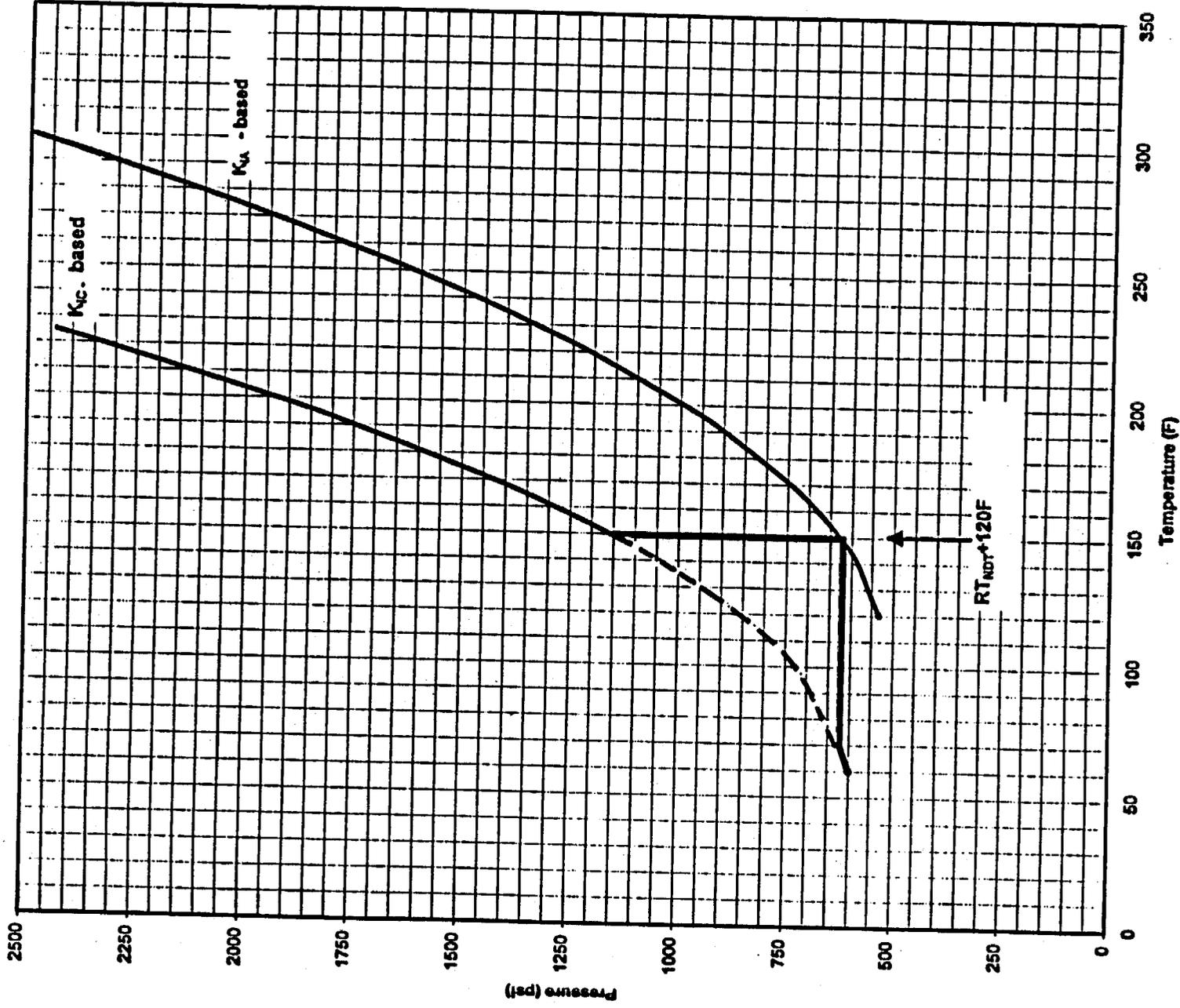


Figure 1-1 Illustration of the Impact of the Flange Requirement for a Typical PWR Plant

## 2.0 TECHNICAL APPROACH

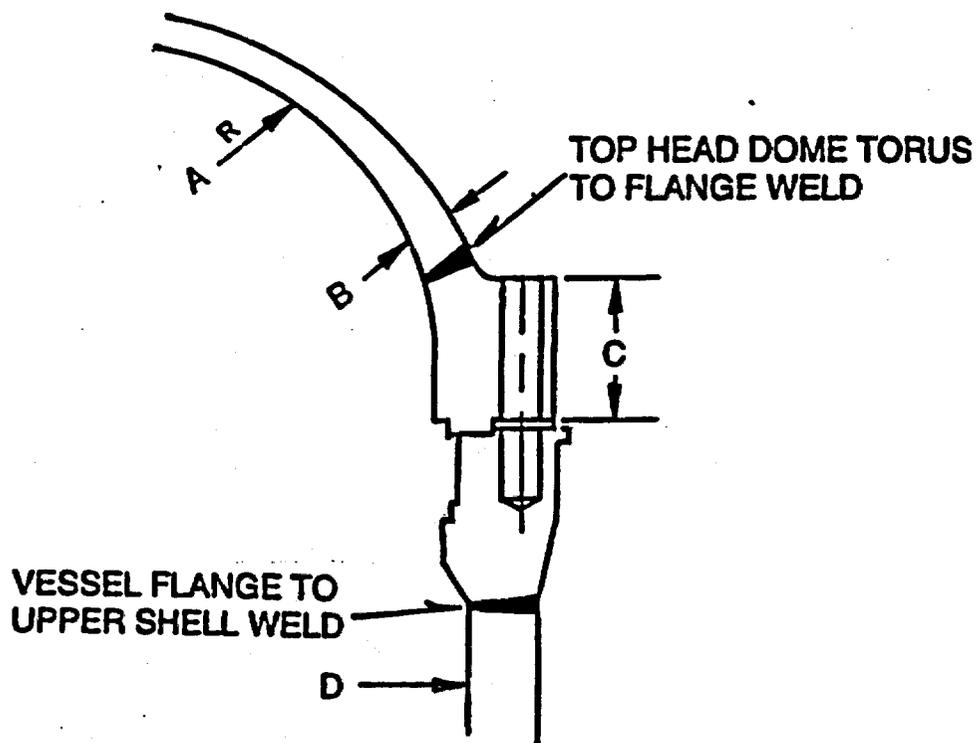
The evaluation to be presented here is intended to cover all operating light water reactor vessels. Fracture evaluations have been performed on the range of geometries which exist, and results will be tabulated and discussed.

The geometry of the closure head region for all the vessels analyzed are shown in Figures 2-1 through 2-4. The geometries for the various PWR vessels are similar, and the same is true for the various BWR vessels. This is also reflected in the stresses, as will be discussed further in Section 4.

Stress analyses have been performed on all of these designs, and these stress results were used to perform fracture mechanics evaluations. The highest stress location in the closure head and vessel flange region is in the head, just above the bolting flange. This corresponds with the location of a weld in nearly all the designs. The highest stressed location is near the outside surface of the head in that region, and so the fracture evaluations have assumed a flaw at this location.

The goal of the evaluation is to compare the integrity of the closure head during the boltup process to the integrity during steady state operation. The question to be addressed is: With the higher  $K_{Ic}$  fracture toughness now known to be applicable, is there still a concern about the integrity of the closure head during boltup?

<b>Plant Type</b>	<b>Head Thickness</b>	<b>Vessel Diameter</b>
Westinghouse 2 Loop	5.66"	132.4
3 Loop	5.75	155.5
4 Loop	7.0	178.9
B&W	6.63	168.4
Combustion Engineering	7.4	173.4
GE Design 1 (CE)	3.6	109.5
Design 2 (B&W)	4.0	122.4
Design 3 (CBI)	4.8	124.8



### UPPER HEAD REGION

	2 LOOP	3 LOOP	4 LOOP
A	83.46	74.59	85.78
B	5.66	5.75	7.00
C	27.56	29.56	27.25
D	132.40	155.50	170.88

NOTE: ALL DIMENSIONS ARE IN INCHES

**Figure 2-1** Geometry of the Upper Head/Flange Region of a Typical Westinghouse Four Loop Plant Reactor Vessel

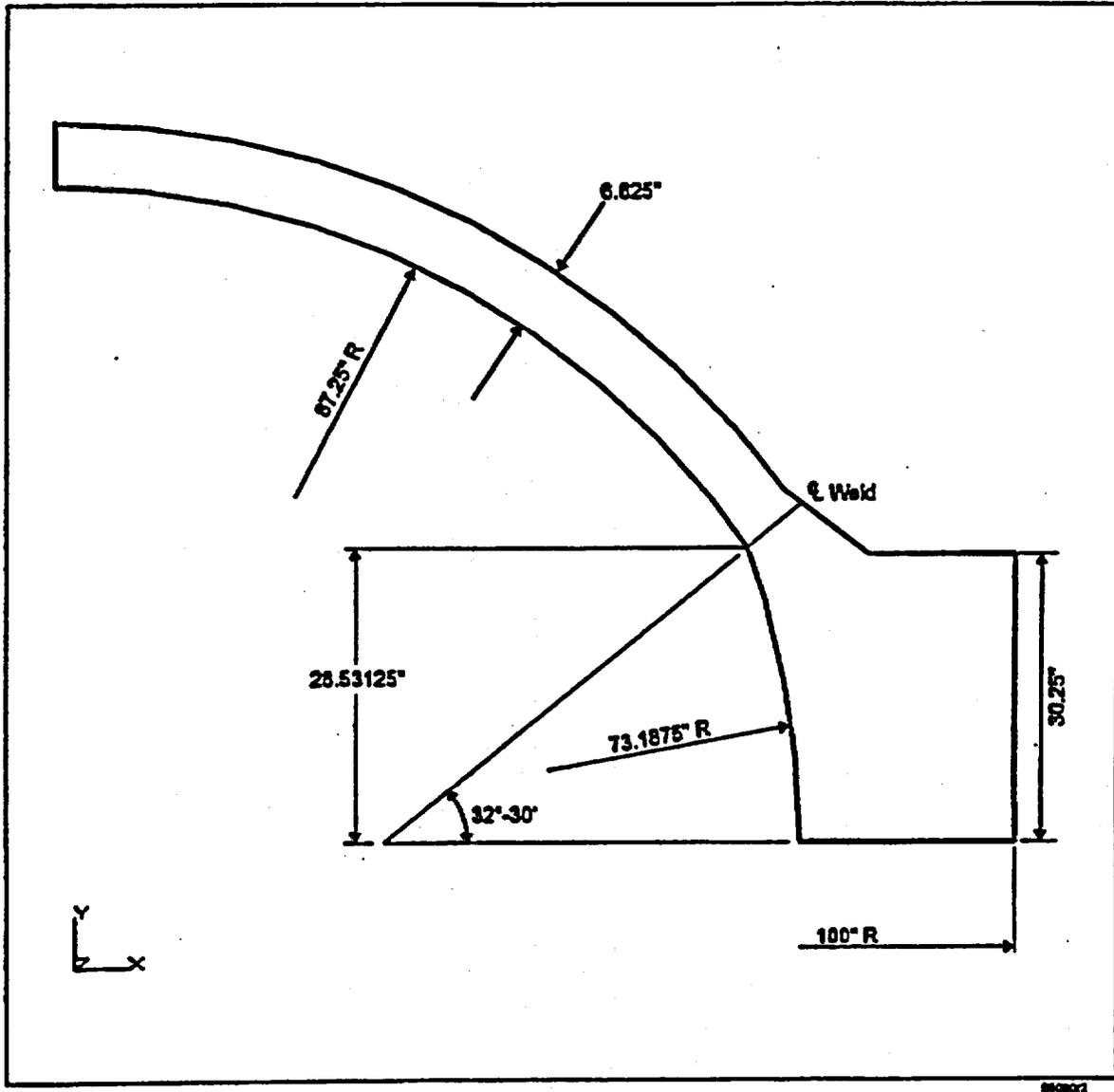


Figure 2-2 Geometry of Closure Head Region – Babcock and Wilcox Reactor Vessels

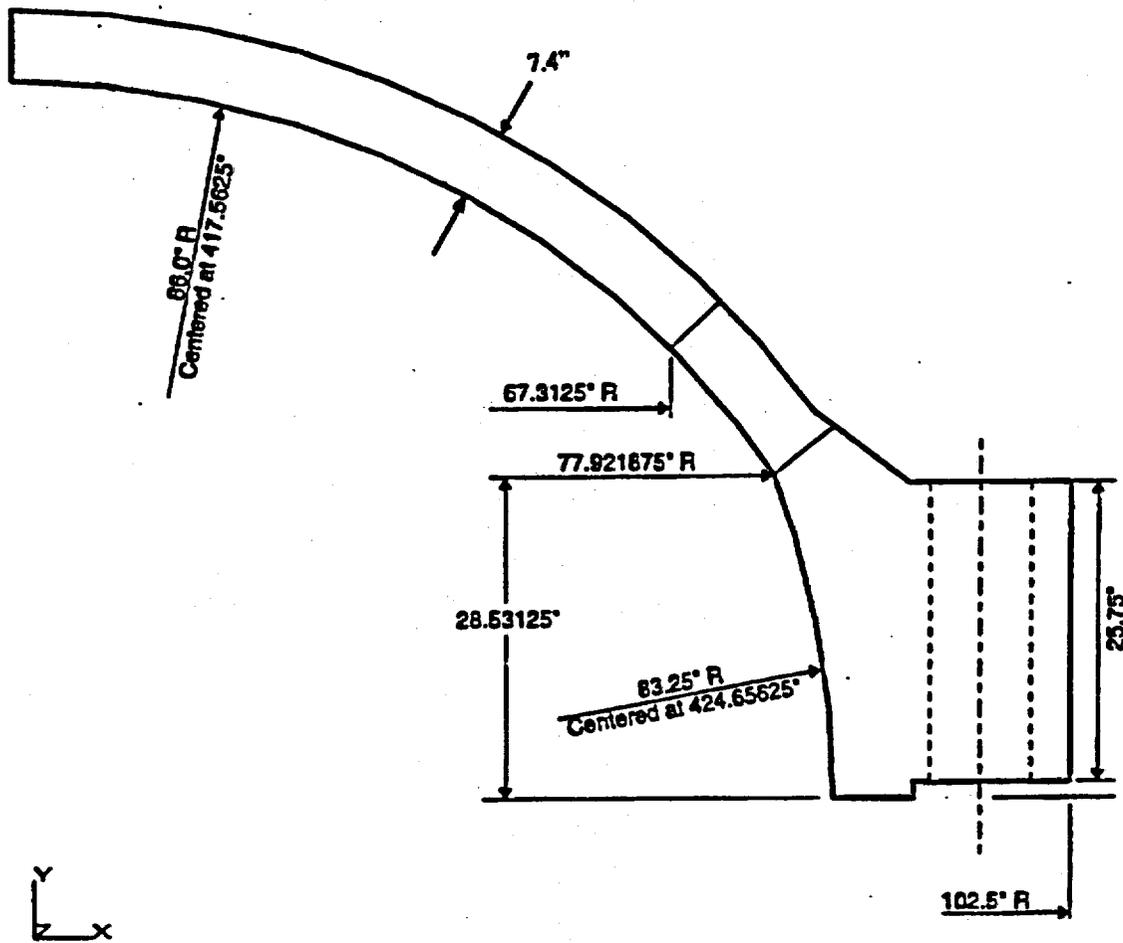
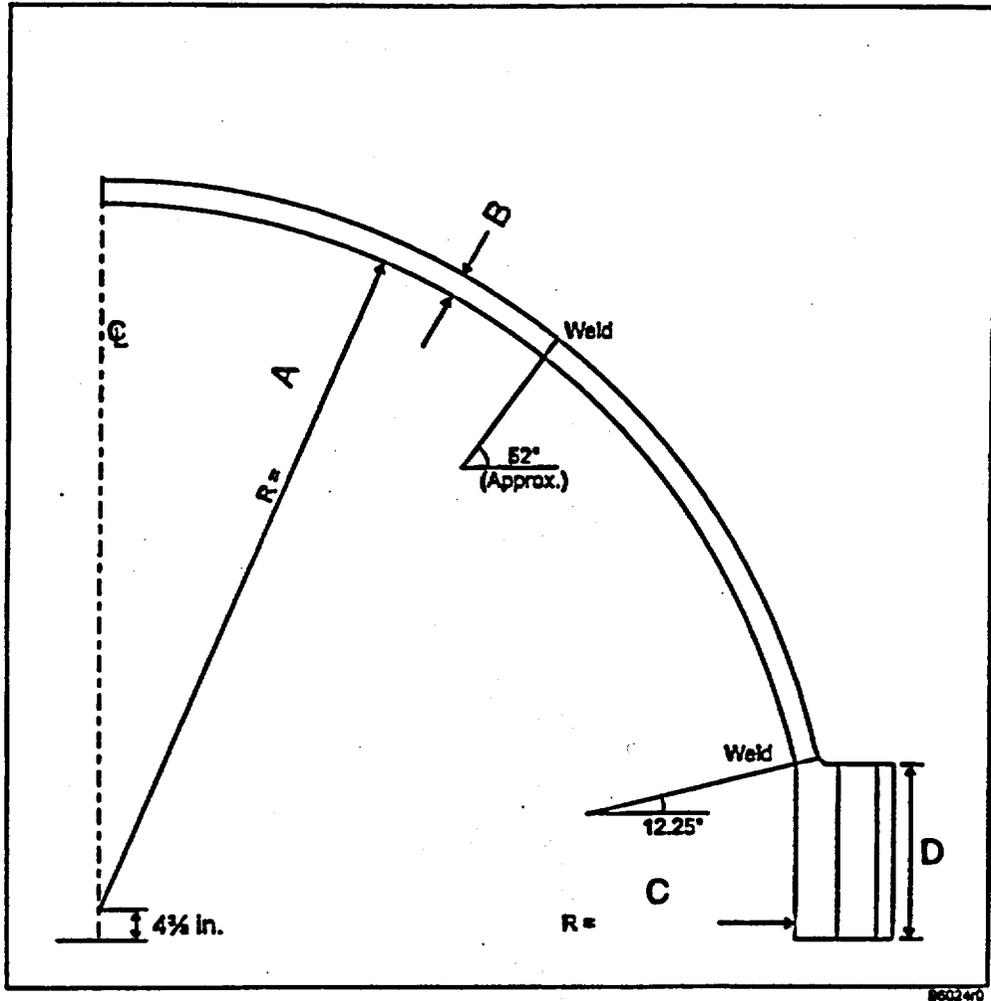


Figure 2-3 Geometry of Closure Head Region: Combustion Engineering Reactor Vessels



	CE	B&W	CB&I
A	109.5	125.6	124.8
B	3.6	4.0	4.8
C	109.5	122.4	124.8
D	24.4	31.0	28.2

NOTE: ALL DIMENSIONS ARE IN INCHES

Figure 2-4 Geometry of Closure Head Region: General Electric Reactor Vessels

### 3.0 FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

The fracture evaluation was carried out using the approach suggested by Section XI Appendix G.[1] A semi-elliptic surface flaw was postulated to exist in the highest stress region, which is at the outside surface of the closure flange. The flaw depth was set at 25 percent of the wall thickness, and the shape was set at a length six times the depth.

#### 3.1 STRESS INTENSITY FACTOR CALCULATIONS

One of the key elements of a fracture evaluation is the determination of the driving force or stress intensity factor ( $K_I$ ). This was done using expressions available from the literature. In most cases, the stress intensity factor for the integrity calculations utilized a representation of the actual stress profile rather than a linearization. The stress profile was represented by a cubic polynomial:

$$\sigma(x) = A_0 + A_1 \frac{x}{t} + A_2 \left(\frac{x}{t}\right)^2 + A_3 \left(\frac{x}{t}\right)^3 \quad (3-1)$$

where

$x$	=	is the coordinate distance into the wall, in.
$t$	=	wall thickness, in.
$\sigma$	=	stress perpendicular to the plane of the crack, ksi
$A_i$	=	coefficients of the cubic fit

For the surface flaw with length six times its depth, the stress intensity factor expression of Raju and Newman [2] was used when a complete stress distribution was available. The stress intensity factor  $K_I(\phi)$  can be calculated anywhere along the crack front. The point of maximum crack depth is represented by  $\phi = 0$ , and this location was found to also be the point of maximum  $K_I$  for the cases considered here. The following expression is used for calculating  $K_I(\phi)$ , where  $\phi$  is the angular location around the crack. The units of  $K_I(\phi)$  are  $\text{ksi}\sqrt{\text{in}}$ .

$$K_I(\phi) = \left[ \frac{\pi a}{Q} \right]^{0.5} \sum_{j=1}^4 G_j(a/c, a/t, t/R, \phi) A_j a^j \quad (3-2)$$

The magnification factors  $G_1(\phi)$ ,  $G_2(\phi)$ ,  $G_3(\phi)$  and  $G_4(\phi)$  are obtained by the procedure outlined in reference [2]. The dimension "a" is the crack depth, and "c" is the crack length, while t is the wall thickness. In some cases only surface stress values were available, and in these cases the stresses were linearized through the thickness of the head, and the Raju-Newman expression was used.

#### 3.2 FRACTURE TOUGHNESS

The other key element in a fracture evaluation is the fracture toughness of the material. The fracture toughness has been taken directly from the reference curves of Appendix A, Section XI.

In the transition temperature region, these curves can be represented by the following equations:

$$K_{Ic} = 33.2 + 20.734 \exp. [0.02 (T - RT_{NDT})] \quad (3-4)$$

$$K_{Ia} = 26.8 + 12.445 \exp. [0.0145 (T - RT_{NDT})] \quad (3-5)$$

where  $K_{Ic}$  and  $K_{Ia}$  are in  $\text{ksi}\sqrt{\text{in}}$ .

The upper shelf temperature regime requires utilization of a shelf toughness which is not specified in the ASME Code. A value of  $200 \text{ ksi}\sqrt{\text{in}}$  has been used here for all the regions except the nozzle inner radius regions, since the upper shelf Charpy energy exceeds 50 ft-lb, even after irradiation. This value is consistent with general practice in such evaluations, as shown for example in reference [3], which provides the background and technical basis of Appendix A of Section XI.

The other key element in the determination of the fracture toughness is the value of  $RT_{NDT}$ , which is a parameter determined from Charpy V-notch and drop-weight tests.

The value of  $RT_{NDT}$  for the closure flange region of operating PWR plants was surveyed for 82 PWR plants world wide, and the average value of  $RT_{NDT}$  was found to be  $9^\circ\text{F}$ . The results ranged from  $-50^\circ\text{F}$  to  $+60^\circ\text{F}$ , with the  $60^\circ\text{F}$  cases representing the few cases where a test result was not available or the maximum allowed by the ordering requirement. For the head region of operating BWR plants, results ranged up to  $40^\circ\text{F}$ , which was the ordering requirement, while the average value of  $RT_{NDT}$  was found to be  $10^\circ\text{F}$ . Therefore, the value of  $10^\circ\text{F}$  was used for the illustrations to be discussed in Sections 4 and 5.

### 3.3 IRRADIATION EFFECTS

Neutron irradiation has been shown to produce embrittlement which reduces the toughness properties of reactor vessel steels. The decrease in the toughness properties can be assessed by determining the shift to higher temperatures of the reference nil-ductility transition temperature,  $RT_{NDT}$ .

The location of the closure flange region is such that the irradiation levels are very low and therefore the fracture toughness is not measurably affected.

## 4.0 FLANGE INTEGRITY

The first step in evaluation of the closure head/flange region is to examine the stresses. The stresses which are affected by the boltup event are the axial, or meridional stresses, which are perpendicular to the nominal plane of the closure head to flange weld. The stresses in this region during steady state operation are summarized in Table 4-1.

The table shows that the stresses in the various PWR designs are very similar during steady state operation, and stresses are not very high. The loadings are primarily membrane stress, and the bending stresses are somewhat lower. For the BWR designs, the membrane stress is very similar, as might be expected from use of the same design code. The bending stresses are higher for the BWR designs, due to the larger diameter and smaller thickness.

Table 4-2 provides a comparison of the stresses at boltup with those at steady state. It is easy to see that the stresses at boltup are mostly bending, with a very small membrane stress. As the vessel is pressurized, the membrane stresses increase.

The relative impact of these stresses can best be addressed through a fracture evaluation. A semi-elliptic surface flaw was postulated at the outer surface of the closure head flange, and the stress intensity factor,  $K$ , (or crack driving force) was calculated. The results are shown for the boltup condition in Figures 4-1 and 4-2. Figure 4-1 shows the results for the governing PWR design (B&W), while Figure 4-2 shows the results for the governing BWR design (B&W, 251 inches). In both cases it can be seen that the applied stress intensity factor at boltup reaches a maximum for a flaw about half way through the head thickness, and then decreases as the flaw extends into the lower stress region near the inside surface of the head. The maximum value of the stress intensity factor for each of the designs is tabulated in Table 4-3, and plots for each of the other design cases appear in the Appendix.

Also shown in Table 4-3 is the fracture toughness at boltup for typical PWR and BWR plants. The boltup temperature for a PWR is typically 60°F, while the boltup temperature for a BWR is typically 80°F. Since we know that the average value of  $RT_{NDT}$  is 10°F for all the plants, both the  $K_{Ic}$  and  $K_{Ia}$  values are easily calculated.

Study of Table 4-3 shows the difference in the integrity story using the two values of fracture toughness. Using the  $K_{Ia}$  toughness (which was the basis for the original flange requirements) it can be seen that the applied stress intensity factor exceeds the toughness for two cases, cases 2 and 6, for flaws about half way through the head thickness.

Using the  $K_{Ic}$  toughness, which has now been adopted by Section XI for P-T Curves, it can be seen that there is significant margin between the applied stress intensity factor and the fracture toughness at virtually all crack depths. Another objective of the requirements in Appendix G is to assure that fracture margins are maintained to protect against service induced cracking due to environmental effects. Since the governing flaw is on the outside surface (the inside is in compression) where there are no environmental effects, there is even greater assurance of fracture margin. Therefore it may be concluded that the integrity of the closure head/flange region is not a concern for any of the operating plants using the  $K_{Ic}$  toughness.

Furthermore, there are no known mechanisms of degradation for this region, other than fatigue. The calculated design fatigue usage for this region is less than 0.1, so it may be concluded that flaws are unlikely to initiate in this region.

**Table 4-1 Axial Stress Comparison Steady State Operation @ 2250 psi (PWR),  
1000 psi (BWR)**

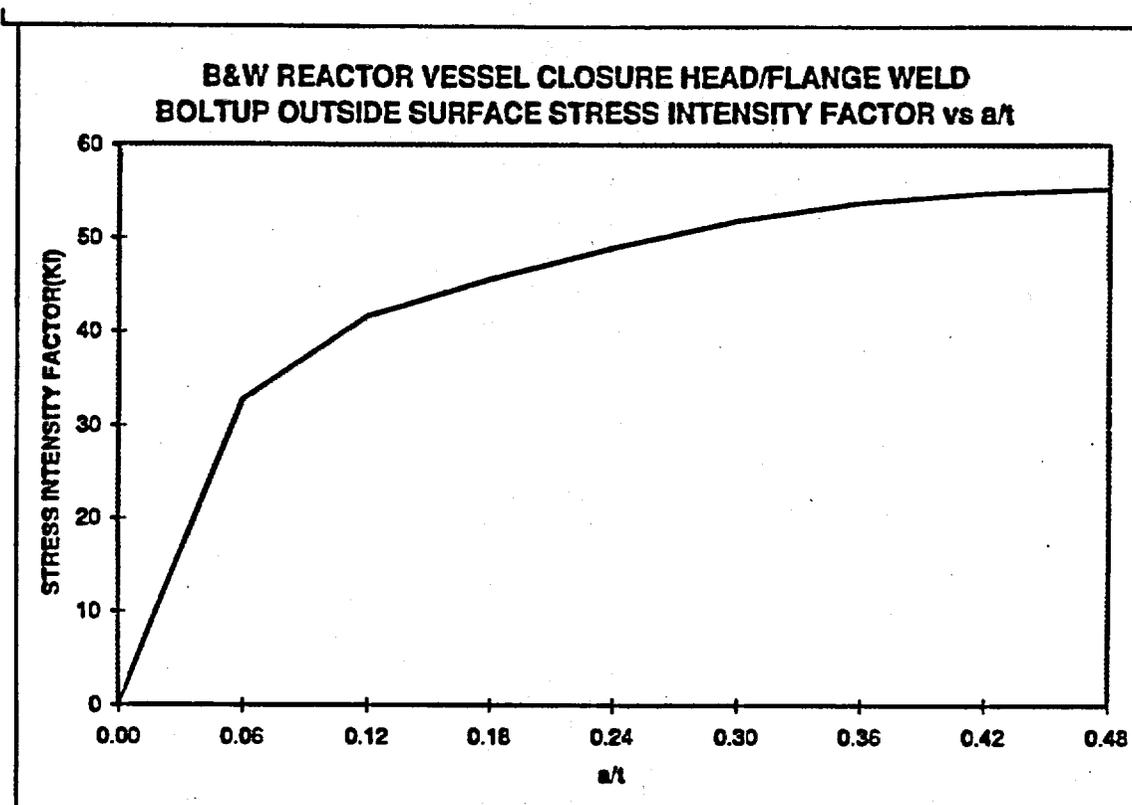
Plant	OD Stress (ksi)	Membrane Stress (ksi)	Bending Stress (ksi)
W 4 Loop	22.8	10.0	12.8
W 3 Loop	20.9	11.6	9.3
CE	46.4	12.8	33.6
B&W	55.7	19.0	36.7
GE BWR Design 1 (CE)	49.6	18.0	31.6
GE BWR Design 2 (B&W)	53.0	15.5	37.5
GE BWR Design 3 (CBI)	52.5	14.3	38.2

**Table 4-2 Stress Comparison Boltup vs. Steady State**

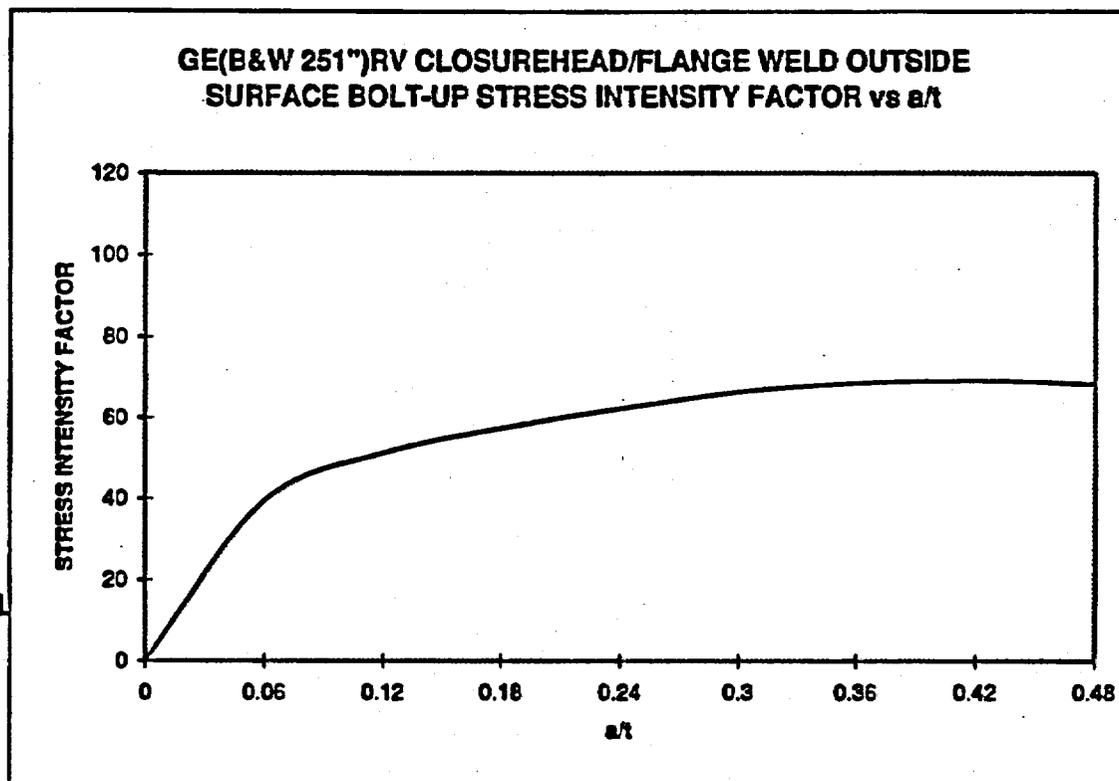
Plant	Boltup Membrane (ksi)	Boltup Bending (ksi)	SS Membrane (ksi)	SS Bending (ksi)
W 4 Loop	1.1	14.2	10.0	12.8
W 3 Loop	2.1	14.5	11.6	9.3
CE	0.8	22.8	12.8	33.6
B&W	4.3	27.6	19.0	36.7
GE BWR Design 1 (CE)	0.8	26.3	18.0	31.6
GE BWR Design 2 (B&W)	0.5	48.5	15.5	37.5
GE BWR Design 3 (CBI)	0.5	35.5	14.3	38.2

<b>Table 4-3 Flange Integrity Results at Boltup</b>			
<b>Design</b>	<b>Maximum K, in <math>\text{ksi}\sqrt{\text{in}}</math> (Flaw Depth/Thickness)</b>	<b>Fracture Toughness at Boltup*</b>	
		<b><math>K_{Ic}</math> (<math>\text{ksi}\sqrt{\text{in}}</math>)</b>	<b><math>K_{Ic}</math> (<math>\text{ksi}\sqrt{\text{in}}</math>)</b>
1. CE	41 (.42)	52.7	89.6
2. B&W	56 (.60)	52.7	89.6
3. W Four Loop	31 (.44)	52.7	89.6
4. W Three Loop	32 (.44)	52.7	89.6
5. GE BWR (CBI 251)	56 (.42)	61.4	117.3
6. GE BWR (B&W 251)	69 (.40)	61.4	117.3
7. GE BWR (CE 218)	37 (.42)	61.4	117.3

\*Boltup is typically at 60°F for PWRs, and 80°F for BWRs.



**Figure 4-1. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for the Governing PWR Design**



**Figure 4-2. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld, for the Governing BWR Design**

## 5.0 ARE FLANGE REQUIREMENTS NECESSARY?

Using the  $K_{Ic}$  curve can support the elimination of the flange requirement. This can be illustrated by examining the stress intensity factor change for a postulated flaw as the vessel is pressurized after boltup, progressing up to steady state operation.

The stresses at the region of interest are shown in Table 4-1, for steady state operation. Included here are the stresses at the outside surface, which is the highest stress location for this region, as well as the membrane and bending stresses. Table 4-2 shows a comparison of the boltup and steady state stresses for the same plant designs. The results are similar for the designs shown, which bracket all plants in service. No comparisons are available for two loop Westinghouse plants, but they are conservatively covered by the four loop Westinghouse plant results.

As the vessel is pressurized, the stresses in the closure flange region gradually change from mostly bending stresses to a combination of bending and membrane stresses. The stress intensity factor, or driving force, increases for a postulated flaw at the outside surface, as the vessel is pressurized.

As mentioned in Section 4, the boltup temperature for a PWR is nominally 60°F, while that for a BWR is nominally 80°F. From Section 3, the average value of  $RT_{NDT}$  for the closure head material is 10°F for all the designs, so boltup is typically at  $RT_{NDT} + 50$  for PWRs, and  $RT_{NDT} + 70$ °F for BWRs.

A direct comparison between the original basis for the boltup requirement and the new  $K_{Ic}$  approach is provided in Table 5-1. This table provides calculated boltup requirements for all the designs, using a safety factor of 2, and a reference flaw depth of  $a/t = 0.10$ , which was used by Randall as the basis for the original requirement [4]. The boltup requirements using  $K_{Ic}$  are shown in the right-most column, and the governing case would have a boltup requirement of  $RT_{NDT} + 118$ °F, which closely matches the requirement of  $RT_{NDT} + 120$ °F now in 10CFR50 Appendix G.

Now consider the equivalent result using  $K_{Ic}$ , which is just to the left of the column just discussed. The boltup requirement using the same margin now ranges from  $RT_{NDT}$  to  $RT_{NDT} + 41$ F for PWR plants, and from  $RT_{NDT}$  to  $RT_{NDT} + 56$  for BWR plants. Since the average value of  $RT_{NDT}$  is 10°F for all the plants, the boltup requirements can be easily translated into actual temperatures. For PWRs the requirement for boltup ranges from 10°F to 51°F, and the actual boltup temperature is 60°F. For BWRs the requirement ranges from 10°F to 66°F, and the actual boltup temperature is 80°F. It is therefore clear that no additional boltup requirements are necessary, and therefore the requirement can be eliminated from 10CFR50 Appendix G.

**Table 5-1 Comparison of Various Plant Designs Boltup Requirements**

Plant	K (a/t = .1)	K with SF = 2	T - RT <sub>NTD</sub> (°F) using K <sub>L</sub> (a/t = .10)	T - RT <sub>NTD</sub> (°F) using K <sub>L</sub> (a/t = .10)
CE	30.0	60.0	13	68
B&W	39.4	79.8	41	100
W 4 Loop	19.7	39.4	0	1
W 3 Loop	19.4	38.8	0	0
GE (CBI 251")	38.7	77.4	38	97
GE (B&W 251")	48.0	96.0	56	118
GE (CE 218")	25.1	50.2	0	43

\*All units in ksi√in

## 6.0 SAFETY IMPLICATIONS OF THE FLANGE REQUIREMENT

There are important safety implications which are associated with the flange requirement, as illustrated by Figure 6-1. The safety concern is the narrow operating window at low temperatures forced by the flange requirement. The flange requirement sets a pressure limit of 621 psi for a PWR (20 percent of hydrotest pressure). Thus, no matter how good the toughness of the vessel, the P-T limit curve may be superceded by the flange requirement for temperatures below  $RT_{NDT} + 120^{\circ}\text{F}$ . This requirement was originally imposed to ensure the integrity of the flange region during boltup, but Section 4 has shown that this is no longer a concern.

The flange requirement can cause severe operational limitations when instrument uncertainties are added to the lower limit (621 psi), for the Low Temperature Overpressure Protection system of PWRs. The minimum pressure required to cool the seals of the main coolant pumps is 325 psi, so the operating window sometimes becomes very small, as shown schematically in Figure 6-1. If the operator allows the pressure to drop below the pump seal limit, the seals could fail, causing the equivalent of a small break LOCA, a significant safety problem. Elimination of the flange requirement will significantly widen the operating window for most PWRs.

An example will be provided to illustrate this situation for an operating PWR plant, Byron Unit 1. This is a forging-limited vessel at 12 EFY, with a low leakage core, and low copper weld material in the core region. The vessel has excellent fracture toughness, which means that the flange notch is very prominent, as shown in the vessel heatup curve of Figure 6-2. As illustrated before in Figure 6-1, Byron has the LTOP setpoints significantly below the flange requirement of 621 psi, because of a relatively large instrument uncertainty. The setpoints of the two power operated relief valves are staggered by about 16 psi to prevent a simultaneous activation. The two PORVs have different instrument uncertainties, and for conservatism the higher uncertainty is used. A similar situation exists for cooldown, as shown in Figure 6-3.

Elimination of the flange requirement for Byron Unit 1 would mean that the PORV curve could become level at 604/587 psig, which are the leading/trailing setpoints to protect the PORV downstream piping, through the temperature range of the  $350^{\circ}\text{F}$  down to boltup at  $60^{\circ}\text{F}$ . The operating window between the leading PORV and the pump seal limit rises from 121 psig (446-325) to 262 psig (587-325). This change will make a significant improvement in plant safety by reducing the probability of a small LOCA, and easing the burden on the operators.

This is only one example of the impact of the flange requirement. Every operating PWR plant will have a different situation, but the operational safety level will certainly be generally improved by the elimination of this unnecessary requirement.

Elimination of the flange requirement has no impact on BWRs. The saturation temperature corresponding to the 300 psig operating pressure (20% of the pre-service hydrostatic test pressure) is  $420^{\circ}\text{F}$ . This is well in excess of the  $RT_{ndt} + 120^{\circ}\text{F}$  requirement. Therefore the flange temperature requirements are satisfied regardless of whether they exist or not. Therefore, elimination of the flange temperature requirement has no impact on BWR flange integrity.

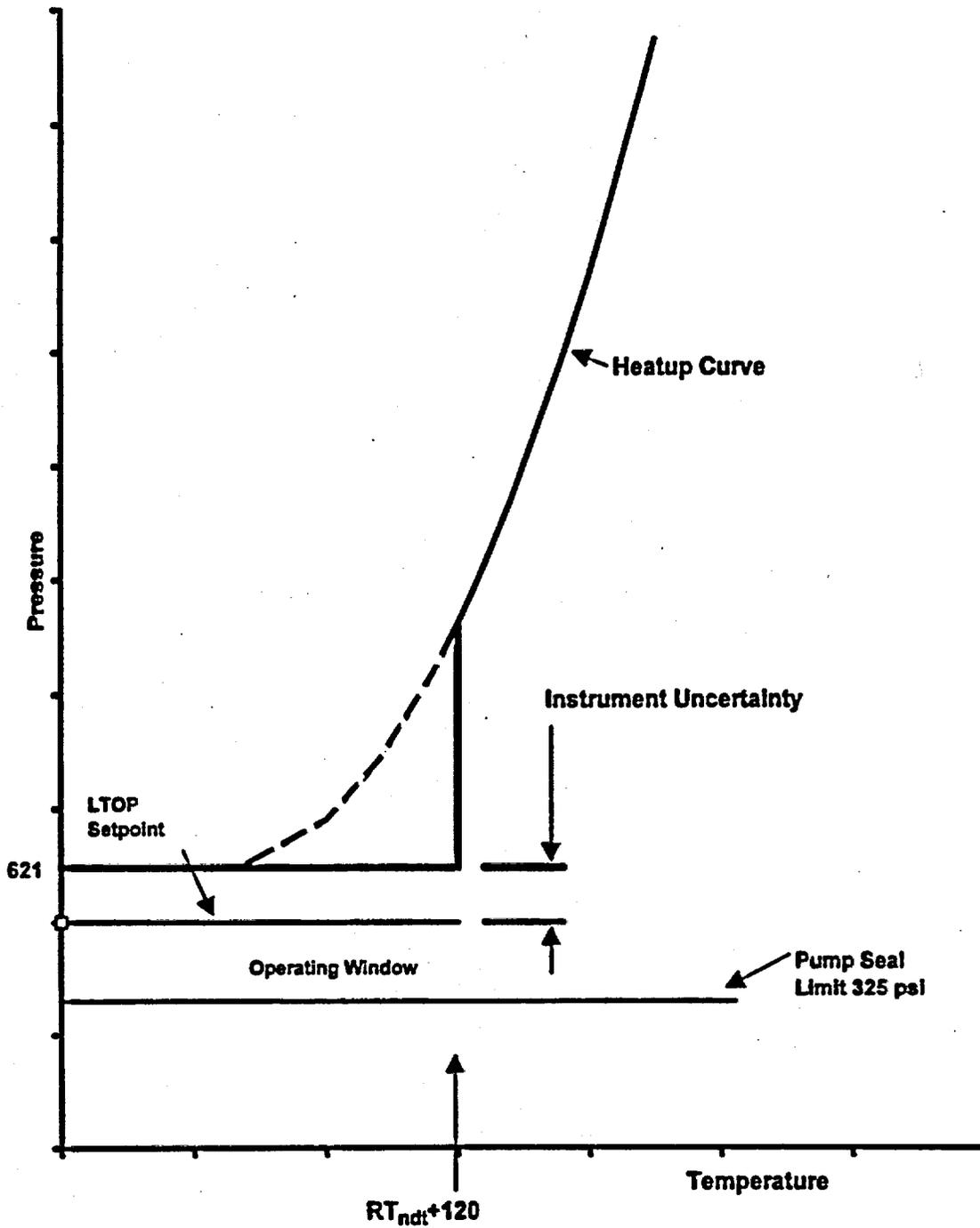


Figure 6-1 Illustration of the Flange Requirement and its Effect on the Operating Window for a Typical Heatup Curve

LIMITING MATERIAL: INTERMEDIATE SHELL FORGING 5P-5933 (using surv. capsule data)  
 LIMITING ART VALUES AT 12 EFY: 1/4T, 70°F  
 3/4T, 60°F

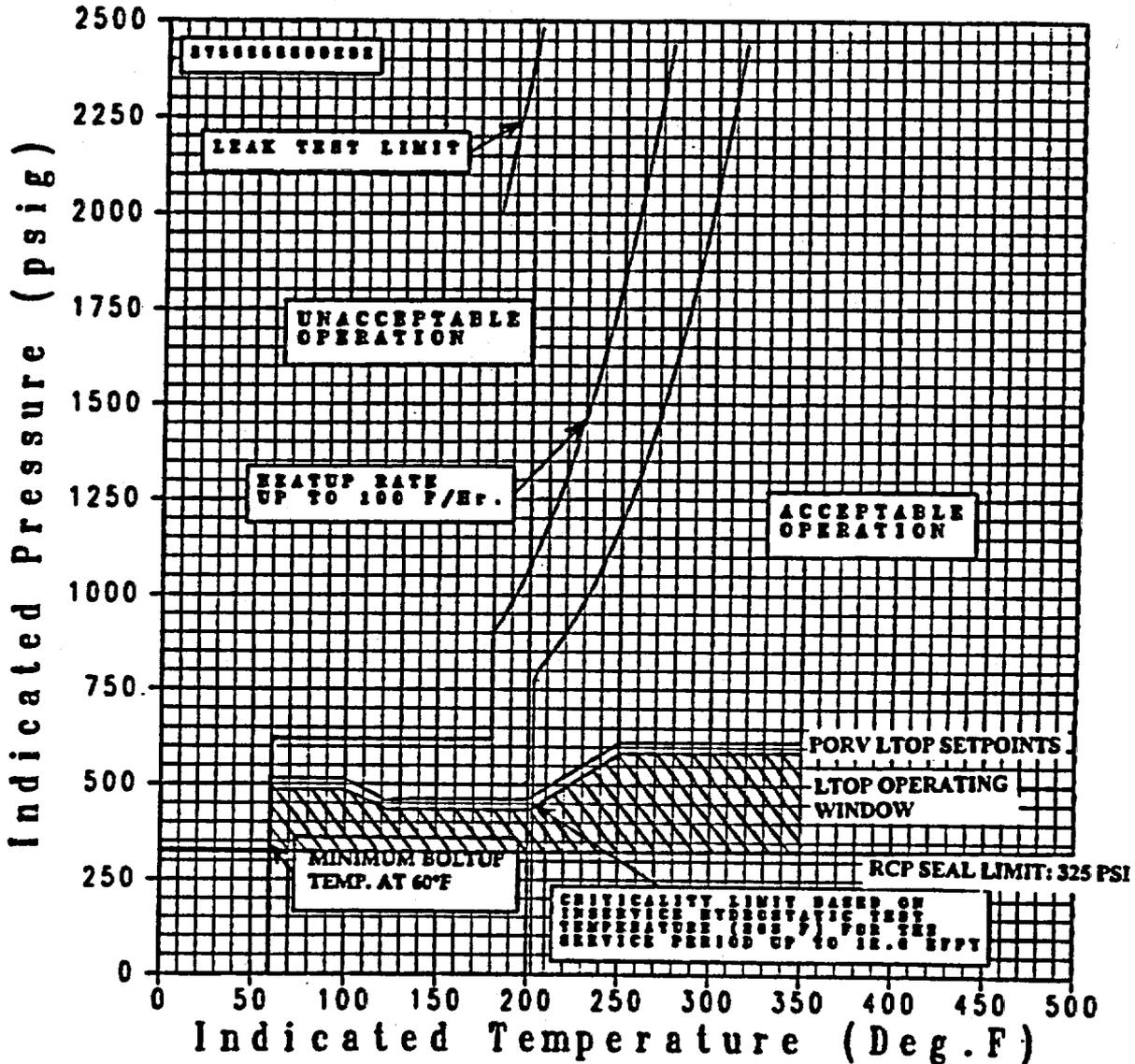


Figure 6-2 Illustration of the Actual Operating Window for Heatup of Byron Unit 1, a Low Copper Plant at 12 EFY

LIMITING MATERIAL: INTERMEDIATE SHELL FORGING 5P-5933 (using surv. capsule data)  
 LIMITING ART VALUES AT 12 EFY: 1/4T, 70°F  
 3/4T, 60°F

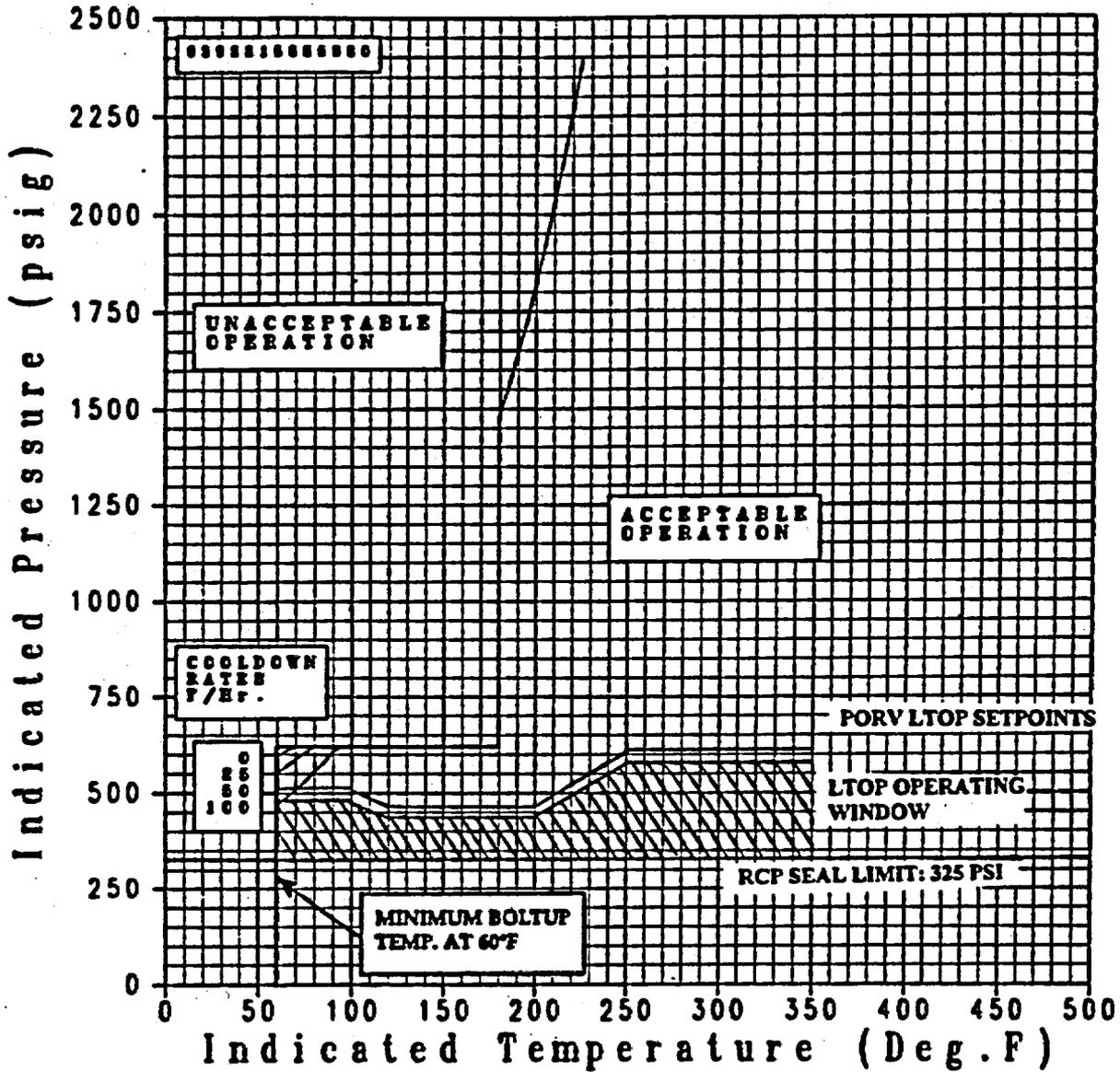


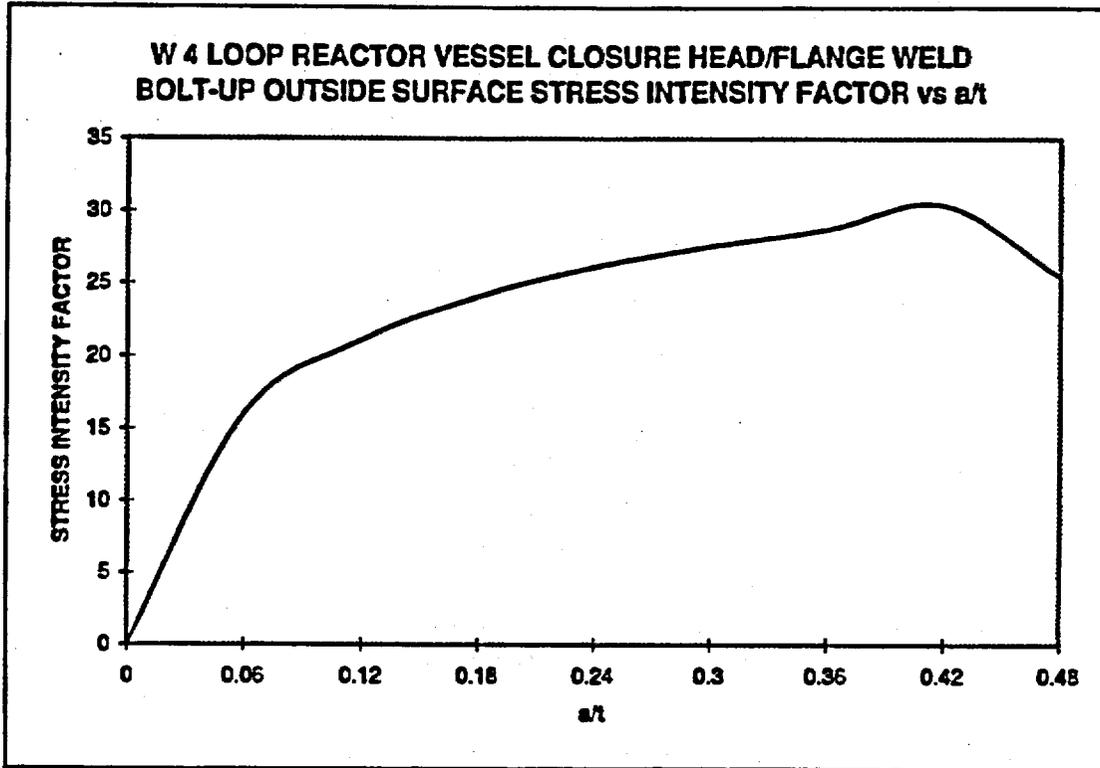
Figure 6-3 Illustration of the Actual Operating Window for Cooldown of Byron Unit 1, a Low Copper Plant at 12 EFY

## 7.0 REFERENCES

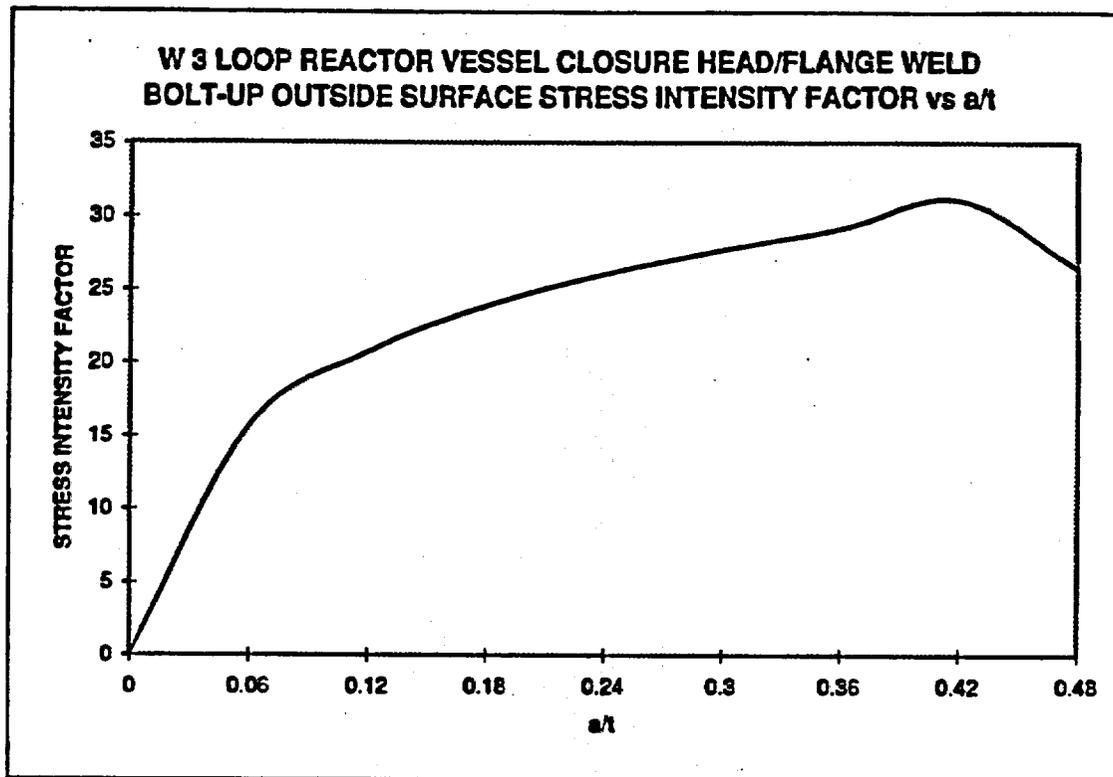
1. ASME Boiler and Pressure Vessel Code, Section XI, Appendix G, 1996 Addenda, ASME, New York.
2. Newman, J. C. Jr. and Raju, I. S., "Stress Intensity Factors for Internal Surface Cracks in Cylindrical Pressure Vessels," Trans. ASME, Journal of Pressure Vessel Technology, Vol. 102, 1980, pp 342-346.
3. Marston, T. U., ed., "Flaw Evaluation Procedures: ASME Section XI," Electric Power Research Institute Report EPRI-NP-719 SR, August 1978.
4. Randall, N., Abstract of Comments and Staff Response to Proposed Revision to 10 CFR Part 50, Appendices G and H, Published for Comment in the Federal Register, November 14, 1980.

**Appendix 1**

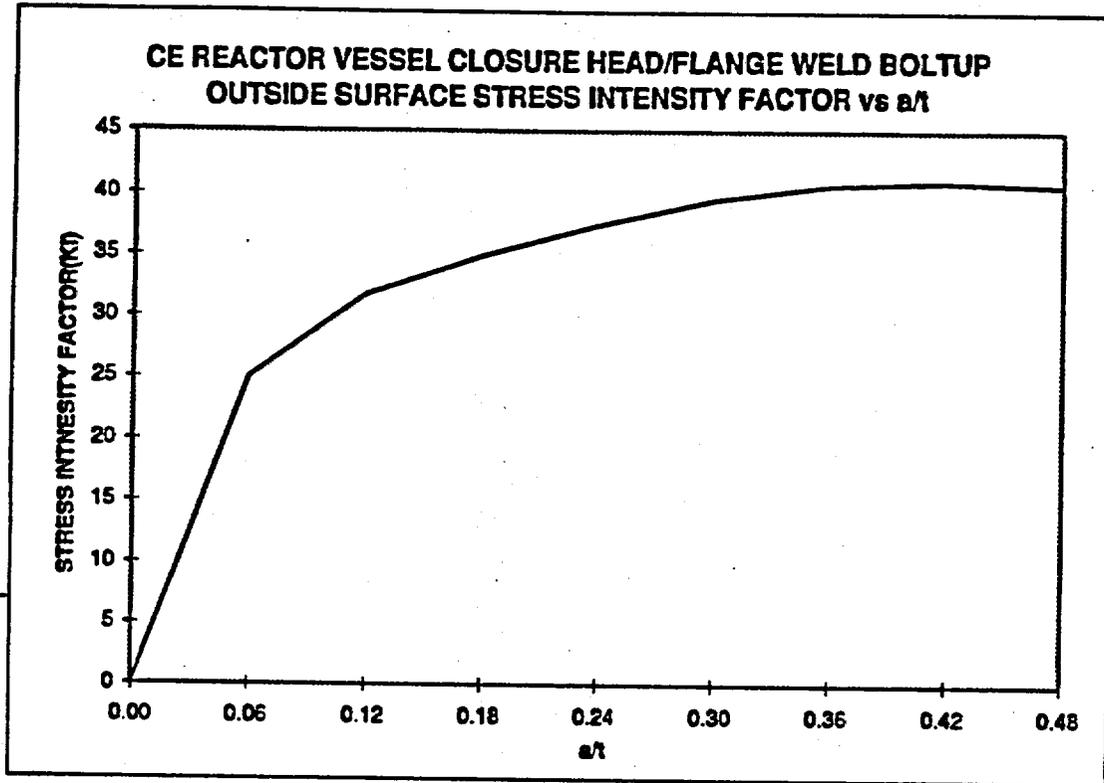
**Stress Intensity Factor Curves for the Boltup Condition**



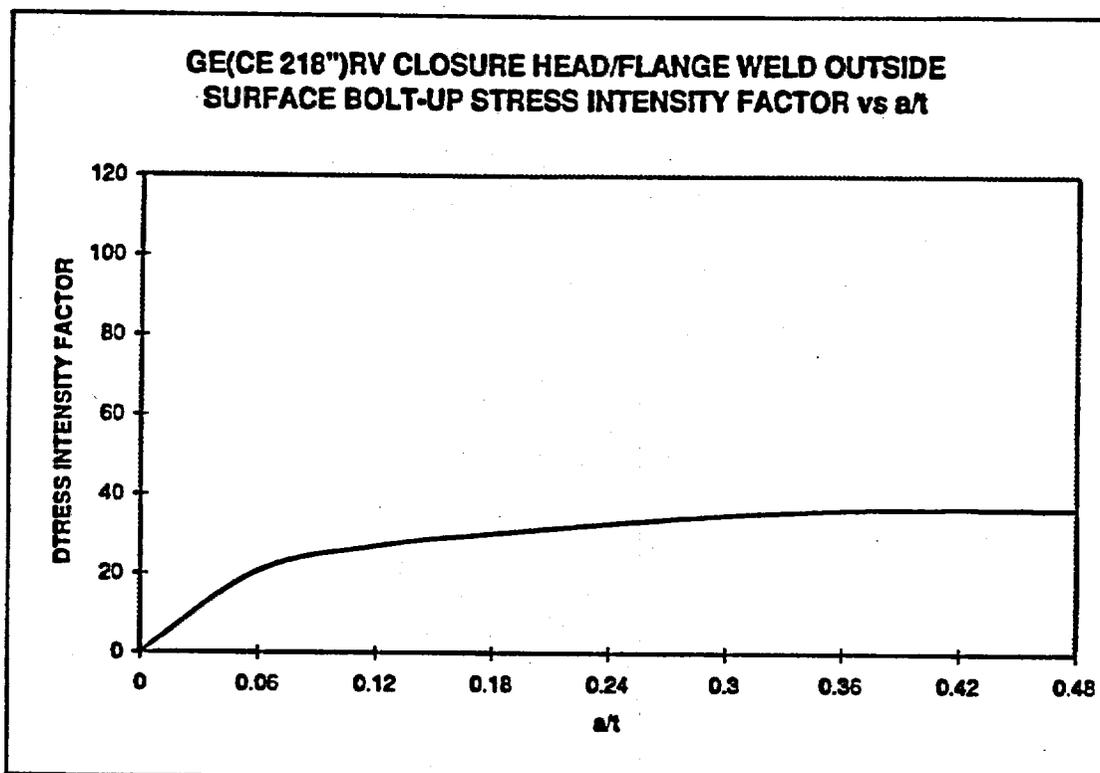
**Figure A-1. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for the Westinghouse Four Loop Plant Design**



**Figure A-2. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for the Westinghouse Three Loop Plant Design**



**Figure A-3. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for the Combustion Engineering Design**



**Figure A-4. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for the General Electric - CE Fabricated Design**

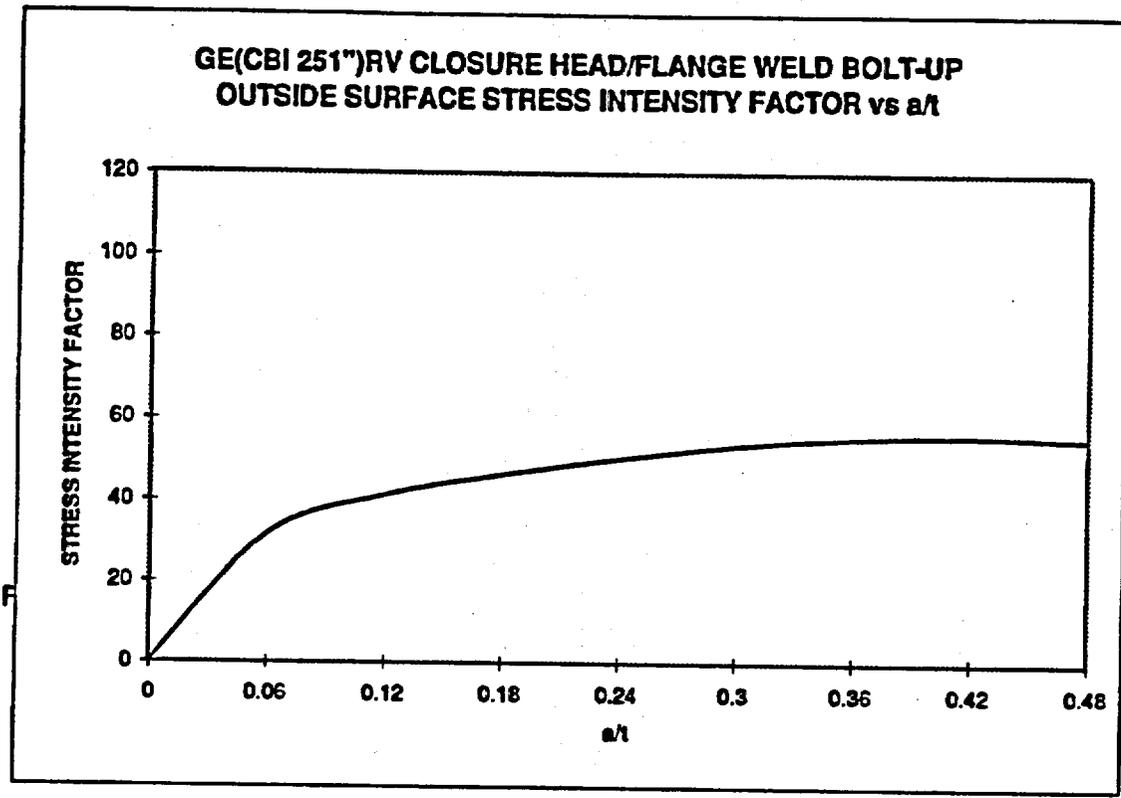


Figure A-5. Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for the General Electric - CBI Fabricated Design