ENCLOSURE 3

TENNESSEE VALLEY AUTHORITY

SEQUOYAH NUCLEAR PLANT (SQN) UNITS 1 AND 2

DOCKET NOS. 50-327 AND 50-328

WESTINGHOUSE ELECTRIC COMPANY

WCAP-15984-NP, REVISION 1

(NON-PROPRIETARY VERSION)

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April 2003

Reactor Vessel Closure Head/Vessel Flange Requirements Evaluation for Sequoyah Units 1 and 2

Westinghouse

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Reactor Vessel Closure Head/Vessel Flange Requirements Evaluation for Sequoyah Units 1 and 2

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April 2003

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1 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_{Ia} 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°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_{Ia} 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 for Sequoyah Units 1 and 2.

Revision 1

Revision 1 of this report was prepared to provide more details of the stress analysis performed, and to provide a detailed discussion of the effects of thermal aging on closure head materials.

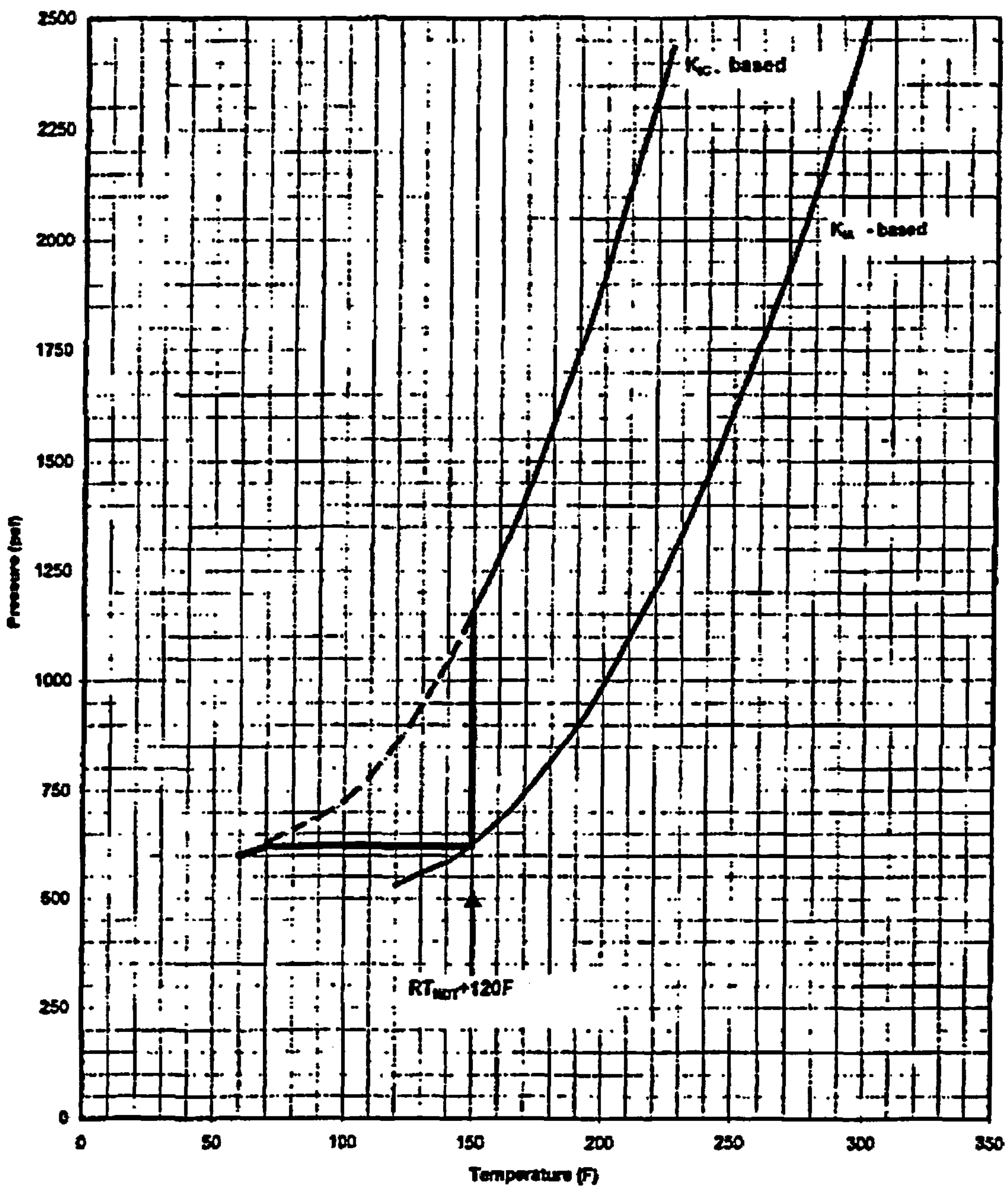


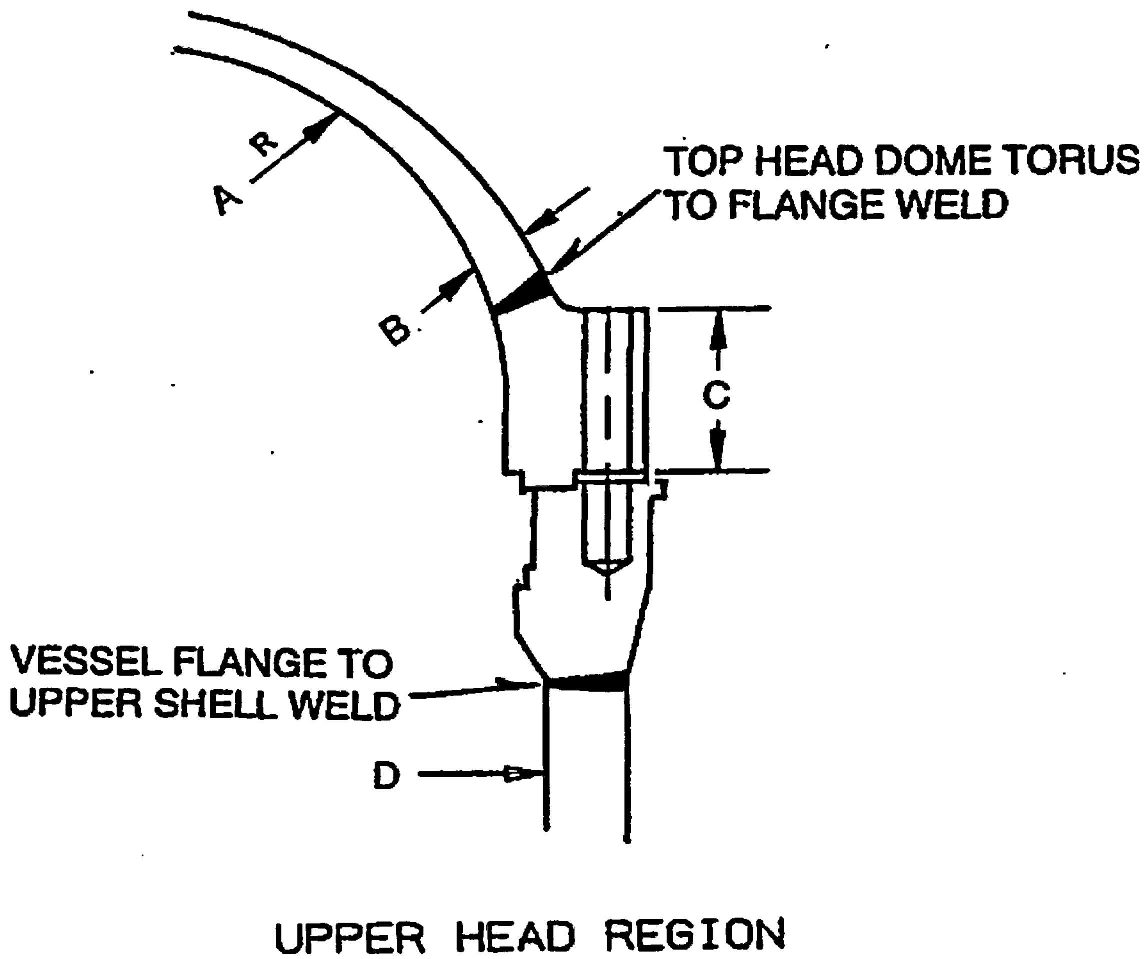
Figure 1-1 Illustration of the Impact of the Flange Requirement for a Typical PWR Plant

2 TECHNICAL APPROACH

The evaluation to be presented here is intended to cover the Sequoyah Units 1 and 2 reactor vessels. Fracture evaluations have been performed on the closure head geometry specific to these units, and results will be tabulated and discussed. The geometry of the closure head region for Sequoyah Units 1 and 2 is shown in Figure 2-1.

Stress analyses have been performed, and these stress results were used to perform fracture mechanics evaluations. Details of the finite element stress analysis are provided in Appendix C. 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. 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 and the heatup and cooldown 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?



	Sequoyah Units 1 and 2
A	88.1
B	6.89
C	29.72
D	170.88

NOTE: ALL DIMENSIONS ARE IN INCHES

Figure 2-1 Geometry of the Upper Head/Flange Region of the Sequoyah Units 1 and 2 Reactor Vessels

3 FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

The fracture evaluation was carried out using the approach suggested by Section XI Appendix G (Ref. 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 assumed to encompass a range of depths into 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). 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:

$$\sigma(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3 \qquad (3\text{-}1)$$

where:

x	=	is the coordinate distance into the wall, in.
σ	=	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 (Ref. 2) was used. The stress intensity factor K_I 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 as a function of the angular location around the crack (ϕ). The units of K_I are $\text{ksi}\sqrt{\text{in}}$.

$$K_I = \left[\frac{\pi a}{Q}\right]^{0.5} \sum_{j=0}^{3} G_j\left(a/c,\ a/t,\ t/R,\ \phi\right) A_j\, a^j \qquad (3\text{-}2)$$

The boundary correction factors G_0, G_1, G_2, and G_3 are obtained by the procedure outlined in reference (2). The dimension "a" is the crack depth, "c" is the crack half length, "t" is the wall thickness, "R" is the inside radius, and "Q" is the shape factor, approximated as $1 + 1.464\,(a/c)^{1.65}$.

3.2 FRACTURE TOUGHNESS

Another 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:

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

$$K_{Ia} = 26.8 + 12.445\ \exp.\ [0.0145\ (T\text{-}RT_{NDT})] \qquad (3\text{-}4)$$

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 $ksi\sqrt{in}$ has been used here. 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 final key element in the determination of the fracture toughness is the value of RT_{NDT}, which is a material parameter determined from Charpy V-notch and drop-weight tests.

The value of RT_{NDT} for the closure flange region of the Sequoyah units was obtained from certified material test reports and the results are shown in Table 3-1. The highest value was 5°F, and so this value 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.

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4 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 the entire heatup and cooldown process are summarized in Appendix C.

The boltup is the key condition to review here, in comparison with the heatup and cooldown operation, since the flange requirement applies to boltup conditions. No other transients result in stresses in this region at low temperatures. One might suggest that the cooldown might be of similar concern, but the boltup is governing for a number of reasons:

1. The heatup and cooldown transient is structured to ensure generous margins are maintained (SF = 2) for a large flaw in the irradiated beltline region. This is a more governing condition than the unirradiated flange region.

2. The cooldown transient has much higher temperatures in the head region than the boltup, and

3. The thermal stresses that are produced tend to counteract the boltup stresses; that is, they are tensile on the inside surface and compressive on the outside surface.

Table 4-1 provides a comparison of the stresses at boltup with those at the governing time step of heatup and cooldown which is end of heatup. 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. These results were taken from a finite element analysis of the heatup/cooldown process, and the boltup was compared with the most limiting time step of the entire heatup/cooldown transient.

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 Figure 4-1, and for the heatup and cooldown transient in Figure 4-2. For a semi-elliptic surface flaw with depth equal to 10 percent of the wall thickness postulated in the highest stress region of the head, the following values were determined for the stress intensity factor.

Boltup: $k = 20.0 \text{ ksi}\sqrt{\text{in}}$

End of Heatup: $k = 54.64 \text{ ksi}\sqrt{\text{in}}$

It will be useful to highlight the difference in the integrity story for the head region using the two values of fracture toughness. The boltup temperature for a typical PWR is 60°F, so if $RT_{NDT} = 5$°F the ASME reference toughness values are $K_{Ia} = 54.4 \text{ ksi}\sqrt{\text{in}}$ and $K_{Ic} = 95.5 \text{ ksi}\sqrt{\text{in}}$. Using the K_{Ia} toughness (which was the basis for the original flange requirements) it can be seen that the toughness exceeds the applied stress intensity factor for boltup for flaws of any depth in the head thickness. The smallest margin of 1.75 occurs for a flaw 42 percent of the wall thickness; for other flaws the margin is larger. For the heatup and cooldown transient, the coolant temperature at the governing time steps, near the end of heatup, is 547°F. The fracture toughness is therefore $200 \text{ ksi}\sqrt{\text{in}}$, so again the margin is very large.

Using the K_{Ic} toughness, which has now been adopted by Section XI for P-T Curves, it can be seen that there is also a significant margin between the fracture toughness and the applied stress intensity factor, for both the boltup and the heatup cooldown transient. 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 the Sequoyah units using the K_{Ic} toughness. There are two possible mechanisms of degradation for this region, thermal aging and fatigue.

Effect of 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.

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Table 4-1 Stress Distributions for the Closure Flange Region – Sequoyah Units 1 and 2		
Distance (x/t)	Boltup Stress (ksi)	End of Heatup 344.2 minutes, 2250 psi (ksi)
0 (ID)	-14.38	-15.32
0.1	-10.77	
0.2	-7.83	-3.42
0.3	-5.14	
0.4	-2.66	4.55
0.5	-0.26	
0.6	2.16	12.15
0.7	4.72	
0.8	7.54	21.76
0.9	11.24	
1.0 (OD)	19.70	38.77

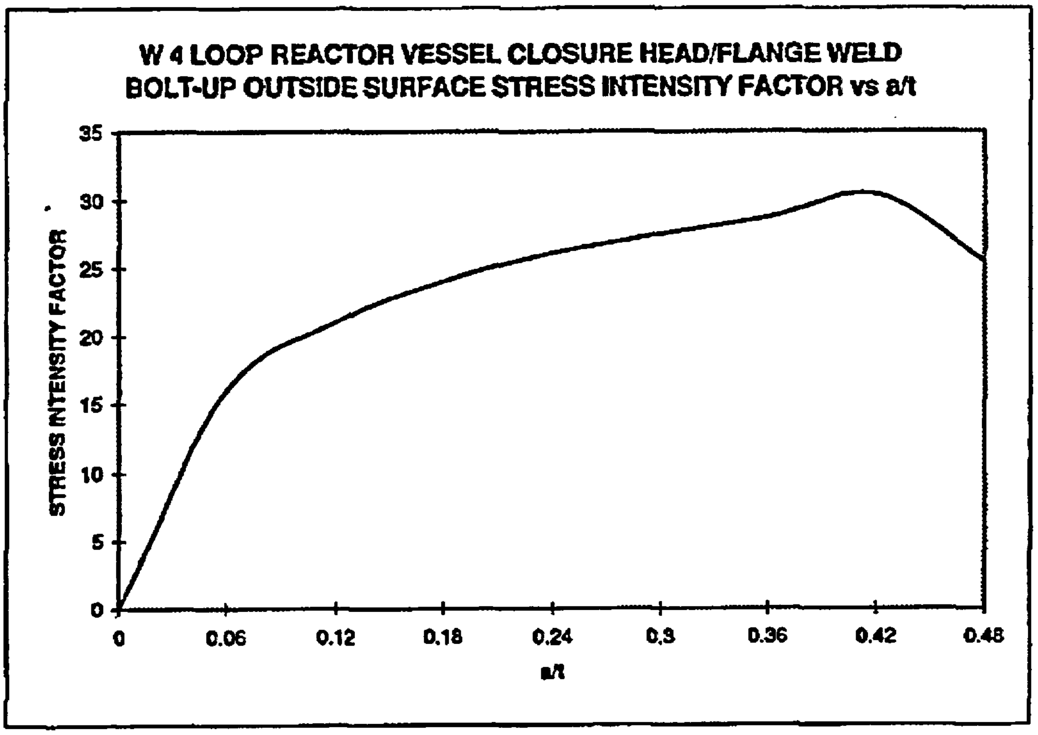
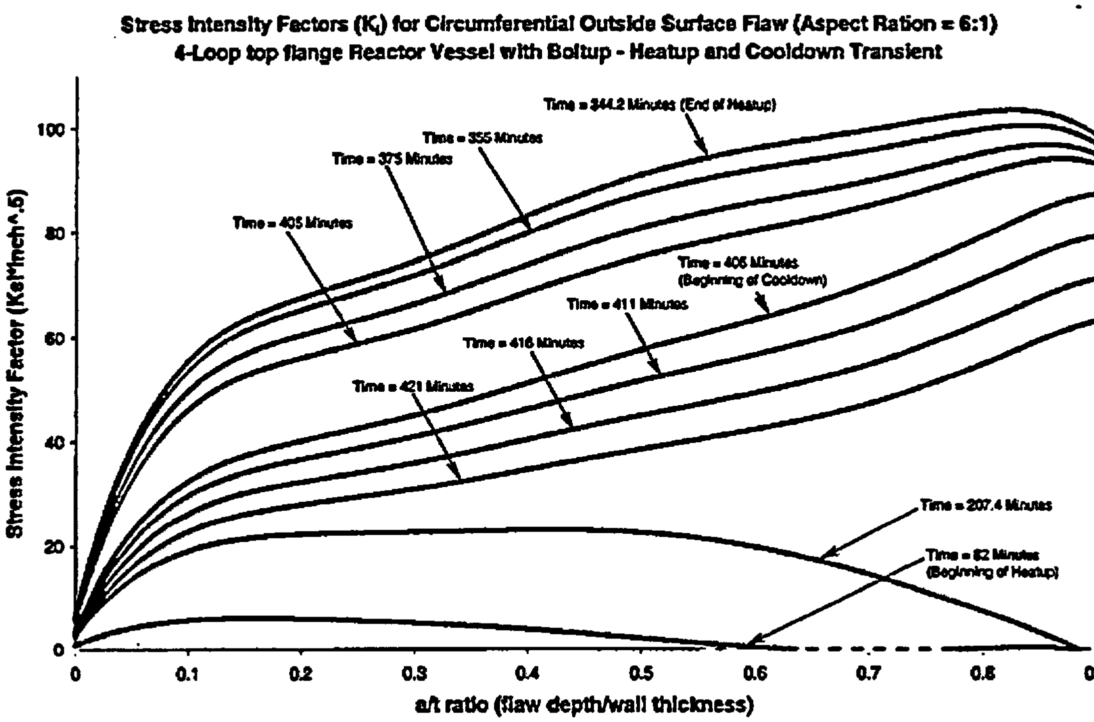


Figure 4-1 Crack Driving Force as a Function of Flaw Size: Outside Surface Flaw in the Closure Head to Flange Region Weld for Sequoyah Units 1 and 2 Boltup Condition (stress intensity factor units are ksi$\sqrt{in}$)



Notes: Stress intensity factors for Time = 474.4, 668.2 (End of Cooldown), 678, 698, and 728 Minutes are zero due to very low stress profile.

Figure 4-2 Crack Driving Force as a Function of Flaw Size in the Closure Head to Flange Region Weld for an Outside Surface Flaw for Sequoyah Units 1 and 2: Heatup and Cooldown Transient (stress intensity factor units are ksi$\sqrt{in}$)

5 ARE FLANGE REQUIREMENTS NECESSARY?

Using the K_{Ic} curve can support the elimination of the flange temperature 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 the end of heatup, as well as boltup. Included here are the stress distributions through the wall, showing that the highest stress location for this region is the outer surface.

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.

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 (Ref. 11) Before discussing the table, it will be helpful to discuss the basis for the reference flaw, in light of current technology, and using the results of the Performance Demonstration Initiative.

Basis for the Reference Flaw Size. Regulatory Guide 1.150 stimulated improvement in examinations of the clad to base-metal interface. The same techniques have been used for more than 10 years for reactor vessel head examinations performed from the outside surface. Capability demonstrations for the clad to base-metal interface have been conducted at the EPRI NDE Center since 1983. These demonstrations were performed initially for the belt-line region. However, similar techniques are used for both the vessel belt-line and the reactor vessel head, although the head exams are done manually.

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Table 5-1 Comparison of Various Plant Designs Boltup Requirements				
Plant	K (a/t = .1)	K with SF = 2	T – RT_{NDT} (°F) using K_{Ic} (a/t = .10)	T – RT_{NDT} (°F) using K_{Ia} (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 $ksi\sqrt{in}$

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Figure 5-1 Probability of Correct Rejection/Reporting (PCR) Considering Passed plus Failed Candidates, Appendix VIII from the Outside Surface. Reporting Criterion A' = 0.15 inch

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Figure 5-2 Probability of Correct Rejection/Reporting (PCR) Considering Only Passed Candidates, Appendix VIII from the Outside Surface. Reporting Criterion A' = 0.15 inch.

6 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°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 EFPY, 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°F down to boltup at 60°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. The flange impact for Sequoyah Unit 2, for example, is shown in Figures 6-4 and 6-5 [13].

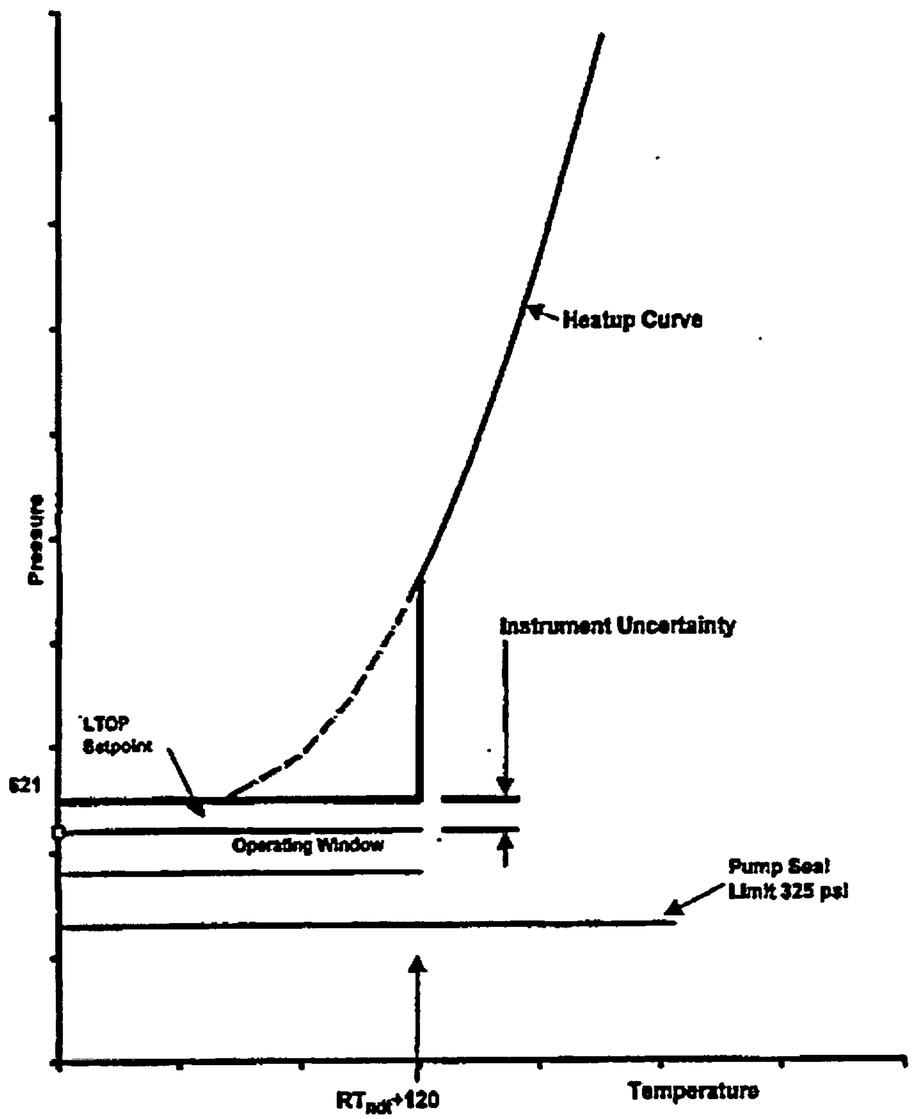

Figure 6-1 Illustration of the Flange Requirement and its Effect on the Operating Window for a Typical Heatup Curve

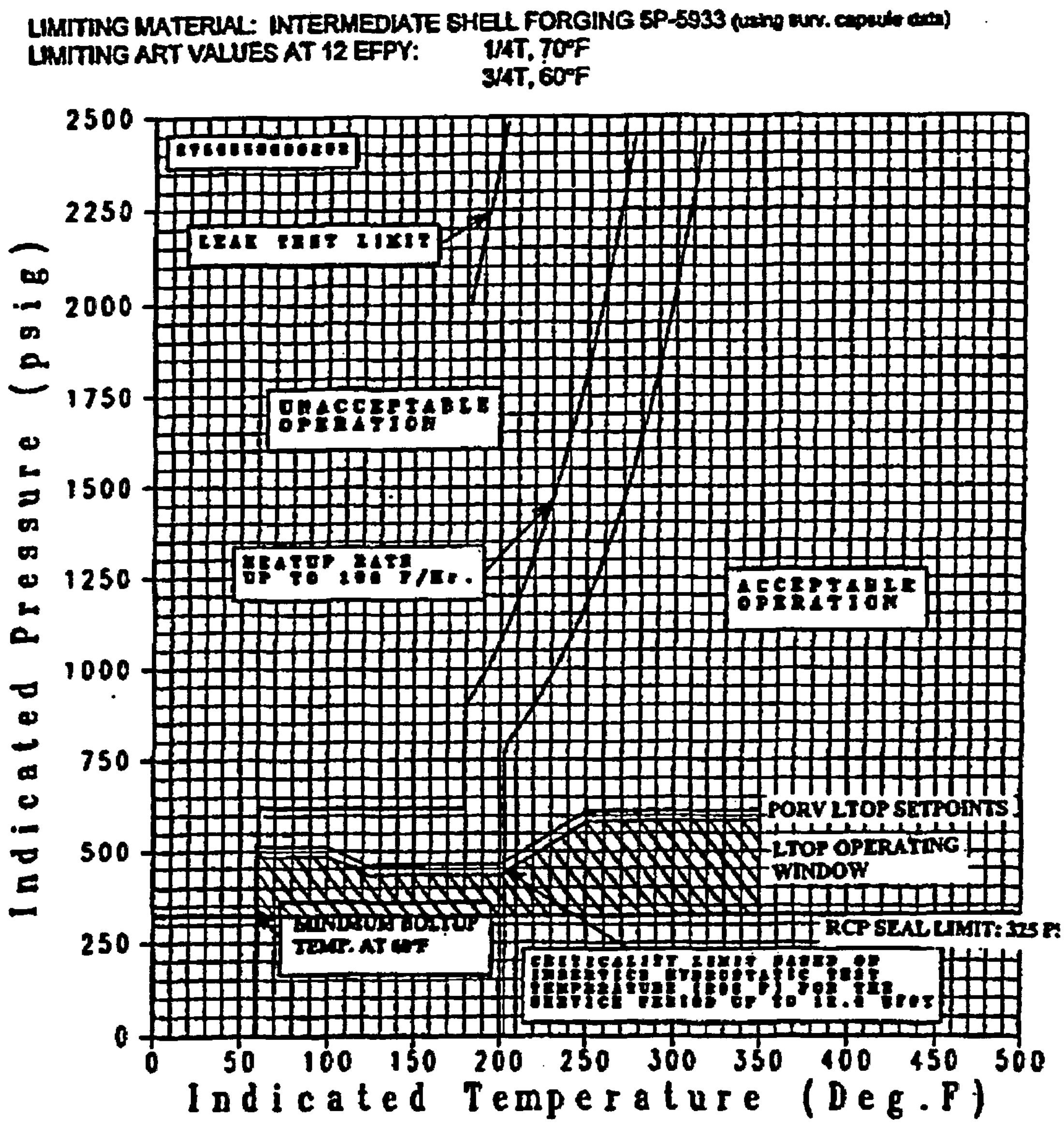

Figure 6-2 Illustration of the Actual Operating Window for Heatup of Byron Unit 1, a Low Copper Plant at 12 EFPY

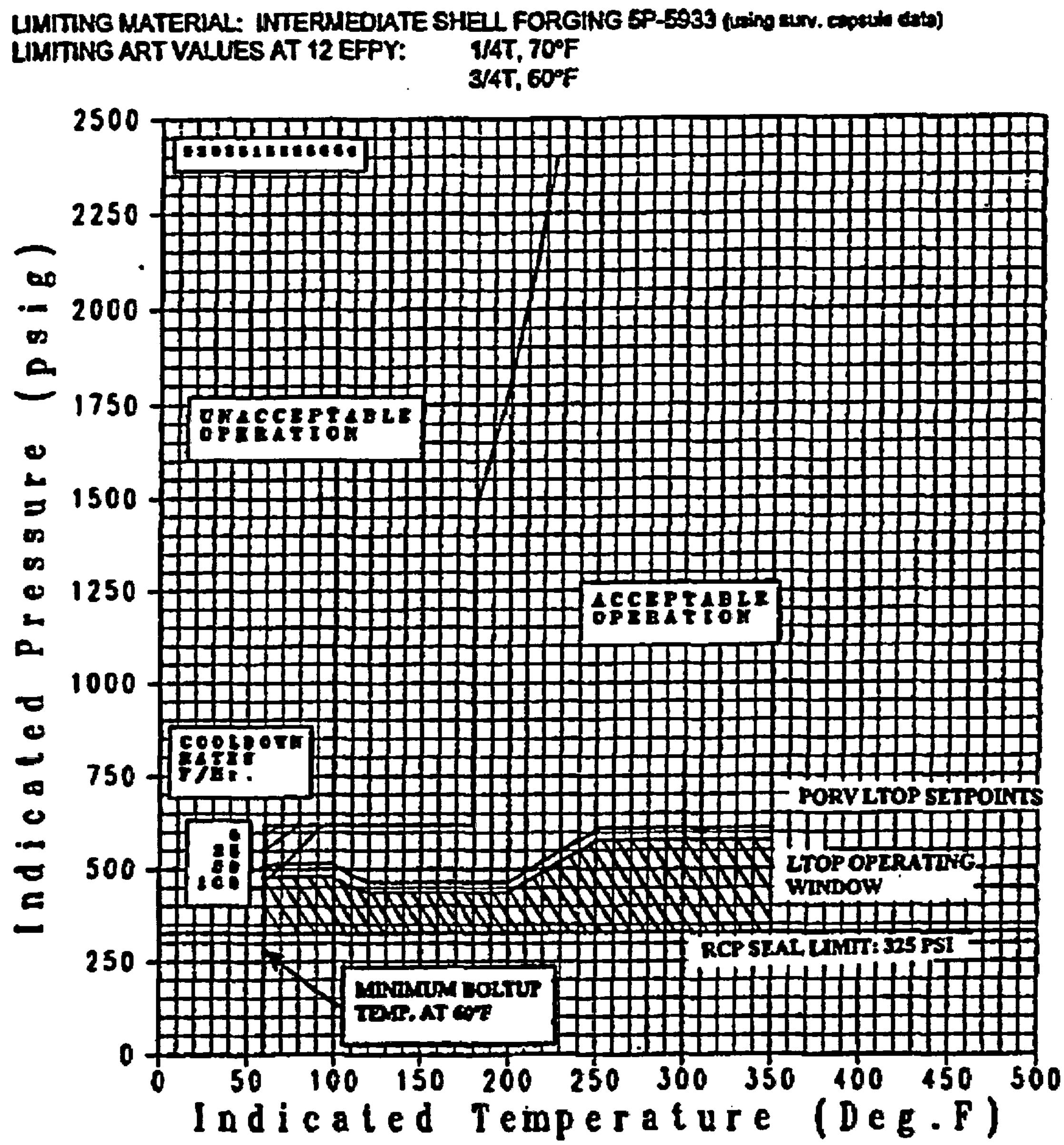

Figure 6-3 Illustration of the Actual Operating Window for Cooldown of Byron Unit 1, a Low Copper Plant at 12 EFPY

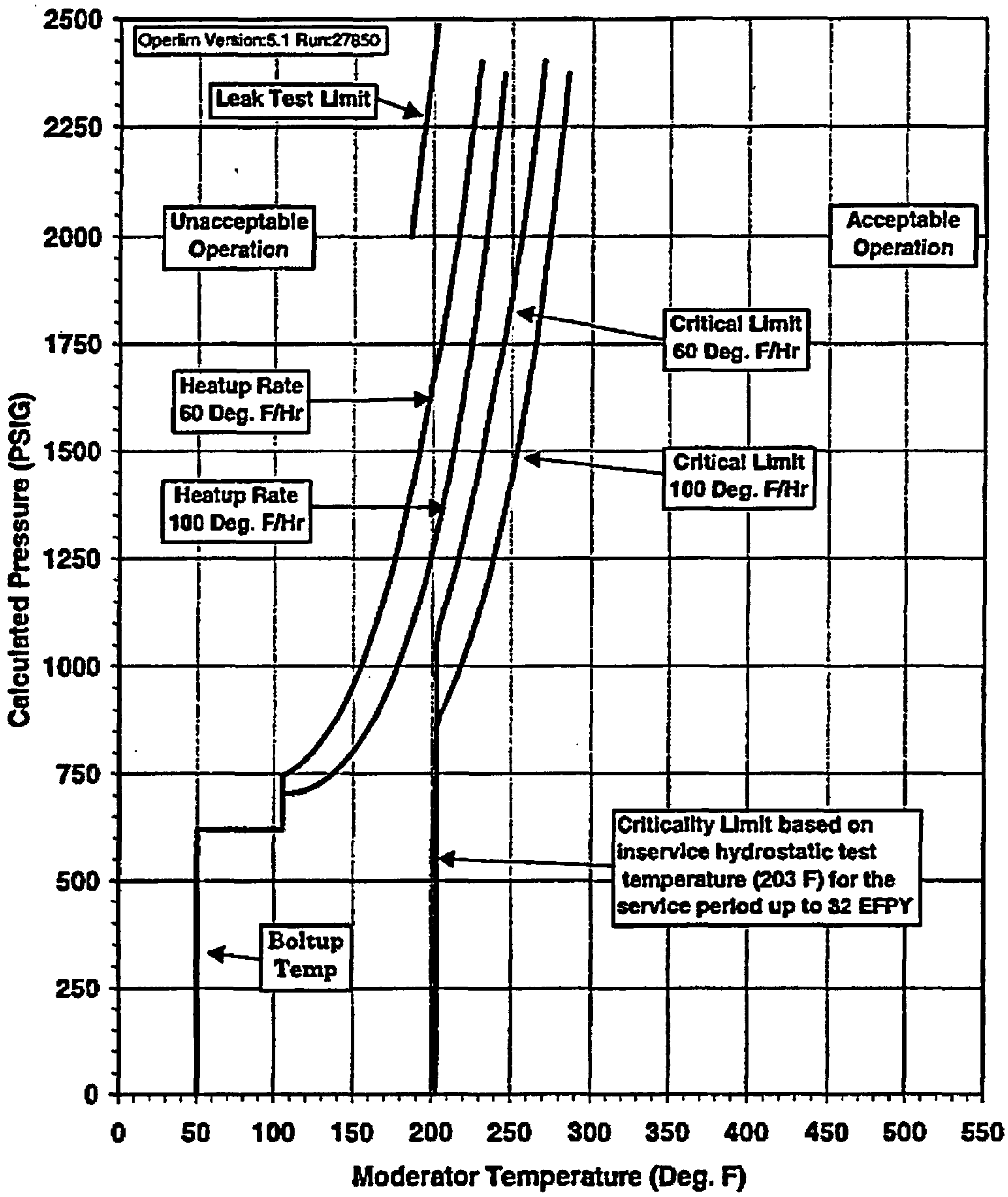

Figure 6-4 **Illustration of the Flange Notch for Sequoyah Unit 2, Heatup Curve, without Instrument Uncertainties [13]**

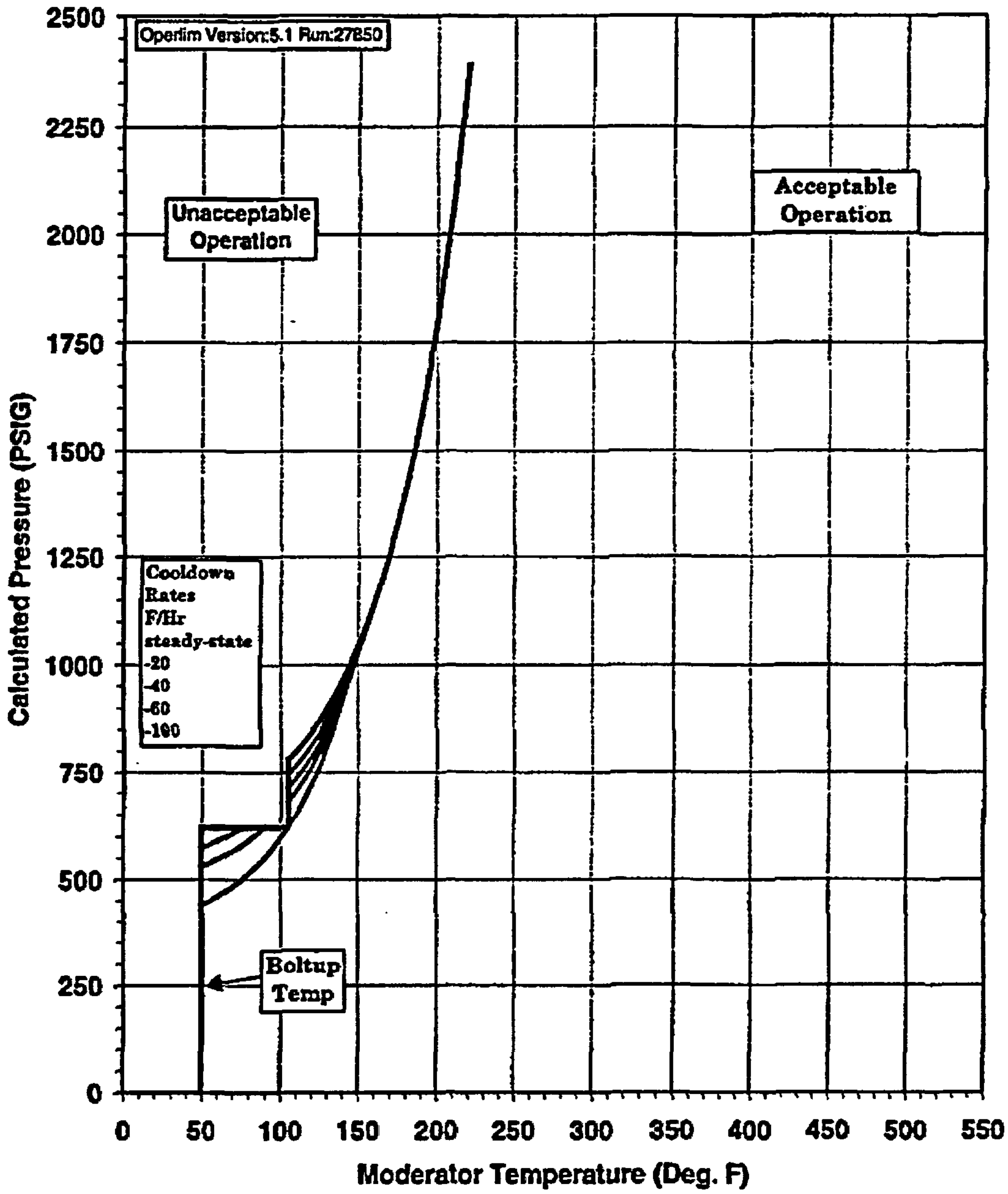

Figure 6-5 Illustration of the Flange Notch for Sequoyah Unit 2, Cooldown Curves, without Instrument Uncertainties [13]

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APPENDIX A
REACTOR PRESSURE VESSEL INSPECTION RELIABILITY*

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EPRI

Charlotte NC

ABSTRACT

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*Presented at the Joint EC-IAEA Technical Meeting on Improvements in Inservice Inspection Effectiveness, Pettan, The Netherlands, November 2002, to be published.

2 DETECTION

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2.1 OUTSIDE SURFACE DEMONSTRATION

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Figure 1 Probability of Detection Performance for Passed and Passed Plus Failed Candidates for Appendix VIII Supplement 4, from the Outside Surface as a function of the flaw through wall extent (TWE). Both automated and manual techniques are included.

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Figure 2 POD for Inside Surface Examinations, Pass and Pass + Failed Candidates, Passed and Pass Plus Failed Candidates are included.

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2.2 COMBINED ID AND OD DETECTION

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Figure 3 Probability of Detection for Automated RPV Examinations Considering Both Inside and Outside Access. Passed and Passed Plus Failed Candidates are shown.

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Figure 4 POD for Pass and Failed Candidates, Considering ID and OD Automated Demonstrations and Manual OD Demonstrations.

3 SIZING

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Figure 5 **Histogram of Depth Successful Sizing Candidate Test Scores, Appendix VIII, Supplement 4. Examinations Were Performed Both From the Inside and Outside Surfaces.**

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Figure 6 Sizing Error Surface Model

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Figure 7 Plan View of Sizing Error Surface Model

4 ACCEPTABILITY EVALUATION

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Figure 8 Probability of Correct Sizing for Passed Candidates, Appendix VIII Supplement 4. Reporting Threshold A' = 0.15 inch.

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Figure 9 Probability of Correct Rejection/Reporting (PCR) for automated techniques, Considering Passed and Passed plus Failed Candidates, includes both inside and outside surface information. Reporting Criterion A' = 0.15 inch.

5 SUMMARY

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6 REFERENCES

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APPENDIX B
THERMAL AGING OF FERRITIC RPV STEELS AT REACTOR OPERATING TEMPERATURES

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APPENDIX C
STRESS DISTRIBUTIONS IN THE CLOSURE HEAD REGION

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