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PRESSURE-TEMPERATURE CURVES PER REGULATORY GUIDE 1.99, REVISION 2 FOR THE OYSTER CREEK NUCLEAR GENERATING STATION

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APPENDICES

1.0 INTRODUCTION

The pressure-temperature (P-T) curves in the Technical Specifications are established to the requirements of 10CFR50, Appendix G [1] to assure that brittle fracture of the reactor vessel is prevented. Part of the analysis involved in developing the P-T curves is to account for irradiation embrittlement effects in the core region, or beltline. The method used to account for irradiation embrittlement is described in Regulatory Guide 1.99, Revision 2 [2], or Rev 2.

In addition to beltline considerations, there are non-beltline discontinuity limits at nozzles, penetrations and flanges which affect the P-T curves. The non-beltline limits are based on generic analyses which are adjusted to the maximum reference temperature (RT_{NDT}) for the applicable Oyster Creek vessel components. The non-beltline limits are also governed by requirements in [1], based on the closure flange region RT_{NDT}.

This report presents P-T curves incorporating irradiation effects for the beltline per Rev 2 and appropriate non-beltline limits. The curves have been developed to present steam dome pressure versus minimum vessel metal temperature. In addition, a refinement has been made which may minimize heating requirements prior to pressure testing, specifically:

- A curve has been included to allow monitoring of the non-beltline regions of the vessel, such as the bottom head, separate from the beltline.

The report contains a description of the methods used to calculate P-T limits and has example calculations for the vessel beltline for pressure testing and heatup/cooldown conditions.

Temperature monitoring requirements and methods are available in GE Services Information Letter (SIL) 430. The specific issue of maintaining a heatup or cooldown rate of 100°F/hr, as it relates to the P-T curves, is discussed in this report.

2.0 INITIAL REFERENCE TEMPERATURES

In order to perform a complete analysis of the vessel P-T requirements, initial RT_{NDT} values are needed for all low alloy steel vessel components. The requirements for establishing the vessel component toughness per the ASME Code prior to 1972 are summarized as follows:

a. Test specimens shall be longitudinally oriented Charpy V-Notch specimens.

b. At the qualification test temperature (specified in vessel purchase specification), no impact test result shall be less than 25 ft-lb, and the average of three test results shall be at least 30 ft-lb.

c. Pressure tests shall be conducted at a temperature at least 60°F above the qualification test temperature for the vessel materials.

The current requirements establish a RT_{NDT} value, and are significantly different For plants constructed to the ASME Code after Summer 1972 the requirements are as follows:

a. Charpy V-Notch specimens shall be oriented normal to the rolling direction (transverse).

b. RT_{NDT} is defined as the higher of the dropweight NDT or 60°F below the temperature at which Charpy V-Notch 50 ft-lb energy and 35 mils lateral expansion are met.

c. Bolt-up in preparation for a pressure test or normal operation shall be performed at or above the RT_{NDT} or lowest service temperature (LST), whichever is greater.

10CFR50 Appendix G states that for vessels constructed to a version of the ASME Code prior to the Summer 1972 Addendum, fracture toughness data and data analyses must be supplemented in an approved manner. GE has developed methods for analytically converting fracture toughness data for vessels constructed before 1972 to comply with current requirements. GE developed these methods from data in WRC Bulletin 217 [3] and from data collected to respond to NRC questions on FSAR submittals in the late 1970s. The GE methods have not been generically approved by the NRC, but they have been accepted on a case-by-case basis in submittals by about 20 utilities. The data used in developing the GE methods cover A533 plate material and submerged arc and shielded metal arc welds. Since the Oyster Creek vessel plates are 302B material, some supplemental evaluation of RT_{NDT} has been done in this report on some of the vessel plates. These methods and example RT_{NDT} calculations for vessel plate, weld, weld HAZ, forging, and bolting material are summarized in the remainder of this section. Calculated RT_{NDT} values for selected RPV locations are given in Table 2-1.

For vessel plate material, the first step in calculating RT_{NDT} is to establish the 50 ft-lb transverse test temperature from longitudinal test specimen data. There are typically three energy values at a given test temperature. The lowest energy Charpy value is adjusted by adding 2°F per ft-lb energy to 50 ft-lb. For example, for plate G-309-2 in the closure head, the test temperature and lowest Charpy energy from Table 2-1 is 28.5 ft-lb at +10°F. The equivalent 50 ft-lb longitudinal test temperature is:

$$T_{50L} = 10°F + [(50 - 28.5) \text{ ft-lb} * 2°F/\text{ft-lb}] = 53°F$$

The transition from longitudinal data to transverse data is made by adding 30°F to the test temperature. In this case, the 50 ft-lb transverse Charpy test temperature is $T_{50T} = 83°F$. The RT_{NDT} is the greater of NDT or (T_{50T} - 60°F). The value based on Charpy data, (T_{50T} - 60°F), is 23°F. For Oyster Creek materials, dropweight testing to establish NDT was not performed, but NRC Branch Technical Position MTEB 5-2 [4] recommends that NDT be estimated as the 30 ft-lb Charpy test temperature, which in this case is 10°F. Thus, the RT_{NDT} for plate G-309-2 is 23°F. Note that the conservative nature of estimating T_{50T} will always result in the estimated (T_{50T} - 60°F) value being higher than the estimated NDT.

Some of the 302B plate materials used in the Oyster Creek vessel exhibit a rather low upper shelf energy (USE). Fortunately, there are full Charpy curves for these materials. In examining the Charpy curves, it was found that the 2°F per ft-lb correction was not conservative for the materials with lower USE values. In these cases, the Charpy data were fit with a hyperbolic tangent relationship to determine the best-estimate T_{50L}. The standard deviation of the data relative to the curve-fit (by temperature) was calculated to serve as σ_I for the beltline materials. For non-beltline materials, the value of T_{50L} used to determine RT_{NDT} was the best-estimate value plus twice the standard deviation. Plots of the Charpy curves for all of the beltline plates and for the most limiting non-beltline plates with low USE are provided in Appendix A. The RT_{NDT} values in Table 2-1 for these plates are based on the Appendix A curves.

For vessel weld material, the Charpy V-Notch results are usually more limiting than dropweight results in establishing RT_{NDT}. The 50 ft-lb test temperature is established as for the plate material, but the 30°F adjustment to convert longitudinal data to transverse data is not applicable to weld metal. For example, weld heat 86054B with flux lot 4D4F has a lowest Charpy energy of 29 ft-lb at 10°F. The 2°F per ft-lb adjustment gives a T_{50T} value of 52°F. The GE procedure requires that, when no NDT is available, the resulting RT_{NDT} be -50°F or higher. In this example, (T_{50T} - 60°F) is -8°F, so the RT_{NDT} is -8°F. Since the method of estimating RT_{NDT} operates on the lowest Charpy energy value, and provides a conservative adjustment to the 50 ft-lb level, the value of σ_I is taken to be 0°F.

For the vessel weld HAZ material, the RT_{NDT} is assumed to be the same as for the base material since ASME Code weld procedure qualification test requirements and post-weld heat treat data indicate this assumption is valid.

For vessel forging material, such as nozzles and closure flanges the method for establishing RT_{NDT} is the same as for vessel plate material. For the CRD return nozzle G-319, the lowest Charpy data at 40°F is 25 ft-lb. In this case, (T_{50T} - 60°F) is [40 + (50-25)*2 + 30 - 60], or 60°F.

For bolting material, the current ASME Code requirements define the LST as the temperature at which transverse Charpy V-Notch energy of 45 ft-lb and 25 mils lateral expansion (MLE) are achieved. If the required Charpy results are not met, or are not reported, but the Charpy V-Notch energy reported is above 30 ft-lb, the requirements of the ASME Code at construction are applied, namely that the 30 ft-lb test temperature plus 60°F is the LST for the bolting materials. Charpy data for the studs did not meet the 45 ft-lb, 25 MLE requirement, but 30 ft-lb energies were met at 10°F. Therefore, the bolting material LST is 70°F.

Table 2-1

INITIAL RT_{NDT} VALUES OF BELTLINE AND OTHER SELECTED RPV MATERIALS

Location	Ident. Number	Heat Number	Test Temp. (°F)	Charpy Energy (ft-lb)	T_{50T}-60 (°F)	σ_I (°F)	RT_{NDT} (°F)
Beltline:							
Lower Shell Plates	G-307-1	T1937-2	see App. A		30	12.6	(a)
	G-308-1	T1937-1	see App. A		21	14.2	(a)
	G-307-5	P2076-2	see App. A		3	13.9	(a)
Lower Intermediate Shell Plates	G-8-7	P2161-1	see App. A		17	10.7	(a)
	G-8-8	P2136-2	see App. A		8	12.8	(a)
	G-8-6	P2150-1	see App. A		31	12.7	(a)
Lower Long. Welds	2-564 A,B,C	86054B Lot 4E5F	10	64,65,66	-50	0.0	-50
Lower-Int. Long. Welds	2-564 D,E,F	86054B Lot 4D4F	10	29,31.5,32	-8	0.0	-8
Lower to Lower-Int. Girth Weld	3-564	1248 Lot 4M2F	10	53.5,57.65	-50	0.0	-50
Non-Beltline:							
Upper Shell Plate	G-307-R1	P2112-2	see App. A		25	5.3	36(b)
Vessel Flange	G-306	X-43162	10	92,143,153	-20	0.0	-20
Head Flange	G-305	X-43162	10	212,261,261	-20	0.0	-20
Top Head Torus	G-309-2	P2074-1	10	28.5,35.39.5	23	0.0	23
Bottom Head Torus	G-301-4	A7153-2	see App. A		45	10.3	66(b)
CRD Return Nozzle	G-319	BT-1676	40	25,34,38	60	0.0	60
Recirc Inlet Forg.	G-312-1	D-4936-2	10	28.5,30.5,31	23	0.0	23

(a) The values of (T_{50T} - 60) and σ_I are used in Section 3 according to the methods in Rev 2.

(b) The RT_{NDT} values for these non-beltline materials are the (T_{50T} - 60) plus $2\sigma_I$.

3.0 ADJUSTED REFERENCE TEMPERATURES FOR BELTLINE

The adjusted reference temperature (ART) of the limiting beltline material is used to correct the beltline P-T curves to account for irradiation effects. Rev 2 provides the methods for determining the ART. These methods, and the limiting material properties used, are discussed in this section.

3.1 REV 2 METHODS

The value of ART is computed by adding the SHIFT term for a given value of effective full power years (EFPY) to the initial RT_{NDT}. For Rev 2, the SHIFT equation consists of two terms:

$$\text{SHIFT} = \Delta RT_{NDT} + \text{Margin}$$

$$\text{where } \Delta RT_{NDT} = [CF] * f^{(0.28 - 0.10 \log f)}$$

$$\text{Margin} = 2(\sigma_I^2 + \sigma_\Delta^2)^{0.5}$$

$$f = \text{fluence for the given EFPY} / 10^{19}$$

Chemistry factors (CF) are tabulated for welds and plates in Tables 1 and 2, respectively, of Rev 2. The margin term σ_Δ has set values in Rev 2 of 17°F for plate and 28°F for weld. However, σ_Δ need not be greater than $0.5 * \Delta RT_{NDT}$. Uncertainty on initial RT_{NDT}, σ_I, is discussed in Section 2.0.

3.2 LIMITING BELTLINE MATERIAL

An evaluation of all beltline plates and submerged arc welds was made, and is summarized in Tables 3-1 and 3-2. The inputs used in determining the limiting beltline material are discussed in the remainder of this section.

3.2.1 Chemistry

The vessel material certification records provided much of the detail of the beltline material chemistries. However, critical information on copper and, in some cases nickel, were not provided with the material certificates. GPUN established values for the missing data in Technical Data Report (TDR) 725 [5]. The data from the material records and from TDR 725 are presented in Table 3-3. The copper and nickel values shown there were used in the Rev 2 calculations.

3.2.2 Fluence

The Oyster Creek surveillance test report [6] presents a calculated value of 32 EFPY fluence at the inside vessel surface. GPUN made an adjustment to the value in [6] to reflect some new information on power history, resulting in a 32 EFPY fluence of 3.74×10^{18} n/cm² reported in TDR 725. GE has just completed an evaluation of lead factor (fluence ratio between the surveillance capsule and the vessel peak) and has computed values very close to those in [6]. Therefore, the fluence value in TDR 725 is used in the Rev 2 calculations.

Rev 2 provides a method of calculating the vessel 1/4 T fluence based on the fluence at the vessel inside surface, f_{surf}. However, Rev 2 also allows for the use of displacement per atom (dpa) analysis to determine the attenuation to the 1/4 T location. A dpa analysis was performed in [6], resulting in an attenuation relationship as follows:

$$f_{1/4\ T} = 0.63 * f_{surf}$$

The resulting 1/4 T fluence is:

$$f_{1/4\ T} = 2.36\times10^{18}\ \text{n/cm}^2.$$

This 1/4 T fluence is about 3% less than the value calculated with the attenuation relationship in Rev 2.

3.3 ART VS EFPY

Combining the inputs of initial RT_{NDT}, chemistry and fluence, Rev 2 is used to compute ART as a function of EFPY. Table 3-1 shows ART values for 32 EFPY of operation. Table 3-2 shows ART for 17 EFPY of operation. In both cases, plate G-8-6 has the highest ART, due to the fact that it also has the highest initial RT_{NDT}. The limiting submerged arc weld has a higher SHIFT value, but a lower initial RT_{NDT} such that the ART is less than that of the plate. Therefore, plate G-8-6 is the limiting material throughout the operating period of 32 EFPY. ART is plotted versus EFPY in Figure 3-1. The ART values at 17 and 32 EFPY are used in the P-T curve development in Section 4.

Table 3-1

BELTLINE EVALUATION FOR OYSTER CREEK AT 32 EFPY OF OPERATION

Shell Thickness = 7.125 inches

Peak I.D. fluence = 3.74E+18
Peak 1/4 T fluence =2.36E+18

COMPONENT	I.D.	HEAT OR HEAT/LOT	%Cu	%Ni	CF	Initial RTndt	Sigma-I	32 EFPY Delta RTndt	Margin	32 EFPY Shift	32 EFPY ART
PLATES:											
Lower Shell	G-307-1	T-1937-2	0.17	0.11	79.5	30	12.6	48.4	42.3	90.8	120.8
Lower Shell	G-308-1	T-1937-1	0.17	0.11	79.5	21	14.2	48.4	44.3	92.7	113.7
Lower Shell	G-307-5	P-2076-2	0.27	0.53	173.9	3	13.9	106.0	43.9	149.9	152.9
Low-Int Shell	G-8-7	P-2161-1	0.21	0.48	139.4	17	10.7	84.9	40.2	125.1	142.1
Low-Int Shell	G-8-8	P-2136-2	0.18	0.46	120.7	8	12.8	73.5	42.6	116.1	124.1
Low-Int Shell	G-8-6	P-2150-1	0.2	0.51	138.2	31	12.7	84.2	42.4	126.6	157.6
WELDS:											
Lower Long.	2-564 A,B,C	86054B, ARCOS FLUX LOT 4E5F	0.35	0.2	168	-50	0	102.4	56.0	158.4	108.4
Low-Int Long.	2-564 D,E,F	86054B, ARCOS FLUX LOT 4D4F	0.35	0.2	168	-8	0	102.4	56.0	158.4	150.4
Lower to Low-Int Girth	3-564	1248, ARCOS FLUX LOT 4M2F	0.22	0.11	105.3	-50	0	64.2	56.0	120.2	70.2

Table 3-2

BELTLINE EVALUATION FOR OYSTER CREEK AT 17 EFPY OF OPERATION

Shell
Thickness = 7.125 inches

Peak I.D. fluence = 1.99E+18
Peak 1/4 T fluence =1.25E+18

COMPONENT	I.D.	HEAT OR HEAT/LOT	%Cu	%Ni	CF	Initial RTndt	Sigma-I	17 EFPY Delta RTndt	Margin	17 EFPY Shift	17 EFPY ART
PLATES:											
Lower Shell	G-307-1	T-1937-2	0.17	0.11	79.5	30	12.6	36.8	42.3	79.2	109.2
Lower Shell	G-308-1	T-1937-1	0.17	0.11	79.5	21	14.2	36.8	44.3	81.1	102.1
Lower Shell	G-307-5	P-2076-2	0.27	0.53	173.9	3	13.9	80.6	43.9	124.5	127.5
Low-Int Shell	G-8-7	P-2161-1	0.21	0.48	139.4	17	10.7	64.6	40.2	104.8	121.8
Low-Int Shell	G-8-8	P-2136-2	0.18	0.46	120.7	8	12.8	55.9	42.6	98.5	106.5
Low-Int Shell	G-8-6	P-2150-1	0.2	0.51	138.2	31	12.7	64.0	42.4	106.5	137.5
WELDS:											
Lower Long.	2-564 A,B,C	86054B, ARCOS FLUX LOT 4E5F	0.35	0.2	168	-50	0	77.8	56.0	133.8	83.8
Low-Int Long.	2-564 D,E,F	86054B, ARCOS FLUX LOT 4D4F	0.35	0.2	168	-8	0	77.8	56.0	133.8	125.8
Lower to Low-Int Girth	3-564	1248, ARCOS FLUX LOT 4M2F	0.22	0.11	105.3	-50	0	48.8	48.8	97.6	47.6

Table 3-3

CHEMICAL COMPOSITION OF RPV BELTLINE MATERIALS

Identification	Heat/Lot No.	Composition by Weight Percent							
		C	Mn	P	S	Si	Ni	Mo	Cu
Lower Shell Plates:									
G-307-1	T1937-2	0.2	1.4	0.011	0.022	0.24	0.11 [a]	0.51	0.17 [a]
G-308-1	T1937-1	0.2	1.4	0.011	0.022	0.24	0.11 [a]	0.51	0.17 [a]
G-307-5	P2076-2	0.2	1.28	0.019	0.030	0.21	0.53	0.52	0.27 [a]
Lower-Intermediate Shell Plates.									
G-8-7	P2161-1	0.19	1.35	0.019	0.021	0.24	0.48	0.46	0.21 [a]
G-8-8	P2136-2	0.19	1.36	0.006	0.024	0.26	0.46	0.47	0.18 [a]
G-8-6	P2150-1	0.2	1.25	0.013	0.026	0.23	0.51	0.46	0.20 [a]
Lower Shell Longitudinal Welds:									
2-564 A,B,C	RACO#3, 86054B ARCOS B-5 Lot 4E5F	0.12	1.54	0.015	0.02	0.34	0.2 [a]	0.51	0.35 [a]
Lower-Intermediate Longitudinal Weld:									
2-564 D,E,F	RACO#3, 86054B ARCOS B-5 Lot 4D4F	0.12	1.67	0.013	0.02	0.41	0.2 [a]	0.50	0.35 [a]
Lower to Lower-Intermediate Girth Weld:									
3-564	RACO#3, 1248 ARCOS B-5 Lot 4M2F	0.097	1.26	0.015	0.02	0.22	0.11 [a]	0.57	0.22 [a]

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[a] Values reported in TDR 725.

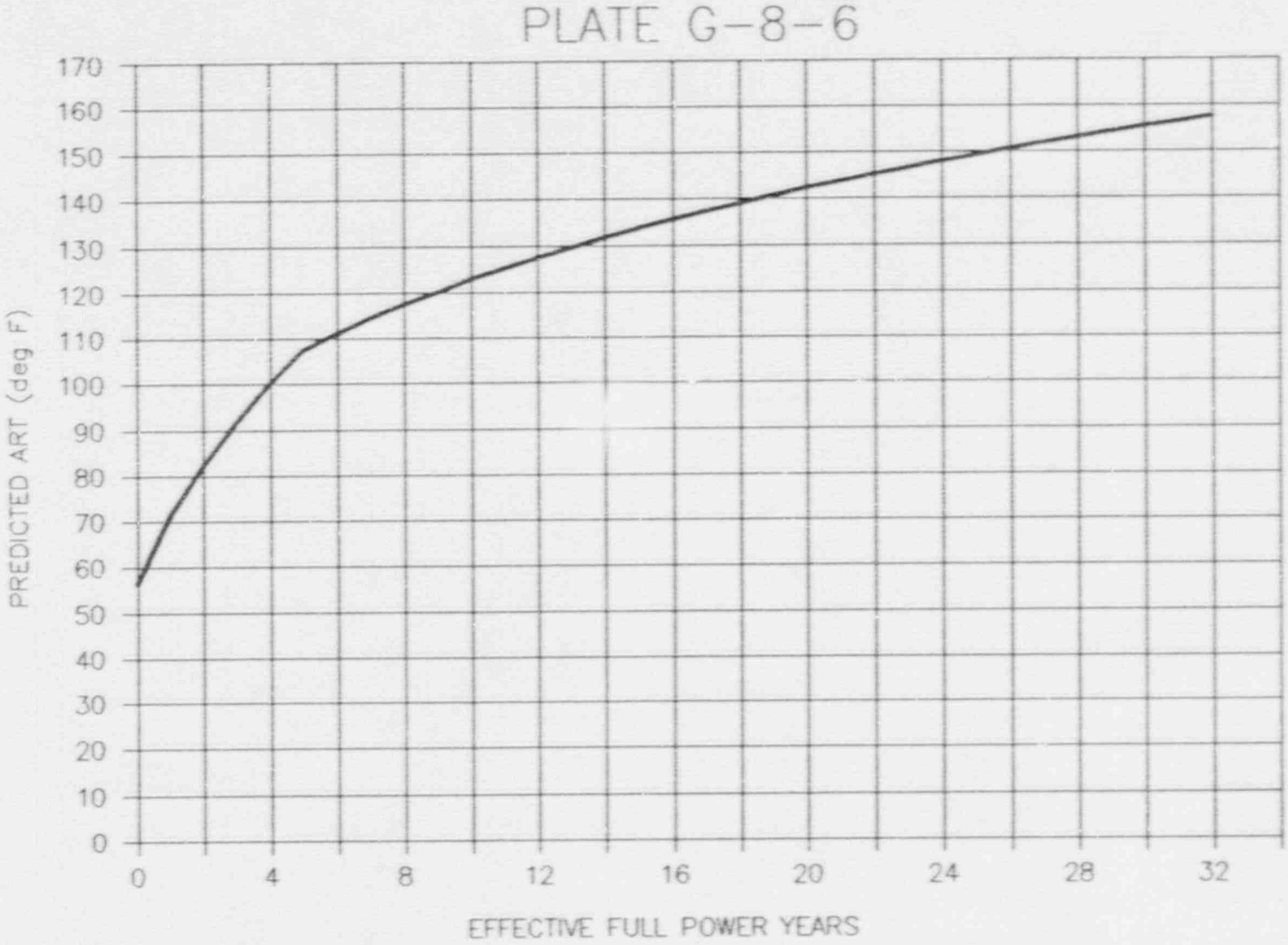


Figure 3-1. Limiting Beltline Material ART

4.0 PRESSURE-TEMPERATURE CURVES

4.1 BACKGROUND

Operating limits for pressure and temperature are required for three categories of operation: (a) hydrostatic pressure tests and leak tests, referred to as Curve A; (b) non-nuclear heatup/cooldown and low-level physics tests, referred to as Curve B; and (c) core critical operation, referred to as Curve C. There are three vessel regions that affect the operating limits: the closure flange region, the core beltline region, and the remainder of the vessel, or non-beltline regions. The closure flange region limits are controlling at lower pressures primarily because of 10CFR50 Appendix G [1] requirements. The non-beltline and beltline region operating limits are evaluated according to procedures in 10CFR50 Appendix G, Appendix G of the ASME Code [7] and Welding Research Council (WRC) Bulletin 175 [8], with the beltline region minimum temperature limits adjusted to account for vessel irradiation.

Figure 4-1 has curves applicable, per Rev 2, for 17 EFPY of operation. Figure 4-2 has curves applicable for 32 EFPY. The requirements for each vessel region influencing the P-T curves are discussed below. Tables 4-1 and 4-2 have tabulations of the P-T values for Figures 4-1 and 4-2, respectively.

4.2 NON-BELTLINE REGIONS

Non-beltline regions are those locations that receive too little fluence to cause any RTNDT increase. Non-beltline components include the nozzles, the closure flanges, some shell plates, top and bottom head plates and the control rod drive (CRD) penetrations. Detailed stress analyses, specifically for the purpose of fracture toughness analysis, of the non-beltline components were performed for the BWR/6. The analyses took into account all mechanical loadings and thermal transients anticipated. Transients considered included 100°F/hr startup and shutdown, SCRAM, loss of feedwater heaters or flow, loss of recirculation pump flow, and all transients involving emergency core cooling injections. Primary membrane and bending stresses and secondary membrane and bending stresses due to the most severe of these transients were used according to [7] to develop plots of allowable pressure (P) versus temperature relative to the reference temperature (T - RT_{NDT}). Plots were developed for the two most limiting BWR/6 regions; the feedwater nozzle and the CRD penetration regions. All other non-beltline regions are categorized under one of these two regions.

The BWR/6 results have been applied to earlier BWR non-beltline vessel components, based on the facts that earlier vessel component geometries are not significantly different from BWR/6 configurations and mechanical and thermal loadings are comparable.

The BWR/6 non-beltline region results were applied to Oyster Creek by adding the highest Oyster Creek RT_{NDT} values for the non-beltline discontinuities to the appropriate P versus (T - RT_{NDT}) curves for the BWR/6 CRD penetration or feedwater nozzle. Table 2-1 shows the most limiting non-beltline RT_{NDT} values for the non-beltline components. The CRD return nozzle RT_{NDT} of 60°F is used with the BWR/6 feedwater nozzle curve. The bottom head RT_{NDT} of 66°F is used with the CRD penetration curve.

There are two nozzles in the Oyster Creek vessel which are not found in later BWR vessels. These are the recirculation inlet nozzle and the isolation condenser nozzle. These nozzles were reviewed to assure that the limits developed for BWR/6 would apply.

The recirculation inlet nozzle is a 1.41 inch thick ring forging welded to the outside of the vessel at the inlet penetration. Since the forging is less than 2.5 inches thick, it is exempt from fracture toughness analysis per ASME Appendix G, paragraph G-2223(c), as long as the RT_{NDT} is at least 60°F below the lowest service temperature. Table 2-1 shows the RT_{NDT} for the forging, 23°F. This is more than 60°F below the lowest service temperature for this nozzle, based on a boltup temperature of 85°F, so adequate fracture toughness is assured.

The isolation condenser nozzle is approximately the same geometry as the feedwater nozzle. The Oyster Creek stress report [9] states that the thermal stresses for the feedwater nozzle are more severe than those for the isolation condenser nozzle. Therefore, the BWR/6 feedwater nozzle limits, adjusted to the highest RT_{NDT} for Oyster Creek nozzles, will provide conservative P-T limits for the isolation condenser nozzle.

4.2.1 Non-Beltline Monitoring During Pressure Tests

While the beltline curves are limiting for pressure test conditions, the non-beltline limits can still be applied to the other regions of the vessel. It is likely that, during leak and hydrostatic pressure testing, the bottom head or top head temperature may be significantly cooler than the beltline. This condition can occur in the bottom head when the recirculation pumps are operating at low speed, or are off, and injection through the control rod drives is used to pressurize the vessel. It is also possible that heat losses from the top head could make it difficult to maintain the same temperatures as those in the beltline.

Monitoring the bottom head or top head separately from the beltline region may reduce the required pressure test temperature by 10°F to 20°F. Some hypothetical temperatures demonstrating the potential benefit of separate bottom head monitoring are shown in Figure 4-3. The Technical Specifications currently require that all vessel temperatures be above the limiting conditions on the P-T curve. That would mean that, for a leak test, the bottom head would have to be heated above 203°F at 17 EFPY, as shown in case (a) of Figure 4-3. The bottom head temperature reading would likely be the limiting reading on the vessel during the test. If, by using the bottom head curve, the required temperature for the bottom head were only 187°F, the limiting reading would probably be near the beltline, as shown in case (b), and the actual vessel temperatures could be lowered compared to case (a).

One condition on monitoring the bottom head or top head separately is that it must be demonstrated that the vessel beltline temperature can be accurately monitored during pressure testing. An experiment has been conducted at a BWR-4 which showed that thermocouples on the vessel near the feedwater nozzles, or temperature measurements of water in the recirculation loops provide good estimates of the beltline temperature during pressure testing. GPUN may need to confirm this before implementing separate monitoring of the bottom head or top head. First, however, it should be determined whether there are significant temperature differences between the beltline region and the bottom head or top head regions.

4.3 CORE BELTLINE REGION

The pressure-temperature (P-T) limits for the beltline region are determined according to the methods in ASME Code Appendix G [7]. As the beltline fluence increases during operation, these curves shift by an amount discussed in Section 3. Typically, the beltline curves shift to become more limiting than the non-beltline curves at some point during operating life. For the Oyster Creek vessel, the non-beltline curves were limiting through about 7 EFPY, at which point the beltline curves became more limiting at typical operating pressures.

The stress intensity factors (K_I), calculated for the beltline region according to ASME Appendix G procedures, were based on a combination of pressure and thermal stresses for a 1/4 T flaw in a flat plate. The pressure stresses were calculated using thin-walled cylinder equations. Thermal stresses were calculated assuming the through-wall temperature distribution of a flat plate subjected to a 100°F/hr thermal gradient. The ART values shown on Figure 3-1 were used to adjust the ($T - RT_{NDT}$) values from Figure G-2210-1 of [7]. More details on the methods used in computing beltline curves are contained in Appendix B.

The beltline P-T curves are calculated assuming an instantaneous heatup/cooldown rate of 100°F/hr. It is permitted to exceed this rate in the Technical Specification, as long as a 100°F change in any one hour period is not exceeded (also note that exceeding the 100°F/hr rate should not be normal practice). The impact on the P-T curves of heatup/cooldown rates in excess of 100°F/hr is discussed in Appendix C.

4.4 CLOSURE FLANGE REGION

10CFR50 Appendix G sets several minimum requirements for pressure and temperature, in addition to those outlined in the ASME Code, based on the closure flange region RT_{NDT}. In some cases, the results of analysis for other regions exceed these requirements and they do not affect the shape of the P-T curves. However, some closure flange requirements do impact the curves. In addition, General Electric has compared the current requirements and the original requirements in determining the minimum boltup temperature.

The current boltup temperature of 100°F is based on the assumption that materials were qualified to meet 30 ft-lb Charpy energy at 40°F, based on the vessel purchase specification. The original Code requirement was that boltup be done at qualification temperature(T_{30L}) plus 60°F. Current Code requirements state, in Paragraph G-2222(c) of [7], that for application of full bolt preload and reactor pressure up to 20% of hydrostatic test pressure, the RPV metal temperature must be at RT_{NDT} or greater. The approach used for Oyster Creek is to determine the highest value of (T_{30L} + 60) and the highest value of RT_{NDT} and base the boltup temperature on the more conservative value.

Table 2-1 shows the RT_{NDT} values for the closure flanges, the limiting closure head plate connected to the closure head flange and the limiting upper shell plate connected to the vessel flange. Connecting weld materials are not shown because they are less limiting than the plates. Table 2-1 shows the highest RT_{NDT} for the closure region to be 36°F for upper shell plate G-307-R1. Figure 4-4 shows the Charpy curve for G-307-R1. The value of T_{30L} is shown as 14°F, with $2\sigma_I = 10.6$°F, so that T_{30L} can be conservatively estimated as 25°F, and (T_{30L} + 60) is 85°F. Selecting the boltup temperature to be 85°F provides 49°F margin on the current Code requirement based on RT_{NDT}. This margin is appropriate, because boltup is one of the more limiting operating conditions (high stress and low temperature) for brittle fracture.

10CFR50 Appendix G, paragraph IV.A.2, sets minimum temperature requirements for pressure above 20% hydrotest pressure based on the RT_{NDT} of the closure region. Curve A temperature must be no less than (RT_{NDT} + 90°F) and Curve B temperature no less than RT_{NDT} + 120°F). The Curve A requirement causes a 41°F shift at 20% hydrotest pressure (375 psig) as shown in Figures 4-1 and 4-2. The Curve B requirement has essentially no impact on the figures because the analytical results for the non-beltline regions require that temperature be greater than 10CFR50 Appendix G requirement of (RT_{NDT} + 120°F) at 375 psig.

4.5 CORE CRITICAL OPERATION REQUIREMENTS OF 10CFR50, APPENDIX G

Curve C, the core critical operation curve shown in Figures 4-1 and 4-2, is generated from the requirements of 10CFR50 Appendix G, paragraph IV.A.3. Essentially paragraph IV.A.3 requires that core critical P-T limits be 40°F above any Curve A or B limits. Curve B is more limiting than Curve A, so Curve C is Curve B plus 40°F.

Another requirement of IV.A.3, or actually an allowance for the BWR, concerns minimum temperature for initial criticality in a startup. The BWR, given that water level is normal, is allowed initial criticality at the closure flange region (RT_{NDT} + 60°F) at pressures below 375 psig. This requirement makes the minimum criticality temperature 96°F, based on the RT_{NDT} of plate G-307-R1. Above 375 psig, the Curve C temperature must be at least that required for the hydrostatic pressure test (Curve A at 1100 psig). In Figure 4-1, the non-beltline curves are more limiting than this requirement at 375 psig, so there is no impact on the shape of the P-T curves. However, in Figure 4-2 there is a step at 375 psig in Curve C due to this requirement.

Table 4-1

P-T CURVE VALUES FOR 17 EFPY

Pressure (psig)	Limiting Curve Temperature (°F)			Non-Beltline Curve Temp. (°F)
	A	B	C	A
0	85.0	85.0	96.0	85.0
10	85.0	85.0	96.0	85.0
20	85.0	85.0	96.0	85.0
30	85.0	85.0	96.0	85.0
40	85.0	85.0	100.0	85.0
50	85.0	85.0	113.0	85.0
60	85.0	85.0	124.0	85.0
70	85.0	93.5	133.5	85.0
80	85.0	101.7	141.7	85.0
90	85.0	108.7	148.7	85.0
100	85.0	114.8	154.8	85.0
110	85.0	120.4	160.4	85.0
120	85.0	125.3	165.3	85.0
130	85.0	130.1	170.1	85.0
140	85.0	134.7	174.7	85.0
150	85.0	139.0	179.0	85.0
160	85.0	142.9	182.9	85.0
170	85.0	146.3	186.3	85.0
180	85.0	149.3	189.3	85.0
190	85.0	152.1	192.1	85.0
200	85.0	154.8	194.8	85.0
210	85.0	157.5	197.5	85.0
220	85.0	160.1	200.1	85.0
230	85.0	162.4	202.4	85.0
240	85.0	164.7	204.7	85.0
250	85.0	166.9	206.9	85.0
260	85.0	169.0	209.0	85.0
270	85.0	171.0	211.0	85.0
280	85.0	173.0	213.0	85.0
290	85.0	174.9	214.9	85.0
300	85.0	176.7	216.7	85.0
310	85.0	178.5	218.5	85.0
320	85.0	180.2	220.2	85.0
330	85.0	181.8	221.8	85.0
340	85.0	183.4	223.4	85.0
350	85.0	185.0	225.0	85.0
360	85.0	186.5	226.5	85.0
370	85.0	188.0	228.0	85.0
375	85.0	188.8	228.8	85.0
375	126.0	188.8	228.8	126.0
380	126.0	189.5	229.5	126.0
390	126.0	191.0	231.0	126.0
400	126.0	192.5	232.5	126.0
410	126.0	194.0	234.0	126.0
420	126.0	195.4	235.4	126.0
430	126.0	196.8	236.8	126.0
440	126.0	198.2	238.2	126.0
450	126.0	199.5	239.5	126.0
460	126.0	200.8	240.8	126.0
470	126.0	202.1	242.1	126.0
480	126.0	203.3	243.3	126.0

Table 4-1

P-T CURVE VALUES FOR 17 EFPY

Pressure (psig)	Limiting Curve Temperature (°F)			Non-Beltline Curve Temp. (°F)
	A	B	C	A
490	126.0	204.5	244.5	126.0
500	126.0	205.7	245.7	126.0
510	126.0	206.8	246.8	126.0
520	126.0	207.9	247.9	126.0
530	126.0	209.0	249.0	126.0
540	126.0	210.0	250.0	126.0
550	126.0	211.0	251.0	126.0
560	126.0	212.0	252.0	126.0
570	126.0	212.9	252.9	126.0
580	127.9	213.8	253.8	127.9
590	130.1	214.7	254.7	130.1
600	132.3	215.5	255.5	132.3
610	134.3	216.3	256.3	134.3
620	136.3	217.1	257.1	136.3
630	138.3	217.8	257.8	138.3
640	140.2	219.0	259.0	140.2
650	142.0	220.3	260.3	142.0
660	143.8	221.5	261.5	143.8
670	145.6	222.8	262.8	145.6
680	147.3	224.0	264.0	147.3
690	149.0	225.2	265.2	149.0
700	150.6	226.4	266.4	150.6
710	152.2	227.6	267.6	152.2
720	154.3	228.7	268.7	153.7
730	156.7	229.8	269.8	155.2
740	159.1	230.9	270.9	156.7
750	161.4	232.0	272.0	158.2
760	163.6	233.1	273.1	159.6
770	165.8	234.2	274.2	161.0
780	167.9	235.2	275.2	162.3
790	169.9	236.2	276.2	163.7
800	171.9	237.2	277.2	165.0
810	173.8	238.2	278.2	166.3
820	175.6	239.2	279.2	167.6
830	177.4	240.2	280.2	168.8
840	179.2	241.1	281.1	170.0
850	180.9	242.1	282.1	171.2
860	182.6	243.0	283.0	172.4
870	184.2	243.9	283.9	173.5
880	[illegible]	244.8	284.8	174.7
890	[illegible]	245.7	285.7	175.8
900	188.9	246.6	286.6	176.9
910	190.4	247.5	287.5	178.0
920	191.9	248.3	288.3	179.0
930	193.3	249.2	289.2	180.1
940	194.7	250.0	290.0	181.1
950	196.1	250.8	290.8	182.2
960	197.5	251.6	291.6	183.2
970	198.8	252.5	292.5	184.1
980	200.1	253.3	293.3	185.1
990	201.4	254.0	294.0	186.1

Table 4-1

P-T CURVE VALUES FOR 17 EFPY

Pressure (psig)	Limiting Curve Temperature (°F)			Non-Beltline Curve Temp. (°F)
	A	B	C	A
1000	202.6	254.8	294.8	187.0
1010	203.9	255.6	295.6	188.0
1020	205.1	256.4	296.4	188.9
1030	206.3	257.1	297.1	189.8
1040	207.4	257.9	297.9	190.7
1050	208.6	258.6	298.6	191.6
1060	209.7	259.3	299.3	192.5
1070	210.8	260.1	300.1	193.3
1080	211.9	260.8	300.8	194.2
1090	213.0	261.5	301.5	195.0
1100	214.0	262.2	302.2	195.8
1110	215.1	262.9	302.9	196.7
1120	216.1	263.6	303.6	197.5
1130	217.1	264.2	304.2	198.3
1140	218.1	264.9	304.9	199.1
1150	219.1	265.6	305.6	199.9
1160	220.1	266.2	306.2	200.6
1170	221.0	266.9	306.9	201.4
1180	222.0	267.6	307.6	202.2
1190	222.9	268.2	308.2	202.9
1200	223.8	268.8	308.8	203.7
1210	224.7	269.5	309.5	204.4
1220	225.6	270.1	310.1	205.1
1230	226.5	270.7	310.7	205.8
1240	227.4	271.3	311.3	206.5
1250	228.3	271.9	311.9	207.2
1260	229.1	272.5	312.5	207.9
1270	229.9	273.1	313.1	208.6
1280	230.8	273.7	313.7	209.3
1290	231.6	274.3	314.3	210.0
1300	232.4	274.9	314.9	210.7
1310	233.2	275.5	315.5	211.3
1320	234.0	276.0	316.0	212.0
1330	234.8	276.6	316.6	212.6
1340	235.6	277.2	317.2	213.3
1350	236.3	277.7	317.7	213.9
1360	237.1	278.3	318.3	214.5
1370	237.8	278.8	318.8	215.2
1380	238.6	279.4	319.4	215.8
1390	239.3	279.9	319.9	216.4
1400	240.0	280.5	320.5	217.0

Table 4-2

P-T CURVE VALUES FOR 32 EFPY

Pressure (psig)	Limiting Curve Temperature (°F)			Non-Beltline Curve Temp. (°F)
	A	B	C	A
0	85.0	85.0	96.0	85.0
10	85.0	85.0	96.0	85.0
20	85.0	85.0	96.0	85.0
30	85.0	85.0	96.0	85.0
40	85.0	85.0	100.0	85.0
50	85.0	85.0	113.0	85.0
60	85.0	85.0	124.0	85.0
70	85.0	93.5	133.5	85.0
80	85.0	101.7	141.7	85.0
90	85.0	108.7	148.7	85.0
100	85.0	114.8	154.8	85.0
110	85.0	120.4	160.4	85.0
120	85.0	125.3	165.3	85.0
130	85.0	130.1	170.1	85.0
140	85.0	134.7	174.7	85.0
150	85.0	139.0	179.0	85.0
160	85.0	142.9	182.9	85.0
170	85.0	146.3	186.3	85.0
180	85.0	149.3	189.3	85.0
190	85.0	152.1	192.1	85.0
200	85.0	154.8	194.8	85.0
210	85.0	157.5	197.5	85.0
220	85.0	160.1	200.1	85.0
230	85.0	162.4	202.4	85.0
240	85.0	164.7	204.7	85.0
250	85.0	166.9	206.9	85.0
260	85.0	169.0	209.0	85.0
270	85.0	171.0	211.0	85.0
280	85.0	173.0	213.0	85.0
290	85.0	174.9	214.9	85.0
300	85.0	176.7	216.7	85.0
310	85.0	178.5	218.5	85.0
320	85.0	180.2	220.2	85.0
330	85.0	181.8	221.8	85.0
340	85.0	183.4	223.4	85.0
350	85.0	185.0	225.0	85.0
360	85.0	186.5	226.5	85.0
370	85.0	188.0	228.0	85.0
375	85.0	188.8	228.8	85.0
375	126.0	188.8	234.0	126.0
380	126.0	189.9	234.0	126.0
390	126.0	192.5	234.0	126.0
400	126.0	197.2	237.2	126.0
410	126.0	199.6	239.6	126.0
420	126.0	201.8	241.8	126.0
430	126.0	204.0	244.0	126.0
440	126.0	206.2	246.2	126.0
450	126.0	208.2	248.2	126.0
460	126.0	210.2	250.2	126.0
470	126.0	212.2	252.2	126.0
480	126.0	214.1	254.1	126.0

Table 4-2

P-T CURVE VALUES FOR 32 EFPY

Pressure (psig)	Limiting Curve Temperature (°F)			Non-Beltline Curve Temp. (°F)
	A	B	C	A
490	126.0	215.9	255.9	126.0
500	126.0	217.7	257.7	126.0
510	126.0	219.5	259.5	126.0
520	126.0	221.2	261.2	126.0
530	126.0	222.9	262.9	126.0
540	126.0	224.5	264.5	126.0
550	126.0	226.1	266.1	126.0
560	126.0	227.7	267.7	126.0
570	126.0	229.2	269.2	126.0
580	127.9	230.7	270.7	127.9
590	130.3	232.1	272.1	130.1
600	134.8	233.6	273.6	132.3
610	139.1	234.9	274.9	134.3
620	143.2	236.3	276.3	136.3
630	147.0	237.7	277.7	138.3
640	150.6	239.0	279.0	140.2
650	154.1	240.3	280.3	142.0
660	157.3	241.5	281.5	143.8
670	160.5	242.8	282.8	145.6
680	163.5	244.0	284.0	147.3
690	166.3	245.2	285.2	149.0
700	169.1	246.4	286.4	150.6
710	171.7	247.6	287.6	152.2
720	174.3	248.7	288.7	153.7
730	176.7	249.8	289.8	155.2
740	179.1	250.9	290.9	156.7
750	181.4	252.0	292.0	158.2
760	183.6	253.1	293.1	159.6
770	185.8	254.2	294.2	161.0
780	187.9	255.2	295.2	162.3
790	189.9	256.2	296.2	163.7
800	191.9	257.2	297.2	165.0
810	193.8	258.2	298.2	166.3
820	195.6	259.2	299.2	167.6
830	197.4	260.2	300.2	168.8
840	199.2	261.1	301.1	170.0
850	200.9	262.1	302.1	171.2
860	202.6	263.0	303.0	172.4
870	204.2	263.9	303.9	173.5
880	205.8	264.8	304.8	174.7
890	207.4	265.7	305.7	175.8
900	208.9	266.6	306.6	176.9
910	210.4	267.5	307.5	178.0
920	211.9	268.3	308.3	179.0
930	213.3	269.2	309.2	180.1
940	214.7	270.0	310.0	181.1
950	216.1	270.8	310.8	182.2
960	217.5	271.6	311.6	183.2
970	218.8	272.5	312.5	184.1
980	220.1	273.3	313.3	185.1
990	221.4	274.0	314.0	186.1

Table 4-2

P-T CURVE VALUES FOR 32 EFPY

Pressure (psig)	Limiting Curve Temperature (°F)			Non-Beltline Curve Temp. (°F)
	A	B	C	A
1000	222.6	274.8	314.8	187.0
1010	223.9	275.6	315.6	188.0
1020	225.1	276.4	316.4	188.9
1030	226.3	277.1	317.1	189.8
1040	227.4	277.9	317.9	190.7
1050	228.6	278.6	318.6	191.6
1060	229.7	279.3	319.3	192.5
1070	230.8	280.1	320.1	193.3
1080	231.9	280.8	320.8	194.2
1090	233.0	281.5	321.5	195.0
1100	234.0	282.2	322.2	195.8
1110	235.1	282.9	322.9	196.7
1120	236.1	283.6	323.6	197.5
1130	237.1	284.2	324.2	198.3
1140	238.1	284.9	324.9	199.1
1150	239.1	285.6	325.6	199.9
1160	240.1	286.2	326.2	200.6
1170	241.0	286.9	326.9	201.4
1180	242.0	287.6	327.6	202.2
1190	242.9	288.2	328.2	202.9
1200	243.8	288.8	328.8	203.7
1210	244.7	289.5	329.5	204.4
1220	245.6	290.1	330.1	205.1
1230	246.5	290.7	330.7	205.8
1240	247.4	291.3	331.3	206.5
1250	248.3	291.9	331.9	207.2
1260	249.1	292.5	332.5	207.9
1270	249.9	293.1	333.1	208.6
1280	250.8	293.7	333.7	209.3
1290	251.6	294.3	334.3	210.0
1300	252.4	294.9	334.9	210.7
1310	253.2	295.5	335.5	211.3
1320	254.0	296.0	336.0	212.0
1330	254.8	296.6	336.6	212.6
1340	255.6	297.2	337.2	213.3
1350	256.3	297.7	337.7	213.9
1360	257.1	298.3	338.3	214.5
1370	257.8	298.8	338.8	215.2
1380	258.6	299.4	339.4	215.8
1390	259.3	299.9	339.9	216.4
1400	260.0	300.5	340.5	217.0

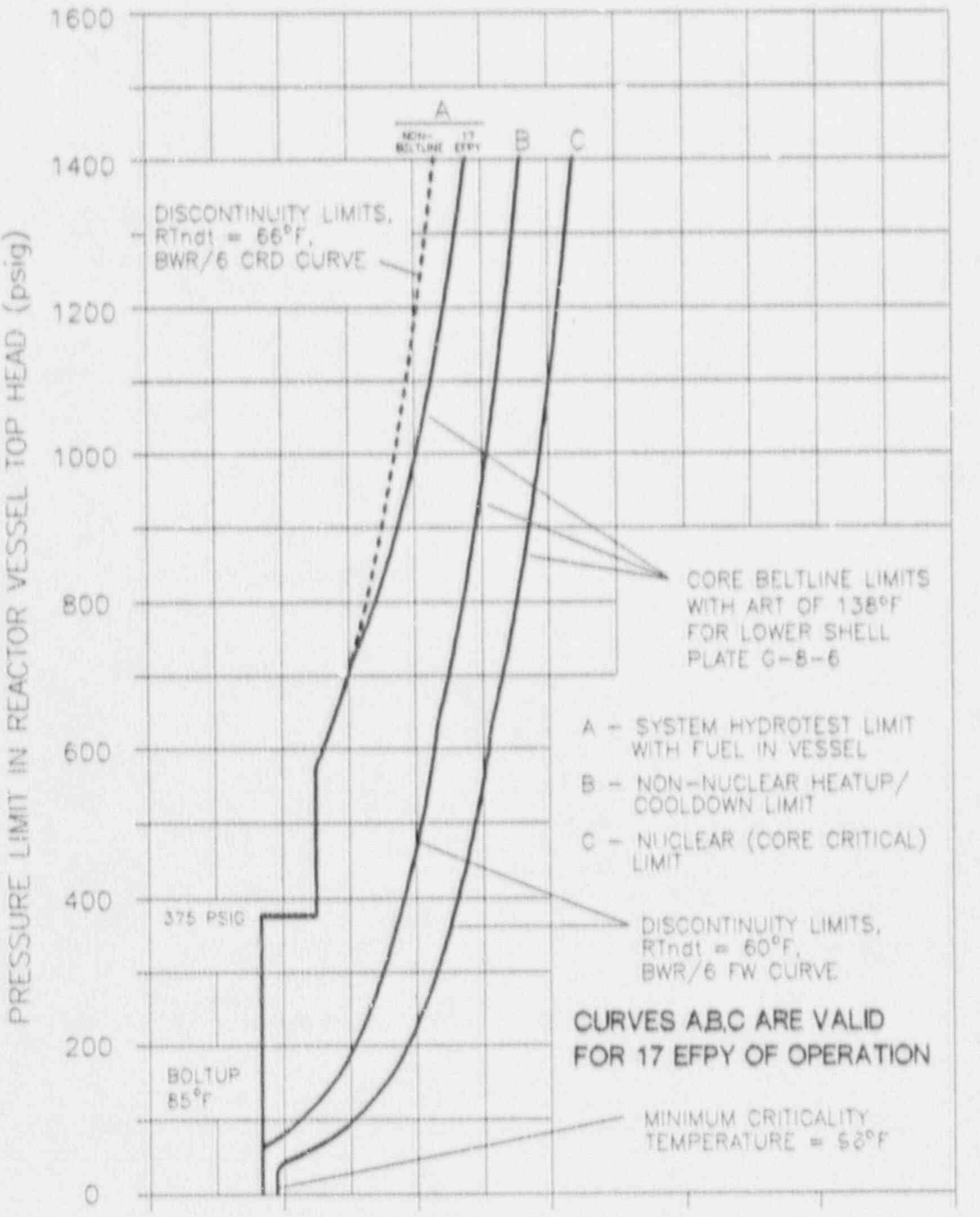


Figure 4-1. Oyster Creek P-T Curve Valid to 17 EFPY

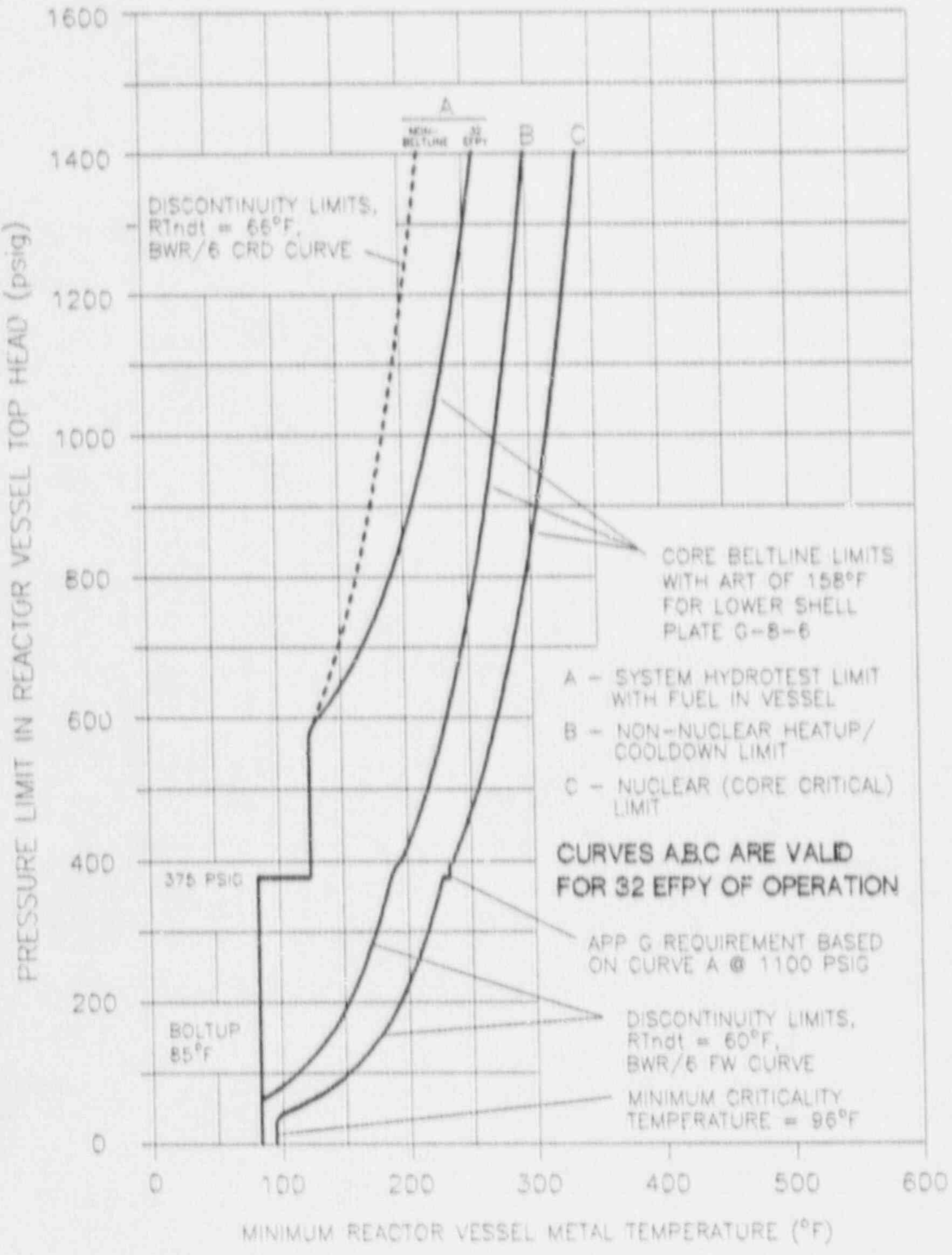
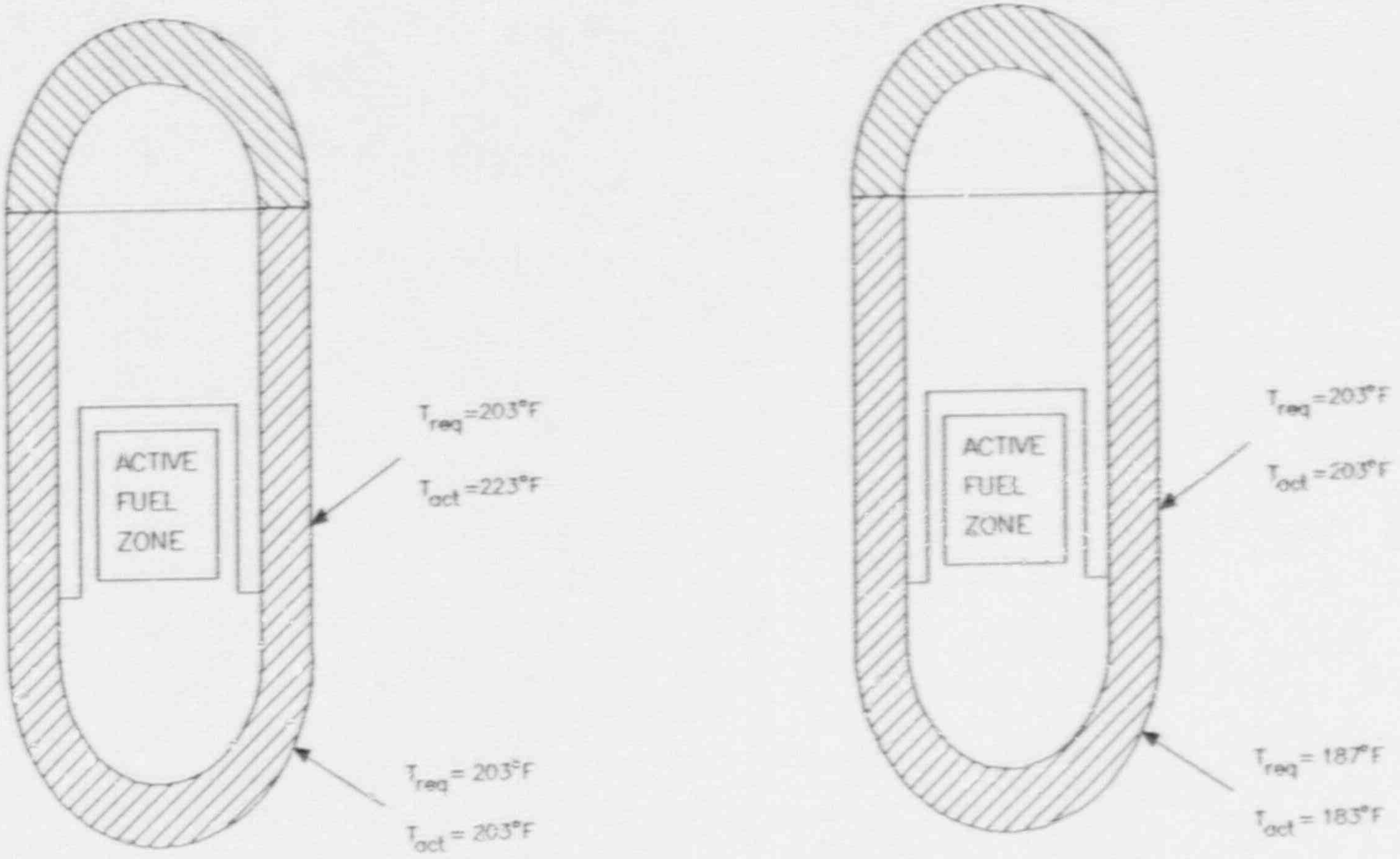


Figure 4-2. Oyster Creek P-T Curve Valid to 32 EFPY



a) Bottom Head Monitored with Beltline Limits

b) Bottom Head Monitored Separately

Figure 4–3. Hypothetical Case of Pressure Test Temperature Reduction from Separate Bottom Head Monitoring

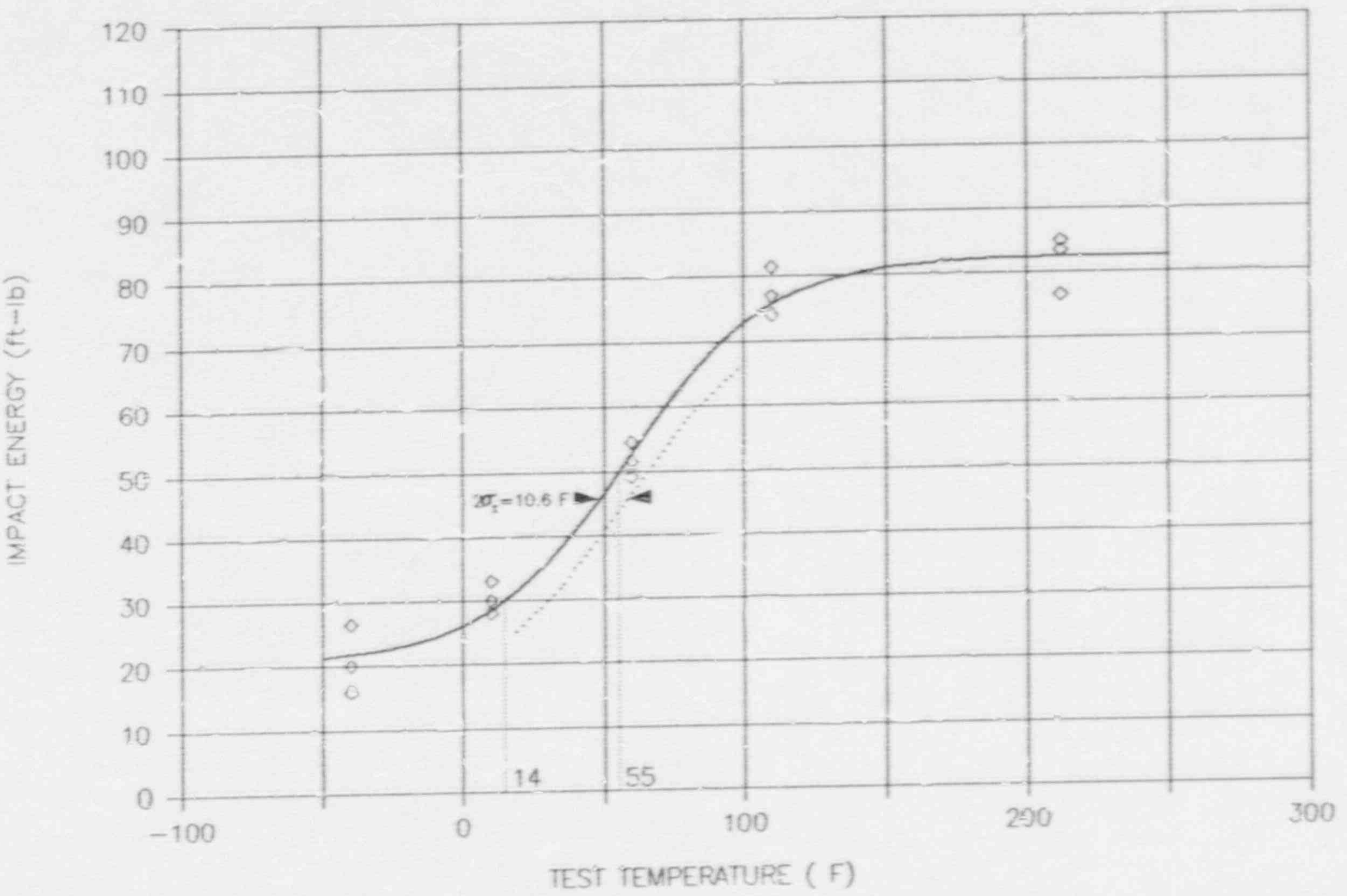


Figure 4-4. Determination of Boltup Temperature for Plate G-307-F1

5.0 REFERENCES

[1] "Fracture Toughness Requirements," Appendix G to Part 50 of Title 10 of the Code of Federal Regulations, July 1983.

[2] "Radiation Embrittlement of Reactor Vessel Materials," USNRC Regulatory Guide 1.99, Revision 2, May 1988.

[3] Hodge, J. M., "Properties of Heavy Section Nuclear Reactor Steels," Welding Research Council Bulletin 217, July 1976.

[4] "Fracture Toughness Requirements," USNRC Branch Technical Position MTEB 5-2, Revision 1, July 1981.

[5] M[illegible]er, R. L., "Testing and Evaluation of Irradiated Reactor Vessel Materials Surveillance Program Specimens," GPU Nuclear TDR 725, Revision 3 (to be published).

[6] Manahan et. al., "Examination, Testing and Evaluation of Specimens from the 210° Irradiated Pressure Vessel Surveillance Capsule for the Oyster Creek Nuclear Generating Station," Battelle Columbus Laboratories Report BCL-382-[illegible]-1, Revision 1, October 1985.

[7] "Fracture Toughness Criteria for Protection Against Failure," Appendix G to Section XI of the ASME Boiler & Pressure Vessel Code, 1989 Edition with 1989 Addenda.

[8] "PVRC Recommendations on Toughness Requirements for Ferritic Materials," Welding Research Council Bulletin 175, August 1972.

[9] Pierson et. al., "Analytical Report for Jersey Central Reactor Vessel," Combustion Engineering Report CENC-1143.

APPENDIX A

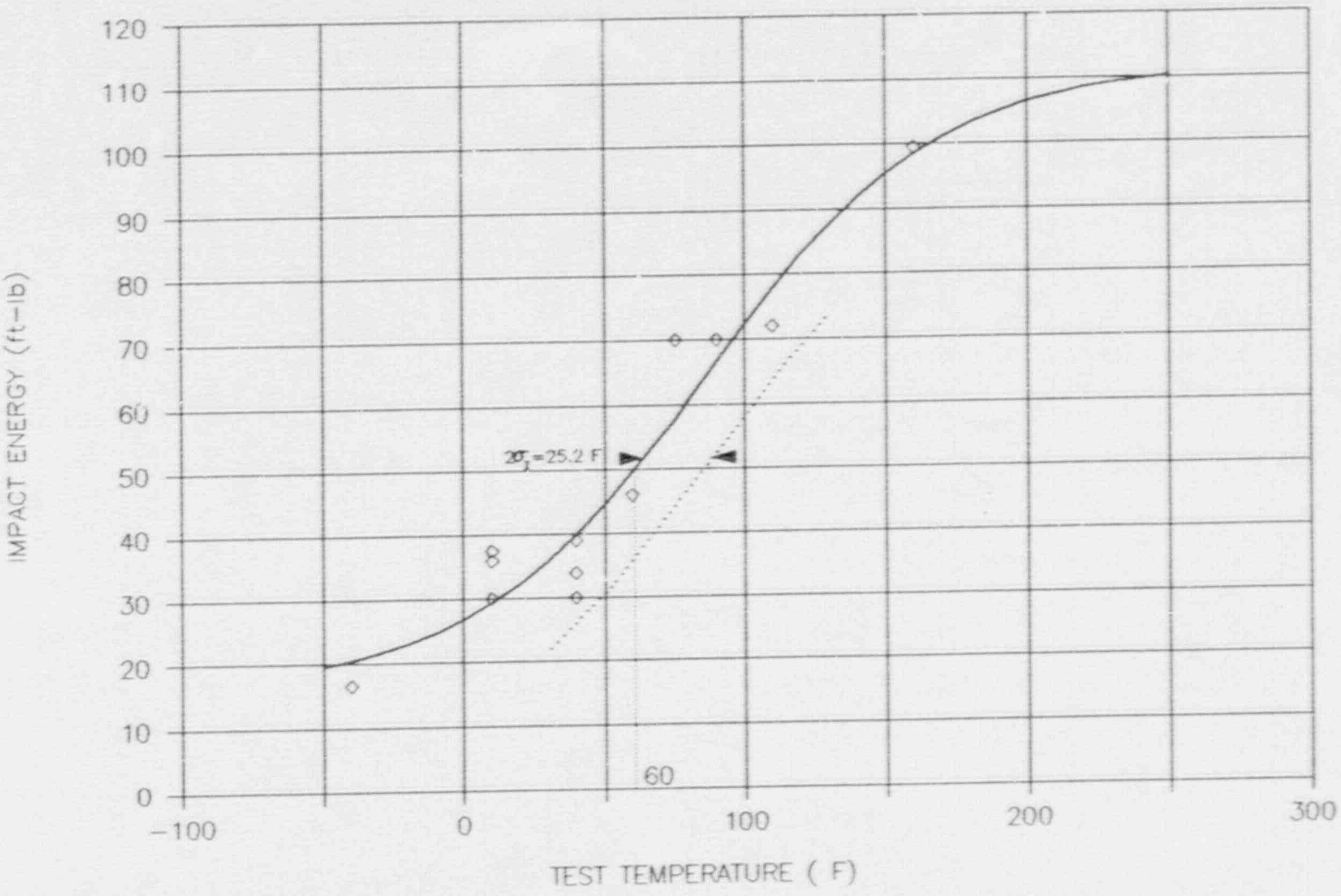
CHARPY CURVES OF SELECTED VESSEL PLATES

In order to establish an appropriate, conservative RT_{NDT} for the beltline plates and several other plates with low USE values, the Charpy data for each plate were curve fit with a hyperbolic tangent relationship:

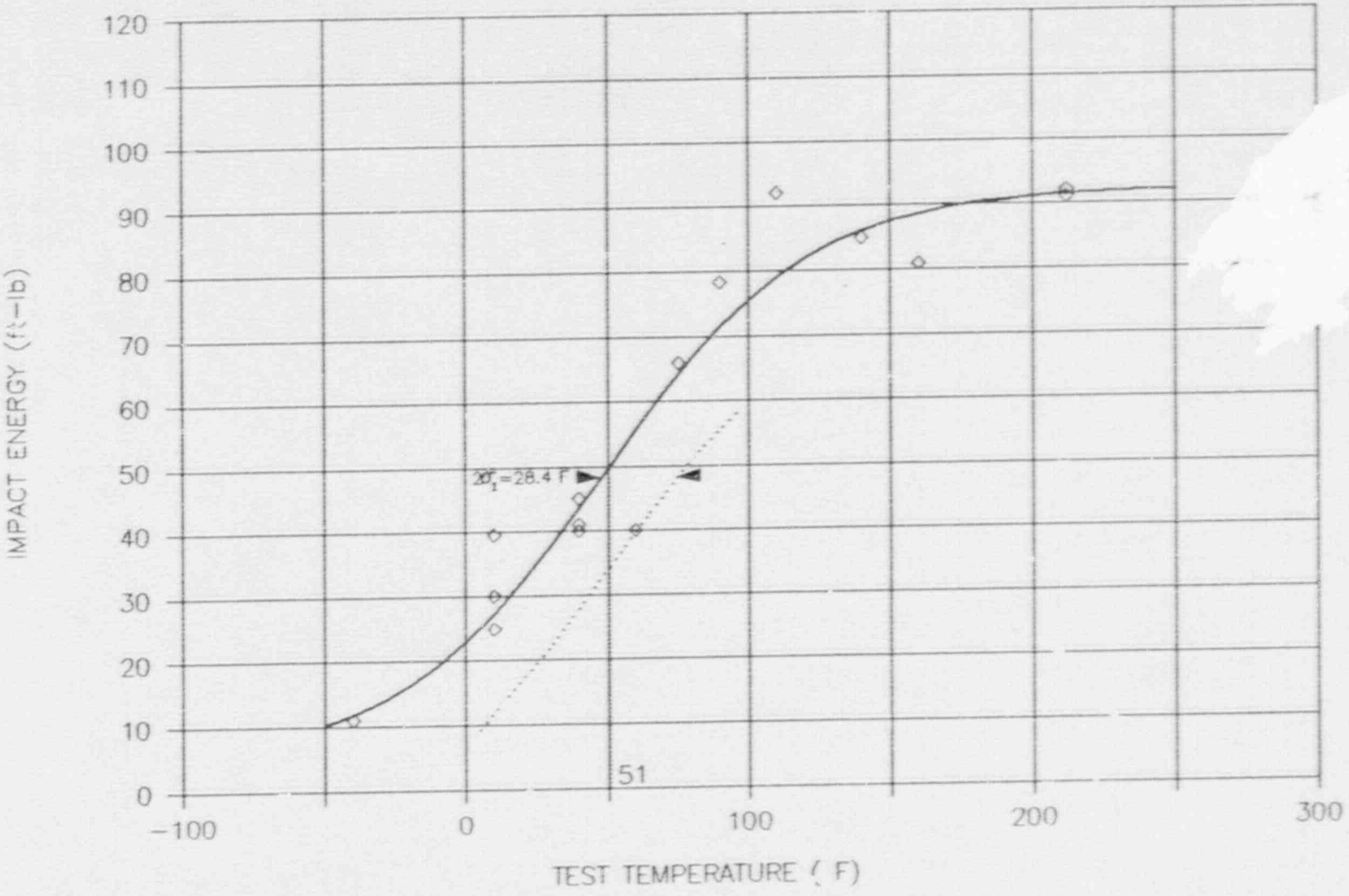
$$ENERGY = A + B \tanh [(T - T_o)/C]$$

where A, B, T_o and C are constants determined by statistically fitting the Charpy data to minimize variance.

Once the curve fit for each material was established, the standard deviation of the data relative to the curve (in terms of temperature) was calculated. These values are reported as σ_I in Section 2 of the report. The value of T_{50L} is shown on the curves in this appendix as well.



Initial Reference Temperature for Plate G−307−1



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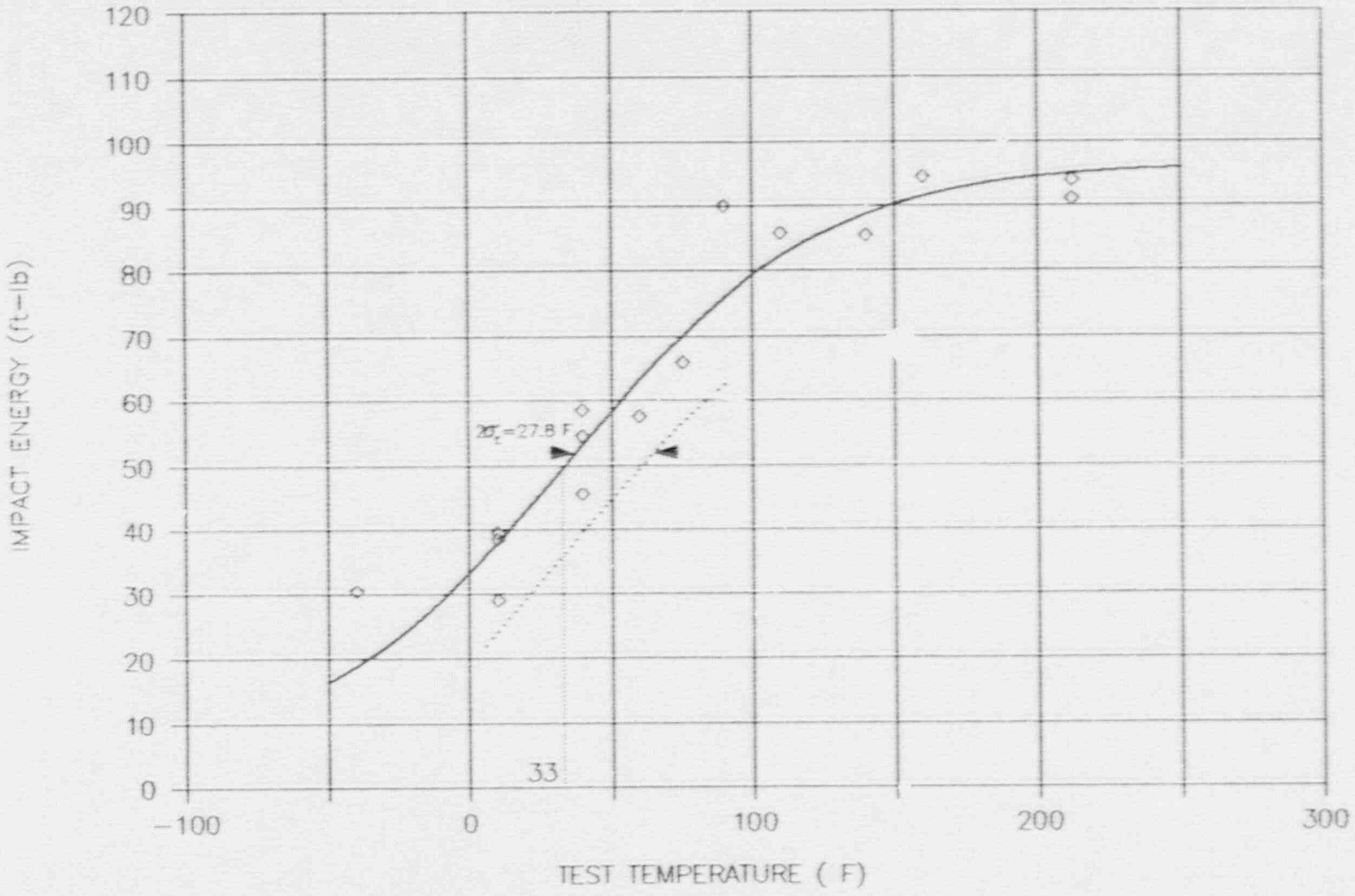
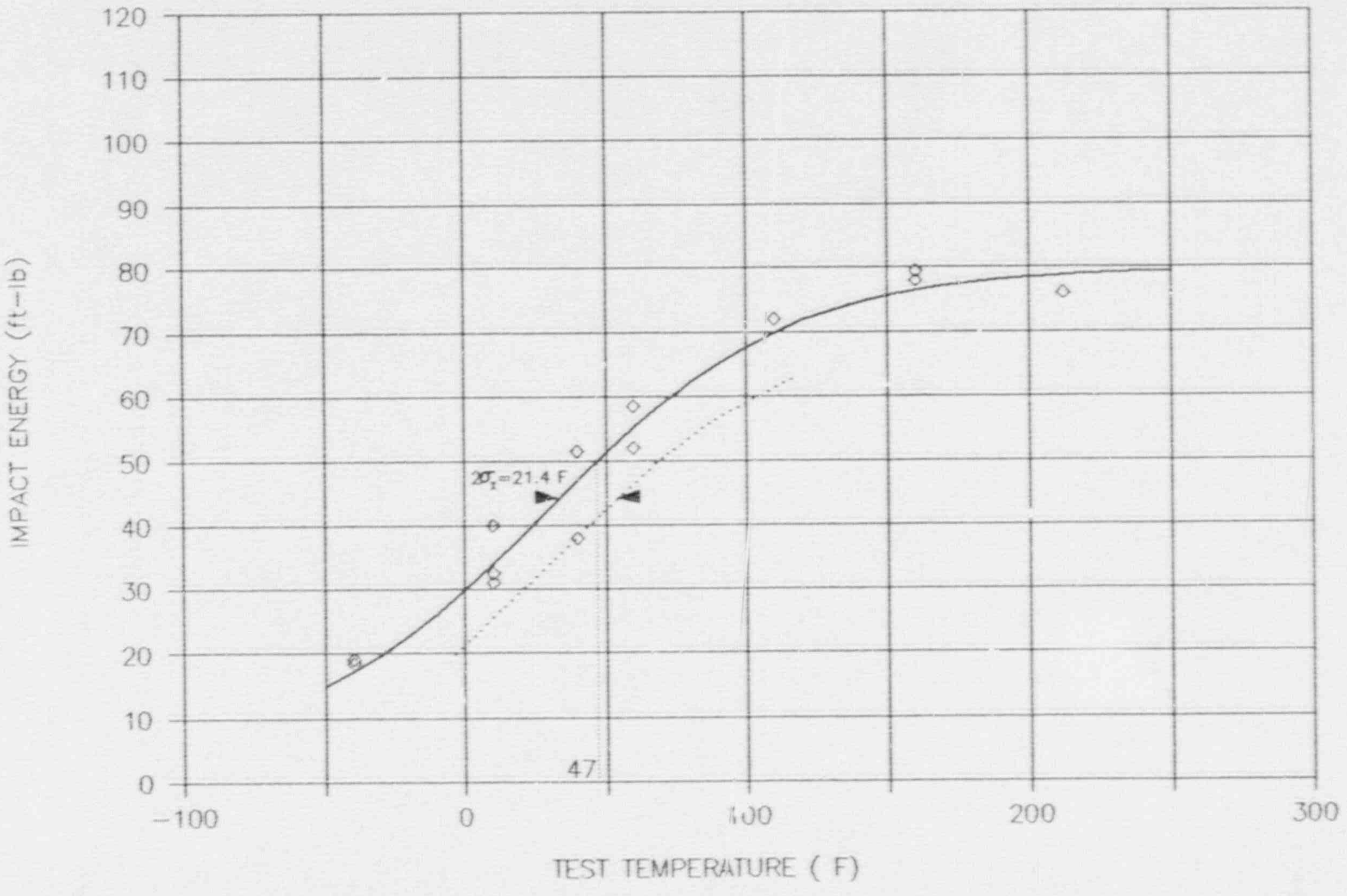
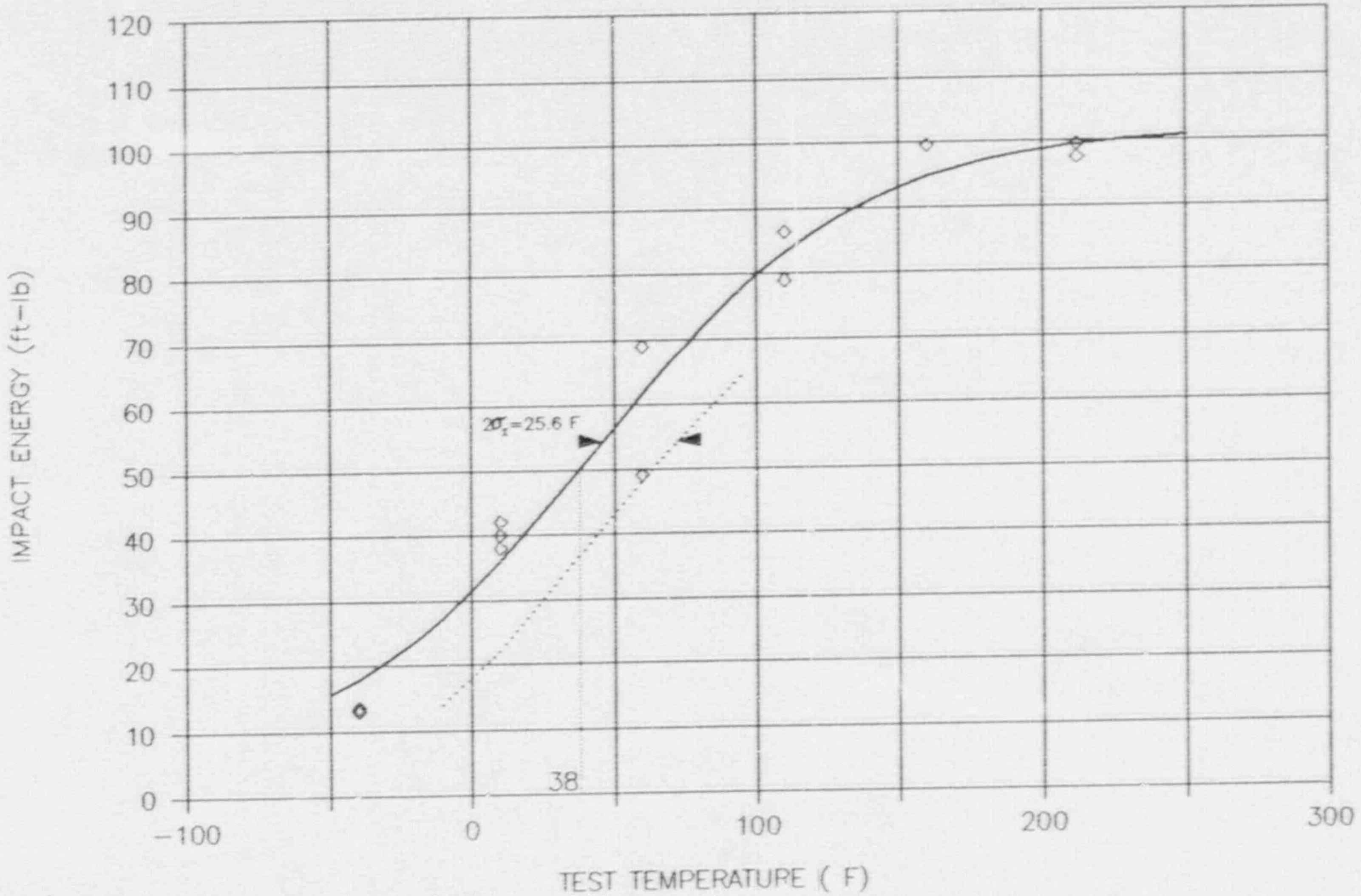


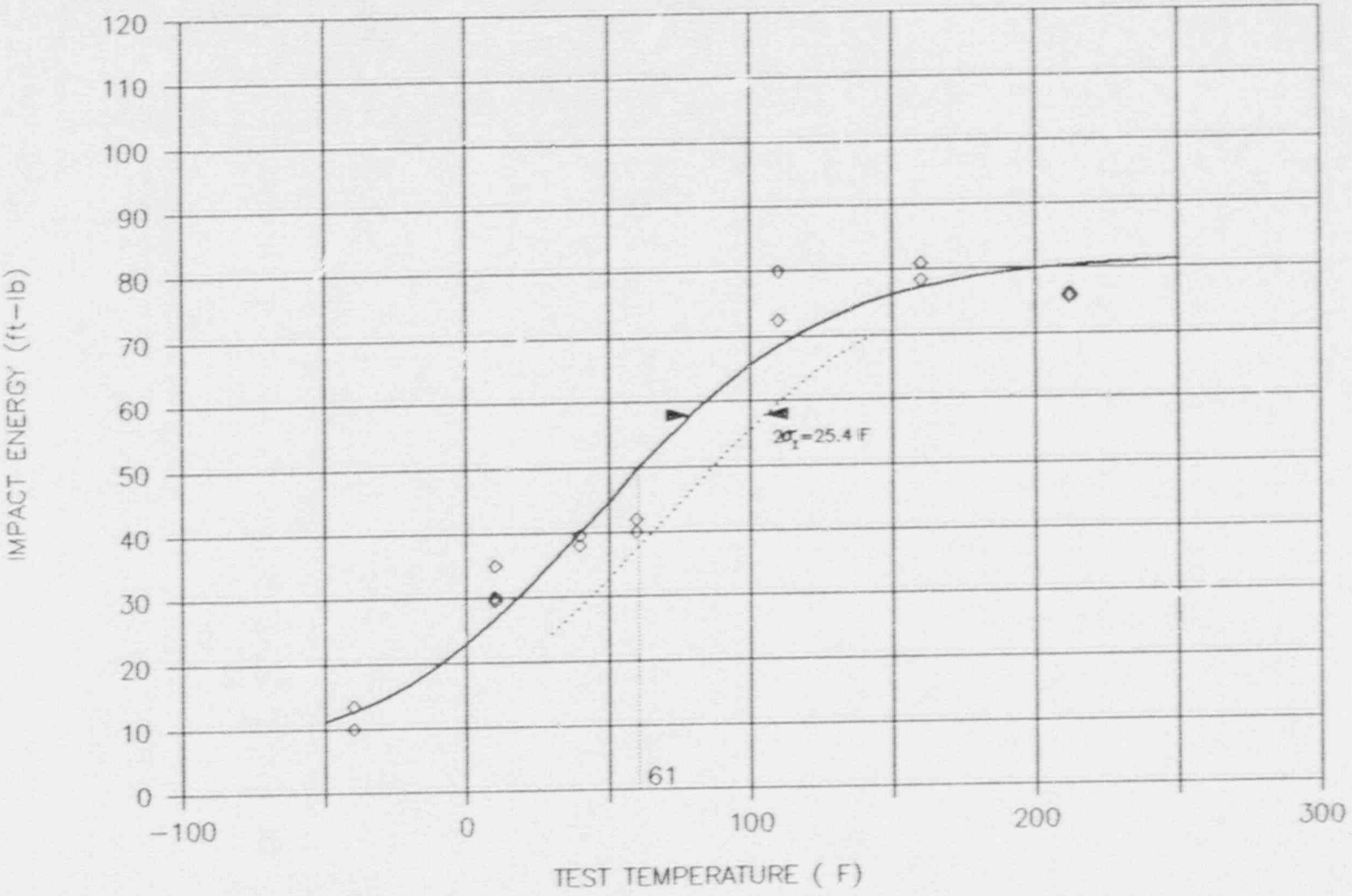
Initial Reference Temperature for Plate G-307-5



Initial Reference Temperature for Plate G-8-7



Initial Reference Temperature for Plate G-8-8



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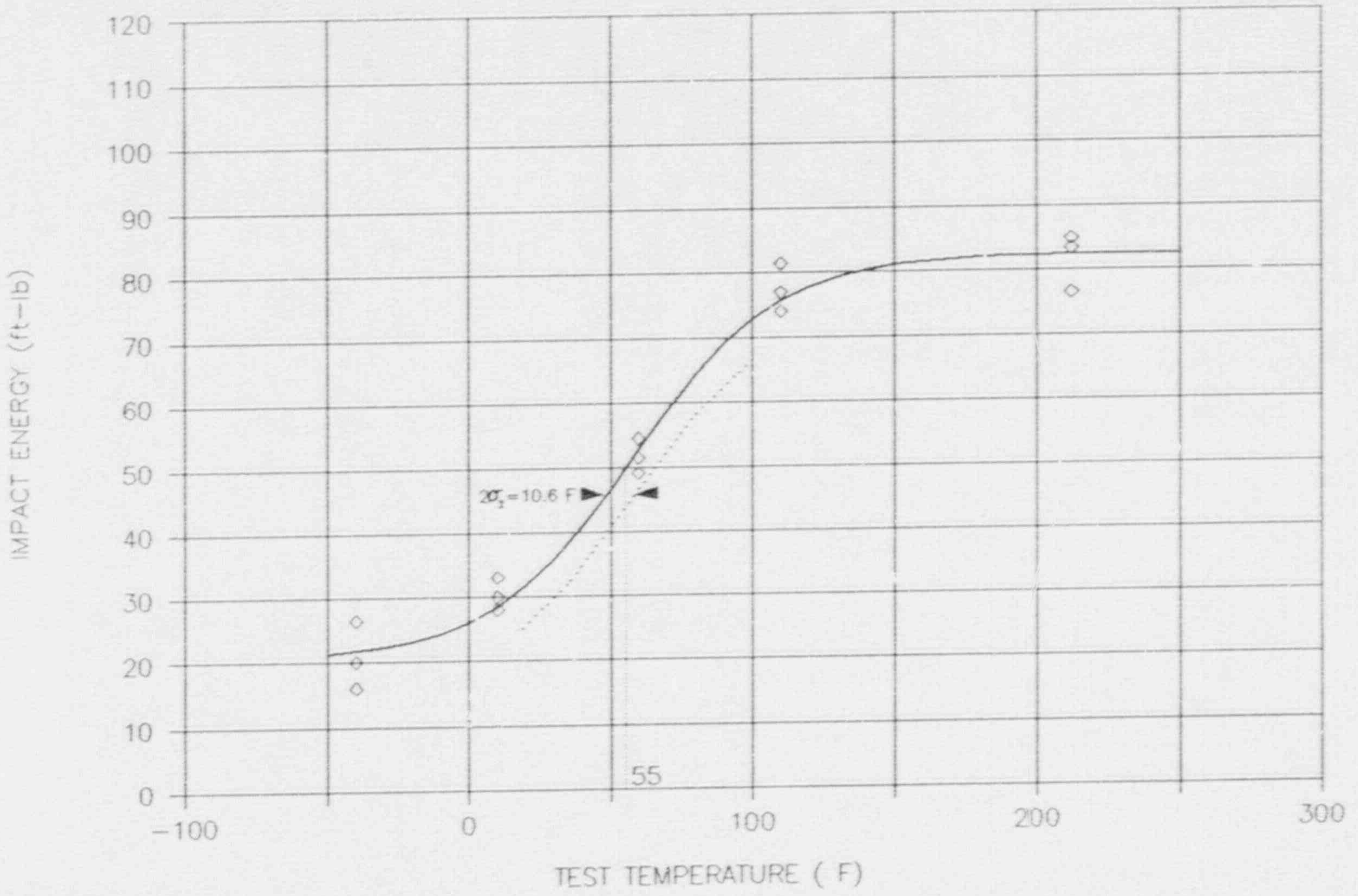
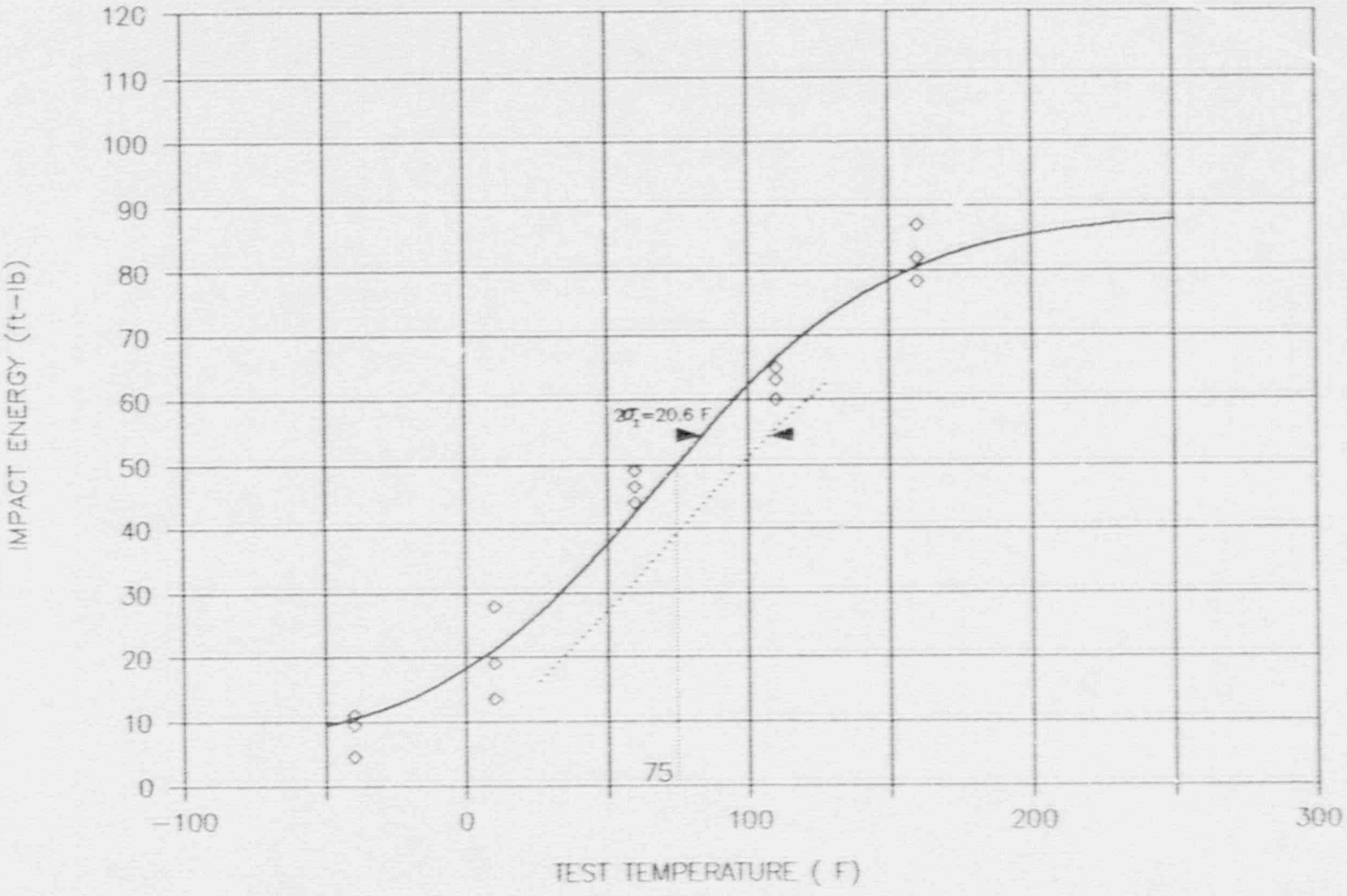


Initial Reference Temperature for Plate G–307–R1



Initial Reference Temperature for Plate G-301-4

APPENDIX B

BELTLINE P-T CURVE CALCULATION METHOD

The beltline is the region of the vessel that will accumulate more than 10^{17} n/cm² fluence during operation. The vessel wall from the bottom of active fuel to the top of active fuel meets these conditions. The Oyster Creek vessel beltline consists of two shells of plates and the connecting welds. Therefore, there are no discontinuity regions to consider in the beltline curve analyses. The methods used for the pressure test and heatup/cooldown curves are described below. The core critical operation curve is simply the heatup/cooldown curve plus 40°F, as required in 10CFR50 Appendix G [1], so the methods for the heatup/cooldown curves apply to the core critical curves as well.

B.1 PRESSURE TEST

In general, the methods of ASME Code Section III, Appendix G [7] are used to calculate the pressure test beltline limits. The vessel shell, with an inside radius (R) to minimum thickness (t_{min}) ratio of 15, is treated as a thin-walled cylinder. The maximum stress is the hoop stress, given as $\sigma_m = PR/t_{min}$.

The stress intensity factor, K_{Im}, is calculated using Figure G-2214-1 of [7], accounting for the proper ratio of stress to yield strength. Figure G-2214-1 was taken from Welding Research Council (WRC) Bulletin 175 [8], and is based on a 1/4 T radial flaw with a six-to-one aspect ratio (length of 1.5 T). The flaw is oriented normal to the maximum stress, in this case a vertically oriented flaw. This orientation is used even in the case where the circumferential weld is the limiting beltline material, as mandated by the NRC in the past.

Pressure test K_{IR} is the calculated value K_{Im} multiplied by a safety factor of 1.5, per [7]. The relationship between K_{IR} and temperature relative to reference temperature ($T - RT_{NDT}$) is shown in Figure G-2210-1 of [7], represented by the relationship

$$K_{IR} = 26.78 + 1.233\, e^{[\,0.0145\,(\,T - RT_{NDT} + 160\,)]} \qquad \text{(B-1)}$$

This relationship is derived in [8] as the lower bound of all dynamic fracture toughness and crack arrest toughness data. This relationship provides values of pressure (from K_{IR}) versus T (from ($T-RT_{NDT}$)).

B.2 HEATUP/COOLDOWN

The beltline curves for heatup/cooldown conditions are influenced by pressure stresses and thermal stresses, according to the relationship in [7]

$$K_{IR} = 2.0\, K_{Im} + K_{It}, \qquad \text{(B-2)}$$

where K_{Im} is primary membrane K due to pressure and
K_{It} is radial thermal gradient K due to heatup/cooldown.

The pressure stress intensity factor K_{Im} is calculated by the method described in section B.1, the only difference being the larger safety factor applied. The thermal gradient stress intensity factor calculation is described below.

The thermal stresses in the vessel wall are caused by a radial thermal gradient which is created by changes in the adjacent reactor coolant temperature in heatup or cooldown conditions. The stress intensity factor is computed by multiplying the coefficient M_t from Figure G-2214-2 of [7] by the through-wall temperature gradient ΔT_w, given that the temperature gradient has a through-wall shape similar to that shown in Figure G-2214-3 of [7].

The relationship used to compute through-wall ΔT_w is based on one-dimensional heat conduction through an insulated flat plate:

$$\delta^2 T(x,t)/\delta x^2 = 1/\beta\ (\delta T(x,t)/\delta t), \text{ where} \qquad (B\text{-}3)$$

$T(x,t)$ is temperature of the plate at depth x and time t
β is thermal diffusivity (ft²/hr).

Maximum stress will occur when the radial thermal gradient reaches a quasi-steady state distribution, so that $\delta T(x,t)/\delta t = dT(t)/dt = G$, where G is the heatup/cooldown rate, in this case 100°F/hr. The differential equation is integrated over x for the following boundary conditions, shown in Figure B-1:

1. Vessel inside surface ($x = 0$) temperature is the same as the coolant temperature, T_o.

2. Vessel outside surface ($x = C$) is perfectly insulated, so the thermal gradient $dT/dx = 0$.

The integrated solution results in the following relationship for wall temperature:

$$T = Gx^2/2\beta - GCx/\beta + T_o \qquad (B\text{-}4)$$

This equation is normalized to plot $(T - T_o)/\Delta T_w$ versus x/C in Figure B-2. The resulting through-wall gradient compares very closely with Figure G-2214-3 of [7]. Therefore, ΔT_w calculated from Equation B-4 is used with the appropriate M_t of Figure G-2214-2 of [7] to compute K_{It} for heatup and cooldown.

The M_t relationships were derived in [8] for infinitely long cracks of 1/4 T and 1/8 T. For the flat plate geometry and radial thermal gradient, orientation of the crack is not important.

The stress generated by the thermal gradient is a bending stress that changes sign from one side of the plate to the other. In combining pressure and thermal stresses, it is usually necessary to evaluate stresses at the 1/4 T location (inside surface flaw) and the 3/4 T location (outside surface flaw). This is because the thermal gradient tensile stress of interest is in the inner wall during cooldown and is in the outer wall during heatup. However, as a conservative simplification, the thermal gradient stress at the 1/4 T is assumed to be tensile for both heatup and cooldown. This results in the conservative approach of applying the maximum tensile stress at the 1/4 T location. This approach is conservative because irradiation effects cause the allowable toughness, K_{IR}, at 1/4 T to be less than that at 3/4 T for a given metal temperature. This conservatism of the approach causes no operation difficulties, since the BWR is at steam saturation conditions during normal heatup or cooldown, well above the heatup/cooldown curve limits.

B.3 EXAMPLE CALCULATION - 17 EFPY PRESSURE TEST AT 1000 PSIG

The following inputs were used in the beltline limit calculation:

ART	138°F
Vessel Height	766 inch
Bottom of Active Fuel Height	209.3 inch
Vessel Radius	106.7 inch
Vessel Thickness	7.125 inch
Beltline Material S_y	62.7 ksi

Pressure was calculated to include hydrostatic pressure for a full vessel:

$$P = 1000 \text{ psi} + (766-209.3)\text{inch} * 0.0361 \text{ psi/inch} = \underline{1020.1 \text{ psig}}$$

Pressure stress:

$$\sigma = PR/t = 1020.1 \text{ psig} * 106.7 \text{ inch} / 7.125 \text{ inch} = \underline{15276 \text{ psi}}$$

The factor M_m depends on (σ/S_y) and $\sqrt{t}$:

$$\sigma/S_y = 15276 / 62700 = 0.24 \text{ (use } \sigma/S_y = 0.5)$$
$$\sqrt{t} = (7.125)^{1/2} = 2.67$$

$$M_m = \underline{2.57}$$

The stress intensity factor, K_{Im}, is $M_m * \sigma$:

$$K_{Im} = 2.57 * 15276 = 39259 \text{ psi}\sqrt{\text{in}} = \underline{39.3 \text{ ksi}\sqrt{\text{in}}}$$

Equation (B-1) can be rearranged, and $1.5*K_{Im}$ substituted for K_{IR}, to solve for $(T - RT_{NDT})$:

$$(T - RT_{NDT}) = \ln[(1.5*K_{Im} - 26.78)/1.233]/0.0145 - 160$$
$$(T - RT_{NDT}) = \ln[(1.5*39.3 - 26.78)/1.233]/0.0145 - 160$$
$$(T - RT_{NDT}) = \underline{65°F}$$

Adding the adjusted RT_{NDT} for 17 EFPY of 138°F:

$$\underline{T = 203°F}$$

B.4 EXAMPLE CALCULATION - 17 EFPY HEATUP/COOLDOWN CURVE AT 1000 PSIG

The heatup/cooldown curve at 1000 psig uses the same K_{Im} as the pressure test curve, but with a safety factor of 2.0 instead of 1.5. In addition, there is a K_{It} term for the thermal stress. The additional inputs used to calculate K_{It} are:

G = 100°F/hr
C = 7.34 inches, including clad thickness
β = 0.354 ft^2/hr at 550°F (most conservative value)

Equation B-4 can be solved for the through-wall temperature ($x=C$), resulting in the absolute value of ΔT for heatup or cooldown of

$$\Delta T = GC^2/2\beta$$

For the values above, ΔT = 52.8°F.

The analyzed case for thermal stress is a 1/4 T flaw depth with wall thickness of 7.34 inches. From ASME Appendix G Figure G-2214-2, the corresponding value of M_t is

$$M_t = 0.32$$

Thus the thermal stress intensity factor, $K_{It} = M_t * \Delta T$, is calculated to be

$$K_{It} = 16.9\ ksi/in$$

The pressure and thermal stress terms are substituted into Equation B-1 to solve for $(T - RT_{NDT})$:

$$(T - RT_{NDT}) = \ln[((2.0*39.2 + 16.9) - 26.78)/1.233]/0.0145 - 160$$
$$(T - RT_{NDT}) = 117°F$$

Adding the adjusted RT_{NDT} for 17 EFPY of 138°F:

$$T = 255°F$$

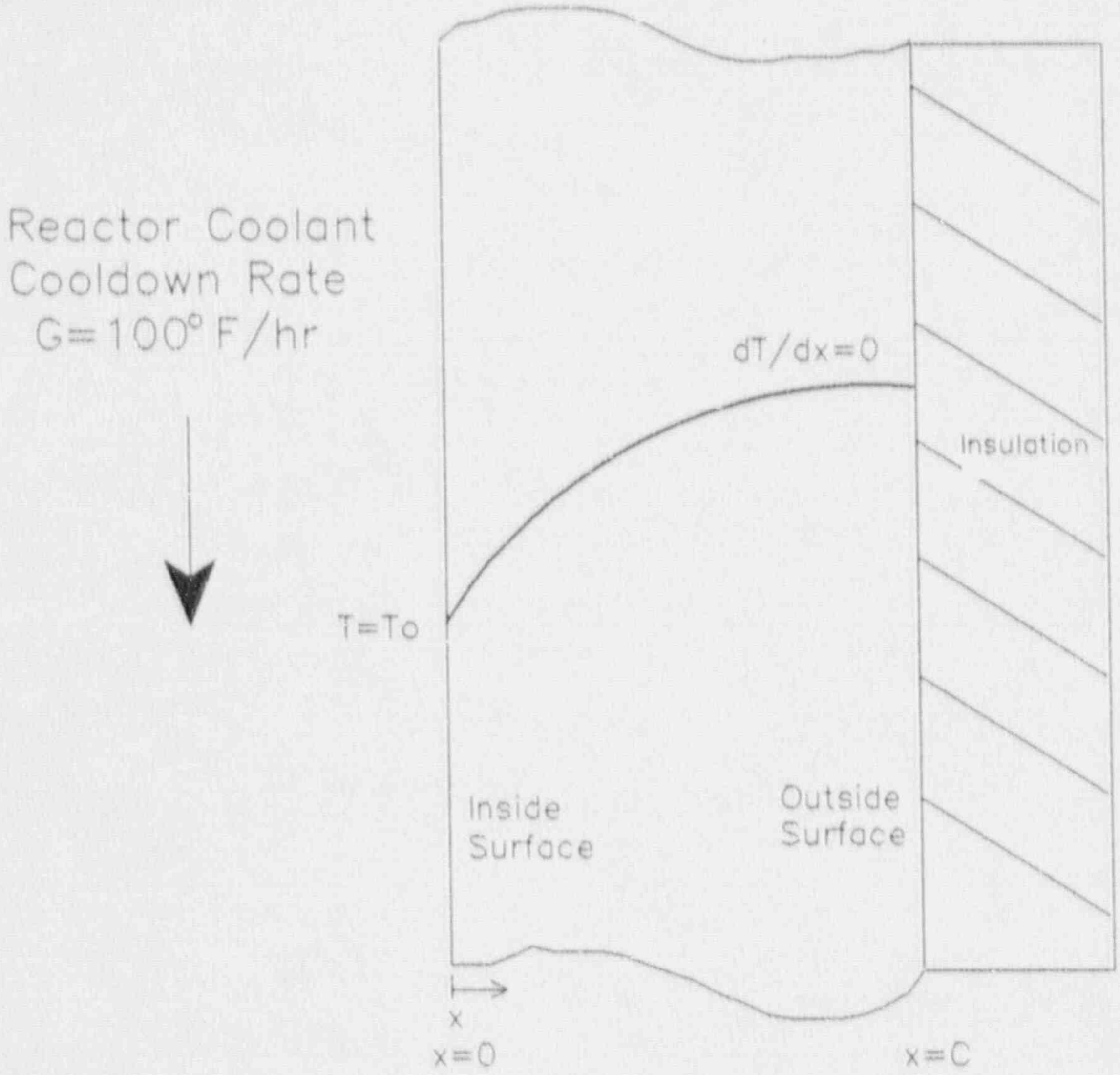


Figure B-1. Boundary Conditions for Heatup/Cooldown Temperature

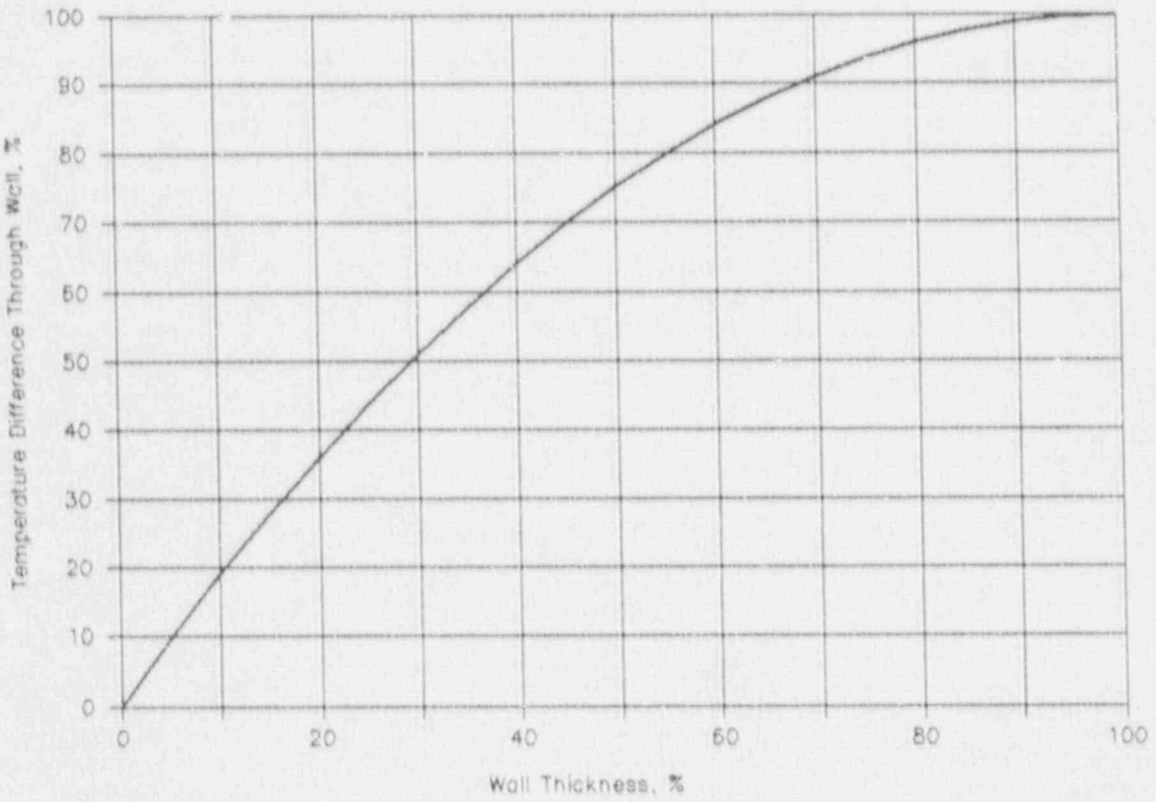


Figure B-2. Assumed Through-Wall Temperature During Heatup/Cooldown

APPENDIX C

IMPACT ON P-T CURVES OF HEATUP/COOLDOWN RATE

Given the form of the equation by which ΔT_w is determined, the heatup/cooldown rate of 100°F/hr for brittle fracture purposes refers to an instantaneous rate. Instantaneous rates in excess of 100°F/hr are allowed for in the Technical Specification, as long as a temperature change of 100°F in a one hour period is not exceeded. This is based on the fact that the 1/4 T location of the assumed flaw sees little if any effect of small perturbations in the 100°F/hr rate, due to the thermal inertia of the vessel wall. It is understood in this Tech Spec allowance that operators will track vessel coolant heatup or cooldown to stay as close to a 100°F/hr rate as possible.

The method of calculating K_{It} in Appendix B can be used to conservatively adjust the P-T curves for higher heatup/cooldown rates. While it is expected that short periods of excessive rates will not affect the 1/4 T location, a conservative approach is to increase the thermal K proportionally to the increased rate. Thus, for a 200°F/hr heatup or cooldown, K_{It} would double.

The calculation of beltline P-T limits was modified to include a 200°F/hr heatup/cooldown rate. The resulting P-T curve for 17 EFPY of operation is shown in Figure C-1. The non-beltline limits are not changed because they are based on more severe transient conditions at the discontinuities. In cases where the vessel coolant instantaneous heatup or cooldown rate, as measured by the steam dome pressure, exceeds 100°F/hr but is less than 200°F/hr, Figure C-1 can be used to assure that vessel P-T requirements have not been exceeded.

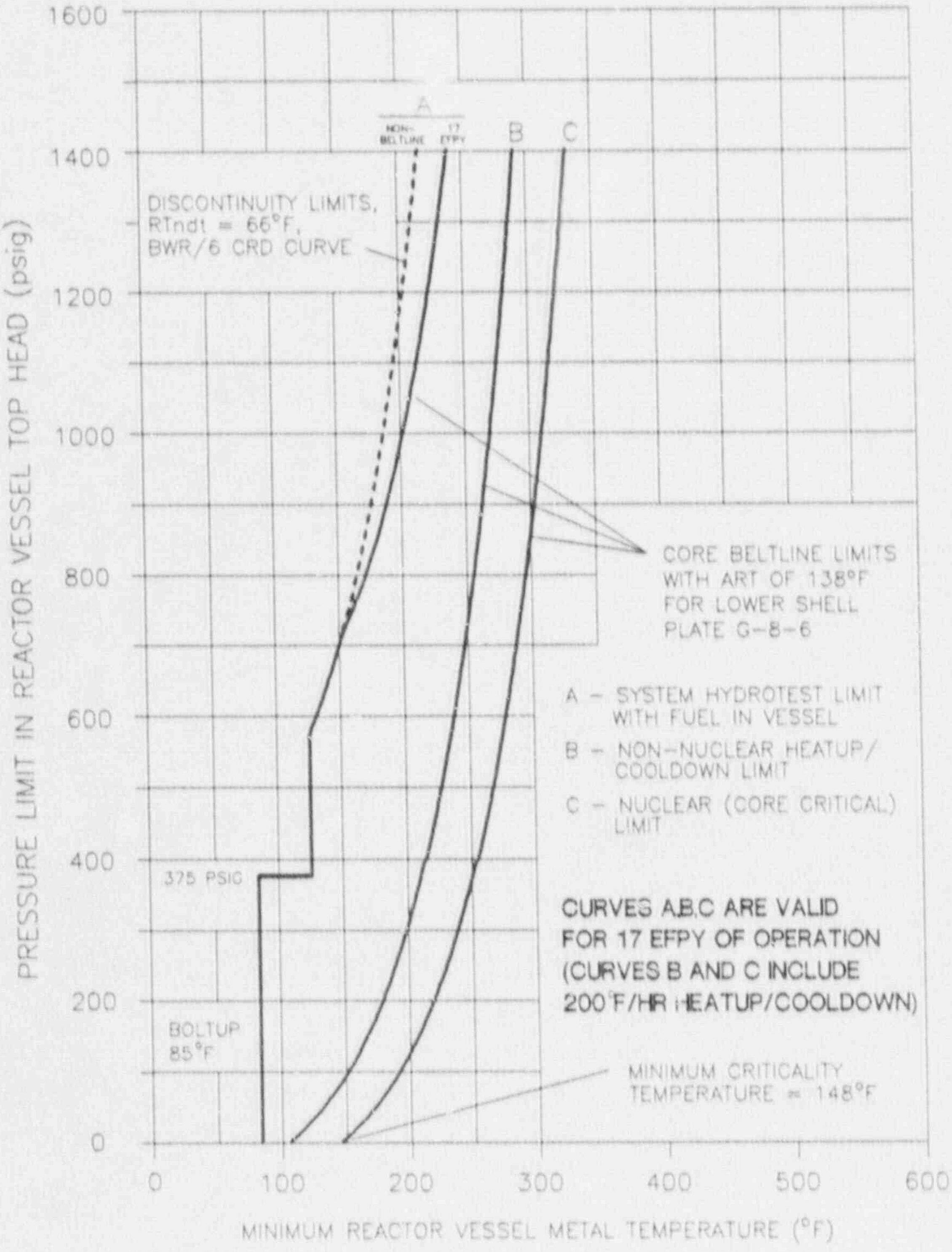


Figure C-1. Oyster Creek P-T Curve Valid to 17 EFPY